Waste Management Implications of Advanced Fuel Cycle Systems Using Fast Reactors (FR)

H. Funasaka, Y. Koma, K. Sato, Y. Nakajima, H. Shiotani, A. Katoh, T. Higuchi, T. Namba
Japan Atomic Energy Agency
4-49 Muramatsu, Tokai-mura, Ibaraki 319-1184
Japan

ABSTRACT

A Feasibility Study on commercialized FR cycle systems has been carried out by a Japanese joint team with the participation of all parties concerned in Japan since 1999. The results of Phase II (2001-2005) will be assessed until March 2006, and then the prospects for the promising concepts and the key issues for commercialization will be summarized. In this paper, the candidate reprocessing systems studied in Phase II are reviewed from the viewpoint of compatibility with the reduction of environmental burden, and a new approach (named the “ORIENT-cycle”), which aims at a fuel cycle system of “dirty fuel and clean waste,” is proposed for further evaluation.

INTRODUCTION

The extensive benefits of a fast reactor (FR) system are derived from a hardened neutron spectrum and good neutron economy. Utilizing those properties enables us to construct flexible nuclear fuel cycle systems including reactors and fuel cycle facilities that breed or burn Pu, transmute transuranium elements and long-lived fission products (FP) for reducing radiotoxicity, and enhance safety and non-proliferation.

Focusing on those properties of FR fuel cycles, the Feasibility Study on commercialized FR cycle systems (FS) has been conducted by a Japanese joint team with the participation of all parties concerned in Japan since 1999. This research program is intended to clarify various perspectives for commercializing the FR cycle system and also to suggest development strategies that correspond flexibly to diverse future needs in the 21st century. After Phase I (1999-2000), Phase II started in 2001 for five years. In this stage the highly feasible candidate concepts for FR cycle systems screened in the previous step were intensively studied by both design study and elemental process tests.

In Phase II (2001-2005), further system design studies for the selected fuel cycle concepts based on innovative technologies were carried out. Four main concepts (expressed in the combination form of “reprocessing technology + fuel fabrication technology”) were examined: “advanced aqueous process + pelletizing”, “advanced aqueous process + sphere pac” and “oxide electrolysis + vibro-packing (vipac)” for oxide fuel, and “metal electrorefining + casting” for metallic fuel. The design studies of the commercial plants for these concepts were performed for two levels of plant capacities (200 and 50 tons of heavy metals per year [tHM/y]) to see the dependency of the fuel cycle cost on plant capacity. The fuel cycle systems were designed so that these would meet as far as possible the development targets not only for reduction of environmental burden, but also for safety, economic competitiveness, efficient utilization of nuclear fuel resources and enhancement of nuclear non-proliferation. Experimental studies were been performed to clarify the feasibility of the selected concepts.

Design requirements for the fuel cycle system to decrease the volume of radioactive waste and rationalize the nuclear waste repository were pursued. The radioactive waste volume per unit power generation (m^3/GWh) should be less than for the LWR cycle systems, e.g., less than 5x10^{-4} m^3/GWh for high-level waste (HLW). Reduction of losses of U, Pu and minor actinide (MA: Np, Am, and Cm) to the waste stream is pursued to decrease radiotoxicity of the waste. For this, the value of less than 0.1% is used as a target for the limited losses of U and TRU (Pu and MA) processed in the fuel cycle system. In an FR cycle, MA nuclides, which are main heat sources of HLW, are to be recycled. As a result, the impacts of heat generation on vitrification could be mitigated in comparison with U/Pu recycling. In the design study, ease of decommissioning of the cycle plant and reduction of the radioactive waste generated in decommissioning have been taken into account as far as possible.

In this paper, the candidate fuel cycle systems examined in Phase II are outlined, and in particular the evaluation of each reprocessing system is presented from the viewpoint of compatibility with the reduction of environmental burden. In addition, a new concept of FR cycle named "ORIENT-cycle," in which HLW would be significantly reduced compared to conventional recycle, is briefly discussed.

CONCEPTUAL DESIGN

Design Requirements

The reprocessing plants were conceptually designed so that the following five design requirements would be satisfied as well as possible. The design requirement for safety is to identify measures of safety assurance, given the characteristics of the plant system, that would assure the same level of safety as that in an LWR reprocessing plant.

For economic competitiveness, the commercialized FR cycle system is intended to achieve a power generation cost comparable to that of future LWR cycle systems and other power generation systems. This goal requires a power generation cost of less than 4.0 Japanese Yen (JPY)/kWh, which in turn requires a fuel cycle cost of less than 1.1 JPY/kWh. Achieving this cost requires a reprocessing plus fuel fabrication cost of less than 0.8 JPY/kWh, excluding the transportation and waste disposal costs. The target cost for reprocessing is tentatively set to less than 0.5 JPY/kWh in this study.[1]

For reduction of environmental burden, the high-level and low-level radioactive waste volumes processed per unit power generation (m^3/GWh) should be less than that for the LWR cycle system, e.g., less than 5x10^{-4} m^3/GWh for HLW. In addition, reduction of the losses of TRU into the waste stream is pursued so as to decrease the radiotoxicity of the radioactive waste. With regard to this goal, a value of less than 0.1% is used as a target for the limited losses of TRU processed in the fuel cycle system. Ease of decommissioning of the cycle plant and reduction of the radioactive waste generated in decommissioning are pursued as far as possible.

For efficient use of resources, the recovery rate of actinides in the fuel cycle system is set to greater than 99 wt%.

For enhancement of nuclear non-proliferation, efficient implementation of the accounting and safeguard systems is factored into the plant system design. They are facilitated by remote monitoring, remote operation, appropriate material accountancy and prevention of pure Pu handling.

Design Conditions

Conceptual design studies of the FR fuel reprocessing plants were conducted assuming specific criteria. Major conditions for the design, including the design requirements mentioned above, are summarized in Table I. The plants can process mixed-oxide (MOX) or metallic spent fuel with an average burn up of 150 GWd/tHM (tons of heavy metal) for core fuel and a cooling time of four years, which is discharged from 1.5 GWe sodium-cooled FRs with two different breeding ratios: 1.10 for breeding core and 1.03 for break-even core.[2,3] Pu contents in fresh fuel are 18-23 wt% in HM for MOX fuel and 11-12 wt% for metallic fuel. The throughputs of 200 and 50 tHM/y (assuming net annual operation of 200 days, excluding maintenance and repair days) were chosen to investigate the effect of "plant capacity." Here, the value of HM weight is defined as that in the fresh fuel. A combined plant for reprocessing and fuel fabrication is designed to reduce the recycle cost. The plant also has one-year temporary storage for spent and fabricated fuels. Low decontamination in the reprocessing system is allowed by the characteristics of a FR using fast neutrons. In this study, a reasonably achievable value for FP concentration in fresh fuel is set for each reprocessing system considering their typical features as follows: 0.14wt% for NEXT and Super-DIREX, 1.4 wt% for Oxide Electrowinning, and 0.3 wt% for Metal Electrorefining.

Table I. Major Conditions for Design of the Reprocessing Plants

Spent fuel	MOX or metal fuel from 1.5 GWe sodium-cooled FR with two differen breeding ratios: 1.10 for breeding core and 1.03 for break-even core
Burn up	150 GWd/tHM (average of core fuel)
Cooling after discharge	4 years
Plant capacity referenced	200 tHM/y for NEXT, and 50 tHM/y for Super-DIREX, Oxide Electrowinning and Metal Electrorefining
Net annual plant operation time	200 days
Recovery of actinides (U and TRU each	> 99% in a recycling plant
FP content in fresh fuel (FP concentration in HM; depend on decontamination factor of FPs in each reprocessing system)	Reasonably achievable value is set for each reprocessing system considering its typical feature: 0.14wt% for NEXT and Super-DIREX, 1.4 wt% for Oxide Electrowinning, 0.3 wt% for Metal Electrorefining.
Pu partitioning	No isolation and purification for Pu
Function of plant	A combined plant of reprocessing and fuel fabrication
Target cost	< 0.8 JPY/kWh for reprocessing and fuel fabrication; < Tentatively 0.5 JPY/kWh for reprocessing
Pu content in fresh fuel (wt% in HM)	Around 18-23 wt% for MOX core fuel, around 11-12 wt% for metal core fuel

Reprocessing Systems and Their Plant Designs

Four reprocessing concepts, NEXT, Super-DIREX, Oxide Electrowinning for MOX fuel and Metal Electrorefining for metallic fuel shown in Fig.1 have been mainly studied in Phase II.

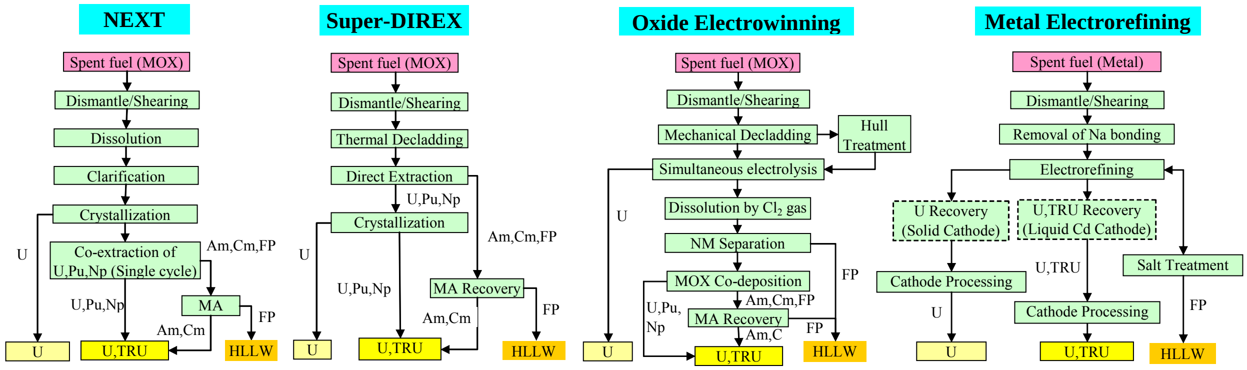


Fig. 1. Process flow diagram of four reprocessing concepts

The NEXT system consists of a simplified solvent extraction process with the addition of a U crystallization step and a MA recovery process using extraction chromatography. The fuel element is pulled out from the wrapper tube, sheared into small pieces of around 1 cm in length, and put into a dissolver to obtain a concentrated solution appropriate for a feed solution for crystallization. Prior to U crystallization, Pu valence is adjusted to tetravalent by NOX bubbling to avoid co-precipitation of Pu with U.[4] In the crystallization process, the nitric acid solution is chilled and around 70 wt% of U is crystallized as uranyl nitrate hexa-hydrate (UNH) to obtain a proper Pu concentration as a new MOX fuel. As a result, the capacity and solvent amount required for the subsequent extraction process is significantly decreased. The simplified solvent extraction process, namely a single-cycle co-extraction process without a following purification process, recovers U, Pu and Np simultaneously with a moderate decontamination factor (DF) of 10^4 or above.

A centrifugal contactor is used in this extraction process to minimize the contact time for extraction, which helps to suppress solvent degradation due to higher radioactivity of the FR spent fuel. For the MA recovery process, the extraction chromatography method was adopted on the basis of a comparison study with the solvent extraction method called "Solvent Extraction for Trivalent f-elements Intra-group separation in CMPO-complexant System" (SETFICS). The chemical principle of the chromatography method is the same as SETFICS, and the extractant, a bifunctional neutral extractant, is also useful for this purpose. In particular, "n-Octyl(phenyl)-N, N-diisobutylcarbamoylmethylphosphine oxide (CMPO)", is adsorbed on the nonflammable silica support which is packed in a chromatography column. In the NEXT system, "salt-free" reagents such as hydrazine oxalate and hydrazine carbonate are used to be easily decomposed and released as gas, and the separation of liquid waste into very-low and high-radioactivity wastes by sequential concentration and evaporation is employed to simplify the effluent treatment system and solidification process.

As a result of this design study, the layout of equipment and tanks in the main cell for reprocessing of an integrated recycle plant with 200 tHM/y throughput was made. The number of components from fuel disassembling to crystallizer is one each, with 17 extraction blocks, 8 evaporators, and 148 tanks. Each component is arranged by considering criticality safety, operability, and maintainability. The total volume of the recycle plant, consisting of 3 stories above the ground and 2 below, is 680,000 m^3, of which the reprocessing part represents about 390,000 m^3.

This system will be also applied for LWR and FR fuel reprocessing in the transition phase from LWRs to FRs by considering their head-end processes and addition of secondary crystallization to remove the larger amount of excess U.[5]

In the Super-DIREX system, actinide elements are directly extracted from the powdered spent fuel in the supercritical fluid carbon dioxide (sf-CO_2)-TBP-nitric acid mixture. In the next stripping step, U, Pu and Np are extracted in the nitric acid. Uranium is separated in the subsequent crystallization process. The same chromatography method as that in NEXT is used for the MA recovery.

The functions of two towers for direct extraction and back extraction correspond to the NEXT processes of fuel dissolution, adjustment, co-decontamination, and stripping. At this preliminary stage of design for a 50 tHM/y processing plant, a tower of about 7 m in height and 0.13 m in inner diameter is assumed for direct extraction. Most other equipment and apparatus have a technical base similar to that of the NEXT process plant. Experience in construction and operation of PUREX plants will be utilized effectively for further experimental and design study.

In the Oxide Electrowinning system, irradiated MOX fuel is dissolved in the molten salt, and decontaminated UO_2 and MOX are collected by electrolysis. Oxide deposits on the cathode are granulated and used directly for vibro-packed fuel.

The process flow considered in this work incorporates simultaneous electrolysis, MOX co-deposition, and MA recovery into the original scheme developed by the Research Institute of Atomic Reactors (RIAR) in Russia.[6] The spent MOX fuel is loaded on the bottom of the electrolysis vessel after being decladded and powdered. In the simultaneous electrolysis step, UO_2 in the spent MOX fuel is anodically dissolved in the molten NaCl-2CsCl salt at approximately 650 °C, and UO_2 is collected on the cathode at the same time. The residual fuel containing U, Pu, MA and FPs is dissolved by blowing chlorine gas into the molten salt. Subsequent electrolysis removes noble metal (NM) FPs by a NM cathode. In the MOX co-deposition step, MOX is deposited on the cathode by controlling its electric potential. As the result of MOX co-deposition tests in RIAR, it was found that the chemical potentials of chlorine and oxygen should be controlled by bubbling the mixture of both gases in the molten salt in order to prevent PuO_2 precipitation on the bottom of the molten salts. The salt adhering to the collected UO_2 and MOX is removed by vacuum distillation. Alkali, alkaline earth and rare earth FPs, and MA accumulate in the molten salt after the repeated collection of UO_2 and MOX. Minor actinides are assumed to be recovered by multi-stage counter-current extraction.[7] The addition of Na_3PO_4 and Cs_3PO_4 into the actinide-free salt causes precipitation of the phosphates of the alkaline earth and rare earth FPs, which can be removed from the salt. The phosphate and some portion of the molten salt are vitrified into the phosphate glass matrix.

Non-conductive densified zircon ($ZrSiO_4$) is adopted as the material of the crucible instead of conductive pyro-graphite in order to extend its lifetime by improving the corrosion resistance. As the result, the electrode structure for an anode is changed from the crucible itself to a solid rod with a flat plate made of pyro-graphite with many vertical holes to push the spent fuel on the bottom. The equipment and material handling system as well as the necessary storage and repair space are installed in hot cells to layout the recycle plant.

In the Metal Electrorefining reprocessing, the irradiated metallic fuel (U-Pu-Zr alloy) is electrorefined in KCl-LiCl molten salt at 500 °C. The irradiated metallic fuel is loaded in the anode basket, and dendritic U metal is deposited on the steel rod cathode. Plutonium is collected in the liquid cadmium (Cd) cathode (LCC), where it is inevitably accompanied by U, MA, and a small amount of rare earth FPs. The salt adhering to the U dendrite and the Cd adhering to the LCC product are removed by distillation in the cathode processors, and the U metal and Pu-U-MA alloy ingots are then obtained. The molten salt in the electrorefiner contains FPs and actinides. Some of the molten salt is periodically taken out of the electrorefiner and brought into contact with the molten Cd-Li-K alloy in the reduction extractor, where actinides are reduced and extracted into the Cd phase. The actinide-free salt containing FPs is transferred to the zeolite column, where the FPs are adsorbed by zeolite and the refreshed salt is recovered. The zeolite including the FPs and the residual salt are transformed into glass-bonded sodalite for disposal. The actinides contained in the Cd phase in the reduction extractor are back-extracted into the refreshed salt and returned to the electrorefiner. In the metal electrorefining process considered in this work, the following improvements were made in the pyrometallurgical process developed originally at Argonne National Laboratory (ANL) in the USA[8]:

- The bond sodium (Na) distillation from the chopped fuel pin is added before electrorefining to avoid the introduction of excessive bond Na into the electrorefiner. The distilled Na is oxidized and utilized as an ingredient in glass materials of the salt waste form.
- A large amount of the salt is recycled after it is passed through the zeolite column. This reduces the salt waste volume.
- The rectangular electrorefiner, with plural electrode assemblies for recovering U on the solid cathodes and U-Pu-MA in the liquid Cd cathodes simultaneously, and the continuous cathode processor are designed to enhance economy, operationality, and throughput.

RADIOACTIVE WASTES FROM REPROCESSING

Classification of Wastes

In Japan, radioactive wastes are classified according to the site of source into power plant wastes, recycling wastes, radioisotope laboratory wastes, and wastes that are sent back from abroad. Wastes resulting from reprocessing are of "recycling wastes" class and further classified as HLW and radioactive wastes containing transuranium elements (referred to as TRU wastes). A highly radioactive effluent of solvent extraction contains most of FP and is vitrified for disposal. The vitrified waste is stored with cooling for several decades and disposed of deep underground. Many kinds of wastes generated in operation of a reprocessing plant usually contain transuranics. The TRU waste is referred to as "LLW" in the context of waste disposal.

The TRU wastes generated in Tokai Reprocessing Plant have been classified according to their generation, composition of radionuclides, and nature of combustion as shown in Table II.

Table II. Classification of Radioactive Wastes from Aqueous Reprocessing

Class	Kind	Example	Expected disposal type*
Process wastes	Low level concentrate	Concentrate of condensates, analytical wastes, washings of gas, decontamination wastes.	LLW-D Class LLW-B Class
	Spent solvent	Residue from spent solvent treatment.	LLW-B Class
	Spent resin	Spent organic ion exchange resins for purification of water which is used in a pool for spent fuel storage.	LLW-B Class
	Spent adsorbent with Ag	Spent adsorbent of particle containing silver for iodine.	LLW-D Class
	Hull and end piece	Structural materials from shearing and dissolution steps.	LLW-C Class
	Spent activated carbon	Spent adsorbent for treatment of water that will be discharged to sea.	LLW-B Class
	Sludge	Residue from agglutination of laundry waste solution.	LLW-B Class
Miscellaneous wastes	Combustible I	Paper, cloth, vinyl acetate, wood, etc.	LLW-D Class
	Noncombustible I	Polyethylene, plastic gloves, etc.	LLW-D Class
	Incombustible I	Metals, glass, concrete, etc.	LLW-D Class
	Combustible II	Combustible wastes of higher radionuclide concentration	LLW-C Class
	Noncombustible II	Noncombustible wastes of higher radionuclide concentration	LLW-B Class
	Incombustible II	Incombustible wastes of higher radionuclide concentration	LLW-B Class

* Refer to Table V.

The “process wastes” generated in operation include a low radioactive concentrate and spent solvent. The “miscellaneous wastes” are those that come from operation, maintenance and repair. The wastes generated are currently stored.

The concentration of TRU in TRU wastes varies in a wide range and the wastes are classified according to their total concentration of α-emitting radionuclides. The paths for disposal have been investigated taking into account the class. The waste which contains radionuclides at a concentration of 1 GBq/t or greater will be disposed of at a deep underground repository, and the others will be buried at a land disposal facility designated as “middle”, “shallow” and “trench”.

Process of waste generation

In aqueous processing, spent fuel is dissolved in a nitric acid solution and most of FP remain in the raffinate after solvent extraction, which results in a highly radioactive waste solution. This is converted into a vitrified waste for disposal. The specification of the vitrified waste is shown in Table III. Corrosion products and actinides were considered as the waste components as well as FP. Corrosion products from process equipment and hulls were assumed to be contained in the feed for vitrification. Since actinides are recovered in reprocessing, the contribution to heat generation from Am and Cm can be ignored and the amount of vitirified waste was determined by the content of FP.

The structural material of fuel assemblies and elements is washed if needed, compressed, and placed in a canister. The amounts of wastes were derived based on the specification of fuel assemblies shown in Table IV. A concentrated waste solution is dried and solidified with cement. The combustible waste is incinerated and placed in a can with cement. Incombustible waste is melted, if needed, and solidified. The amounts of vitrified waste and wastes from the fuel structure were estimated based on the specifications such as Table III and the amounts of other wastes were from the actual waste results.

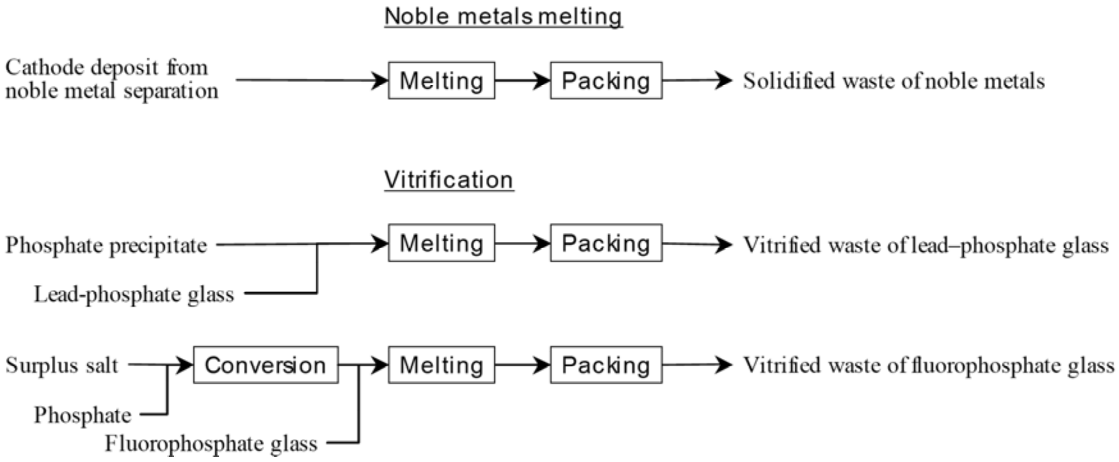
The oxide electrowinning process will generate HLW as cathode deposit in noble metal separation, phosphate precipitate, and surplus salt. The process flow concerning process waste is shown in Fig. 2. The cathode deposit in noble metal separation is melted and solidified as a metal ingot in a container for disposal. The phosphate precipitate is vitrified as a lead-phosphate glass and the surplus salt is vitrified as a fluorophosphate glass after converting it from chloride into phosphate.

Table III. The Vitrified Waste Specification in a Borosilicate Glass Form

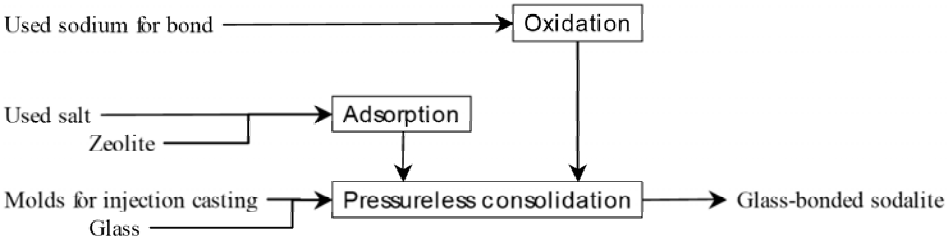
Weight of glass		~400 kg/canister
Composition	FP oxides	12 wt%
	Na_2O	10 wt%
Maximum heat		~2.3 kW/canister
Dimensions	Outer diameter	~430 mm
	Height	~1,340 mm
Thickness of canister		6 mm
Material of canister		Stainless steel

Table IV. The Structure of MOX Fuel Assembly for the Sodium Cooled-FR

Assembly	Length	4,570 mm
	Number of fuel pins	255
Wrapper tube	Material	PNC-FMS steel
	Distance between outer faces	201.6 mm
	Thickness	5.0 mm
Element	Length	2,690 mm
	Material of tube	ODS steel
	Outer diameter	10.4 mm
	Thickness	0.71 mm
	Length of stuck	1,400 mm including axial blanket of (200+200) mm
Spacer wire	Material	PNC-FMS steel
	Diameter	1.03 mm
Weight of structure	Handling head	110 kg
	Upper shield	41 kg
	Wrapper tube with internal duct	97 kg
	Hull, wire, end plug, etc.	129 kg
	Lower shield, entrance nozzle	86 kg



(a) Oxide Electrowinning process



(b) Metal Electrorefining processes

Fig. 2. Flow diagrams of highly active waste generation in the oxide electrowinning and the metal electrorefining processes

The metal electrorefining process generates zeolite which contains used salt, used bonding sodium, and used molds for the injection casting as potential HLW. Alkaline and alkaline earth FP that remain after recovery of actinides in the salt are adsorbed in zeolite matrices. The flow diagram of HLW generation is shown in Fig. 2. The mixture of zeolite, oxidized bonding sodium, surplus salt, and molds is treated by pressureless consolidation to form a glass-bonded sodalite. The density is assumed as 2 g/cm^3, and the concentrations of FP and salt are 4 and 5 wt%, respectively. Crucibles for Cd cathode and cathode treatment, sheared plenum, noble metal FP from the Cd pool, residue from dross treatment, and cladding hulls will be TRU wastes. These will be compressed or smashed, if needed, and solidified with cement. However, it will be also examined to treat the noble metal FPs as a high-level metallic form waste because a stainless steel-Zr-noble metal FPs alloy has been developed at INL (the former ANL-W).

Estimating and comparing volume of wastes

The volume of wastes that is generated in three methods of processing (NEXT, oxide electrowinning and metal electrorefining) was estimated. The stage of realization differs among the reprocessing methods. The Tokai Reprocessing Plant of aqueous PUREX process reprocessed 1,000 tons of spent fuel, and generated wastes. This actual result was employed for this estimation. On the other hand, the pyroprocesses are at their early stage of realization and commercialization, and the estimation was based on the design study of process and apparatus.

The estimated amounts of wastes were compared after normalizing the volume with unit electricity generation by using reprocessing capacity, averaged burn-up, and efficiency of electricity conversion for reactors with those expected for the Rokkasho Reprocessing Plant.

The volume of HLW is dependent on the contents of the waste fraction (that is, FPs, corrosion products and sodium) and also heat generation from the waste fraction. One advantage of whole-actinides recovery is the suppression of heat generation, which allows the presence of FPs as far as their solubility in the glass phase permits. A unit generation of HLW was estimated as 1.2 canisters per tHM, assuming a limiting heat density of 2.3 kW/canister. Fig. 3 shows the estimated amount of HLW and LLW in each reprocessing system, in terms of the values generated per unit power generation (m^3/kWh) normalized to the comparable values for the PUREX process with LWR fuel.

The amount of HLW in the system except for the metal electrorefining process, in which the amount of FP content is limited due to the characteristics of salt-occluded zeolite, will be reduced compared with a conventional LWR reprocessing plant of the equivalent throughput.

The amount of LLW is also reduced in all systems. Simplifying the main reprocessing processes contributes to the decrease of LLW, although waste from the fuel assembly components such as wrapper tubes, entrance nozzles and handling heads will increase in case of FR fuel reprocessing. In particular, the amount of LLW from the metal electrorefining system is less compared with the other systems.

COSTS REGARDING THE PROCESSING AND DISPOSAL

The costs regarding the processing and disposal of the wastes were also estimated in the course of the fuel cycle cost evaluation. Fig. 4 shows the flow from waste processing to waste disposition (including the wastes from the decommissioning of the plants). As for the wastes generated from decommissioning, the costs for decontamination, dismantlement, treatment, transport, and disposal of the wastes were summed up. Regarding the wastes generated from usual operation, treatment costs were not included in this evaluation because they were included in the costs of reprocessing or fuel fabrication. Therefore, the costs from the processing to disposal of the wastes from usual operation of the facilities included the transport and disposal costs related to the wastes other than HLW and the transport, storage, and disposal costs related to the HLW. Although the transport costs from the storage facilities to the disposal sites were counted, the costs to transport HLW from the reprocessing facilities to the storage facilities were not counted because the HLW storage facilities were assumed to be built next to the reprocessing facilities.

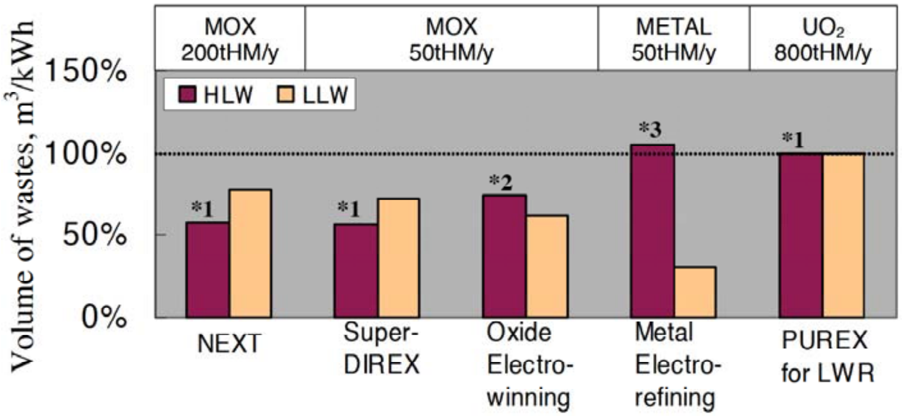


Fig. 3. The estimated waste generation from several reprocessing systems.

The FR fuel is of breeding core. The contents of HLW are *1: borosilicate glass, *2: phosphate glass and alloy (noble metals), *3: glass-bonded sodalite. The LLW includes concentrates, structure materials of fuel assembly and element, and used equipments and others.

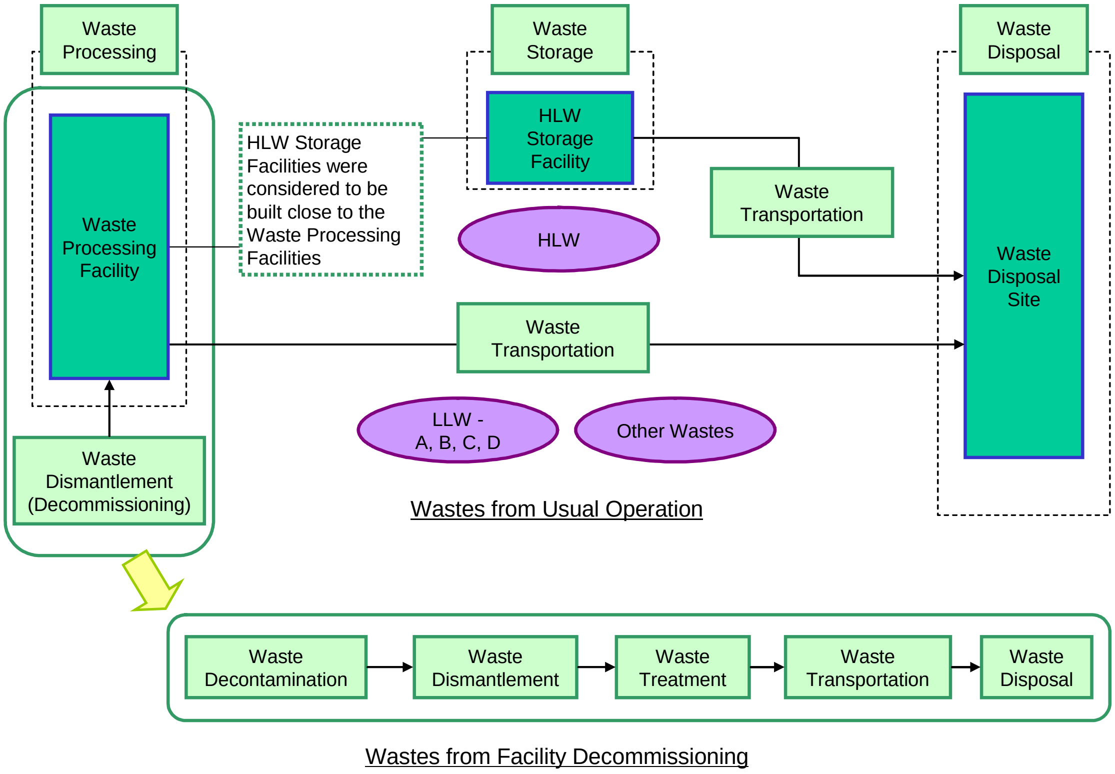


Fig. 4. Flow from waste processing to waste disposal

Table V shows the unit costs regarding the processing and disposal of the waste from fuel cycle facilities used in the FS Phase II Final Evaluation. Most of the unit costs were derived by considering the study results of the Japanese Advisory Committee for Natural Resources and Energy’s subcommittee to study costs and other issues.[9] The costs related to waste processing and disposal were derived from the multiplication of the waste volumes and the corresponding unit costs. Table VI shows the costs per unit power generation regarding the wastes from several reprocessing systems. The trends for costs are almost the same as the trends for estimated waste volumes (Fig. 3). As for HLW, NEXT and Super-DIREX systems were considered to be able to reduce the costs because of their little HLW generation. In contrast, oxide electrowinning and metal electrorefining systems generated less LLWs than NEXT and Super-DIREX systems, so the costs related to the LLWs from the oxide electrowinning and metal electrorefining systems were lower.

Table V. Unit Costs Used in the FS Phase II Final Evaluation

Process	Waste Type	Unit Cost (JPY/m^3)	Reference
Waste Dismantlement	LLWs (Decommissioning)	19.89M	Report [a](herein after referred to as "Report")
Waste Processing, etc.	LLWs (Decommissioning)	7.23M	Report
Waste Storage	HLW	655.09M	Report The volume of unit HLW was assumed to be 0.15m^3
	Other Wastes		Not Considered (The wastes were assumed to be transported directly to the disposal facilities)
Waste Transportation	HLW	15.33M	Report, The volume of HLWs were supposed to be 0.15m^3
	LLW-D Class (Geological Disposal)	6.0M	Report
	LLW-C Class (Medium Underground Disposal)	6.0M	Report
	LLW-B Class (Shallow Land Concrete Pit Disposal)	1.0M	Report
	LLW-A Class (Shallow Land Trench Disposal)	0.5M	Materials of Nuclear Energy Subcommittee of Advisory Committee for Energy (1999)
	Radioactive Wastes with activities below the clearance level	0.0035M	Report
	Non-Radioactive Wastes	0.0035M	Report (the unit cost was considered as same as the unit cost for the wastes with activities below the clearance level)
Waste Disposal	HLW	480M	Report
	LLW-D Class (Geological Disposal)	45.0M	Report
	LLW-C Class (Medium Underground Disposal)	12.0M	Report
	LLW-B Class (Shallow Land Concrete Pit Disposal)	2M	Report
	LLW-A Class (Shallow Land Trench Disposal)	0.4M	Materials of Nuclear Energy Subcommittee of Advisory Committee for Energy (1999)
	Radioactive Wastes with activities below the clearance level	0.0017M	Report
	Non-Radioactive Wastes	0.0017M	Report (the unit cost was considered as same as the unit cost for the wastes with activities below the clearance level)

[a] See Ref. 9.

Table VI. Estimated Costs per Unit Power Generation regarding the Wastes from Several Reprocessing Systems*1

Plant Concepts	NEXT	Super DIREX	Oxide Electrowinning	Metal Electrorefining
Fuel Type	MOX	MOX	MOX	Metal
Plant Capacity	200 tHM/y	50 tHM/y	50 tHM/y	50 tHM/y
HLW (Storage, Transport, and Disposal)	1.00	0.98	1.30	1.88
LLWs (Transport and Disposal)*2	1.00	0.86	0.77	0.38

*1: The costs in Table VI are written in the relative values (The costs regarding the wastes from NEXT =1.00).

*2: The costs related to the LLWs from decommissioning of the reprocessing plants are not included.

AN EVOLUTIONARY CONCEPT "ORIENT-CYCLE"

A further extension of high allowance of impurities fuel in FR system and a new reversal of approach in the fuel cycle system - from clean fuel and dirty waste to dirty fuel and clean waste - has been explored, leading to a new concept of FR cycle named as "ORIENT-cycle"

"Unnecessary elements" were independently determined from various viewpoints of each process composed of nuclear fuel cycle such as fuel fabrication, core design, waste conditioning, and final disposal. For instance, stable and semi-stable FPs were identified as "unnecessary elements" from both a neutronic aspect and a final disposal aspect. The stable and semi-stable elements including Xe, Mo, Nd, etc. account for approximately 60 wt% of all FPs. In order to reduce the volume of HLW, Cs, Sr and Mo were also defined as "unnecessary elements" for the vitrified waste. These exothermic (Cs, Sr) and electro-conductive (Mo) FPs inhibit the vitrification process and limit the concentration of FPs in HLW, therefore reduction of Cs, Sr and Mo from HLW allows to increase concentration of FPs in vitrified waste.

For the ORIENT-cycle concept, some ideal element-wise partitioning schemes are proposed taking into account various aspects, such as those mentioned above, for each link in the FR, reprocessing, fuel manufacturing, and repository fuel cycle chain. The HLW generated per unit energy in the new concept is reduced by about one order of magnitude compared to the conventional recycle procedure. Preliminary waste mass analysis shows reactivity of FR could be satisfied even in multiple recycle. It turns out that the ORIENT-cycle is feasible as a FR recycle system and is effective in reducing HLW production.

CONCLUSIONS

Based on the Phase II study of the FS, the candidate reprocessing systems such as NEXT, Super-DIREX, and Oxide Electrowinning for oxide fuel and Metal Electrorefining for Metallic fuel were designed conceptually by reflecting the latest results of research and development. The amount of wastes was estimated for the four reprocessing systems as HLW and LLW including concentrates, structure materials of fuel assembly and element, and used equipments and others. It was found that the expected amount of HLW and LLW, which was normalized with electric power generation, would be decreased compared with that from the conventional reprocessing for LWR fuel, except for HLW from metal electrorefining process. The unit costs that were used to estimate the costs for processing, storage, transportation and disposal of waste were summarized. A new approach (named the "ORIENT-cycle"), which aims at a fuel cycle system of "dirty fuel and clean waste," was proposed for further improvement of managing waste.

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