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COMPATIBILITY ANALYSIS OF DUPIC FUEL (PART V)

- FUEL CYCLE ECONOMICS ANALYSIS

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COMPATIBILITY ANALYSIS OF DUPIC FUEL (PART V) - FUEL CYCLE ECONOMICS ANALYSIS

ABSTRACT

A preliminary conceptual design of a direct use of spent pressurized water reactor (PWR) fuel in Canada deuterium uranium (CANDU) reactors (DUPIC) fuel fabrication plant was studied, which annually converts spent PWR fuel of 400 MTHE into the CANDU fuel. The capital and operating costs were estimated from the viewpoint of conceptual design. Assuming that the annual discount rate is 5% during construction (5 yr) and operation period (40 yr) and contingency is 25% of the capital cost, the levelized unit cost (LUC) of DUPIC fuel fabrication was estimated to be 616 $/kgHE, which is mostly governed by annual operation and maintenance costs that correspond to 63% of LUC. Among the operation and maintenance cost components being considered, the waste disposal cost has the dominant effect on LUC (~49%). From sensitivity analyses of production capacity, discount rate and contingency, it was found that the production capacity of the plant is the major parameter that affects the LUC.

The DUPIC fuel handling technique in a CANDU plant has been investigated through a conceptual design study in order to estimate the unit cost that can be used for the DUPIC fuel cycle cost calculation. The conceptual design study has shown that fresh DUPIC fuel can be transferred to the core following the existing spent-fuel discharge route, provided that new fuel handling equipment such as the manipulator, new fuel magazine, new fuel ram, dryer, etc. are installed. The reverse path loading option is known to minimize the number of additional pieces of equipment for fuel handling, because it utilizes the existing spent-fuel handling equipment and the discharge of spent DUPIC fuel can be done through the existing spent-fuel handling system without any modification. However, because the decay heat of spent DUPIC fuel is much higher than that of spent natural uranium fuel, the extra cooling capacity should be supplemented in the spent fuel storage bay. Based on the conceptual design study, the capital cost for DUPIC fuel handling and extra storage cooling capacity was estimated to be $ 3,750,000 (as of January, 2000) per CANDU plant. The levelized unit cost of DUPIC fuel handling was then obtained by considering the amount of fuel that will be required during the life-time of a plant, which is 5.13 $/kgHM. Compared with the other unit costs of the fuel cycle components, it is expected that DUPIC fuel handling has only a minor effect on the overall fuel cycle cost.

The disposal costs of spent PWR, CANDU reactor and DUPIC fuels have been estimated based on available literature data and the engineering design of a spent CANDU fuel disposal facility by the Atomic Energy of Canada Limited (AECL). The cost estimation was carried out by the normalization concept of total electricity generation. Therefore, the future electricity generation scale was analyzed in order to evaluate the appropriate capacity of the high-level waste disposal facility in Korea, which is a key parameter of the disposal cost estimation. Based on the total electricity generation scale, it is concluded that the disposal unit costs for spent CANDU natural uranium, CANDU-DUPIC and PWR fuels are 189, 343, and 617 \$/kgHE, respectively.

The economics of the DUPIC fuel cycle was examined using unit costs of fuel cycle components estimated based on conceptual designs. The fuel cycle cost (FCC) was calculated by a deterministic method in which reference values of fuel cycle components are used. The FCC was then analyzed by a Monte Carlo simulation to get the uncertainty of the FCC associated with the unit costs of the fuel cycle components. From the deterministic analysis on the one-batch equilibrium fuel cycle model, the DUPIC FCC was estimated to be 6.55-6.72 mills/kWh for DUPIC fuel options, which is a little smaller than that of the once-through FCC by 0.04-0.28 mills/kWh. Considering the uncertainty (0.45-0.51 mills/kWh) of the FCC estimated by the Monte Carlo simulation method, the cost difference between the DUPIC and once-through fuel cycle is negligible. On the other hand, the material balance calculation has shown that the DUPIC fuel cycle can save natural uranium resources by ~20% and reduce the spent fuel arising by ~65% compared with the once-through fuel cycle. In conclusion, the DUPIC fuel cycle is comparable with the once-through fuel cycle from the viewpoint of FCC. In the future, it should be important to consider factors such as the environmental benefit due to natural uranium saving, the capability of reusing spent pressurized water reactor fuel, and the safeguardability of the fuel cycle when deciding an advanced nuclear fuel cycle option.

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1. INTRODUCTION

Selecting an option for the back-end of the nuclear fuel cycle is an important decision for all countries with nuclear power programs. The decision-making process requires consideration of various factors including economics. It is not easy, however, to forecast an appropriate fuel cycle cost because of the uncertainties involved in the cost estimation. In general, the technical components in the front-end cycle are relatively well demonstrated, while some of the back-end components, like high-level-waste disposal, are yet to be established. In addition, there are many floating parameters in evaluating economics of a new fuel cycle concept like the direct use of spent pressurized water reactor (PWR) fuel in Canada deuterium uranium (CANDU) reactors (DUPIC), especially because it comes to a case for a technology still in the experimental phase. The DUPIC technology, now under experimental verification by a multilateral cooperative effort, is to reuse spent light water reactor fuel again in a heavy water reactor by direct refabrication as an alternative to the conventional fuel cycle.

For the DUPIC fuel cycle economics analysis, three distinctive features should be considered: the fuel fabrication, handling of fresh and spent fuels, and disposal of spent DUPIC fuel. The fuel fabrication is performed remotely in a hot cell through a dry process. Because the fresh DUPIC fuel is radioactive, the DUPIC fuel handling process is different from the existing one, especially for the transportation, storage and loading into a reactor. The disposal cost of the spent DUPIC fuel is also different from that of the standard spent CANDU fuel, because of extended fuel burnup in CANDU reactors. In order to assess the DUPIC fuel cycle economics, these fuel cycle component costs have been evaluated and the results are described in this report.

In Sec. 2, the DUPIC fuel fabrication cost is estimated through a conceptual design of a commercial scale fabrication facility. The feasibility of DUPIC fuel handling in a CANDU plant is assessed in Sec. 3 for the design changes of existing fuel loading/unloading and storage facilities with the cost estimation of the new fuel loading/unloading facility. The disposal cost of spent DUPIC fuel is estimated in Sec. 4. Using the updated unit costs of fuel cycle components, the DUPIC fuel cycle cost is estimated in Sec. 5 along with the conventional fuel cycle. Finally, the summary and conclusions are given in Sec. 6.

2. DUPIC FUEL FABRICATION COST

A feasibility study[1] on the direct use of spent PWR fuel in CANDU reactors (DUPIC) was initiated by Korea, as a joint evaluation program with Atomic Energy of Canada Limited (AECL) and the United State Department of State (U.S.DOS). The feasibility study concluded that the DUPIC technology is feasible and safeguardable. During the feasibility study, several technical options were examined. Among them, the oxidation and reduction of oxide fuel (OREOX) [Ref. 2] option was chosen as the most promising method for fabricating the high quality DUPIC fuel. Following the study, the experimental verification of the OREOX technology in a laboratory scale is now being conducted. With such experimental efforts, compatibility studies[3,4] of the DUPIC fuel including DUPIC fuel cycle economics are being carried out to see the possibility of commercialization of DUPIC fuel cycle.

The DUPIC fuel cycle economics have been an important issue from the initial stage of DUPIC fuel development program. The Korea Atomic Energy Research Institute (KAERI) launched a systematic study[5] of DUPIC fuel cycle economics by parametric analysis. At that time, the unit cost of DUPIC fuel fabrication was regarded as an unknown and the break-even cost of DUPIC fuel fabrication was searched by comparing DUPIC fuel cycle costs with the direct disposal option through parametric analyses. Though the parametric study provided a break-even cost for the DUPIC fuel cycle relative to other fuel cycle options, this "indirect" method contains a high degree of uncertainty due to many assumptions made for the DUPIC fuel fabrication cost. Therefore, an engineering analysis was conducted to derive capital and operating costs through a conceptual design of a DUPIC fuel fabrication plant using the best available technical concept, so that the overall levelized cost could be directly derived.

The preliminary conceptual design analysis for the DUPIC facility was performed based on Atomics International Reduction Oxidation (AIROX) report[6] issued by Idaho National Engineering Laboratory (INEL) in 1992, which used a dry refabrication process. The unit cost of DUPIC fuel manufacturing was estimated from capital cost, operating cost, decommissioning cost, contingency, etc. The result of the preliminary conceptual design was reviewed independently by Oak Ridge National Laboratory (ORNL) with a major focus on remote system operation and maintenance. The independent review was performed to reduce uncertainty that could be included in the preliminary conceptual design and cost estimation.

This study presents the conceptual design and cost estimation of DUPIC fuel fabrication plant of 400 metric ton heavy element per year (MTHE/yr) capacity. In this study, a set of technical requirements based on the results of basic research programs conducted over the past few years was established, and a functional flow diagram and material balance sheet were developed based on the technical requirements. After selecting process components, the configuration of the building facility was developed, which includes process component arrangements, hot cell layout, building design, and interface with the plant boundary. Then, the cost evaluation was performed based on the conceptual design of DUPIC fuel fabrication facility, using a standard cost estimating methodology applicable for a large scale facility construction and operation analysis. Input data for the capital and operating costs were identified and determined based on established industrial practices and quotes from equipment vendors. The cost evaluation also includes sensitivity analyses on the cost parameters. The overall cost estimating procedure used in this study is shown in Fig. 2.1.

2.1. DUPIC FACILITY DESIGN REQUIREMENTS

In order to estimate capital and operating costs of the reference DUPIC facility, some cost data of the system components and operation activities were referred to results of similar studies. A close example was the AIROX technology which intends to recycle spent light water reactor (LWR) fuel again into LWRs by means of a dry-processing technique (in contrast with DUPIC technology that recycles spent PWR fuel in CANDU reactors). The technical requirements for a conceptual design of a commercial-size DUPIC fabrication facility were defined by re-evaluating the AIROX technology for the applicable regulations and standards.

2.1.1. Facility Performance Requirements

This section defines the performance and design requirements for a commercial size nuclear fuel recycle facility capable of converting PWR fuel into CANDU fuel (identified as DUPIC fuel). These requirements were intended to guide the conceptual design of a facility which in turn was used to estimate the cost of design, licensing, construction, operation, and decommissioning of the commercial size DUPIC fuel facility

2.1.1.1. Overall Facility Performance

a. Plant capacity: The design throughput of the DUPIC facility is 400 MTHE of spent PWR fuel per year.
b. Plant availability: The facility is sized and operated for an average of 70% plant production, which covers allowances for normal process systems startup and shutdown times, scheduled and unscheduled plant equipment maintenance and repair activities, material accountability-related tasks that affect plant operation, and any scheduled plant-wide outage period for major systems refurbishing activities (e.g., a scheduled one-month long plant-wide outage period per year for refurbishing one or more of the sintering furnaces in the plant).
c. Plant design life: The design life of the facility is 40 years.
d. Scope of plant: The DUPIC facility is a complete fuel recycle plant that covers all functions and equipment for processing spent PWR fuel and converting it to CANDU DUPIC fuel. The non-fuel components required by the CANDU fuel bundle (e.g., fuel cladding, end caps, spacers, end plates, and dysprosium poison fuel rods) will be fabricated by off-site facilities and shipped to the DUPIC facility. The facility will contain all support systems (material handling/storage, waste processing, packaging, storage, and utilities) necessary for DUPIC fuel production. The DUPIC facility shall have provisions for emergency power generation and related equipment for sustaining essential plant operation and safe plant shutdown procedures.

2.1.1.2. Plant Operation and Maintenance

a. Facility: The layout and configuration of the facility shall be optimized for remote operation and maintenance, which is operable and maintainable without human intervention in the shielded area. The facility shall be provided with adequate remote systems and storage spaces for radioactive materials and equipment to be handled or maintained remotely. The facility shall be provided with work areas for remote decontamination and maintenance of failed equipment as part of the special operation in the facility. The facility shall be provided with radioactive waste collection, treatment, packaging and shipping systems. The facility shall also be designed to minimize radioactive waste generation.
b. Equipment: The equipment shall be optimized for remote operation and maintenance. The equipment shall be as light as possible to facilitate handling, transfer, replacement, etc. The

equipment shall be modularized, as far as possible, to facilitate remote maintenance. Drive units of motors that are prone to failure shall be designed to facilitate remote replacement and repair. Equipment design life-time shall be 10 years for the long life items and 5 years for short ones. The equipment shall be designed to maximize automation of the process operation and control.

c. Instrumentation and control (I&C): The facility shall be provided with I&C for facility operation, maintenance, and surveillance. The I&C systems shall be designed to facilitate in-place calibration as well as man-machine interface. The I&C systems shall be designed to facilitate nuclear materials safeguards and facility safety monitoring.

2.1.1.3. Nuclear Material Management

a. Spent fuel feedstock: The reference feed stock used in the DUPIC facility is standard 17x17 spent PWR fuel assemblies with a minimum cooling time of 10 years after discharge from the reactor.
b. DUPIC fuel product: The product of the facility is 43-element CANDU fuel bundles. The design specifications and the configuration of the DUPIC fuel bundle are provided in Table 2.1 and Fig. 2.2, respectively.
c. Fuel material composition: A nominal fissile content of 1.60 wt% with a ±5% allowable variation is assumed. The 1.60 wt% fissile content corresponds to a burnup level of 35 MWd/kgU of the spent PWR fuel.
d. Fission product waste: The gaseous fission products are released during the decladding process. The volatile and semi-volatile fission products are also released depending on the process conditions. Provisions for capturing these fission products shall be made in all process steps including fuel decladding, oxidation-reduction, and pellet sintering cells.
e. Spent fuel storage: It is assumed that the spent fuel will be shipped in licensed rail-car or truck shipping casks, then unloaded and stored in a dry storage. The spent PWR fuel receiving and storage system shall accommodate a minimum of three-month operational feed stock capacity (~ 100 MTHE of spent PWR fuel).
f. DUPIC fuel storage: The storage and shipping system shall accommodate a minimum of six-week of DUPIC fuel production (50 MTHE).
g. Waste storage: The storage system for different forms of waste materials generated in the DUPIC facility shall accommodate the anticipated quantities over a minimum of 10 years

of facility operation. The storage containers shall be designed to facilitate eventual waste disposal.

2.1.1.4. DUPIC Facility Safety and Environment

a. Fissile material criticality: The DUPIC facility and equipment design shall meet, as a minimum, requirements of American Nuclear Society (ANS) 8 Series on Nuclear Criticality Safety, including double contingency. Process designs shall incorporate sufficient factors of safety so that at least two unlikely and independent concurrent charges must occur in process conditions before a criticality accident is initiated. Structures, systems, and components that provide nuclear criticality safety shall be designed as safety class systems. A criticality monitoring and alarm system shall be provided where necessary to meet the requirements of ANS 8.3.
b. Facility air changes: The rate of air change for areas occupied by personnel is six times per one hour for potentially contaminated areas and once per one hour for all other areas.
c. Hot cell shielding: Shielding shall be provided such that the radiation level in personnel operating areas shall be 0.5 mrem/hr or less.

2.1.1.5. DUPIC Facility Safeguards and Accountability

A near real-time accountability (NRTA) system with non-destructive analysis (NDA) and other measurement systems shall be used in the plant. Three material balance areas (MBA) shall be used as shown in Fig. 2.3. The material balance by item and bulk accounting will be monitored by DUPIC safeguards neutron counter (DSNC) [Ref. 7] which was designed to measure the amount of curium in the fuel. Plutonium and uranium contents are estimated from the neutron counting, and the neutron inventory balance can be established during the DUPIC process.

2.1.2. DUPIC Fuel Processing Requirements

The DUPIC fuel processing is a key factor that determines the configuration of the facility. The DUPIC fuel fabrication is performed in several steps as shown in Fig. 2.4. Among them, the OREOX process is the key process that determines the DUPIC fuel fabrication plant capacity and size.

2.1.2.1. DUPIC Fuel Powder Preparation

a. Fuel disassembly: The spent PWR fuel disassembly shall be performed in dry cells using commercially available technology, including volume reduction of structural components. Structural quantity processed is assumed to be 0.07 MT/MTHE of spent fuel.
b. Fuel pin puncturing and decladding: A conventional mechanical process such as shear cutter or laser type metal cutting technology is used. The loss of fuel material with the discarded cladding shall be less than 1% of incoming fuel material. Conventional volume reduction processes shall be used to treat the discarded cladding. The cladding quantity processed is assumed to be 0.29 MT/MTHE of spent fuel.
c. Oxidation/reduction: A three-cycle process (i.e., 60-minute oxidation period of the fuel material followed by a 120-minute reduction step) shall be used, with an oxidation temperature of 400°C and a reduction temperature of 600°C. The reduction step shall be in a hydrogen-enriched atmosphere at atmospheric pressure. The two-cycle (i.e., oxidation and reduction) process will be iterated three times for optimum size reduction of the fuel material.
d. Powder processing: Further milling of the powder shall be required after the oxidation/ reduction process. Adequate blending shall be provided to meet the material composition requirements and homogeneity. Fuel material pre-compaction and granulation using standard fabrication procedures, followed with addition of the lubricant, shall be provided.

2.1.2.2. DUPIC Fuel Pellet Preparation

a. Pelletization: Pellet pressing shall be assumed in conventional dies. Therefore, the pellet process leaves an hourglass shape after sintering, which requires a subsequent grinding process.
b. Sintering: Conventional sintering conditions shall be used, i.e., 1650°C in a reducing atmosphere. Additional volatile fission products will be released during sintering, which requires a trapping process in the furnace or furnace effluent.
c. Pellet grinding: A dry grinding process shall be used. Pellet surface finish shall be controlled by appropriate selection of the grinding mechanism and material. Debris from grinding shall be collected for recycling.

2.1.2.3. DUPIC Fuel Bundle Preparation

a. Pin loading: Tubing shall be provided with pre-brazed spacers, and with one end-cap already welded. Conventional resistance welding shall be used.
b. Bundle assembly: Conventional CANDU bundle fabrication techniques shall be used.
c. Recycle: A separate module shall be provided to recycle all fuel material. The recycle system shall be based on dry treatment technologies. All rejected pellets, pins, and bundles shall be treated for recycling. The nominal levels of the recycle streams of the DUPIC process are given in Table 2.2.

2.2. CONCEPTUAL DESIGN OF DUPIC PROCESS SYSTEM

The conceptual designs of the process systems contained in this section serve as reasonable bases for developing the equipment sizing, facility layout, and cost estimate. Detailed evaluation of available technologies, tradeoff studies, and further process development at the laboratory and pilot scale levels could lead to alternative and improved approaches to the design of the process systems.

2.2.1. Process Mass Balance

Figure 2.5 shows the major process flow steps and the point index for the mass balance of the process based on metric ton of heavy elements of incoming spent PWR fuel assemblies. The annual throughput of the corresponding mass balance of the DUPIC facility can be easily determined by multiplying each of the numbers by 400 (i.e., for a 400 MTHE/yr throughput plant).

2.2.1.1. Material Throughput for Process Equipment Sizing

The required throughput of the DUPIC facility is 400 MTHE/yr of spent PWR fuel. Designed with an operational availability of 70%, the facility is not available for fuel material processing up to 30% of the time when various plant maintenance, repair, and administrative activities are underway. To account for these plant non-operational activities, the process systems are sized at a throughput of 570 MTHE/yr (i.e., 400/0.7=571). A slightly conservative throughput of 600 MTHE/yr is used as the basis for the conceptual design and sizing of the process systems.

In developing the DUPIC facility conceptual design, an early strategic decision was to use multiple and independent process lines in the main processing building. These lines permit the use of smaller process equipment sizes, which provide higher operational reliability. As a system redundancy they also ensure the operational availability of the DUPIC facility during unexpected failures of process equipment.

A preliminary system evaluation of the DUPIC process requirements indicates that a desirable configuration of the main process design is one with four parallel process lines, each designed at 150 MTHE/yr throughput capacity. To facilitate preventive maintenance support and to provide isolated process lines for major outage shutdowns, the four process lines are best located in two separate canyons, with each canyon containing two process lines. The two canyons are structurally isolated from each other. The two process lines in each canyon are designed with identical process systems and equipment to facilitate operation and maintenance. Based on the above, the material flow in the main process building is summarized in Table 2.3.

2.2.1.2. Fuel Material Batch Size Selection

The maximum lumped mass of ~350 kgHE of spent fuel material (assumed to be equivalent to 2 wt% of ^{235}U) is known to be criticality safe when optimally moderated (homogeneous UO_2-H_2O mixture) in a spherical shape.[8] To provide a margin of safety and employing the rule of limiting the lumped mass to one half of the maximum allowable level, the batch size is limited to 200 kgHE of fuel material in this conceptual design.

The 200 kgHE limit of lumped process fuel material is a reasonable design limit assumption adopted for this study. Depending on process considerations and material containment configuration in the final system design, a criticality safe batch limit could be determined accurately for each specific process step and utilized for each subsystem design.

For equipment sizing purposes, the nominal batch size of fuel processing material is assumed to be 160 kgHE (i.e., allowing a 20% margin for batch-to-batch size variation). This batch size is used for the design and sizing of process systems such as the fuel powder blending and storage equipment.

For the design and sizing of the fuel oxidation and reduction process system, a batch size of 80 kgHE is selected. The reason for using the selection of this smaller batch size is to have a more desirable process efficiency (i.e., improved fuel material thermal, mechanical mixing, and chemical reaction performance). Another reason for using the smaller batch size is to have a more desirable size and weight for the design of an automated material transfer system in-between the process ovens. This mass of fuel material (i.e., 80 kgHE) will have a volume of about 7700 cm^3 (i.e., 10.4 g/cm^3 pellet density). The material will have a 32% volume increase (to ~10200 cm^3) after the oxidation process.

As indicated in the material flow summary provided in Sec. 2.2.1.1 (see Table 2.3), the oxidation/ reduction process rate is 460 kgHE per day, per process line (i.e., with recycle streams). Based on the above batch size consideration, the nominal lumped mass of process material is 80 kgHE. Consequently, the oxidation/reduction process will require a minimum of six (i.e., 460/80; considering mass flow with recycle streams) separate batches of process material going through the process step per day, per process line.

2.2.2. Conceptual Design of Fuel Process Systems

As described in Sec. 2.2.1.1, there are four identical fuel process lines in the DUPIC facility located in two separate process cells. The conceptual design of the fuel process systems presented below is based on one fuel process line. An exception is the receiving, storage, and shipping of spent PWR fuel and new DUPIC fuel which are processed in one combined work area only. The substantial fabrication processes are described in this section.

2.2.2.1. Spent PWR Fuel Receiving and Storage

The as-received spent fuel is classified by the information (e.g. fissile content) characterized and evaluated by the fuel design data and the burnup characteristics, and stored in the classified area

2.2.2.2. Disassembly and Decladding

The spent PWR fuel rods are removed from the spent fuel structure. The fuel structural hardware is compacted for volume reduction and packaging for off-site disposal. The cladding of the fuel rod is punctured in a controlled environment such that fission gases are collected for waste treatment. The cladding of the fuel rod is sliced longitudinally with a laser cutter and spent fuel pellets are removed from the cladding. The cladding hulls are also compacted with density of approximately 4.7 g/cm^3 and packaged as a solid waste.

2.2.2.3. Fuel Oxidation and Reduction

The spent fuel pellet fragments and its debris go through three oxidation and reduction processing cycles to get a powder form with suitable characteristics for fuel fabrication. Three conduction ovens are used for each batch of fuel material: the first is used in the oxidation step ($UO_2 \rightarrow U_3O_8$ at ~400°C, diluted oxygen), the second is used for flushing out the reaction gas in the fuel material (at ~500°C, argon), and the third is used in the reduction step ($U_3O_8 \rightarrow UO_2$ at ~600°C, hydrogen/argon). These three ovens are arranged in a series and equipped with specially designed automatic material transfer mechanism. The resulting fuel powder is mixed, sampled for size distribution, and assayed for fissile content. The acceptable powder material is temporarily stored in batch quantities for fuel pelletization. During these processes, volatile and semi-volatile fission products, and particulate are trapped by an appropriate filter system.

2.2.2.4. Fuel Pelletization

Before the powder material is formed into pellets, the powder material is pre-compacted and granulated to increase its flowability. A lubricant is added to the powder to facilitate the pelletization process and improve the press tooling life. The powder material is then compacted to a desired green density. The resulting pellets are stacked onto boats and conveyors for sintering. The sintering step is then conducted at a high temperature in reducing atmosphere to achieve the high pellet density required. After that, the sintered pellets are transferred to the pellet grinding station to achieve the final dimension and surface finish within specification tolerances. All defective pellets and scrap materials are forwarded to the scrap recycle station. The finished pellets are stacked in specially designed containers for fuel pin fabrication.

2.2.2.5. Fuel Pin Fabrication

The fresh fuel cladding and end-cap components processed at off-site are shipped to the DUPIC facility with one end-cap already welded. The stacked fuel pellets are loaded into the fuel pins and moved to the end-cap welding station. The welded fuel pins are non-destructively tested for weld quality including a helium leak testing. The defective fuel pin is transferred to the scrap material recycle station. The completed fuel pin is also assayed for fissile content and then transported to the fuel bundle assembly work area.

2.2.2.6. Fuel Bundle Assembly

According to 43-element CANDU fuel bundle design, the DUPIC fuel bundle consists of two different diameter fuel pins. The center fuel pin (the larger size) contains a poison material (dysprosium) mixed with standard natural uranium or spent PWR fuel. The bundle assembly station receives the finished fuel pins from the respective fuel pin fabrication lines and assembles the fuel bundle. The assembled bundles are non-destructively tested for weld quality, dimensions fit, and clearance. Defective fuel bundles are forwarded to the repair station or scrap recycle station. The acceptable fuel bundles are loaded into baskets and storage containers for transfer to the storage or shipping area.

2.2.3. Facility Description

The following sections describe the layout of the DUPIC facility. Sizing a facility at the conceptual design stage is an activity that may vary significantly depending on the level of conservatism applied by the design organization. The DUPIC fuel fabrication facility is conceptually designed to accommodate the DUPIC fuel process system.

2.2.3.1. Plant Site and Building Layout

Figure 2.6 shows the plant site and building layout. The plant requires approximately 0.4 km^2 of dry and flat land. The main processing building is located at the center of the site. Other surface features for support systems are scattered around the main processing building with approximately 30 m buffer zone. Dose rate at site boundary will be below the regulatory limit of 5 mrem/yr.

2.2.3.2. Main Processing Building

Figure 2.7 shows the hot cell layout and system arrangement of the main process building. The main process building is a 73m x 130m rectangular-shaped structure that is 23 m high above the ground level with access from three sides. The main entrance at the south side leads to the main process control centers and operation-related offices. Receiving and shipping of the spent fuel material and the non-fuel material is available through the west and the north side, respectively.

In the north side of the building, as shown in a plan view of the hot cell (Fig. 2.7), two straight, identically shaped process canyons are configured side-by-side with process monitoring through shielded viewing windows or closed-circuit television (CCTV). The inside dimensions of the cell, including the disassembly area, are approximately 85 m in length, 9.75 m in width, and 20 m in height. The cell is separated into dirty and clean areas to prevent the spread of dust-type contamination from the powder processing steps into the fuel pin and assembly fabrication areas where a relatively clean, dust-free, environment is desired. The total floor area of the hot cell is approximately 829 m^2.

2.2.3.3. Process Systems and Operations

As shown in Fig. 2.7, there are two fuel fabrication process lines in one cell. Disassembly system is a common process for each cell, and the other systems contain processes from the decladding to the final assembly of the DUPIC fuel bundle. The as-received spent PWR fuels are inspected and stored in the storage vault. A number of selected spent fuels for an appropriate batch are picked up and transported to the west end of the process cell. The spent PWR fuel is processed in each process line as explained in the process description. The new DUPIC fuel bundles from four process lines are transported to the inspection and packaging area located at the south-east end of the building. The loaded fuel basket is transported to the new DUPIC fuel storage vault located at the west end of the main process building.

All remote operations, with a few exceptions, would be performed by bridge-mounted servomanipulators. The exceptions would be minor repairs on the servomanipulators, themselves, which would be performed at a window station. A ~1.6 m wide space is provided on both sides or the front of the equipment for access by the servomanipulators. A center aisle between the two process lines with a minimum width of 1.6 m is provided to move recycle and/or waste material. Individual equipment items have integral lifting fixtures for the replacement required.

2.3. FABRICATION COST ESTIMATION

The DUPIC fuel fabrication cost was developed as if the DUPIC facility was to be designed, tested, licensed, and operated to the requirements defined in Sec. 2.1. This assumption established labor rates, licensing fees, taxes, insurance rates and general costs for equipment. Conservative estimates were used as this type of facility has never been previously designed and built.

2.3.1. Cost Evaluation Data

The basic method used to develop the cost estimates was to develop the conceptual design sufficiently to be able to define structural sizes, process flows, equipment sizes and quantities, and reliability goals. Once this design was established, vendors were contacted to get 1999 cost estimates for the equipment and estimates for labor to install the equipment. For example, the estimated costs of the waste treatment system were based on information obtained from vendors and experience gained from other waste treatment facilities.

However, development of accurate cost data for the DUPIC facility is complicated by the fact that some of the key process technologies have not been demonstrated on a commercial scale. Therefore, cost data from studies of similar processes, AIROX process (AIROX was developed by Rockwell International and a prior assessment study was performed by INEL), are used as a reference for cost evaluation. Typical construction costs are determined using the construction industry standards, Richardson's Construction Estimating Standards and Mean's Facilities Cost Data by Scientech's experts. Some equipment costs for handling of the spent fuel were revised by recommendations of ORNL.

2.3.1.1. Main Assumptions

- The facility operation period is 2020 ~ 2059 (40 years).
- The facility construction period is 2015 ~ 2019 (5 years).
- The basis year of cost data is 1999.
- The discount rate is 5%.
- The capital cost includes direct cost, indirect cost, and contingency.

- The operation and maintenance cost includes staff, utilities, material, equipment replacement, and process waste disposal cost.
- The decontamination and decommissioning of the facility after 40-year design life will be made via an annual sinking fund of 1.25% of the direct cost for the life of the plant.

2.3.1.2. Capital Cost

The direct capital cost includes 12 major elements as shown in Table 2.4. These elements are then divided into ~300 sub-elements. The cost of each element was estimated for material, labor, and subcontractors. Labor costs have been estimated for in-house labor only. Labor costs for subcontractors are included in the total subcontractor cost. The selection of in-house labor or subcontractor labor is at the discretion of the project management organization. The total direct capital cost was estimated to be 585 M$.

The indirect cost includes the costs for design (14%), engineering and construction management (10%), licenses (20%), building permits (3%), taxes and insurance (2%), general and administrative (6%), startup and testing (20%), training (3%), etc., in which the number in parenthesis is a percentage of the total direct cost. The total indirect capital cost is estimated to be 456 M$. Assuming that the contingency is 25% of the total capital cost, the total capital cost for the 400 MTHE/yr facility is estimated to be 1302 M$.

2.3.1.3. Annual Operation and Maintenance Cost

The annual labor cost is summarized in Table 2.5. This estimate was based on an average annual labor rate of 993600 $/yr for managers, 55200 $/yr for engineers, 55200 $/yr for technicians, 40840 $/yr for administrative people, and 27600 $/yr for clerical personnel.

The estimated annual non-labor operational cost is summarized in Table 2.6. The cost for equipment replacement is assumed to be 10% of the total equipment cost, which is equivalent to that of the mean life-time of the process equipment which was established to be 10 years. The process radioactive wastes include vitrified dirty scrap waste (1% of the production capacity) of ~10 m^3, vitrified semi-volatile waste of ~41 m^3, compacted fuel structural material of ~65 m^3, and miscellaneous waste of ~764 m^3. The estimated total annual operation and maintenance cost for the 400 MTHE/yr facility is 155 M$.

2.3.2. *Fuel Fabrication Cost*

Life cycle cost (LCC) and levelized unit cost (LUC) models were used for the cost evaluation of DUPIC facility. The net present value (NPV) methodology is used for calculating LCC. The LCC is defined as the total discounted cost necessary to construct, operate, and decommission the DUPIC fuel fabrication facility. Life cycle cost shall be described with a form of NPV as follows;

$$NPV = \sum_i \frac{C_i}{(1+d)^i} \tag{2.1}$$

where C_i is the cost in the i-th year, and d means a discount rate. The LUC method will be used to evaluate the fabrication unit cost as follows;

$$LUC = \frac{NPV}{NPB} \tag{2.2}$$

where the net present benefit is given as;

$$NPB = \sum_i \frac{Q_i}{(1+d)^i}, \tag{2.3}$$

and Q_i is the benefit (production amount) to be derived in the i-th year.

For sensitivity analysis of production capacity, the power factor method based on reference capacity was used, instead of designing the facility with a new capacity.

2.3.2.1. Reference Model

The throughput capacity of the DUPIC facility is 400 MTHE/yr. This is roughly equivalent to the fuel needs of seven CANDU reactors, each with a capacity of 1000 MWe. A conservative direct capital cost contingency of 25% and a discount rate of 5% are used for the reference model. The input values used in the reference LCC model are found in Table 2.7. Using the input values, the reference model LCC is determined as shown in Table 2.8. The LCC provides an estimate of the fund required to build, operate, and dispose of the facility during the stated time period (2015-2059) in absolute dollars. The reference model LCC is estimated to be 7885 M$.

In order to determine fuel fabrication cost, the LCC must be discounted by an annual factor. This process yields the NPV and provides a reference point for future cost comparisons. The calculated reference model NPV is 1311 M$. Once the NPV of the LCC is determined, it is then possible to calculate the LUC. The LUC is determined by dividing the sum of the life cycle discounted cost by the sum of the life cycle discounted production. The LUC of the reference model is calculated to be 616 $/kgHE. The cost break-down for the reference DUPIC model is summarized in Table 2.9.

2.3.2.2. Sensitivity Analysis for Cost Parameter

The purpose of the sensitivity analysis is to determine the effect of the individual input parameter on the fabrication cost. By performing this analysis, it is also possible to identify which input value has the greatest effect on the final fuel fabrication cost. As the DUPIC design process continues, the value identified to have the greatest impact on the fuel fabrication cost can undergo further detailed analysis to determine final DUPIC fabrication cost more accurately.

The discount rate, production capacity and contingency were chosen as items of the sensitivity analysis. The fabrication cost was estimated for the cost parameter ranging from 50% to 150% of the reference value, and the results are shown in Table 2.10 and Fig. 2.8. The results have shown that the contingency factor has relatively small effect on the unit cost of production while the variations in production volume have the most significant impact on the unit cost. The discount rate change from 2.5 to 6.25% and the production volume change from 200 to 500 MTHE create a unit cost variation of 26 and 33%, respectively.

Since variations in the contingency factor have little impact, conservatism is warranted. To a lesser degree, the same argument holds for the discount rate. Since production capacity has the greatest impact on the cost, the anticipated facility throughput is the primary component for the determination of the cost effectiveness for the DUPIC fuel fabrication facility.

2.3.2.3. Sensitivity Analysis for Adding Uranium

DUPIC fuel composition changes depending on initial enrichment, discharge burnup, and specific power of the PWR fuel. In order to resolve the fuel composition heterogeneity, the composition adjustment method has been proposed.[9] In this method, contents of major fissile isotopes are tightly controlled by adding fresh uranium to spent PWR fuel powder during DUPIC fuel fabrication process. In this section, the effects of adding extra uranium during DUPIC fuel fabrication process on fabrication cost are examined. For this, the following approaches and assumptions are used.

- The amount of slightly enriched uranium (SEU) or natural uranium is estimated; then, the cost of SEU or natural uranium is evaluated.
- The cost of SEU or natural uranium is included in the fabrication cost as the operation and maintenance cost.
- Natural uranium (U_3O_8) cost is assumed to be 62.5 \$/kgU, which is referred from OECD/NEA report.[10] The reference cost used in OECD/NEA is 50 \$/kgU as of 1991 and an escalation rate of U.S. (1.25) was reflected to get the cost at the end of 1999.
- The SEU (3.5 wt%) cost is assumed to be 1175 \$/kgU. The value was calculated by assuming that the uranium, conversion, and enrichment costs are 62.5 \$/kgU, 10 \$/kgU, and 137.5 \$/SWU, respectively.

The results of the sensitivity analysis for adding uranium are shown in Tables 2.11 and 2.12 for natural uranium and SEU, respectively. As shown in Table 2.11, adding natural uranium during DUPIC fuel fabrication process shows only a slight increase of the fabrication unit cost. Even though natural uranium is added to the spent fuel powder by 50%, the fabrication unit cost shows an increase of only 4.5%, from 616 to 644 \$/kgU. However, Table 2.12 shows that adding enriched uranium is significant to the fabrication unit cost. A 10% addition of enriched uranium causes ~17% increase in the fabrication unit cost, from 616 to 720 \$/kgU.

2.4. SUMMARY

Since the initial technical feasibility study on the DUPIC process, significant interests have been drawn to the economics of the DUPIC fuel cycle. For this reason, the conceptual design of a commercial scale DUPIC fuel fabrication facility was initiated to provide some insights into the costs associated with construction, operation, and decommissioning. The primary conclusion of this study is that it is feasible to design, license, construct, test, and operate a facility that will process 400 MTHE/yr of spent PWR fuel and reconfigure the fuel into CANDU fuel bundles at a reasonable fabrication cost. This study has used representative costs of currently available technologies as the bases for cost estimation. It should also be noted that the conceptual design and cost information contained in this study was extracted from the public domain and general open literature.

Table 2.1

Characteristics of DUPIC Fuel Bundle

Physical geometry	
Bundle diameter	102.5 mm max
Number of large pins	8
Number of small pins	35
Length	49.53 mm
Heavy metal weight per bundle	17.64 kg
Bundle weight	23.6 kg
Number of pellets in a large pin	30
Number of pellets in a small pin	36
Pellet density	10.4 (±0.15) g/cm^3
Pellet surface finish	0.8-1.6 micron RA

Table 2.2

Nominal Level of Recycle Stream for DUPIC Process

Reference fuel material flow	1 MTHE of processed spent PWR fuel
Fuel material loss	
- In fuel decladding process step	1 wt%
- In dust form (e.g., trapped in HEPA filters and non repairable equipment)	Negligible
Recycle streams	
- Rejected pellets before sintering	0.5 wt%
- Rejected pellets after sintering	5.0 wt%
- Rejected pellets after grinding/finishing	5.4 wt%
- Net rejected fuel pin after welding	1.0 wt%
- Initial rejected fuel pin	3.0 wt%
- Repairable fuel pins	2.0 wt%
- Net rejected fuel bundle after welding	0.1 wt%
- Initial rejected fuel bundle	1.0 wt%
- Repairable fuel bundle	0.9 wt%
Total recycled fuel material to oxidation/reduction process	12.0 wt%

Table 2.3

Material Flow in Main Process Building

Net DUPIC facility throughput	400 MTHE/year
Design throughput at 70% plant availability	600 MTHE/year
Number of parallel process lines	4
Design throughput per process line	150 MTHE/year
Daily process rate (i.e., 150/365)	0.41 MTHE/day/line
PWR spent fuel disassembly rate (0.41/0.44)	1 fuel assembly/day/line
PWR fuel rod decladding rate (×264)	264 fuel rods/day/line
Fuel oxidation/reduction process rate (w/o recycle stream)	410 kgHE/day/line
Fuel oxidation/reduction process rate with recycle stream	460 kgHE/day/line
Larger pellet production rate (w/o recycle stream)	4,830 pellets/day/line
Larger pellet production rate with recycle stream	5,410 pellets/day/line (+12%)
Smaller pellet production rate (w/o recycle stream)	28,980 pellets/day/line
Smaller pellet production rate with recycle stream	32,460 pellets/day/line (+12%)
Larger fuel pin production rate (w/o recycle stream)	161 pins/day/line
Larger fuel pin production rate with recycle stream	163 pins/day/line (+1.1%)
Smaller fuel pin production rate (w/o recycle stream)	805 pins/day/line
Smaller fuel pin production rate with recycle stream	814 pins/day/line (+1.1%)
CANDU DUPIC bundle production rate	23 bundles/day/line

Table 2.4

Estimated DUPIC Direct Capital Cost

Element	Estimate ($)
Site Preparation	12,592,224
Process System	328,640,928
Main Process Building	204,429,888
Health Physics Facility	7,330,560
Safeguards and Security	8,106,672
Utilities	12,111,984
Fire Department	1,711,200
Simulation and Training	397,440
Administration Facilities	1,501,440
Specialty Gases Building	1,693,536
Warehouse	579,600
Off-Site Facilities	6,045,504
Total Direct Cost	585,140,976

Table 2.5

Estimated Annual DUPIC Labor Cost

Department/Division	Staff	Labor(k$)	Total(k$)
General manager staff (total)	5		282
Staff	5	282	
Administration (total)	65		3191
Manager/Staff	2	127	
Legal	5	220	
Human resources	14	604	
Procurement	13	607	
Comptroller	10	440	
Computer/Information science	15	845	
Public relations	6	348	
Safety and health (total)	93		4812
Manager/Staff	4	209	
Industrial safety	20	1121	
Radiation safety	17	898	
Medical	6	304	
Emergency preparedness	20	1034	
Analytical laboratory	20	1010	
Data processing/Records	6	237	
Safeguards and security (total)	62		1633
Manager/Staff	3	168	
Nuclear material safeguards & accountability	19	1051	
Security	40	414	
Environmental & waste management (total)	54		2862
Manager/Staff	2	127	
Environmental/Waste management & compliance	16	885	
Waste Operations	36	1849	
Engineering and quality assurance (total)	86		4564
Manager/Staff	4	182	
Nuclear safety engineering	17	955	
Process mechanical engineering	18	1010	
Electrical/Instrumentation engineering	19	1065	
Construction engineering	7	403	
Quality engineering	21	948	
Compliance/Standards (total)	15		675
Manager/Staff	15	675	
Operations (total)	113		5976
Manager/Staff	12	550	
Process/Utility operations	67	3643	
Operational maintenance	34	1783	
DUPIC Staff Total	**493**		23993

Table 2.6

Estimated Annual DUPIC Non-Labor Cost

Category	Gross(k$)	Specific Item	Cost(k$)	Cost Basis
Materials	22,339	Dysprosium pins	883	1 pin per bundle/21,500 bundles per year
		DUPIC fuel assembly components	19,872	21,500 CANDU bundles per year
		Process gases	83	Scale up from AIROX 200MTHE
		Analytical supplies	55	Scale up from AIROX 200MTHE
		Materials for waste treatment	0	
		Kr-85 cylinders	221	264 Cylinders per year
		Vitrified waste canisters	166	41.2 MT glass/24 cubic meters per year
		Greater-than-Class-C containers	166	60 cubic meters per year
		Low level waste containers	442	756 cubic meters per year
		Liquid argon/Nitrogen	66	Scale up from AIROX 200MTHE
		Filters (HEPA, charcoal, liquid)	83	Scale up from AIROX 200MTHE
		Health physics contamination supplies	221	Scale up from AIROX 200MTHE
		Personnel protective equipment	83	Scale up from AIROX 200MTHE
Equipment replacement	23,405		23,405	1/10 of total cost for process equipment
Utilities	10,102	Electricity	6,624	46 million kWh per year
		Fuel oil	276	Scale up from AIROX 200MTHE
		Transportation fuel and lubricants	83	Scale up from AIROX 200MTHE
		Spare parts	2,760	1/10 of total cost for utility equipment
		Chemicals	83	Scale up from AIROX 200MTHE
		Miscellaneous	55	Scale up from AIROX 200MTHE
		Janitorial supplies	138	Scale up from AIROX 200MTHE
		Miscellaneous (e.g., Office supplies)	83	Scale up from AIROX 200MTHE
Radwaste Disposal	74,851		74,851	Scale up from AIROX disposal cost
Non Labor Total	**130,697**			

Table 2.7

Inputs for Life Cycle and Unit Cost Estimation

Content	Sub-content	Cost(k$)
Capital Cost	Direct cost	585,141
	· Site preparation	12,592
	· Process systems	328,641
	· Main processing building	204,430
	· Site support facilities	39,478
	Indirect cost	456,411
	Contingency	260,388
	Total	1,301,941
Operation & Maintenance Cost (annual basis)	Staff	23,993
	Utilities	10,102
	Materials	22,339
	Equipment replacement	23,405
	Radwaste disposal	74,851
	Total	154,690
Decommissioning Cost (annual basis)	Decommissioning cost	9,143

Table 2.8
Life Cycle Cost and Unit Cost Estimation for DUPIC Fuel Fabrication

(Discount 5%, Capacity 400 MT, Contingency 25%)

Year	Cost (k$)					Production (MTHE)	Discounted Production (MTHE)
	Capital	Operation & Maintenance	Decontamination & decommissioning	Total	NPV		
2015	130,194			130,194	49,069		
2016	260,388			260,388	93,464		
2017	260,388			260,388	89,014		
2018	390,582			390,582	127,162		
2019	260,388			260,388	80,738		
2020		154,690	9,143	163,833	48,380	400	118
2021		154,690	9,143	163,833	46,077	400	113
2022		154,690	9,143	163,833	43,882	400	107
2023		154,690	9,143	163,833	41,793	400	102
2024		154,690	9,143	163,833	39,803	400	97
2025		154,690	9,143	163,833	37,907	400	93
2026		154,690	9,143	163,833	36,102	400	88
2027		154,690	9,143	163,833	34,383	400	84
2028		154,690	9,143	163,833	32,746	400	80
2029		154,690	9,143	163,833	31,186	400	76
2030		154,690	9,143	163,833	29,701	400	73
2031		154,690	9,143	163,833	28,287	400	69
2032		154,690	9,143	163,833	26,940	400	66
2033		154,690	9,143	163,833	25,657	400	63
2034		154,690	9,143	163,833	24,435	400	60
2035		154,690	9,143	163,833	23,272	400	57
2036		154,690	9,143	163,833	22,164	400	54
2037		154,690	9,143	163,833	21,108	400	52
2038		154,690	9,143	163,833	20,103	400	49
2039		154,690	9,143	163,833	19,146	400	47
2040		154,690	9,143	163,833	18,234	400	45
2041		154,690	9,143	163,833	17,366	400	42
2042		154,690	9,143	163,833	16,539	400	40
2043		154,690	9,143	163,833	15,751	400	38
2044		154,690	9,143	163,833	15,001	400	37
2045		154,690	9,143	163,833	14,287	400	35
2046		154,690	9,143	163,833	13,607	400	33
2047		154,690	9,143	163,833	12,959	400	32
2048		154,690	9,143	163,833	12,342	400	30
2049		154,690	9,143	163,833	11,754	400	29
2050		154,690	9,143	163,833	11,194	400	27
2051		154,690	9,143	163,833	10,661	400	26
2052		154,690	9,143	163,833	10,153	400	25
2053		154,690	9,143	163,833	9,670	400	24
2054		154,690	9,143	163,833	9,209	400	23
2055		154,690	9,143	163,833	8,771	400	21
2056		154,690	9,143	163,833	8,353	400	20
2057		154,690	9,143	163,833	7,955	400	19
2058		154,690	9,143	163,833	7,577	400	19
2059		154,690	9,143	163,833	7,216	400	18
Total	1,301,940	6,187,611	365,713	7,855,264	1,311,118	16000	2128
Net Present Values (k$) = 1,311,118 Levelized Unit Cost ($/kg) = 616							

Table 2.9
Estimated Costs for DUPIC Fuel Fabrication Plant of 400 MTHE/yr Capacity

(Reference Case)

Item		NPV (M$)	Fraction of Levelized Unit Cost
Capital Life Cycle Cost	Direct Costs	198	
	Indirect Costs	155	*33.6 %*
	Contingency	88	
Operation and Maintenance Costs (annual basis)	Staff	129	
	Utilities	53	
	Materials	117	*62.7 %*
	Equipment Replacement	124	
	Process Waste Disposal	400	
Decontamination and Decommissioning Life Cycle Cost		49	*3.7 %*
40-years Life Cycle Cost (M$) in Net Present Value			1,311
Levelized Unit Cost ($/kgHE)			***616***

Table 2.10

Sensitivity Analysis on Cost Parameters

Items	Sensitivity Variable	Unit Cost ($/kg HE)
Discount Rate (%)	2.50	545
	3.75	578
	5.00	616
	6.25	658
	7.50	703
Contingency (%)	12.50	593
	18.75	605
	25.00	616
	31.25	627
	37.50	639
Production (MTHE)	200	757
	300	669
	400	616
	500	591
	600	553

Table 2.11

Sensitivity Analysis for Adding Natural Uranium

Natural uranium fraction (wt%)	Annual natural uranium feed (MTU)	Annual natural uranium cost (k$)	Fabrication cost ($/kgHM)
5	20	1,104	619
10	40	2,208	622
15	60	3,312	625
20	80	4,416	627
25	100	5,520	630
30	120	6,624	633
35	140	7,728	636
40	160	8,832	638
45	180	9,936	641
50	200	11,040	644

Table 2.12

Sensitivity Analysis for Adding Slightly Enriched Uranium

SEU fraction (wt%)	Annual SEU feed (MTU)	Annual SEU cost (k$)	Fabrication cost ($/kgHM)
1	4	4,151	626
2	8	8,302	637
3	12	12,453	647
4	16	16,604	658
5	20	20,755	668
6	24	24,906	678
7	28	29,057	689
8	32	33,208	699
9	36	37,359	710
10	40	41,510	720

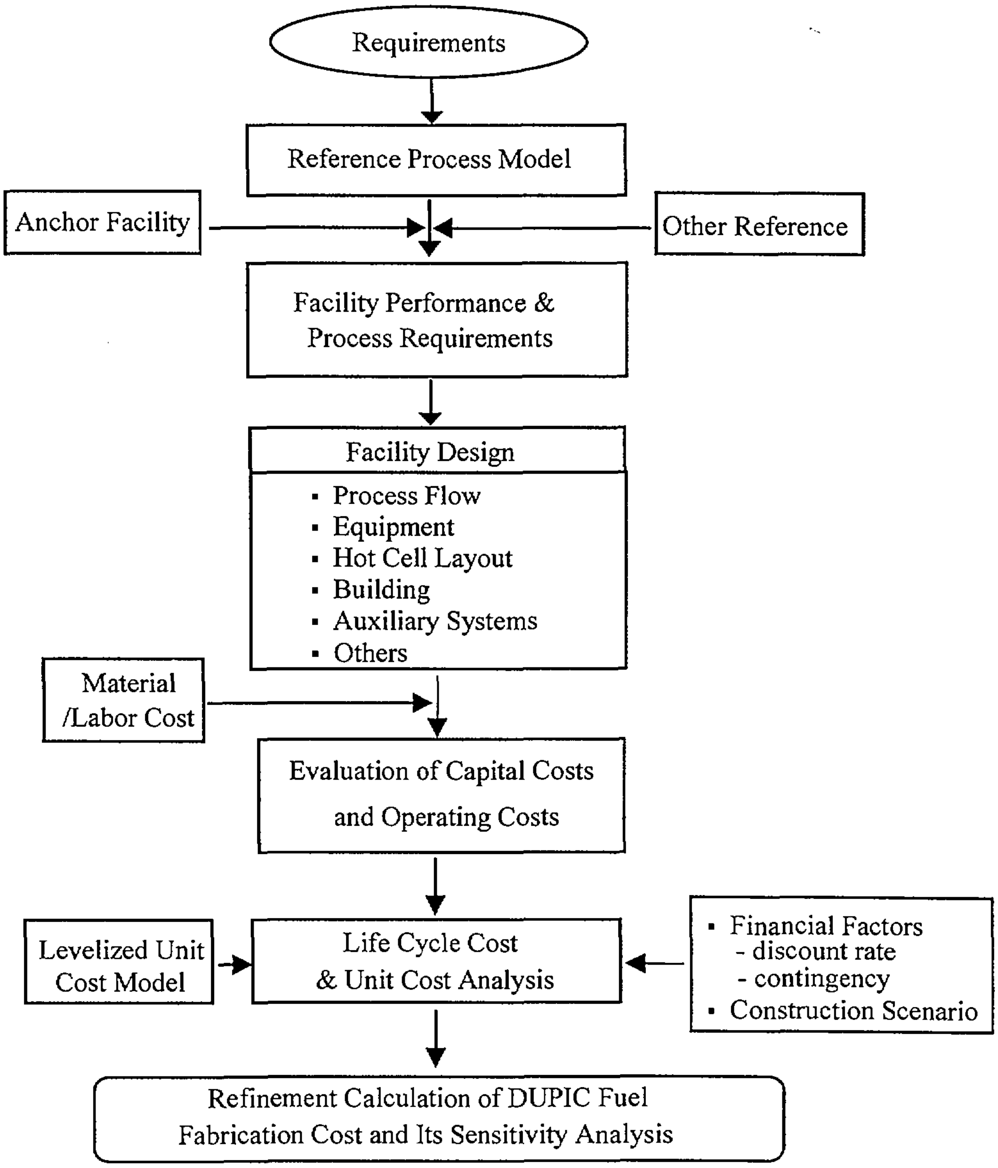
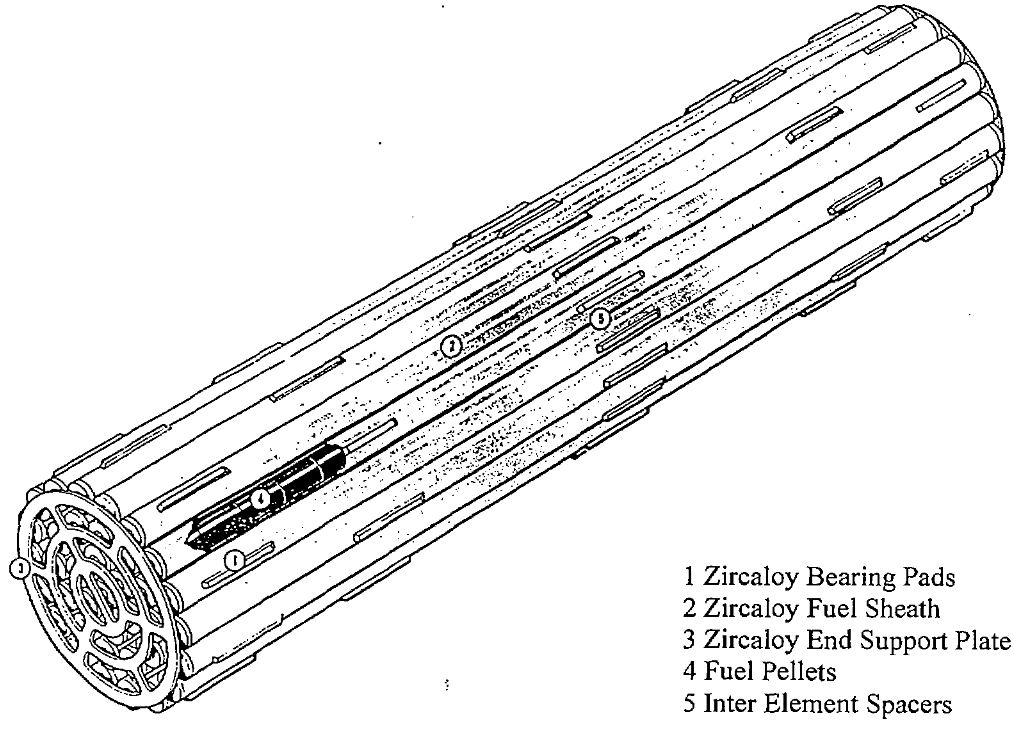


Fig. 2.1 Schematic Process for DUPIC Facility Cost Evaluation



1 Zircaloy Bearing Pads
2 Zircaloy Fuel Sheath
3 Zircaloy End Support Plate
4 Fuel Pellets
5 Inter Element Spacers

Fig. 2.2 Configuration of DUPIC Fuel Bundle

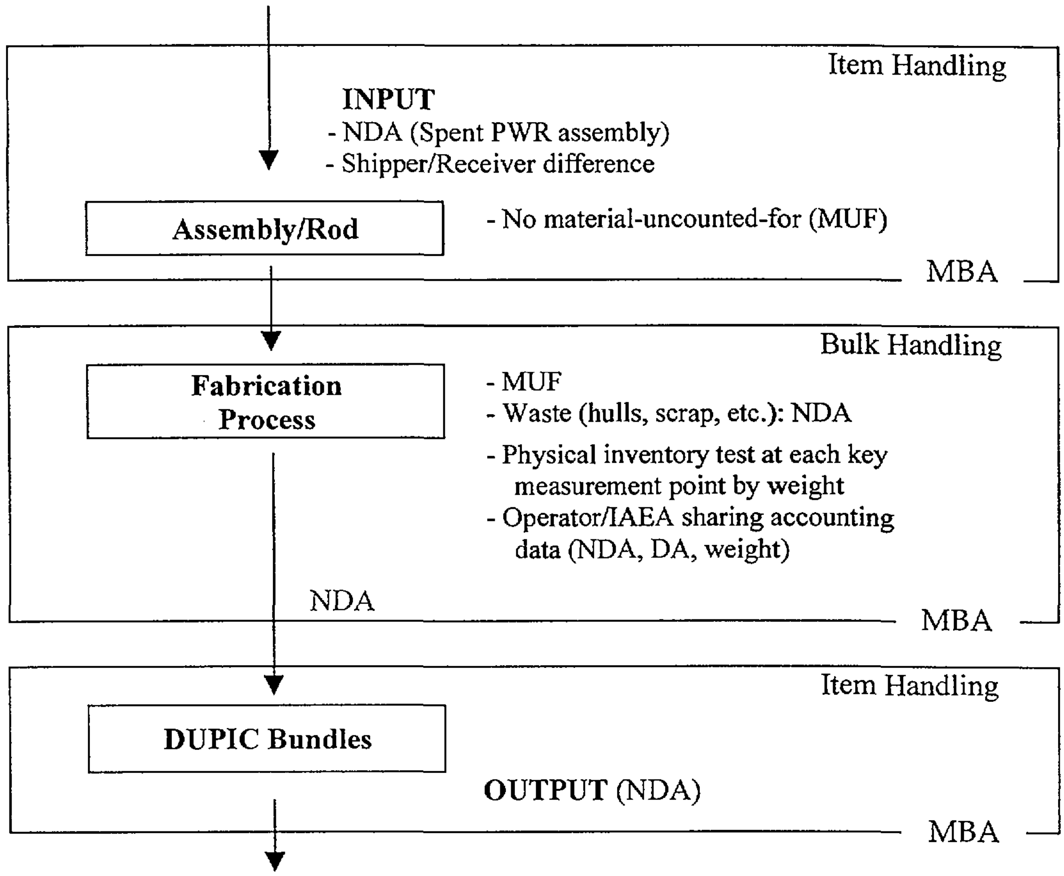


Fig. 2.3 Accounting Methodology in DUPIC

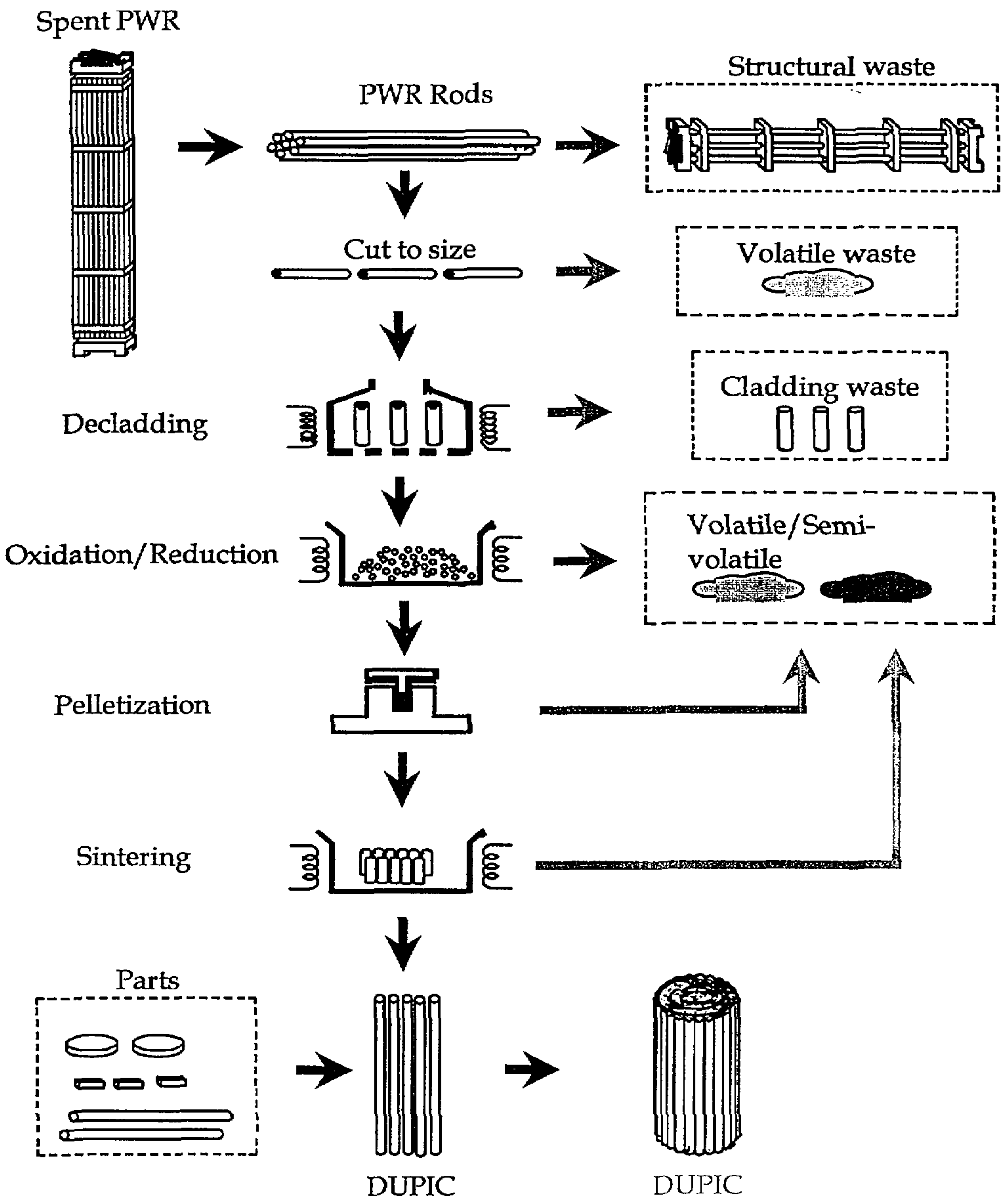


Fig. 2.4 Pictorial Illustration of DUPIC Process

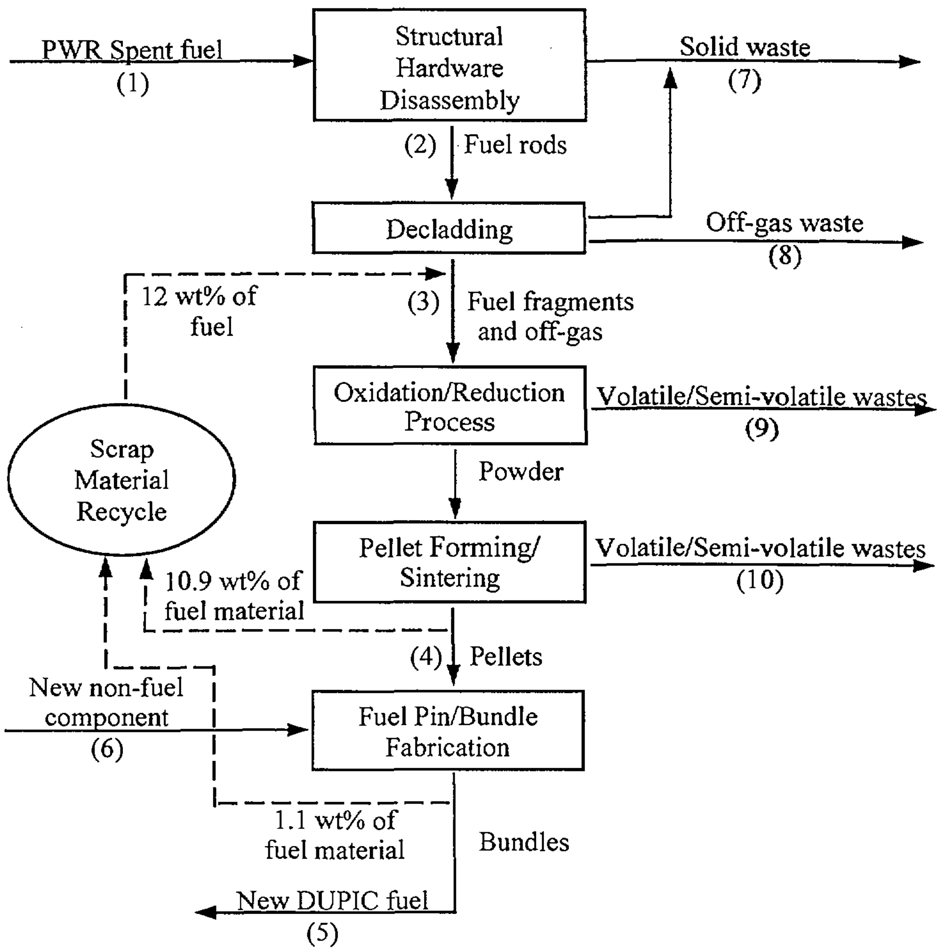


Fig. 2.5 DUPIC Process Mass Balance Schematic

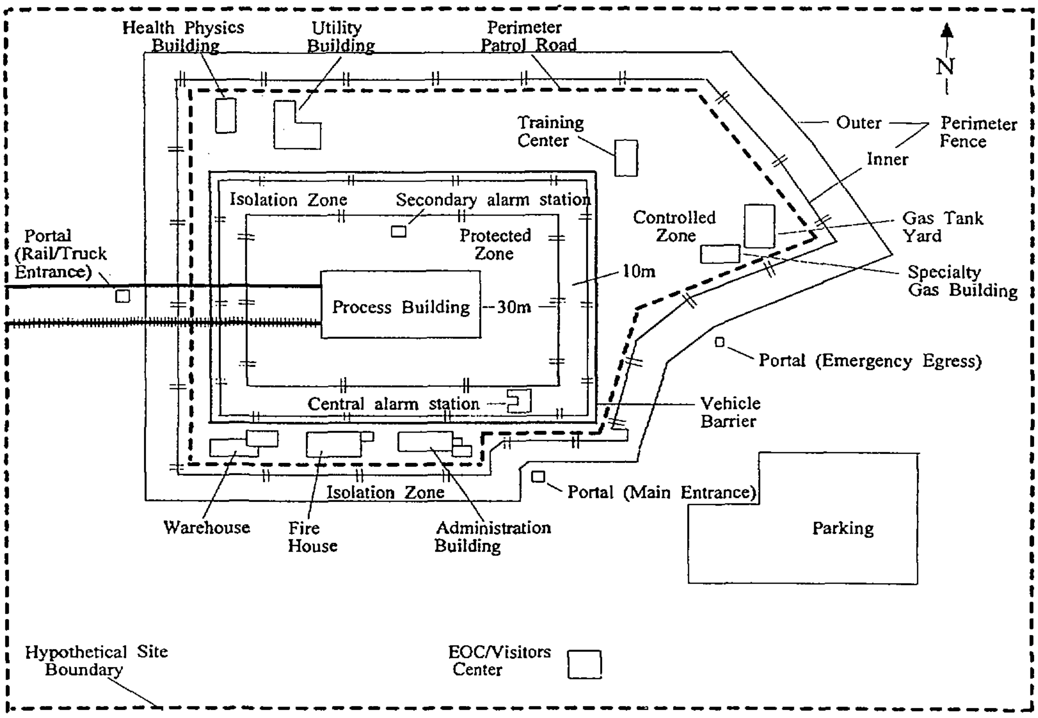


Fig. 2.6 DUPIC Facility Area Plot

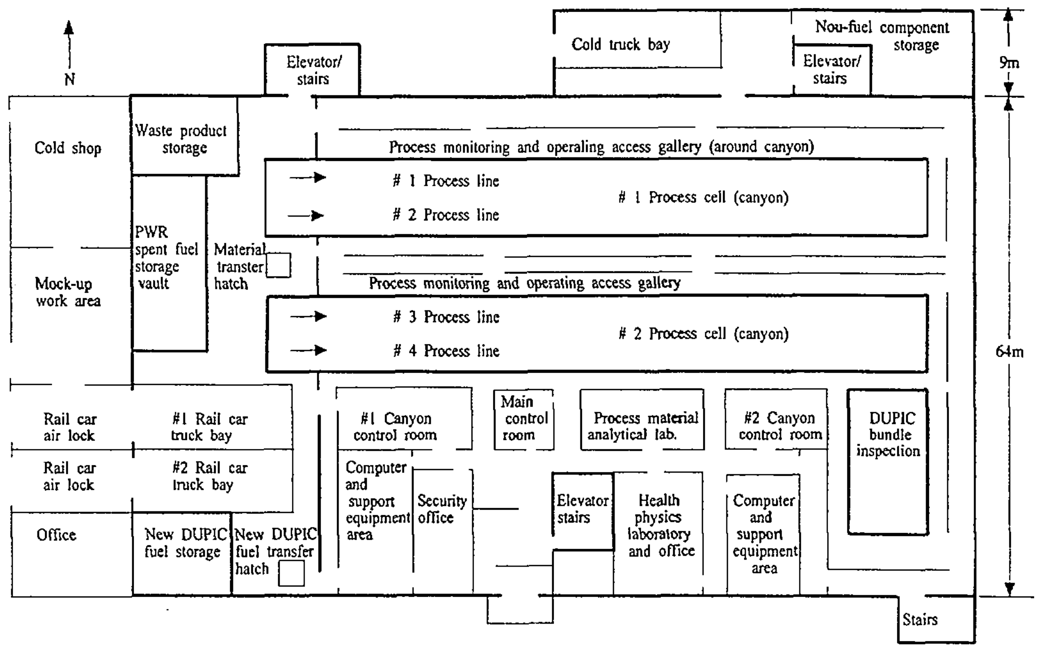


Fig. 2.7 Main Process Building Floor Plot

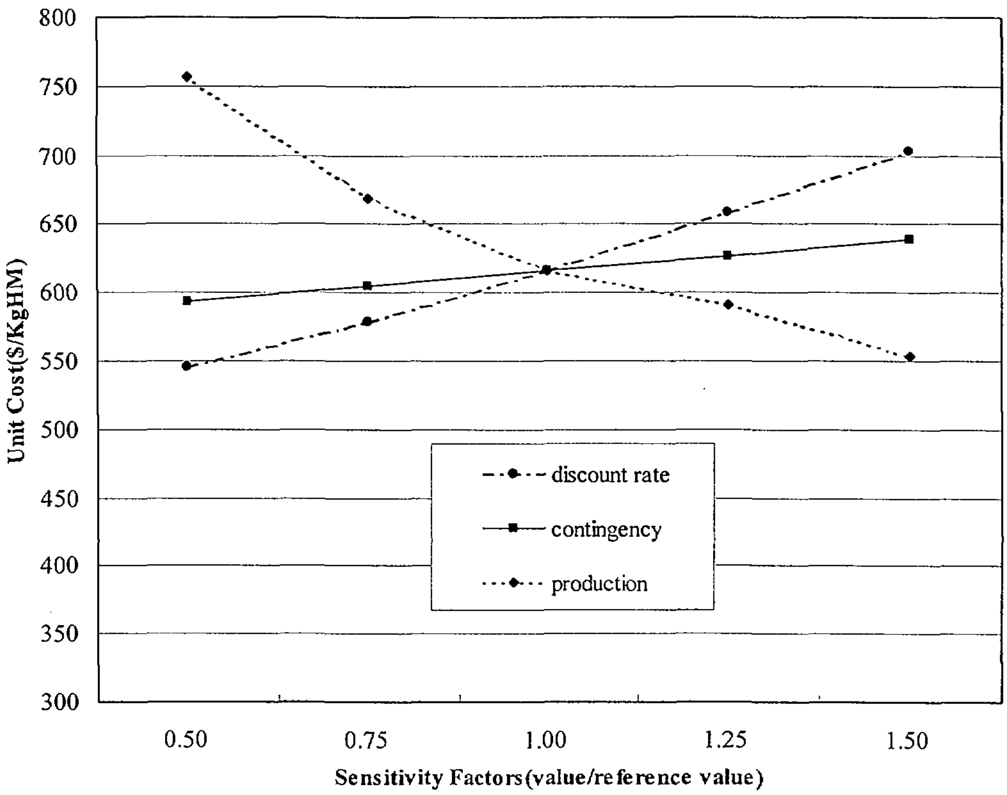


Fig. 2.8 Sensitivity of Cost Parameters

3. DUPIC FUEL HANDLING COST

One of the distinctive features of DUPIC fuel from standard CANDU fuel is that DUPIC fuel is radioactive even in the fresh condition, because spent PWR fuel is directly refabricated into DUPIC fuel. The radioactivity of DUPIC fuel essentially provides a good safeguardability, however, it also causes difficulties when DUPIC fuel is practically implemented in the CANDU reactor system which was originally designed for natural uranium fuel. In the CANDU plant, for example, fresh fuel is brought into the reactor building through the air-lock and handled manually. However, it is prohibited to handle DUPIC fuel manually due to its radioactivity.

The DUPIC fuel cycle utilizes the existing CANDU reactor system to burn spent PWR fuel again without major changes to the CANDU-6 design. However, due to the radioactivity of DUPIC fuel, new design and equipment would be required for DUPIC fuel to be implemented in the current CANDU reactor, which results in a penalty to DUPIC fuel cycle economics. The purpose of this study is then to investigate the loading path of DUPIC fuel in an existing CANDU reactor. This study also includes an assessment of the fueling machine and spent fuel storage performance when DUPIC fuel is implemented in a CANDU reactor. Based on the results of the conceptual design and performance analysis, the unit cost of DUPIC fuel handling is estimated and used for an economic analysis of the DUPIC fuel cycle.

This study focuses on the feasibility and potential concept of placing a DUPIC fuel handling system in the reactor building with a new system in which fresh DUPIC fuel is transferred to the fueling machines from outside the reactor building, essentially via the existing CANDU-6 irradiated fuel transfer system. Once the fuel is located in the fueling machine, the fuel can be charged into a fuel channel following the current loading/unloading procedure. However, because DUPIC fuel achieves a higher burnup (~15000 MWd/t) compared with natural uranium fuel, the decay heat load in the fueling machine and eventually in the spent fuel storage bay increases. Therefore the cooling capacity of this equipment will be assessed based on their design requirements.

3.1. CHARACTERISTICS OF DUPIC FUEL

The reference DUPIC fuel model is the 43-element bundle design, which is shown in

Fig. 2.2. The mass of the DUPIC fuel bundle is almost the same as that of 37-element (standard) fuel bundle. The 43-element fuel bundle was designed to be mechanically compatible with the current CANDU-6 fuel handling system. The characteristics of the DUPIC fuel bundle are given in Table 3.1 and compared with those of the standard fuel bundle.

3.1.1. Fresh DUPIC Fuel

DUPIC fuel is directly fabricated from spent PWR fuel. It is assumed that spent PWR fuel had been irradiated to a burnup of 35 MWd/kg of (initial) heavy elements on average and allowed to decay for 10 years. The irradiated and decayed PWR fuel is fabricated into CANDU fuel elements with most of gaseous fission products removed from the fuel during the sintering process used to form the DUPIC fuel elements.[2] The resulting composition is that of a 'fresh' DUPIC fuel bundle, which is given in Table 3.2.

3.1.1.1. Radiation Field

A fresh DUPIC fuel bundle introduces two radiation hazards not normally present in a natural uranium fuel bundle. These are the alpha-particle activity, which will contaminate the bundle from the fabrication process, and the external gamma fields from the fission product activity that remains after the 10-years decay and the sintering process. The annual dose from contamination on a fresh DUPIC fuel bundle could be 2.60 Sv/yr (effective whole body dose), which is not an acceptable radiation hazard. Therefore, it is recommended that all inspections and handling of fresh DUPIC fuel bundles should be performed remotely. The external gamma dose rate from a fresh DUPIC fuel bundle is 3.71×10^{6} mSv/yr on contact, 2.17×10^{3} mSv/yr at 30 cm away, and 7.35 mSv/yr at 5.5 m away. A concrete wall of 43 cm or a steel wall of 12.7 cm is required to bring the dose rate to a target level of <6 μSv/h.

3.1.1.2. Criticality

Fresh DUPIC fuel will contain approximately 1.5 wt% fissile material (^{235}U, ^{239}Pu and ^{241}Pu).[9] A preliminary study was conducted to estimate criticality in the shipping cask, storage bay and handling facility.[11] This study has also shown that there is no possibility of criticality as long as the DUPIC fuel bundle configuration is maintained.

3.1.2. *Spent DUPIC Fuel*

The composition of spent DUPIC fuel was simulated by the ORIGEN code[12] for a burnup of 15 MWd/kg of heavy elements and a decay of 10-years, as given in Table II. The inventory of short-lived fission products after this irradiation depends on the characteristics of the bundle power immediately before discharge, rather than on the burnup. Consequently, the external gamma fields from the irradiated DUPIC bundles, when freshly discharged, will be comparable with those from natural uranium fuel bundles.

3.1.2.1. Radiation Field

At longer decay times, the higher burnup of DUPIC fuel will create larger inventories of long-lived fission products. Consequently, there will be a substantial increase in the neutron source from a DUPIC fuel bundle compared with a natural uranium fuel bundle. The neutron dose from a natural uranium fuel bundle after a 10-years decay is 1.3 μSv/h, while the neutron dose from a spent DUPIC fuel bundle after 10-years decay is 163.6 μSv/h.

3.1.2.2. Heat Load from Spent DUPIC Bundle

In the longer-term, the radiation fields from spent DUPIC fuel will be larger than those from natural uranium fuel. This effect will be particularly important for the heat load during the interim storage period. The decay heat was conservatively estimated for the bundle power of 600 kW, which is typical for natural uranium fuel. The decay heat of a DUPIC fuel bundle is 216 Watts after a one-year decay and 16.5 Watts after a 10-years decay. The decay heat curves are shown in Figs. 3.1 and 3.2 for short and long term decays, respectively.

3.2. DUPIC FUEL LOADING ROUTE AND DESIGN REQUIREMENTS

In the present CANDU-6 plant, fresh fuel arrives at the station in pallets via a truck. The pallets are moved to the fresh fuel storage area in the service building on specially designed racks for storage. Up to a nine months supply of pallets can be stored in this room. Each week, enough fuel for one week's operation is removed from the fresh fuel storage room and transported through the equipment air-lock into the reactor building to the storage area of the fresh fuel transfer room. After uncrating, each fuel bundle is inspected and the bundle diameter is checked with the fuel spacer gauge and the serial number is recorded before it is placed in the loading trough of the transfer mechanism, using the bundle lifting tool and the air-balance hoist which are manually operated.

Figure 3.3 shows the overall flow of fuel bundles in the current CANDU 6 plant. The fuel loading and discharge routes currently being adopted for natural uranium CANDU fuels are summarized in Fig. 3.4. For DUPIC fuel loading in a CANDU 6 reactor, two options have been investigated:

- DUPIC fuel loading through an existing new-fuel loading route (front loading)
- DUPIC fuel loading through an existing spent-fuel discharge route (reverse loading).

3.2.1. Front Loading Routes

This option utilizes the existing new-fuel loading equipment. Depending on where the transportation cask is opened, there could be two alternatives: one that uses the fueling-machine pit and another that uses a hot cell in the containment building. A brief description of each option is given in Table 3.3. In principle, the transportation cask is moved into the containment building and fresh DUPIC fuel is transferred to the fueling-machine magazine. Therefore, the fuel loading operation should be fully automated and it is inevitable to contaminate the new-fuel magazine. It is also recommended to install extra air-cleaning system to minimize the air-contamination during the refueling operation in the containment building.

3.2.1.1. Fueling Machine Pit Option

The transportation cask is moved to the fueling machine pit and opened. DUPIC fuel is then remotely loaded into the new-fuel magazine. During a refueling operation, the fueling machine proceeds to the new-fuel port and fresh DUPIC fuel is transferred to the fueling-machine, and the rest of the process is the same as the current practice. In this option, the operator should move the transportation cask to the fueling machine pit and move the empty cask outside the containment building.

3.2.1.2. Hot Cell Option

This option assumes a small hot cell in the new-fuel loading area so that the air-contamination during a refueling operation is minimized. In this option, the transportation cask is opened in the hot cell and DUPIC fuel is remotely placed in the fueling machine magazine. The rest of the fuel loading process is the same as the existing process. This option requires the operator to work inside the containment building and the time required to place the fresh fuel in the fueling machine could be more than that currently required, due to the hot-cell operation. It is also required to install an air-cleaning system in the hot cell.

3.2.2. Reverse Loading Routes

In the normal process, spent fuel is discharged through the spent-fuel discharge port and transferred to the discharge bay, reception bay and storage bay. Fresh DUPIC fuel could be loaded through one of these three places. However, the discharge bay is inside the containment building and too small to install remote handling equipment. Therefore, DUPIC fuel should be loaded through either the reception or storage bay. A brief description of each option is given in Table 3.4. The advantage of this option is that the transportation cask is open in the bay, which can minimize the radiation hazard to the operator.

3.2.2.1. Loading Through the Reception Bay

For DUPIC fuel to be loaded through the reception bay, the remote handling equipment should be installed in the reception bay. However, this option will reduce the working area necessary for transferring spent fuel. This option also requires modification of the reception bay area structure to install the remote handling equipment, which may cause a problem when there is a emergency full core dump.

3.2.2.2. Loading Through the Storage Bay

In a CANDU 6 plant spent fuel storage bay, there is a dry storage facility (welding station) which is used to transfer spent fuels, cooled for more than 6 years in the storage bay, from the storage bay to dry storage. This facility could be used to transfer fresh DUPIC fuel in the reverse direction. This option can reduce the cost, minimize the extra working area, and reduce the radiation hazard to the operator. This option does not require the operator to work inside the containment building for a fueling operation.

3.2.3. Design Requirements

Four options have been surveyed for loading fresh DUPIC fuels in the CANDU 6 reactor. These studies have shown that it is most feasible to utilize the discharge route through the storage bay if new equipment is provided to remotely handle the radioactive fuel and reverse the fueling path. For the implementation of new equipment in the existing CANDU-6 design, the design basis and requirements were established.

3.2.3.1. Design Bases

The design study is based on the basic ground rule that any changes to the existing CANDU-6 fuel transfer system shall be limited to those required to incorporate an automated fresh fuel handling system. Moreover, there was no attempt to change or improve the existing CANDU-6 irradiated fuel transfer system, which generally has a good operating record. During the course of this study, it has been determined that criticality is not a concern and no additional shielding is required in the irradiated fuel discharge room.

It has been established that fresh DUPIC fuel can be transported dry, hence placing fresh DUPIC fuel in a dry shielded station is feasible. However, it would appear that removal of fresh DUPIC fuel in the bay from an immersed transportation cask would require significantly less automated equipment. Therefore, the system would be less costly and more reliable.

3.2.3.2. General Requirements

The basic design requirements have been postulated for the conceptual design of the DUPIC fuel handling system as follows:

- An integrated fresh and irradiated fuel transfer system shall be provided in which fresh fuel is transferred from outside the reactor building to the fueling machines.
- All fresh and irradiated fuel handling operations in the reactor building shall be fully automated.
- The maintenance of the fresh and irradiated fuel handling equipment in the reactor building shall be provided during scheduled plant shut-downs.
- The integrated fresh and irradiated fuel transfer system shall be capable of routinely handling up to 56 fuel bundles per week (100% capacity factor). The system shall have a minimum excess reserve capacity of 50% to meet special needs of the plant when required.

- The overall fueling cycle period, including fresh and irradiated fuel handling, shall not exceed the capacity of the CANDU-6 fueling-machine system.

3.2.3.3. Fuel Loading Requirements

- Fresh fuel shall be supplied in an immersible transportation cask. A multi-layer rack in the transportation cask shall be easily removable.
- Fresh fuel inspection facilities shall be provided in the storage bay for inspecting fresh fuel.
- A manipulator shall be provided for transferring fresh fuel bundles from the transportation rack onto one of the existing fuel racks residing at the bottom of the bay.
- The present CANDU-6 irradiated fuel conveyor, which transports irradiated fuel from the discharge bay to the reception bay on fuel racks, shall also transfer fresh fuel on the same racks back into the discharge bay.
- The irradiated fuel ladles on the two CANDU-6 elevators in the discharge bay shall also transport fresh fuel bundles from the fuel racks out of the water to the fresh fuel magazine.
- The present fuel racks, which are used for transporting irradiated fuel bundles out of the discharge bay into the reception bay, shall also be used for transporting fresh fuel in the reverse direction.
- Two fuel magazines shall be provided. It shall be possible to push the fuel bundles in pairs, directly from a magazine into the fueling machine clamped on the fuel transfer port.
- Air drying tools shall be provided on each fuel magazine so that the fresh fuel, which is initially brought in wet light water, is dried before it is transferred into the fueling machine heads.
- A fuel pusher, outside of each spent fuel discharge port, shall be provided for transferring two fresh fuel bundles from the elevator ladle into the fueling-machine.

3.2.3.4. Maintenance and Monitoring

- All equipment mounted under water shall be maintainable from above the water surface directly or be mounted so that it can readily be lifted out of the water for maintenance when required.
- Underwater lighting shall be provided to light up the area where fresh fuel can be visually inspected.
- A television camera shall be provided in the discharge bay to monitor fuel transfer operations

at the fuel transfer port.

3.3. CONCEPTUAL DESIGN OF THE DUPIC FUEL HANDLING SYSTEM

Among the fuel handling processes, the on-power refueling of DUPIC fuel is a key step that will enable the practical use of DUPIC fuel in the existing CANDU-6 reactor. Because the activity level and external particulate contamination will prohibit handling the DUPIC fuel manually or exposing it to the service or reactor building normal ventilation systems, the use of a spent fuel discharge path in the reverse direction has been proposed as an alternative to the current new-fuel loading path. Once fresh DUPIC fuel is transported to the plant, it will be transferred to the reactor core following the path described below;

- The fresh fuel is in the transportation cask.
- The fresh fuel is moved to the fuel basket by a flask support in the welding station.
- The fuel basket is lowered into the storage bay and onto the carousel.
- The tilt mechanism changes the vertical orientation of the fuel basket to a horizontal one.
- The fuel bundles are located in the tray (or fuel rack).
- The fuel bundles are transferred to the discharge bay.
- The spent-fuel elevator operates in the reverse direction to move the fresh fuel to the discharge port.
- The fuel bundles are moved into the fueling machine.
- The fresh fuels are automatically located in the fuel channel and discharged.
- The spent-fuel follows the existing discharge route.

3.3.1. Fresh Fuel Handling System Design and Operation

The automated fresh fuel transfer system is generally comprised of the following equipment:

- A new fuel transportation cask and rack lay-down area
- Hoisting equipment for handling the transportation cask
- A new fuel inspection area in the bay where individual bundles are inspected for shipping damage
- A new fuel manipulator for transferring fresh fuel bundles from the transportation rack to the inspection table. The transportation rack will be used interchangeably with the existing fuel racks.

- Existing hoisting equipment for transferring loaded fuel racks onto the end of the conveyor for transfer from the storage bay into the discharge bay in the reactor building
- Two fuel magazines, one for each fueling machine, each storing a minimum supply of 24 fresh fuel bundles ready for loading into the fueling machine through the fuel transfer port
- A new fuel magazine loading ram, one for each magazine, for transferring the fresh fuel bundles from the ladle on the elevator into the magazine
- A new fuel ram, one for each magazine, for transferring fresh fuel bundles from the fuel magazine directly into a fueling machine through the fuel transfer port
- A new fuel drying system on each fueling machine magazine, for drying fresh fuel bundles before they are transferred into the fueling machines

3.3.1.1. New-Fuel Storage and Handling Equipment

Fresh fuel arrives in an immersible transportation cask and is lowered into the storage bay with a high capacity overhead crane. After removal of the cover, fresh DUPIC fuel bundles are removed in a fresh fuel transportation rack and placed on the lay-down area beside the cask. Individual bundles are transferred to the inspection table using the fuel bundle manipulator, where the bundles are gauged and inspected using equipment similar to the standard CANDU-6 equipment modified for use under water. After inspection, the bundles are placed on the fresh fuel rack. The loaded fresh fuel rack is then transported by an overhead crane, using the existing CANDU-6 rack handling tool, and placed on the end of the common fresh and irradiated fuel transfer conveyor. The conveyor then transports the fuel rack into the discharge bay to a position under the existing two irradiated fuel elevators.

The transportation racks are used to transfer fresh fuel in the reverse route from the existing irradiated fuel system. The fuel bundle manipulator, shown in Fig. 3.5, is used to remove the fresh fuel bundles from the transportation rack and place them on the inspection table for gauging and visual inspection for shipping damage. The manipulator is then used to transfer the fresh fuel bundles onto the existing fuel racks for transfer into the discharge room. An alternative is to remove the fresh fuel in a dry shielded station. However, this would entail a considerable amount of automated equipment, which would be costly. Removal of fresh fuel from the cask underwater would allow manual operation of much of the equipment at significant cost savings.

3.3.1.2. New-Fuel Magazine and Loader

The new-fuel magazine is shown in Fig. 3.6, which is an unpressurized vessel with open ends to permit the fuel to be air-dried. Each magazine is comprised of 14 tubes, 12 for the storage of 24 fuel bundles in pairs and the other two remain open for the operation of the fresh fuel rams. The magazine is loaded with a fresh fuel loading actuator. It is comprised of the fuel pusher for pushing two fuel bundles and a rotary actuator for rotating the fuel pusher out of the way during the return stroke. The fresh fuel on the fuel rack is lifted off the rack by one of the two ladles of the two existing irradiated fuel elevators and loaded into the fresh fuel magazine. This process is repeated until the magazine, which can store 24 bundles, has a sufficient supply to meet the scheduled fueling operation. Although the fresh fuel magazines are not required for functional reasons, the overall fuel transfer process would be too slow otherwise.

3.3.1.3. Fuel Drying System

An air-drying system is installed, as shown in Fig. 3.6, to dry the fresh fuel before it is pushed into the fueling machine. This is needed so that D_2O in the fueling machine is not contaminated with light water. The fresh fuel is essentially drip-dried by the time it reaches the magazine. It is fully dried in the magazine by air-blast drying. This process, which typically takes 20 to 30 minutes, is carried out while the fueling machines are on the reactor or idle. Accordingly, the drying time does not affect the fueling cycle time.

3.3.1.4. A New-Fuel Loader into the Fueling Machine Head

A new-fuel ram is used for loading each fueling machine head with fresh fuel, as shown in Fig. 3.6. The Bi-stem actuator[13] type ram is required because of the long stroke of about 4.9 m. A special ram lock is mounted on each magazine (see Fig. 3.7). It serves to lock the ram in a fuel-stop position which is required during the irradiated fuel transfer operation. It replaces the present CANDU-6 back-stop mechanisms which cannot be used in this application because of space restrictions. The process of transferring fresh fuel from the fuel magazine directly into the fueling machine head is done after the fueling machines have been completely unloaded of irradiated fuel. The number of bundles transferred into the machine varies depending on the pre-planned fueling schedule.

3.3.1.5. Irradiated Fuel Transfer

The process of unloading irradiated fuel from the fueling machines is essentially the same as the normal unloading process of a CANDU-6, except for the fuel positioning method on the ladle. The new fuel ram piston acts as a fuel-stop. A ram-head lock secures the ram head firmly in position and absorbs the axial load from the C-ram of the fueling machine. The ram-head lock could be eliminated by using a new fuel ram to accurately position the fuel on the ladle after an over-travel push from the C-ram. This process is schematically shown in Fig. 3.7.

3.3.2. The Fueling Process

Generally, the overall fueling cycle time for the DUPIC fuel appears to be lower than that for the standard CANDU fuel. Operation of the fueling system will depend on the prevailing fuel management program and fueling schedule. For the assessment of the fueling process, it was assumed that the two-bundle bi-directional fueling scheme is used and there is no fuel shuffling. With the new system under study, the overall fuel transfer operations are simplified since the existing fresh fuel transfer ports with associated fresh fuel handling equipment have been eliminated. The overall fueling cycle is comprised of:

- The upstream fueling machine proceeds to their respective fuel transfer ports and receives a load of fresh fuels.
- The two fueling machines proceed to the reactor to carry out a fueling operation.
- The downstream fueling machines moves to the respective fuel transfer ports and discharge irradiated fuel.
- The two fueling machines repeat the process or move to rest position.

3.3.2.1. Fueling Process Cycle

Two fueling machines are operating together at the up- and down-stream of a fuel channel when a refueling operation is performed. Each fueling machine can contain eight fuel bundles. In order to avoid the possibility of fueling spent fuel back to the channel, it would be appropriate to refuel in one direction only during one fueling cycle. For example, one fueling machine receives fresh DUPIC fuels from the new-fuel port and refuels two channels consecutively (two fuel bundles per channel) in the up-stream. At the same time, the other fueling machine in the down-stream receives only the spent fuel bundles. By performing this operation twice a day in two opposite directions, the reactor core maintains excess reactivity and a symmetric power distribution.

Depending on the number of fuel channels refueled per refueling machine operation, the residence time of the spent fuel in the fueling machine is determined, which is used to estimate the temperature of the fueling machine.

3.3.2.2. Fueling Machine Cooling

As the fuel bundles are moved to the fueling machine, the internal temperature of the fueling machine increases due to the decay heat of the fuel. In order to estimate the internal temperature of the fueling machine, an energy balance equation can be written as below;

$$\rho_d c_d Q_{in} T_c - \rho_d c_d Q_{out} T + \dot{q} - h_m A_m (T - T_{amb}) = (c_d M_d + c_m M_m)\frac{dT}{d\tau} \tag{3.1}$$

where $\dot{q}$: decay heat from the spent fuel bundle (W)

M_d : D_2O mass in the fueling magazine (kg)

M_m : fueling magazine mass (kg)

Q_{in} : flow rate into the magazine (m^3/sec)

Q_{out} : flow rate out of the magazine (m^3/sec, $Q_{in} = Q_{out}$)

$\frac{dT}{d\tau}$: D_2O temperature change inside the magazine (℃/sec)

T : D_2O temperature inside the magazine (= outgoint D_2O temperature) (℃)

T_c : incoming D_2O temperature (= Tconst , ℃)

T_{amb} : ambient temperature (℃)

ρ_d : D_2O density (kg/m^3)

c_d : D_2O specific heat (J/kg℃=W·sec/kg℃)

c_m : magazine specific heat (J/kg℃)

A_m : magazine outer surface area (m^2)

h_m : magazine outer surface heat transfer coefficient (W/m^2℃)

The left-hand side of Eq. (3.1) includes the heat of incoming D_2O, outgoing D_2O, spent fuel in the magazine, and convection to the outside of the magazine. The right-hand side of Eq.

(3.1) includes the heat change of D_2O and the magazine. In fact, the decay heat of spent fuel drops when it is out of the fuel channel. In other words, decay heat, $\dot{q}$, is a function of time (τ). Considering this and neglecting the convection term that has only a minor effect, the finite-difference form of Eq. (3.1) can be written as follows;

$$T_i = \frac{(A+\dot{q}_i)\cdot(\tau_i - \tau_{i-1}) + C\cdot T_{i-1}}{B\cdot(\tau_i - \tau_{i-1}) + C} \qquad (3.2)$$

where $A = \rho_d c_d Q_{in} T_c$, $B = \rho_d c_d Q_{out}$, and $C = c_d M_d + c_m M_m$. Using Eq. (3.2) and the decay heat curves shown in Fig. 3.1, the temperature of the fueling machine magazine can be calculated, which is shown in Fig. 3.8.

When the incoming D_2O temperature is constant (44℃), the D_2O temperature in the magazine is highest at the time of entry of the last fuel bundle into the fueling machine magazine. After that, the temperature decreases slowly but increases slightly again when the fueling machine is clamped on the discharge port. This is due to the procedure that stops D_2O circulation temporarily in order to prevent D_2O leakage when the fueling machine is connected to the discharge port and opens the snout and ball valve. Once the D_2O level in the magazine is lowered and the D_2O supply is resumed, the discharge of spent fuel begins.

Figure 3.8 shows the magazine temperature when two fuel channels are refueled consecutively under two-bundle shift refueling scheme. For the DUPIC fueling cycle, the normal two-bundle shift operation is performed with a total of two channel refueling per a refueling job. In this case, the operation time is ~1.5 hours from the opening of the first channel to the discharge of last fuel bundle. At the time of entry of the last bundle into the fueling machine magazine, it was estimated that the magazine temperature increases up to 54.2℃ (130 °F) in the downstream machine. At the time the channel closure enters the snout on close up, the temperature of the return D_2O is estimated to be 51.6℃ (125 °F).

The temperature limit of the fueling machine design[14] is 150℃ (300 °F) for the snout assembly, magazine housing, gland plate, coolant connector, snout emergency lock assembly, ram housing assembly, and ball screw seal assembly, and 65℃ (150 °F) for the magazine main shaft and tape drive. Therefore, it is believed that the DUPIC fueling cycle is acceptable and there is no need for design modification of the fueling machine.

3.3.3. Spent Fuel Transfer

The existing spent fuel transfer system, including defective fuel inspection and storage, is suitable for handling DUPIC fuel. But since fresh fuel and spent fuel could be using the same equipment, time and fuel management in the bay will become more critical and gamma detectors, which differentiate between fresh and spent fuel, will be required at certain locations.

To integrate the automated fresh fuel transfer system with the irradiated fuel transfer system of a CANDU-6, some changes to the system are required and should be studied more in the future. These studies are:

- The system now has to transfer fuels in two directions, irradiated fuel out of the discharge bay, and fresh fuel into the discharge bay and up the two irradiated fuel elevators. A detailed study of the mechanical design will be required to ensure that the components have the required degree of precision for this dual role.
- The semi-automated irradiated fuel transfer mechanism of the standard CANDU-6 needs to be improved for the new application. Modifications are required, both mechanical and control, to provide this capability. The function of this mechanism may be expanded to carry out the operation of the new fuel bundle manipulator.

3.3.4. Spent Fuel Storage Bay

The storage bay is filled with light water, which is used to protect both the radiation emission and decay heat from spent fuel. Since the total heat generation from the spent fuel depends on the amount of spent fuel stored and its time-history in the bay, it is necessary to estimate both the amount of spent fuel and the accumulated heat in order to assess the performance of the storage bay when DUPIC fuel is implemented in the CANDU 6 reactor. The cooling capacity of the storage bay was designed as follows:[15]

- The normal storage bay heat exchange capacity is 2 MW to keep the bay temperature below 38℃ and to remove the decay heat of spent fuel generated from 10-years operation at 80% full power.
- The emergency storage bay heat exchange capacity is 4 MW to keep the bay temperature below 49℃ and to remove heat from the half core dump over 20 days after 10-years

operation at 80% full power.

3.3.4.1. Storage Capacity

For DUPIC fuel, the discharge burnup is almost twice that of natural uranium fuel. The two-bundle shift refueling scheme is adopted for the DUPIC CANDU core and four channels are refueled per day. This means that a total of eight spent fuel bundles on average are discharged everyday. For the storage tray that is currently used to stack spent fuels in the bay, 24 fuel bundles are placed on a tray and maximum of 16 trays are allowed in a stack of spent fuel tray. Therefore, the total number of fuel bundles that can be stored in the storage bay is 112×24×16=43008, which corresponds to the amount of spent fuel discharged over ~14.7 years. However, if fresh DUPIC fuel is loaded in the core through the storage bay, a part of the storage area should be allocated for the installation of fuel handling equipment. In that case, the total number of fuel bundles that can be stored will be reduced to 98×24×16=37632, which is approximately the number of fuel bundles discharged over 12 years.

It is also possible to stack spent fuel bundles in a compact tray (hexagonal array), which is currently being studied to improve the storage capacity of the CANDU 6 plant. If the compact stack model is adopted, the storage bay can accept spent fuel bundles for 31 years as far as the storage space is concerned. The cooling capacity should be assessed for both the regular and compact stack models when the DUPIC fuel is to be stored in the bay.

3.3.4.2. Cooling Capacity

In order to estimate the bay temperature, a heat balance equation was formulated as was done for the assessment of the fueling machine performance. The discharge time is different for each spent fuel bundle, so the time-dependent decay heat should be considered in the equation. Therefore, the energy balance equation has been formulated as follows;

$$\begin{aligned} \rho\, c\, Q\, T_c - \rho\, c\, Q\, T + \dot{q}_{fuel} - k_{wall} A_{wall} \frac{(T - T_{env})}{dx} - h_{water} A_{surf} (T - T_{amb}) \\ = (c_{water} M_{water} + c_{fuel} M_{fuel}) \frac{dT}{d\tau} \end{aligned} \quad (3.3)$$

where $\dot{q}$: decay heat of the spent fuel bundle (W)

M_{water} : storage bay water mass (kg)

M_{fuel} : spent fuel mass (kg)

Q : water flow rate (m^3/sec)

T : storage bay water temperature (℃)

T_C : incoming water temperature (= Tconst, ℃)

T_{env} : ground temperature around the storage bay (9℃ at 20 m away from the bay)

T_{amb} : ambient air temperature around the storage bay (22℃)

dx : distance between the bay and surrounding ground (20 m)

ρ : water density (kg/m^3)

c_{water} : specific heat of water (J/kg℃=W·sec/kg℃)

c_{fuel} : specific heat of fuel (J/kg℃)

k_{wall} : conductivity of surrounding ground (0.061 W/m℃)

h_{surf} : heat transfer coefficient on water surface (= $1.32(\Delta T/L)^{0.25}$ for flat surface)

The left-hand side of Eq. (3.3) includes the incoming water heat, outgoing water heat, spent fuel decay heat, heat conduction through the storage wall and convection heat loss through the bay water surface. The heat loss by evaporation on the water surface was neglected because it is too small compared with the convection heat loss. The right-hand side of Eq. (3.3) includes the energy change of the spent fuel and bay water. For convenience, the heat transfer coefficient, h_{surf}, was simply estimated by fixing the ambient temperature and storage temperature to 22℃ and 34℃, respectively, and using a storage width of 12 m (L). The above equation can be simplified as a finite-difference form for numerical analysis as below;

$$T_i = \frac{(A+\dot{q}_i)\cdot(\tau_i-\tau_{i-1})+C\cdot T_{i-1}}{B\cdot(\tau_i-\tau_{i-1})+C} \tag{3.4}$$

where $A = \rho c Q T_c + \frac{k_{wall}A_{wall}}{dx}T_{env} + h_{water}A_{surf}T_{amb}$,

$$B = \rho c Q + \frac{k_{wall}A_{wall}}{dx} + h_{water}A_{surf},$$

$$C = c_{water}M_{water} + c_{fuel}M_{fuel}.$$

Figure 3.9 shows the storage bay temperature for 80% and 100% full power operations. Though the storage design requirement was defined for 80% full power operation, the 100% full power operation case was also assessed to estimate the temperature-history conservatively. For both the 80% and 100% full power operations, the bay temperatures are 31.6℃ and 32.8℃, respectively, after 31 years, which are below the temperature limit of 38℃. In this case, it should be noted that the calculation over 31 years implies that the compact tray (hexagonal array) is used for the storage of spent fuel. If the regular tray is used, the calculation only continues up to 12-years, and the temperature of the bay is even lower than that for 31-years storage.

In order to estimate the margin of the heat exchanger cooling capacity, the calculation was performed again based on the heat load. The calculation of the accumulated heat has shown that it is required to increase the heat exchanger capacity from 2 MW to 2.5 MW, if the reqular tray is used to store spent fuel bundles for 12 years. If the compact storage tray is used, the heat exchanger capacity should be increased to 3 MW for 31-years operation.

For an emergency core dump, the temperature and heat load of the storage bay are summarized in Table 3.5. For a core dump after 12-years operation at 80% full power, the bay temperature increases up to 37.0℃ and 36.2℃ temporarily for a half and full core dump, respectively, when the regular tray is used. Therefore the temperature limit of 49℃ is satisfied for both the half and full core dumps. When the compact storage tray is used, the bay temperature increases up to 38.4℃ and 37.5℃ for the half and full core dump after 31-years operation, respectively, which also satisfies the temperature limit of 49℃.

For the cooling capacity of the storage bay, the asymptotic heat load converges to 2.5 and 3.4 MW for a half and full core dump, respectively, after 12-years operation at 80% full power, if the regular tray is used. For the compact tray, it is assumed that the core is discharged after 31-years operation at 80% full power. In this case, the converged heat loads are 3.3 and 4.2 MW for the half and full core dump, respectively. Considering the normal daily discharge operation, emergency core dump, compact stack option, and conservative operation scenario at 100% full power, it is recommended that the cooling capacity of the storage bay is increased by 1 MW when DUPIC fuel is implemented in the existing CANDU 6 reactor system.

3.4. COST ESTIMATION OF DUPIC FUEL HANDLING

The most appropriate method of loading DUPIC fuel in the CANDU 6 reactor was determined as putting fresh DUPIC fuel in the fueling machine through the dry storage facility (welding station), spent fuel storage bay, and spent fuel discharge port, which is considered to be the most economic and radiation-protective. The discharge path of the spent DUPIC fuel is the same as the current discharge path. Based on the DUPIC fuel loading scenario and performance analysis of the related facility, the DUPIC fuel handling cost has been estimated. Most of the cost data were collected from the existing data used for the CANDU-6 design. Some of them have been extrapolated considering the quality required for the radiation-resistant function.

3.4.1. Cost Estimation of Fuel Handling Equipment

For the reverse loading of fresh DUPIC fuel, new equipment and design modification of existing facility are required as follows:

- Modification of the dry storage facility to be compatible with the transportation cask,
- Installation of a new-fuel loading port, pushing ram, and dryer,
- Increase of the spent fuel storage bay cooling capacity,
- Installation of a gamma-ray detector to identify fresh or spent DUPIC fuel,
- Modification of the computer program for the fuel handling system,
- Revision of the technical specification of the fuel handling system.

The estimated cost for the design modification of the fuel handling system is given in Table 3.6 as of December, 1999. Assuming a labor cost of 100000 Korean Won/hr, the total labor cost is ~1800 million Korean Won and the hardware cost is ~2700 million Korean Won.[16] Therefore the total cost is ~4500 million Korean Won, which is 3.75 million U$ as of December, 1999, when the currency rate is 1200 Korean Won/U$.

3.4.2. Unit Cost of Fuel Handling

For the fuel handling cost to be used for the fuel cycle cost analysis, the unit cost of the DUPIC fuel handling cost is needed. Therefore, the levelized unit cost (LUC) concept was used, which considers the amount of fuel required during the life-time of a plant. The life cycle cost

(LCC) of DUPIC fuel handling can be written in terms of the net present value (NPV) as follows;

$$NPV = \frac{\sum_i C_i}{(1+d)^i} \qquad (3.5)$$

where C_i is the cost in the i-th year, and d means a discount rate. The LUC method will be used to evaluate the DUPIC fuel handling unit cost as follows;

$$LUC = \frac{NPV}{NPB} \qquad (3.6)$$

where the net present benefit (NPB) is given as;

$$NPB = \frac{\sum_i Q_i}{(1+d)^i}, \qquad (3.7)$$

where Q_i is the benefit (the amount of fuel) to be derived in the i-th year and the discount rate is 5% in this study.

The average discharge burnup of reference DUPIC fuel is 14900 MWd/t. Therefore, the annual fuel requirements for DUPIC fuel is 47.6 MTU, assuming a 713 MWe CANDU reactor with a capacity factor of 90% and an efficiency of 33%. The levelized unit cost of DUPIC fuel handling was then estimated to be 5.13 $/kgHM. The life cycle cost calculation is shown in Table 3.7 for the reference DUPIC fuel option used for the physics analysis.

3.5. SUMMARY

The current fresh fuel transfer system in the Wolsong nuclear power plant is not suitable for handling fresh DUPIC fuel. An alternative loading path through the spent fuel storage bay, reception bay, spent fuel discharge bay and spent fuel elevator requires least modification and disruption to the current system. Since the proposed fuel bundle is compatible with the fueling machine, the fuel changing process poses no problems and requires no changes in the fueling machine. The spent fuel transfer system is suitable for the transfer of spent DUPIC fuel without modification. However, the equipment and control systems will require modifications to allow for its use for both fresh and spent fuels. Also, the safeguard system may require modification to enable it to distinguish between fresh and spent fuel.

This study has shown that it is feasible to transfer fresh DUPIC fuel to the reactor core using the current spent fuel transfer system with several design modifications. The LUC of DUPIC fuel handling was estimated to be 5.13 $/kgHM based on the conceptual design and performance analysis of the fuel handling system. It can be seen that the cost rise due to the design modification for DUPIC fuel handling is relatively small compared with the other fuel cycle component costs. Therefore, it is concluded that DUPIC fuel handling in a CANDU plant is technically feasible and economically competitive.

Table 3.1

Comparison of Fuel Bundle Characteristics

	DUPIC	Standard
Physical geometry		
Bundle diameter	102.5 mm	102.1 mm
Bundle length	49.53 mm	49.53 mm
Number of fuel pins	43	37
Material mass per bundle		
Actinides	17.84 kg	19.1 kg
Actinides + fission products	18.40 kg	19.1 kg
Pellet total	20.84 kg	21.78 kg
Bundle total	22.94 kg	23.99 kg

Table 3.2

Actinide Activity and Annual Dose from Fresh DUPIC Fuel

Isotope	After 10 year decay		Surface Contamination (g/m^2)	Airborne Activity (Ci/m^3)	Effective Whole Body Dose (Sieverts)
	Inventory (g/kg)	Activity (Curies)			
^{87}Rb	7.669E-02[a]	6.713E-09	1.426E-08	1.898E-18	1.110E-13
^{115}In	1.820E-03	1.132E-14	3.383E-10	3.201E-24	1.108E-16
^{123}Te	2.847E-03	8.277E-13	5.292E-10	2.340E-22	9.005E-17
^{138}La	8.233E-04	1.581E-11	1.530E-10	4.470E-21	6.192E-14
^{144}Nd	7.295E-01	8.633E-13	1.356E-07	2.441E-22	9.580E-14
^{147}Sm	9.951E-02	2.262E-09	1.850E-08	6.396E-19	3.002E-10
^{148}Sm	7.498E-02	2.264E-14	1.394E-08	6.401E-24	2.611E-15
^{152}Gd	1.716E-04	3.739E-15	3.190E-11	1.057E-24	1.790E-15
^{232}Th	3.859E-01	4.234E-08	7.173E-08	1.197E-17	2.672E-08
^{233}U	1.400E-02	1.356E-04	2.602E-09	3.834E-14	2.036E-05
^{234}U	1.680E-02	1.050E-04	3.123E-09	2.969E-14	1.554E-05
^{235}U	9.986E+00	2.159E-05	1.856E-06	6.104E-15	2.866E-06
^{236}U	2.996E+00	1.939E-04	5.569E-07	5.482E-14	2.658E-05
^{238}U	9.514E+02	3.200E-04	1.768E-04	9.048E-14	3.969E-05
^{237}Np	3.451E-01	2.434E-04	6.415E-08	6.882E-14	7.945E-05
^{238}Pu	1.100E-01	1.884E+00	2.045E-08	5.327E-10	1.230E+00
^{239}Pu	4.494E+00	2.795E-01	8.353E-07	7.903E-11	1.946E-01
^{240}Pu	1.781E+00	4.059E-01	3.311E-07	1.148E-10	2.826E-01
^{241}Pu	4.260E-01	4.391E+01	7.919E-08	1.242E-08	5.542E-01
^{242}Pu	3.526E-01	1.347E-03	6.554E-08	3.809E-13	9.086E-04
^{241}Am	6.271E-01	2.153E+00	1.166E-07	6.087E-10	0.000E+00
^{242m}Am	4.000E-04	3.889E-03	7.435E-11	1.100E-12	0.000E+00
^{243}Am	7.310E-02	1.458E-02	1.359E-08	4.122E-12	8.566E-03
^{243}Cm	2.000E-04	1.033E-02	3.718E-11	2.921E-12	4.496E-03
^{244}Cm	1.080E-02	8.741E-01	2.008E-09	2.471E-10	3.233E-01
^{245}Cm	1.000E-03	1.718E-04	1.859E-10	4.858E-14	1.009E-04
^{246}Cm	1.000E-04	3.073E-05	1.859E-11	8.689E-15	1.805E-05
Total	1.134E+03	4.954E+01	2.108E-04	1.401E-08	2.599E+00

[a] Read as 7.669×10^{-2}

Table 3.3

Comparison of Front Loading Paths for DUPIC Fuel

Key path	Refueling machine pit	Hot cell in containment building
New facility and modification	1. Remote handling equipment in fueling machine pit 2. Cooling and purification system for pit water 3. Air-purification system in containment building 4. Modification of new-fuel port for remote control 5. Modification of structural material around fueling machine pit	1. Installation of a hot cell in containment building for handling DUPIC fuel 2. Air-purification system in containment building 3. Modification of new-fuel port for remote control 4. Modification of structural material around new-fuel storage area
Radiation hazard to operators	1. Operators are working in the containment building and exposed to radiation. 2. Possibility of radiation release due to malfunction of remote handling equipment	1. Operators are working in the containment building and exposed to radiation. 2. Possibility of radiation release due to malfunction of hot cell operation
Anticipated problems during operation	1. Difficulties in regular inspection and maintenance of the remote handling facility 2. Operators should stay in the containment building during refueling operation. 3. No emergency dump place for fueling machine 4. Possibility of interfering in the fueling machine working route	1. Difficulties in hot cell maintenance and operation 2. Operators should stay in the containment building during refueling operation.

Table 3.4

Comparison of Reverse Loading Paths for DUPIC Fuel

Key path	Through reception bay	Through storage bay
New facility and modification	1. Installation of remote handling equipment for opening/sealing of shipping casks 2. Installation of a fuel loading ram at the discharge port 3. Installation of gamma-ray detectors to identify fresh and spent fuel 4. Modification of fuel handling control program 5. Modification of structural material around reception bay	1. Modification of dry storage facility for opening/sealing of shipping casks 2. Installation of fuel loading ram at the discharge port 3. Installation of gamma-ray detectors to identify the fresh and spent fuel 4. Modification of fuel handling control program
Radiation hazard to operators	1. The transportation cask is opened in the reception bay and the radiation hazard to the operator can be minimized.	1. The transportation cask is opened in the storage bay and the radiation hazard to the operator can be minimized.
Anticipated problems during operation	1. Due to the installation of remote handling equipment in the reception bay, the working area is restricted. 2. Because the fresh and spent fuel is transferred through the same route, a stringent fuel management schedule is required.	1. Because the fresh and spent fuel is transferred through the same route, a stringent fuel management schedule is required.

Table 3.5

Storage Bay Temperature and Decay Heat of Spent Fuel due to a Core Dump

		80% full power		100% full power	
		After 31 years	After 12 years	After 31 years	After 12 years
Full core dump	Maximum temperature	37.5℃	36.2℃	38.6℃	37.0℃
	Asymptotic heat load	4.20 MW	3.40 MW	4.80 MW	3.80 MW
Half core dump	Maximum temperature	38.3℃	37.0℃	39.4℃	37.8℃
	Asymptotic heat load	3.25 MW	2.50 MW	3.85 MW	2.85 MW

Table 3.6

The Capital Cost of DUPIC fuel Handling Cost

Content	Sub-content	Hardware (1,000 Won)	Man-hour	Total cost (1,000 Won)	Total cost (k$)
Capital Cost Per Plant	New-fuel loading equipment in storage bay	1,000,000	2,000	1,200,000	1,000.0
	New-fuel port pusher	500,000	3,000	800,000	666.7
	New-fuel port blow dryer	100,000	1,000	200,000	166.7
	Gamma-ray detector	100,000	1,000	200,000	166.7
	Modification of fuel loading system control program	NA	4,000	400,000	333.3
	Design documentation	NA	6,000	600,000	500.0
	Upgrade of cooling capacity for storage bay	1,000,000	1,000	1,100,000	916.7
	Total	2,700,000	18,000	4,500,000	3,750.0

* Assumption

-100,000 Won/Man-hour

-1200 Won/$

Table 3.7

Life Cycle Cost and Unit Cost of DUPIC Fuel Handling

Year	Capital cost (U$)	Net present value (U$)	Annual feed of DUPIC fuel (kg)	Net present value of feed (kg)
2020	3,750,000	1,413,336		
2021			47,592	17,083
2022			47,592	16,269
2023			47,592	15,495
2024			47,592	14,757
2025			47,592	14,054
2026			47,592	13,385
2027			47,592	12,747
2028			47,592	12,140
2029			47,592	11,562
2030			47,592	11,012
2031			47,592	10,487
2032			47,592	9,988
2033			47,592	9,512
2034			47,592	9,059
2035			47,592	8,628
2036			47,592	8,217
2037			47,592	7,826
2038			47,592	7,453
2039			47,592	7,098
2040			47,592	6,760
2041			47,592	6,438
2042			47,592	6,132
2043			47,592	5,840
2044			47,592	5,562
2045			47,592	5,297
2046			47,592	5,045
2047			47,592	4,804
2048			47,592	4,576
2049			47,592	4,358
2050			47,592	4,150
Total		1,413,335.56		275,734.49
Levelized Unit Cost ($/kg) = 5.13				

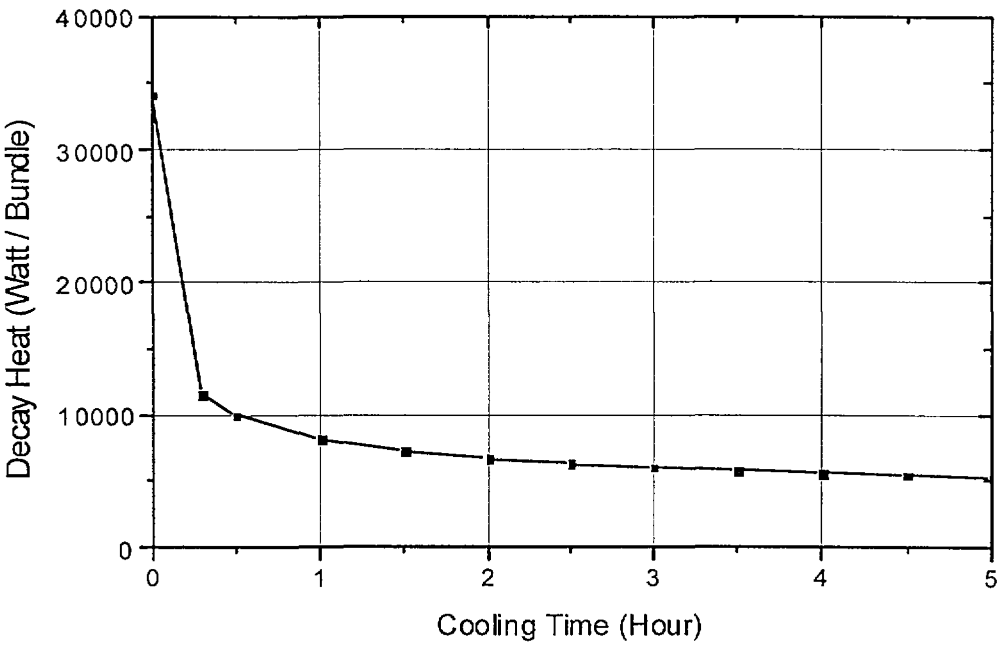


Fig. 3.1 Short-Term Spent DUPIC Fuel Decay Heat per Bundle

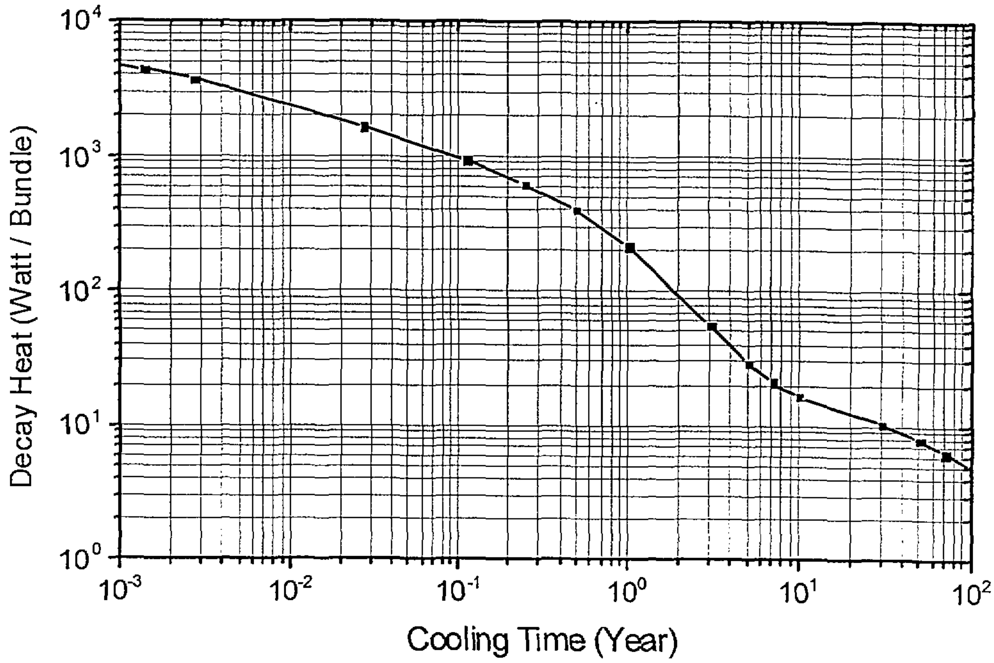


Fig. 3.2 Long-Term Spent DUPIC Fuel Decay Heat per Bundle

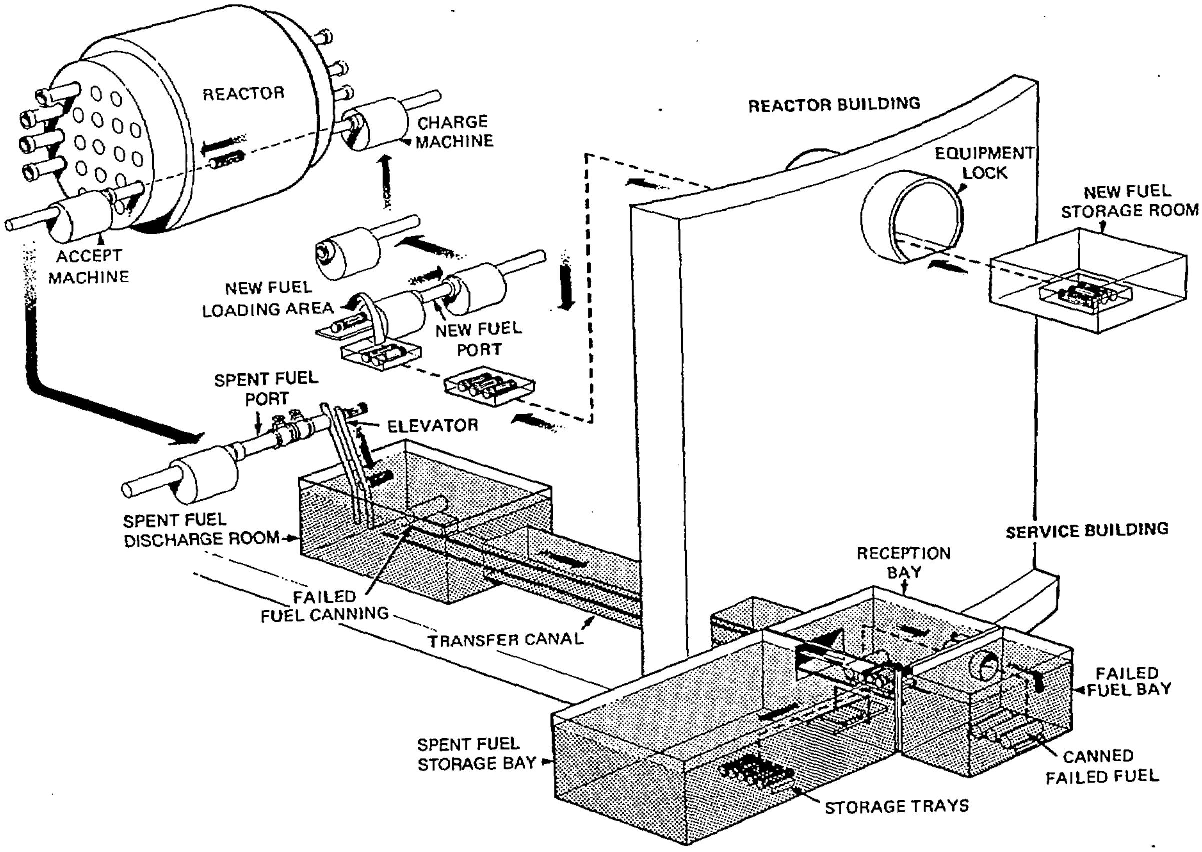


Fig. 3.3 Fuel Bundle Flow in a CANDU 6 Reactor

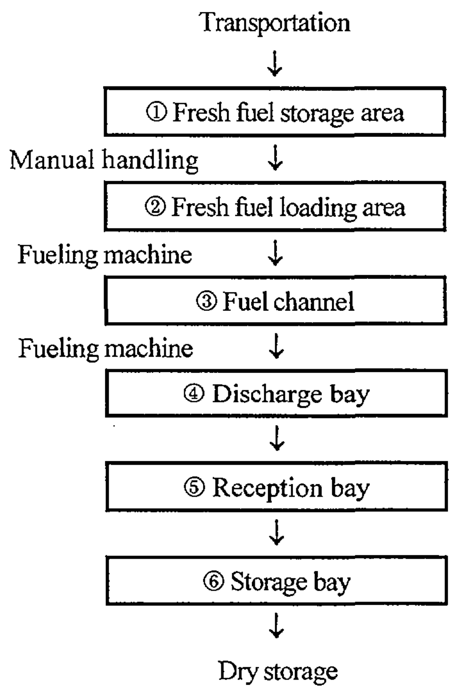


Fig. 3.4 CANDU Fuel Loading and Discharge Route

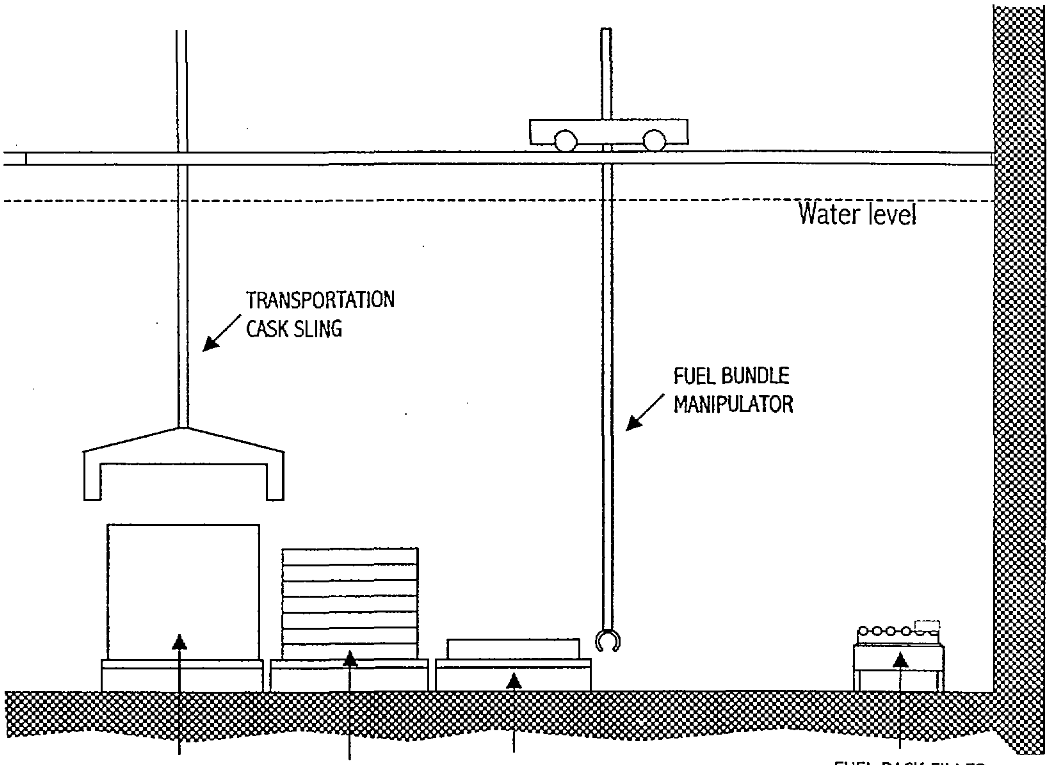


Fig. 3.5 Fuel Bundle Manipulator

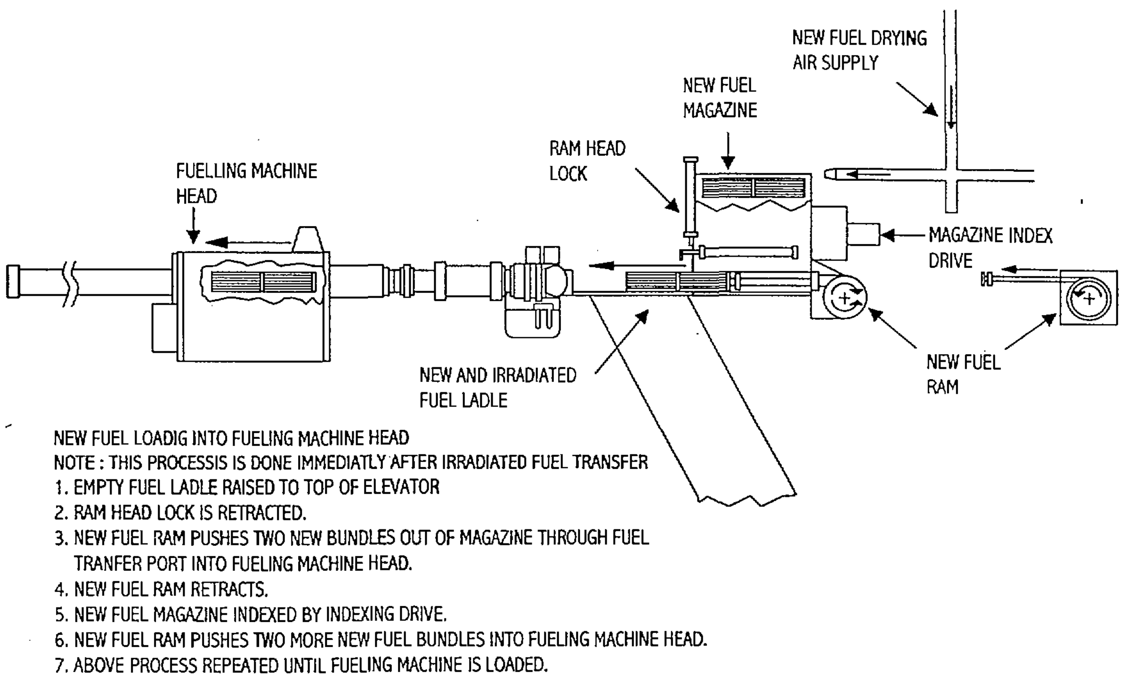


Fig. 3.6 New-Fuel Magazine, Loader, Ram, Dryer and Fueling Machine Head

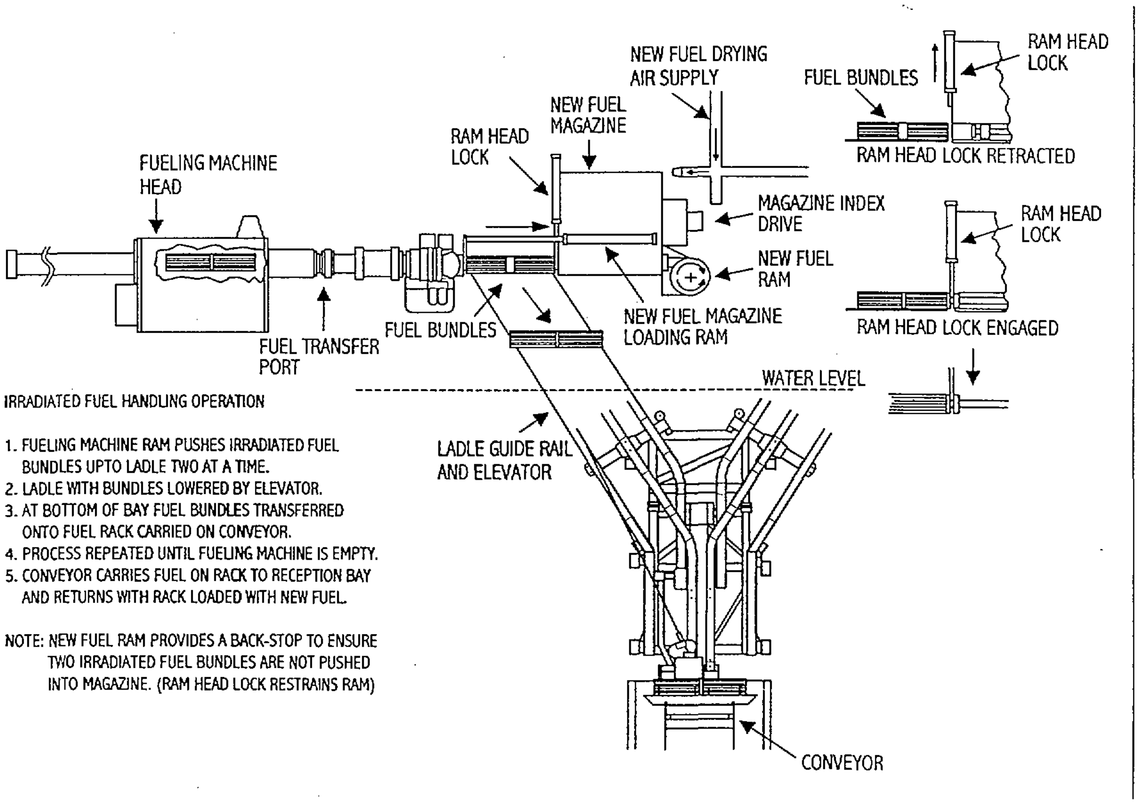


Fig. 3.7 Irradiated Fuel Transfer System

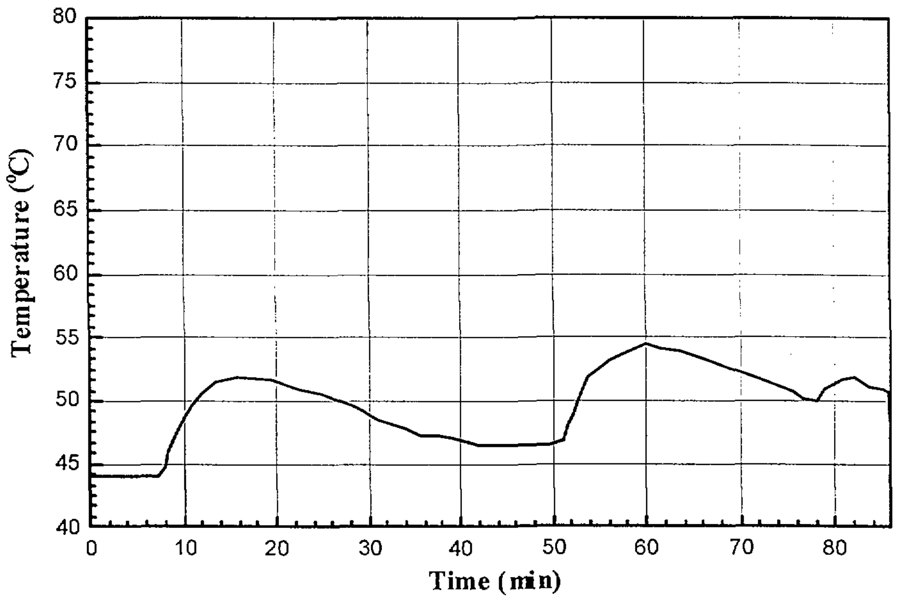


Fig. 3.8 Magazine Temperature from Refueling 4 Bundles (2 Bundles per Channel)

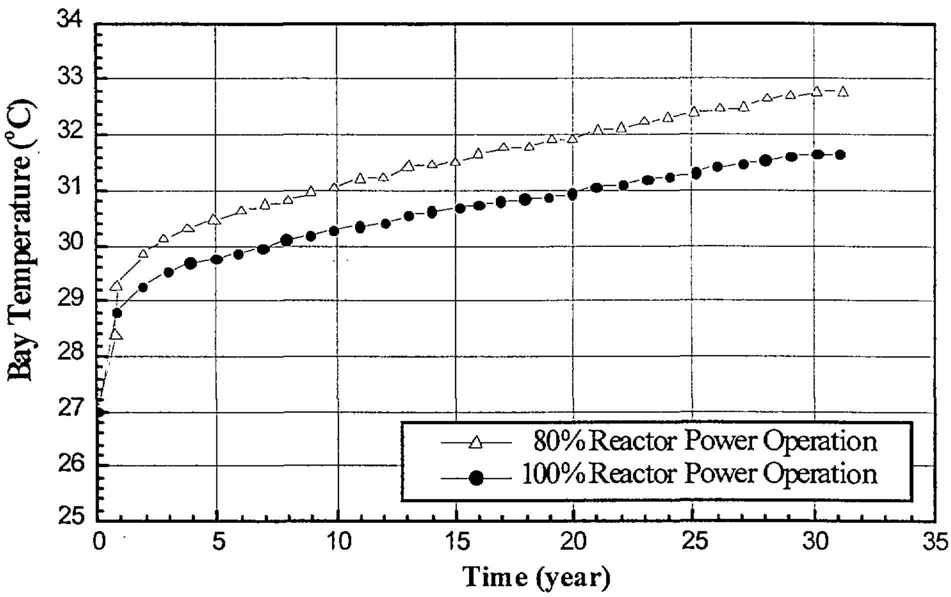


Fig. 3.9 Storage Bay Temperature from Spent Fuel Decay Heat

4. SPENT DUPIC FUEL DISPOSAL COST

Korea with both PWR and CANDU reactors initiated a feasibility study on the DUPIC fuel cycle concept in the early 1990's as a joint evaluation program with Canada and the United States (US). The conclusion of the earlier study has led to a subsequent program on experimental verification of the DUPIC concept. During the feasibility study, the Korea Atomic Energy Research Institute (KAERI) conducted a study for benchmarking the overall range of DUPIC fuel cycle economics in comparison with the once-through option, using the usual methodology and data from literature.

After the feasibility study concluded that the DUPIC technology is feasible and safeguardable, KAERI launched a more systematic study of DUPIC fuel cycle economics by a parametric analysis. A DUPIC fuel cycle model was elaborated from the once-through cycle model for parametric studies. However, among fuel cycle components, the disposal cost of high level wastes (HLW), including spent DUPIC fuel, has been debated since the commercial disposal facility of HLW has not yet been demonstrated and established throughout the world.

This study assesses the feasibility of using existing spent CANDU fuel disposal facility model to spent DUPIC fuel disposal. In addition, the disposal cost of spent DUPIC fuel was estimated based on the total electricity generation in Korea, which can be used for the fuel cycle cost analysis. Figure 4.1 shows the procedure of the disposal cost estimation. First, the state-of-the-art of HLW disposal facility development was examined. Secondly, the future electricity generation scale of Korea was analyzed in order to evaluate an appropriate capacity of the HLW disposal facility, which is the main cost parameter. The Atomic Energy of Canada Limited (AECL) publication[17] titled "The Disposal of Canada's Nuclear Fuel Waste: Engineering for a Disposal Facility" is the primary source used in this study.

4.1. BASIC DESIGN CONCEPT OF DISPOSAL FACILITY

There are two typical approaches for the management of spent fuel: direct disposal of suitably packaged spent fuel as waste and reprocessing of the spent fuel to recover useful products (uranium and plutonium) followed by disposal of remaining waste products. Direct disposal of spent fuel is the main option in Canada, Finland, Spain, Sweden and US, while reprocessing is the main option in Belgium, France, Japan, Netherlands, Switzerland and the United Kingdom. Though a commercial disposal facility of HLW, including spent fuels, has not been established yet, most countries are trying to develop a safer and more economical system based on their own legal system, which is suitable to their natural and social environment.

4.1.1. Current Status of HLW Disposal Technology

In general, there are many similarities in repository designs. For the surface facilities, there is a common design concept and system. However, for the underground disposal system, there are different waste loading patterns such as horizontal and vertical loading, which are considered in US and Sweden/Canada, respectively. The current status of HLW disposal technology[18] is summarized in Secs. 4.1.1.1 to 4.1.1.3.

4.1.1.1. Engineered Barrier Characteristics

In most cases, the disposal system design follows the multiple-barrier principle such as: the waste form, a corrosion-resistant container, sealing systems and the geological medium. For the direct disposal of spent fuel, a separate disposal container is always used, while an extra container (overpack) is proposed in some concepts for vitrified HLW (vitrified in a stainless steel canister). For the reprocessing option, the waste form and stainless steel canister are considered to provide an adequate first barrier. For the disposal container, different materials are used, such as iron, stainless steel, titanium, copper and ceramics. For the alpha-bearing waste from reprocessing, no extra disposal container is normally needed.

It is important to define an appropriate engineered barrier characterization because it has an effect on the disposal cost as well as the safety of the disposal facility. For example, titanium and copper canisters are being developed in Canada. A canister made of iron structure coated with copper is being developed in Sweden. The multi-purpose canister is being considered as a disposal canister in the US. As the buffer, backfill, and seal material, bentonite, cement, and concrete are being considered, respectively, and the physical properties such as swelling, permeability, and strength have been studied in detail.

4.1.1.2. Geologic Environment Evaluation

The determination of the HLW disposal site is based on a synthetic safety assessment, which considers long-term stability of the geological environment, stability of the disposal site, waste packaging by groundwater movement, radio-nuclide transport through groundwater, chemical interaction with surrounding media, effects on the rock environment, etc. There are several geological media, which are being considered for disposal such as crystalline rock, salt, clay, etc. The design, construction and operating conditions of the repository depend on the choice of geological media. Therefore, a number of different repository designs have evolved in different countries.

4.1.1.3. Long-term Safety Assessment

The uncertainty in the long-term safety of a disposal facility is a major concern for the construction of a commercial disposal facility. The scenario that describes the long-term process of the disposal system has uncertainty mostly in the area of safety analysis. Therefore, the safety analysis is focusing on the quantification and reduction of uncertainty. The experiments on the leaching or transport of radio-nuclides according to the natural/engineered barrier and types of buffer/backfill materials have been executed and the databases are being accumulated.

4.1.2. Disposal Facility Model

The reference disposal facility model for spent DUPIC fuel is the Canadian design for natural uranium spent CANDU fuel. The AECL has performed studies on the disposal of spent fuels since 1978. Based on the survey on disposal concepts developed in several countries, the AECL has introduced a room-and-pillar configuration for underground excavations. This is widely used in mining and civil engineering projects. The room-and-pillar configuration consists of a series of regularly spaced disposal rooms and connecting tunnels excavated on one or more levels within the geological medium. Figure 4.2 shows a single-level configuration in which all of the waste is placed at the same elevation in the rock body. The room-and-pillar disposal vault concept provides advantages such as;

- modularity in design, which allows the arrangement of disposal rooms to be adapted to variations in site conditions and total waste volumes,
- flexibility in the spacing of disposal rooms and the spacing of disposal containers to limit the temperature increase on specific engineered and natural barriers, and
- flexibility in the size, shape and orientation of excavations to enhance both the short- and long-term stability.

4.1.2.1. Disposal Capacity

The spent fuel disposal facility is sized to accept and dispose of ~191000 Mg of uranium, which corresponds to ~10.1 million CANDU spent fuel bundles. This capacity represents the amount of spent fuel that may arise in Canada during ~100 years of nuclear power generation at the current rate of production.

4.1.2.2. Surface Facility

The disposal facility consists of two parts: the surface facilities and the disposal vault. The surface facilities receive spent fuel from nuclear generating stations in road or rail casks. The spent fuel bundles are sealed into corrosion-resistant, titanium containers in a fuel packaging plant before they are transported to the disposal vault or temporary storage area. Therefore the surface facility includes the used-fuel packaging plant, auxiliary building, administrative building, sealing material storage bin, switchyard, etc.

4.1.2.3. Underground Facility

The disposal vault is reached and serviced by five shafts grouped into a service-shaft complex (three shafts) and an upcast-shaft complex (two shafts) at opposite ends of the excavation. The disposal rooms are arranged in panels that are constructed on a horizontal level at a depth of 1000 m in the plutonic rock. The containers are transported into the underground facilities and are placed into short, vertical boreholes drilled into the floor of the disposal rooms, as shown in Fig. 4.3. The container is surrounded by the clay-based buffer material within each borehole. Each disposal room is backfilled with clay-based backfill materials, and the room entrance is sealed when all of the boreholes have been filled.

The construction of additional disposal rooms occurs concurrently with emplacement of disposal containers in separate panels. The disposal rooms are constructed sequentially, starting in panels nearest the upcast-shaft complex and then retreating toward the service-shaft complex. When all of the disposal rooms in the vault are filled and sealed, all remaining underground openings are also sealed with clay-based backfill. The operation stage of the disposal facility is projected to last 41 years. The full life-cycle for this conceptual design is 89 years from the beginning of siting to the end of closure.

4.2. ESTIMATION OF SCALED DISPOSAL COST

The Organization for Economic Cooperation and Development (OECD)/Nuclear Energy Agency (NEA) report[19] "The Cost of High Level Waste Disposal in Geological Repositories" presents an international review of cost estimates for the disposal of spent fuel or reprocessing waste (high level vitrified waste and long-lived alpha-bearing waste from reprocessing) in geological repositories. In general, it provides adequate support for planning a disposal facility and establishing a relevant cost estimation.

The disposal costs of spent fuel were estimated based on the Canadian and Swedish designs for the spent CANDU and PWR fuels, respectively. The reference disposal capacity and cost are reviewed in Sec. 4.2.1. The disposal container type for each spent fuel is described in Sec. 4.2.2. The disposal vault layout and the scaled disposal cost for different disposal capacity are given in Secs. 4.2.3 and 4.2.4, respectively.

4.2.1. Reference Disposal Cost Model

The cost estimates for disposal of spent fuel for both Canada and Sweden are summarized in Table 4.1. It should be noted that the cost estimates included in Table 4.1 represent costs for the selected parts of the waste system, such as the direct costs associated with waste packaging and disposal. Therefore, the cost estimates do not include costs for research and development (R&D), site screening and evaluation, and waste transportation outside the repository site.

4.2.1.1. Cost Base and Procedure

The first two rows of Table 4.1 show the amount of uranium assumed in the disposal program and the corresponding electricity generation. In the third row, the volume of waste to be disposed of is given. The waste volume includes canisters and overpacks. The fourth row, "packaging", gives information about the container used for the spent fuel or high level waste. The fifth row, "characteristics of the repository", shows depth, host rock, excavated rock volume, operating period and sealing material. Operating period is defined here as the period between the start and the end of waste emplacement.

In the sixth row, the costs are first shown in the original form as was estimated by

Canada. The number in parentheses under the currency unit indicates the base year of the money value. The original cost is then converted to the US dollar of July, 1991. It should be noted that all costs are presented without discounting. The conversion to US dollars has been done by the NEA Secretariat. Firstly, the estimates have been changed to the base year and month, July, 1991. For this conversion, the Consumer Price Index (CPI) ratio between time of estimate and July, 1991 was used. Secondly, the adjusted estimates have been converted to US dollar using the actual exchange rate as of July, 1991.

When comparing cost estimates, one complicating factor is the economic and financing considerations that are included in the cost. This is particularly true for the funding estimate, where interest and discounting factors are included. As the time span, over which the cost for disposal will occur, is very long, these factors strongly distort the comparison. In order to avoid this complication, only undiscounted costs in price value of July, 1991 US dollars are used in OECD/NEA report. This means that the specific cost per electricity generation (TWh) is greater than one obtained by accumulating funds to cover the disposal cost.

4.2.1.2. Comparison of Normalized Costs

The cost estimates could vary over a significant range because of national nuclear strategies, scale of nuclear programs, reactor designs and other factors. In order to compare the costs, the costs must be normalized to a specific basis in such a way that will remove some of this variability. The costs can be typically normalized by the total electricity generation and the amount of waste, as shown in Table I, for the direct disposal of spent fuel. The normalization is intended to reduce the effect of differences in the magnitude of the disposal programs.

In the seventh row of Table 4.1, the total cost was divided by the amount of electricity generated (M$/kWh). The radioactivity and decay heat produced by the spent fuel (or HLW resulting from reprocessing) determines the heat energy produced. This corresponds closely to the electric energy produced, as the majority of nuclear power plants have a thermal efficiency of ~30%. This normalization takes into account the fact that waste density in the disposal facility is dependent on the rate of heat generation, which is in turn dependent on the total energy generated by the fuel. The low values of Canadian estimates indicate the economy of scale in the packaging and disposal cost estimations, because the nuclear program of Canada is considerably larger than that of Sweden.

The total cost was also divided by the amount of uranium in the waste to be disposed of (k$/tU). For Canadian estimation, the discharge burnup of CANDU fuel is very low, and the low heat generation in the spent fuel enables a more compact disposal with a very low cost per ton of uranium.

4.2.2. Disposal Container Model

In this section, the analysis on the disposal cost of spent DUPIC fuel relative to the cost of disposing spent PWR and spent natural uranium CANDU fuel is summarized. Baumgartner et al.[20] have estimated disposal costs of three spent fuel types including spent DUPIC fuel. The relative cost for different spent fuel was established by investigating the general engineering feasibility of disposal. Subsequent cost calculations for each spent fuel type are done for generally feasible disposal conditions (e.g., cooling time of spent fuel and container spacing) that are unique to each spent fuel type. Even though the cost estimation was based on the Canadian environment, it provides a general basis for indirectly estimating disposal cost of spent DUPIC fuel.

4.2.2.1. Main Assumption

Three spent fuel types are considered in this study, which are CANDU-NU (conventional CANDU natural uranium fuel), CANDU-DUPIC (DUPIC fuels which are refabricated from spent PWR fuel), and PWR (conventional slightly enriched uranium fuel). Table 4.2 shows key characteristics of the spent fuel that is used as the reference model for disposal cost estimation in this study. The typical discharge burnups of these fuels are 7.5, 50, and 35 MWd/kgHE for CANDU-NU, CANDU-DUPIC, and PWR fuels, respectively. The discharge burnup of DUPIC fuel was estimated as the sum of burnup in PWR and CANDU reactors.

The cooling time before disposal was assumed to be 10 years for CANDU-NU fuels and 40 years for CANDU-DUPIC and PWR fuels. The decay heat of spent fuel, which can be one of important parameters for engineering work of disposal facility, was calculated by ORIGEN code.[12] Figure 4.4 shows the decay heat from different spent fuel. It can be seen that the decay heat of the spent DUPIC fuel (0.4985 W/kgHM) is a little smaller than that of spent PWR fuel (0.6631 W/kgHM) because Cesium (Cs) is removed naturally from the spent PWR fuel during the OREOX process and the actinides (^{241}Am, ^{241}Pu and ^{239}Pu) with relatively short half-lives are transmuted in the CANDU reactor.

Considering the range of electricity generation given in Table 4.1, a base quantity of 5000 TWh electricity generation is set for each spent fuel type to establish the amount of spent fuel per container and container spacing in the repositories. Then, 2000 TWh and 10900 TWh are used to provide upper and lower bounds for cost estimation purposes. Disposal quantities are estimated with a thermal efficiency of 30% for both PWR and CANDU reactors. For example, the disposal quantity of CANDU-DUPIC for 5000 TWh of electricity generation is 13890 MTHE (= $5000 \times 10^6/50000/24/0.3$).

4.2.2.2. Disposal Container

The reference disposal containers for the spent natural uranium CANDU fuel is the titanium-shell container (Fig. 4.5) that holds 1362.7 kgU in 72 fuel bundles. When filled with 72 fuel bundles of spent fuel cooled for 10 years, the heat generation of the container is ~308 W. The disposal container of the spent DUPIC fuel is assumed to be the same as that of the spent natural uranium CANDU fuel in this study. Therefore, the container has a capacity to hold a maximum of 72 spent DUPIC fuel bundles. The actual quantity of spent fuel in the container should be determined from the calculations of the temperatures in the repository.

The spent PWR fuel container is assumed to be a copper-shell, which is similar to the container in the Swedish program. According to the OECD/NEA study,[19] there is ~7840 MgHE of spent fuel generated as a result of producing 2000 TWh of electricity and the spent fuel is disposed in ~5300 containers. Thus each container contains ~1480 kgHE of spent fuel. This container will produce ~981 W when filled with spent fuel cooled for 40 years. Table 4.3 summarizes the container specifications for the three types of spent fuel.

4.2.3. Disposal Vault Layout

Spent fuel is assumed, in all cases, to be disposed within boreholes drilled into the floor of disposal rooms in the underground repository as shown in Figs. 4.2 and 4.3. The disposal room spacing in the repository and the container spacing in the rooms are determined by the container temperature limit. The temperature design limit for the CANDU-NU and CANDU-DUPIC repository is 90°C. Baumgartner[21] have calculated the temperatures for the general waste emplacement configuration (see Fig. 4.3) in the repository and determined the final waste emplacement geometry for each spent fuel type. For the PWR repository, the temperature limit was set to be 85°C based on the OCED/NEA report.[19]

4.2.3.1. Spent CANDU-NU Fuel Repository

Spent CANDU-NU fuel, cooled for 10 years following reactor discharge, is packaged in a container that holds 72 fuel bundles. A typical disposal room is about 5 m high and 8 m wide. Three containers are placed across the width of a disposal room. The disposal rooms are excavated at a depth of 1000 m, and are accessed through a system of shafts and tunnels. The repository for the spent fuel resulting from 5000 TWh of electricity production has an operating period of ~20 years, when the disposal rate is 3471 containers per year of the repository operation.

4.2.3.2. Spent CANDU-DUPIC Fuel Repository

Spent CANDU-DUPIC fuel is assumed to be packaged into containers that are used for spent CANDU-NU fuel. Due to high decay heat from the spent CANDU-DUPIC fuel, only one container is placed across the width of the disposal room. So disposal room is 4 m wide and 5 m high. The disposal rooms are excavated at a depth of 1000 m.

Once the reference spent fuel (40 years cooling) and the capacity of the disposal container (72 bundles) are given, the design parameters of underground area such as borehole pitch and disposal room pitch distances are determined. These parameters can generally be obtained through thermal analysis of the underground facility. Therefore a series of parametric calculations has been performed against the borehole pitch distance to obtain the surface temperature of the disposal container,[21] which provides a database to estimate the borehole pitch distance with a specific heat load of a container for a given disposal room pitch distance. Figure 4.6 shows the borehole pitch distance between containers in a disposal room with disposal room pitch distance of 16 m for spent CANDU-DUPIC fuel as a function of decay heat per container. When the storage period is 40 years and the number of fuel bundles in a container is 72, the temperature design limit is satisfied if the containers are placed about 7.1 m apart along the room length.

4.2.3.3. Spent PWR Fuel Repository

Spent PWR fuel has a higher heat output than spent CANDU-NU fuel and, therefore, is disposed after a longer storage period (e.g., 40 years). To accommodate the effects of higher heat output, only one disposal container is placed across the width of the disposal room. Based on the repository design parameters of the Swedish program, the containers are placed 6 m apart and the repository depth is 500 m in order to keep the outer surface temperature of the disposal container below 85°C. The disposal rate for the PWR repository is ~200 containers per year of operation. At this rate, a repository for the spent fuel corresponding to 5000 TWh has an operating period of ~68 years.

4.2.3.4. Summary

The repository design parameters resulting from the consideration of general engineering feasibility are summarized in Table 4.4. Except for the distances DX, DY and HX (see Fig. 4.3), these parameters are independent of the total spent fuel quantities. The distances DX, DY and HX vary only slightly with varying fuel quantities. Therefore, the variation in the magnitude of these parameters, caused by the change in the spent fuel amounts, are not considered to be significant for the purpose of a preliminary cost calculation. The distances DX, DY and HX in Table 4.3 are specific to the spent fuel quantities resulting from 5000 TWh of electricity production.

The operational parameters for repositories are provided in Table 4.5. The electricity production for CANDU-DUPIC fuel is the sum of the electricity production in PWR and CANDU reactors. For example, the electricity production of 5330 TWh is the sum of 2000 TWh in CANDU reactors, which was generated by the spent PWR fuel that has produced 3330 TWh in PWR. For the electricity production of 13330 and 29070 TWh, the electricity production in CANDU reactors are 5000 and 10900 TWh, respectively, which are the data points selected for both PWR and CANDU reactors.

The container disposal rate is kept constant for the base case and for the upper and lower bound cases for each type of spent fuel. This is to reduce the number of variables for comparison, which is appropriate in the scope of this study. Other operational parameters are calculated to be directly proportional to the quantity of spent fuel. The repository sub-surface area is also included in Table 4.5 to indicate relative land requirements for disposal. It represents the minimum waste emplacement area, excluding the area needed for access tunnels and underground infrastructure. The design and operational parameters given in Tables 4.4 and 4.5

are the bases of the cost calculation.

4.2.4. Cost of Spent Fuel Disposal

The OECD/NEA performed a study on the costs of high-level-waste disposal in geological repositories in 1993. This study considers factors such as currency differences and inflation rates, and the costs were normalized to a basis like the amount of electricity generated. The costs include design, construction, operation, decommissioning and closure-related works, but exclude site screening, site selection and evaluation, waste storage and transportation, and research and development (R&D) costs. The R&D, siting and licensing requirements vary among countries. The exclusion of these costs allowed the OECD/NEA to compare the costs on a more common technical base.

For the purpose of comparing the relative cost for disposal of spent CANDU-NU, CANDU-DUPIC, and PWR fuels, the new cost data were derived on a similar basis as was used by OECD/NEA to facilitate the comparison. The cost data in Table 4.6 is a breakdown of the cost in terms of construction, operation and decommissioning. The operation cost is provided with a further breakdown such as direct and indirect costs. The direct cost includes container fabrication, spent fuel packaging, vault excavation, container emplacement, and vault sealing. The indirect costs are the management and site services costs.

4.3 ESTIMATION OF SCALED DISPOSAL COST FOR KOREAN NUCLEAR GRID STRUCTURE

The disposal costs of spent CANDU-NU, CANDU-DUPIC, and PWR fuels have been estimated for different disposal capacities. In order to use the unit disposal cost for the fuel cycle cost analysis, the discounted cash flow calculation should be followed. In Sec. 4.3.1, the total electricity generation in Korea is estimated to search for a specific disposal cost. The repository parameters considering Korean fuel data and electricity capacity is recalculated in Sec. 4.3.2.

4.3.1. Analysis of Electricity Generation Size in Korea

Since the first commercial commissioning of a nuclear power plant in 1978, there are now 15 units in operation (with a total capacity of 12716 MWe) and 5 more units (with total capacity of 5000 MWe) are under construction in Korea. As of December 1999, the total capacity of electric power in Korea reached 45484 MWe, of which 28% is shared by nuclear energy. In terms of electricity generation, the nuclear energy share is to increase to 34% in the year 2015.

4.3.1.1. Nuclear Grid Model

Table 4.7 shows the nuclear systems up to the year 2030, as assumed for this study. Nuclear systems up to the year 2015 are based on the official plan of the Korean Government.[22] Because the nuclear power system after the year 2016 is not determined, nuclear systems from the year 2016 to 2030 are assumed. These assumptions are based on studies[23,24] on the nuclear energy policy for Korea, which suggests that the PWR concept, including the next-generation reactor,[25] is maintained as the main reactor type. Evolutionary pressurized heavy water reactor (PHWR) is the supplementary reactor type for a long-term strategy in Korea.

Figure 4.7 shows the total capacity change during the life-time of all nuclear plants. There are 40 PWR and 19 CANDU units, which is a DUPIC-oriented nuclear fuel cycle with an appropriate number of CANDU reactors in order to fit the reactor balance between PWR and CANDU in accordance with the DUPIC fuel cycle requirements.

4.3.1.2. Material Flow

In order to calculate the material flow, reactor parameters and fuel loading characteristics have to be determined. For plants in operation and under construction, historical and actual reactor data were used. For planned reactors which will be introduced after year 2016, it was assumed that the reactor properties are similar to those of current reactor types.

To evaluate the material flow for each option, some assumptions were made as follows:

- ^{235}U content in natural uranium is 0.711 wt%,
- Tail assay in the enrichment facility is 0.25 wt%,
- Loss factors are 0.5% for conversion and 1% for PWR and DUPIC fuel fabrication.

Using the above assumptions and reactor grid scenarios, the material flow and cumulated electricity generation were estimated using the fuel cycle analysis code NUFCAP,[26] which was developed by KAERI in 1996. The results are shown in Table 4.8 for electricity generation and spent fuel quantity, which are obtained for the lifetime of all nuclear power plants starting from 1978.

4.3.2. Repository Parameters for Korean Fuel Data and Electricity Capacity

In this section, repository parameters considering Korean fuel data and electricity capacity are examined. The repository data are summarized in Table 4.9, which are obtained from the burnup data of spent fuels, as described in Sec. 4.2.3.4. The repository operation data such as the size of the disposal facility, number of containers and disposal rate can be obtained from the analysis of the total electricity capacity. The analysis has shown that the sizes of the disposal facility are 36861 MTHM for CANDU-DUPIC and PWR fuels and 53671 MTHM for CANDU-NU fuel. In this case, the number of containers is 39377, 27044 and 24906 for CANDU-NU, CANDU-DUPIC and PWR fuels, respectively.

For the calculation of disposal rate (container/year), the operation period was fixed to 27 years for all cases, which is considered to be a reasonable assumption for the calculation the levelized life cycle unit cost and comparison among fuel cycle options. When the operation period is 27 years, the disposal rate is 1459, 1002 and 923 containers/year for CANDU-NU, CANDU-DUPIC and PWR fuel, respectively.

4.4. LEVELIZED UNIT COST OF SPENT FUEL DISPOSAL

The disposal unit costs for spent CANDU-NU, CANDU-DUPIC and PWR fuels can be estimated based on the reference data given in Table 4.6, with the electricity generation sizes derived in Sec. 4.3.1. For the fuel cycle cost analysis, the discounted disposal unit cost is required. In order to calculate the discounted disposal cost, the cash flow generated during the lifetime of the disposal facility is needed. Therefore, the capital, operation and decommissioning costs described in Table 4.6 were used to obtain the cash flow. Table 4.10 shows the capital cost, operating cost and decommissioning cost interpolated based on the electricity generation described in Sec. 4.3.1.

4.4.1. Spent Fuel Disposal Cost

The total electricity generation is 12411 TWh for all fuel cycle options. In case of the direct disposal option, the total electricity generation is divided into 9289 TWh for PWR and 3219 TWh for CANDU reactors. Using the amount of electricity generation, the disposal unit costs were obtained by interpolation, as shown in Fig. 4.8. It is indicated that the disposal unit costs for spent CANDU-NU, CANDU-DUPIC and PWR fuels are 77, 168, and 270 $/kgHE, respectively. The undiscounted unit costs, based on the unit electricity production, can be directly derived from Table 4.10. The unit costs are 1.59 M$/TWh for CANDU-NU, 0.53 M$/TWh for CANDU-DUPIC, and 1.37 M$/TWh for PWR fuels.

It is important to note that the cost data in Table 4.10 are based on the year 1991 U$ and do not include costs for R&D, siting, licensing and transportation. In order to use the disposal cost as an input to the nuclear fuel cycle cost analysis, those parameter have to be included and the cost data basis shall be the year 1999 for consistency with other costs. The recalculated cost data considering those parameters are described in Table 4.11. For this, the U.S. Consumer Price Index (CPI) ratio between December 1999 and July 1991, 1.104, was used for escalation of previous values. It was assumed that the R&D and siting costs are 20% of the construction cost and the licensing cost is 25% of the construction cost, which is typical in conceptual design study.

4.4.2. Discounted Spent Fuel Disposal Cost

The discounted disposal cost is estimated using the life cycle cost (LCC) and levelized unit cost (LUC) models. The net present value (NPV) methodology is used for calculating the LCC, which is defined as the total discounted cost necessary to construct, operate, and decommission the disposal facility. The NPV of the LCC shall be described as follows;

$$NPV = \sum_i \frac{C_i}{(1+d)^i} \tag{4.1}$$

where C_i is the cost in the i-th year, and d is a discount rate.

The LUC method will be used to calculate the disposal unit cost as follows:

$$LUC = \frac{NPV}{NPB} \tag{4.2}$$

where the net present benefit (NPB) is given as;

$$NPB = \sum_i \frac{Q_i}{(1+d)^i}, \tag{4.3}$$

and Q_i is the benefit (disposal quantity) to be derived in the i-th year.

The main assumptions for the cash flow calculation are as follows:

- Facility operation period: 27 years (2020 ~ 2046)
- Facility construction period: 10 years (2010 ~ 2019)
- Decontamination and decommissioning period: 2 years (2047 ~ 2048) after the operation of the facility is finished.
- The R&D and siting costs are discharged in 2009, just one year before the construction begins.
- Cost base year : 1999 (receiving year of spent fuels)
- Discount rate: 5%

Tables 4.12, 4.13, and 4.14 show the cash flows and their discounted costs of spent fuel disposal facilities for spent CANDU-NU, CANDU-DUPIC and PWR fuels, respectively, calculated with the aforementioned assumptions. Table 4.15 summarizes the life cycle cost in NPV and the levelized unit cost for the disposal of three spent fuel types. The life cycle cost is the discounted total cost during the facility life-time from construction to decommissioning. It was estimated that the levelized unit costs are 188.5 $/kgHM for CANDU-NU, 342.8 $/kgHM for CANDU-DUPIC, and 616.8 $/kgHM for PWR fuels.

4.5. SUMMARY

This study involves the preliminary analyses of technical factors that may affect the direct disposal and the disposal costs, specifically related to spent CANDU-DUPIC fuel. Based on the amount of electricity generation, the undiscounted unit disposal costs are estimated to be 1.59 M$/TWh for CANDU-NU, 0.53 M$/TWh for CANDU-DUPIC fuel, and 1.37 M$/TWh for PWR fuels. The disposal cost of spent CANDU-DUPIC fuel is much lower than that of spent PWR fuel, which is primarily due to the extra electricity generation achieved by the additional fuel burnup in a CANDU reactor with little decay heat difference relative to spent PWR fuel.

Considering the electricity generation scale in Korea, the levelized disposal unit costs (discounted unit costs) were also estimated for CANDU-NU, CANDU-DUPIC, and PWR fuels, which are 188.5, 342.8, and 616.8 $/kgHM, respectively. It can be seen that the disposal cost of CANDU-DUPIC fuel is relatively low compared with PWR fuel, which is due to the difference in the canister type and the fuel size. The results of this study indicate that the disposal of spent

CANDU-DUPIC fuel is technically and economically feasible compared with other spent fuel types.

Table 4.1

Cost Estimates for Packaging and Geological Disposal of Spent Fuel [Ref. 19]

		Canada	Sweden
Spent Fuel (tU)		191000	7840
Corresponding Electricity generation (TWh)		10900	2000
Volume of waste (m³)		99000	12900
Packaging	Inclusion of packing cost	Yes	Yes
	Container (thickness)	Titanium (6.3 mm)	Copper (10 cm)
Characteristics of the repository	Depth (m)	1,000	500
	Host rock	Crystalline rock	Crystalline rock
	Volume of excavated rock (Mm³)	7.2	0.8
	Operating period (year)	41	27
	Sealing material	Bentonite/sand	Bentonite/sand
Estimated cost	In national currency unit (base year)	9,500 M C$ (1990)	20.2 b SKr (1990)
	In billion of U$ of July 1991	8.7	3.2
Normalized cost	Cost per unit electricity generation (M$/TWh)	0.80	1.6
	Cost per unit weight of waste (k$/tU)	46	410

Table 4.2
Characteristics of Spent Fuels

	Spent Fuel Type		
	CANDU-NU	CANDU-DUPIC	PWR
Initial enrichment (wt%)	0.71	-	3.5
No. of fuel rods per assembly	37	37	17 x 17
Discharge burnup (MWD/MTU)	7500	50000	35000
Cooling time before disposal (year)	10	40	40
Decay heat (W/kgHM)	0.2260	0.4985	0.6631

Table 4.3

Comparison of Disposal Containers

	Spent Fuel Type		
	CANDU-NU	CANDU-DUPIC	PWR
Overall length (mm)	2246	2246	4500
Overall diameter (mm)	645	645	800
Thickness (mm)	6.3	6.3	100
Capacity (number of fuel assemblies)	72	72	4

Table 4.4

Summary of Repository Data for 5000 TWh Electricity Production

	CANDU-NU	CANDU-DUPIC	PWR
Cooling time of spent fuel	10	50	40
Container capacity (max. no. of fuel assemblies)	72	72	4
Actual amount of fuel per container (kgHM)	1363	1363	~1480
Initial container heat output (W)	308	680	~981
No. of containers across the room width	3	1	1
Borehole pitch distance across the room width - DX (m)	2.1	-	-
Borehole pitch distance along the room length - DY (m)	3.1	10	6
Disposal room pitch distance - HX (m)	30	16	25
Room width (m)	8	4	4
Room length (m)	230	230	250
Max. container outer-surface temperature (°C)	89	89	<85

Table 4.5
Summary of Repository Operation Data

	CANDU-NU (Ti container)			CANDU-DUPIC (Ti container)			PWR (Cu container)		
Spent fuel repository (TWh)	2000	5000	10900	5330	13330	29070	2000	5000	10900
Amount of spent fuel (Mg HE)	33330	83330	181660	13220	33060	72070	7840	19610	42750
Number of containers	24460	61150	133300	9700	24256	52876	5300	13250	28890
Disposal rate (containers/year)	3471	3471	3471	3471	3471	3471	196	196	196
Years of operation	8	18	39	3	7	16	27	68	147
Sub-surface plan area (km^2)	0.8	2.1	4.2	2.0	5.1	10.2	1.4	3.5	7.6

Table 4.6

Breakdown of Disposal Costs (1991 U$ million)

		CANDU-NU (Ti container)			CANDU-DUPIC (Ti container)			PWR (Cu container)		
Spent fuel repository (TWh)		2000	5000	10900	5330	13330	29070	2000	5000	10900
Construction		1380	1610	2070	1380	1725	2300	1955	2415	2875
Operation	Direct	1265	2990	6900	1380	3450	7475	1265	3105	6670
	Indirect	345	920	2070	230	460	1035	345	805	1725
Decommissioning		920	1265	1725	920	1265	1725	690	1380	3450

Table 4.7
Nuclear System Scenario up to 2030

Year	Nuclear Power Plant Name	Generating Capacity (MWe)				Installed Capacity (MWe)			Power Generation (MWyr)		
		New		Decommission							
		PWR	PHWR	PWR	PHWR	PWR	PHWR	Total	PWR	PHWR	Total
1978	Kori#1	587				587		587	205	0	205
1979						587		587	364	0	364
1980						587		587	393	0	393
1981						587		587	329	0	329
1982						587		587	434	0	434
1983	Kori#2/Wolsong#1	650	679			1,237	679	1,916	636	316	952
1984						1,237	679	1,916	888	455	1,343
1985	Kori#3	950				2,187	679	2,866	1,127	638	1,766
1986	Kori#4/Yongkwang#1	1,900				4,087	679	4,766	2.582	543	3,125
1987	Yongkwang#2	950				5,037	679	5,716	3,713	631	4,344
1988	Uljin#1	950				5,987	679	6,666	3,872	536	4,408
1989	Uljin#2	950				6,937	679	7,616	4,682	618	5,300
1990						6,937	679	7,616	5,462	584	6,045
1991						6,937	679	7,616	5,811	618	6,429
1992						6,937	679	7,616	5,827	581	6,408
1993						6,937	679	7,616	5,931	672	6,603
1994		1,000				6,937	679	7,616	5,550	577	6,127
1995	Yongkwang#3	1,000				7,937	679	8,616	6,350	577	6,927
1996	Yongkwang#4					8,937	679	9,616	7,150	577	7,727
1997	Wolsung#2	1,000	700			8,937	1,379	10,316	7,150	1,172	8,322
1998	Uljin#3/Wolsong#3	1,000	700			9,937	2,079	12,016	7,950	1,767	9,717
1999	Uljin#4/Wolsong#4		700			10,937	2,779	13,716	8,750	2,362	11,112
2000						10,937	2,779	13,716	8,750	2,362	11,112
2001						10,937	2,779	13,716	8,750	2,362	11,112
2002	Yongkwang#5,#6	2,000				12,937	2,779	15,716	10,350	2,362	12,712
2003						12,937	2,779	15,716	10,350	2,362	12,712
2004	Uljin#5	1,000				13,937	2,779	16,716	11,150	2,362	13,512
2005	Uljin#6	1,000				14,937	2,779	17,716	11,950	2,362	14,312
2006						14,937	2,779	17,716	11,950	2,362	14,312
2007	NPP[a]#1,#2	2,000				16,937	2,779	19,716	13,550	2,362	15,912
2008	NPP#3	1,000		587		17,350	2,779	20,129	13,880	2,362	16,242
2009	NPP#4	1,000				18,350	2,779	21,129	14,680	2,362	17,042
2010	NPP#5/KNGR[b]#1	2,300				20,650	2,779	23,429	16,520	2,362	18,882
2011	NPP#6/KNGR#2	2,300				22,950	2,779	25,729	18,360	2,362	20,722
2012						22,950	2,779	25,729	18,360	2,362	20,722
2013	KNGR#3	1,300		650	679	23,600	2,100	25,700	18,880	1,785	20,665
2014	KNGR#4	1,300				24,900	2,100	27,000	19,920	1,785	21,705
2015				950		23,950	2,100	26,050	19,160	1,785	20,945
2016	CANDU#1,#2		1,400	1,900		22,050	3,500	25,550	17,640	2,975	21,615
2017	KNGR#5,#6/CANDU#3	2,600	700	950		23,700	4,200	27,900	18,960	3,570	22,530
2018	CANDU#4,#5		1,400	950		22,750	5,600	28,350	18,200	4,760	22,960
2019	KNGR#7,#8	2,600		950		24,400	5,600	30,000	19,520	4,760	24,280
2020	KNGR#9/CANDU#6,#7	1,300	1,400			25,700	7,000	32,700	20,560	5,950	26,510
2021	CANDU#8,#9		1,400			25,700	8,400	34,100	20,560	7,140	27,700
2022	KNGR#10/CANDU#10	1,300	700			27,000	9,100	36,100	21,600	7,735	29,335
2023	KNGR#11/CANDU#11	1,300	700			28,300	9,800	38,100	22,640	8,330	30,970
2024	KNGR#12	1,300				29,600	9,800	39,400	23,680	8,330	32,010
2025	CANDU#12		1,400	1,000		28,600	11,200	39,800	22,880	9,520	32,400
2026	KNGR#13,#14	2,600		1,000		30,200	11,200	41,400	24,160	9,520	33,680
2027	CANDU#13		700		700	30,200	11,200	41,400	24,160	9,520	33,680
2028	KNGR#15,#16	2,600		1,000	700	31,800	10,500	42,300	25,440	8,925	34,365
2029	KNGR#17/CANDU#14	1,300	700	1,000	700	32,100	10,500	42,600	25,680	8,925	34,605
2030	KNGR#23/CANDU#15	1,300	700			33,400	11,200	44,600	26,720	9,520	36,240

*The nuclear system form the year 2016 is based on the following assumptions:
- Electricity capacity reserve ratio is 20% from the year 2016.
- Average Increase rate of maximum electricity demand is 2%/year.
- Nuclear share of electricity capacity is 37% up to the year 2020. 40% up to the year 2030.
- Plant load factor is 80% for CANDU.
- Plant life-time is 30 year for all types.

[a]NPP means the type of Korean standard Nuclear Power Plant (Uljin#3,#4).
[b]KNGR means the Korean Next Generation Reactor being developed.

Table 4.8

Results of Material Flow and Electricity Generation for Fuel Cycle Options

Items			Total quantity
DUPIC Cycle	PWR Interim Storage (ton) CANDU/DUPIC Interim Storage (ton)		23,230 31,700
	DUPIC Facility (ton)		21,188
	Disposal Capacity (ton)	PWR	7,930
		CANDU	10,512
		DUPIC	21,188
	Cumulated Electricity Generation (TWh)	PWR	9,289
		CANDU	3,129
		Total	12,411
Direct Disposal	PWR Interim Storage (ton) CANDU Interim Storage (ton)		29,118 42,094
	Disposal Capacity (ton)	PWR	29,118
		CANDU	42,094
	Cumulated Electricity Generation (TWh)	PWR	9,289
		CANDU	3,129
		Total	12,411

Table 4.9

Summary of Repository Data Considering Korean Capacity

		CANDU-NU (Ti container)	CANDU-DUPIC (Ti container)	PWR (Cu container)
Repository Data	Burnup(MWD/MTU)	7,500	15,000	35,000
	Cooling time of spent fuel	10	40	40
	Initial container heat output (W)	308	680	981
	Decay heat(W/kgHM)[a]	0.226	0.499	0.663
	Actual amount of fuel per container (MTHM)[b]	1.363	1.363	1.480
	No. of containers across the room width	3	1	1
	Borehole pitch across the room width (m)	2.1	-	-
	Borehole pitch distance along the room length (m)	3.1	10	6
	Disposal room pitch distance (m)	30	16	26
	Room width (m)	8	4	4
	Room length (m)	230	230	250
	Max. container outer-surface temperature (°C)	89	89	<85
Repository Operation Data	Spent fuel repository(TWh)	3,129	12,411	9,289
	Amount of spent fuel(Mg HE)	53,671	36,861	36,861
	Number of containers	39,377	27,044	24,906
	Years of operation[c]	27	27	27
	Disposal rate(containers/year)	1,459	1002	923
	Sub-surface plan area(km^2)	1.37	4.30	6.10

a) For this, ORIGEN 2 Code was used.
b) Derived from initial container heat output (W) / decay heat (W/kgHM).
c) The operation period is fixed to 27 years for a reasonable comparison.

Table 4.10

Cost Break-Down for Disposal Facility (1991 U$ million)

		CANDU-NU (Ti container)	CANDU-DUPIC (Ti container)	PWR (Cu container)
Spent fuel repository (TWh)		3129	12411	9289
Spent fuel repository (MTHM)		53671	36861	36861
Construction		1467	1685	2749
Operation	Direct	1914	3212	5697
	Indirect	561	434	1474
	Total	2475	3646	7171
Decommissioning		1050	1225	2885
Total Cost		4992	6556	12805

Table 4.11

Cost Break-Down for Disposal Facility (1999 U$ million)[a]

Items		CANDU-NU (Ti container)	CANDU-DUPIC (Ti container)	PWR (Cu container)
Siting and R&D[b]		366.9	421.4	687.5
Licensing[c]		458.6	526.7	859.3
Construction		1,834.3	2,106.9	3,437.3
Operation	Direct	2,393.2	4,016.2	7,123.4
	Indirect	701.5	542.7	1,843.0
	Total	3,094.7	4,558.8	8,966.4
Decommissioning		1,312.9	1,531.7	3,607.3
Total Cost		10,161.9	13,704.4	26,524.1

a) The U.S. Consumer Price Index (CPI) ratio between December of 1999 and July of 1991, 1.104, was used.

b) It is assumed to be 20% of the construction cost for this study.

c) It is assumed to be 25% of the construction cost for this study.

Table 4.12

Discounted Disposal Costs for CANDU-NU Spent Fuel

Year	Cost (k$)					Production (MTHM)	Discounted Production(MTHM)
	Capital	O&M	Decommissioning	Total	Total NPV		
2009	366900.00			366900.00	225244.773		
2010	229290.00			229290.00	134061.114		
2011	229290.00			229290.00	127677.252		
2012	229290.00			229290.00	121597.382		
2013	229290.00			229290.00	115807.031		
2014	229290.00			229290.00	110292.410		
2015	229290.00			229290.00	105040.391		
2016	229290.00			229290.00	100038.468		
2017	229290.00			229290.00	95274.731		
2018	229290.00			229290.00	90737.839		
2019	229290.00			229290.00	86416.990		
2020		114618.52		114618.52	41141.442	1987.81	713.51
2021		114618.52		114618.52	39182.326	1987.81	679.53
2022		114618.52		114618.52	37316.501	1987.81	647.18
2023		114618.52		114618.52	35539.525	1987.81	616.36
2024		114618.52		114618.52	33847.166	1987.81	587.01
2025		114618.52		114618.52	32235.396	1987.81	559.05
2026		114618.52		114618.52	30700.378	1987.81	532.43
2027		114618.52		114618.52	29238.455	1987.81	507.08
2028		114618.52		114618.52	27846.147	1987.81	482.93
2029		114618.52		114618.52	26520.140	1987.81	459.94
2030		114618.52		114618.52	25257.277	1987.81	438.03
2031		114618.52		114618.52	24054.549	1987.81	417.18
2032		114618.52		114618.52	22909.094	1987.81	397.31
2033		114618.52		114618.52	21818.185	1987.81	378.39
2034		114618.52		114618.52	20779.224	1987.81	360.37
2035		114618.52		114618.52	19789.737	1987.81	343.21
2036		114618.52		114618.52	18847.369	1987.81	326.87
2037		114618.52		114618.52	17949.875	1987.81	311.30
2038		114618.52		114618.52	17095.119	1987.81	296.48
2039		114618.52		114618.52	16281.066	1987.81	282.36
2040		114618.52		114618.52	15505.777	1987.81	268.91
2041		114618.52		114618.52	14767.407	1987.81	256.11
2042		114618.52		114618.52	14064.197	1987.81	243.91
2043		114618.52		114618.52	13394.473	1987.81	232.30
2044		114618.52		114618.52	12756.641	1987.81	221.24
2045		114618.52		114618.52	12149.182	1987.81	210.70
2046		114618.52		114618.52	11570.649	1987.81	200.67
2047			656450.00	656450.00	63112.487		
2048			656450.00	656450.00	60107.131		
Total	2659800.00	3094700.00	1312900.00	7067400.00	2067965.29	53671.00	10970.36
Net Present Values(k$) = 2067965.3							
Levelized Unit Cost ($/kg) = 188.505							

Table 4.13

Discounted Disposal Costs for CANDU-DUPIC Spent Fuel

year	Cost (k$)					Production (MTHM)	Discounted Production(MTHM)
	Capital	O&M	Decommissioning	Total	Total NPV		
2009	421400.00			421400.00	258703.045		
2010	263360.00			263360.00	153981.138		
2011	263360.00			263360.00	146648.702		
2012	263360.00			263360.00	139665.431		
2013	263360.00			263360.00	133014.696		
2014	263360.00			263360.00	126680.663		
2015	263360.00			263360.00	120648.250		
2016	263360.00			263360.00	114903.096		
2017	263360.00			263360.00	109431.520		
2018	263360.00			263360.00	104220.495		
2019	263360.00			263360.00	99257.614		
2020		168844.44		168844.44	60605.424	1365.22	490.04
2021		168844.44		168844.44	57719.452	1365.22	466.70
2022		168844.44		168844.44	54970.906	1365.22	444.48
2023		168844.44		168844.44	52353.244	1365.22	423.31
2024		168844.44		168844.44	49860.232	1365.22	403.15
2025		168844.44		168844.44	47485.936	1365.22	383.96
2026		168844.44		168844.44	45224.701	1365.22	365.67
2027		168844.44		168844.44	43071.143	1365.22	348.26
2028		168844.44		168844.44	41020.137	1365.22	331.68
2029		168844.44		168844.44	39066.797	1365.22	315.88
2030		168844.44		168844.44	37206.473	1365.22	300.84
2031		168844.44		168844.44	35434.736	1365.22	286.51
2032		168844.44		168844.44	33747.368	1365.22	272.87
2033		168844.44		168844.44	32140.350	1365.22	259.88
2034		168844.44		168844.44	30609.858	1365.22	247.50
2035		168844.44		168844.44	29152.245	1365.22	235.72
2036		168844.44		168844.44	27764.043	1365.22	224.49
2037		168844.44		168844.44	26441.946	1365.22	213.80
2038		168844.44		168844.44	25182.806	1365.22	203.62
2039		168844.44		168844.44	23983.624	1365.22	193.92
2040		168844.44		168844.44	22841.547	1365.22	184.69
2041		168844.44		168844.44	21753.854	1365.22	175.89
2042		168844.44		168844.44	20717.956	1365.22	167.52
2043		168844.44		168844.44	19731.387	1365.22	159.54
2044		168844.44		168844.44	18791.797	1365.22	151.94
2045		168844.44		168844.44	17896.950	1365.22	144.71
2046		168844.44		168844.44	17044.714	1365.22	137.82
2047			765850.00	765850.00	73630.434		
2048			765850.00	765850.00	70124.223		
Total	3055000.00	4558800.00	1531700.00	9145500.00	2582728.93	36861.00	7534.40
Net Present Values(k$) = 2582728.9							
Levelized Unit Cost ($/kg) = 342.792							

Table 4.14

Discounted Disposal Costs for PWR Spent Fuel

year	Cost (k$)					Production (MTHM)	Discounted Production(MTHM)
	Capital	O&M	Decommissioning	Total	Total NPV		
2009	687500.00			687500.00	422065.362		
2010	433260.00			433260.00	253318.149		
2011	433260.00			433260.00	241255.380		
2012	433260.00			433260.00	229767.028		
2013	433260.00			433260.00	218825.741		
2014	433260.00			433260.00	208405.468		
2015	433260.00			433260.00	198481.398		
2016	433260.00			433260.00	189029.903		
2017	433260.00			433260.00	180028.479		
2018	433260.00			433260.00	171455.694		
2019	433260.00			433260.00	163291.137		
2020		332088.89		332088.89	119200.771	1365.22	490.04
2021		332088.89		332088.89	113524.544	1365.22	466.70
2022		332088.89		332088.89	108118.613	1365.22	444.48
2023		332088.89		332088.89	102970.108	1365.22	423.31
2024		332088.89		332088.89	98066.769	1365.22	403.15
2025		332088.89		332088.89	93396.923	1365.22	383.96
2026		332088.89		332088.89	88949.451	1365.22	365.67
2027		332088.89		332088.89	84713.763	1365.22	348.26
2028		332088.89		332088.89	80679.774	1365.22	331.68
2029		332088.89		332088.89	76837.880	1365.22	315.88
2030		332088.89		332088.89	73178.933	1365.22	300.84
2031		332088.89		332088.89	69694.222	1365.22	286.51
2032		332088.89		332088.89	66375.450	1365.22	272.87
2033		332088.89		332088.89	63214.714	1365.22	259.88
2034		332088.89		332088.89	60204.489	1365.22	247.50
2035		332088.89		332088.89	57337.609	1365.22	235.72
2036		332088.89		332088.89	54607.247	1365.22	224.49
2037		332088.89		332088.89	52006.902	1365.22	213.80
2038		332088.89		332088.89	49530.382	1365.22	203.62
2039		332088.89		332088.89	47171.793	1365.22	193.92
2040		332088.89		332088.89	44925.517	1365.22	184.69
2041		332088.89		332088.89	42786.207	1365.22	175.89
2042		332088.89		332088.89	40748.768	1365.22	167.52
2043		332088.89		332088.89	38808.351	1365.22	159.54
2044		332088.89		332088.89	36960.334	1365.22	151.94
2045		332088.89		332088.89	35200.318	1365.22	144.71
2046		332088.89		332088.89	33524.112	1365.22	137.82
2047			1803650.00	1803650.00	173406.715		
2048			1803650.00	1803650.00	165149.252		
Total	5020100.00	8966400.00	3607300.00	17593800.00	4647213.65	36861.00	7534.40
Net Present Values(k$) = 4647213.6							
Levelized Unit Cost ($/kg) = 616.800							

Table 4.15

Disposal Unit Costs for Three Different Spent Fuels

	CANDU-NU (Ti container)	CANDU-DUPIC (Ti container)	PWR (Cu container)
Construction cost total (M$)	2,660	3,055	5,020
Annual operation and maintenance (M$)	115	169	332
Decommissioning total (M$)	1313	1,532	3,607
Life cycle cost in net present value (M$)	2,068	2,583	4,647
Waste production in net present value (MTHM)	10,970	7,534	7,534
Levelized unit cost ($/kgHM)	188.5	342.8	616.8

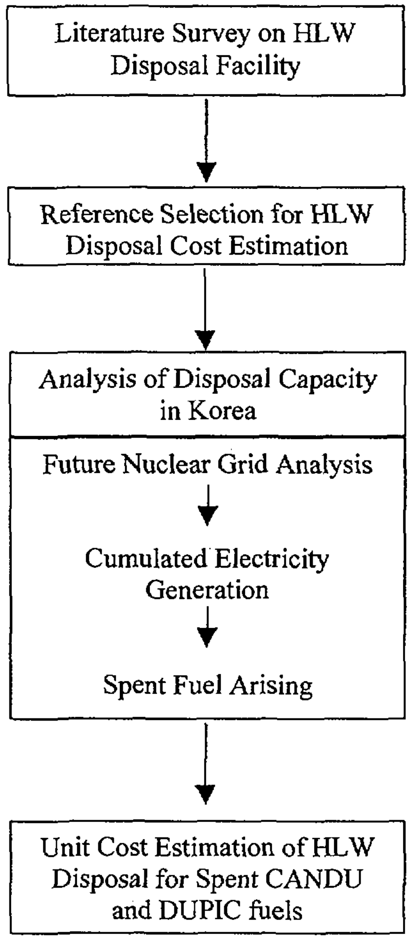


Fig. 4.1 Procedure of HLW Disposal Cost Estimation

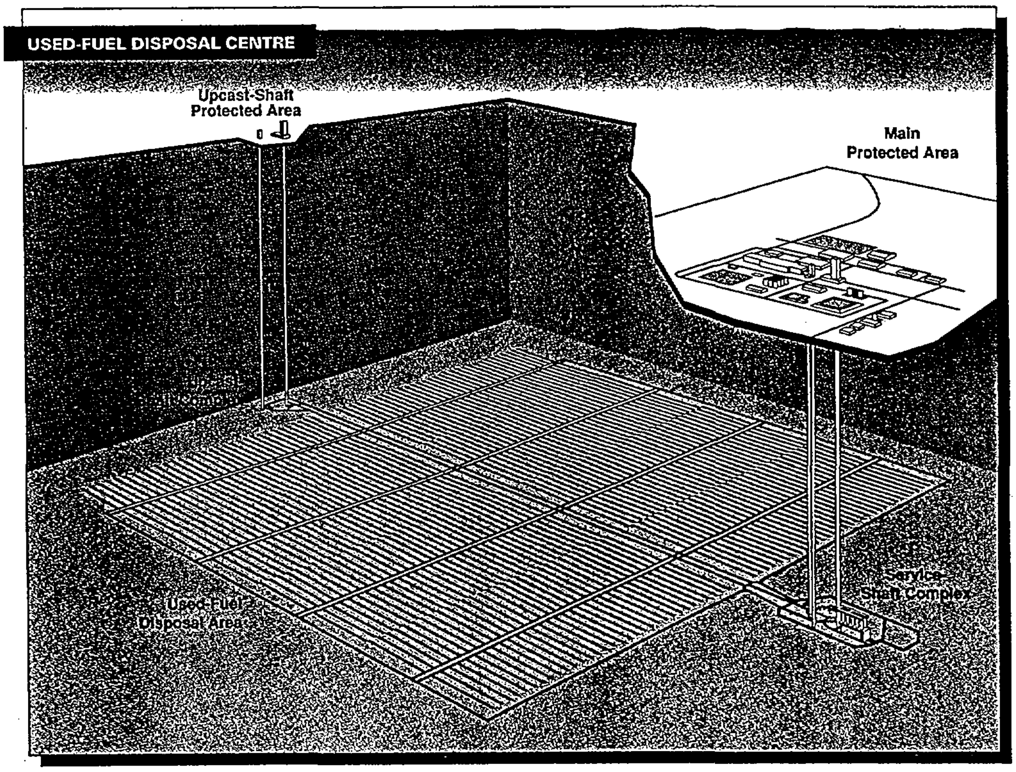


Fig. 4.2 Spent Fuel Disposal Facility Perspective [Ref. 17]

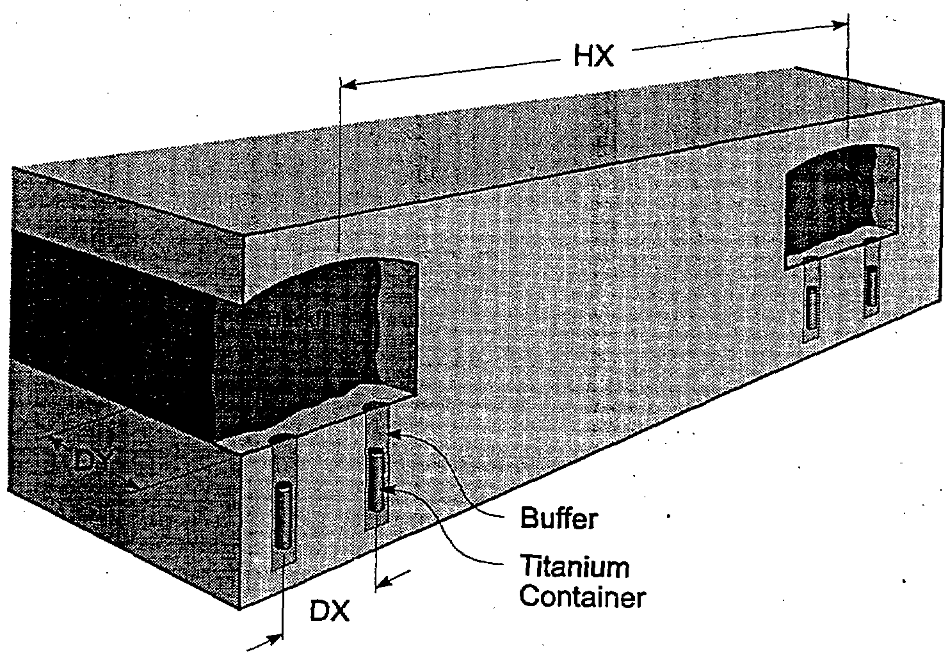


Fig. 4.3 Waste Emplacement Geometry for an Underground Facility

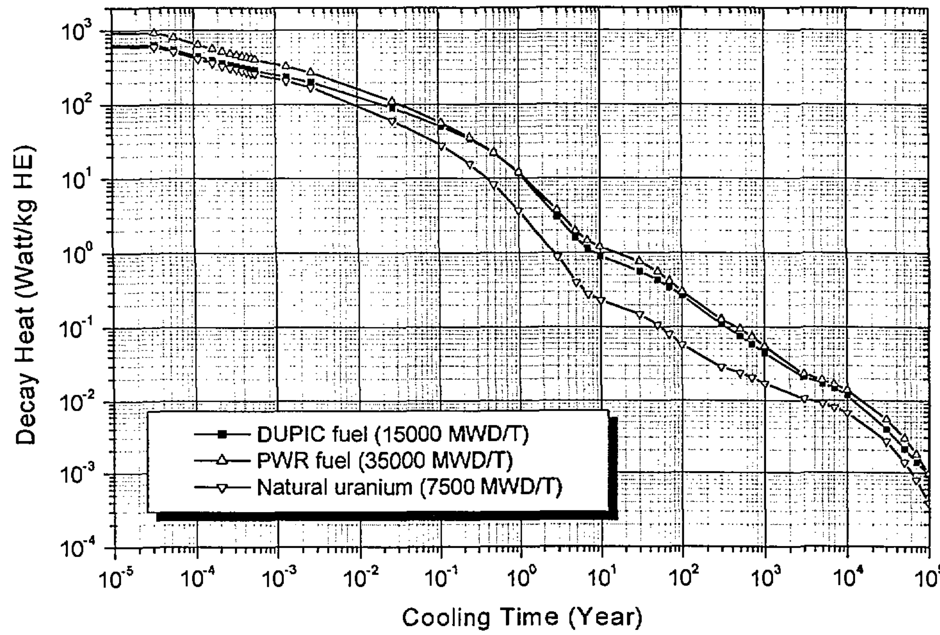


Fig. 4.4 Decay Heat Curves of Spent Fuels

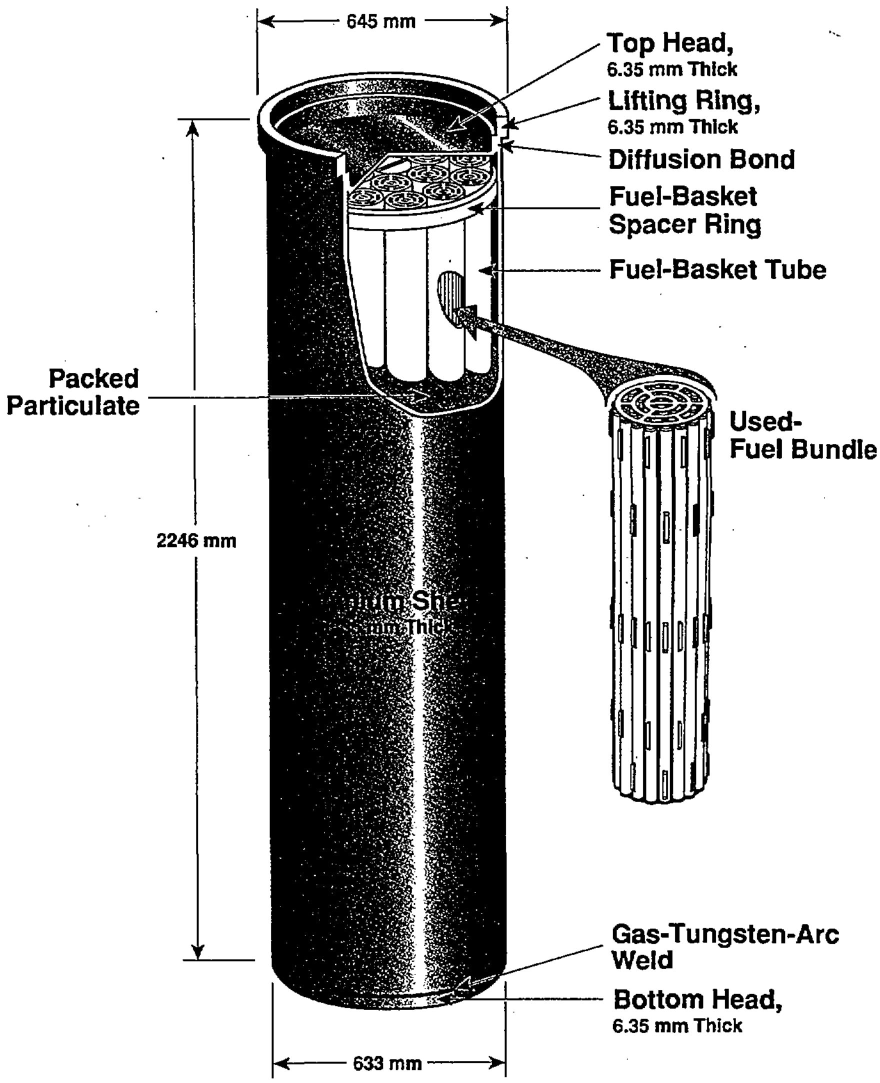


Fig. 4.5 Titanium-Shell Disposal Container [Ref. 17]

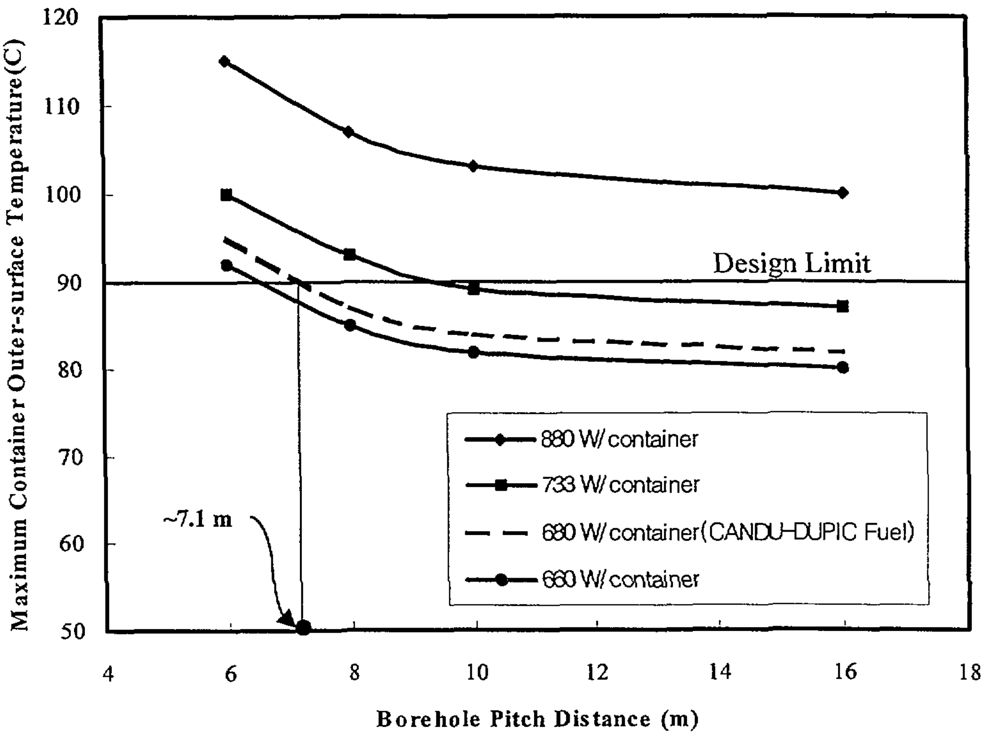


Fig. 4.6 Borehole Pitch Distance between Containers in a Disposal Room for Spent CANDU-DUPIC Fuel

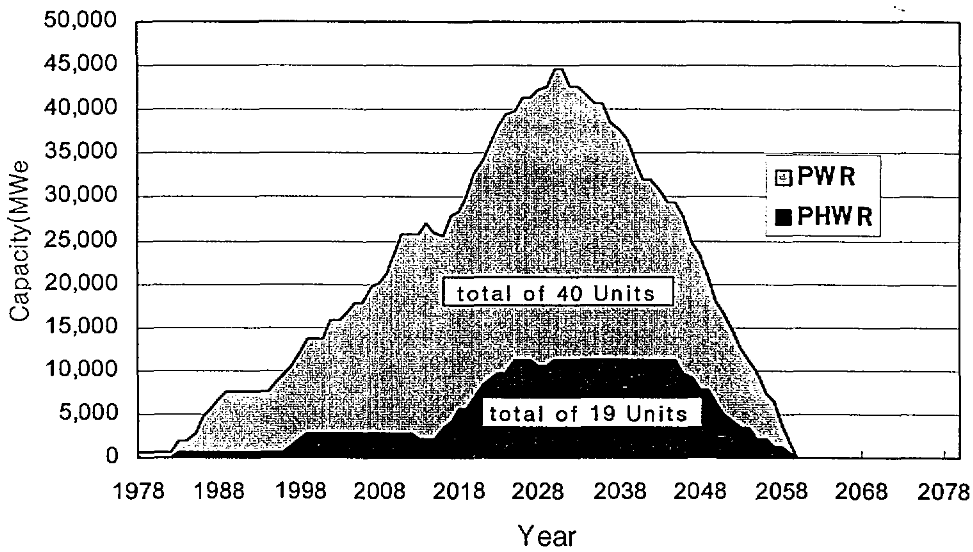


Fig. 4.7 Installed Capacity of Nuclear Power Plants

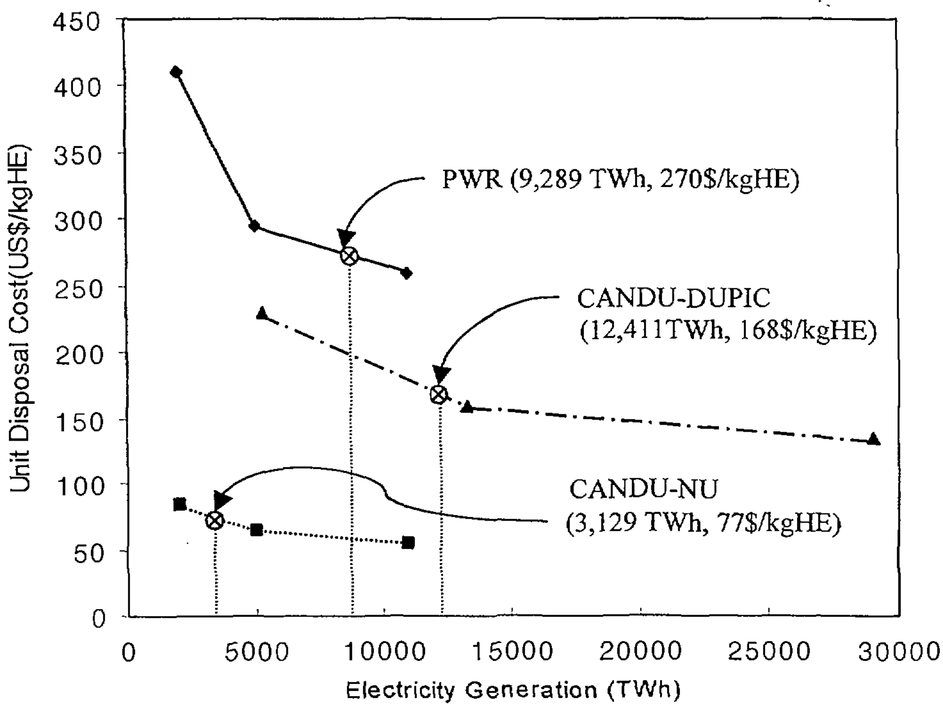


Fig. 4.8 Disposal Unit Costs for Spent CANDU-NU, CANDU-DUPIC and PWR Fuels

5. DUPIC FUEL CYCLE COST

In Korea, there are 11 PWRS and 4 CANDU reactors in operation. It is well known that spent PWR fuel contains as much fissile as approximately twice that of natural uranium used in CANDU fuel material. Considering the unique Korean reactor strategy and residual fissile content of spent PWR fuel, one of the fuel cycle concepts that could be an alternative to either once-through or recycling is to exploit the natural synergism that exists between two reactor types.[1,2] The feasibility study of this synergistic fuel cycle has been initiated under the title DUPIC, which stands for the direct use of spent PWR fuel in CANDU reactors.

The technical feasibility, safeguardability, and environmental benefit of the DUPIC fuel cycle have been studied and recognized in the international nuclear community. However, the DUPIC fuel cycle has never been demonstrated on a commercial scale, which results in uncertainties in the economics of the DUPIC fuel cycle option. For example, the DUPIC fuel cycle has three distinct features from the conventional once-through fuel cycle, such as the remote fabrication of DUPIC fuel, the handling of radioactive fuel in the power plant, and the disposal of highly irradiated CANDU DUPIC fuel. Therefore, the unit costs of these fuel cycle components have been estimated based on conceptual design studies. At the same time, a physics study has developed the reference DUPIC fuel model, which is technically feasible in existing CANDU reactors. These preliminary studies have enabled a reliable analysis of DUPIC fuel cycle economics.

In this section, a model for the DUPIC fuel cycle cost is suggested with a simple equilibrium core concept. The DUPIC fuel cycle costs are then compared with the once-through fuel cycle costs in order to estimate the competitiveness as an alternative fuel cycle option. The fuel cycle cost is estimated with the unit costs of the fuel cycle components that have been estimated based on conceptual design studies. The fuel cycle cost is calculated by a deterministic method in which the reference fuel cycle component costs are used. The uncertainty of the fuel cycle cost is then estimated by a Monte Carlo simulation method by treating the fuel cycle component costs as random variables.

5.1. REFERENCE DUPIC FUEL MODEL

In the DUPIC fuel cycle, spent PWR fuel is directly used in a CANDU reactor after a dry refabrication process. Because there is no separation of isotopes from the spent PWR fuel during the dry refabrication process, DUPIC fuel contains all the actinides and non-volatile fission products, resulting in a high variation in fissile content and isotopic composition depending on the initial and discharge conditions of PWR fuel. Therefore, fuel composition adjustment methods have been previously studied in order to determine the reference DUPIC fuel composition that can be used for the feasibility analysis of the DUPIC fuel in the existing CANDU reactors.

The reference DUPIC fuel models have been searched under following requirements:

- The fuel composition variation is minimized.
- The spent PWR fuel utilization is maximized.
- The fresh uranium feed is minimized.
- The DUPIC fuel lattice property is acceptable.
- The DUPIC fuel core performance is acceptable.

The fuel composition adjustment has been performed in two approaches: fissile content control and reactivity control. When necessary, both approaches are allowed to blend spent PWR fuel with fresh uranium such as slightly enriched uranium (SEU) and/or depleted uranium (DU). Currently, three options have been proposed to reduce the composition heterogeneity of DUPIC fuel and satisfy the physics design requirements of a CANDU reactor, which are

- Option 1: adjustment of the major fissile content using SEU and DU, [9]
- Option 2: reactivity control of DUPIC fuel using SEU and DU, [27] and
- Option 3: adjustment of the isotopic composition by partially mixing spent PWR fuels.[28]

The characteristics of the candidate DUPIC fuel options are summarized in Table 5.1 with the other parameters necessary for the economics analysis.

5.1.1. Fissile Content Adjustment (Option 1)

In the fissile content adjustment option, the fuel composition is adjusted in two steps. First, two spent PWR fuel assemblies with the highest and lowest ^{239}Pu content are mixed together. This operation is performed three times to reduce variations in the isotopic composition. Secondly, fresh uranium is blended with the spent PWR fuel mixture and the quantity of the fresh uranium is determined such that the ^{239}Pu content is the same for all the mixtures. At the same time, by adjusting the ratio of 3.5 wt% SEU and 0.25 wt% DU in the fresh uranium feed, a unique composition of ^{235}U and ^{239}Pu can be achieved. For this option, the reference fissile content of DUPIC fuel has been determined as 1.0 and

0.45 wt% for ^{235}U and ^{239}Pu, respectively. Under this condition, 96% of spent PWR fuel can be refabricated as DUPIC fuel satisfying the reference fissile content. The amount of SEU and DU used for the composition adjustment are 6.5% and 10.8% of DUPIC fuel on average, respectively.

5.1.2. Reactivity Control by SEU/DU (Option 2)

A reactivity control method that maintains the uniform neutronic characteristics of DUPIC fuel was proposed as an alternative to the fissile content adjustment option. A uniform reactivity of DUPIC fuel can be achieved when the reactivity of the spent PWR fuel is between those of SEU and DU. After mixing spent PWR fuels with the highest and lowest reactivity three times, either SEU or DU is added to the spent PWR fuel mixture to achieve the target reactivity. For the selection of an optimum target reactivity, the sensitivities of the lattice property, core performance and amount of fresh uranium feed were considered. The target reactivity (k_∞) of DUPIC fuel was determined to be 1.18 for the reactivity control option by SEU/DU. Under this condition, 100% of spent PWR fuel can be refabricated as DUPIC fuel satisfying the target reactivity. The amount of SEU and DU used is 2.3 and 1.1% of the DUPIC fuel on average, respectively.

5.1.3. Isotopic Composition Control by Partial Mixing (Option 3)

In principle, it is possible to have a uniform fuel composition if all spent PWR fuels are mixed together. However, mixing all spent PWR fuel in one batch is practically limited and, therefore, a genetic algorithm was developed to search for the optimum combination of spent PWR fuel to obtain the reference fuel composition with a practically acceptable batch size. In fact, various spent PWR fuels can also be used as source material for fuel composition adjustment. A preliminary simulation[28] has shown that it is feasible to achieve the reference fuel composition through rod-wise mixing of spent PWR fuel. The fissile content of DUPIC fuel can be increased by preferentially using low-burnup spent PWR fuels. In this study, the reference DUPIC fuel model was determined by utilizing 80% of the spent PWR fuel accumulated in Korea by the middle of 1996. Under this condition, the fissile content of the reference DUPIC fuel is 1.57 wt%.

5.2. DUPIC FUEL CYCLE COST ANALYSIS MODEL

Figure 5.1 shows the procedure of the nuclear fuel cycle cost analysis. At first, the DUPIC fuel cycle model with typical PWR and CANDU reactors is suggested. In this model, reference PWR and CANDU reactors are chosen and the reactor characteristics such as the plant efficiency, capacity factor and fuel characteristics (e.g., discharge burnup and initial enrichment) are defined for material balance analyses. Secondly, following the material flow analyses, the levelized unit cost is calculated using the one-batch equilibrium model. The uncertainty analyses of the fuel cycle cost are then performed using the probabilistic simulation technique.

5.2.1. Fuel Cycle Model

For DUPIC fuel cycle cost analysis, an equilibrium fuel cycle model, in which PWRs are linked to a CANDU reactor, is assumed as shown in Fig. 5.2. The fuel cycle cost calculation includes the estimation of total electricity generation, integration of fuel cycle component costs and the levelization of the fuel cycle cost.

5.2.1.1. Electricity Generation

a. The amount of DUPIC fuel required by one CANDU reactor is estimated based on the reactor parameters such as

$$\text{Fuel loading per core} = \frac{P \times 100}{\varepsilon \times SH} \quad (5.1)$$

where *P*, *SH* and ε are the electric power (MWe) of a CANDU reactor, the specific heat (MWt/MTHM) and efficiency (%), respectively.

b. The annual requirement of DUPIC fuel is calculated based on fuel burnup and other parameters such as

$$\text{Annual requirement} = \frac{P \times 365 \times C}{\varepsilon \times BU} \quad (5.2)$$

where *C* and *BU* are the capacity factor (%) and burnup (MWD/MTHM), respectively.

c. The number of PWR plants is then calculated using Eq. (5.2) and the equilibrium core ratio between PWRs and a CANDU reactor is estimated.

d. The material flow analysis of the DUPIC fuel cycle is performed based on one CANDU reactor.

e. The electric power generation per fuel loading (MTHM) is calculated as follows:

$$\text{Power generation per fuel loading} = \frac{24 \times loading(MTHM) \times BU}{\varepsilon} \tag{5.3}$$

f. The total power generation is then discounted to the year of PWR fuel loading by a continuously discounted present worth factor[7] as follows:

$$E = \frac{1-\exp(-r' \times t)}{(r' \times t)} \tag{5.4}$$

where $r' = \ln(1+r)$, r = discount rate, t = time, and E is the discounted power generation.

The once-through fuel cycle consists of one CANDU reactor and an appropriate number of PWRs, which is the same for the DUPIC fuel cycle. Therefore, the total electricity generation of the once-through fuel cycle is the same as that of the DUPIC fuel cycle. The number of PWRs is determined from the equilibrium core ratio mentioned above.

5.2.1.2. Fuel Cycle Cost

The basic method adopted for the calculation of the fuel cycle cost is the constant money (levelized life-time cost) method that is explained in the Organization for Economic Cooperation and Development, Nuclear Energy Agency (OECD/NEA) report published in 1993. The levelized unit cost is based on the cash flow of all component costs discounted to the base year. To get the total fuel cycle cost, the net present value (NPV) is used, which can be expressed as follows:

$$NPV = \sum_i \sum_{t=t_0-T_1}^{t=t_0+L+T_2} \frac{F_i(t)}{(1+r)^{(t-t_0)}} \tag{5.5}$$

where t_o is the base year of the monetary count, L is the reactor life time, T_1 is the maximum value of the lead time in the front-end fuel cycle, and T_2 is the maximum value of the lag time in the back-end fuel cycle. $F_i(t)$ is the fuel cycle component cost at time t, and r is the discount rate.

5.2.1.3. Levelized Fuel Cycle Cost (LFCC)

The LFCC is derived in terms of mills/kWh by dividing the NPV of the entire fuel cycle cost by the NPV of the total electricity output over the plant life-time as follows:

$$\text{LFCC} = \frac{\sum_{i} \sum_{t=t_0-T_1}^{t=t_0+L+T_2} \frac{F_i(t)}{(1+r)^{(t-t_0)}}}{\sum_{t=t_0}^{t=t_0+L} \sum_{time} \frac{E_i(t)}{(1+r)^{(t-t_0)}}} \qquad (5.6)$$

where t is the particular time in the fuel cycle span and $E_i(t)$ is the electric power generated from the nuclear power plant at time t. In fact, the electricity is generated continuously during the reactor life and a continuous discounting method, Eq. (5.4), can be used.

5.2.2. Uncertainty Analysis Model Using a Probabilistic Simulation Method

In general, most of the nuclear fuel cycle economics assessments rely on deterministic methods. The deterministic method, however, does not provide uncertainties inherent in the cost estimates. The uncertainty of the fuel cycle cost can be estimated using a Monte Carlo simulation technique.[29,30]

For the sensitivity analysis by the Monte Carlo simulation, samplings are carried out by the Latin Hypercube Sampling (LHS) technique.[31] The LHS is a special kind of stratified sampling in which the range of each variable is divided into intervals of equal probability. It is well known that the LHS technique generally captures the probability behavior of the dependent variables better with fewer samples than either random or stratified sampling.[31] The estimates of the statistical parameters characterizing the distribution function of a dependent variable obtained with LHS will have a smaller variance than those obtained with either random or stratified sampling.

5.2.2.1. Probability Distribution Function of Unit Cost

A typical non-parametric distribution is the triangular distribution function, which is most commonly used. The triangular distribution is defined as follows:[32,33]

$$f(x) = \frac{2(x-a)}{(m-a)(b-m)} \qquad for \quad a \le x \le m \tag{5.7}$$

$$f(x) = \frac{2(b-x)}{(b-m)(b-a)} \qquad for \quad m \le x \le b \tag{5.8}$$

where *a* and *b* are the lower and upper limits, respectively, and *m* is the most likely value.

The mean value and the standard deviation (STD) of the triangular distribution are given as follows:

$$mean = \frac{(a+m+b)}{3} \tag{5.9}$$

$$\text{STD} = \left(\frac{a^2 + b^2 + m^2 - ab - am - bm}{18} \right)^{0.5} \tag{5.10}$$

Figure 5.3 shows an example of the triangular distribution function for the uranium component with a minimum value of 18.8 $/lb$U_3O_8$, a most likely value of 24.0 $/lb$U_3O_8$ and a maximum value of 43.8 $/lb$U_3O_8$. The statistical mean and standard deviation from Eqs. (5.9) and (5.10) are 28.9 $/lb$U_3O_8$ and 5.4 $/lb$U_3O_8$, respectively.

5.2.3. Sensitivity Analysis

The sensitivity analysis on the fuel cycle components can be performed with the results of Latin Hypercube sampling described in Sec. 5.2.2. The purpose of a sensitivity analysis is, in general, to determine the change of the response to changes of the model parameters and specifications. In this study, sensitivity analyses of the fuel cycle costs are performed by the

Spearman rank correlation method.

The input matrix obtained by the Latin Hypercube sampling of the fuel cycle components and the output vector can be expressed as follows:

$$\underset{=}{X} = \begin{pmatrix} X_{11} & X_{12} & - & - & X_{1k} \\ X_{21} & X_{22} & - & - & X_{2k} \\ - & - & - & - & - \\ - & - & - & - & - \\ X_{N1} & X_{N2} & - & - & X_{Nk} \end{pmatrix}, \quad (5.11)$$

$$\bar{Y} = (y_1, y_2, y_3, \text{------}, y_N) \quad (5.12)$$

where k, N and $\bar{Y}$ are the number of variables, the number of samplings and the output vector under consideration, respectively. The quantitative measure of the linear relationship between X and Y is provided by the Pearson correlation coefficient, and is defined as follows;[34]

$$Pear(y, X_j) = \frac{\sum_{i=N}^{N} (X_{ij} - \bar{X}_j)(y_i - \bar{y})}{(\sum_{i=1}^{N} (X_{ij} - X_j)^2 \sum_{i=1}^{N} (y_i - \bar{y})^2)^{1/2}}, \quad (5.13)$$

where $\bar{x}_j$ and $\bar{y}$ are the sample means. The Spearman coefficient is a preferred measure of correlation for non-linear models, which is essentially the same as the Pearson method, but uses the ranks of both Y and X_j instead of the raw values as follows:[34]

$$Spear(y, X_j) = Pear(R(y), R(X_j)) \quad (5.14)$$

where $R(y_i)$ is, for instance, a number that indicates the rank of y_i if all y_i's $(i=1,2,\ldots\ldots N)$ are ordered from the lowest to the highest value. If the value of the coefficient approaches −1 or 1, it indicates that the variables are highly correlated.

5.3. UNIT COST OF THE DUPIC FUEL CYCLE COMPONENTS

The unit costs of the fuel cycle components used in this study were basically quoted from the OECD/NEA report[10] of fuel cycle economics and other published data. The cost data used in this study are described in Table 5.2. All cost data were converted to the reference year of December 1999. The cost data of the OECD/NEA were based on July 1991, and an escalation rate between July 1999 and December 1999 was reflected. The U.S. Consumer Price Index was used for the escalation. For the cost data in Table II, the three distinctive unit costs of the DUPIC fuel cycle components were estimated based on the conceptual design studies to improve the credibility of the fuel cycle cost calculation, as summarized in Secs. 5.3.1 to 5.3.4.

5.3.1. DUPIC Fuel Fabrication Cost

A preliminary conceptual design[35] of a DUPIC fuel fabrication plant was studied, which annually converts spent PWR fuel of 400 MTHE into CANDU fuel. Assuming that the annual discount rate is 5% during construction (5 yr) and the operation period (40 yr), and the contingency is 25% of the capital cost, the levelized unit cost (LUC) of DUPIC fuel fabrication was estimated to be 616 \$/kgHE as of December, 1999 (cf. 558 \$/kgHE as of 1995). The LUC is mostly governed by annual operation and maintenance costs that correspond to 63% of LUC. For DUPIC fuel options 1 and 2 (see Sec. 5.1) which utilize fresh uranium to maintain the composition homogeneity, the reference fabrication cost was adjusted to consider the amount of annual fresh uranium use.

5.3.2. DUPIC Fuel Handling Cost

The conceptual design study[16] has shown that fresh DUPIC fuel can be transferred to the core following the existing spent-fuel discharge route, provided that new fuel handling equipment such as the manipulator, new fuel magazine, new fuel ram, dryer, etc. are installed. The reverse path loading option is known to minimize the amount of additional equipment for fuel handling, because the discharge of spent DUPIC fuel can be done through the existing spent-fuel handling system without any modification. However, because the decay heat of DUPIC fuel is much higher than that of natural uranium fuel, the storage should be optimized and the extra storage cooling capacity should be supplemented. Based on the conceptual design study, the capital cost for DUPIC fuel handling and extra storage cooling was estimated to be \$ 3,750,000 (as of December 1999) per plant. The levelized unit cost (LUC), based on the amount of fuel required during the life-time of a plant, was estimated to be 5.0-5.3 \$/kgHM.

5.3.3. Transportation and Interim Storage Cost

The OECD/NEA data[10] for the transportation cost of spent CANDU fuel and the Korea

Atomic Energy Research Institute (KAERI) data[36] for the storage cost of spent DUPIC fuel were referred, respectively. The cost for spent CANDU fuel storage, 40.4 $/kgHM (as of December 1999), was referred to the result of the study on the dry storage of spent CANDU fuels in a concrete silo that has been carried out by KAERI in 1994.[36] The transportation cost for spent CANDU fuel (16.3 $/kgHM as of December 1999) was also referred to the OECD/NEA report. For the transportation and storage cost of spent DUPIC fuel the decay heat is used, because the cost of dry storage of spent fuel generally depends on the magnitude of the decay heat generated from the spent fuel. The decay heat from spent DUPIC fuel and spent standard CANDU fuel at 10 years after discharge are 0.8683 and 0.2254 kW/MTU, respectively. The decay heat of the spent DUPIC fuel is 3.85 times higher than that of spent standard CANDU fuel. The transportation and storage cost of spent DUPIC fuel are estimated as follows:

- Transportation cost of spent DUPIC fuel: 16.3 x 3.85 x 0.7 = 43.9 $/kgHM
- Storage cost of spent DUPIC fuel: 40.4 x 3.85 x 0.7 = 152.8 $/kgHM

where the factor 0.7 means the portion of total transportation or storage cost increase due to the decay heat.

5.3.4. *Spent Fuel Disposal Cost*

The disposal costs of spent PWR, CANDU natural uranium and CANDU-DUPIC fuels have been estimated based on the engineering design of a disposal facility by Atomic Energy of Canada Limited (AECL).[17] The cost estimation was carried out by a parametric calculation on the total electricity generation. Therefore, a future electricity generation scale in Korea was analyzed in order to evaluate the appropriate capacity of the high-level waste disposal facility, which is a key parameter to the disposal cost estimation. Based on the total electricity generation scale, it was found that the disposal unit costs for spent PWR, CANDU natural uranium, and CANDU-DUPIC fuels are 617, 189, and 343 $/kgHE, respectively.[37]

5.3.5. *Cost Distribution for the Uncertainty Analysis*

Table 5.3 shows the range of the fuel cycle component costs and their distribution parameters. In this study, all probability density functions are assumed to be triangular distributions. For the parameters of the triangular distributions, the sensitivity range of each fuel cycle component cost in the OECD/NEA report was quoted. The reference value used in the

OECD/NEA was used as a most likely value in the triangular distribution. The range of the sensitivity analysis used in the OECD/NEA was used for the minimum and the maximum value in the triangular distributions. For the minimum and the maximum values of spent fuel disposal, DUPIC fuel fabrication, transportation and storage costs, the relative ratios of the minimum and maximum values to the reference values, which were used in sensitivity analysis of the OECD/NEA, were taken.

5.4. CALCULATION OF FUEL CYCLE COST

In this section, the fuel cycle costs are estimated using the DUPIC fuel cycle model and input data described in Secs. 5.2 and 5.3. The reference plant and components involved in the DUPIC and once-through fuel cycles are described in Sec. 5.4.1. The results of the DUPIC fuel cycle cost and environmental effect analyses are described in Sec. 5.4.2.

5.4.1. Reference Plant and Fuel Cycle Component

The fuel cycle models considered in this study are the DUPIC and once-through fuel cycles, of which the basic concept and components are illustrated in Fig. 5.4. In the DUPIC fuel cycle, spent PWR fuel is directly refabricated into CANDU fuel to be burnt again in CANDU reactors before being disposed of permanently. On the other hand, the once-through fuel cycle is to dispose all spent fuel generated from both PWR and CANDU reactors. As shown in Fig. 5.4, the front-end fuel cycle components for a PWR were established to be the same for both fuel cycles. For the DUPIC fuel cycle, however, several services such as the transportation of spent PWR fuel to the DUPIC fuel fabrication plant, DUPIC fuel fabrication and transportation of as-fabricated DUPIC fuel to the CANDU power station are introduced, which are comparable with the front-end fuel cycle components of the CANDU once-through fuel cycle (from uranium ore to CANDU fuel fabrication). The back-end fuel cycle components for both fuel cycles were established to be the same.

Figure 5.4 also shows the time frame of the fuel cycle components, which are used as input data for calculating the levelized fuel cycle cost at different time points of each fuel cycle component. The time frame is classified into lead and lag time based on the time when the fuel is loaded in the reactor. The lead time of the front-end cycle components for a PWR are established to be identical and the lag time after being discharged from the reactors for spent fuel storage and disposal are established to be identical for both fuel cycles. The fresh DUPIC fuel was assumed to be fabricated from spent PWR fuel after a cooling time of 10 years. Therefore, the fuel loading time for a PWR was established to be earlier by 10 years than that for the CANDU reactor, which is common for both the DUPIC and once-through fuel cycles.

For a substantial analysis, a 950 MWe PWR and a 713 MWe CANDU reactor, which are now operating in Korea, were taken as the reference reactor system. The characteristic parameters of the reference reactor systems are summarized in Table 4.4, which were used as input data for determining the fuel material flow/balance and the fuel cycle cost.

For the purpose of fuel cycle cost estimation, a few assumptions were made for the consistency as follows:

- The base year for the cost data is December, 1999.
- The discount rate is 5%.
- The escalation rate is 1.2% for uranium (U_3O_8) cost and zero for all other components.

5.4.2. Fuel Cycle Cost Calculation

The characteristics of the reference DUPIC fuels were given in Table 5.1, which were tentatively determined as reference fuels for the purpose of the compatibility studies of DUPIC fuel with existing CANDU-6 reactors. In this study, three reference DUPIC fuel options are used for the fuel cycle cost analysis, which are described in Sec. 5.1. In a CANDU reactor, the discharge burnup of DUPIC fuel, which has a strong effect on the fuel cycle cost, is ~15000 MWd/tHM.

5.4.2.1. Material Flow Analysis

Table 5.5 shows the material flow of the PWR and CANDU reactors adopted as reference reactor types in this study. Table 5.6 shows the material flow of the DUPIC fuel cycle for the three DUPIC fuel options, which is based on one CANDU reactor and an appropriate number of PWRs. In order to establish the DUPIC fuel cycle, the PWR-to-CANDU reactor ratio (equilibrium core ratio) was also calculated, which varies from 1.7 to 2.0.

To evaluate the material flow for each option, assumptions were made as follows:

- The ^{235}U content in natural uranium is 0.711 wt%.
- The tail assay in the enrichment facility is 0.25 wt%.
- The loss factors are 0.5% for conversion, 1% for PWR and DUPIC fuel fabrication, and 0.5% for CANDU fuel fabrication.

5.4.2.2. Fuel Cycle Cost Calculation by a Deterministic Method

According to the fuel cycle cost calculation method mentioned in Sec. 5.2.1, the levelized fuel cycle costs were calculated as listed in Tables 5.7, 5.8 and 5.9 for the three DUPIC fuel options. In principle, the front-end service costs for a PWR are the same for both the DUPIC and once-through fuel cycles. However, other fuel cycle component costs are different for the DUPIC and once-through fuel cycles. This difference is due to the basic concept of the DUPIC fuel cycle: the spent PWR fuel is directly refabricated into DUPIC fuel to be burnt again in CANDU reactors without long-term storage and final disposal. Therefore, in the DUPIC fuel cycle, the costs for uranium ore purchasing, conversion for CANDU fuel fabrication and the spent PWR fuel storage and disposal could be offset by only one service (i.e., DUPIC fuel fabrication), though additional costs are required for the transportation of spent PWR fuel from a PWR power plant to the DUPIC fuel fabrication plant, and transportation of fresh DUPIC fuel from the DUPIC fuel fabrication plant to the CANDU power plant.

For DUPIC fuel option 1, deterministic calculations have shown that the fuel cycle costs are 6.721 and 6.764 mills/kWh for the DUPIC and once-through fuel cycle, respectively. The DUPIC fuel cycle cost is very similar to the once-through fuel cycle cost. For DUPIC fuel option 2, the fuel cycle costs are 6.656 and 6.840 mills/kWh for the DUPIC and once-through fuel cycle, respectively. For DUPIC fuel option 3, which does not use SEU for DUPIC fuel fabrication, the fuel cycle costs are 6.546 and 6.830 mills/kWh for the DUPIC and once-through fuel cycle, respectively.

Table 5.10 shows the summary of the fuel cycle costs calculated by the deterministic method. The difference in the fuel cycle cost between the DUPIC and once-through fuel cycle is 0.043, 0.184 and 0.280 mills/kWh for DUPIC fuel options 1, 2, and 3, respectively. These results show that the DUPIC fuel cycle could have economic competitiveness compared with the once-through fuel cycle, if the SEU is not used too much during DUPIC fuel fabrication. However, the cost difference between the DUPIC and once-through fuel cycle is very small.

Table 5.10 also includes PWR-only and CANDU-only fuel cycle costs, of which the base year is December 1999 as was used for other fuel cycle cost calculations. It should be noted that the direct comparison between PWR-only and DUPIC fuel cycle costs is not fair because the fuel cycle model is composed of different reactor types. Nonetheless, these costs are given just for comparison among fuel cycle options.

5.4.2.3. Uncertainty Analysis of Fuel Cycle Cost by a Probabilistic Method

Table 5.11 shows the results of the sampling frequency in 10000 trials for each DUPIC fuel option. For DUPIC fuel option 1, the fuel cycle costs are 6.921±0.46 and 6.879±0.50 mills/kWh for the DUPIC and once-through cycle, respectively. For DUPIC fuel option 2, the fuel cycle costs are 6.870±0.46 and 6.96±0.51 mills/kWh for the DUPIC and once-through fuel cycle, respectively. For DUPIC fuel option 3, the fuel cycle costs are 6.738±0.45 and 6.950±0.51 mills/kWh for the DUPIC and once-through fuel cycle, respectively. On the whole, considering the uncertainty (one standard deviation) of the fuel cycle cost, it is concluded that the cost difference between the once-through and DUPIC cycle is too small to have any significance.

There are some differences between the mean values calculated by the deterministic and probabilistic simulation method. This is due to the fact that the cost distributions of the fuel cycle components are not symmetric. On the whole, the mean values calculated by the probabilistic simulation method are a little higher than those calculated by the deterministic method. This means that the cost distribution of most fuel cycle components are positively-skewed. The cost components with the positive skewness are the disposal cost, enrichment cost, storage cost, transportation cost and conversion cost as shown in Table 5.3.

Figures 5.5, 5.6 and 5.7 show the comparison of distribution functions generated by the probabilistic simulation. As shown in these figures, the difference of the cost distribution between the once-through and DUPIC cycle is small. All resulting distributions for both cases have shown a small positively-skewed shape, which means that the distribution shifts to the left. This is primarily due to the distribution of the uranium cost, which is the most important component of all fuel cycle cost parameters.

Figures 5.8, 5.9 and 5.10 are the results of the sensitivity calculation by Eq. (5.14) for the three DUPIC fuel options, which show the coefficient of the rank correlation. The results of the sensitivity analysis indicate that the components in the front-end are generally more sensitive than those in the back-end, and that the uranium price is the most important factor among all fuel cycle components. The plant modification cost for the DUPIC option is the smallest factor of all the components. It is also shown that the DUPIC fuel fabrication cost is a factor with great impact on the fuel cycle cost, showing the third rank of all components.

5.4.2.4. Environmental Effect

Uranium saving and spent fuel reduction for the DUPIC fuel cycle were estimated from the material flow analysis, and the results are shown in Figs. 5.11, 5.12 and 5.13. For DUPIC fuel option 1, ~39 tons of uranium with an enrichment of 3.5 wt% ^{235}U and ~95 tons of natural uranium are required for the once-through cycle, which is equivalent to 978 tons of natural uranium (U_3O_8). For the DUPIC cycle, on the other hand, ~39 tons of spent PWR fuel with additional uranium used during the DUPIC fuel fabrication are charged in a CANDU reactor as DUPIC fuel. Therefore, the natural uranium feed for a CANDU reactor is no longer necessary in the DUPIC fuel cycle.

The replacement of natural uranium CANDU fuel with DUPIC fuel enables the saving of natural uranium resources at the front-end of the CANDU once-through fuel cycle and the elimination of spent PWR fuel arising at the back-end of the PWR once-through cycle. Consequently, the amount of natural uranium required for the DUPIC fuel cycle, which is composed of 1.7 PWRs and one CANDU reactor, is 786 tons. Therefore, there is a ~20% uranium saving in the DUPIC fuel cycle compared with the once-through fuel cycle. It is also expected that the percent saving of natural uranium in the DUPIC fuel cycle could increase if high discharge burnup is achieved in a CANDU reactor. For DUPIC fuel options 2 and 3, the uranium saving by the DUPIC fuel cycle is 20 and 23%, respectively. Table 5.12 shows the summary of the environmental effect.

It is also possible to estimate the projected annual spent fuel arising from both the DUPIC and once-through fuel cycles. For DUPIC fuel option 1, the amount of spent fuel annually discharged from the once-through fuel cycle is ~134 tHM while the DUPIC fuel cycle generates only ~48 tHM. Therefore, the spent fuel reduction by the DUPIC fuel cycle is ~65%. For DUPIC fuel options 2 and 3, the spent fuel reduction rates are 66 and 67%, respectively.

Therefore, the DUPIC fuel cycle has a great potential benefit for natural resource savings and environmental protection.

Table 5.13 shows the summary of natural uranium requirement and spent fuel production per electricity generation (per GWh) for various fuel cycle models, including PWR-only and CANDU-only fuel cycles. Regarding to uranium utilization, the CANDU-only fuel cycle could be the best option, which shows ~30% saving of natural uranium compared with the PWR-only fuel cycle. It can be seen that the uranium utilization of DUPIC option is as good as that of CANDU-only once-through cycle, because the spent fuel is used again. For the spent fuel production per electricity generation, the DUPIC fuel cycle shows an excellent advantage over the CANDU-only fuel cycle; the spent fuel production rate of the DUPIC fuel cycle is only one-seventh of the CANDU-only once-through cycle.

5.5. SUMMARY

This study examined the economics of the DUPIC fuel cycle in comparison with that of the once-through fuel cycle. In addition, the environmental benefits of the DUPIC fuel cycle were examined in terms of the amount of spent fuel to be disposed of and fresh uranium required. According to the one-batch equilibrium model for the fuel cycle cost calculation, the levelized fuel cycle costs were calculated by the deterministic method for the three DUPIC fuel options. On the whole, it is concluded that the DUPIC fuel cycle option has economic competitiveness compared with the once-through fuel cycle, if slightly enriched uranium is not used too much during DUPIC fuel fabrication. However, the cost difference between the DUPIC and once-through fuel cycle is very small.

A probabilistic simulation has confirmed that the cost difference between the DUPIC and once-through fuel cycle is too small to have any significance, considering the uncertainty of the fuel cycle cost. In addition, a sensitivity analysis has shown that the uranium price is the most important factor of all the fuel cycle components. This means that if the uranium cost is increased in the future more than the annual escalation rate of 1.2 %, the once-through cycle cost will be much higher than the DUPIC fuel cycle cost. On the other hand, the analysis on the environmental effect has shown that the DUPIC fuel cycle can save uranium resources by 20~23% and reduce the spent fuel arising by 65~67%. Therefore, the DUPIC fuel cycle has a great potential benefit for environmental protection.

Table 5.1
Characteristics of Reference DUPIC Fuel

		DUPIC Fuel Model		
		Option 1	Option 2	Option 3
Fissile content (wt%)	^{235}U	1.00	0.97	0.98
	^{239}Pu	0.45	0.53	0.54
	^{241}Pu	0.04	0.05	0.05
Fuel composition (%)	Spent PWR fuel	82.7	96.6	100.0
	SEU (3.5 wt%)	6.5	2.3	0.0
	DU (0.25 wt%)	10.8	1.1	0.0
	Natural U. (0.711 wt%)	0.0	0.0	0.0
Spent PWR fuel utilization (%)		96	100	80
Discharge burnup in CANDU (MWd/T)		14900	14500	15400
Annual Fuel requirement (MTU)		47.6	48.9	46.0

Table 5.2

Input Values for the Fuel Cycle Components

Component	Loss Rate (%)	Lead/Lag (months)	Unit Cost[2]
Uranium ($/lb$U_3O_8$)[1]			
- PWR		-24	24.0
- CANDU		-17	24.0
Conversion ($/kgU)			
- PWR	0.5	-18	10.0
- CANDU	0.5	-13	10.0
Enrichment ($/SWU)		-12	137.5
Modification of CANDU Reactor for DUPIC ($/kgHM)		-12	Option 1: 5.1 Option 2: 5.0 Option 3: 5.3
Fabrication ($/kgHM)			
- PWR	1	-6	343.8
- CANDU	1	-10	81.3
- DUPIC	1	-10	Option 1 : 683.4 Option 2 : 640.3 Option 3 : 616.0
Transportation ($/kgHM) - DUPIC		120	43.9
Trans./Storage ($/kgHM)			
- PWR		120	287.5
- CANDU		120	56.7
- DUPIC		120	152.8
Disposal ($/kgHM)			
- PWR		360	616.8
- CANDU		360	188.5
- DUPIC		360	342.8

1 Escalation is 1.2% for uranium cost and zero for all other components

2 Price as of December, 1999. Using the U.S. Consumer Price Index, an escalation factor of 1.25 between July, 1991 and December, 1999 and a factor of 1.104 between July, 1995 and December, 1999 were considered.

Table 5.3
Distribution Parameters of Input Values for the Uncertainty analysis

Component	Distribution	Min.	Most likely value (Mode)	Maximum
Uranium ($/lb$U_3O_8$)				
- PWR	Triangular	18.8	24.0*	43.8
- CANDU		18.8	24.0	43.8
Conversion ($/kgU)				
- PWR	Triangular	7.5	10.0	13.8
- CANDU		7.5	10.0	13.8
Enrichment ($/SWU)	Triangular	100.0	137.5	162.5
Modification of CANDU		Option1: 4.6	5.1	8.7
Reactor for DUPIC ($/kgHM)	Triangular	Option2: 4.5	5.0	8.5
		Option3: 4.8	5.3	9.0
Fabrication ($/kgHM)				
- PWR		250.0	343.8	437.5
- CANDU		58.8	81.3	103.8
- DUPIC	Triangular	Option1: 496.8	683.4	870.0
		Option2: 465.9	640.3	814.8
		Option3: 448.2	616.0	738.8
Transportation ($/kgHM)				
- DUPIC	Triangular	11.5	43.9	55.4
Trans./Storage ($/kgHM)				
- PWR		75.0	287.5	362.5
- CANDU	Triangular	14.8	56.7	71.4
- DUPIC		39.9	152.8	192.7
Disposal ($/kgHM)				
- PWR		141.6	616.8	677.5
- CANDU	Triangular	43.3	188.5	207.0
- DUPIC		78.7	342.8	376.5

*62.4 $/kgHM (December 1999)

Table 5.4

Characteristics of the Reference Reactors and Fuels for Once-through and DUPIC Fuel Cycles

Item	Characteristic Parameters		
	PWR	CANDU	CANDU-DUPIC
Reactor			
- Electric power (MWe)	950	713	713
- Thermal power (MWth)	2,775	2,159	2,159
- Specific power (MW/ton U)	40.2	25.5	25.5
- Load factor	0.8	0.9	0.9
- Cycle length (Full Power Day)	290	-	-
- No. of fuel assemblies or bundles per core	157	4,560	4,560
- No. of batches for PWR	3	-	-
- Loading per core (MTU)	69.1	80.3	80.3
- Annual fuel requirement (MTU)	23.15	94.5	see Table 5.1
Fuel			
- Initial enrichment	3.5wt%	Nat. U	see Table 5.1
- No. of fuel rods per assembly	264	37	43
- Discharge burnup (MWd/kgHM)	35	7.5	see Table 5.1
- Reference cooling time for refabrication of spent PWR fuel into DUPIC fuel (year)	10	-	-

Table 5.5

Material Flow of the Once-through Fuel Cycle based on a One-Batch Equilibrium Model

	PWR	CANDU
Uranium purchase (lb U_3O_8)	428461	223748
Conversion (MTU)	168.80	86.06
Enrichment (TSWU)	111.90	-
Fabrication (MTU)	23.26	85.63
Reactor condition		
Electricity power (MWe)	950	713
Thermal efficiency (%)	34.23	33.03
Specific power (MW/MTU)	40.2	25.5
Burnup (MWd/MTU)	35000	7900
Transportation (MTHM)	23.03	84.79
Interim storage (MTHM)	23.03	84.79
Disposal (MTHM)	23.03	84.79

MTU: Metric Ton Uranium

TSWU: Ton Separative Work Unit

MTHM: Metric Ton Heavy Metal

Table 5.6
Material Flow of the Once-through Fuel Cycle based on One CANDU Reactor

	DUPIC Fuel Option		
	Option 1	Option 2	Option 3
Uranium purchase (lb U_3O_8)	1,317,551	1,539,002	1,593,170
Conversion (MTU)	560.78	591.96	612.79
Enrichment (TSWU)	344.11	401.95	416.10
Fabrication (MTU)	71.53	83.55	86.49
PWR core (MTU)	70.82	82.27	85.63
Transportation (MTHM)	70.82	82.27	85.63
Fabrication (MTHM)	85.63	85.63	85.63
Spent PWR fuel (%)	82.7	96.6	100
SEU (%)	6.5	2.3	-
DU (%)	10.8	1.1	-
Natural U (%)	0.0	0.0	-
Transportation (MTHM)	84.79	84.79	84.79
CANDU reactor			
Electric power (MWe)	713	713	713
Thermal efficiency (%)	33.03	33.03	33.03
Specific power (MW/MTU)	25.5	25.5	25.5
Burnup (MWd/MTU)	14900	14500	15400
Transportation (MTHM)	84.79	84.79	84.79
Interim storage (MTHM)	84.79	84.79	84.79
Disposal (MTHM)	84.79	84.79	84.79
Equilibrium core ratio	1.688	2.037	1.989

MTU: Metric Ton Uranium
TSWU: Ton Separative Work Unit
MTHM: Metric Ton Heavy Metal
SF: Spent PWR Fuel
NU: Natural Uranium
SEU: Slight Enriched Uranium (3.5 wt%)
DU: Depleted Uranium
Equilibrium core ratio = CANDU annual requirement /PWR annual Requirement

Table 5.7
Levelized Costs (mills/kWh) of the Once-through and DUPIC Fuel Cycle for Option 1
(Deterministic Method)

Components		Once-through		DUPIC
		PWR	CANDU	
PWR	Uranium (U_3O_8)	1.628	-	1.628
	Conversion	0.229	-	0.229
	Enrichment	2.084	-	2.084
	Fabrication	1.057	-	1.057
	Transportation	-	-	0.099
	Trans. & Storage	0.453	-	-
	Disposal	0.367	-	-
CANDU	Plant Modification*		-	0.019
	Uranium (U_3O_8)		0.268	-
	Conversion		0.038	-
	Fabrication		0.301	1.251
	Transportation		-	0.066
	Trans. & Storage		0.191	0.156
	Disposal		0.147	0.132
Total		6.764		6.721

*Fuel handling equipment for DUPIC fuel loading and heat exchanger for pool storage capacity increase etc. are included in the cost.

Table 5.8

Levelized Costs (mills/kWh) of the Once-through and DUPIC Fuel Cycle for Option 2
(Deterministic Method)

Components		Once-through PWR	Once-through CANDU	DUPIC
PWR	Uranium (U_3O_8)	1.168	-	1.168
	Conversion	0.237	-	0.237
	Enrichment	2.158	-	2.158
	Fabrication	1.094	-	1.094
	Transportation	-	-	0.102
	Trans. & Storage	0.469	-	-
	Disposal	0.379	-	-
CANDU	Plant Modification		-	0.017
	Uranium (U_3O_8)		0.232	-
	Conversion		0.033	-
	Fabrication		0.260	1.039
	Transportation		-	0.069
	Trans. & Storage		0.165	0.138
	Disposal		0.127	0.117
Total		6.840		6.656

Table 5.9

Levelized Costs (mills/kWh) of the Once-through and DUPIC Fuel Cycle for Option 3
(Deterministic Method)

Components		Once-through		DUPIC
		PWR	CANDU	
PWR	Uranium (U_3O_8)	1.679	-	1.679
	Conversion	0.236	-	0.236
	Enrichment	2.149	-	2.149
	Fabrication	1.090	-	1.090
	Transportation	-	-	0.102
	Trans. & Storage	0.467	-	-
	Disposal	0.378	-	-
CANDU	Plant Modification		-	0.017
	Uranium (U_3O_8)		0.236	-
	Conversion		0.033	-
	Fabrication		0.265	0.961
	Transportation		-	0.069
	Trans. & Storage		0.168	0.133
	Disposal		0.129	0.112
Total		6.831		6.546

Table 5.10

Summary of Levelized Fuel Cycle Costs by the Deterministic Method (mills/kWh)

	DUPIC Fuel Option		
	Option 1	Option 2	Option 3
Direct disposal fuel cycle (with both PWRs and a CANDU)	6.764	6.840	6.831
DUPIC fuel cycle (PWR-to-CANDU)	6.721	6.656	6.546
PWR-only	7.520		
CANDU-only	4.610		

Table 5.11

Results of the Monte Carlo Simulation for the Uncertainty Analysis of Fuel Cycle Costs (Statistical Parameters and Percentile)

Items		Option1		Option2		Option3	
		DUPIC	Once-through	DUPIC	Once-through	DUPIC	Once-through
Minimum		5.4916	5.4791	5.3911	5.4638	5.4464	5.5525
Maximum		8.4420	8.4399	8.4624	8.7639	8.2490	8.5769
Mean		6.9211	6.8788	6.8704	6.9599	6.7381	6.9501
Std Deviation		0.4571	0.5049	0.4610	0.5083	0.4531	0.5080
Variance		0.2089	0.2549	0.2125	0.2583	0.2053	0.2581
Skewness		0.2321	0.2675	0.2099	0.2466	0.2505	0.2752
Kurtosis		2.7102	2.6523	2.6468	2.6239	2.6915	2.6725
Mode		6.2871	6.3289	6.0823	6.3665	6.1963	6.2530
Percentile	5%	6.2139	6.1103	6.1472	6.1876	6.0416	6.1757
	10%	6.3397	6.2523	6.2900	6.3199	6.1762	6.3204
	15%	6.4414	6.3528	6.3896	6.4274	6.2631	6.4252
	20%	6.5230	6.4361	6.4666	6.5097	6.3382	6.5090
	25%	6.5938	6.5087	6.5377	6.5857	6.4060	6.5778
	30%	6.6566	6.5781	6.6021	6.6553	6.4696	6.6470
	35%	6.7171	6.6411	6.6601	6.7210	6.5304	6.7153
	40%	6.7801	6.7097	6.7206	6.7908	6.5950	6.7782
	45%	6.8382	6.7774	6.7801	6.8618	6.6529	6.8408
	50%	6.8961	6.8416	6.8459	6.9283	6.7103	6.9108
	55%	6.9521	6.9082	6.9069	6.9925	6.7670	6.9816
	60%	7.0158	6.9809	6.9686	7.0608	6.8307	7.0482
	65%	7.0786	7.0518	7.0372	7.1377	6.8936	7.1265
	70%	7.1472	7.1297	7.1098	7.2187	6.9662	7.2031
	75%	7.2242	7.2199	7.1876	7.3093	7.0444	7.2924
	80%	7.3130	7.3253	7.2739	7.4101	7.1360	7.3965
	85%	7.4214	7.4388	7.3797	7.5255	7.2350	7.5095
	90%	7.5495	7.5795	7.4987	7.6602	7.3590	7.6562
	95%	7.7169	7.7677	7.6732	7.8499	7.5305	7.8435

* 10,000 trials using Latin Hypercube Sampling Technique
* Probabilistic distribution of input costs: all triangular distribution

Table 5.12
Summary of the Environmental Benefit of the DUPIC Fuel Cycle

	DUPIC Fuel Option		
	Option 1	Option 2	Option 3
Natural Uranium Saving Rate (%)	19.7	20.4	22.7
Disposal Waste (HLW) Reduction Rate (%)	64.5	65.5	67.2

Table 5.13

Natural Uranium and Waste Production

		Specific natural uranium requirement (U_3O_8 klb/MWh)	Specific spent fuel production (kgU/GWh)
PWR-only		64.704	3.497
CANDU-only		44.387	16.820
Once-through cycle	Fuel option 1	57.190	8.424
	Fuel option 2	58.021	7.879
	Fuel option 3	57.906	7.954
DUPIC cycle	Fuel option 1	46.470	2.815
	Fuel option 2	46.781	2.556
	Fuel option 3	45.347	2.450

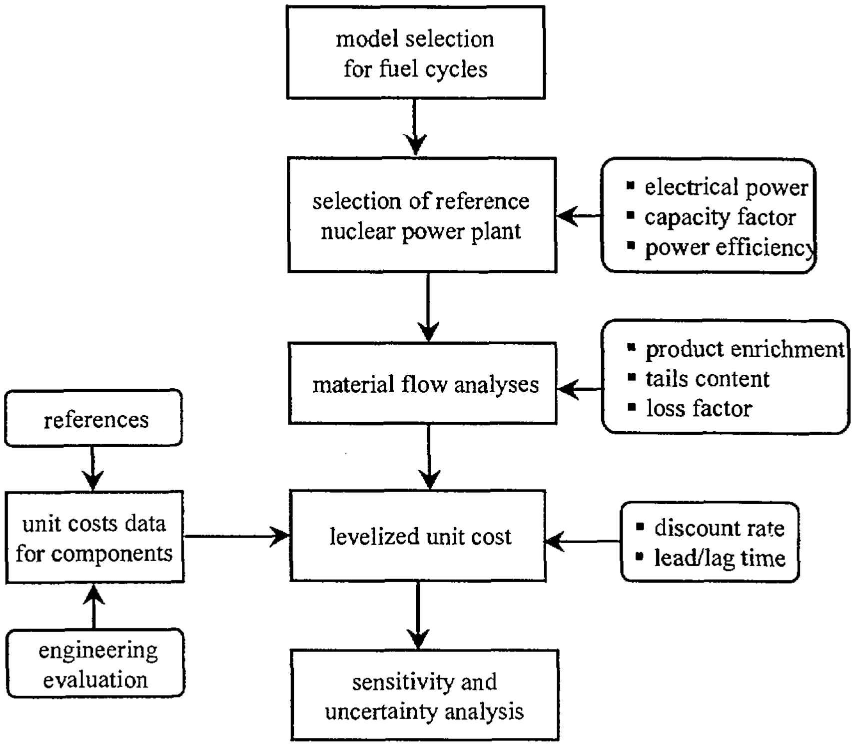


Fig. 5.1 Procedure of the Cost Analysis for the DUPIC Fuel Cycle

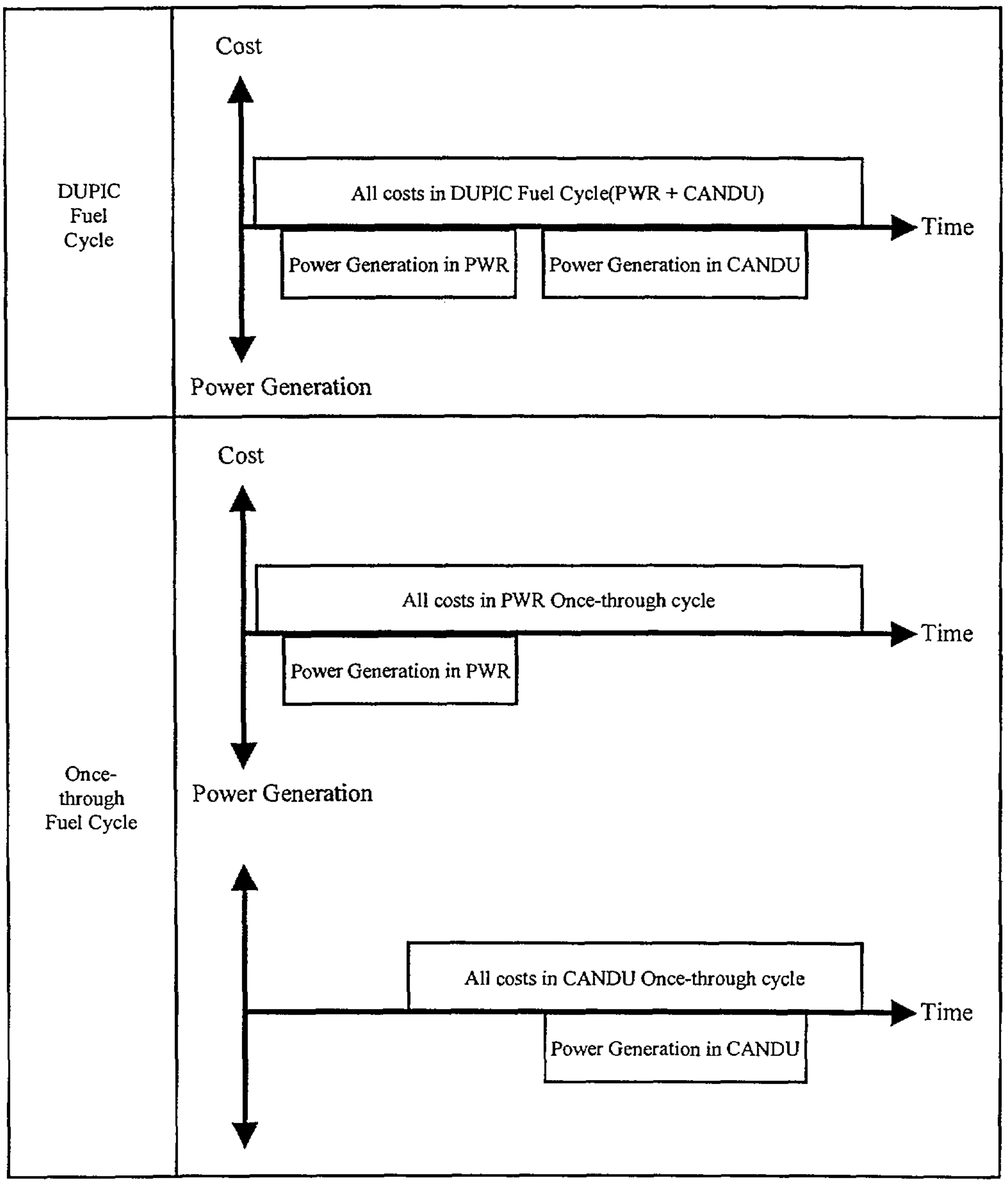


Fig. 5.2 DUPIC Fuel Cycle Cost Model

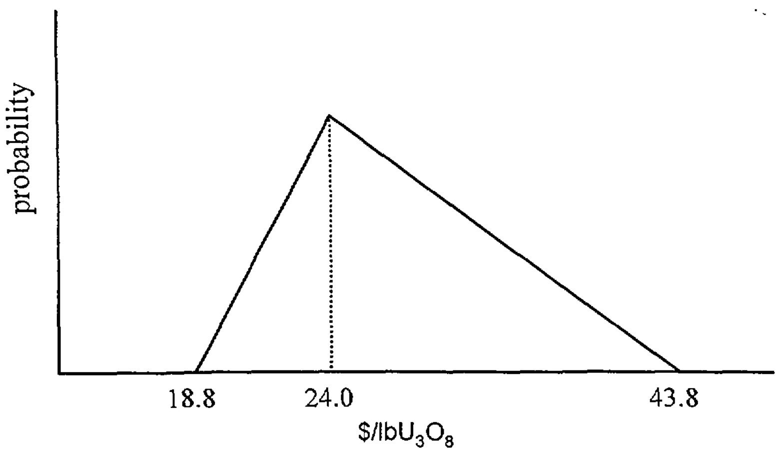


Fig. 5.3 Triangular Distribution Function of Uranium Cost with Minimum=18.8, Mode=24.0 and Maximum=43.8$/kg

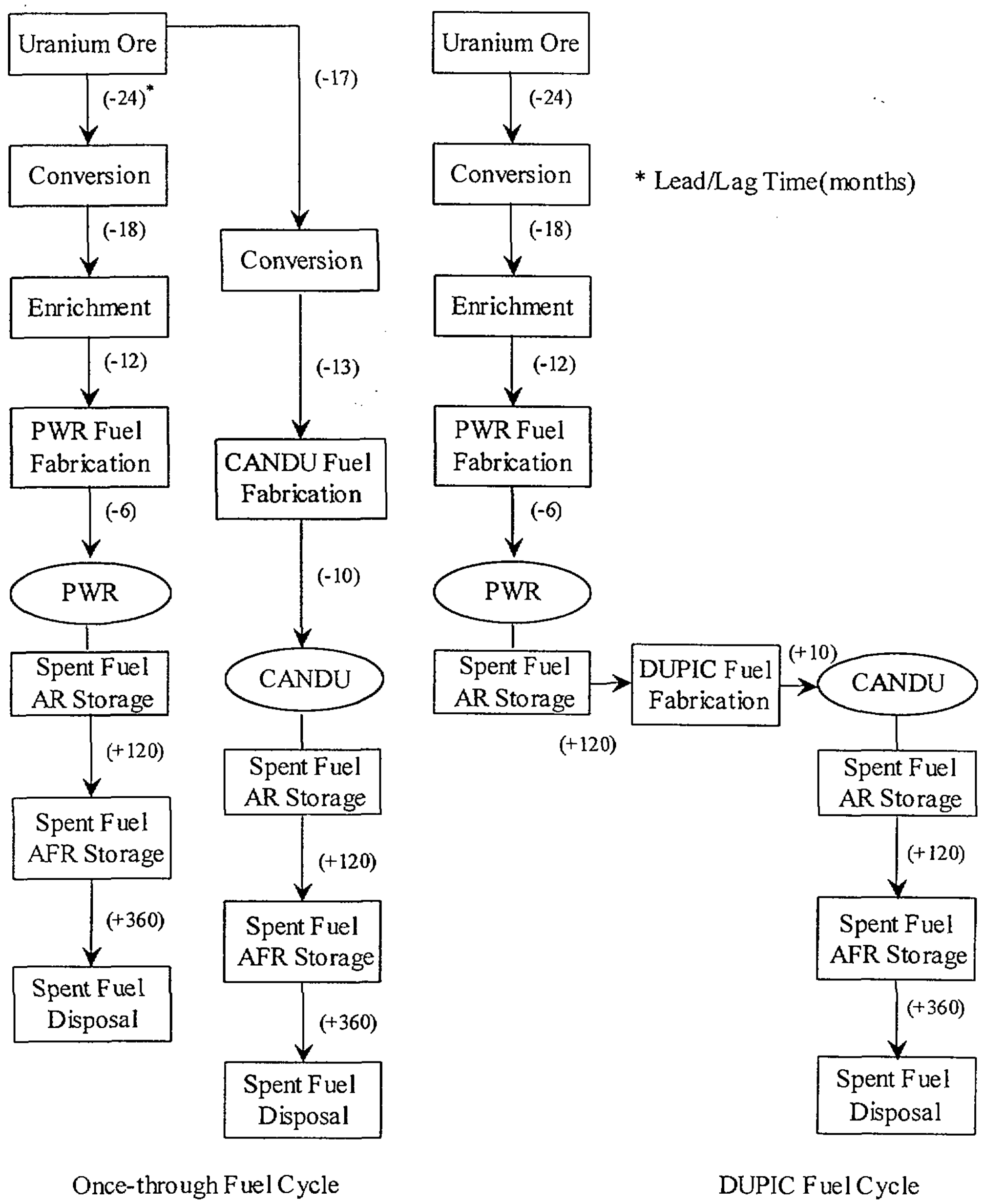


Fig. 5.4 Components and Time Frame of Once-through and DUPIC Fuel Cycles

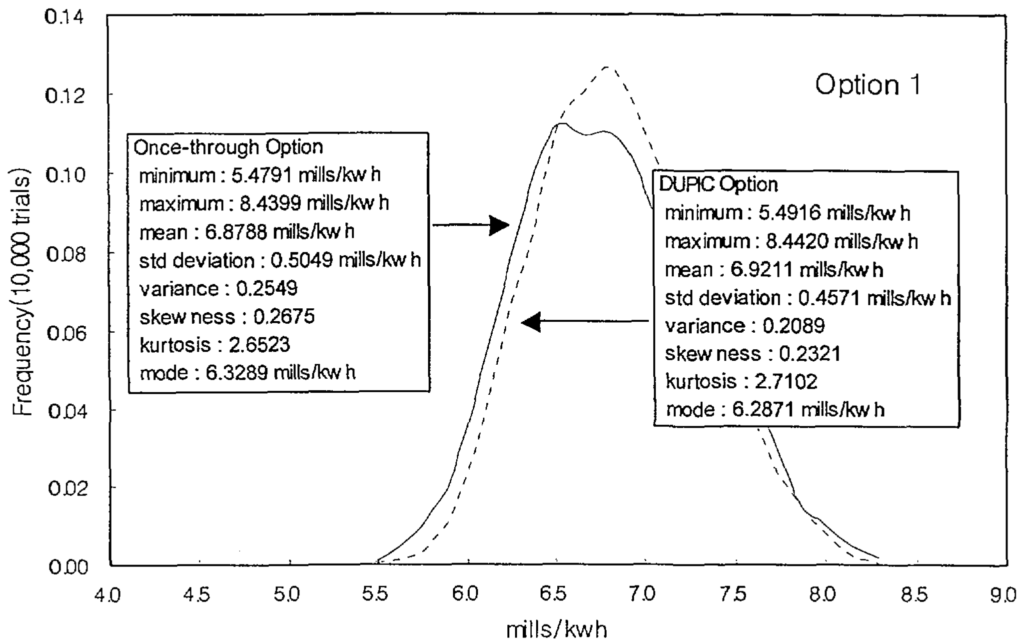


Fig. 5.5 Comparison of Probabilistic Density Function of Fuel Cycle Cost for Option 1

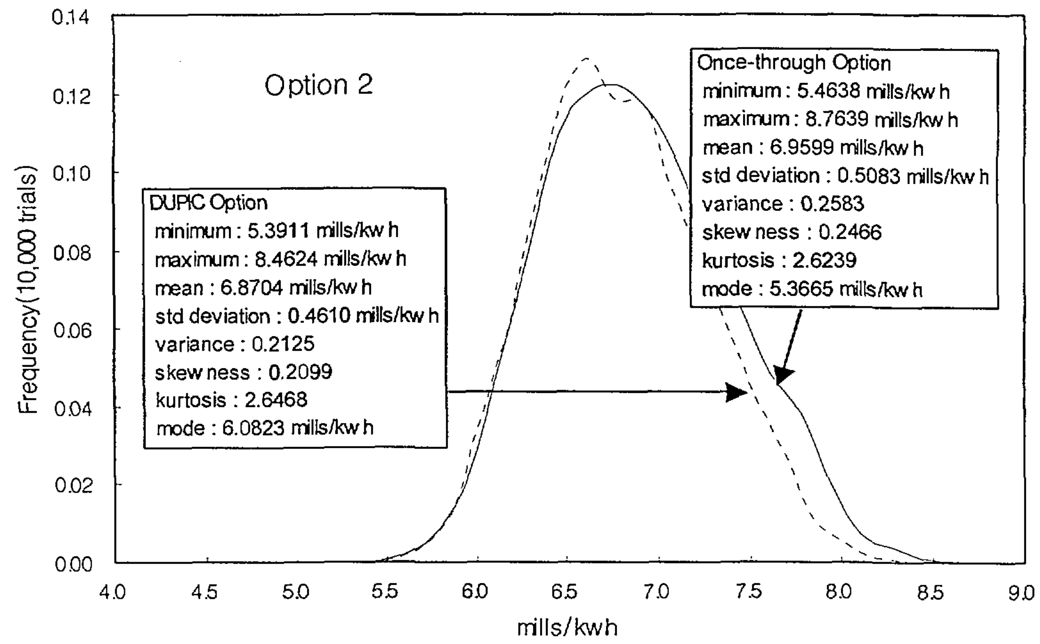


Fig. 5.6 Comparison of Probabilistic Density Function of Fuel Cycle Cost Option 2

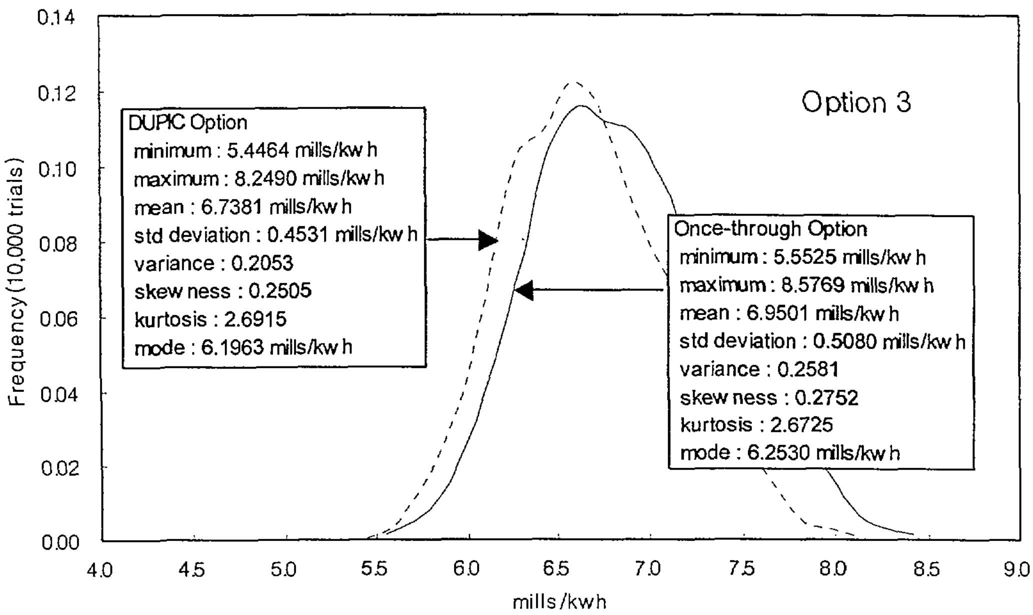
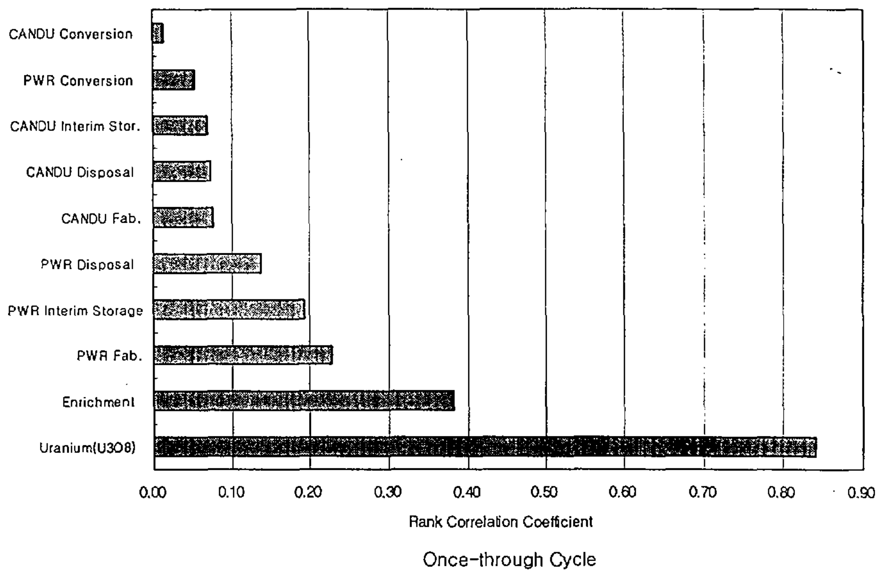


Fig. 5.7 Comparison of Probabilistic Density Function of Fuel Cycle Cost for Option 3



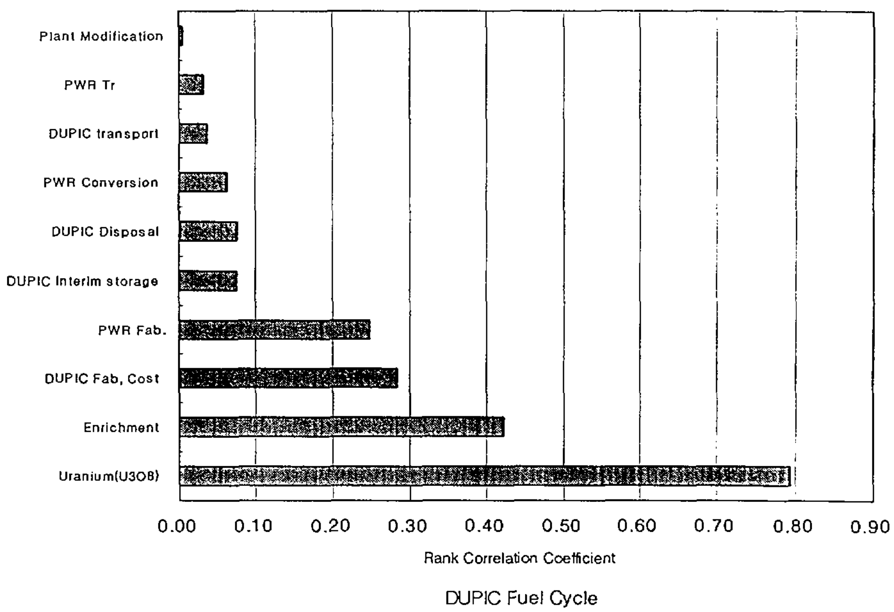
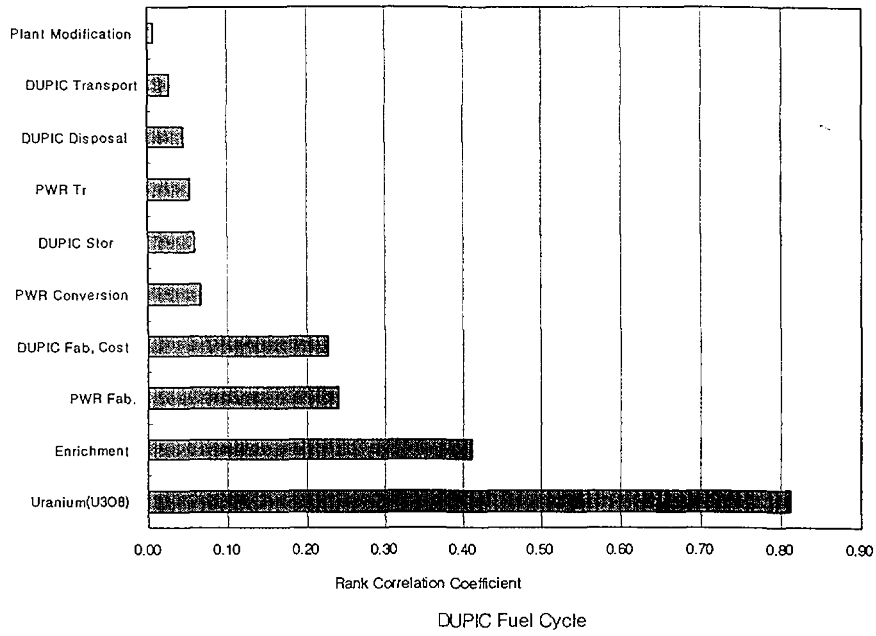


Fig. 5.8 Sensitivity Calculation for Option 1



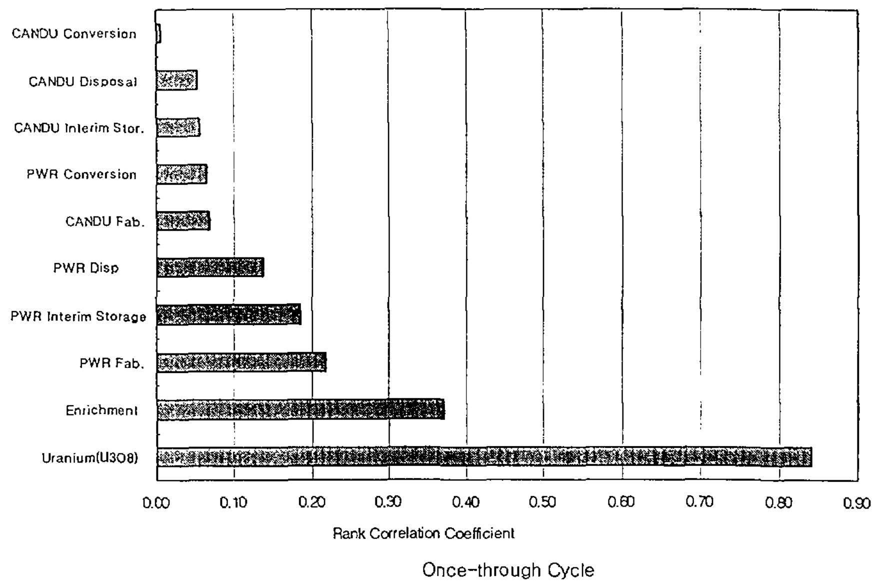
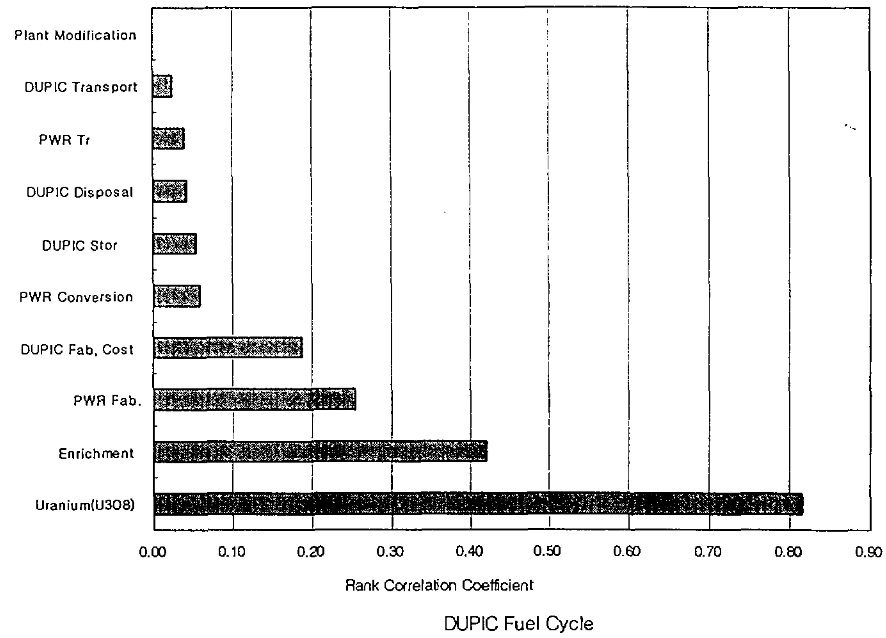


Fig. 5.9 Sensitivity Calculation for Option 2



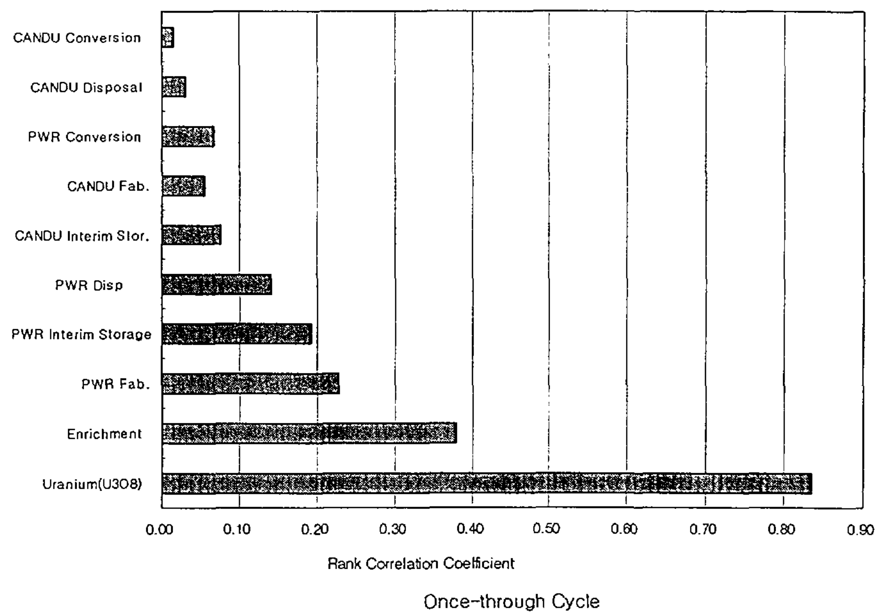
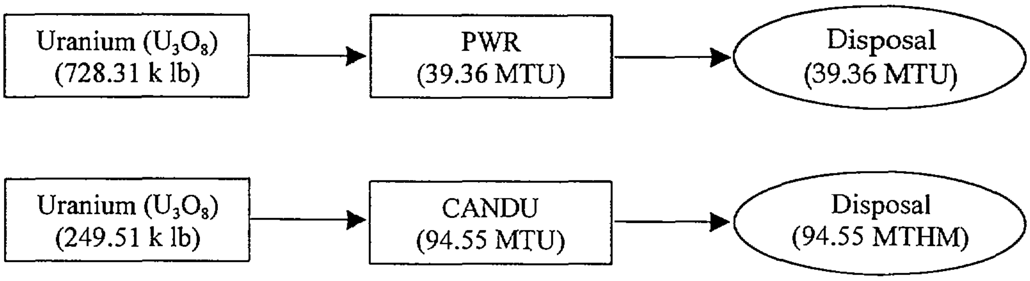
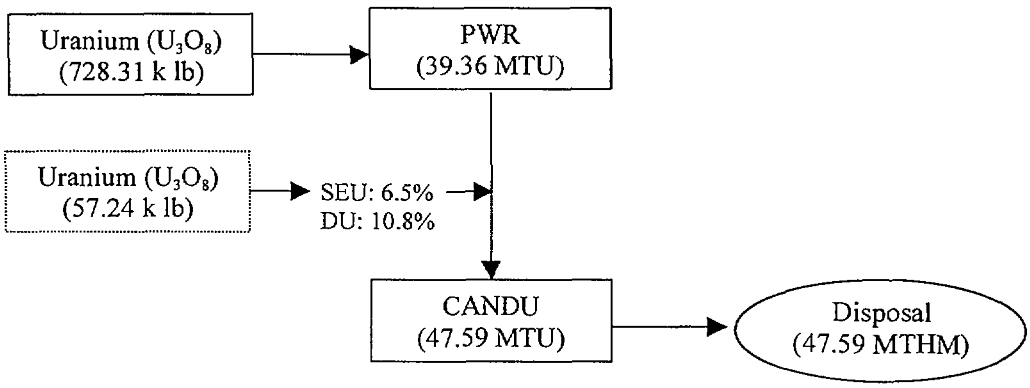


Fig. 5.10 Sensitivity Calculation for Option 3



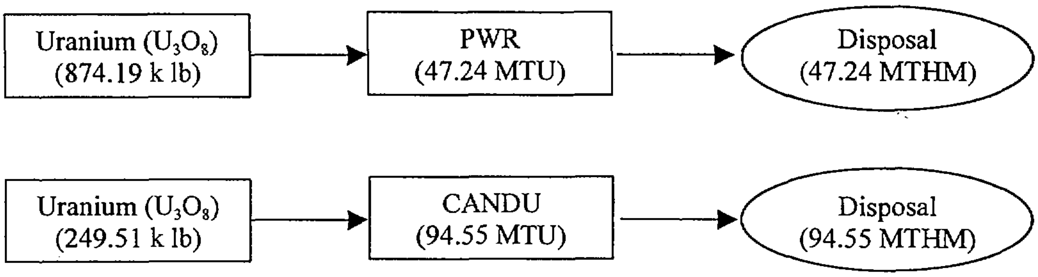
(Once-Through Fuel Cycle)



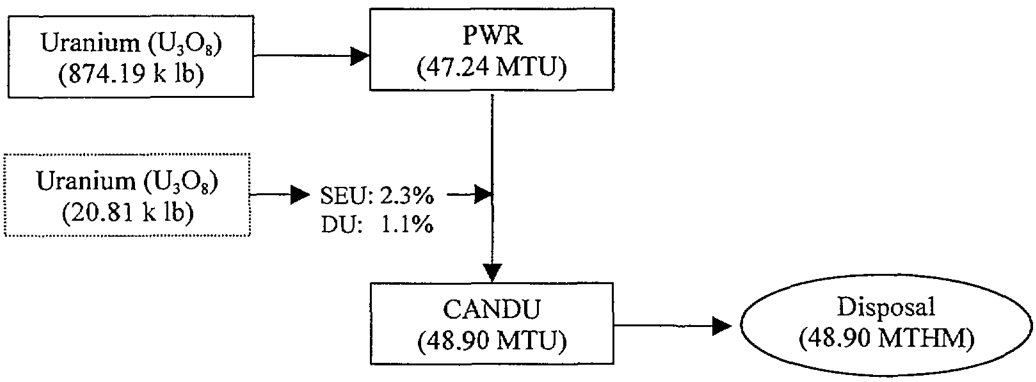
Equilibrium core ratio = 1.70
Uranium saving rate of DUPIC fuel cycle: 19.7%
Disposal reduction rate of DUPIC fuel cycle: 64.5%

(DUPIC Fuel Cycle)

Fig. 5.11 Natural Uranium Saving and Disposal Reduction Analysis for DUPIC Fuel Option 1 (based on the annual requirement of a CANDU reactor)



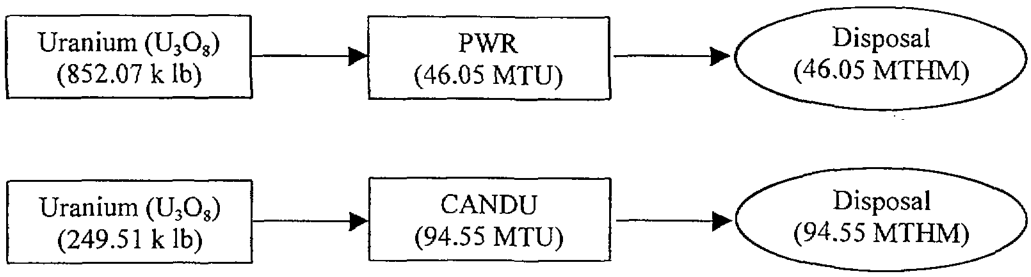
(Once-Through Fuel Cycle)



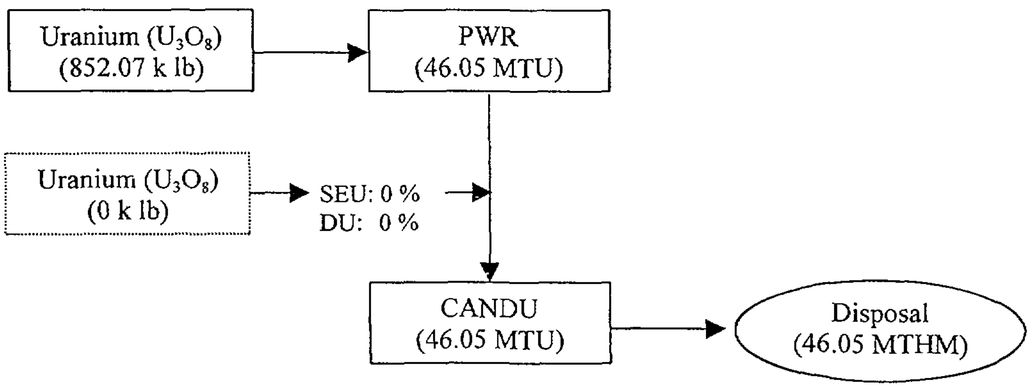
Equilibrium core ratio = 2.04
Uranium saving rate of DUPIC fuel cycle: 20.04%
Disposal reduction rate of DUPIC fuel cycle: 65.5%

(DUPIC Fuel Cycle)

Fig. 5.12 Natural Uranium Saving and Disposal Reduction Analysis for DUPIC Fuel Option 2 (based on the annual requirement of a CANDU reactor)



(Once-Through Fuel Cycle)



Equilibrium core ratio = 1.99
Uranium saving rate of DUPIC fuel cycle: 22.7%
Disposal reduction rate of DUPIC fuel cycle: 67.2%

(DUPIC Fuel Cycle)

Fig. 5.13 Natural Uranium Saving and Disposal Reduction Analysis for DUPIC Fuel Option 3 (based on the annual requirement of a CANDU reactor)

6. SUMMARY AND CONCLUSIONS

The economics of the DUPIC fuel cycle, in comparison with that of the once-through fuel cycle, has been comprehensively analyzed in this study. This study has distinctive features from the previous DUPIC economic analysis works as follows:

- Engineering analyses on DUPIC fuel handling system in a CANDU reactor were carried out and the handling costs were newly included in the DUPIC fuel cycle cost analyses.
- By considering reference DUPIC fuel options which use slightly enriched uranium during DUPIC fuel fabrication, DUPIC fuel fabrication costs were re-evaluated.
- Disposal costs were more realistically evaluated through a simple engineering analysis considering key parameters of the disposal cost estimation.
- All component costs included in the nuclear fuel cycle were recalculated based on December 1999 with an appropriate escalation rate.
- Uncertainty of each fuel cycle cost was also evaluated by introducing a probabilistic simulation technique.

Therefore, the results of this economic analysis should be more accurate and updated compared with the previous one. The levelized unit costs of the DUPIC fuel fabrication were estimated to be 683.4, 640.3 and 616 $/kgHE for fuel options 1, 2 and 3, respectively, as of December 1999. These values are much higher than previous one of 558 $/kgHE obtained from 1995's study. Based on the conceptual design study on DUPIC fuel handling, the capital cost for DUPIC fuel handling and extra storage cooling was estimated to be $ 3,750,000 (as of December, 1999) per plant. The levelized unit cost, based on the amount of fuel required during the life-time of a plant, was estimated to be 5.0-5.3 $/kgHM. The disposal costs have been estimated based on the engineering design of a disposal facility by AECL. The estimated disposal unit costs for spent PWR, CANDU natural uranium, and CANDU-DUPIC fuels are 617, 189, and 343 $/kgHE, respectively. In addition, the environmental benefit of the DUPIC fuel cycle was examined in terms of the amount of spent fuel and fresh uranium feed.

From the fuel cycle cost analysis considering aforementioned features and component costs, it is concluded that:

- For DUPIC fuel option 1, which is considered to be the first priority, deterministic calculations have shown that the fuel cycle costs are 6.721 and 6.764 mills/kWh for the

DUPIC and once-through fuel cycle, respectively.

- For DUPIC fuel option 2, the fuel cycle costs are 6.656 and 6.840 mills/kWh for the DUPIC and once-through fuel cycle, respectively. For DUPIC fuel option 3, which does not use SEU during the DUPIC fuel fabrication, the fuel cycle costs are 6.546 and 6.830 mills/kWh for the DUPIC and once-through fuel cycle, respectively.

- These results indicate that the DUPIC fuel cycle could has the economic competitiveness compared with the once-through fuel cycle, if the SEU is not used too much during the DUPIC fuel fabrication. However, the cost difference between the DUPIC and once-through fuel cycle is very small and negligible.

- From the uncertainty analysis of the fuel cycle cost by a probabilistic method, it is indicated that the fuel cycle costs of fuel option 1 are 6.921±0.46 and 6.879±0.50 mills/kWh for the DUPIC and once-through cycle, respectively. For fuel option 2, the fuel cycle costs are 6.870±0.46 and 6.96±0.51 mills/kWh for the DUPIC and once-through fuel cycle, respectively. For fuel option 3, the fuel cycle costs are 6.738±0.45 and 6.950±0.51 mills/kWh for the DUPIC and once-through fuel cycle, respectively. On the whole, the difference of the fuel cycle cost between the once-through and DUPIC cycle is within the uncertainty range (one standard deviation) of the fuel cycle cost and, therefore, has no significance.

- From the sensitivity analysis of nuclear fuel cycle costs, it can be concluded that the components in the front-end are generally more sensitive than those in the back-end. The uranium price is the most important factor among all fuel cycle components. On the other hand, the plant modification cost for the DUPIC option is the smallest factor among all fuel cycle components.

- The environmental effect analysis has shown that the DUPIC fuel cycle can have ~20% uranium saving compared with the once-through fuel cycle. In addition, the DUPIC fuel cycle can achieve the spent fuel reduction up to 67% compared with the once-through fuel cycle. Therefore, the DUPIC fuel cycle has a great potential benefit of natural resources saving and environmental protection.

7. FUTURE WORKS AND RECOMMENDATIONS

Though this study has used recent information as much as possible and focused on reducing uncertainties embedded in the fuel cycle cost, it is true that there could be large uncertainties remained in the cost estimation. Therefore it is recommended that further works should be emphasized on the efforts to reduce the uncertainty and estimate more accurate costs. In addition, it would be necessary to find out ways to decrease the DUPIC fuel cycle cost more so that the DUPIC option possesses a definite advantage over the once-through fuel cycle option, even when the current uncertainty level of ~0.51 mills/kWh is included.

For the method to decrease the uncertainty, it is recommended to consider following items:

- For fuel cycle components with large uncertainties such as transportation, disposal and fabrication costs, higher level engineering works are needed to decrease the uncertainty.
- More accurate uranium price (U_3O_8), which is the most important factor among all fuel cycle components, has to be forecasted in the future.
- Uncertainty values (the minimum and maximum values in the triangular distribution) used in this study are mostly referred from the OECD/NEA report published in 1993. This report is relatively aged now and, therefore, there is a necessity to re-estimate the boundary values considering up-to-dated information.

As potential options to decrease the DUPIC fuel cycle cost, it is suggested to consider following options in the future:

- The DUPIC fuel fabrication cost may be decreased through a design optimization such as the cost-effect analysis. In addition, the DUPIC fuel fabrication cost could be decreased by introducing a new process such as vibropacking technique even though it has not been demonstrated for the DUPIC fuel.
- Reuse of spent DUPIC fuel in a CANDU reactor could improve the DUPIC fuel cycle economics because the amount of spent DUPIC fuel is decreased. In this case, however, there is a possibility that the DUPIC fuel fabrication cost increases a little because enriched uranium is fed continuously during the fabrication process.
- In this study, the DUPIC fuel fabrication plant is assumed to be a stand-alone facility. If the fabrication plant is located near to other facilities such as the interim storage, disposal facility or existing nuclear complex, the unit cost of the DUPIC fuel fabrication plant could

be decreased. In this case, spent fuel transportation cost will be saved too.

In order to determine an option for the back-end of the nuclear fuel cycle in a country, an integrated analysis considering the environmental impact, public acceptance, security of energy and proliferation-resistance as well as economics will be needed. It is strongly recommended that the integrated evaluation of the fuel cycle alternatives is performed in the near future.

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서 지 정 보 양 식

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초록 (15-20줄내외)

DUPIC 핵연료 주기의 경제성 여부를 판단하기 위하여 DUPIC 핵연료 주기 및 직접처분주기에 대한 비용 평가가 수행되었다. 주기 부문들에 대한 단위 비용들은 가능한 한 엔지니어링 분석을 통하여 이루어졌다. 먼저 결정론적인 방법으로 one-batch equilibrium 모델을 사용하여 비용평가가 이루어 졌으며, 또한 핵연료 주기비의 불확실성을 평가하기 위하여 확률론적 시뮬레이션 방법이 적용되었다. 결정론적인 방법으로 DUPIC 핵연료 주기 비용을 평가한 결과 6.55~6.72 mills/kWh으로 나타났으며, 직접처분 주기비는 6.76~6.83 mills/kWh으로 나타났다. DUPIC 핵연료주기는 직접처분주기 보다 약 0.04~0.28 mills/kWh 정도 경제성이 있는 것으로 나타났다. 그러나 이는 매우 미미한 차이이며, 불확실성 평가결과 주기 비용의 불확실성이 0.45~0.51 mills/kWh로 나타났기 때문에 현재 단계에서 경제성 우열을 논하기는 어려운 것으로 나타났다. 한편 핵연료 주기에 대한 환경영향을 평가한 결과 DUPIC 핵연료 주기는 직접처분주기에 비해서 천연 우라늄 소요량이 약 20% 감축되는 효과를 보였으며, 처분대상의 사용후핵연료 발생량을 약 65% 적게 발생하는 것으로 나타났다. 이는 DUPIC 핵연료 주기가 환경영향 측면에서 분명한 우위를 보이고 있음을 보여주고 있다.

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Abstract (15-20 Lines)

This study examines the economics of the DUPIC fuel cycle using unit costs of fuel cycle components estimated based on conceptual designs. The fuel cycle cost (FCC) was calculated by a deterministic method in which reference values of fuel cycle components are used. The FCC was then analyzed by a Monte Carlo simulation to get the uncertainty of the FCC associated with the unit costs of the fuel cycle components. From the deterministic analysis on the one-batch equilibrium fuel cycle model, the DUPIC FCC was estimated to be 6.55-6.72 mills/kWh for proposed DUPIC fuel options, which is a little smaller than that of the once-through FCC by 0.04-0.28 mills/kWh. Considering the uncertainty (0.45-0.51 mills/kWh) of the FCC estimated by the Monte Carlo simulation method, the cost difference between the DUPIC and once-through fuel cycle is negligible. On the other hand, the material balance calculation has shown that the DUPIC fuel cycle can save natural uranium resources by ~20% and reduce the spent fuel arising by ~65%, compared with the once-through fuel cycle. In conclusion, the DUPIC fuel cycle possesses a strong advantage over the once-through fuel cycle from the viewpoint of the environmental effect.

Subject Keywords (About 10 words)	DUPIC Fuel Cycle, Proliferation Resistance, Fuel Cycle Model