ORNL/TM-13275/V2

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FMDP REACTOR ALTERNATIVE SUMMARY REPORT

VOL. 2—CANDU HEAVY WATER REACTOR ALTERNATIVE

Reactor Alternative Team
Fissile Materials Disposition Program

OAK RIDGE NATIONAL LABORATORY

LOCKHEED MARTIN

MANAGED AND OPERATED BY
LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL-27 (3-96)

ORNL/TM-13275/V2
Dist. Category UC-523

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Date Published: September 1996

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U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-96OR22464

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Acronyms and Abbreviations

ABB-CE	Asea Brown Boveri–Combustion Engineering
ABWR	advanced boiling water reactor
AE	architect-engineer
AEA	Atomic Energy Act of 1954
AECB	Canadian Atomic Energy Control Board
AECL	Atomic Energy of Canada, Limited
AFI	allowance for indeterminates
ALARA	as low as reasonably achievable
ANL	Argonne National Laboratory
ARIES	Advanced Recovery and Integrated Extraction System
ASLB	Atomic Safety Licensing Board
B&W	Babcock & Wilcox
BAPL	Bettis Atomic Power Laboratory
BNFL	British Nuclear Fuels, Limited
BNL	Brookhaven National Laboratory
BNPD	Bruce Nuclear Power Development
BOP	balance-of-plant
BWR	boiling-water reactor
CANDU	Canadian deuterium-uranium reactor
CDM	core discharge monitor
CFR	*Code of Federal Regulations*
CHF	critical heat flux
Ci	curie
CRNL	Chalk River Nuclear Laboratory
CRWMS	Civilian Radioactive Waste Management System
C/S	containment and surveillance
D&D	decontamination and decommissioning
DNA	Defense Nuclear Agency
DNFSB	Defense Nuclear Facilities Safety Board
DoD	Department of Defense
DOE	Department of Energy
DOE/MD	Department of Energy Office of Fissile Materials Disposition
DOE-NE	Department of Energy Office of Nuclear Energy
DOT	Department of Transportation
DP	Defense Program
DSC	dry shielded canister
DUI	direct-use irradiated
DUU	direct-use unirradiated
EC	estimated cost
ECIS	Emergency Coolant Injection System
EFADS	emergency filtered air discharge system
EIA	Energy Information Agency
EIS	Environmental Impact Statement

ELWR	evolutionary light-water reactor
EPA	Environmental Protection Agency
EPA	Energy Policy Act of 1992
ER	Environment Report
ES&H	environmental, safety, and health
EURATOM	European Community's Safeguarding Agency
FDI	Fluor Daniel Incorporated
FFTF	Fast Flux Test Facility
FMDP	Fissile Materials Disposition Program
FMEF	Fuel and Material Examination Facility
FPD	full-power day
FSU	Former Soviet Union
FTE	full-time equivalent (manpower measure)
G&A	general and administrative
GA	General Atomic
GE	General Electric
GJPO	Grand Junction Project Office
GoCo	government-owned contractor-operated
HEPA	high-efficiency particulate air
HEU	highly enriched uranium
HLW	high-level waste (radioactive)
HM	heavy metal
HSM	horizontal storage module
HWR	heavy water reactor
HYDOX	hydride/dehydride/oxidation
IAEA	International Atomic Energy Agency
ICPP	Idaho Chemical Processing Plant
INEL	Idaho National Engineering Laboratory
ISG	international safeguard
ITAAC	Inspections, Tests, and Analyses of Acceptance Criteria
ITRI	Inhalation Toxicology Research Institute
IWG	Interagency Working Group
KAPL	Knolls Atomic Power Laboratory
KD	key decision
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkley Laboratory
LCC	life cycle cost
LEHR	Laboratory for Energy-Related Health Research
LEU	low-enriched uranium
LLNL	Lawrence Livermore National Laboratory
LLW	low-level waste (radioactive)
LOCA	loss-of-coolant accident
LOECI	loss-of-emergency-coolant injection
LTA	lead test assembly
LUA	lead use assembly
LWR	light-water reactor

M&O	management and operating contractor
MAA	materials access area
MBA	material balance area
MC&A	materials control and accounting
MOU	Memorandum of Understanding
MOX	mixed oxide (plutonium plus uranium)
MT	metric ton
MTHM	metric tons heavy metal
MW	mixed waste (radioactive)
NAS	National Academy of Sciences
NATU	natural uranium
NBL	New Brunswick Laboratory
NDA	nondestructive assay
NEPA	National Environmental Policy Act of 1969
NFWMP	Nuclear Fuel Waste Management Program
NGS	nuclear generating station
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
O&M	operations and maintenance
OCRWM	Office of Civilian Radioactive Waste Management
OPC	operating-funded project cost
ORISE	Oak Ridge Institute of Science and Education
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
PA	protected area
PCV	primary containment vessel
PDD-13	Presidential Decision Directive-13, "U.S. Nonproliferation and Export Control Policy," September 27, 1993
PDR	plutonium disposition reactor
PEIS	Programmatic Environmental Impact Statement
PGDP	Paducah Gaseous Diffusion Plant
PHB	Putnam, Hayes, and Bartlett
PIDAS	perimeter intrusion detection and assessment system
PIE	postirradiation examination
PILT	payments-in-lieu of taxes
PSF/NSR	plutonium storage facility/new special recovery
Pu	plutonium
PuO_2	plutonium oxide
PuP	plutonium processing
PWR	pressurized-water reactor
QA	quality assurance
R&D	research and development or research and engineering development
RASR	Reactor Alternative Summary Report
RCRA	Resource Conservation and Recovery Act
RD&D	research, development, and demonstration
RFETS	Rocky Flats Environmental Technology Site

ROD	Record of Decision
RxAT	Reactor Alternative Team
S&S	safeguards and security
SAR	safety analysis report
SER	safety evaluation report
SFBC	spent fuel bundle counter
SFS	Spent Fuel Standard
SMR	security monitoring room
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
SNL-CA	Sandia National Laboratories, California Site
SNM	special nuclear material
SOR	shutoff rod
SQ	significant quantity
SRS	Savannah River Site
SST	safe, secure trailer
START	Strategic Arms Reduction Treaty
T&PD	Transportation and Packaging Department
TEC	total estimated cost
TID	tamper indicating device
TLCC	total life cycle costing
TPC	total project cost
TRU	transuranic waste (radioactive)
TSD	Transportation Safeguards Division
TSR	technical summary report
U	uranium
UO_2	uranium oxide
URL	underground research laboratory
VA	vital area
WIPP	Waste Isolation Pilot Plant (Carlsbad, NM)
WSRC	Westinghouse Savannah River Company

1. Introduction

Significant quantities of weapons-usable fissile materials [primarily plutonium and highly enriched uranium (HEU)] have become surplus to national defense needs both in the United States and Russia. These stocks of fissile materials pose significant dangers to national and international security. The dangers exist not only in the potential proliferation of nuclear weapons but also in the potential for environmental, safety, and health (ES&H) consequences if surplus fissile materials are not properly managed.

1.1 Weapons-Usable Plutonium Inventories—A Cold War Legacy

The first and second Strategic Arms Reductions Treaties (START I and START II) call for deep reductions in the strategic nuclear forces of both the United States and the former Soviet Union. In addition, in the aftermath of the Cold War, both the United States and Russia have initiated unilateral steps to increase the pace of strategic disarmament. Under START I and II and subsequent unilateral initiatives, some 10,000 to 20,000 warheads in the United States (and a similar or greater number in the former Soviet Union) could possibly be declared "surplus" to national security needs. Thus, significant quantities of weapons-usable fissile materials have or will become surplus to national defense needs both in the United States and Russia.

1.2 Recent Developments

In September 1993, President Clinton issued the U.S. Nonproliferation and Export Control Policy[1] that commits the United States to undertake a comprehensive management approach to the growing accumulation of fissile materials from dismantled nuclear weapons. This policy directs that the United States will:

- *Seek to eliminate, where possible, accumulation of stockpiles of highly enriched uranium or plutonium, and to ensure that where these materials already exist they are subject to the highest standards of safety, security, and international accountability.*

- *Initiate a comprehensive review of long-term options for plutonium disposition, taking into account technical, nonproliferation, environmental, budgetary and economic considerations. Russia and other nations with relevant interests and experience will be invited to participate in the study.*

Further, in January 1994, President Clinton and Russia's President Yeltsin issued a *Joint Statement Between the United States and Russia on Nonproliferation of Weapons of Mass Destruction and Means of their Delivery*. In accordance with these policies, the focus of the U.S. nonproliferation efforts is fivefold: to secure nuclear materials in the former Soviet Union; to ensure safe, secure, long-term storage and disposition of surplus fissile materials; to establish transparent and irreversible nuclear reductions; to strengthen the nuclear nonproliferation regime; and to control nuclear exports.

To demonstrate the U.S. commitment to the five objectives articulated in the Joint Statement, President Clinton announced on March 1, 1995, that 200 metric tons (MT) of U.S. fissile materials (~38.2 MT of which is weapons-grade plutonium) had been declared surplus to the U.S. nuclear defense needs.[2] In addition, it is anticipated that several metric tons of reactor-grade material containing weapons-usable plutonium will be declared surplus in the future. Thus, it appears that ~50 MT of weapons-usable plutonium will become surplus to U.S. defense needs.

1.3 The Danger Posed by Surplus Plutonium Inventories

In its 1994 study, *Management and Disposition of Excess Weapons Plutonium*,[3] the National Academy of Sciences (NAS) stated, "*The existence of this surplus material constitutes a clear and present danger to national and international security.*" In many respects, the nuclear threat posed by this material is now more diffuse, harder to manage, and more dangerous than the nuclear tensions of the Cold War era. The international community is concerned about the adequacy of safeguards and security (S&S) of this material, the dangers associated with the potential proliferation of nuclear weapons, and the potential for ES&H consequences if surplus fissile materials are not managed properly. In a Joint Declaration from the Moscow Nuclear Safety Summit,[4] the leaders of the seven largest industrial countries and the Russian Federation endorsed the need to render surplus plutonium as

proliferation-resistant as possible in Russia and the United States.

In June 1994, the Department of Energy (DOE) issued a Notice of Intent to prepare a "Programmatic Environmental Impact Statement (PEIS) for Long-Term Storage and Disposition of Weapons-Usable Fissile Materials," and to issue a Record of Decision (ROD) regarding long-term storage and disposition of weapons-usable fissile materials. The primary goal of disposition is to render weapons-usable fissile materials inaccessible and unattractive for weapons use while protecting human health and the environment. In its 1994 report, the NAS recommended that plutonium disposition strategies endeavor to attain the "Spent Fuel Standard" (SFS). The NAS defined the SFS as follows:

> *We believe that options for the long-term disposition of weapons plutonium should seek to meet a "spent fuel standard"—that is, to make this plutonium roughly as inaccessible for weapons use as the much larger and growing quantity of plutonium that exists in spent fuel from commercial reactors.*[3]

DOE has subsequently revised the SFS definition:

> *. . . make the plutonium as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in the spent fuel from commercial reactors.*

The enhanced SFS makes explicit the concepts of material attractiveness and potential use in weapons that were implicit in the NAS definition.

The SFS does not imply that conversion of the plutonium to spent nuclear fuel (SNF) is the only way to achieve the SFS, but rather that approaches should effect an equivalent level of proliferation resistance.

Thus, achieving the SFS provides increased proliferation resistance by transforming surplus fissile materials into a less accessible form; it leads to decreased reliance on institutional barriers to protect the material from theft or diversion.

1.4 DOE's Role in Plutonium Disposition

Following President Clinton's September 1993 nonproliferation policy announcement, an Interagency Working Group (IWG) was established to conduct a comprehensive review of the options for disposition of surplus plutonium from nuclear weapons activities of the United States and the former Soviet Union. The IWG is cochaired by the White House Office of Science and Technology Policy and the National Security Council. In response to the President's nonproliferation policy, Secretary O'Leary created a department-wide project for control and disposition of surplus fissile materials on January 24, 1994. Later that year, this project became the DOE Office of Fissile Materials Disposition (DOE/MD). DOE has a lead role within the IWG for evaluating technical options and developing analyses of economic, schedule, environmental, and other aspects of potential disposition options.

"...make the plutonium as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in the spent fuel from commercial reactors."

Figure 1.1 is a simplified illustration of the overall fissile materials disposition decision process. The purpose of the process is to provide an orderly analysis of potential alternatives for plutonium disposition as input to the ROD. The detailed evaluation consists of a thorough assessment of the reasonable alternatives to be presented in the PEIS, along with a parallel, two-step process that includes technical, economic, and nonproliferation analyses. This will determine preferred alternatives and will ultimately support the ROD.

The screening process, the first step in implementing the president's September 1993 nonproliferation policy, was completed in March 1995 with the publication of DOE's Summary Report of the Screening Process. That report summarized the results of a preliminary screening process conducted to identify a spectrum of reasonable alternatives for long-term storage and disposition of surplus weapons-usable materials (plutonium, HEU, and ^{233}U). Thirty-five alternatives for plutonium disposition were considered in the screening analysis. Sixteen of these

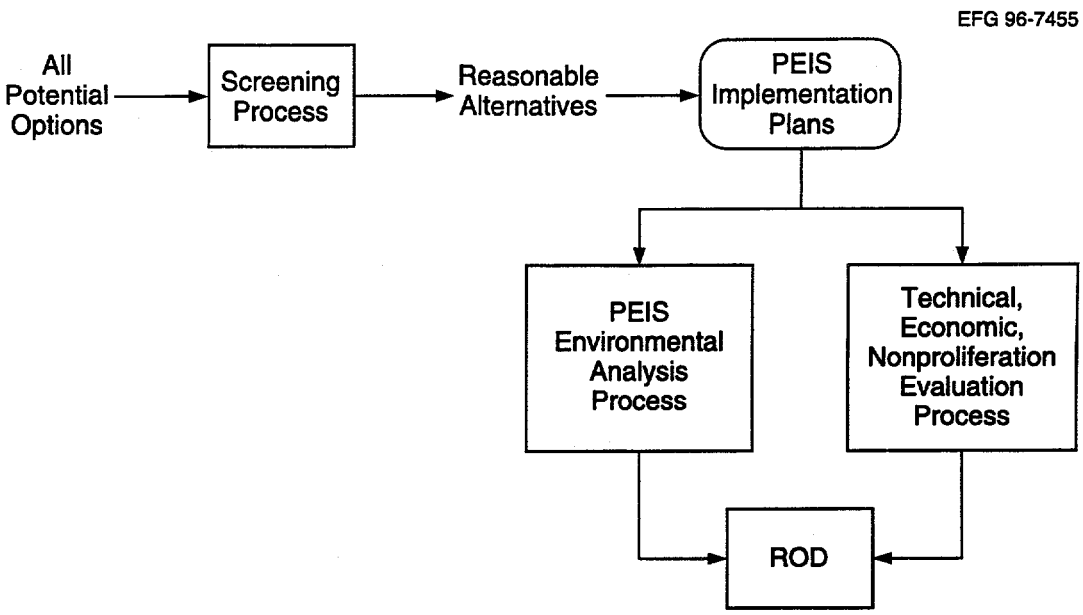


Figure 1.1. Fissile Materials Disposition Program (FMDP) ROD process

alternatives involved the use of uranium/plutonium mixed-oxide (MOX) fuel in nuclear reactors to convert the plutonium to a form similar to that contained in commercial spent nuclear reactor fuel.

Five of the reactor-based plutonium disposition alternatives, two borehole alternatives, and four immobilization alternatives were ultimately selected as reasonable plutonium disposition alternatives for further evaluation in the PEIS and detailed technical, economic, and nonproliferation evaluations. The five reactor-based plutonium disposition alternatives are existing light-water reactors (LWRs) [pressurized-water reactors (PWRs) and boiling-water reactors (BWRs)], the Canadian deuterium-uranium (CANDU) heavy water reactors (HWRs), partially complete LWRs (PCLWRs), evolutionary LWRs (ELWRs), and EuroMOX (an alternative in which PuO_2 is transported to Europe, fabricated into MOX fuel in European MOX fuel fabrication facilities, irradiated in commercial European reactors, and emplaced in European HLW repositories).

Surplus plutonium currently exists in a variety of forms: "pits" from dismantled nuclear weapons, pure and impure metal, pure and impure plutonium oxide (PuO_2), alloys, unirradiated reactor fuels, and PuO_2 and uranium oxide (UO_2) materials. A reactor-based plutonium disposition alternative is defined as the entire sequence of processes and facilities necessary for conversion of stable, stored, weapons-usable plutonium forms into MOX fuel, irradiation conversion of the plutonium to a form similar to that in existing commercial spent nuclear fuel via nuclear reactors, and the geologic emplacement of the spent fuel from the reactors (Fig. 1.2). The MOX fabrication and reactor utilization of MOX fuel are well-established, mature commercial technologies. Three commercial MOX fuel fabricators currently exist in Europe, and more than 40 commercial power reactors are licensed to utilize MOX fuel from spent fuel in Europe. Reactor-based disposition of plutonium requires no new or novel technologies or processes and involves no major technical risks.

1.5 Purpose of This Report

Following the screening process, DOE/MD, via its national laboratories, initiated a more detailed analysis activity to further evaluate each of the ten plutonium disposition alternatives that survived the screening process. Three "Alternative Teams," chartered by DOE and composed of technical experts from across the DOE national laboratory complex, conducted these analyses. One team was chartered for each of the major disposition classes (borehole, immobilization, and reactors).

During the last year and a half, the Fissile Materials Disposition Program (FMDP) Reactor Alternative Team (RxAT) has conducted extensive analyses of the cost, schedule, technical maturity, S&S, and other

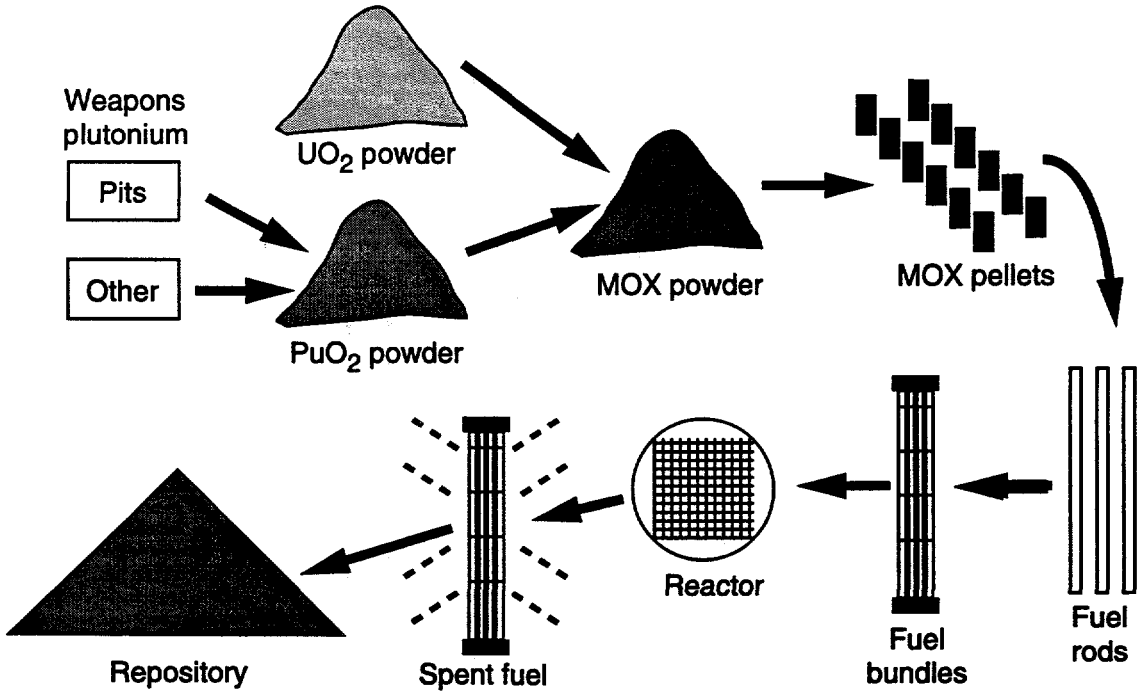


Figure 1.2. Generic reactor alternative

characteristics of reactor-based plutonium disposition. The results of the RxAT's analyses of the existing LWR, PCLWR, and ELWR alternatives are documented in Vols. 1, 3, and 4 of this report. This document (Vol. 2 of the four-volume report) summarizes the results of these analyses for the CANDU reactor-based plutonium disposition alternative.

Chapter 2 provides the results of analyses for the base case CANDU option. Licensing, construction, operations, and decontamination and decommissioning (D&D) are described for each facility. Schedule, cost, technical viability, S&S, and transportation summaries are presented for each facility following the detailed discussions.

Chapter 3 provides the results of analyses conducted for the hypothetical CANDU/immobilization "hybrid" option. Licensing, construction, operations, and D&D are described for each facility. Schedule, cost, technical viability, S&S, and transportation summaries are presented for each facility following the detailed discussions.

Chapter 4 provides a discussion of some of the benefits of using the reactor-based disposition options.

Appendixes are included to provide additional background and supporting information on the CANDU reactor alternative. Appendix A provides summary descriptions for all the reactor alternatives and variants. Appendix B presents the approach to developing the schedule information. Appendix C describes the approach to developing the cost information. Appendix D provides the approach for developing the S&S information. Appendix E includes the quantitative technical viability assessment. Appendix F describes the feed materials. Appendix G presents transportation and packaging information. A glossary is provided in Appendix H.

1.6 References

1. Presidential Decision Directive-13, "U.S. Nonproliferation and Export Control Policy," September 27, 1993.
2. DOE Openness Initiative, February 6, 1996.
3. National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, National Academy Press, 1994.
4. Joint Declaration from Moscow Nuclear Safety Summit, April 20, 1996.

2. Existing CANDU Reactor Alternative Base Case (50SFC2-4)

2.1 Introduction

The base case for the CANDU reactor alternative consists of completing plutonium processing and MOX fuel fabrication at U. S. facilities, irradiation in Canada, and disposal of the reactor fuel bundles at a Canadian repository. This base case assumes that 50 MT of plutonium are available from surplus plutonium for disposition as reactor fuel.

The top-level flow diagram, Fig. 2.1, shows the four major facilities in this alternative: the plutonium processing facility, MOX fuel fabrication facility, reactor facility, and spent fuel repository.

The plutonium processing facility is proposed to be a government-owned facility located on a site already having plutonium handling infrastructure, and the MOX fuel fabrication facility would be a government-owned, contractor-operated (GoCo) facility in an existing building located at an existing federal site. Fuel assemblies would be fabricated to Canadian specifications and packaged into fuel bundles that would be irradiated in Canadian reactors. The Canadian reactors are located at the Bruce Nuclear Generating Station (NGS) near Kincardin, Ontario. All spent fuel would be stored by the Canadians for 6 to 10 years in the spent fuel pool at the reactor site before being transferred to either a Canadian repository or dry storage. No material would be returned to the United States.

It must be understood that the power rating of the reactor chosen for the plutonium disposition mission, coupled with the reactor core design, establishes the plutonium throughput for the reactors. This value, in turn, establishes the throughput for all upstream operations.

The reactors will use reference MOX fuel containing pins with 1.6 and 3.1 wt % plutonium in two Bruce reactors for 5 years, while the testing program of an advanced fuel known as CANFLEX, which is currently under development using natural uranium, is completed. After 5 years, the reactors would transition to the new CANFLEX fuel containing pins with 2.6 and 4.6 wt % plutonium. Four Bruce reactors would then be used for irradiation. Loading of fresh

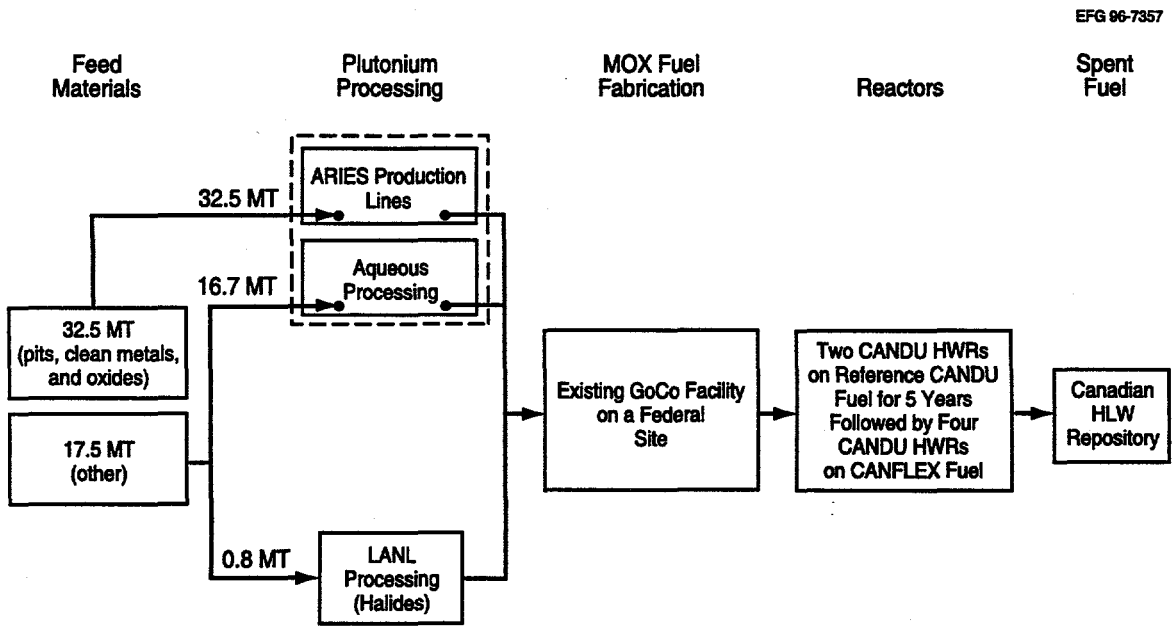


Figure 2.1. 50-MT base case plutonium disposition flow diagram

CANFLEX fuel to the reactors would continue for an additional 7.2 years or until completion of the inventory of PuO_2 available for reactor disposition.*

Only two CANDU reactors are used with the initial reference fuel because the heavy metal throughput required from the MOX fuel fabrication facility for additional reactors would make the MOX facility uneconomically large. CANFLEX fuel would have higher plutonium loading than reference fuel, a much larger burnup rate, and would, therefore, allow the fuel fabrication facility to provide the fuel bundles at a more economical rate. Approximately 5 years of research and development (R&D) must be completed on CANFLEX fuel before its authorized use. This R&D will be completed while two Bruce units are operating on reference fuel.

2.1.1 Summary Description of CANDU Alternative Disposition Facilities

The following facilities are included in this alternative:

PuP Facility—It is assumed that the PuP facility is located in an existing building at an existing federal site. The plutonium pits and clean metal (~32.5 MT of plutonium) would be processed by the Advanced Recovery and Integrated Extraction System (ARIES) hydride dehydride/oxidation (HYDOX) "dry" processing procedure. The other feed material (~17.5 MT of plutonium) would be processed by an aqueous procedure. A small amount of halide-contaminated plutonium is assumed to be processed at available facilities at LANL. The end product of the PuP facility is plutonium oxide (PuO_2) that meets the specifications for feed to the MOX fuel fabrication facility. The PuP facility will be subject to external review by the Defense Nuclear Facilities Safety Board (DNFSB).

MOX Fuel Fabrication Facility—A federally owned MOX fuel fabrication facility located in an existing building on an existing federal site will receive the PuO_2, pin and bundle components, depleted UO_2, and additives for fabrication of MOX fuel; perform the assembly of fuel bundles; and ship the fuel to the Bruce station in Canada. This facility will be NRC licensed.

CANDU Reactors—The MOX fuel will be irradiated by two CANDU reactors for 5 years and then by four reactors for an additional 8.3 years (final fuel load plus 15 months) until it achieves the characteristics defined in the FMDP Spent Fuel Standard. When the standard is reached, the fuel will be unloaded to the spent fuel pool, bundled in racks, and stored on site for an appropriate time before being moved to the Canadian high-level waste (HLW) repository.

Canadian HLW Repository—The Canadian HLW repository will receive the spent fuel in large canisters, transfer the inner sealed canister to disposal casks, and move the casks underground for geologic emplacement.

Transportation—Plutonium will be packaged and transported from its present locations [i.e., post-DNFSB 94-1 interim storage] to a government-owned PuP facility using safe, secure trailers (SSTs) operated by the DOE Transportation Safeguards Division (TSD). Following conversion to PuO_2, SSTs will again be employed to transport the PuO_2 canisters to the MOX fuel fabrication facility. Following fabrication as MOX fuel, the fresh fuel bundles will be packaged and transported by SSTs to the Bruce station reactors. Following irradiation and a 10-year cooling time, the spent fuel will be transported to the Canadian HLW repository.

In addition to dispositioning plutonium, the FMDP is responsible for packaging and transport of all feed materials (plutonium, uranium oxide, etc.) and transport, packaging, and disposal of process waste materials from the plutonium processing and fuel fabrication facilities. Operation of the reactors and the HLW repository is not a Canadian government responsibility; both are private company responsibilities. Waste disposal for any waste streams created by the PuP and MOX fabrication facilities as well as transportation and packaging to the Canadian border are the responsibility of the U.S. government. Transportation beyond the Canadian border will be handled by the Canadian utility.

2.1.2 Description of Facility Interfaces

Multiple facilities are required for disposition of ~50 MT of excess weapons-usable plutonium as MOX fuel in CANDU reactors. Between each facility is a series of sequential movements of the plutonium from its present locations (storage vaults at a number of DOE facilities) through the various processing,

*Enhancements to this schedule and possible cost implications are discussed in Sects. 2.6.1 and 2.6.2.

fabrication, and reactor facilities, and, ultimately, emplacement as spent fuel at a Canadian HLW repository. Figure 2.2 provides a simplified flow chart of the transportation segments associated with the CANDU HWR disposition alternative. Actual facility locations will be determined by DOE following the ROD. For analysis purposes, it has been assumed that the excess plutonium is in interim storage at many locations within the DOE weapons complex. This material is first packaged and transported to a PuP facility [assumed to be located at the Savannah River Site (SRS)], where the material is converted to PuO_2. The PuO_2 is then repackaged and transported to the MOX fuel fabrication facility (assumed to be constructed in an existing building elsewhere on the SRS). Once fabricated, the fresh MOX fuel is packaged and transported across the Canadian border to the Bruce Nuclear Power Development (BNPD) site. Spent fuel discharged from each reactor is first stored in a spent fuel pool for 6 to 10 years. Ultimately, the spent fuel is packaged and transported to a Canadian HLW repository.

2.1.3 General Assumptions

- The inventory of surplus plutonium is 50 MT. Of this, 32.5 MT is from pits and clean metals, and 17.5 MT comes from other sources such as impure metals, oxides, and unirradiated reactor fuels.
- Alternatives were designed to address the entire inventory. This does not mean necessarily that all material will ultimately channel through the same set of operations, only that any alternatives had to provide a disposition path for all surplus material.
- Disposition of the plutonium will begin within ~10 years and be completed within ~25 years after the ROD.
- Authorization for initiation of the line item funding process coincides with the ROD.
- All necessary operations to implement a disposition alternative (e.g., design, construction, licensing, operations, D&D, storage, transportation, S&S, inspections, and packaging operations) from the inception of the program until disposition to the spent fuel standard must be included.

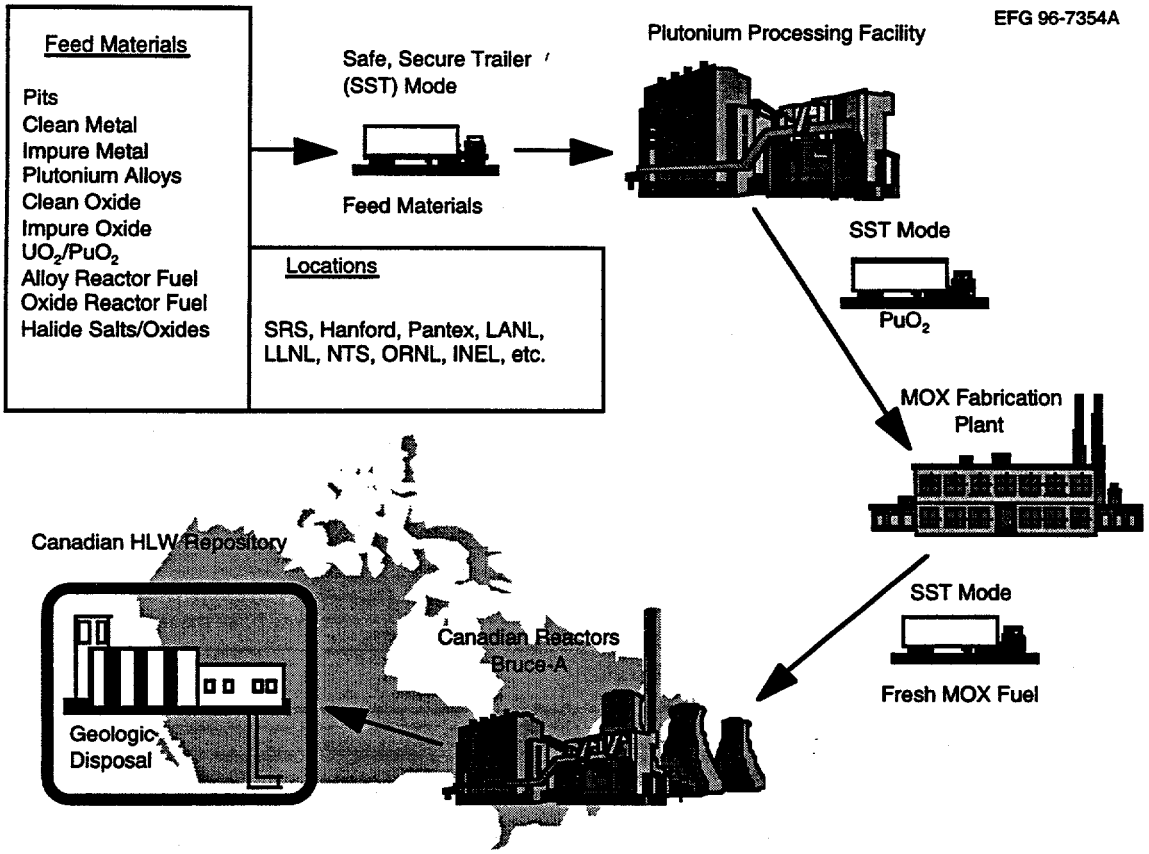


Figure 2.2. Simplified flow chart showing transportation segments for the CANDU HWR alternative

- Adequate funding will be available, when required, to support the design and construction of the chosen disposition alternatives.
- Facilities will comply with applicable U.S. federal, state, and local laws and regulations, DOE orders, and Canadian laws and regulations (as applicable).
- Schedules presume legislation is available to support implementation of the alternatives. In all cases, some legislation will be required to enable a disposition alternative to be implemented.
- Prior to disposition as reactor fuel, the plutonium must meet the *Stored Weapons Standard,* as the term was coined by the NAS, and as specified in DOE orders and guides.
- All operations involving surplus plutonium will be performed under International Atomic Energy Agency (IAEA) safeguards, except those involving classified parts, shapes, and information.
- The Waste Isolation Pilot Plant (WIPP) will be available to accept small amounts of transuranic (TRU) wastes generated in the PuP and MOX fabrication operations.
- Waste minimization and pollution control principles consistent with DOE policy will be applied in the design considerations of each technology.

2.2 PuP Facility

2.2.1 PuP Facility Description

The PuP facility receives surplus material from the various sites in the DOE complex and converts it into a form suitable for feed to the MOX fuel fabrication facility. Surplus fissile materials to be processed include pits, clean and impure metal, plutonium alloys, clean and impure oxide, uranium/plutonium oxides, unirradiated plutonium alloy reactor fuels, unirradiated oxide reactor fuels, and halide salts. Pits and clean metal will be converted to PuO_2 using the ARIES (HYDOX) process. A large fraction of the gallium will be removed, if necessary, using a thermal process; the resulting oxide will be packaged, assayed, and stored awaiting shipment to the MOX fuel fabrication facility. If thermal processing proves to be inadequate for reducing gallium concentration to acceptable levels, aqueous processing will be used. Impure oxides will be dissolved, purified using ion exchange or solvent extraction, precipitated, and calcined. The oxide product will then be packaged, assayed, and stored with the oxide from pits and clean metal. Alloy and oxide reactor fuel must be disassembled and cladding removed before processing by HYDOX and dissolution/purification, respectively.

It is assumed that the PuP facility will be located in an existing building on one of several existing federal sites. One such candidate is Building 221-F located on the SRS in the F-canyon area. Approximately 21,000 ft^2 of space has been identified that could be adapted for the plutonium disposition mission without interfering with ongoing operations. It is assumed that the 32.5 MT of pits and clean metal (throughput of 3.25 MT/year for 10 years) be processed using the ARIES (HYDOX) dry method in the present plutonium storage facility/new special recovery (PSF/NSR) area on the fifth level of Building 221-F. The aqueous equipment (gloveboxes, dissolvers, furnaces, etc.) presently housed in the PSF/NSR area would be moved to areas on the second and third levels of Building 221-F. This aqueous equipment, supplemented by some additional new equipment, would be used to process the 17.5 MT mixed feed plutonium (throughput of 1.75 MT/year for 10 years).

A small amount of halide-contaminated plutonium (about 800 kg) is assumed to be processed by specially designed aqueous chloride processing lines at existing facilities at LANL.

An additional location for possible use would be the Fuel and Material Examination Facility (FMEF) on the Hanford reservation in Washington state. This facility has ~85,000 ft^2 of space and much of the needed equipment available. It was initially designed to support the Fast Flux Test Facility (FFTF) for the production of MOX fuel. An extensive study of conversion of this facility to support the CANDU fuel fabrication process was conducted for DOE by AECL. Use of this facility for plutonium processing is equally feasible.

Additional federal sites will also be considered for the PuP facility location.

2.2.2 PuP Facility Design and Construction

2.2.2.1 PuP Facility Design and Construction Schedule

The duration and path of the design and construction tasks are based on a generic DOE Major System Acquisition–Capital Construction Project. The design and construction process will begin at ROD with the

start of the selection process for an architect-engineering (AE) firm. This contractor will be responsible for developing the required designs for the facility modification and completing these modifications. Work on the conceptual design will begin as soon as the AE contractor has been selected. The first key decision (KD-1) to start work on the Title I design will be made after the conceptual design is complete and the initial line item funding has been approved. With the approval of the Title I design (KD-2) and final line item funding, work on Title II design will begin. The facility modifications and equipment procurement start after Title II has been approved (KD-3). Equipment installation will proceed in a staged process so that the preoperational checkout of the facility will start 6 months before completion of the installation. The design and construction schedule is shown in Table 2.1 and as part of Sect. 2.2.6.

Research, development, and demonstration (RD&D) of the various PuP technologies are currently underway. The prototype phase of the ARIES process is scheduled to begin in 1998.

A 1-year site and facility selection process will begin after ROD to determine the most appropriate existing facility on a federal site for the PuP facility.

2.2.2.2 PuP Facility Design and Construction Cost

This category represents the bulk of the up-front or investment costs for the PuP facility; in government accounting it is called total estimated cost (TEC). It also represents the line item funding appropriated by Congress. In the FMDP life cycle costing format, it is covered under categories 7–12 in the table appearing in Appendix C. Research and engineering development (R&D) and other preoperational costs are discussed in Sect. 2.2.3.2.

The design and construction cost of the PuP facility is based on modifying existing facilities at a DOE site. The cost values determined for this option are specifically based on modifying Building 221 in the F-canyon area on the SRS and account for using existing equipment and infrastructure.

Table 2.1. PuP facility design and construction schedule

Task ID	Task name	Duration (months)	Start	Finish
1.	**R&D Funding Available**			10/1995
2.	**FMDP ROD**			12/1996
3.	**Congressional Funding Approval**	36	12/1996	12/1999
4.	Initial Funding Process	24	12/1996	12/1998
5.	Final Funding Approval	12	12/1998	12/1999
6.	**RD&D**	36	10/1995	9/1998
7.	**Site and Facility Selection**	12	12/1996	12/1997
11.	**Design Process**	61	12/1996	1/2002
12.	AE Selection	3	12/1996	2/1997
13.	Conceptual Design	25	3/1997	3/1999
14.	Approval of New Start (KD-1)			3/1999
15.	Title I	12	3/1999	3/2000
16.	Approval to Commence Title II (KD-2)			3/2000
17.	Title II	22	3/2000	1/2002
18.	**Facility Modification**	48	1/2002	1/2006
19.	Approval to Start Construction (KD-3)			1/2002
20.	Construction, Procurement, and Equipment Installation	48	1/2002	1/2006

The 1996 constant dollar design and construction cost for the PuP facility located in existing facilities at the SRS is summarized in Table 2.2. The cost for engineering design and inspection is estimated to be $17M. The cost for capital equipment (equipment necessary for feed materials receiving, pit processing, mixed feed processing, and equipment necessary for the facility modification) is estimated to be $34M. The estimate for direct and indirect construction necessary for site modification and update is estimated to be $32M. The sum of the cost for design and construction, plus allowances for construction management and initial spares, is $89M. An allowance for indeterminates (AFI) of $25M (27.8%) was included. A risk contingency of 50% ($56M) was included to account for the preliminary nature of the cost estimate. The total plutonium facility design and construction cost, including contingency, is $171M.

2.2.3 PuP Facility Oversight and Permitting

The licensing approach for the reactor-based plutonium disposition options is to satisfy the NAS ES&H criteria "that any disposition option to operate in the United States:

- should comply with NRC regulations governing allowable emissions of radioactivity to the environment, and allowable radiation doses to worker and the public, from civilian nuclear-energy activities;
- should comply with international agreements and standards covering the disposition of radioactive materials in the environment; and
- should not add significantly to the ES&H burdens that would be expected to arise, in the absence of the weapons-usable plutonium disposition, from appropriate management of the environmental legacy of past nuclear-weapons production and from appropriate management of the ES&H aspects of past and future nuclear-energy generation."[1]

For those operations and processes conducted in existing or converted facilities owned by DOE as planned for the PuP facility, the regulation of nuclear activities and the protection of ES&H will be conducted under DOE regulations, safety guides, technical standards, directives, and compliance agreements with the oversight of the DNFSB, the Environmental Protection Agency (EPA) where applicable, and the state within which the facility is located. For such unlicensed DOE-owned facilities, the facility will be held to a standard of nuclear safety and quality equivalent to that of a facility licensed by the NRC. The mechanism for doing this is implemented through the regulations issued under the *Price-Anderson Amendments Act of 1988* and the *Atomic Energy Act of 1954*, as amended. All permitting requirements from applicable federal statutes will apply.

National Environmental Policy Act (NEPA)—The conversion and utilization of DOE-owned facilities for the plutonium disposition mission may require additional specific NEPA actions (under 10 CFR Part 1021.400) beyond that of the PEIS.

Atomic Energy Act of 1954, as amended—Unlicensed DOE-owned facilities will be operated by qualified, responsible DOE contractors subject to the

Table 2.2. PuP facility design and construction cost

Category	Cost category description	PuP at SRS [lump sum (1996 $M)]
	Capital or TEC front-end costs:	
7	Title I, II, III engineering, design, and inspection	17
8a	Capital equipment	34
8b	Direct and indirect construction/modification	32
9	Construction management	4
10	Initial spares (technology dependent)	3
11	AFI	25
12	Risk contingency (SRS estimate)	56
	TOTAL (TEC)	$171

indemnification requirements of the *Price-Anderson Amendments Act of 1988* and therefore subject to the nuclear safety regulations issued under and the enforcement provisions of Sect. 234A of the *Atomic Energy Act of 1954*, as amended.

Applicable regulations include the DOE rules for nuclear safety and radiation protection as given in 10 CFR Parts 820, 830, 834 (draft), and 835 and for classifying certain DOE-owned nuclear materials as given in 10 CFR Part 962.

Comparability to licensed facilities will be achieved by enforcing contractually mandated compliance with appropriate safety guides and technical standards implementing the DOE regulations. These DOE technical standards are periodically reviewed and updated to be comparable to current NRC licensing requirements. Key technical standards currently applicable to plutonium operations in DOE nonreactor nuclear facilities include the following:

- DOE-STD-101-92, *Compilation of Nuclear Safety Criteria for Potential Application to DOE Nonreactor Nuclear Facilities*, March 1992;
- DOE-STD-3009-94, *Preparation Guide for U.S. DOE Nonreactor Nuclear Facility Safety Analysis Reports*, July 1994; and
- DOE-STD-3013-94, *Criteria For Safe Storage of Plutonium Metals and Oxides*, December 1994.

These DOE standards implement requirements for handling, processing and storage of special nuclear materials (SNMs) consistent with or analogous to pertinent portions of 10 CFR Parts 70, 71, 73, and 74. These DOE standards also incorporate by reference pertinent NRC technical and regulatory guidance from the Division 3 series (Fuels and Materials Facilities) and other relevant portions of the NRC regulatory guides as well as industry standards.

In this case, a clear path forward exists, and regulatory criteria and guidance are available to define an appropriate strategy and plan for satisfying DOE regulations. Transportation of SNMs to and from the PuP facility will be done in accordance with NRC regulations in 10 CFR Part 71, Department of Transportation (DOT) regulations in 49 CFR Parts 171-179, and for wastes, EPA regulations in 40 CFR Part 263.

RCRA—Plutonium disposition represents no new or special permitting situation with regard to compliance with RCRA for treatment or disposal of hazardous waste. However, as a DOE program, all facets of the plutonium disposition mission are subject to the waste minimization/pollution prevention policies of the President and the Secretary of Energy with regard to the plans required of waste generators under Sect. 3002(b) of RCRA. Such a plan will be developed and implemented consistent with EPA guidelines published in the *Federal Register*. Special attention will be directed to avoiding the accumulation of hazardous and mixed wastes (MWs) without treatment options so that exemption requests to the enforcement provisions of Sect. 3004(j) of RCRA can be avoided.

Clean Air Act and Clean Water Act—New permits may be required if existing permits cannot be amended; however, no new or unusual permitting situations or special requirements are anticipated.

2.2.3.1 PuP Facility Oversight and Permitting Schedule

For this analysis, it has been assumed that the DNFSB oversight review will start at ROD with the site selection process and will require 5 years. The NEPA process and other site-specific permitting will require 3 years and will start after the site has been selected. The oversight and permitting schedule is shown in Table 2.3 and as a part of Sect. 2.2.6.

Table 2.3. PuP facility oversight and permitting schedule

Task ID	Task name	Duration (months)	Start	Finish
1.	**Oversight and Permitting**	60	12/1996	12/2001
2.	DNFSB Review of Existing DOE Facility	60	12/1996	12/2001
3.	Environmental/NEPA/DOE	36	12/1997	12/2000

2.2.3.2 PuP Facility Operation-Funded Project Cost

This section will cover life cycle cost categories 1–6 in the 24-category estimating format described in Appendix C. These six categories constitute what is termed preoperational or operation-funded project cost (OPC) in government accounting. OPC is the portion of the total project cost [(TPC) investment, or up-front cost] budgeted with operating dollars rather than congressional line item capital or TEC dollars. Because this facility is likely to be government owned and funded, this distinction is important.

OPC generally includes the majority of the preconstruction activities and many of the startup activities carried on by the operating contractor prior to full-capacity operation of the facility and after construction is complete. As seen in Table 2.4, oversight and permitting is just one of several needed cost centers.

All preoperational costs, including cost for oversight, are discussed in this section. These costs are consistent with siting the PuP facility in an existing facility (Building 221-F) on the SRS, as discussed in Sect. 2.2.1. The preoperational costs are summarized in Table 2.4.

The cost for R&D is estimated to be $81M, which includes the necessary R&D at Savannah River and $41M for continued R&D at LANL for ARIES. The cost for NEPA, oversight, and permitting is estimated to be $6M. The conceptual design cost required for the facility modification is estimated to be $3M. Postconstruction start-up costs at the SRS are estimated to be $50M. A contingency of $10M was allowed (~10% of the total of the Savannah River portion of the R&D cost, the oversight cost, the conceptual design cost, and startup cost). The total 1996 constant dollar preoperational cost, including contingency, is $151M, as indicated in Table 2.4.

2.2.4 PuP Facility Operations

2.2.4.1 PuP Facility Shipment and Storage

The surplus plutonium feed materials will be packaged and transported from their present locations to the PuP facility where they will be converted to PuO_2. Once in oxide form the material will be repackaged and stored in vaults until it is needed by the MOX fuel fabrication facility. The PuP facility is planned to operate over a shorter period (generally 10 years), while the MOX fuel fabrication facility is planned to manufacture fuel over a period that coincides with the CANDU reactor fueling requirements. The required lead/lag storage vaults will be constructed at both the PuP facility and the MOX fuel fabrication facility.

Excess weapons-usable materials located at various DOE facilities include pits, clean metal, impure metal, plutonium alloys, clean oxide, impure oxide, uranium/plutonium oxide, alloy reactor fuel, oxide reactor fuel, and halide salts and oxides. Due to the variety of materials involved, no single Type B package design is appropriate. Therefore, DOE will utilize a number of different package designs for the packaging and transport of the feed materials to the plutonium processing facility. Shipment will be by safe, secure trailer (SST). Each SST will transport between 20 and 24 packages with approximately three SSTs per convoy.

Table 2.4. PuP facility preoperational cost

Category	Cost category description	Lump sum (1996 $M)
	Preoperational or OPC up-front costs:	
1	R&D	81
2	NEPA, oversight, permitting	6
3	Conceptual design	3
4	Quality assurance (QA), site qualification, and S&S plans	1
5	Postconstruction start-up	50
6	Risk contingency	11
	SUBTOTAL OPC	$151

Shipment Information—Based on the schedule assumptions, the ~50 MT of surplus plutonium will be shipped from its present locations to the PuP facility over a 10-year campaign. Table 2.5 summarizes estimates of the number of packages and shipments required for this shipment leg.

2.2.4.2 PuP Facility Operations Process

The PuP facility process diagrams are shown in Figs. 2.3 and 2.4. The facility has five major processing and handling sections: receiving, pit processing, mixed feed processing, gallium removal, and shipping.

Receiving—In the receiving area, pits and mixed plutonium feed stocks will be received by truck. In addition to plutonium pits in their shipping containers, other plutonium forms will be received in a variety of certified transport packages. Shipping containers aboard SSTs will be unloaded by forklifts onto a secured dock. The shipping containers will be inspected, checked for contamination, and unpacked. Storage vaults will be required for empty shipping containers and primary pit storage containers. In-line NDA equipment will be used to establish the plutonium content of all materials received.

Pit Processing (ARIES)—All pits will be gas-sampled to check for potential contamination. Contaminated pits will be sent to special recovery; noncontaminated pits will be sent to the standard disassembly station. Noncontaminated pits will be opened using a simple pit bisector and converted to PuO_2 using the ARIES (HYDOX) process. Clean metal will also be converted to oxide using this process. Contaminated pits will be decontaminated, and the plutonium-bearing components will be converted to PuO_2.

A passivation furnace will be used to convert glovebox sweepings to stable oxides after which the oxide is routed to the mixed feed processing stream. A PuO_2 packaging station will be provided to remove the PuO_2 from the glovebox.

Mixed Feed Processing—These streams include the remaining portion of the plutonium feed material. These feed streams will be processed primarily by aqueous means. The aqueous process includes the following steps: dissolution, purification (by solvent extraction or ion exchange), oxalate precipitation, and calcination. The clean and impure oxide streams will enter the aqueous process without additional preparation. However, the alloy reactor fuel and oxide reactor fuel must first go through a decladding/disassembly and size reduction procedure, and the impure metal and plutonium alloys proceed through the ARIES (HYDOX) process before entering the aqueous processing line.

Halide salts/oxides will be converted to PuO_2 using an existing aqueous processing line at LANL.

Gallium Removal—A substantial fraction of gallium is removed from the PuO_2 via a thermal treatment process. If necessary, PuO_2 will be reconditioned to meet MOX fuel feed specifications.

Shipping—PuO_2 will be packaged in appropriate certified packages specifically designed for shipment of oxide. A final assay of the processed material will be completed using nondestructive testing. The packages will then be placed in interim storage until transported to the MOX fuel fabrication facility.

2.2.4.3 PuP Facility Operations Schedule

The preoperational checkout of the PuP facility will start 6 months before the equipment installation is complete and will take 1 year. The facility is scheduled to operate for 10 years with an annual plutonium throughput of 5 MT. The first PuO_2 will be available for shipment 2 months after the start of operation. The operational schedule is shown in Table 2.6 and as a part of Sect. 2.2.6.

Table 2.5. Parameters for feed materials transport leg

Maximum plutonium material/package (kg)	Quantity of plutonium/campaign (kg)	Estimated packages to be shipped	Number of SST shipments/campaign
4.5	50,000	31,000	1,100

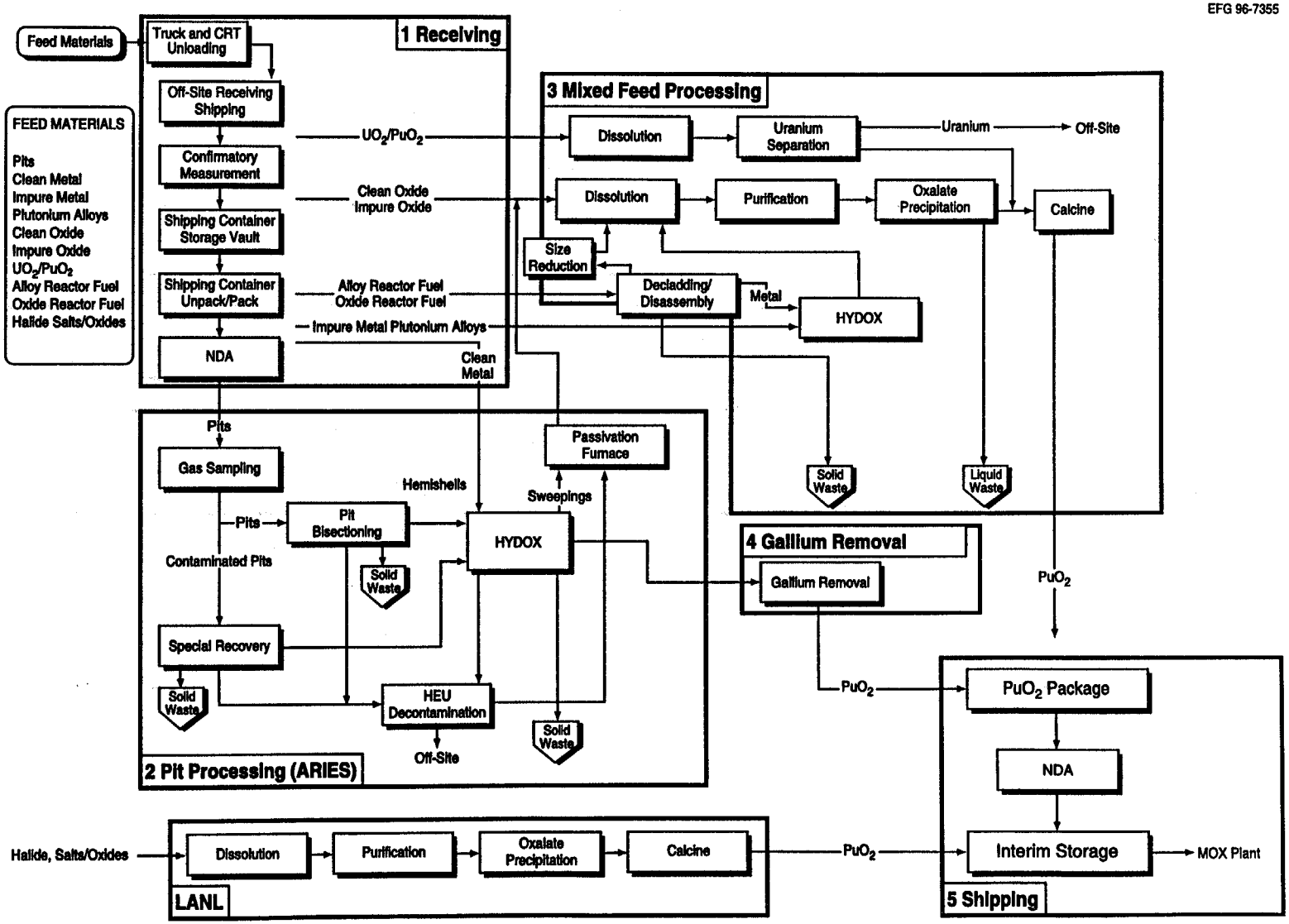


Figure 2.3. Process flow diagram for the PuP facility

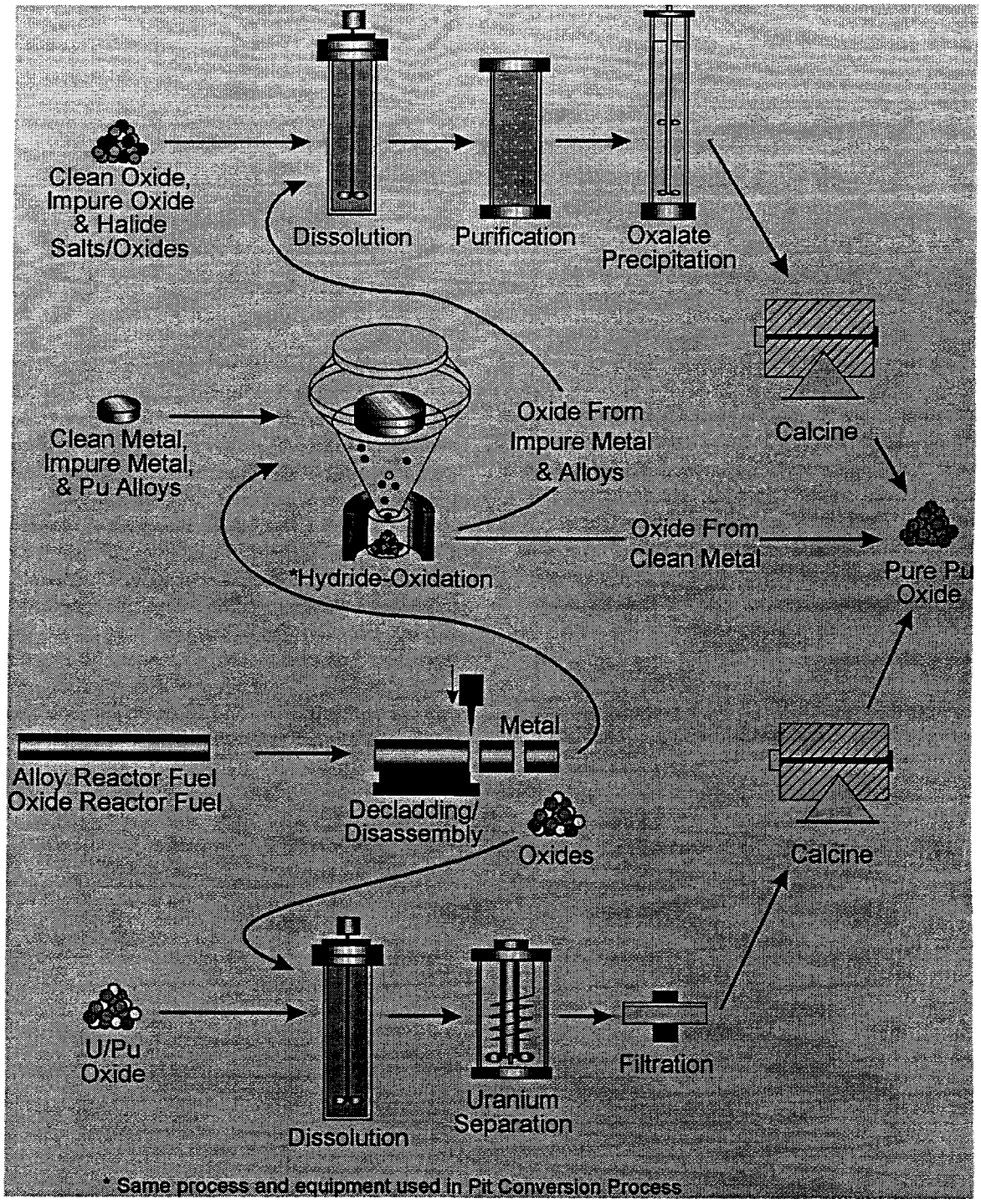


Figure 2.4. Process flow depiction for the PuP facility. Note: This figure is not meant to convey the actual process flow of the PuP facility, only to show the kinds of process steps that will be used.

Table 2.6. PuP facility operational schedule

Task ID	Task name	Duration (months)	Start	Finish
1.	**Preoperational Phase**	12	8/2005	7/2006
2.	**Operation**	120	7/2006	7/2016
3.	Approval to Commence Operation (KD-4)			7/2006
4.	PuP Duration	120	7/2006	7/2016
5.	First Material Available	2	7/2006	9/2006

2.2.4.4 PuP Facility Operations Cost

Operations costs for the PuP facility consist of more than the cost of staffing and consumables for the 10 years of plutonium operations; also included are waste handling, fees, capital upgrades, transportation, and oversight. These costs are reflected in categories 13–19 and 23 of the 24-category format. These costs are often called recurring costs, because the annual costs tend to remain almost constant over the plant lifetime for a given production rate (in this case 5 MT plutonium/year).

The other life cycle costs (LCCs), including annual operating costs, are shown in Table 2.7. This table presents annual costs, as well as 10-year lump-sum values, in 1996 constant dollars. The annual O&M cost was estimated to be $78.5M. Of this annual amount, about $70M/year is assumed to be staff cost. At an average full-time equivalent (FTE) loaded salary of $77,900/year, a total staff count of 899 FTEs results. This value was based on a required direct staff of 344, which includes 156 operators, 55 radiological control officers, 12 systems engineers, 35 system maintenance workers, and 86 analytical laboratory support personnel. The annual operating cost includes allowances for indirect staff, site general and administrative (G&A) staff, and security personnel, of which there are estimated to be 555 FTEs (in addition to the 344 direct FTEs). The $78.5M/year also includes

Table 2.7. PuP facility other LCCs

Category	Cost category description	PuP at SRS	
		Lump sum ($M)	Annual ($M/year)
	Years of operation = 10 years		
	Other LCCs:		
13	O&M staffing	785	78.5
14	Consumables including utilities (included in category 13)	0	0
15	Major capital replacements or upgrades (included in category 13)	0	0
16	Waste handling and disposal	66	6.6
17	Oversight	10	1.0
18	M&O contractor fees (2% of categories 13–16)	17	1.7
19	Payments-in-lieu-of-taxes to local communities	9	0.9
20	D&D (% of capital or $ estimate)	169	Nonrecurring
23	Transportation of plutonium forms to facility	35	3.5
24	Storage of plutonium at existing 94-1 site facility	Not in scope	
	PuP at LANL (halide)	1	0.1
	TOTAL OTHER LCC	$1,092	$92.2

consumables and capital replacements for a total of $8.5M/year. A value of $6.6M/year was estimated for waste handling and disposal, and $1M/year was included for oversight charges. Of the sum of the above costs, 2% was allowed for management and operating (M&O) contractor fees ($1.7M/year), and 1% ($0.9M/year) was allotted for payment-in-lieu-of-taxes to the local communities. Decommissioning costs are also included under other LCCs and are discussed in Sect. 2.2.5.2. A value of $169M is estimated for this activity. A value of $35M was estimated for transporting the plutonium feedstock from the various storage locations to the SRS over the 10-year operating period. In addition, about $1M over the 10-year period is estimated for processing 800 kg of halide-contaminated plutonium at LANL. As shown in Table 2.8, the total other LCC estimate for the 10-year PuP campaign is $1092M.

2.2.5 PuP Facility D&D

The PuP facility will be modified for the sole purpose of dispositioning surplus plutonium identified by this program. At the completion of this mission the PuP facility will be promptly decontaminated and decommissioned.

2.2.5.1 PuP Facility D&D Schedule

D&D is projected to take 2 years for removal of contaminated equipment and return of the building to habitable condition.

2.2.5.2 PuP Facility D&D Cost

The cost for decommissioning the PuP facility is included in Sect. 2.2.4.4. and estimated to be $169M.

2.2.6 PuP Facility Schedule Summary

The overall PuP facility implementation schedule is summarized in Table 2.8 and is shown in Fig. 2.5. This facility schedule is also included in the discussion of the overall alternative schedule in Chap. 3. This schedule does not include any contingency for schedule slip due to site selection difficulties, redesign, construction delays, or delay in the approval of line item funding.

The critical path through the development of this facility is through the design and construction process. If any of these tasks slip in their schedule, the rest of the implementation process will also be delayed. This critical path is shown in Fig. 2.5. If the start of operations at the PuP facility slips more than 3 months, the start of operations at the MOX fuel fabrication facility will also slip because the PuO_2 will not be available to begin fuel fabrication.

2.2.7 PuP Facility Cost Summary

Table 2.9 shows a summary of the PuP facility LCCs in the 24-category format. All anticipated plutonium-related costs from FY 1997 forward are included in this table.

Table 2.8. PuP facility schedule summary

Task ID	Task name	Duration (months)	Start	Finish
1.	**R&D Funding Available**			10/1995
2.	**FMDP ROD**			12/1996
3.	**Congressional Funding Approval**	36	12/1996	12/1999
4.	**Research, Development, and Demonstrations**	36	10/1995	9/1998
5.	**Site and Facility Selection**	12	12/1996	12/1997
6.	**Oversight and Permitting**	60	12/1996	12/2001
7.	**Design Process**	61	12/1996	1/2002
8.	**Facility Modification**	48	1/2002	1/2006
9.	**Preoperational Phase**	12	8/2005	7/2006
10.	**Operation**	120	7/2006	7/2016
11.	**D&D**	24	8/2016	7/2018

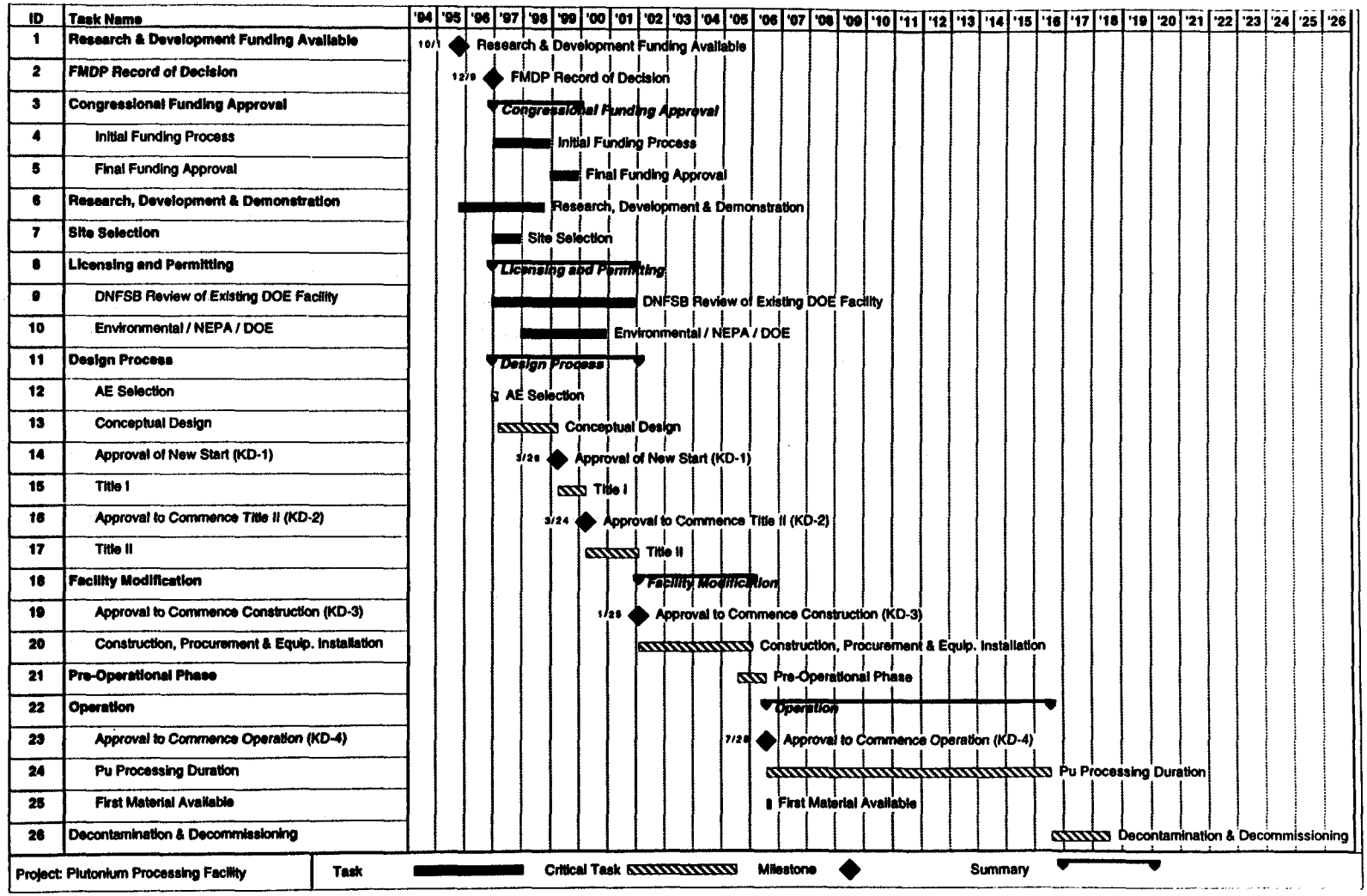


Figure 2.5. PuP facility schedule summary

Table 2.9. Summary of PuP facility LCCs

Category	Cost category description	PuP at SRS	
		Lump sum ($M)	Annual ($M/year)
	Years of operation = 10 years		
	Preoperational or OPC costs		
	Up-front costs:		
1	R&D	81	
2	NEPA, oversight, permitting	6	
3	Conceptual design	3	
4	QA, site qualification, S&S plans	1	
5	Postconstruction start-up	50	
6	Risk contingency	10	
	SUBTOTAL OPC	151	
	Capital or TEC costs:		
7	Title I, II, III engineering, design, and inspection	17	
8a	Capital equipment	34	
8b	Direct and indirect construction/modification	32	
9	Construction management (percentage of category 8)	4	
10	Initial spares (technology dependent)	3	
11	AFI (percentage of categories 7–10)	25	
12	Risk contingency	56	
	SUBTOTAL TEC	171	
	SUBTOTAL UP-FRONT COST	322	
	PuP at LANL (halide, ARIES demonstration and prototype)	$0	
	TOTAL UP-FRONT COST(TPC)	322	
	Other LCCs:		
13	O&M staffing (includes categories 14 and 15)	785	78.5
14	Consumables including utilities (included in category 13)	0	
15	Major capital replacements or upgrades (included in category 13)	0	
16	Waste handling and disposal	66	6.6
17	Oversight	10	1.0
18	M&O contractor fees (2% of categories 13–16)	17	1.7
19	Payments-in-lieu-of-taxes to local communities	9	0.9
	RECURRING COST SUMMARY	887	88.7
20	D&D (% of capital or $ estimate)	169	
21	Revenues (if applicable)	N/A	
22	Government subsidies or fees to private-owned facility	N/A	
23	Transportation of plutonium forms to facility	35	3.5
24	Storage of plutonium at existing 94-1 site facility	N/A	
	PuP at LANL (halide, ARIES demonstration and prototype)	1	
	TOTAL OTHER LCC	$1,092	$92.2
	GRAND TOTAL ALL LCC	$1,414	

2.2.8 PuP Facility Technical Viability

DOE has identified five items to consider in developing a qualitative assessment of the technical viability of a concept: a definition of the technological maturity of a process; the specification of the technical unknowns for the process and the technical risk associated with the application of the process; the R&D needs of the process; the condition, capacity, and reliability of infrastructure; and the regulatory and licensing requirements. Each of these items, except infrastructure, are addressed in the following sections.

Technological Maturity—Judging the maturity of the technologies employed in plutonium disposition facilities requires an assessment of the current level of development of each fuel cycle stage. Technologies can be categorized as being at the conceptual design stage, the laboratory or bench-scale testing stage (demonstrating scientific feasibility), the prototype stage (demonstrating engineering feasibility), or the industrialization/commercialization stage. Even if a significant domestic development base does not exist, a foreign experience base may be available.

All of the technology needed for pit disassembly and plutonium conversion exists at the laboratory and bench-scale testing stage and has been implemented to a limited degree. Ongoing R&D is moving the technologies to the prototype stage.

Technical Risks—Certain technologies have associated technical unknowns. Consequently risks are associated with the application of the technologies based on these parameters.

Technical risks of the PuP facility are thought to be minimal. All processes have been demonstrated in existing facilities. The principal technical risk is the degree of reliability of these processes when applied at the level needed to achieve disposition goals. Throughput must be assessed; if found to be insufficient, processes would have to be optimized. The precision and accuracy of assay measurements when conducted at the desired throughput levels remain to be determined.

R&D Needs—Various parameters were identified as unknown or poorly known for this alternative. The R&D necessary to address each of these technology development needs is presented subsequently.

The nondestructive assay (NDA) subsystem for pits consists of four computer-based NDA instruments; a robot to load and unload the instruments; and a host computer to sense and control the instruments, schedule measurements, archive the results of the assays, and direct the activities of the robot. Integration of the instruments is untested. The reliability of the system and the precision and accuracy of the measurements remain to be determined. This information will permit the evaluation of the nuclear measurement requirements for the baseline processes in the facility and the effects of measurement requirements on the facility flowsheets.

The current DOE pit stockpile contains a variety of pit configurations. Some pits are relatively simple in design, whereas others are more complicated and difficult to disassemble. A relatively simple, inexpensive single-axis bisector has been developed for use with simple pit designs. This system must be tested and demonstrated as a part of an automated disassembly system that can process specified pit types more efficiently, with less wastes, and reduced operator radiation exposure. Disassembly flow sheets must be generated for families of weapons components. Processes for handling the more complicated pit designs are currently under development and must be tested and demonstrated.

Nonpit conversion processes must be optimized to lower costs, improve throughput, and reduce wastes. The conversion processes that will have the most impact are the processing of plutonium reactor fuels and alloys, dissolution and treatment of high-fired plutonium oxides, and the separation of impurities from plutonium-rich forms.

2.2.9 PuP Facility S&S Summary

DOE and its predecessor agencies have successfully managed S&S of SNMs for several decades. DOE maintains an impeccable record of providing adequate measures to ensure against theft or unauthorized access to SNMs. These measures include physical security, material accountability, inventory safeguards, and other technologies. These measures have been applied to SNMs in a variety of material forms, ranging from bulk SNM powders and solutions to pits.

An assessment has been performed to identify critical vulnerabilities that might exist in operations or

processes that make up the reactor disposition alternative. The purposes of the assessment were to (1) determine whether any inherent vulnerabilities exist that represent unique or novel threats to maintaining adequate measures against theft or unauthorized access and (2) identify any threats in the reactor disposition alternative operations that will require particular attention by facility designers to ensure that potential vulnerabilities are properly addressed.

This section discusses the vulnerabilities to theft and unauthorized access intrinsic to the material forms and processing environments in the plutonium processing facility. In the sense employed here, a "risk" is a set of conditions that require specific measures to ensure proper physical control of SNMs. These risks should *not* be interpreted as the overall risk that the material will be subject to in the as-built facilities. The overall risk in the as-built facility is driven to very small values by the S&S measures incorporated in the design and operation of the facility.

Possible Diversion, Theft, or Proliferation Risks—For this facility most of the material is in a very attractive form with minimal intrinsic barriers. A large number of processing steps provides increased opportunities of covert theft. Except for the tamper-protected containers in which the metal and/or oxide is placed, the material is fairly accessible. In addition, many of the processes involve bulk material and bulk accountability measurements. For a high-throughput facility this provides increased opportunity for possible covert theft, and the potential risk is high. In the case of an overt theft attempt, the targets of greatest concern would be the pits and pure metal and oxides which are transportable. However, these materials would be under stringent protection, such that the risk associated with an overt event would be acceptable.

Environmental Conditions— Table 2.10 provides process environmental conditions, material form, and other S&S information. The PuP facility involves a large number of processing steps with a relatively high throughput. Based on the quantity and attractiveness of the material, the facility will be a category I facility, see Table 2.11. Waste streams containing fissile material will be generated and thus require monitoring to prevent possible theft. Lag storage in a fairly active vault will be performed. There will be no intrasite transport movements [e.g., outside of the materials access area (MAA)]. SSTs will be used to deliver and pick up the material. Although operations for a single batch (e.g., ~4.5 kg) are relatively short (8 h), a large number of batches will be needed to meet the 5-MT/year throughput, and therefore, the window of opportunity for possible adversary actions is large.

Material Form—The material received at the PuP facility is the most attractive material for this particular alternative (e.g., pits, pure metal, and oxide). Table 2.12 provides the DOE attractiveness categories and quantities. In the case of pit conversion, the attractiveness goes from IB to IC. For oxides and other high-grade material, the attractiveness level remains at IC. In some cases the feed material may be low-grade material, and the attractiveness may actually increase from IID to IC after processing. The material overall has very low intrinsic barriers. It is transportable. It has only a very low radiological barrier primarily due to the presence of americium. It is in most cases in a very pure form, as a metal or oxide, and its isotopic composition makes it usable for a nuclear device. There are no new or unique (to DOE) material forms handled in the PuP facility. It is reasonable, therefore, to assume that existing S&S design practices, material accountability and operating procedures, and facility protection approaches will result in acceptable process risk.

S&S Assurance—Material received into the PuP facility [e.g., pits and containers with tamper indicating devices (TIDs)] would utilize item accountancy. Once the material has been removed from the container, then bulk accountancy would be necessary. Many of the operations will involve hands-on activities, and the material is very accessible. The items being handled are not particularly large and do not require any special handling equipment. Most of the operations will be performed inside a glovebox. In addition to destructive assay, an NDA would be performed. Because pits and other weapons material are being processed, some of the material will be classified. This may also apply to waste streams.

Potential Risks to Diversion—This facility has several processing stages and is handling large quantities of material. The high attractiveness of the material for this facility makes possible conversion and reuse easier, and because a lower level of effort is required to reuse this material, the ability to detect these covert activities is diminished. These factors must be anticipated and countered in the facility design by application of appropriate S&S measures.

Difficulty of Diversion, Retrieval, Extraction, and Reuse—The PuP facility involves very attractive material and high throughputs. The accessibility of the material, low intrinsic barriers, and the large number

Table 2.10. Nonproliferation and S&S risk assessment for the PuP facility

Environment								
Facility	**Activity**	**Duration (h)**	**Throughput**	**Waste streams**	**Maximum inventory**	**Intrasite transport**	**Number of processing steps**	**Barriers**
PuP			5 MT plutonium	Yes <0.1 g/L plutonium	0.5 MT plutonium	No	16	MAA
	Receiving, NDA, and unpacking	8	4.5 kg plutonium per batch (criticality limit)			No, SST unload	0	
	Pit processing	8				No	3	Glovebox
	Mixed feed processing	8	4.5 kg plutonium per batch			No	11	Glovebox
	Gallium removal	8	4.5 kg plutonium per batch			No	2	Glovebox
	Shipping, NDA, and unpacking	8	4.5 kg plutonium per batch			No, SST load	0	
Transport	PuP to MOX fuel fabrication facility							

Note: MAA—material access area.

Table 2.10. Nonproliferation and S&S risk assessment for the PuP facility (cont.)

Material form										
Facility	**Activity**	**SNM input**	**SNM output**	**Plutonium quantity**	**Concentration of plutonium**	**SNM* category**	**Item mass/ dimensions**	**Radiation barrier**	**Chemical composition**	**Isotopics**
PuP				Other fissile material present	Other fissile material	DUU				
	Receiving, NDA, and unpacking	Metal, oxide	Metal, oxide	4.5 kg per batch (criticality limit)	>0.9 g/g (<0.1 g/g) (other fissile material)	IB-IID		No	Pure metal, oxides, miscellaneous	
	Pit processing	Metal	Metal			IB		No	Metal	
	Mixed feed processing	Metal, oxide, fuels, miscella-neous	Oxide	4.5 kg (per batch)		IC		No	Oxide, miscellaneous	
	Gallium removal	Oxide	Oxide	4.5 kg (per batch)		IC		No	Oxide	Mixed plutonium isotopes
	Shipping, NDA, and unpacking	Metal, oxide	Metal, oxide	4.5 kg (per batch)		IC		No	Oxide	
Transport	PuP to MOX fuel fabrica-tion facility									

Note: DUU—direct-use unirradiated.
*See Table 2.12.

Table 2.10. Nonproliferation and S&S risk assessment for the PuP facility (cont.)

S&S								
Facility	**Activity**	**Number of MBAs**	**Accounting system type**	**Nuclear measure methods**	**Classified material**	**Physically accessible**	**Access**	**Special handling equipment**
PuP		1–3	30% Item	Calorimetry, gamma, segmented gamma, neutron			Both	No
	Receiving, NDA, and unpacking		Both	0.8% (domestic) 1.5% (international)	Yes	Yes No (pits, TIDs)		
	Pit processing		Item		Yes	Yes		
	Mixed feed processing		Bulk		Yes/No	Yes		
	Gallium removal		Bulk		No	Yes		
	Shipping, NDA, and unpacking		Bulk		No	Yes No (TIDs)		
Transport	PuP to MOX fuel fabrication facility							

Note: TID—tamper-indicating device.

Table 2.11. DOE attractiveness categories and quantities from DOE Order 5633.3B

	Attractiveness level	Plutonium and ^{233}U category (kg)			
		I	II	III	IV[a]
Weapons	A	All quantities	N/A	N/A	N/A
Pure products	B	≥ 2	≥ 0.4 < 2	≥ 0.2 < 0.4	< 0.2
High-grade material	C	≥ 6	≥ 2 < 6	≥ 0.4 < 2	< 0.4
Low-grade material	D	N/A	≥ 16	≥ 3 < 16	< 3
All other materials	E	N/A	N/A	N/A	Reportable quantities

[a]The lower limit for category IV is equal to reportable limits in this order.

Table 2.12. MOX fuel fabrication facility design and construction schedule

Task ID	Task name	Duration (months)	Start	Finish
1.	**FMDP ROD**			12/1996
2.	**Congressional Funding Approval**	36	12/1996	12/1999
3.	Initial Funding Process	24	12/1996	12/1998
4.	Final Funding Approval	12	12/1998	12/1999
5.	**Fuel Qualification Demonstration**	60	4/1996	4/2001
6.	**Site and Facility Selection**	12	12/1997	12/1998
7.	**Select M&O Contractor**	12	12/1998	12/1999
8.	**Design Process**	60	12/1996	11/2001
9.	Conceptual Design	12	12/1996	12/1997
10.	Title I	12	12/1999	12/2000
11.	Title II	12	12/2000	11/2001
12.	**Facility Modification**	36	12/2001	12/2004
13.	Construction	36	12/2001	12/2004
14.	Procurement	24	12/2001	12/2003
15.	Equipment Installation	12	12/2003	12/2004

of processing steps makes the intrinsic risk to possible diversion high. Once the material has been diverted, the pure metal and oxide could be reused in a nuclear device relatively easily. Because pits and other material in this facility are classified, they would not be under international safeguards unless restricted data could be protected. Once again, however, similar or identical operations have been safely carried out for several decades in DOE facilities, and standard S&S measures are available to counter the intrinsic risks posed by material forms and process environments.

Assurance of Detection of Retrieval and Extraction—Because the PuP facility will involve large quantities of bulk material and very high throughputs, it may be very difficult to detect (using material accountability alone) the diversion of a significant quantity of material. The presence of classified material further complicates safeguards with respect to international inspection. Standard containment surveillance and other S&S measures can be employed to ensure that material is not being diverted.

2.3 MOX Fuel Fabrication Facility

2.3.1 MOX Fuel Fabrication Facility Description

The MOX fuel fabrication facility converts the PuO_2 from the PuP facility to MOX fuel to supply the reactors. The MOX fuel fabrication facility is assumed to be federally owned and separate from the PuP facility although the two facilities could be collocated at the same federal site.

The MOX fuel fabrication facility receives PuO_2 from the PuP facility and other feed materials (such as UO_2, additives, fuel pins, and bundle components) from offsite and produces fuel bundles. The feed oxide is received, stored as needed, purified if required, milled, screened and blended into lots. It is then fabricated into pellets, the pellets fabricated into pins, and the pins assembled into bundles. The bundles are then stored on site to await shipment to Bruce NGS A.

The overall facility size for the annual throughput rate of 2.9 MT of plutonium [138.1 MTHM (metric tons heavy metal)/year] will depend on the existing building ultimately chosen. A number of such buildings are being considered that are located on a federal site with a plutonium-handling infrastructure. The MOX fuel fabrication facility annual plutonium throughput is based on planned reactor consumption. The MOX fuel fabrication facility will have PuO_2 homogeneity storage capacity of roughly 15 MT to enable reload and interim storage. Any additional storage will be located at either the PuP facility or another vault that is part of the DOE complex.

2.3.2 MOX Fuel Fabrication Facility Design and Construction

2.3.2.1 MOX Fuel Fabrication Facility Design and Construction Schedule

The duration and path of the design and construction tasks for the MOX fuel fabrication facility are based on a generic DOE major system acquisition—capital construction project. The design and construction process will begin at ROD with the preconceptual design in order to start the NRC licensing process as soon as possible. The 1-year site and facility selection process to determine the most appropriate existing facility on a federal site for the MOX fuel fabrication facility will start after the completion of the preconceptual design. The selection process for the M&O contractor will start after the intermediate approval for line item funding. This contractor will be responsible for developing the Title I and II designs and for completing the facility modifications required for the MOX fuel fabrication facility. Work on Title II starts after approval of the Title I design and the final line item funding. The facility modifications and equipment procurement starts after completion of Title II design and up to 1 year before the completion of the NRC licensing process. However, no safety-related construction may be done until after the license has been granted. The design and construction schedule is shown in Table 2.12 and Sect. 2.3.6.

The fuel qualification demonstration is currently under way and is scheduled to be completed in 2001. Additional fuel development work will be performed during the first 5 years of reactor operation in anticipation of changing to the advanced fuel design at the end of 5 years.

2.3.2.2 MOX Fuel Fabrication Facility Design and Construction Cost

This category represents the bulk of the up-front or investment costs for the MOX fuel fabrication facility and in government accounting is called TEC. It also represents the line item funding appropriated by Congress. In the LCC format, it is covered under categories 7–12 in Table C.1 in Appendix C.

Development of these cost estimates involved modifying estimates for new or greenfield private facilities and converting them to estimates for a refurbished MOX fuel fabrication facility that would consist only of new equipment installed in an existing building on a government site already having a plutonium-handling infrastructure such as analytical laboratories, S&S, waste handling, etc. Essentially most of the civil works costs for a new category-I building could be removed from a new building cost estimate. It is assumed, however, that even an existing building would need significant civil modifications to safely contain gloveboxes and other MOX fuel fabrication equipment. It is assumed that automated rather than hands-on MOX fuel fabrication technology can be used. The higher fabrication line capacities (on the order of 45 MTHM/year) of automated plants as compared to hands-on plants (35 MTHM/year or less) allow the use of fewer lines (and hence less floor space and staff) for a given total desired plant capacity. For the CANDU MOX fuel fabrication facility, an average HM throughput capacity of 141 MTHM/year

is used for cost calculations.* The following algorithm was used to calculate the TEC (sum of categories 7–12) for the MOX fuel fabrication facility for all reactor alternatives:

For a capacity up to 45 MTHM/year, the TEC = $200M. For *each* 45 MTHM/year of additional capacity above 45 MTHM/year, add another $50M. Therefore, for a capacity of 141 MTHM/year, the TEC is $200M + (3 × $50M) = $350M.

Although CANDU bundles and LWR assemblies are quite dissimilar, the model for estimating CANDU costs using an LWR model would give reasonable approximations because most of the operations in the two fuel fabrication facilities would be similar. In particular, the powder processing and pellet sintering operations would be nearly the same at the level of detail available now. Only in the fuel assembly portion of the facility are the unit operations significantly different. The LWR model would likely overestimate the CANDU fuel cost.

The MOX economics model partitions the TEC into the proper categories 7–12, as shown in Table 2.13. The design cost (category 7) includes Title I and II design and Title III inspection. It is calculated as ~20% of the sum of categories 8, 9, and 10. The capital equipment cost (category 8a) of $175M includes all of the new gloveboxes, process equipment, and auxiliary equipment. It is presumed that the process equipment will be purchased from, installed by, and tested by the private equipment vendor. It is estimated that $60M (category 8b) is needed for the modifications to the existing structure in order to house the equipment. This category also contains the indirect costs for the construction project such as equipment rentals and QA. [It is assumed that a perimeter intrusion detection and assessment system (PIDAS) fence is already in place.] Category 9 (construction management) is included in categories 8a and 8b. Category 10 (spares) is calculated as a percentage of the process equipment cost and includes purchase of the necessary spare process-equipment items needed to keep the plant running during its early operating life. The allowance for indeterminates (AFI) of $45M represents 15% of the sum of categories 7–10 and is considered reasonable for a facility that has undergone conceptual design in vendor studies. Category 12 (risk contingency) is designed to eventually cover out-of-scope risks such as schedule slip and the need for redesign or retrofit of the facility. It will be calculated by a future uncertainty analysis.

It should be noted that the MOX fuel fabrication facility TEC algorithm and others to follow have been examined by an LWR fuel vendor and found to give reasonable numbers for a facility whose location and mission schedule have not yet been identified in any detail.

*For cost estimating purposes, a weighted average MOX HM throughput of 141 MTHM/year was used (average of 138 MTHM for 5 years and 149 MTHM for 7.2 years).

Table 2.13. Design and construction costs for MOX fuel fabrication facility

Category	Cost category description	141-MTHM/year government MOX plant in existing building [lump sum (1996 $M)]
	Average annual HM throughput in MTHM/year = 141	
	Capital or TEC part of up-front cost	
7	Title I, II, III engineering, design, and inspection	56
8a	Capital equipment	175
8b	Direct and indirect construction/modification	60
9	Construction management	0
10	Initial spares (technology dependent)	14
11	AFI (15% of categories 7–10)	45
12	Risk contingency	0
	SUBTOTAL (TEC)	$350

2.3.3 MOX Fuel Fabrication Facility Licensing and Permitting

It has been assumed that the MOX fuel fabrication facility, whether federally or privately owned, will be subject to NRC licensing. There is a clear path forward provided in the existing licensing regulations promulgated by the NRC with regard to nuclear safety and radioactive waste management at MOX facilities. All permitting requirements from applicable federal statutes will apply.

The licensing approach for the reactor-based plutonium disposition options is to satisfy the NAS ES&H criteria "that any disposition option to operate in the United States:

- should comply with U.S. regulations governing allowable emissions of radioactivity to the environment, and allowable radiation doses to worker and the public, from civilian nuclear-energy activities;
- should comply with international agreements and standards covering the disposition of radioactive materials in the environment; and
- should not add significantly to the ES&H burdens that would be expected to arise, in the absence of the weapons-usable plutonium disposition, from appropriate management of the environmental legacy of past nuclear-weapons production and from appropriate management of the ES&H aspects of past and future nuclear-energy generation."[1]

NEPA—The construction and operation of a NRC-licensed MOX fuel fabrication facility requires an Environmental Impact Statement (EIS) under 10 CFR Part 51.20(b)(7).

Atomic Energy Act of 1954, as amended—Operations subject to NRC licensing or authorizations at the MOX fuel fabrication facility include:

- Possession, handling, and storage of source material (10 CFR Part 40) and SNM (10 CFR Part 70) plus access authorizations to SNM (10 CFR Part 11);
- Packaging and transportation of radioactive material (10 CFR Part 71); and, if applicable,
- Land disposal of radioactive waste (10 CFR Part 61).

In each case, a clear path forward exists, and regulatory criteria and guidance, although somewhat dated and subject to review and revision, are available to define an appropriate licensing strategy and plan if required.

Transportation of SNMs to and from the MOX fuel fabrication facility will be done in accordance with NRC regulations in 10 CFR Part 71; DOT regulations in 49 CFR Parts 171–179; and for wastes, EPA regulations in 40 CFR Part 263.

RCRA—Plutonium disposition represents no new or special permitting situation with regard to compliance with RCRA for treatment or disposal of hazardous waste. However, as a DOE program, all facets of the plutonium disposition mission are subject to the waste minimization/pollution prevention policies of the President and the Secretary of Energy with regard to the plans required of waste generators under Sect. 3002(b) of RCRA, and such a plan will be developed and implemented consistent with EPA guidelines published in the *Federal Register*. Special attention will be directed to avoiding the accumulation of hazardous and MWs without treatment options so that exemption requests to the enforcement provisions of Sect. 3004(j) of RCRA can be avoided.

Clean Air Act and Clean Water Act—New permits may be required if existing permits cannot be amended; however, no new or unusual permitting situations or special requirements are anticipated.

2.3.3.1 MOX Fuel Fabrication Facility Licensing and Permitting Schedule

For this analysis, it has been assumed that the duration of the NRC licensing process will be 5 years and that the process will start after the conceptual design is complete. The NEPA process and the other site-specific permitting will require 3 years; each process will start after the site has been selected. The licensing schedule is shown in Table 2.14 and Sect. 2.3.6.

2.3.3.2 MOX Fuel Fabrication Facility Operation-Funded Project Cost

This section will cover LCC categories 1–6 in the 24-category estimating format described in Appendix C of this report. These six categories constitute what is termed preoperational or OPC in government accounting. OPC is the portion of the TPC (investment or up-front cost) budgeted with operating dollars rather than congressional line item capital or TEC dollars.

Table 2.14. MOX fuel fabrication facility licensing and permitting schedule

Task ID	Task name	Duration (months)	Start	Finish
8.	**Licensing and Permitting**	60	12/1997	12/2002
9.	NRC Licensing	60	12/1997	12/2002
10.	Environmental / NEPA / DOE	36	12/1998	11/2001
11.	Permitting	36	12/1998	11/2001

Because this facility is likely to be government owned and funded, this distinction is important.

OPC generally includes the majority of the preconstruction activities and many of the start-up activities carried on by the operating contractor prior to full capacity operation of the facility and after construction is complete. As seen in Table 2.15, licensing is just one of several needed cost centers.

R&D costs represent early estimates from the R&D plans submitted by the DOE national laboratories. It should be noted that the MOX fuel qualification tests are covered under the reactor facility costs. The $35M for NEPA (post-1996 PEIS and new EIS activity), licensing, and permitting assume that the licensing or oversight body, whether it be NRC or DNFSB, will be reimbursed for the time required to process the license application. Conceptual design and the preparation of implementation plans are activities undertaken by the project office and contractors. (These costs do not include DOE salaries). The start-up activities funded are those undertaken by the contractor that will operate the plant at eventual full production and do not include startup costs that are part of the construction contractor's mission. The costs in categories 1–5 have some contingency imbedded in each; however, the risk from a significant schedule slip or the need for redesign are not included. A future uncertainty analysis will provide an estimate of the additional risk contingency. The total preoperational estimate of $100M is in line with the vendor estimates, and in this cost model, the OPC does not vary with the production capacity of the plant.

2.3.4 MOX Fuel Fabrication Facility Operations

2.3.4.1 MOX Fuel Fabrication Facility Shipping and Storage

Following conversion to PuO_2 at the PuP facility, the PuO_2 will be repackaged (using many of the packages described in Appendix G) and shipped to the MOX fuel fabrication facility. This facility will operate on a schedule similar to the CANDU HWR operation schedule. This will require that some of the PuO_2 be placed in a lead storage vault, since the shipment campaign will be completed in 10 years. The lead storage vault could be accommodated in the design of the

Table 2.15. Licensing and permitting LCCs for the CANDU MOX fuel fabrication facility

Category	Description	Lump-sum cost (1996 $M)	Basis
1.	R&D	21	R&D plan
2.	NEPA, licensing, and permitting	35	1995 estimate
3.	Conceptual design	2	Vendor estimate
4.	Implementation plans for S&S, QA, and site qualification	1	
5.	Postconstruction startup	41	Multiplier on annual operations staff
6.	Contingency to cover cost/schedule risk		Not yet assigned
	TOTAL PREOPERATIONAL COST	$100	OPC in 1996 dollars

MOX fuel fabrication facility design, or any excess vault capacity at another DOE site.

Table 2.16 summarizes estimates of the number of packages and shipments required for this shipment leg. Shipment will be by SST. Each SST will transport between 20 and 24 packages with approximately 3 SSTs per convoy.

2.3.4.2 MOX Fuel Fabrication Facility Operations Process

The MOX fuel fabrication facility contains nine material processing and handling sections as shown in Fig. 2.6.

Receiving and Storage—In the materials receiving and storage area, all fuel fabrication components are received, inspected, and sampled. After establishing accountability, the materials are stored, observing criticality controls on plutonium and surrounding materials.

The interim storage vault receives PuO_2 that accumulates because of the higher throughput levels of the PuP facility as compared to the MOX fuel fabrication facility. This vault will have a maximum capacity of 15 MT of PuO_2.

PuO_2 Purification—In this process, PuO_2 is purified to the specifications for production of MOX fuel pins

Table 2.16. Parameters for PuO_2 transport leg

Maximum plutonium/package (kg)	Quantity of plutonium/campaign (kg)	Estimated packages to be shipped	Number of SST shipments/campaign
4.5	50,000	31,000	1,100

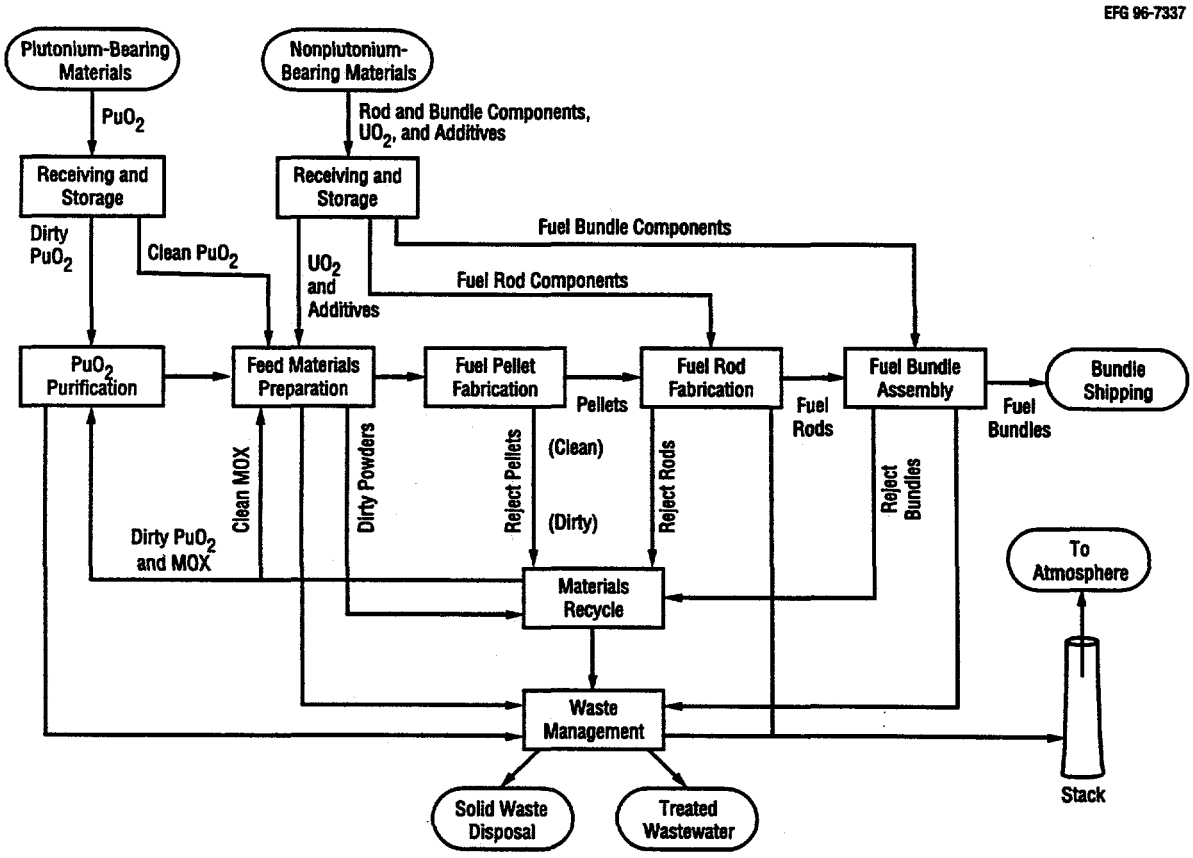


Figure 2.6. Generic MOX fuel fabrication facility process diagram

required for the CANDU HWRs. The PuO_2 powder is analyzed for contamination and, if it meets purity requirements, goes to PuO_2 storage without further processing. PuO_2 that does not meet the purity requirements is dissolved, and the plutonium solution is processed through an ion exchange process to separate the plutonium from impurities. It is then treated to precipitate the plutonium, filtered, and calcined to PuO_2 powder. After analysis, PuO_2 meeting purity requirements is sent to PuO_2 storage. PuO_2 that still does not meet purity requirements is recycled through the purification process.

It is assumed that ARIES and other processes in the PuP facility produce a sufficiently gallium-free PuO_2 product that can go directly to the PuO_2 storage without additional processing.

Feed Material Preparation—PuO_2 from receiving and storage, the PuO_2 purification process, and/or the materials recycle process is milled and screened to specification in batch lots. Any PuO_2 that does not meet dimensional specifications is recycled through milling. Any PuO_2 powder that does not meet purity specifications is sent to the materials recycle process. Several lots are then blended to ensure consistency through extended periods of production. The PuO_2 is then stored until needed. UO_2 received from off-site in ready-to-use condition is stored for later use. As needed, UO_2, PuO_2, and recycled MOX are removed from storage and placed in feed bins. Each quantity is weighed in correct proportion to form a batch and is placed in the mill/blender to achieve homogeneity. Portions from several batches are separated and cross-blended, then reblended by passing through the mill/blender again to form a large lot. The powder is agglomerated to form a free-flowing press feed and is placed in storage. Batch size is determined by criticality safety limits on mass, but uniformity over much larger process units is desired to minimize sampling and optimize product consistency. All operations are performed in gloveboxes, including those that are automated.

Fuel Pellet Fabrication—Conditioned feed material from either the storage or feed materials preparation process is pressed into pellets, loaded into sintering boats, and then stored until needed. Reject pellets are sent to material recycle. After placing the boats in the sintering furnace, they are sintered in an atmosphere of argon (or nitrogen) with low levels of hydrogen. The pellets are then removed from the furnace and held in storage until needed. Reject pellets are sent to material recycle. Sintered pellets are then ground to dimension and inspected for dimensional conformance, purity, and fissile content. Unacceptable pellets are sent to the materials recycle process. Acceptable pellets are placed in storage until needed. All pellet operations except sintering are performed in gloveboxes.

Fuel Pin Fabrication—Fuel pin fabrication begins by preparing pins for loading with fuel pellets. Stacks of pellets, springs and spacers are assembled and loaded into the pins. The open end of the pin is decontaminated and the end cap welded on. The pin is inspected for dimensional tolerance and fissile loading, and a leak test is performed. Defective pins are recycled. Acceptable pins are cleaned and stored pending assembly into fuel bundles. Completely assembled dysprosium pins for the center ring of the bundle are supplied by Ontario Hydro.

Fuel Bundle Assembly—This process prepares the components for fuel bundle assembly and removes the fuel pins from storage. The bundle is assembled, welded, cleaned, and inspected for dimensional conformance. The bundle is then stored pending transfer to a reactor. Rejected bundles are sent to the materials recycle process.

Materials Recycle—When possible, materials are recycled to reduce amounts going to the on-site waste management.

Waste Management—Wastes are sent to the on-site waste management facility for processing and packaging before being sent to WIPP or a low-level waste (LLW) burial ground.

Bundle Shipping—Shipping the MOX fuel bundles to the Bruce reactor facility is discussed in the Reactor Shipment and Storage section.

Table 2.17 lists the batch characteristics for the receiving and shipping, fuel fabrication, and shipping processes.

2.3.4.3 MOX Fuel Fabrication Facility Operations Schedule

The preoperational checkout of the facility starts as soon as the construction is complete and will take 2 years. To supply fuel for the two CANDU reactors with reference MOX fuel bundles, the MOX fuel fabrication facility will operate for 5 years with an annual plutonium throughput rate of 2.9 MT. This

Table 2.17. MOX fuel fabrication facility batch process data

Process	Process cycle data[a]	Data (average)
Receiving and storage	Plutonium throughput	725 kg Reference 1240 kg CANFLEX
	Cycle time	3 months
	Plutonium input form	PuO_2
	Plutonium output form	PuO_2
MOX fuel fabrication	Plutonium throughput	2950 kg Reference 4960 kg CANFLEX
	Cycle time	1 year
	Plutonium input form	PuO_2
	Plutonium output form	MOX fuel bundles
Bundle shipping	Plutonium throughput	754 Reference bundles 0.33 kg Plutonium/bundle 875 CANFLEX bundles 0.47 kg Plutonium/bundle
	Cycle time	1 month
	Plutonium input form	MOX fuel bundles
	Plutonium output form	MOX fuel bundles

[a]Plutonium throughput represents amount of PuO_2 received in a single shipment. Cycle time represents interval between expected shipments of PuO_2.

throughput assumes an annual output of 9,050 bundles for a total of 45,250 bundles. A sufficient number of reference MOX bundles for the initial reactor loads will be available 6 months after the start of operation. The production lines will then be converted to fabricate CANFLEX fuel to supply four CANDU reactors with an annual throughput of 4.9 MT for 7.2 years, which corresponds to an annual output of 10,500 CANFLEX bundles, for a total of 75,279 bundles. Plant downtime required to conduct the shift from reference to CANFLEX fuel was determined to be insignificant for the level of detail needed at this stage of the project. The operational schedule is shown in Table 2.18.

2.3.4.4 MOX Fuel Fabrication Facility Operations Cost

Operation costs for the MOX fuel fabrication facility constitute more than just the cost of staffing and

Table 2.18. MOX fuel fabrication facility operational schedule

Task ID	Task name	Duration (months)	Start	Finish
1.	**Preoperational Phase**	24	12/2004	12/2006
2.	**Plutonium Processing Lead Time Complete**			9/2006
3.	**MOX Facility Ready for PuO_2**			12/2006
4.	**Operation**	152	12/2006	2/2019
5.	MOX Facility Operation Start			12/2006
6.	Fabrication of Initial Loads	6	12/2006	6/2007
7.	Reference MOX Fuel Fabrication	60	12/2006	12/2011
8.	CANFLEX Fuel Fabrication	86	12/2011	2/2019

consumables for the 12.2 years of facility operations; waste handling, fees, capital upgrades, transportation, and oversight are also included. These costs are reflected in categories 13–19 and item 23 of the 24-category format. These costs are often called recurring costs, since the annual costs tend to remain nearly constant over the plant lifetime for a given production rate (in this case a time-weighted average of 141 MTHM/year for the reference and CANFLEX fuel designs combined.).

Again, an algorithm was used to calculate the sum of all recurring costs, not including transportation of PuO_2 powder to the MOX fuel fabrication facility from the PuP facility. The algorithm essentially scales with throughput (MTHM/year) plus the addition of a fixed component of $50M/year, which exists independently of the production rate up to 45 MTHM/year. (This means that it costs $50M/year just to keep the doors of a plutonium handling facility open, even if there is no production. Experience at the DOE/ Defense Program sites shows this tendency to be true.) The MOX fuel fabrication facility is assumed to use automated rather than hands-on technology, thus, reducing the number of staff needed and reducing personnel radiation exposure. The algorithm used is as follows:

Annual recurring cost (not including transportation) = $50M/year + 0.6 (MTHM/year – 45).

For the 141-MTHM/year production rate for the MOX fuel fabrication facility, a recurring cost total of $107.6M/year results. This cost is incurred for all 12.2 years of MOX production for a total of $1313M. The short life of the facility (12.2 years) should significantly reduce the capital upgrade rate, that is, the fraction of TEC that represents the need to replace major equipment items that fail or wear out. The fact that an existing federal site is being used also results in shared indirect or overhead costs with other site functions as opposed to a greenfield plant where all overheads would be assigned to the MOX fuel fabrication facility cost center. Such overhead functions include security, waste handling, and analytical laboratories. The recurring costs are essentially being estimated by algorithms derived from commercial LWR MOX experience. (There is no commercial experience for CANDU MOX fuel.) The argument has been made by AECL and others that the smaller bundle size and lower plutonium enrichment of the CANDU fuel should result in lower annual costs than for LWR fuel. This possibility is discussed in Sect. 2.3.7. It was again necessary to partition the annual cost calculated from the algorithm into the 24-categories needed for the LCC analysis. Table 2.19 shows the result of this partitioning and the cost basis for most of the entries. A few assumptions should be noted regarding some of the entries:

O&M Staffing (category 13)—Staff costs are based on the employment of 325 total FTEs at an average loaded salary of $77,900/year, which represents $70,000/year for directs or operators/mechanics/ technicians on the plant floor and $80,000/year for each indirect or overhead person, including plant management. The high ratio of indirects to directs (over 3) is typical of plutonium-handling facilities and reflects the stringent ES&H, regulatory, and QA requirements for operation of such facilities. The MOX fuel fabrication facility is projected to need 65 direct and 260 indirect FTEs for a total of 325 employees.

Major Capital Replacements or Upgrades (category 15)—The capital replacement rate is based on 4% of TEC per year.

Waste Handling and Disposal (category 16)—Annual waste disposal costs of $8.2M/year include the disposal of TRU and LLWs. The TRU waste disposal cost is based on 705 barrels of waste per year sent to WIPP at a cost of $10,000/bbl. LLW disposal costs are based on 5750 ft^3/year of waste at a disposal fee of $200/$ft^3$. It should be noted that in this cost partitioning model, waste disposal costs are assumed to scale with throughput; thus, compared to the other reactor alternatives (Appendix A) this CANDU MOX fuel fabrication facility has the highest waste disposal cost because it has the highest throughput (141 MTHM/year).

Oversight (category 17)—It is assumed that NRC oversight and inspections will be paid for by FMDP. An annual cost of $1M/year is projected for this purpose.

M&O Contractor and Fees and PILT (categories 18 and 19)—M&O contractor and PILTs are calculated as fixed percentages of the total of categories 13–16.

MOX Revenue (category 21a)—The U.S. Government (DOE-FMDP) bears all of the LCCs for the CANDU MOX fuel fabrication facility. To obtain some return, it is assumed that DOE-FMDP charges the Canadian utility an annual amount for the MOX

Table 2.19. LCCs for CANDU MOX fuel fabrication facility operation

Category	Cost category description	141-MTHM/year government MOX plant in existing building	
		[Lump sum ($M)]	[Annual ($M)]
	Average annual HM throughput in MTHM/year = 141		
	Years of operation = 12.2		
	Other LCCs:		
	Staff size (total): FTEs @ $77,900/year/FTE = 325		
	Staff size (directs): FTEs = 65		
	Staff size (indirects): FTEs = 260		
13	O&M staffing	309	25.3
14	Consumables (including utilities)	611	50.2
15	Major capital replacements or upgrades	242	19.8
16	Waste handling and disposal	101	8.2
17	Oversight	12	1.0
18	M&O contractor fees (2% of categories 13–16)	25	2.1
19	PILT to local governments (1% of categories 13–16)	13	1.0
	ANNUAL RECURRING COST SUBTOTAL	1313	107.6
20	D&D (20% of TEC)	70	
21	Revenues (MOX sale)	–320	–26.2
22	Government subsidies or fees to private owned facility	N/A	
23	Transportation of plutonium forms to facility (or T&PT)	18	1.5
24	Storage of plutonium at existing 94-1 site facility	N/A	
	TOTAL OTHER LCC	$1081	$82.9

fuel that is the same as the amount the utility pays for natural uranium (NATU) CANDU fuel. The cost equivalency is on an energy basis, and it takes 1.7 times as much CANDU NATU fuel to produce the same amount of electrical energy as one unit of MOX fuel. Given that CANDU natural uranium fuel costs on the order of $100/kg HM, the total revenue to FMDP can be calculated by multiplying this unit cost times 1.7 times the number of kilograms of MOX charged to the CANDU reactors annually. Over the 12.2 years of MOX use, this number totals $320M in revenue to the United States. This amount makes the Canadian utility indifferent in the cost sense to the choice of uranium or MOX fuel. Any financial incentive to the utility is assumed to be handled by the fee (category 22 in the reactor facility cost estimate).

Transportation (category 23)—The annual transportation cost of $1.5M/year represents transportation of PuO_2 powder from the existing SRS PuP facility to the MOX fuel fabrication facility site and the transportation of wastes from the facility to their final disposal site.

Summing the partitioned recurring and transportation costs gives a total of $82.9M/year for the MOX fuel fabrication facility. Examination of this value by a European LWR MOX vendor indicates that it is reasonable for a plant of this size that uses a site shared with other plutonium-handling functions.

2.3.5 MOX Fuel Fabrication Facility D&D

The MOX fuel fabrication facility will be constructed for the sole purpose of dispositioning surplus plutonium identified by this program. At the completion of this mission the facility will be promptly decontaminated and decommissioned.

2.3.5.1 MOX Fuel Fabrication Facility D&D Schedule

The duration for the D&D of the facility has been estimated to be 2 years (Table 2.20).

2.3.5.2 MOX Fuel Fabrication Facility D&D Costs

At the end of the weapons-usable plutonium MOX campaign, it is assumed that the MOX fuel fabrication facility will not be used for commercial MOX fabrication and that the plant will undergo D&D. The goal of D&D is not to return to greenfield but rather removal and disposal of contaminated equipment and return of the building to a habitable status. At this stage of cost estimating D&D is usually calculated as a percentage of TEC.

A 10% rule of thumb is common for new or greenfield facilities. A higher value of 20% is used here because the TEC is low compared to a greenfield facility and FMDP will be required to return a clean building to the site management at end of life. Therefore, 20% of $350M provides $70M for D&D (cost category 20).

2.3.6 MOX Fuel Fabrication Facility Schedule Summary

The overall MOX fuel fabrication facility implementation schedule is summarized in Table 2.20 and shown in Fig. 2.7. This schedule does not include any contingency for schedule slip due to site selection difficulties, redesign, construction delays, or a delay in the approval of line item funding.

The critical path through development of this facility is through the conceptual design and the NRC licensing process before construction may begin. If either of these tasks slip in their schedule, the rest of the implementation process will also be delayed. This critical path is shown in Fig. 2.7.

2.3.7 MOX Fuel Fabrication Facility Cost Summary

Table 2.21 shows a summary of the base case MOX fuel fabrication facility LCCs in the 24-category format. All anticipated related costs from FY 1997 forward are included in this table.

The cost-estimating algorithms were derived mainly from data on greenfield MOX fuel fabrication facility estimates prepared by vendors of LWR fuel. In these algorithms the main scaling parameter is the HM throughput of the plant. Because of the low plutonium-loadings of CANDU fuel, the heavy metal throughput required to service the CANDU options is very high compared to LWRs (i.e., around 140 MTHM/year compared to a range of 50–120 MTHM/year for LWR MOX fuel fabrication

Table 2.20. MOX fuel fabrication facility schedule summary

Task ID	Task name	Duration (months)	Start	Finish
1.	**FMDP Record of Decision**			12/1996
2.	**Congressional Funding Approval**	36	12/1996	12/1999
5.	**Fuel Qualification Demonstration**	60	4/1996	4/2001
6.	**Site and Facility Selection**	12	12/1997	12/1998
7.	**Select M&O Contractor**	12	12/1998	12/1999
8.	**Licensing and Permitting**	60	12/1997	12/2002
12.	**Design Process**	60	12/1996	11/2001
16.	**Facility Modification**	36	12/2001	12/2004
20.	**Preoperational Phase**	24	12/2004	12/2006
21.	**PuP Facility Lead Time Complete**			9/2006
22.	**MOX Fuel Fabrication Facility Ready for PuO_2**			12/2006
26.	**Reference MOX Operation**	60	12/2006	12/2011
27.	**CANFLEX Operation**	86	12/2011	2/2019
28.	**D&D**	24	2/2019	1/2021

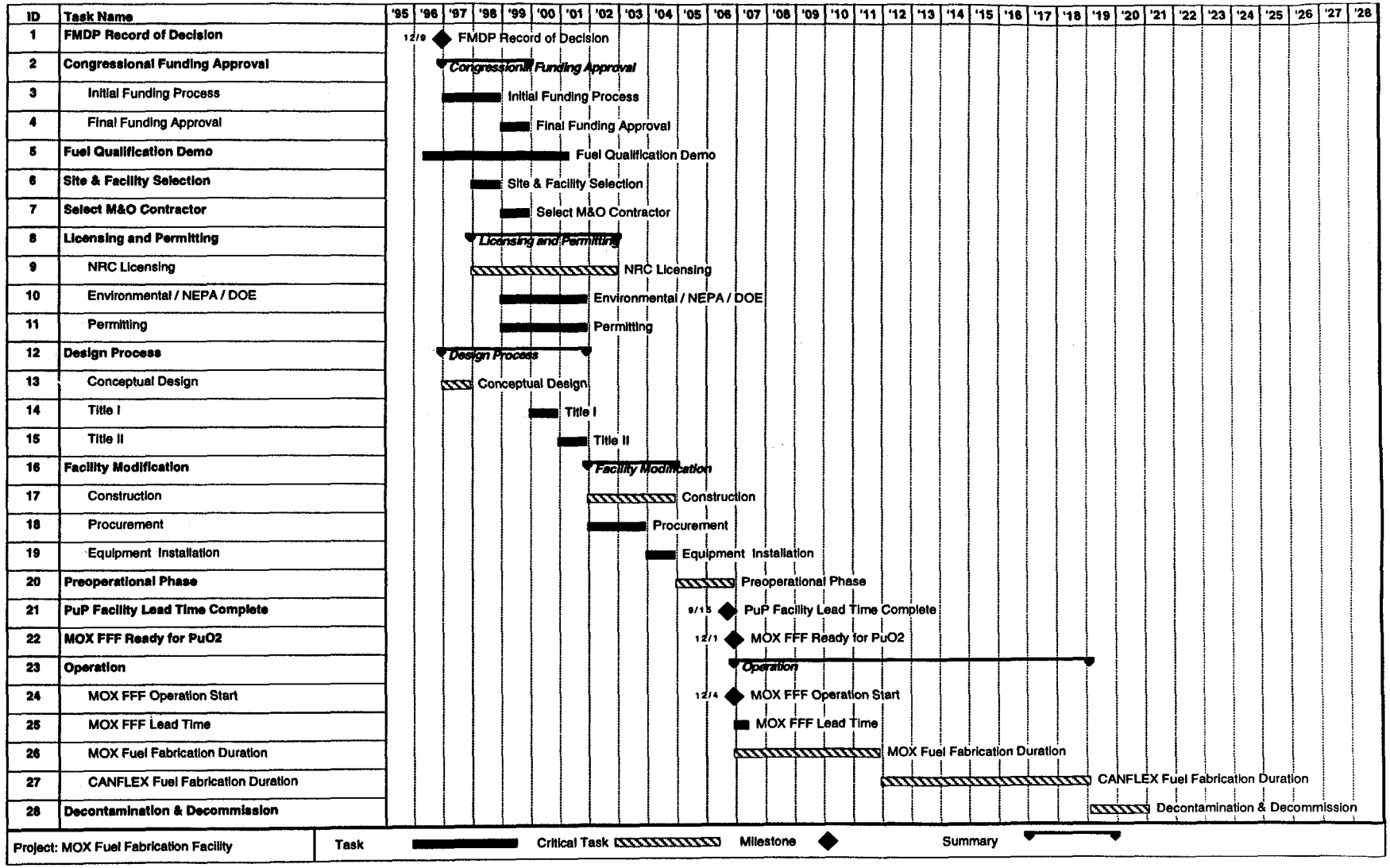


Figure 2.7. MOX fuel fabrication facility schedule summary

Table 2.21. LCCs for CANDU MOX fuel fabrication facility in 24-category format

Category	Cost category description	141-MTHM/year government MOX plant in existing building	
		[Lump sum ($M)]	[Annual ($M)]
	Average annual HM throughput in MTHM/year = 141		
	Years of Operation = 12.2		
	Preoperational or OPC up-front costs:		
1	R&D	21	N/A
2	NEPA, licensing, permitting	35	N/A
3	Conceptual design	2	N/A
4	Implementation plans: QA, site qualification, S&S plans	1	N/A
5	Postconstruction start-up	41	N/A
6	Risk contingency	0	N/A
	SUBTOTAL OPC	100	N/A
	Capital or TEC up-front costs:		
7	Title I, II, III engineering, design, and inspection	56	N/A
8a	Capital equipment	175	N/A
8b	Direct and indirect construction/modification	60	N/A
9	Construction management (included in category 8b)	0	N/A
10	Initial spares (technology dependent)	14	N/A
11	AFI (15% of categories 7–10)	45	N/A
12	Risk contingency	0	N/A
	SUBTOTAL (TEC)	350	N/A
	TOTAL UP-FRONT COST(TPC)	450	
	Other LCCs:		
	Staff size (total): FTEs = 325		
	Staff size (directs): FTEs = 65		
	Staff size (indirects): FTEs = 260		
13	O&M and staffing	309	25.3
14	Consumables (including utilities)	611	50.1
15	Major capital replacements or upgrades	242	19.8
16	Waste handling and disposal	101	8.2
17	Oversight	12	1.0
18	M&O contractor fees (2% of categories 13–16)	25	2.1
19	PILT to local governments (1% of categories 13–16)	13	1.0
	RECURRING COST SUBTOTAL:	1,313	107.6
20	D&D (20% of TEC)	70	
21	Revenues from MOX sales	–320	–26.2
22b	Government subsidies or fees to private-owned facility	N/A	
23	Transportation of plutonium forms to facility	18	1.5
24	Storage of plutonium at existing 94-1 site facility	N/A	
	TOTAL OTHER LCC	$1,081	$82.9
	GRAND TOTAL ALL LCC (1996 dollars)	$1,531	

facilities). The same algorithms for all MOX plants, CANDU or LWR, were used for reasons of consistency, given the very preliminary status of the MOX estimates. These algorithms may overestimate the cost of CANDU fuel fabrication due to the fact that the CANDU fuel bundle is smaller and less complex than an LWR bundle. The lower plutonium enrichment may make CANDU MOX powder easier to handle than LWR MOX powder.

Two costing modifications have been considered; the first deals with only the annual operating cost and staffing for the CANDU MOX fuel fabrication facility and uses the same proposed building as the base case presented in Sect. 2.3.2.2. The second deals with all components of the LCC and analyzes the proposed location of the MOX fuel fabrication facility in the Hanford FMEF, an existing hardened building on the Hanford reservation originally built for fabrication of liquid metal reactor plutonium-based fuel. Table 2.22 shows the MOX fuel fabrication facility LCCs for three different cases: (1) the CANDU base case for the TSR and this Reactor Alternative Summary Report (RASR); (2) the case where the annual O&M cost is reduced; and (3) a case for an FMEF-based MOX fuel fabrication facility. The table also shows the savings in the overall LCCs that would result from these changes, provided the PuP facility and reactor costs remain the same. The first set of proposed changes would remove $177M in LCCs from the RASR CANDU MOX fuel fabrication facility estimate, and the second set of proposed changes would remove $726M in LCCs.

2.3.8 MOX Fuel Fabrication Facility Technical Viability

DOE has identified five items the consideration of which constitutes a qualitative assessment of the technical viability of a concept: a definition of the technological maturity of a process; the specification of the technical unknowns for the process and the technical risk associated with the application of the process; research and engineering development needs of the process, the condition, capacity, and reliability of the infrastructure; and, lastly, the regulatory and licensing requirements associated with the process. The first three of these items are discussed in this section. The infrastructure is discussed within the facility description and design and construction sections. The licensing item is discussed in a separate section for each facility.

Technological Maturity—MOX fabrication is a well-developed technology, considerably into the industrialization/commercialization stage, with commercial LWR MOX plants currently operating in Great Britain [British Nuclear Fuels, Limited (BNFL)], France (COGEMA), and Belgium (Belgonucleaire). Most of the processes employed in these commercial operations will also be employed in the U.S. MOX fuel fabrication facility. European LWR MOX experience will likely be combined with Canadian reference fuel and CANFLEX fuel experience with natural uranium to develop the appropriate fuels for use in the FMDP.

Variations from commercial technology will be required to meet the goals of the disposition program. These new/additional processes are at varying levels of technological development (from the "idea" stage for the addition of burnable absorbers to the MOX to the commercialized but proprietary stage for processes to ensure fuel homogeneity).

An important variation from commercial technology will be the use of weapons-grade plutonium isotopics instead of reactor-grade fuel. However, this change will likely not influence the choice of technology but only the engineering implementation of a technology (e.g., sizing of equipment).

The small size of CANDU bundles (10-cm diam, 50-cm length) simplifies glovebox production when compared to the 366-cm length of LWR fuel pins. The burnable poison for CANDU fuels is not an integral part of the MOX fuel. The poison is contained in separate, depleted uranium oxide pins. Fuel testing for the poisoned pins has already been conducted. The fissile content of the CANDU CANFLEX fuel is approximately the same as in the existing LWR fuel. However, the fissile content is considerably higher than for the reference CANDU fuel. Hence, criticality safety and shielding will be a greater concern for CANFLEX fuel relative to CANDU reference MOX fuel. (For the natural uranium CANDU fuel cycle, there are no criticality safety concerns in the fuel fabrication facility.) An optimized MOX facility would require that equipment be sized and shielded on the basis of CANFLEX fuel production.

Technical Risks—Certain technologies have associated technical unknowns. Generally these unknowns are parameters whose values are known for certain "reference" fuel cycles but whose behavior for MOX

Table 2.22. Comparison of CANDU MOX fuel fabrication facility LCCs

Category	Cost category description	Case 1 CANDU 2–4 reactor base case		Case 2 CANDU 2–4 alternative with revised MOX O&M cost per LANL		Case 3 CANDU 2–4 alternative with FMEF MOX LCCs supplied by AECL	
	Cost type	Lump sum ($M)	Annual ($M)	Lump sum ($M)	Annual ($M)	Lump sum ($M)	Annual ($M)
	Average annual HM throughput in MTHM/year = 141 Years of operation = 12.2						
	Preoperational or OPC up-front costs:						
1	R&D	21		21		8	
2	NEPA, licensing, permitting	35		35		13	
3	Conceptual design	2		2		3	
4	QA, site qualifications, S&S	1		1		2	
5	Postconstruction start-up	41		41		13	
6	Risk contingency	0		0		15	
	SUBTOTAL OPC	100		100		54	
	Capital or TEC front-end costs:						
7	Title I, II, III engineering, design, and inspection	56		56		34	
8a	Capital equipment	175		175		24	
8b	Direct and indirect construction/modification	60		60		12	
9	Construction management	0		0		7	
10	Initial spares (technology dependent)	14		14		7	
11	Allowance for indeterminates (AFI)	45		45		16	
12	Risk contingency	0		0		0	
	SUBTOTAL (TEC)	350		350		100	
	TOTAL UP-FRONT COST (TPC)	450		450		154	

Table 2.22. Comparison of CANDU MOX fuel fabrication facility LCCs (cont.)

Category	Cost category description	Case 1 CANDU 2–4 reactor base case		Case 2 CANDU 2–4 alternative with revised MOX O&M cost per LANL		Case 3 CANDU 2–4 alternative with FMEF MOX LCCs supplied by AECL	
	Cost type	Lump sum ($M)	Annual ($M)	Lump sum ($M)	Annual ($M)	Lump sum ($M)	Annual ($M)
	Other LCCs:						
	Staff size total: FTEs = 325 Staff size (directs): FTEs = 65 Staff size (indirects): FTEs = 260						
13.	O&M staffing	309	25.3	309	25.3	310	25.4
14	Consumables include utilities	611	50.2	439	36.0	315	25.8
15	Major capital replacements or upgrades	242	19.8	242	19.8	44	3.8
16	Waste handling and disposal	101	8.2	101	8.2	50	4.3
17	Oversight	12	1.0	12	1.0	46	4.0
18	M&O contractor fees (2% of categories 13–16)	25	2.1	22	1.8	126	10.9
19	PILT to local governments (1%)	13	1.0	11	0.9	7	0.6
	SUM	1313	107.6	1135	93.1	913	74.9
20	D&D (20% of TEC)	70		70		40	
21	Revenues from MOX sales	–320	–26.2	–320	–26.2	–320	–26.2
22	Government subsidies or fees to privately owned facility	0		0		0	
23	Transportation of plutonium forms to facility	18	1.5	18	1.5	26	1.8
24	Storage of plutonium at existing 94-1 site facility						
	TOTAL OTHER LCC	$1081	$82.9	$904	$74.1	$659	$54.0
	GRAND TOTAL ALL LCC	$1531		$1354		$813	
	SAVINGS FROM CASE 1	0		$177		$726	

fuel cycles is unknown or poorly known. Consequently, risks are associated with the application of the technologies based on these parameters.

MOX fabrication is a well-developed technology with a large amount of commercial experience. One technical issue that must be resolved is that the plutonium feed material will have impurities that are not present in plutonium that results from reprocessed LWR spent fuel. Specific technical issues that must be resolved include acceptable chemical interactions with fuel and/or clad and demonstration of acceptability of plutonium oxide from multiple feed stocks and proper treatment of waste.

The risks associated with these technical unknowns (except for the waste studies) are all the same. Unacceptable fuel production will delay the disposition of plutonium and jeopardize achievement of program goals. If fuel fails in the reactor, then the reactor may be damaged. Even if no damage occurs, failed fuel will have a less-than-desired burnup and may be unshippable to or unacceptable by the repository. Improper treatment of wastes would likely increase the cost of the disposition program. The degree of risk associated with the MOX fabrication facility procedure is thought to be low.

Research and Engineering Development Needs— Previously, various parameters are identified as unknown or poorly known for this alternative. Research and engineering development are necessary to address each of these technology development needs.

Four R&D items are associated with MOX fabrication.

- Large-scale impurity removal: DOE surplus plutonium contains impurities that might be unacceptable to either fabrication or reactor operations and thus require removal. The R&D proposed to resolve this issue is focused on developing impurity removal processes that would have minimal waste streams.

- Feed plutonium impurity impact: As indicated before, the feed material of interest contains impurities that might adversely affect either fabrication or reactor operations. However, it is not certain that the effect of these impurities will be unacceptable, so R&D has been proposed to determine if removal of impurities is unnecessary.

- PuO_2 feed morphology: The powder-blending stage of the fuel fabrication process is extremely sensitive to the morphology of the powder feeds. Because the feed material is coming from a variety of sources, it will be necessary to demonstrate that the morphology of the oxides can be altered to meet feed specifications.

- Process scrap recovery: Technology currently exists for recovery and recycle of materials that fail to meet specifications at the various stages of fabrication. However, these processes are all aqueous-based processes and are significant waste generators. Several advanced processes have been proposed that would perform these operations with dramatically reduced waste streams. Thus, R&D is proposed to develop these other alternatives.

2.3.9 MOX Fuel Fabrication Facility S&S Summary

DOE and its predecessor agencies have successfully managed S&S of SNMs for several decades. DOE maintains an impeccable record of providing adequate measures to ensure against theft or unauthorized access to SNMs. these measures include physical security, material accountability, inventory safeguards, and other technologies. These measures have been applied to SNMs in a variety of material forms, ranging from bulk SNM powders and solutions to pits.

An assessment has been performed to identify critical vulnerabilities that might exist in operations or processes that make up the reactor disposition alternative. The purposes of the assessment were to (1) determine whether any inherent vulnerabilities exist that represent unique or novel threats to maintaining adequate measures against theft or unauthorized access and (2) identify any threats in the reactor disposition alternative operations that will require particular attention by facility designers to ensure that potential vulnerabilities are properly addressed.

This section discusses the vulnerabilities to theft and unauthorized access intrinsic to the material forms and processing environments in the plutonium processing facility. In the sense employed here, a "risk" is a set of conditions that require specific measures to ensure proper physical control of SNMs. These risks should *not* be interpreted as the overall risk that the material will be subject to in the as-built facilities. The overall risk in the as-built facility is driven to very small

values by the S&S measures incorporated in the design and operation of the facility.

Possible Diversion, Theft, or Proliferation Risks—Although the material will be changing form and concentration in this facility, it all still meets the definition for category IC material. However, with respect to both covert and overt theft there are considerable differences as the material is made into MOX fuel. The facility operations involve a large number of processing steps where material is relatively accessible. The input material will be fairly pure oxide powder; the risk to covert and overt theft is greatest in the early process steps. As the PuO_2 is blended with UO_2 to make pellets, the concentration of the plutonium decreases. Because these forms are accessible and transportable, they are still attractive targets for both covert and overt theft, although more material would be needed to make a nuclear device. After the pellets are fabricated into fuel pins and subsequently into fuel assemblies, they are much less transportable; thus, they become more difficult for overt theft. Likewise, the fissile material within the fuel pins and assemblies is no longer physically accessible and is now accounted for using item accountancy, thereby reducing the opportunities for covert theft to a low risk and overt risk to medium.

Environmental Conditions—Table 2.23 provides process environmental conditions, material form, and other S&S information. The environment for the first part of the MOX fuel fabrication facility is very similar to that of the PuP facility, and the risk is high; after fuel pins and assemblies are made, the risk becomes medium. The MOX fuel fabrication facility will be a Category I facility with a high throughput and a nearly continuous operation. No intrasite transport will be required outside the MAA, and again SSTs will be used to both deliver and pick up the material.

Material Form—As in the case of the PuP facility, the initial feed material is very attractive material (IC). The intrinsic attributes of this material are the same as described above. Once the material has been blended, it would be slightly more difficult to convert to a weapons-usable form, and because the concentration of the plutonium is lower, more material would be required to acquire a significant quantity. Once the MOX is placed into fuel pins and then fuel assemblies, its chemical, isotopic, and radiological attributes would not change, but the mass/dimensions of the "containers" would increase, thus making it more difficult to move.

S&S Assurance—During the initial processing operations—until the material is placed into the fuel pins—bulk accountancy would be conducted, and then item accountancy would be performed. Although devices are being developed to perform NDA on fuel pins/assemblies, this is still a very time consuming activity. Once the material is placed inside the fuel pins, it is not accessible and requires special handling equipment to move the assemblies.

Potential Risks to Diversion—Similar diversion opportunities exist in this facility for the initial process operations, as exist in the PuP facility. After the material has been blended, it becomes a less attractive target. Once the material is made into fuel pins and assemblies and item accountancy is used, the possibility for diversion is reduced and the risk is medium. Because the fuel pins and assemblies are quite large and require special handling equipment, containment and surveillance measures can more easily detect diversion attempts.

Difficulty of Diversion, Retrieval, Extraction, and Reuse—The attractiveness of the material in the early processing steps is similar to the PuP activities and is high. If diversion does occur, only moderate chemical barriers exist to prevent conversion and reuse, and the risks are medium. Once the material is blended, the concentration of plutonium is decreased, and its attractiveness is reduced. Once the material is made into MOX fuel and placed into fuel pins and assemblies, the material becomes more difficult to divert.

Assurance of Detection of Retrieval & Extraction—The front-end operations in this facility are similar to those in the PuP facility. After the material has been blended, a greater amount of material will be required to accumulate a significant quantity. Once it has been placed into fuel pins and assemblies, the individual items will be accounted for, increasing the ability to detect diversion.

2.4 Existing CANDU Reactor Facility

The CANDU reactor facility takes in MOX fuel containing surplus plutonium and irradiates it to achieve the characteristics defined in the FMDP SFS.

Table 2.23. Nonproliferation and S&S risk assessment for the CANDU MOX fuel fabrication facility

Environment								
Facility	**Activity**	**Duration**	**Throughput plutonium**	**Waste streams**	**Maximum plutonium inventory**	**Intrasite transport**	**Number of processing steps**	**Barriers**
MOX fuel fabrication facility			2.9 MT Reference 4.9 MT CANFLEX	Yes (1 g/L)	4.9 MT	No	5	
	Receiving and storage	2 month	500–700 kg plutonium			No, SST unload	0	
	MOX fuel fabrication	1 year	2990–4900 kg batch			No	5	Glovebox
	Fresh fuel shipping	1 month	755–875 bundles 0.33–0.47 kg/ plutonium bundle			No, SST load	0	
Transport	MOX fuel fabrication to reactor							

Table 2.23. Nonproliferation and S&S risk assessment for the CANDU MOX fuel fabrication facility (cont.)

Material form										
Facility	**Activity**	**SNM input**	**SNM output**	**Quantity**	**Concentration of plutonium (other)**	**SNM category***	**Item mass/ dimensions**	**Radiation barrier**	**Chemical composition**	**Isotopics**
MOX fuel fabrication facility					0.068 g plutonium/g HM	DUU				
	Receiving and storage	Oxide, MOX fuel unirradiated	Metal, oxide, MOX fuel			IC		No	Oxide	
	MOX fuel fabrication	Oxide	Fuel assemblies			IC		No	Oxide, pellets, pins, assemblies	
	Fresh fuel shipping	MOX fuel assemblies (fresh)	Fuel assemblies			IC	24 kg 10 × 50 cm	No		
Transport	MOX fuel fabrication to reactor									

*See Table 2.12.

Table 2.23. Nonproliferation and S&S risk assessment for the CANDU MOX fuel fabrication facility (cont.)

S&S								
Facility	**Activity**	**Number of MBAs**	**Type accounting system**	**Nuclear measure**	**Classified material**	**Physically accessible**	**Access**	**Special handling equipment**
MOX fuel fabrication facility		~5	50% Item	0.6% (domestic) 2.5% (international)				
	Receiving and storage		Both	Calorimetry, neutron, gamma	No	Yes	Hands-on	No
	MOX fuel fabrication		Bulk		No, proprietary	No	Hands-on, remote	No–Yes (for pins/ assemblies —crane)
	Fresh fuel shipping		Item		No	No		Yes (for assemblies—crane)
Transport	MOX fuel fabrication to reactor					Yes		

Note: MBA—material balance area.

2.4.1 CANDU Reactor Facility Description

Bruce nuclear generating station (NGS) A has been selected as the reference station for this study. Bruce NGS A is a four-unit station located on the northernmost point of the 2300-acre BNPD site. BNPD is located on the eastern shore of Lake Huron, approximately 300 km northeast of Detroit. In addition to Bruce NGS A, the BNPD site (Fig. 2.8) also has the four-unit Bruce B station; the Bruce Heavy Water Plant; a steam transformer plant associated with Bruce NGS A, providing process steam heat to the site as well as to the Bruce Energy Centre; and an industrial development site adjoining the BNPD. The decommissioned Douglas Point prototype CANDU power reactor is also located at BNPD, together with a fully operational, safeguarded dry-fuel storage facility containing all the spent fuel from operation of Douglas Point.

Although all CANDU reactors can utilize fissile plutonium in the form of MOX fuel, Bruce NGS A has been selected as the reference plant because of a number of favorable technical and site-related reasons:

1. The Bruce NGS A reactors are designed with an unflattened core; that is, they do not have normally inserted thermal-neutron-absorbing control pins that are used to "flatten" the power distribution in the central, high-powered region of the core. The use of MOX fuel in CANDU, as opposed to natural uranium fuel, in conjunction with associated fuel management schemes, would also tend to flatten the power distribution, which is beneficial to thermal power margins.

2. Bruce NGS A is operated as a base-load station, which is considered desirable for the plutonium disposition mission since this minimizes the total dispositioning time and does not subject fuel to load-maneuvering power changes. Consequently, there is no required change in operating mode for the station, nor is there an impact on Ontario Hydro's grid system control strategies.

3. Bruce NGS A is located at a site with a significant, well-developed infrastructure, remote from major population areas, with reasonably close access to the United States via the Port Huron/Sarnia border crossing. This access limits fuel transportation mileage.

4. Bruce NGS A has up-to-date IAEA safeguards and perimeter intrusion security systems.

CANDU reactors use a number of pressure tubes (480 in the case of a Bruce reactor) instead of a single large pressure vessel used with U.S. LWRs. When the pressure tubes reach the end of their life, the utility decides whether to replace them ("retube"), depending upon such factors as the demand for electricity and the marginal cost of options for incremental generating capacity. Replacing the pressure tubes in a unit takes about 2 years and has been proven economically successful as Ontario Hydro retubed all four units at Pickering NGS A, the last of which was retubed in 19 months. Current planning projects that the pressure tubes in the four Bruce NGS A units will reach their end of life over the period 1995 to 2008; with Unit 2 starting in 1995 and Units 1, 3 and 4 in the years 2000, 2008 and 2006, respectively. Early retubing may be accomplished if necessary to meet the plutonium disposition project schedule.

For the purposes of this study, it is assumed that during the mission time, the average capacity factor of the units is 80%, which is generally consistent with Ontario Hydro's experience and, in the case of Bruce NGS A, takes into account factors that have limited capacity in the past, such as transmission line capacity limitations from the BNPD site during part of the 1980s and Ontario Hydro's recent voluntary derating of the eight Bruce units to maintain safety margins while safety-related, corrective design modifications were being implemented.

2.4.1.1 Process Operation Descriptions

The reactor facility has four major processing and handling steps: storage and handling of fresh MOX fuel, irradiation of MOX fuel in the reactors, and storage of irradiated ("spent") nuclear fuel in on-site water pools comprise the first three process steps. Ideally, after a 10-year postirradiation period spent fuel will be removed from the spent fuel pools and be transported directly to an HLW repository for final disposal. However, in the event that the HLW repository may not be ready in time to receive spent fuel, the reactor process also includes a fourth process step whereby spent fuel would be removed from the pools and placed into on-site dry storage in specially designed canisters. This practice is currently in place at the BNPD site.

Fresh MOX Fuel Storage and Handling—The reactor facility MOX-handling process for new fuel is based on provision of a new fuel storage building on

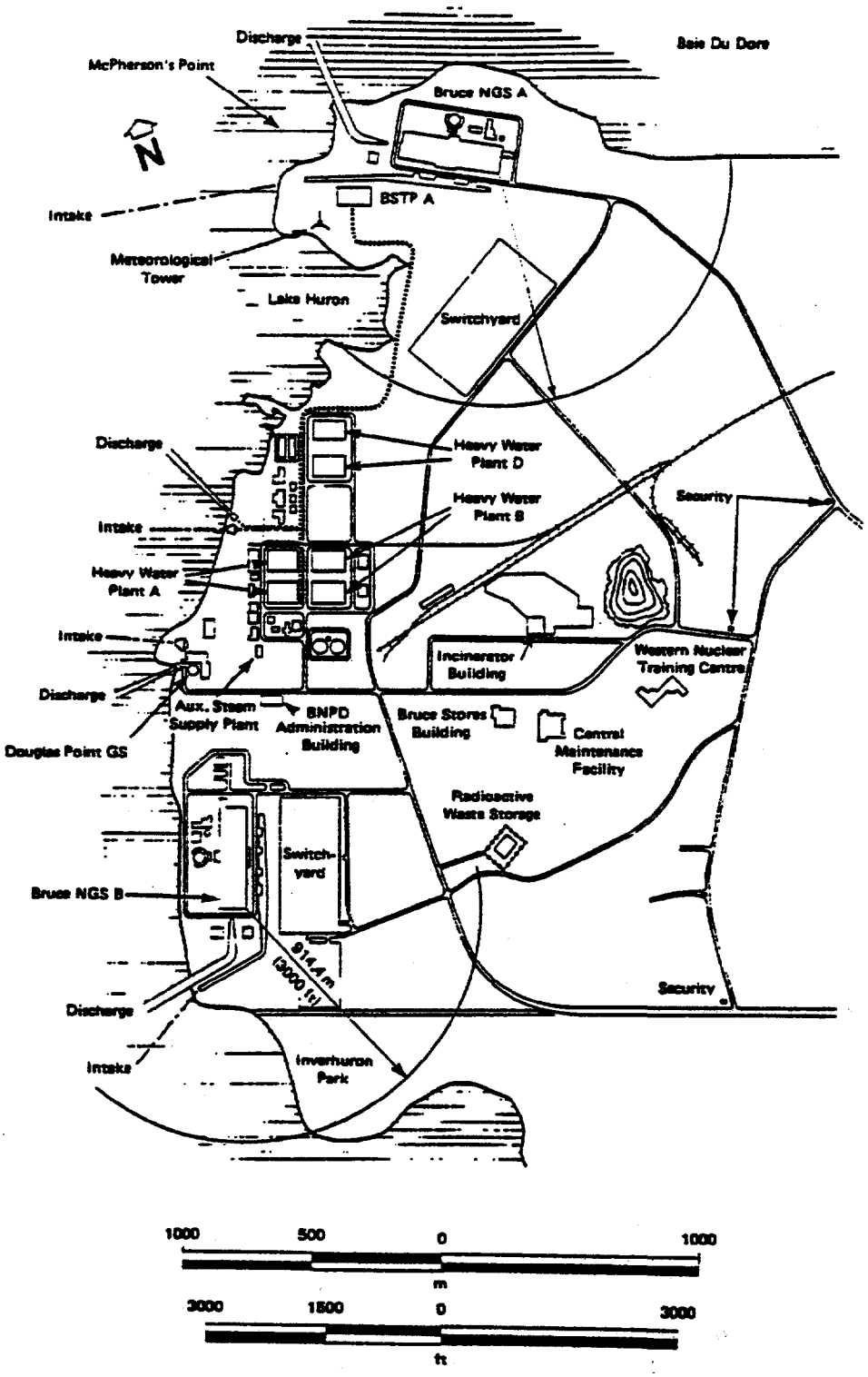


Figure 2.8. BNPD site layout

the Bruce-A site adjacent to the existing common services area of the station. This building will be a secure facility for receiving, inspecting, and storing new fuel transported to the site by SSTs.

A new 8500-ft^2 MOX fuel storage building will need to be built as shown in Fig. 2.9. This size includes 1200 ft^2 for a hardened corridor to transfer MOX fuel from the receiving facility to the new fuel transfer room. The new MOX fuel storage building is sized to maintain a minimum fuel inventory for two units for 3 full-power months.

The new fuel storage building will be an IAEA Category I facility with a reinforced concrete floor, walls, and roof. An internal security fence surrounding the SST parking area and building will provide security access. In addition, the building will have controlled access entrances, alarms, and additional internal security features.

New fuel will be moved from the new fuel storage building to the existing new fuel-loading room where it is loaded into fueling machines. Each day, 24 reference bundles will be moved to the new fuel-loading room for 2 units operating on reference fuel, and 28 CANFLEX bundles will need to be moved to the loading room for 4 reactors operating on CANFLEX fuel. The existing new fuel-loading room will be hardened to IAEA Category I requirements with additional access control and security provisions.

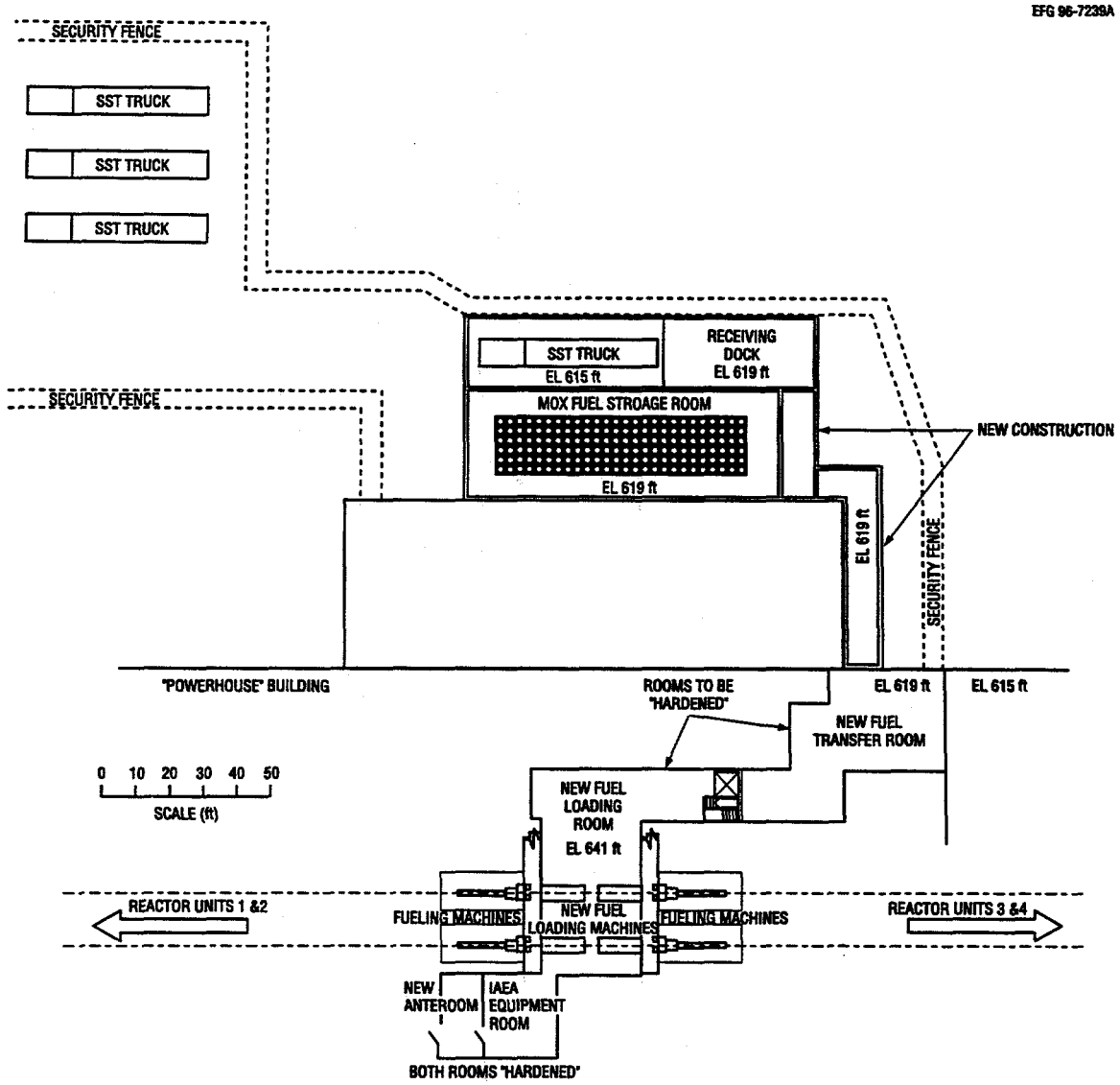


Figure 2.9. New fuel storage building

Irradiation in Reactor—Fuel transfer from the new fuel-loading area to the reactors is performed by the fueling machine, which is shown in Fig. 2.10. This machine is remotely controlled from the main control room by means of computers. Fueling is accomplished while the reactor is operating. The reactor vessel (known as the calandria) is shown in Fig. 2.11. A simplified station flow diagram for one Bruce-A unit is shown in Fig. 2.12.

For reference MOX fuel, each unit is fueled at an average rate of 15 bundles per full-power day. Reference fuel bundle residence in-core is an average 360 full-power days for an average burnup of 9700 MWd/MT (corresponding to 450 calendar days at an 80% capacity factor). For CANFLEX fuel, each unit is fueled at an average rate of nine bundles per full-power day and also resides in-core for 450 calendar days for an average burnup of 17,100 MWd/MT.

Spent Fuel Pool Storage—Spent fuel bundles removed from the reactor are transferred by the same remotely controlled fueling machines shown in Fig. 2.10 to the water storage pools of the irradiated fuel storage bays. The fuel bundles are placed in modules consisting of an array of 20 welded steel tubes, each tube containing 2 bundles. These modules provide a fixed geometry for bundle storage in the water pools and provide a multibundle assembly for unit operations in the water storage pools.

Irradiated fuel is first stored in trays in the primary storage bay of the fuel storage pool, which can hold 27,522 fuel bundles stacked in trays of 20 fuel bundles up to 15 trays high with 13.5 ft of water covering the top tray. Irradiated fuel is stored in the primary bay for a minimum of 6 months before being moved underwater to the secondary irradiated fuel storage bay. The layout of the secondary spent fuel pool is shown in

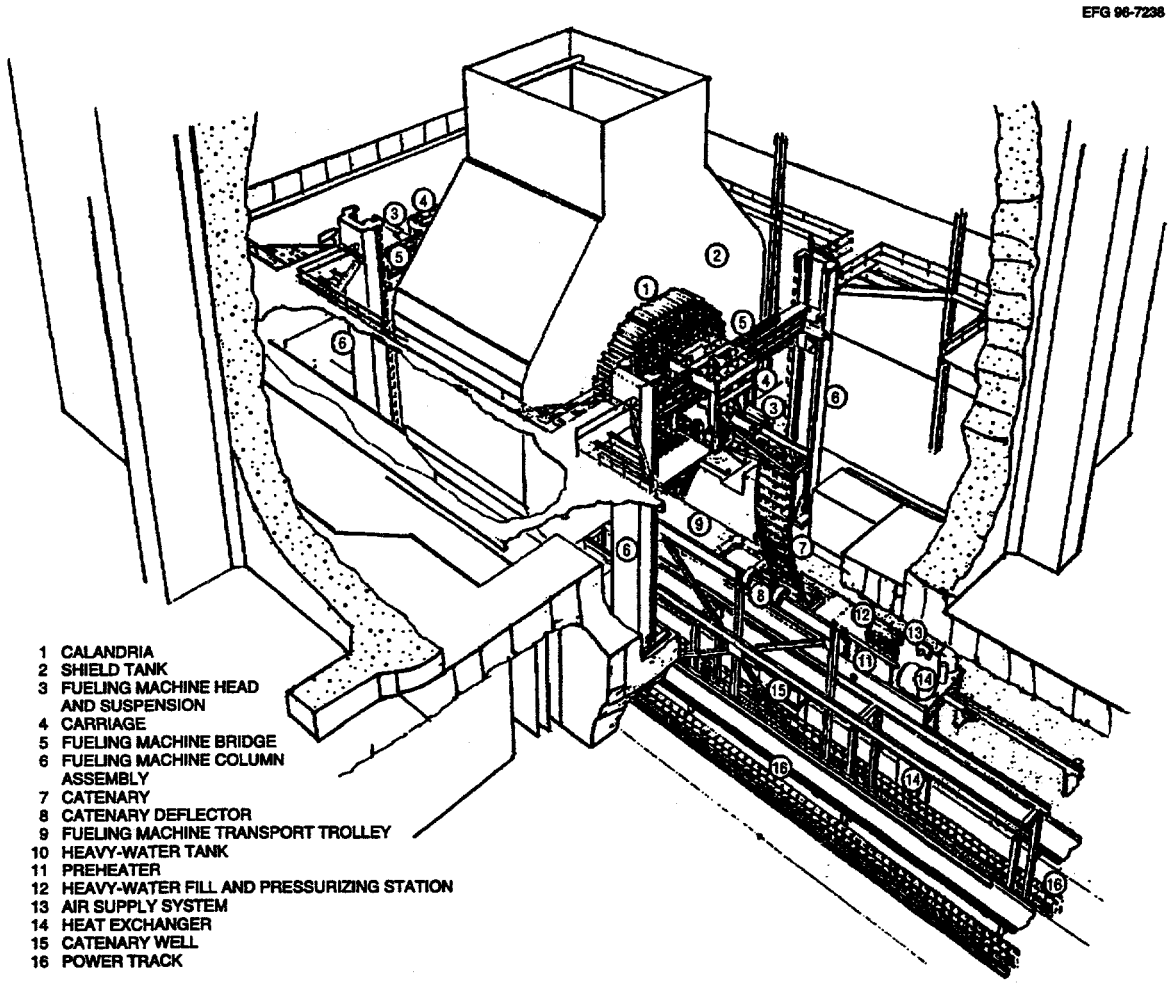
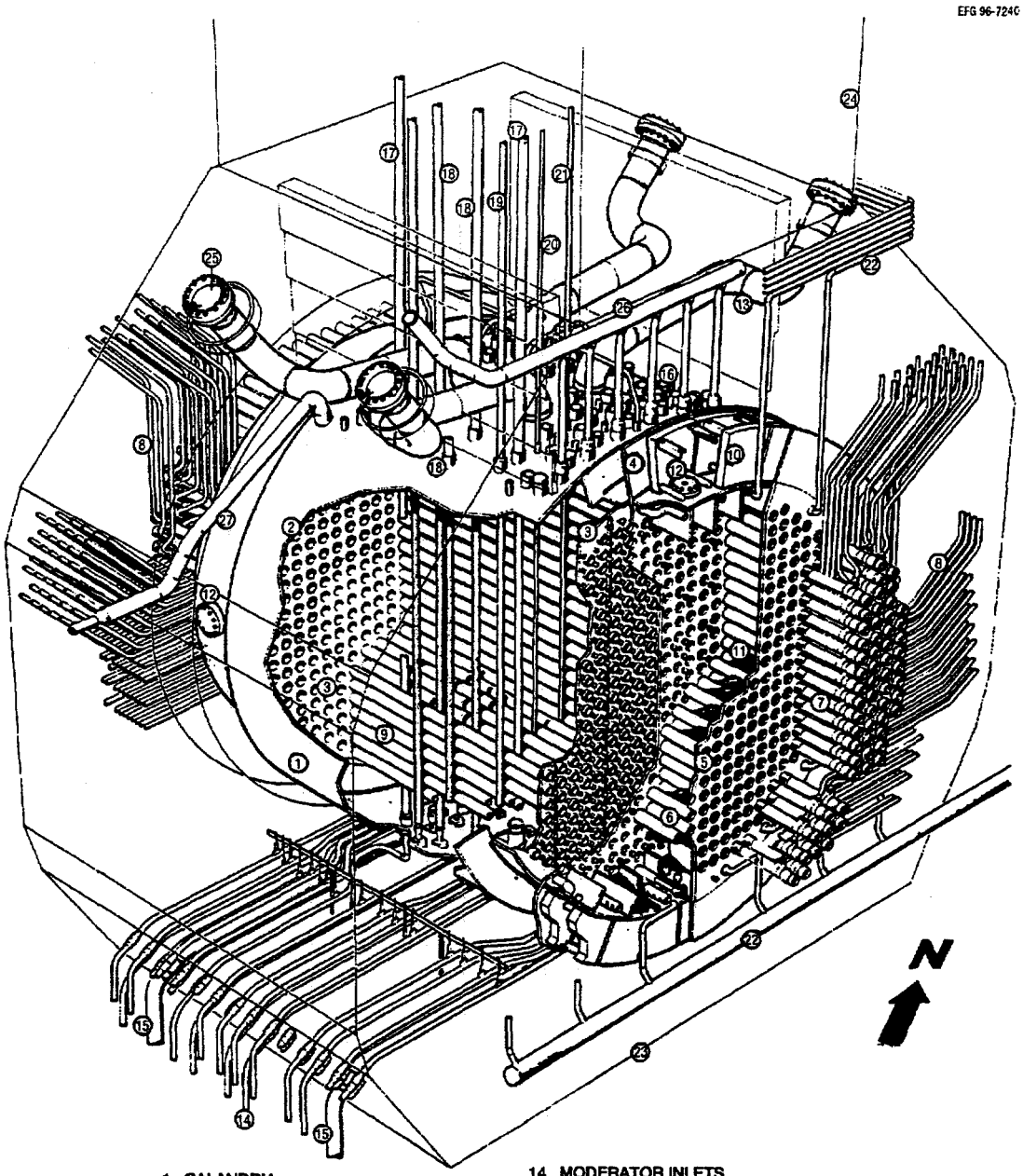


Figure 2.10. Fueling machine system



1 CALANDRIA
2 CALANDRIA SHELL
3 CALANDRIA SIDE TUBE SHEET
4 BAFFLE PLATE
5 FUELING MACHINE SIDE TUBE SHEET
6 LATTICE TUBE
7 END FITTINGS
8 FEEDERS
9 CALANDRIA TUBES
10 SHIELD TANK SOLID SHIELDING
11 STEEL BALL SHIELDING (END SHIELD)
12 MANHOLE
13 PRESSURE RELIEF PIPES
14 MODERATOR INLETS
15 MODERATOR OUTLETS
16 REACTIVITY CONTROL ROD NOZZLES
17 BOOSTER ROD
18 SHUTOFF ROD
19 ZONE CONTROL ROD
20 FLUX MONITOR
21 FLUX MONITOR AND POISON INJECTION
22 END SHIELD COOLING PIPING
23 SHIELD TANK
24 SHIELD TANK EXTENSION
25 RUPTURE DISC ASSEMBLY
26 MODERATOR INLET HEADER
27 MODERATOR OVERFLOW

Figure 2.11. Reactor assembly

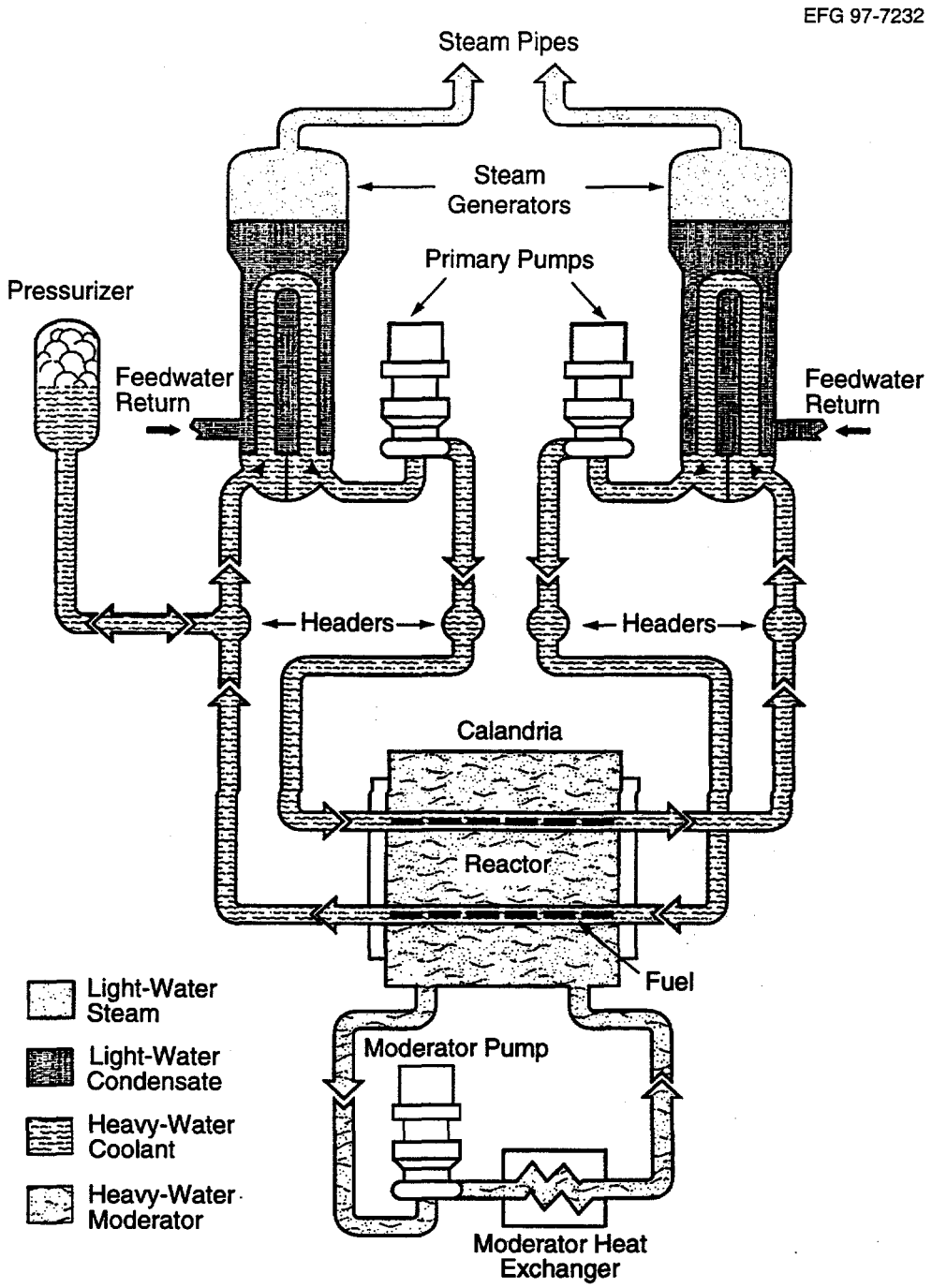


Figure 2.12. Simplified CANDU reactor flow diagram

Fig. 2.13. The secondary bay provides long-term storage of irradiated fuel until eventual transfer to dry cask storage or to an HLW repository. The secondary bay can hold up to 351,648 spent fuel bundles stacked to a maximum height of 15.4 ft.

Dry Spent Fuel Storage (Optional)—A new dry spent fuel storage facility is planned for BNPD. One module of the facility is shown in Fig. 2.14. The facility is scheduled for operation about the year 2000. This facility will be capable of storing both spent natural uranium fuel and spent MOX fuel. When this facility is operational, it will be possible to transfer the current inventory of spent natural uranium fuel to dry storage. This will permit storage of all spent MOX fuel in the storage pools. If MOX fuel is transferred to

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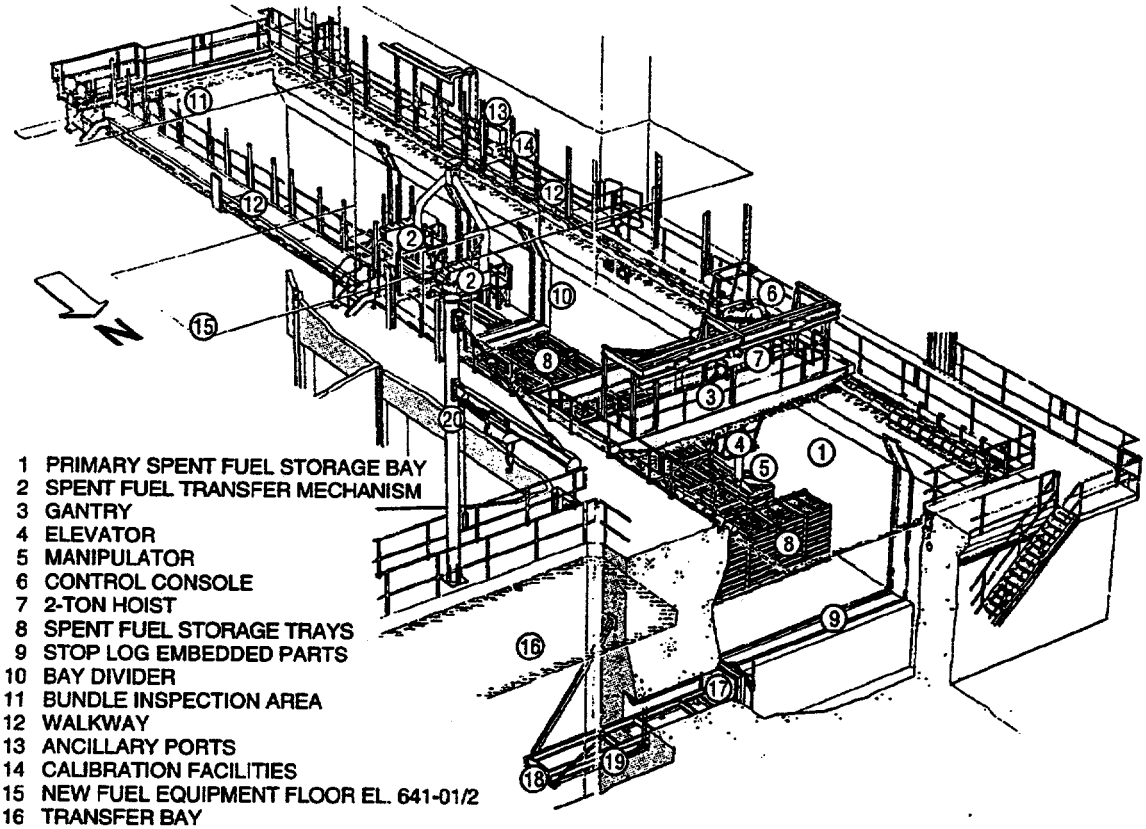


1 PRIMARY SPENT FUEL STORAGE BAY
2 SPENT FUEL TRANSFER MECHANISM
3 GANTRY
4 ELEVATOR
5 MANIPULATOR
6 CONTROL CONSOLE
7 2-TON HOIST
8 SPENT FUEL STORAGE TRAYS
9 STOP LOG EMBEDDED PARTS
10 BAY DIVIDER
11 BUNDLE INSPECTION AREA
12 WALKWAY
13 ANCILLARY PORTS
14 CALIBRATION FACILITIES
15 NEW FUEL EQUIPMENT FLOOR EL. 641-01/2
16 TRANSFER BAY
17 GATE
18 STORAGE TRAY CONVEYOR
19 CONVEYOR TRACK
20 3-TON J B CRANE

Figure 2.13. Spent fuel pool

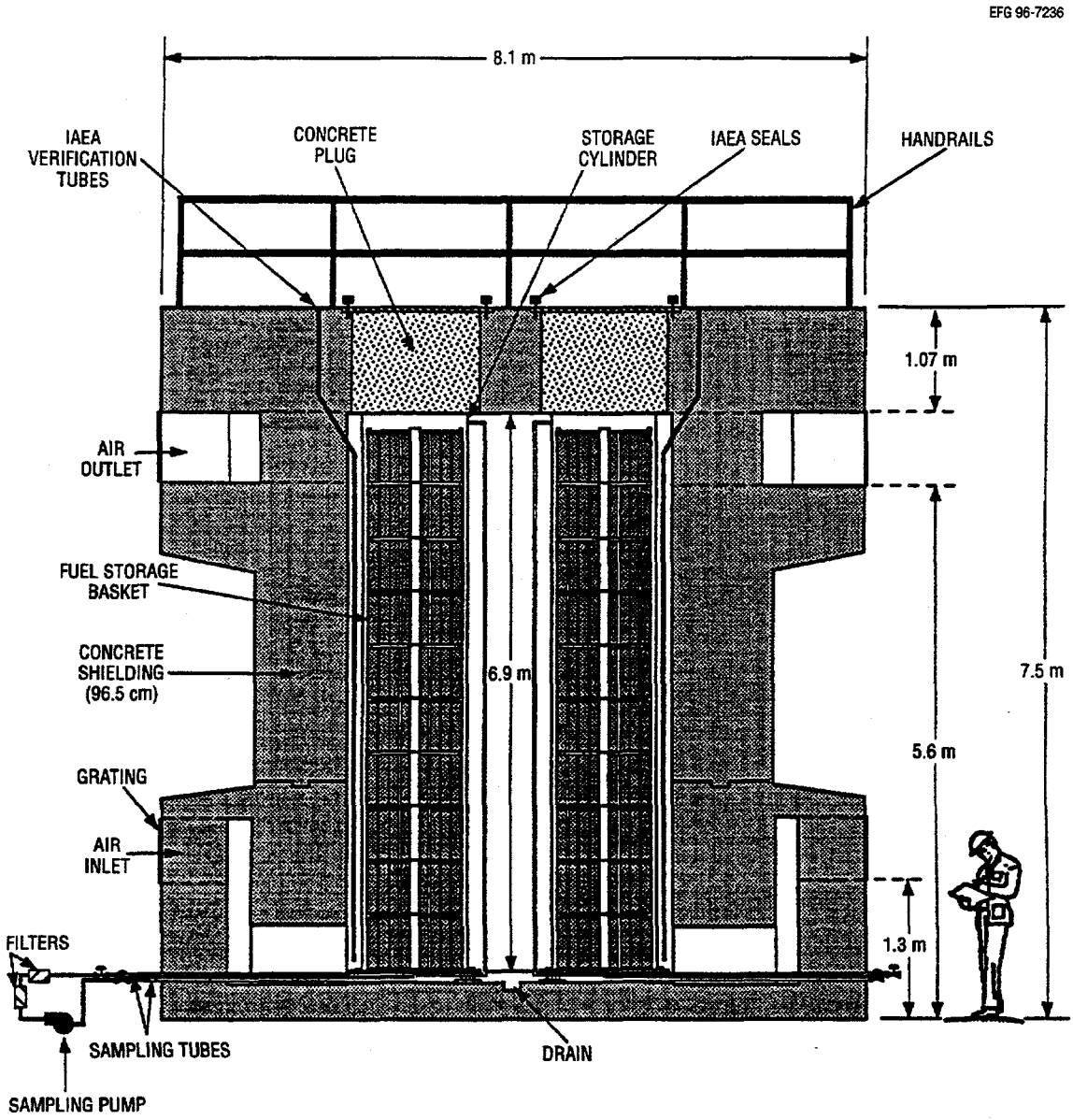


Figure 2.14. Dry spent fuel storage module

dry storage, it will be transferred to the facility in modules holding 40 fuel bundles (Fig. 2.15). Approximately eight of these modules will be stored in a vertical concrete cask, and the casks will be located on a concrete pad.

2.4.1.2 Process Stream Identification and Quantification

Table 2.24 lists the batch characteristics of each processing section of the reactor portion of the CANDU alternative.

Information concerning the plutonium disposition rate for the reactors for the two phases of this alternative is shown in Table 2.25. Fuel cycle characteristics for the reactors are shown in Table 2.26. The plutonium dispositioned and the number of assemblies moved through the facilities is displayed in Figs. 2.16 and 2.17. For the reference MOX fuel, the annual disposition of plutonium per reactor would be 1.45 MT. The annual reference MOX fuel bundle disposition would be 4525 MOX fuel bundles per reactor at a burnup of 9700 MWd/MT.

The initial core configuration of the CANFLEX-fueled reactors has not been calculated. It is planned that both the reference MOX-fueled reactors and the other two natural uranium–fueled Bruce reactors could transition to CANFLEX fuel in 3 to 6 months. After the transition to CANFLEX, each reactor would disposition 1.24 MT of plutonium per year (4.96 MT total per year). The corresponding number of fuel bundles would be reduced to 2628 per reactor per year due to the higher burnup of 17,100 MWd/MT. This is approximately half the amount of natural uranium bundles currently being used by Bruce-A reactors.

Since CANDU HWRs operate on a continuous refueling program, there are no planned shutdowns for refueling as in LWRs. Periodic outages are planned for maintenance purposes; however, these downtimes are accounted for in the 80% capacity factor used to determine throughputs, etc.

The MOX fuel-loading schedule for the entire mission is shown in Table 2.27 for the base case.

2.4.2 CANDU Reactor Facility Design and Construction

Engineering changes in the existing CANDU plants that may be required to receive, store, and handle the MOX fuel were assessed and are discussed subsequently. This review was done with assistance from Ontario Hydro personnel at Bruce-A and with the intent of ensuring that the conversion of Bruce-A units to MOX fuel does not result in any negative effects on station operability. From the standpoint of engineering changes to the plant, the largest item is the need for enhanced security for the MOX fuel. For cost information associated with these changes, see Sect. 2.4.2.2.

Receipt and Storage of New Fuel

New Fuel Storage Building—A secure facility for receiving, inspecting, and storing new fuel is required. Existing facilities and procedures used for natural uranium fuel are inadequate for MOX fuel, mostly because of the low level of security required for natural uranium fuel. An approximate size and layout for this new building was established, based on a requirement to maintain a minimum fuel inventory for two units for 1 month. A location inside the main station building was evaluated but judged too disruptive to essential station maintenance operations. A possible location for a new building is shown in Fig. 2.9, and the route for fuel transfer to the new fuel-loading room is indicated.

The new fuel storage building will be an IAEA Category I facility, with reinforced concrete floor, walls, and roof; controlled access entrances; and alarms and other security features.

New Fuel Loading Room—This room contains the equipment that loads fuel into the fueling machines, which carry it to the reactors. Because it will contain a minimum inventory of 1 day's fuel for two units (31 bundles, containing 10.23 kg of plutonium), it will be hardened to category 1 requirements, with additional access control and security provisions.

Occupational Radiation Exposure—Radiation fields from new MOX fuel were compared to fields from natural uranium fuel, and measures required to protect personnel inspecting and handling new fuel were assessed. Gamma fields from MOX fuel are about four times higher than for natural uranium fuel (20-mrem/h contact for MOX fuel, 5 mrem/h for natural uranium fuel). In addition to the gamma field, the MOX fuel will have a 5-mrem/h neutron field. This analysis assumed no removal of americium during fuel fabrication.

MOX fuel bundles will be placed in shielding sleeves (water-extended polyester surrounded by stainless

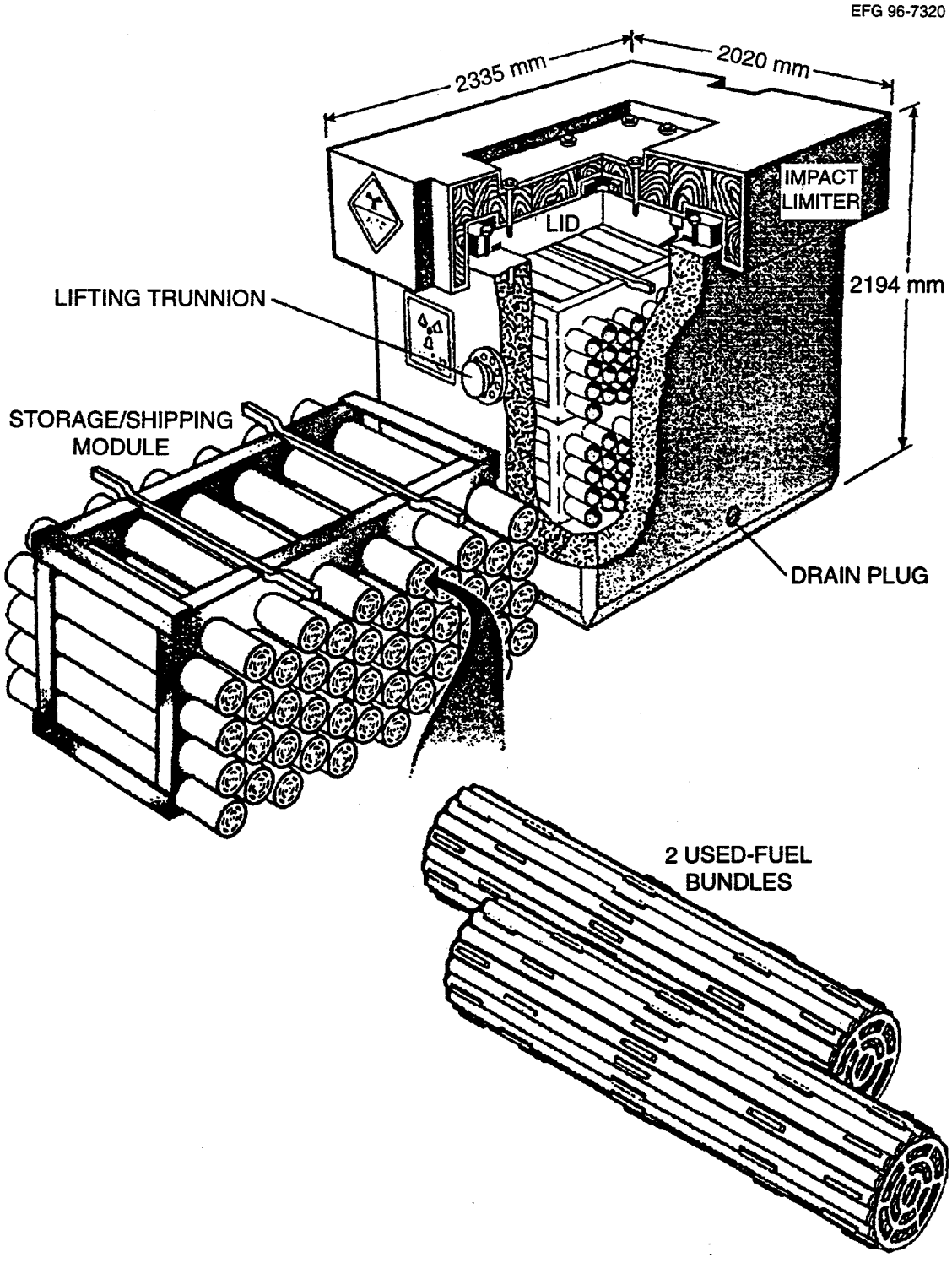


Figure 2.15. Transportation cask

Table 2.24. Reactor facility batch process data

Process box	Process cycle data	Data (average)[a]
Fresh MOX fuel storage and handling	Batch size (kg of plutonium)	2986 reference 4941 CANFLEX
	Cycle time[b]	360 days
	Plutonium input form	MOX bundles
	Plutonium output form	MOX bundles
Irradiation in reactor	Batch size (kg of plutonium) One full reactor load	2059 reference 2932 CANFLEX
	Cycle time	450 days
	Plutonium input form	MOX bundles
	Plutonium output form	MOX bundles
Fuel storage pool (postirradiation)	Batch size (kg of plutonium/tray)	7.92 reference 11.28 CANFLEX
	Cycle time	10.0 years
	Plutonium input form	24 MOX bundles in trays
	Plutonium output form	60 MOX bundles in storage baskets
Dry storage of spent fuel	Batch size (kg of plutonium/basket)	19.8 reference 28.2 CANFLEX
	Cycle time[c]	10.0 years
	Plutonium input form	60 MOX bundles in storage baskets
	Plutonium output form	Undetermined

[a]Data given are for two reactors on reference fuel and four reactors on CANFLEX fuel.
[b]Fresh MOX fuel could reside in the fuel storage and handling facility for up to one full fuel cycle (450 days).
[c]Assumes that dry storage of the spent fuel is needed for the reactors for at least 10 years.

Table 2.25. Plutonium disposition rate, CANDU alternative

Plutonium disposition rate (base case)		
Parameter	**Reference MOX (2 Reactors)**	**CANFLEX MOX (4 Reactors)**
Plutonium per bundle (kg)	0.33	0.47
Plutonium disposition per year (MT)	2.90	4.96
Plutonium dispositioned during phase of program (MT)	14.5	35.5

Table 2.26. Fuel cycle characteristics, CANDU alternative

Fuel cycle characteristics				
Parameter	**Reference MOX**		**CANFLEX MOX**	
	1 Reactor	**2 Reactors**	**1 Reactor**	**4 Reactors**
Reload batch size (bundles/year)	4,525	9,050	2,628	10,512
Average discharge exposure (burnup) (MWd/MT)	9,700	9,700	17,100	17,100

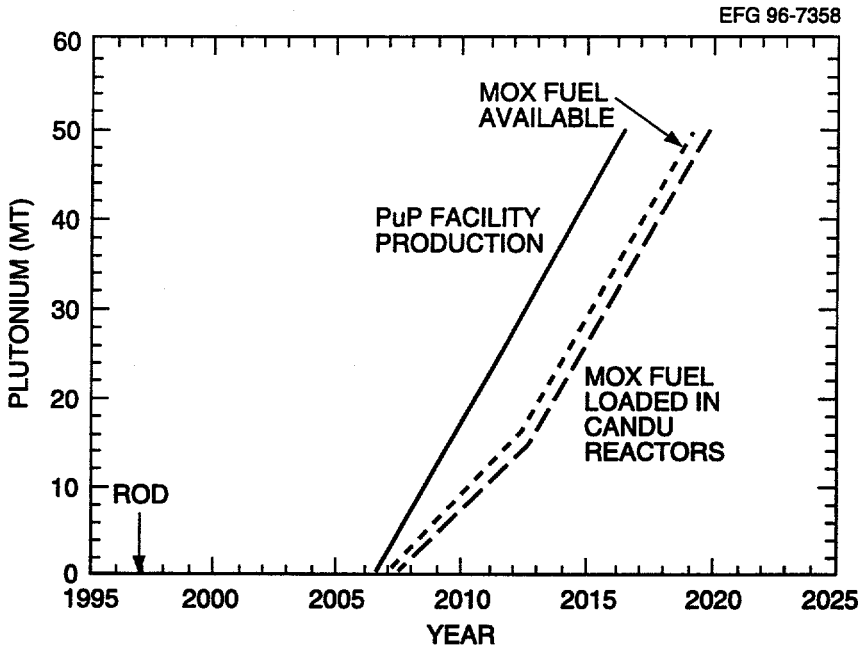


Figure 2.16. Plutonium production and use

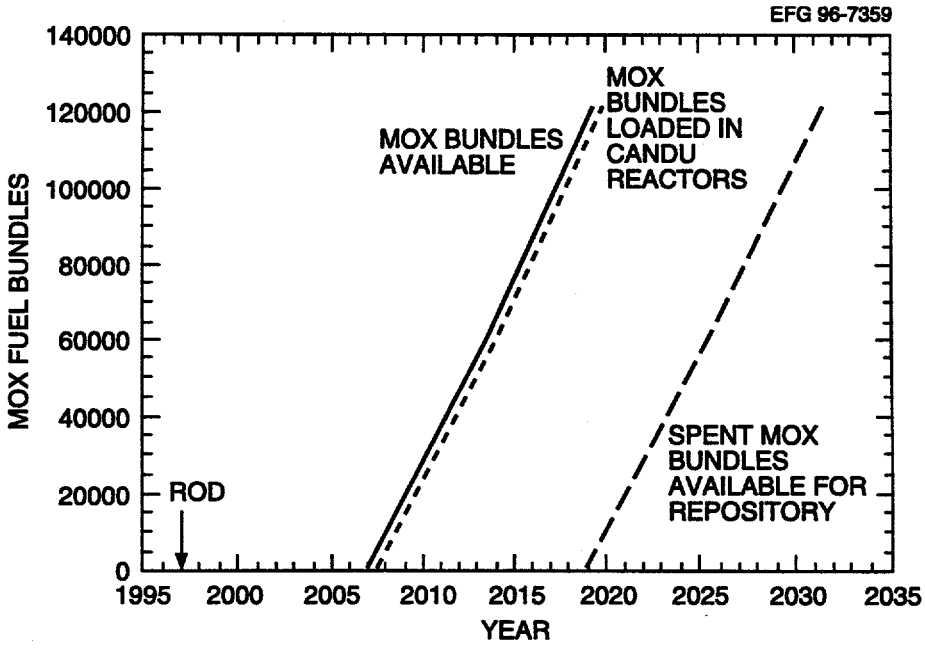


Figure 2.17. MOX fuel bundles production and disposition

Table 2.27. MOX fuel charging/discharging schedule

Time from MOX load in first reactor (years)	Assemblies loaded in reactor					Cumulative plutonium loaded (MT)	Cumulative HM loaded (MT)	Cumulative assemblies discharged
	1	2	3	4	Cumulative			
0.0[a]	4,525	4,525			9,050	2.9	138.1	
1.0	4,525	4,525			18,100	5.8	276.2	4,525
2.0	4,525	4,525			27,150	8.7	414.3	13,575
3.0	4,525	4,525			36,200	11.6	552.4	22,625
4.0	4,525	4,525			45,250	14.5	690.5	31,675
5.0[b,c]	2,628	2,628	2,628	2,628	55,762	19.5	840.4	40,725
6.0	2,628	2,628	2,628	2,628	66,274	24.4	990.3	50,506
7.0	2,628	2,628	2,628	2,628	76,786	29.4	1,140.2	66,274
8.0	2,628	2,628	2,628	2,628	87,298	34.3	1,290.1	76,786
9.0	2,628	2,628	2,628	2,628	97,810	39.3	1,440.0	87,298
10.0	2,628	2,628	2,628	2,628	108,322	44.3	1,589.9	97,810
11.0	2,628	2,628	2,628	2,628	118,834	49.2	1,739.8	108,322
12.0[d]	851				119,685	50.0	1,775.9	113,578
13.0								119,685

[a]First 5 years: Plutonium enrichment = 2.2% average
Plutonium per CANDU bundle = 0.33 kg
HM per CANDU bundle = 18.80 kg
Average burnup = 9700 MWd/MT
Reload batch size = 15.5 bundles per day
Plutonium throughput = 1.45 MT/year per reactor
HM throughput = 138.1 MT/year (2 reactors)

[b]Transition after year 5 from two reactors on reference fuel to four reactors on CANFLEX fuel.

[c]Remaining years: Plutonium enrichment = 3.4% average
Plutonium per CANDU bundle = 0.47 kg
HM per CANDU bundle = 18.36 kg
Average burnup = 17,100 MWd/MT
Reload batch size = 9 bundles per day
Plutonium throughput = 1.24 MT/year per reactor
HM throughput = 149.9 MT/year (four reactors)

[d]Remainder of 50 MT plutonium charged to Unit 1. At 12.2 years, Unit 1 begins transition to natural uranium fuel as MOX fuel reaches 17,100 MWd/MT.

steel) at the fabrication plant and left in these until loaded into the reactor fueling machine. This will allow the fuel to be handled with radiation doses equivalent to or lower than natural uranium fuel. The shipping containers and fuel storage facilities will provide additional shielding. In the new fuel-loading machine, a ram will push the bundle out of the sleeve and into the machine's magazine.

Additional local shielding, simple equipment that helps the worker maintain an arm's length distance from the fuel, and a bar code reader or video camera to read the bundle serial number will help minimize exposure.

Fueling Rate—The fueling rate of MOX fuel was compared to that of natural uranium fuel, and the ability of the fuel-handling system to meet the required fueling rate was assessed. The fueling rate for MOX fuel is 15.5 bundles/day per unit for reference fuel and 9 bundles/day per unit for CANFLEX fuel, lower than the rate for natural uranium fuel (18 bundles/day). The current fuel-handling system is capable of fueling reactors with MOX fuel.

New Fuel Loading—All new fuel-loading machines will be modified to accommodate MOX fuel in shielding sleeves. If natural uranium fuel is in use in

one or more units, it will be loaded using shielding sleeves in the same way as MOX fuel.

Fueling Machines—A fueling machine carries 16 bundles at a time in a magazine flooded with heavy water. This has been assessed, and there is no danger of criticality.

Radiation fields and thermal heat generation associated with high burnup MOX fuel are very close to those of natural uranium fuel taken to a similar burnup. No modification of fueling machines is necessary.

Reactor Control—Additional requirements for reactivity control systems were evaluated, including:

- requirements for changes to hardware or controls,
- profile and worth of liquid zone control units,
- speed and depth of shut off pins, and
- type, number, and spatial disposition of flux, and detectors/reactivity measuring devices.

No significant changes have yet been identified.

Moderator and Endshield Cooling Systems—The capability of the moderator and endshield cooling systems to reject additional heat caused by the increased neutron fields produced by MOX fuel was evaluated. The moderator system heat exchangers are oversized for the current heat loads and can accommodate the additional heat without changes. The primary heat load for the endshields does not come from neutron fields, and the 10% increase in neutron fields is judged to be insignificant.

In-Core Components—The effects on core components (pressure tubes, calandria tubes, and reactivity control mechanisms) of increased neutron fields were evaluated. Fast neutron fluences from MOX fuel at pressure tube and calandria tube locations are very close to those from natural uranium fuel. There will be no significant difference in the neutron-induced effects on core components.

Discharge, Handling, and Storage of Irradiated Fuel—The most significant change to the plant is the replacement of the equipment in the primary spent fuel bay with new machinery to load the fuel into storage modules similar to those in use at Ontario Hydro's Darlington and Pickering stations. The design of this equipment will be based on equipment used for the same purpose at Darlington. In addition, new racks will be needed in both the primary and secondary spent fuel bays to store the modules. The conveyor that moves fuel through the transfer duct from the primary to the secondary spent fuel bays will be modified to accept the modules.

2.4.2.1 CANDU Reactor Facility Design and Construction Schedule

The duration and path of the design and construction tasks are based on information from AECL. After approval of intermediate line item funding, the project begins with completion of the required design and reactor facility modifications and construction of the new fuel storage building. The design and construction schedule is listed in Table 2.28 and shown in Sect. 2.4.5.

2.4.2.2 CANDU Reactor Facility Design and Construction Cost

The design and construction costs for the reactor facility are not for construction of reactors but rather for the modification of two CANDUs (followed by two more that use CANFLEX fuel) to burn full MOX fuel. Most of the data in Table 2.29, which shows these costs, is derived from AECL's Phase II report and from AECL's response to the RxAT data call in 1995. The actual modifications to the Bruce-A plant are minimal, and no replacement power need be

Table 2.28. CANDU facility design and construction schedule

Task ID	Task name	Duration (months)	Start	Finish
1.	**FMDP Record of Decision**			12/1996
2.	**Intermediate Line Item Funding Approval**	24	12/1996	12/1998
8.	**Reactor and Design Modifications**	48	12/1998	11/2002
9.	Design Modifications	24	12/1998	12/2000
10.	Reactor Modifications	24	12/2000	11/2002

Table 2.29. Design and modification costs for the CANDU reactor facility

Cost category	Category description	Cost [1996 ($M)]	Cost basis
	Capital or TEC up-front costs:		
7	Title I, II, III engineering, design, and inspection	0	Included in category 8
8	Direct and indirect construction/modification	32	Escalation of data in 1994 Phase II AECL study
9	Construction management (percentage of category 8)	0	Included in category 8 costs
10	Initial spares	0	None required
11	AFI (percentage of categories 7–10)	0	Included in category 8
12	Risk contingency	0	To be calculated from uncertainty analysis at later date
	TOTAL TEC	$32	TEC in 1996 dollars

purchased during the modification process (an advantage of on-line fueling). These costs do not include the initial MOX core or the $355M needed to retube the Bruce NGS A units and replace steam generators. The $32M shown in category 8 includes preliminary and detailed design ($2M), construction and procurement ($20M), plus AFI and risk contingency ($10M). Management and spares are included in the modification category 8. Because of the nature of the fuel cycle and the inclusion of control pins in the fuel bundle, the modifications required for CANDU MOX burning are significantly smaller in cost and scope than the costs to modify existing LWRs. Unlike LWRs, however, CANDUs do not benefit from the significant European LWR MOX experience.

2.4.3 CANDU Reactor Facility Licensing and Permitting

2.4.3.1 CANDU Reactor Facility Licensing and Permitting Approach

There is a clear path forward provided in the existing regulations promulgated by the NRC with regard to obtaining the special license required for the export of SNM. SNM would include the MOX fuel elements for the CANDU reactors at Bruce NGS A in Ontario, Canada. Since the Bruce Station is outside the United States, other environmental permitting requirements under U.S. law apply only to the extent of and within the context of applicable agreements between the U.S. and Canadian governments or to the extent that environmental laws of the United States can be interpreted to apply in transboundary situations.

Since the CANDU option does not involve reactors operated in the United States, the reactor licensing criteria used by the Canadian Atomic Energy Control Board (AECB) and other cognizant Canadian government agencies will be applied to ensure nuclear safety and environmental protection during plan operations and for waste handling and disposal.

It is the responsibility of the utility operating a nuclear generating station to ensure that the station is sited, designed, constructed, and operated to meet safety requirements established by the AECB. Operating licenses are granted for a limited period of time, typically between 1 to 3 years, and prior to the expiration of the current license an application for renewal must be submitted.

Ontario Hydro has successfully obtained and maintained operating licenses for all its nuclear units since the inception of its nuclear power program in the early 1970s when start-up of the first Pickering NGS A unit occurred. The Bruce NGS A units are licensed in accordance with the AECB Siting Guide requirements that define reference individual and total population dose limits for single failure (process system failure) and dual failure (process system failure plus failure of one of the special safety systems) events as well as

specifying maximum frequencies of occurrence of these failure events.

The U.S. licensing of the MOX export will be conducted under 10 CFR Part 110.

National Environmental Policy Act (NEPA)—It is assumed that for the use of the CANDU reactors in plutonium disposition, the NEPA actions in the DOE PEIS and in any follow-on option-specific EIS comply with the requirements of 40 CFR 1502.3 and 1508.23 with regard to alternative selection and 1508.18 with regard to a major federal action. The decision on whether to prepare an option-specific EIS with regard to the use of a CANDU reactor licensed in Canada will be made consistent with the provisions and conditions specified in Appendix B to Subpart D of 10 CFR Part 1021 and in Sect. 2 of Presidential Executive Order 12114, *Environmental Effects Abroad to Major Federal Actions*, January 4, 1979. An option-specific EIS should address any transboundary issues identified in the *North American Agreement for Environmental Cooperation*, the *Great Lakes Water Quality Agreement*, other bilateral agreements relating to relevant environmental issues, and obligations under international law relating to transboundary pollution and environmental quality.

Currently, for specific export licenses, the NRC regulations at 10 CFR 51.1 exempt export licensing under 10 CFR Part 110 from the NRC NEPA regulations at 10 CFR Part 51 since the environmental impacts of such exports were addressed for the uranium fuel cycle in the *Final Environment Statement: U.S. Nuclear Power Export Activities*, ERDA-1542, April 1976. Therefore, there is no environmental report required to be submitted under 10 CFR 110.31 and 110.32, nor are there NRC review criteria for such in 10 CFR 110.40 and 110.42. A hearing request or intervention petition is allowed under 10 CFR 110.82, and the NRC has reserved the right of discretion in addressing environmental matters as discussed at 10 CFR 51.20(a)(2). Therefore, action by the NRC to address NEPA for the MOX export is possible but is assumed not to be likely under NRC regulations unless in the judgment of the NRC, an intervenor introduces significant new information or issues that have not been addressed adequately in the PEIS or in an option-specific EIS.

Atomic Energy Act of 1954, as Amended, and Related Legislation—Sections 54 and 57 and Title XI, Sects. 121 through 132, of the *Atomic Energy Act of 1954*, as amended, apply to the export of MOX for plutonium disposition in Canada. The licensing requirements for the export of MOX to Canada are addressed in 10 CFR 110. These regulations require both an NRC review (10 CFR 110.40) and an executive branch review (10 CFR 110.41) of the licensing application. The executive branch is required to confirm that the proposed license complies with the terms of an agreement for cooperation executed under Sect. 123 of the act.

Canada will be responsible for the geologic disposal of spent fuel under Canadian laws and regulations. International safeguards applicable to the monitoring of spent fuel repositories will apply.

Resource Conservation and Recovery Act (RCRA)—RCRA will only apply to wastes generated in the operation of the Bruce NGS A to the extent of applicable provisions in bilateral transnational agreements between the United States and Canada or to the extent that environmental laws of the United States can be interpreted to apply in transboundary situations. The applicability of RCRA provisions would be subject to detailed review in an option-specific EIS. However, as a DOE-supported program, all facets of the plutonium disposition mission are subject to the waste minimization/pollution prevention policies of the President and the Secretary of Energy with regard to the plans required of waste generators under Sect. 3002(b) of RCRA. As determined appropriate by the U.S. and Canadian governments, such waste minimization/pollution prevention plans may be negotiated within the agreement on cooperation.

Clean Air Act and Clean Water Act—These laws will only apply to the operation of Bruce NGS A to the extent of applicable provisions in bilateral transnational agreements between the United States and Canada or to the extent that the environmental laws of the United States can be interpreted to apply in transboundary situations. The applicability of these laws would be subject to a detailed review in an option-specific EIS. Since the Bruce station is located on Lake Huron, the provisions of the *Great Lakes Water Quality Agreement* apply.

2.4.3.2 CANDU Reactor Facility Licensing and Permitting Schedule

There are two licensing and permitting tasks for the CANDU facility: the required interactions with the AECB and the environmental assessment for using MOX fuel in the reactors and for building the new fuel

storage building. These tasks are listed in Table 2.30 and shown in Sect. 2.4.5.

2.4.3.3 CANDU Reactor Facility Licensing and Permitting Cost

Table 2.31 shows the major assumptions used to determine the reactor facility design, cost, and schedule.

The licensing cost estimation for the CANDU facility will cover more cost areas than licensing and permitting. This section covers LCC categories 1–6 in the 24-category estimating format described in Appendix C. These six categories constitute what is termed preoperational or OPC. OPC is the portion of the TPC (investment or up-front cost) budgeted with operating dollars rather than congressional line item capital or TEC dollars.

OPC generally includes the majority of the preconstruction activities and many of the start-up activities carried on by the operating contractor prior to full capacity operation of the facility and after construction is complete. As can be seen in Table 2.32, licensing is just one of several needed cost centers.

R&D costs ($35M) represent early estimates from the R&D plans. Table 2.32 shows the preoperational costs for the CANDU base case, which total $67M; $35M of this is for R&D, of which $25M is for work in Canada. The $18M for licensing and permitting includes AECB licensing, the provincial EIS, and the licensing of the fuel transport package. Commissioning of the CANDUs on MOX is projected at $4M. $7M in risk contingency has been added to cover uncertainties in the modification program.

2.4.4 CANDU Reactor Facility Operations

2.4.4.1 CANDU Reactor Facility Shipment and Storage

Approximately 119,685 CANDU MOX fuel bundles will be fabricated from the 50 MT of PuO_2. The MOX fuel bundles will be shipped from the MOX fuel fabrication facility to the Bruce-A CANDU reactor facility

Table 2.30. CANDU facility license and permit schedule

Task ID	Task name	Duration (months)	Start	Finish
5.	**Licensing and Permitting**	72	12/1996	11/2002
6.	AECB Interactions	48	12/1998	11/2002
7.	Environmental Assessment	24	12/1996	12/1998

Table 2.31. CANDU reactor facility assumptions

Average plant throughput	2.9 MT plutonium for two units followed by 4.96 MT plutonium for four units
Plant location	Bruce site on Lake Huron, Ontario
Plant owner	Ontario Hydro (utility)
Licensing	Canadian regulatory authorities
Feedstocks	Fabricated MOX from U.S. government-owned MOX plant located in existing facility in the United States
Plant operational lifetime	Nominal 12.2 years to dispose 50 MT of plutonium
Time to plan campaign, license, design, and modify plants, and start-up	11 years
Data source for cost information	ORNL and AECL

Table 2.32. Licensing and other preoperational costs for a CANDU reactor facility

Cost category	Category description	Cost ($M)	Cost basis
	Preoperational or OPC portion of investment or up-front costs:		
1	R&D	35	Data from 1995 R&D plans
2	NEPA, licensing, permitting	18	Based on AECL data
3	Conceptual design	1	AECL data
4	QA, site qualification, S&S	2	ORNL estimate
5	Postconstruction start-up	4	AECL data
6	Risk contingency (derived from uncertainty analysis)	7	AECL data
	TOTAL OPC OR PREOPERATIONAL COST	$67	OPC in 1996 dollars

in Ontario, Canada. The MOX fuel fabrication facility, in providing fuel bundles for each reactor reload, must have the capacity to store completed bundles at the MOX fuel fabrication facility until they are needed. In addition, each reactor provides sufficient storage capacity to continue operations while additional fuel bundles are shipped to the reactor.

Table 2.33 provides estimates of the number of shipments required to transport the fresh MOX fuel from the fuel fabrication facility to the Bruce-A CANDU reactors.

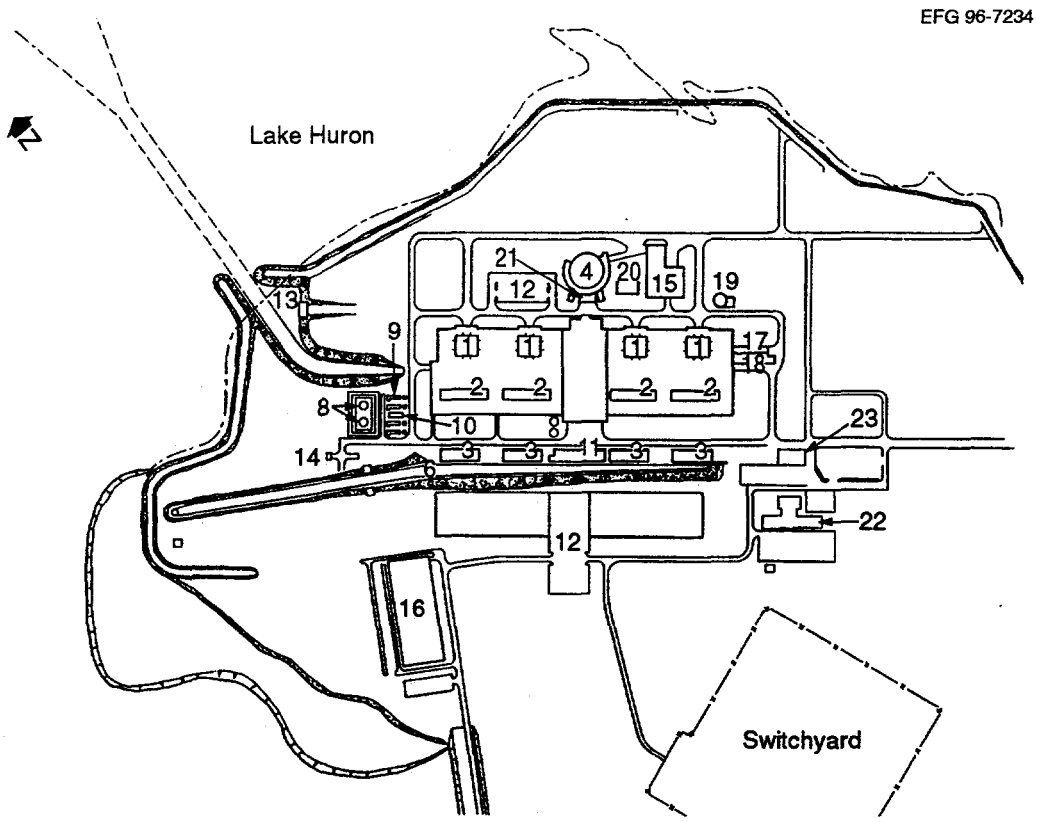
2.4.4.2 CANDU Reactor Facility Operations Process

Bruce NGS A comprises four nuclear reactors, four turbine generators and associated equipment, and services and facilities arranged as shown in Fig. 2.18. The main station buildings and structures are four reactor buildings; four reactor auxiliary bays; a common powerhouse, including turbine hall and turbine auxiliary bay running the entire length of the station; a central services area; a vacuum building; an ancillary services building; four pumphouses; a water treatment building; a steam transformer plant; emergency filtered-air discharge system building; and emergency coolant injection system structures, including an accumulator building, recovery pump room and storage tank, and four standby generator enclosures.

The reactor building is a rectangular, reinforced concrete structure that serves as a support and containment enclosure for the reactor and some of its associated equipment. The reactor vault is a portion of the reactor building forming part of the containment system and is connected to the vacuum building via the fueling duct. The fueling duct runs the length of the station under the reactor vaults and serves as connection to the fuel handling and fuel storage areas located in the central services area. The reactor vaults are inaccessible during reactor operation above a few percent of full power, and services to the reactor vaults can be isolated outside the containment envelope. Provision is made to permit isolation of a nonoperating reactor vault from the rest of the station containment system.

Table 2.33. Parameters for fresh MOX fuel transport leg

Maximum material/package	Quantity plutonium/campaign	Estimated packages to be shipped	Number of SST shipments/campaign
7 MOX CANDU fuel bundles (first 5 years)	14.5 MT	6,465	270
7 MOX CANFLEX fuel bundles (last 7.2 years)	35.5 MT	10,850	452



1 Reactor Building
2 Turbine Generator
3 Pump House
4 Vacuum Building
5 Service Building
6 Forebay & Open Channel
7 Discharge Channel
8 Fuel Oil Tanks
9 Standby Generators
10 Fuel Oil Pump House
11 Water Treatment Building
12 Parking Areas
13 Dock Area
14 Recirculating Duct
15 Ancillary Services Building
16 Steam Transformer Plant "A"
17 East Service Area
18 ECI Pump Room
19 ECI Storage Tank
20 Accumulator Building
21 EFADS Building
22 Project Office
23 Guard House

Figure 2.18. Bruce station reactor facility general arrangement

Reactor and Auxiliary Systems—The reactor consists of a horizontal, cylindrical tank (the calandria tank) with integral end shields; 480 fuel channel assemblies with integral end fittings; and reactivity control units (Fig. 2.11). The whole assembly is enclosed by another tank (the shield tank) that is filled with light water. The calandria contains heavy water that acts as neutron moderator and reflector. The calandria, two end shields, and shield tank form an integral multicompartment structure providing building operational shielding and full shutdown shielding between the calandria and the reactor vault.

Each fuel channel assembly consists of a Zirconium-2.5% Niobium alloy pressure tube contained within a Zircaloy-2 calandria tube that provides a gas filled thermally insulating annulus separating the high-pressure and temperature heavy water coolant in the pressure tube from the low-pressure and temperature heavy water moderator in the calandria. At each end of a fuel channel the pressure tube is rolled into the hub of an alloy steel end fitting. Each fuel channel, with its contained fuel and heavy water coolant, is supported by the end shield lattice tubes through sliding bearings and partially by the pressure tube/calandria tube annular spacers. The end fitting assemblies are designed with annulus bellows to allow relative axial movement between the fuel channel assemblies and the lattice tubes to accommodate thermal expansion and irradiation-induced pressure tube creep.

A removable breech-type closure plug is located at outboard ends of end fittings to allow on-line fueling.

A latched steel shield plug is located within a liner tube inside the end fitting to attenuate neutron and gamma flux from the reactor. This shield plug is removed during a fueling operation and is subsequently reinserted at the end of a fueling operation.

Heat Transport System—The heat transport system (Fig. 2.12) circulates pressurized heavy water coolant through the fuel channels to transport heat from the fuel to the steam generators where the heat is transferred to the light water in the secondary side circuit. The heat transport system includes four circulating pumps, six large diameter headers, a system of small diameter feeder pipes connecting the fuel channel end fittings to the headers, and the primary side of eight steam generators and four separate preheaters. These components are connected in a "figure-of-eight" piping circuit arrangement such that the flow in fuel channels is in opposite directions in an interlaced, checkerboard pattern.

Pressure control is provided by a pressurizer connected to one of the two reactor outlet headers. At high power the pressure is controlled by steam bleed valves connected to the pressurizer and immersion heaters within the pressurizer vessel.

Fuel Handling and Storage—On-power fueling is a unique feature of the CANDU reactor. The Bruce NGS A reactors are fueled by a system consisting of three fueling machine systems and associated new and spent fuel-handling systems. Each fueling machine system consists of two fueling machine heads, head suspensions and elevating tables, and heavy water and air auxiliary systems, all mounted on a transport trolley. The fueling machines are controlled remotely from consoles located in the main control room in the central services area. The transport trolleys travel on two sets of rails in the fueling duct, between the fuel-handling and service facilities at the central and east service areas and the bridge and carriage assemblies at each reactor.

New fuel bundles, stored at a new fuel receiving area in the central services area and at new fuel storage racks, are loaded into the fueling machines at the new fuel-loading area. Bundles are transferred to the loading area in crates, and are uncrated, inspected, and transferred to the new fuel transfer mechanisms. The new fuel transfer mechanisms transfer fuel through a transfer port in the containment wall to fueling machine heads in the fueling machine room located within containment. Once the fueling machine head is charged with the required number of new bundles, the head and suspension assemblies are lowered onto a trolley by the service area bridges. The trolley is then driven along the fueling duct to the selected reactor unit to be fueled.

When the transport trolley is correctly located under the selected reactor, the heads and suspensions are picked up and raised by carriages on the reactor bridge to the correct vertical elevation of the channel to be fueled. The carriages then traverse across the reactor face to the selected end fitting to which the heads are then locked on. The closure plugs on the end fittings at both ends of the channel are then removed allowing removal of the shield plugs. Once the channel closures and shield plugs are removed, one fueling machine inserts new fuel bundles, two at a time, into the channel. This shifts the string of 13 bundles down the channel, pushing 2 irradiated bundles into an empty fuel carrier of the other fueling machine head. When the required number of new bundles has been inserted into the channel, the shield plugs and channel closures are replaced and the heads unlocked from the end fittings. This procedure is repeated until the required number of channels have been fueled. The heads and suspensions are then lowered by the bridge onto the transport trolley elevating table, which in turn is lowered onto the trolley. The troller then returns to the central services area where irradiated fuel is discharged into the primary irradiated fuel storage bay, a reinforced concrete tank with epoxy lined walls, and a steel-lined floor. This bay is used to store discharged fuel for a minimum of 6 months after removal from the reactor, following which the fuel is transferred to the secondary irradiated fuel storage bay. The primary irradiated fuel storage bay is sized to store 4 reactor years of fuel at 80% capacity factor.

A small transfer bay and water-filled duct connects the primary and secondary irradiated fuel storage bays. Fuel stacked on trays is moved from the primary bay to the transfer bay by a conveyor, where the tray is transferred by a hoist and tray-handling tool to a cable-driven cart. This cart, which can carry two trays, is driven through the underwater tunnel to a small receiving bay adjoining the secondary irradiated fuel storage bay. The trays are transferred and stacked by a bridge crane over the secondary bay. The storage capacity of the secondary irradiated fuel storage bay is approximately 16 station years (64 reactor years) of irradiated fuel.

Moderator System—The heavy water moderator fluid is circulated through the calandria vessel and cooled by heat rejection to heat exchangers. Helium is

used as a cover gas over the heavy water. Chemistry control of the moderator fluid is maintained by the moderator purification circuit, which contains ion-exchange columns.

Reactivity and Power Control—Normal short-term control of bulk and spatial reactor power is achieved by light water zone control units. These consist of 14 compartments, distributed within the reactor to define 14 zone regions of the core, containing controllable amounts of light water. The volume of water in the compartments is adjusted in unison to maintain the reactivity balance for bulk power control and differentially to regulate the spatial power distribution.

In-core self-powered neutron flux detectors, distributed in each of the 14 zone regions, and 22 fully instrumented channel thermal power measurements distributed in 7 axial pairs of zones provide power measurements used by the reactor control system. At low power levels these measurements are augmented by out-of-core ion chambers.

Additional negative reactivity control to augment the zone controllers is provided by four mechanical control absorber pins, normally positioned outside the core and capable of being driven in the core at variable speed. Long-term reactivity control is maintained by the combination of on-power quelling and the adjustment of the amount of soluble neutron absorbing material (boron or gadolinium compounds) in the moderator.

Access to these reactivity control devices and in-core detectors is from the reactivity mechanisms deck directly above the reactor outside containment on the outer surface of the reactor vault ceiling.

Reactor Auxiliary Systems—Some of the more significant of the auxiliary systems associated with the nuclear portion of the plant follow:

- Moderator liquid poison system, moderator cover gas system, moderator purification system, heat transport purification system, and moderator and heat transport resin handling systems.
- Shutdown cooling system, maintenance cooling system, and shield cooling system.
- Liquid zone control system and annulus gas system.
- Irradiated fuel storage bay circulation and purification system.
- Heavy water supply system and heavy water transfer and collection system.

Reactor Special Safety Systems—Four special safety systems are provided to mitigate against the consequences of accidents. They are the two independent shutdown systems, the emergency coolant injection system, and the negative pressure containment system, described subsequently.

Shutdown system no. 1—This shutdown system consists of 30 spring-assisted gravity drop shutoff rods (SORs) of cadmium sandwiched in stainless steel construction. The rods are located vertically above the core in drive mechanisms mounted on the reactivity mechanisms deck. They are maintained out of core by normally energized electromagnetic clutches. An independent triplicated logic system senses the requirement for a reactor trip, based upon two-out-of-three local coincidence voting logic, and deenergizes the direct current clutches to release the shutoff pins.

Shutdown system no. 2—The second independent shutdown system utilizes the injection of gadolinium nitrate solution into the moderator fluid through seven horizontally oriented nozzles. The gadolinium nitrate solution is driven at high pressure from the poison tanks by pressurized helium gas admitted to the tanks when fast-acting solenoid valves are opened on a reactor trip initiation signal.

An independent triplicated logic system, physically separated from the SDS1 logic, is employed to sense the requirement for reactor trip, based upon two-out-of-three general coincidence voting logic.

Emergency Coolant Injection System (ECIS)—The emergency coolant injection is designed to refill the heat transport system and keep it refilled following a loss-of-coolant accident (LOCA). The system also provides one of the long-term heat sinks for emergency core cooling.

The ECIS is common to all four units with a 30-in. common supply header running the length of the station. Injection lines to the individual units contain a parallel pair of normally closed light water injection valves located outside containment. An inverted U-bend provides an air gap forming an interface separating the light water of the ECIS from the heavy water of the heat transport system. Four branch lines then penetrate containment, with each line containing a check valve just outside containment in series with a parallel pair of motorized valves inside containment which provide further isolation from the heat transport system. Two of the branch lines connect to the two

heat transport system reactor outlet headers, and the other two connect to the reactor inlet headers through the preheater bypass line.

A high-pressure accumulator system connects to the common supply header and provides the means of initial high-pressure injection of light water into any one of the four units. The accumulator system consists of six large steel tanks located in a building separate from the main station structure. Two of the tanks, containing pressurized nitrogen gas, are normally isolated from the other four tanks, containing light water, by fast-acting valves.

Another source of water for the emergency coolant injection system is the grade level tank that connects to the suction side of four 50% ECIS pumps. The four pumps also connect to a recovery sump inside containment by a suction line containing a normally closed motorized valve. The pumps discharge to the common header through two of three heat exchangers and a heat exchanger bypass line. The heat exchangers cool the injected water when the system is operating in recovery mode.

The ECIS is initiated upon detection of a LOCA in any unit by triplicated, independent heat transport low-pressure signals conditioned by either high reactor vault pressure or temperature signals that act as LOCA conditioning parameters. During the short-term phase of operation, water from the accumulator tanks is injected at pressure into the unit that initiated the LOCA signal by opening the gas accumulator isolation valves and the isolation valves on the lines to the affected unit. At this time, cooldown of the secondary side is also initiated by opening the safety relief valves on the steam generators. The ECIS recovery pumps and cooling water flow to the ECIS heat exchangers are also started.

When the water level in the accumulator tanks becomes low, the tanks are isolated to prevent gas from entering the heat transport system. Injection of water from the grade level tank by the recovery pumps proceeds until this tank is almost empty, at which time long-term recovery mode operation is initiated by opening the sump isolation valves and closing the valves in the heat exchanger bypass line.

Negative Pressure Containment System—The containment system provides a subatmospheric envelope around the nuclear components of the reactor coolant system such that, in the event of failure of these components, any significant amount of released radioactivity will be contained in the envelope.

The containment envelope consists of the following interconnected volumes: reactor vaults, the fueling duct, fueling duct extension, ECIS recovery sump, central fueling area, pressure relief duct, pressure relief manifold, and vacuum building. The containment volumes are maintained subatmospheric, typically 6.9 to 10.3 kPa absolute in the vacuum building and –2.5 to –3.5 kPa gauge in the rest of the containment envelope. Controlled access into the containment for personnel and equipment is provided by means of 44 airlocks and 10 transfer chambers. Operation of the containment pressure suppression function is automatic and is based upon using the energy released into containment by the LOCA. The pressure relief valves are actuated by a rise in pressure in the pressure relief duct, and the vacuum building dousing spray system is actuated by a rise in the vacuum building pressure.

There are 12 main pressure relief valves, 4 instrumented main pressure relief valves, 4 auxiliary pressure relief valves, and 2 reverse flow valves. All of these valves are located in the pressure relief valve manifold. The auxiliary pressure relief valves are pneumatically operated butterfly valves designed to open automatically at a valve manifold pressure of 1.5 kPa(g) and reclose at –5.1 kPa(g). The main and instrumented pressure relief valves open at a valve manifold pressure of 6.9 kPa(g) and reclose at a valve manifold pressure of 2.4 kPa(g) for the main pressure relief valves and –2 kPa(g) for the instrumented pressure relief valves.

The vacuum building dousing system is designed to condense steam discharged into the building and cool the steam/air mixture to limit any further pressure rise. The system consists of an emergency water tank located at the top of the vacuum building connected to a system of spray headers through a vacuum chamber. If the vacuum building pressure rises 26.9 kPa above the pressure in the vacuum chamber, water is discharged from the emergency water storage tank, over a weir in the vacuum chamber and into the spray headers, from which it sprays into the main chamber of the vacuum building. Vacuum is maintained in the vacuum building and the vacuum chamber by a system of vacuum pumps located in the basement of the building, an area outside of the containment envelope.

Heat removal from containment is provided by a number of air coolers. Each reactor vault has four axial fans and ten main air-to-water heat exchangers, as well as six wall-mounted coolers. Four separate air coolers are located in the central fueling area to remove heat rejected by fueling machines when parked in this area.

A hydrogen ignition system, consisting of 12 igniters per unit located in the reactor vault and fueling machine ducts, is provided for controlled removal of hydrogen gas that may be generated during a lower probability design basis accident involving a LOCA, coincident with loss-of-emergency-coolant injection (LOECI).

An emergency filtered-air discharge system (EFADS) is provided to maintain containment subatmospheric in the long-term following a LOCA and to allow controlled and monitored release of radioactivity from containment. The system consists of two 100% filters and blowers plus duct work and isolation dampers. Each filter contains a demister, heater, prefilter, upstream high-efficiency particulate air (HEPA) filter, charcoal filter, and downstream HEPA filter. Exhaust flow is drawn from the vacuum building and is monitored by a postaccident radiation monitoring system before being released to atmosphere via the system exhaust stack. The postaccident radiation monitoring system provides on-line radioisotope analysis for noble gases, and gross gamma detection and off-line radioisotopic analyses for particulates, iodine, and tritium.

Safety-Related Systems—A number of other systems and functions are designed solely to provide safety support functions:

- an emergency boiler cooling system to supply water to the steam generators to establish an adequate heat sink for decay heat removal when normal feedwater supply is unavailable,
- a qualified emergency power supply system to provide power for equipment and instrumentation necessary to maintain and monitor the reactors in a safe shutdown state following a main steam piping failure, and
- an emergency venting system to limit internal pressure in the powerhouse in the event of a main steam piping failure.

Secondary Systems—The secondary side consists of a conventional, light water, closed steam cycle driving the turbine generator. Steam from the two steam generators is delivered to a steam drum that contains the steam dryers. The dry steam is delivered by large diameter steam lines to a tandem compound, single-shaft turbine directly connected to the generator. The turbine consists of one double-flow high-pressure cylinder, followed by live steam reheat, and three double-flow low-pressure cylinders. The generator is cooled by water and hydrogen and is provided with a rectified AC excitation system.

Connected to the turbine is a surface condenser supplied with cooling water from Lake Huron, suitable for full-power operation and capable of accepting ~75% of main steam flow as direct rejection. Condensate is returned to the steam generator through five stages of feed heating, consisting of three low-pressure heaters, one deaerating heater and one high-pressure heater.

Reference MOX CANDU Fuel

Introduction—CANDU reactors have excellent neutron economy because of the use of heavy water as moderator and coolant. On-power refueling enables CANDU reactors to operate with minimum excess reactivity in the core. These features allow CANDU reactors to operate with a wide variety of fuel cycles, including natural uranium, slightly enriched uranium, and MOX fuel. Present CANDU reactors are designed to use natural uranium fuel, which contains only 0.71 wt % ^{235}U. The requirement of disposing of 50 MT of weapons-grade plutonium over a period of 25 years could be met by using two reactors; however, mission time could be significantly reduced (to 12.3 years) if after 5 years, a shift were made to four reactors on the advanced design CANFLEX fuel. Each reactor will utilize 1.45 MT of weapons-grade plutonium metal per year. This plutonium disposition rate requires the MOX fuel to contain an average of 2.2% fissile plutonium with the existing 37-element fuel design operating within current burnup limits.

The use of MOX fuel in an existing CANDU reactor, such as Bruce-A, introduces changes to the neutronic characteristics relative to the natural uranium core, that is,

- an increase in the reactivity of the fuel lattice,
- a decrease in the reactivity depth of the control and safety systems,
- a decrease in the delayed neutron fraction,

- a decrease in the prompt neutron lifetime, and
- a decrease in the negative fuel temperature feedback.

These changes nominally result in a faster response to reactivity perturbations in the MOX core compared to that in the natural uranium core. The flexibility of the CANDU reactor design allows modifications to be made in the MOX fuel design such that the resulting MOX reactor operates within the safety and licensing parameters for the existing natural uranium CANDU reactor.

The most significant innovation in the MOX fuel design is the strategic placement of burnable poison in the fuel bundles (the inner 7 fuel pins). The purpose of the burnable poison is to:

- suppress the excess lattice reactivity, and
- reduce the coolant void reactivity.

Dysprosium is the ideal burnable poison for CANDU reactors because its burnout rate matches the depletion rate of the fissile materials such as ^{235}U and ^{239}Pu. Figure 2.19 shows the arrangement of fuel elements in the standard 37-element design. In the reference MOX fuel design, dysprosium is mixed with 0.2% depleted uranium in the central two rings, and plutonium is mixed with 0.2% depleted uranium in the outer two rings. The amount of dysprosium and plutonium in the MOX fuel bundle depends on the requirements for the plutonium disposition rate, MOX fuel production rate, and the maximum allowable element burnup.

Coolant void reactivity also depends on the amount of dysprosium in the fuel bundle. To offset the faster neutronic response of the MOX fuel, an appropriate amount of dysprosium is added to the fuel to produce a slightly negative void reactivity. It is shown later that this negative void reactivity adds stability to the MOX core.

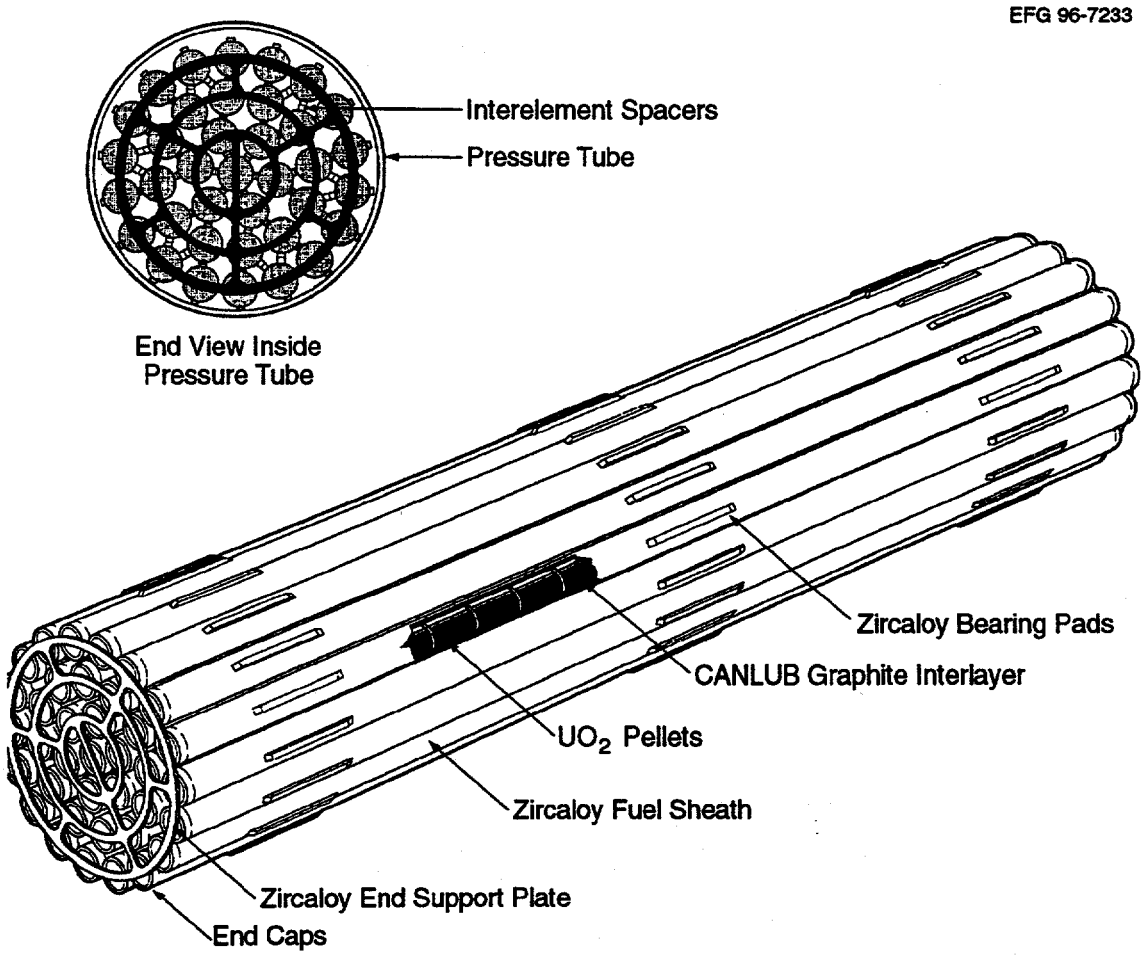


Figure 2.19. CANDU reactor reference fuel bundle

Specifications of the Reference MOX Fuel Design—The reference MOX fuel design uses the standard Bruce 37-element fuel bundle geometry. The WIMS lattice code was used to carry out scoping calculations for several combinations of the plutonium and dysprosium contents in the MOX fuel bundle that could satisfy the following design targets:

- The maximum burnup in the discharged MOX fuel elements should not exceed the maximum element burnup for natural fuel, which is about 16,000 MWd/MT.
- The minimum plutonium metal disposition rate should be 1 MT per year per reactor.
- The average MOX fuel burnup should be sufficiently high such that the estimated MOX fuel fabrication rate of 150 MT/year can support two reactors.
- Coolant void reactivity should be between 0 and –5 mk.
- Existing safety and operating limits on maximum channel power, maximum bundle power, and maximum element rating should not be exceeded.

The three-dimensional fuel management code, RFSP, was used to determine the power distribution, fuel burnup, and void reactivity in a Bruce-A reactor using the burnup, dependent MOX lattice cross-sections generated by WIMS. These calculations were used to select the MOX fuel design that would satisfy all the design targets. Several iterations between WIMS and RFSP were required to establish the specifications for the reference MOX fuel design.

Table 2.34 compares the nuclear characteristics of the reference MOX fuel design with those for the standard natural fuel design. In CANDU reactors, fission is caused by thermal neutrons entering the fuel channel from the moderator. Fuel elements in the third ring are shielded from these thermal neutrons by the elements in the outermost ring, that is, ring 4. This reduced neutron flux level results in a much lower power output in ring 3 compared to that in ring 4. The power output of the entire fuel bundle is often limited by the maximum allowable power rating for an individual fuel element. Therefore, it is desirable to design a fuel bundle such that all fuel elements operate at comparable power ratings.

Table 2.34. Comparison of natural fuel and MOX fuel characteristics

	Existing Bruce-A station	MOX-fueled Bruce-A station
Fuel bundle dimension	102 mm (4.02 in.) diam. 495 mm (19.5 in.) long	Same as existing NUO_2 fuel bundle
Pellet material composition (percentage based on weight of HM in fuel)	Natural UO_2 in all rings (37 pins)	Ring 4 (18 pins) 1.6% plutonium Ring 3 (12 pins) 3.1% plutonium Ring 2 (6 pins) 15% dysprosium Ring 2 (1 pin) 15% dysprosium All rings have 0.2% ^{235}U
Bundle material composition (fuel material only)	^{235}U 0.13 kg ^{238}U 18.67 kg O_2 2.53 kg Total: 21.33 kg	Plutonium 0.33 kg ^{235}U 0.04 kg ^{238}U 17.92 kg Dysprosium 0.51 kg O_2 2.53 kg Total: 21.33 kg
Average burnup	8,300 MWd/MT	10,000 MWd/MT
Maximum burnup	15,000 MWd/MT	15,500 MWd/MT
Bundle/FPD	18	15.0
Fuel management scheme	2, 4, 8 Bundle shift	2 Bundle shift
Maximum channel power	7,200 kW	7,000 kW
Maximum bundle power	950 kW	780 kW
Moderator/coolant purity	99.75%	97.00 %
LOCA void reactivity	11 mk	–5.0 mk

In the reference MOX fuel design, the plutonium content of the elements in the third ring is 3.1%, which is higher than the 1.6% plutonium content in the fuel elements of the fourth ring. The higher enrichment level in ring 3 is designed to compensate for the reduced neutron flux level. This enrichment grading scheme enables the elements in ring 3 to operate at a power level comparable to that in ring 4 in spite of the reduced neutron flux level. This allows the fuel bundle to operate at a high power level without exceeding the maximum allowable power rating for individual fuel elements.

The neutron flux level in the central seven elements, which contains 0.2% depleted uranium, 15% dysprosium, and no plutonium, is so low that these elements do not produce any significant amount of power compared to the MOX elements in the two outer rings. Hence, all the power in the MOX bundle is effectively produced by 30 fuel elements instead of 37. This requires the MOX fuel bundles to operate at a lower maximum bundle power limit than that for natural fuel bundles. The 2-bundle shift fueling scheme chosen for the MOX core flattens the radial and axial power distributions such that the maximum channel and bundle powers in the MOX core, 7000 and 780 kW respectively, are lower than those in the natural uranium core, 7200 and 950 kW, respectively.

The maximum fuel element burnup of the MOX fuel is calculated to be 15,500 MWd/MT, which is essentially the same as the maximum fuel burnup attained by natural fuel elements in Bruce-A. The MOX fueling rate is 15.5 bundles per full-power day, which is lower than the present fueling rate of 18 bundles per full-power day with natural uranium fuel.

The major difference between the natural uranium fueled reactor and the MOX fueled reactor is the reactivity effect during a hypothetical LOCA. Full-core LOCA reactivity in Bruce-A is estimated to be +11 mk for the natural uranium reactor and –4.7 mk for the MOX reactor. It is shown later that this negative void reactivity in the MOX core enhances the performances of the control and safety systems in the existing natural uranium CANDU reactor. The transition from a natural uranium CANDU reactor to a MOX reactor can be achieved without hardware modifications to the existing control and safety systems.

Table 2.35 compares the uranium and plutonium content in the natural fuel with that in the reference MOX fuel. Fresh natural uranium fuel contains 133 g of ^{235}U per bundle. At discharge, each bundle contains 38.7 g of ^{235}U and 67.4 g of fissile plutonium (^{239}Pu and ^{241}Pu). Each fresh MOX fuel bundle contains 36.0 g of ^{235}U and 315.0 g of fissile plutonium. At discharge, each MOX bundle contains 22.2 g of ^{235}U and 186.0 g of fissile plutonium.

Although the nuclear characteristics of the MOX fuel are different from those of natural uranium fuel, a fuel management scheme has been devised for the MOX fuel to ensure that the performance of the MOX core is comparable to that of the natural uranium core in the areas of fuel power rating, control, and safety.

Reactor Power Distribution—Figure 2.20 shows the arrangement of the fuel channels in a Bruce-A reactor. There are 13 fuel bundles in each of the 480 fuel channels. The active length of the core is 12 bundles; therefore, the end bundles, 1 and 13, are only halfway inside the core region. New fuel bundles are inserted

Table 2.35. Actinide inventory for natural and reference MOX fuel bundle (g/bundle)

	New		Exit burnup	
	Natural uranium	**Reference MOX**	**Natural uranium (8300 MWd/MT)**	**Reference MOX (9700 MWd/MT)**
^{235}U	133.0	36.0	38.7	22.2
^{238}U	18670.0	17923.6	18534.0	17831.1
^{239}Pu		313.8	46.8	172.9
^{240}Pu		19.4	20.6	69.3
^{241}Pu		1.2	4.3	13.1
^{242}Pu		0.1	1.3	2.9

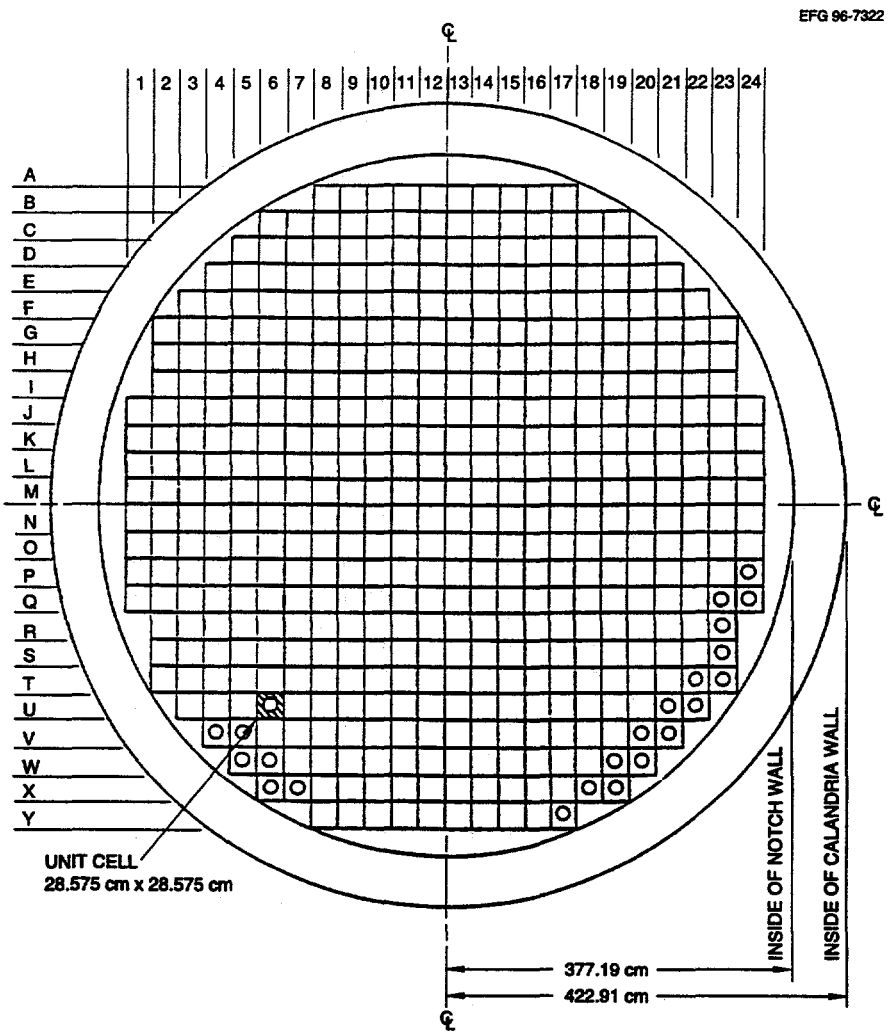


Figure 2.20. Bruce channel arrangement

into the inlet end of the fuel channel, and irradiated fuel bundles are discharged from the outlet end. A mixed 2-, 4-, and 8-bundle shift fueling scheme is presently used in Bruce-A with natural uranium fuel. The 2-bundle shift fueling scheme is used in the high-power inner region. The 8-bundle shift fueling scheme is used in the low-power outer channels. The 4-bundle shift fueling scheme is used in the intermediate channels. This mixed fueling scheme is devised to minimize the power ripple caused by refueling and to optimize fueling machine usage. The slightly higher fuel burnup of the MOX fuel reduces the fueling machine usage and therefore allows the use of a 2-bundle shift fueling scheme over the whole core. This simple fueling scheme significantly reduces the refueling power ripple in the MOX core.

Control—Table 2.36 gives the reactivity worths of the control and safety reactivity devices in Bruce-A with natural fuel and with the reference MOX fuel. Equilibrium xenon load, average reactivity caused by refueling a single channel, and full core void reactivity are also given for both cases. It can be seen that the control and safety reactivity device worths in the MOX core are typically 25% lower than the corresponding values in the natural MOX core. This reduction in device worth is caused by the 30% increase in the cell average absorption in the MOX lattice over that in the natural fuel lattice. However, the reactivity perturbations in the MOX core, that is, the refueling and xenon effects, are also proportionately lower than those in the natural core. Hence, control of the MOX core is not expected to be significantly different from that in the natural core.

Table 2.36. Reactivity effects in Bruce-A natural and MOX cores

	Natural core (mk)	Reference MOX core (mk)
14 zone controllers inserted	–6.0	–3.5
30 SORs inserted	–40.2	–13.3
28 SORs inserted (2 best rods missing)	–31.2	–12.1
4 MCAs inserted	–7.2	–5.5
One channel refueled	+0.2	+0.1
Full core coolant void	+11.0	–5.0
Equilibrium xenon load	–28.0	–20.0

Kinetics—Table 2.37 gives the kinetics data for natural uranium Bruce-A and MOX Bruce-A at equilibrium conditions. Most perturbations in a CANDU reactor operating with natural uranium fuel, with the exception of a large LOCA, are small and slow and can be handled easily by the control system. The positive void reactivity of natural uranium fuel generates an increase in power prior to operation of the shutdown systems during a LOCA. All modern CANDU reactors are equipped with two independent fast-acting shutdown systems. Each system can quickly terminate any increase in power during the most severe LOCA. The void reactivity of the MOX fuel lattice is negative, which is a beneficial effect of the dysprosium in the inner region of the fuel bundle. When coolant is voided, the neutron-scattering effect from the coolant in the fuel channel is curtailed. This allows more neutrons to reach the centre of the fuel bundle (i.e., the poisoned region). The negative reactivity generated by the higher neutron absorption in the poisoned inner region more than compensates for the increase in reactivity in the MOX region. The overall coolant void reactivity effect is therefore negative.

Advanced MOX CANDU Fuel—CANFLEX Bundle

Introduction—The major difference between the reference MOX design and the CANFLEX MOX design is the MOX fuel fabrication requirement. For the same plutonium disposition rate, the advanced fuel design requires only half the MOX fuel production rate of the reference fuel design. This reduction in MOX fuel fabrication requirement is due to the increase in the maximum allowable fuel element burnup. The larger number of fuel elements in the CANFLEX fuel design reduces the element power rating, thus allowing the fuel elements to reach higher burnup without undue degradation of fuel performance.

Table 2.37. Delayed neutron data for equilibrium reference MOX fuel and natural fuel

	Reference MOX fuel		Natural fuel	
Group	Delayed neutron fraction (β)	Time constant (s^{-1})	Delayed neutron fraction (β)	Time constant (s^{-1})
1	0.207×10^{-3}	0.470×10^{-3}	0.295×10^{-3}	0.612×10^{-3}
2	0.788×10^{-3}	0.311×10^{-1}	1.165×10^{-3}	0.316×10^{-1}
3	0.662×10^{-3}	0.132×10^{-0}	1.033×10^{-3}	0.122×10^{0}
4	0.139×10^{-2}	0.327×10^{-0}	2.350×10^{-3}	0.318×10^{0}
5	0.474×10^{-3}	0.135×10^{1}	0.780×10^{-0}	0.139×10^{1}
6	0.144×10^{-3}	0.357×10^{1}	0.197×10^{-3}	0.378×10^{1}
Total	0.366×10^{-2}		5.819×10^{-3}	

Note: Prompt neutron lifetime = 0.00047 s (reference) = 0.0009 s (natural)
Fuel temperature coefficient = –2.9 μk/°C (reference) = –6.0 μk/°C (natural)
Full core void reactivity = –5.0 mk (reference) = +11.0 mk (natural)

The amount of plutonium in the advanced fuel design is higher than that used in the reference fuel design to increase the fuel discharge burnup and reduce the MOX fuel fabrication requirement. The maximum allowable fuel element burnup increases from 15,000 MWd/MT to about 28,000 MWd/MT. The CANFLEX fuel bundle design is specifically designed to enable the fuel elements to achieve burnups of over 30,000 MWd/MT. Hence, the CANFLEX fuel bundle geometry, as shown in Fig. 2.21, is chosen for the advanced MOX bundle design.

Specifications of the Advanced MOX Fuel Design—The specifications of the advanced MOX fuel design are obtained from a series of iterations between the lattice code WIMS and the three-dimensional fuel management code RFSP. The procedures are similar to those used to establish the specifications of the reference MOX fuel design.

Table 2.38 compares the nuclear characteristics of the advanced MOX fuel design with those for the reference MOX fuel design. In both designs, plutonium is mixed with 0.2% ^{235}U depleted uranium in the outer two rings, whereas dysprosium is mixed with 0.2% ^{235}U depleted uranium in the inner two rings. The plutonium content is increased from 334.5 g and the reference MOX bundle to 472.6 g in the advanced MOX bundle. The amount of dysprosium is increased from 510 to 630 g, correspondingly. This allows the discharge burnup of the advanced MOX fuel bundle to be increased to 17,1000 MWd/MT. The rate of refueling is 9 bundles per full-power day for the advanced MOX fuel design as compared to 15.5 bundles for the reference MOX fuel design. The higher plutonium content of the advanced fuel design increases the maximum rippled bundle power from 770 to 800 kW. However, the maximum element rating in the advanced fuel design is still about 10% lower than that in the reference fuel design because the bundle power is spread over 43 elements rather than 37. The advanced MOX core has a slightly higher power form factor (i.e., higher power flattening) than the reference MOX core. This enables both the reference MOX core and the advanced MOX core to operate with the same maximum rippled channel power of 7.0 MW(thermal).

Table 2.39 compares the uranium and plutonium contents in the advanced MOX fuel with those in the reference MOX fuel. Each advanced MOX fuel bundle contains 472.6 g of plutonium when it is fresh and

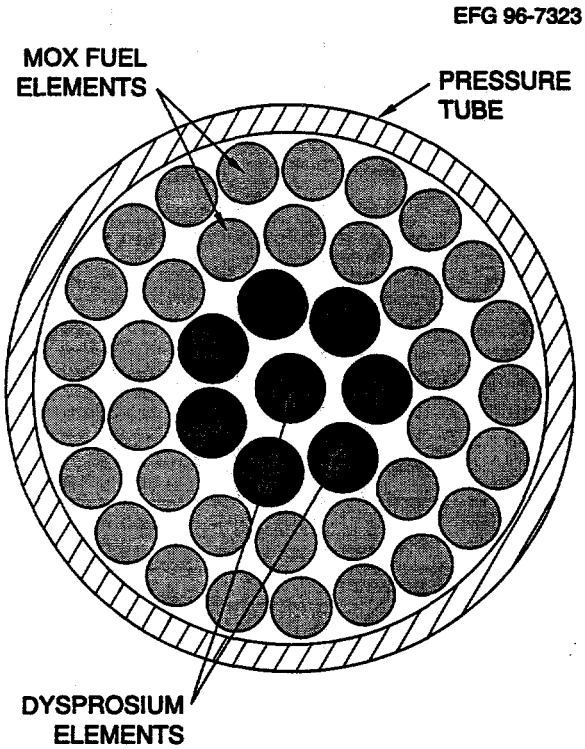


Figure 2.21. CANFLEX bundle geometry

Table 2.38. Comparison of advanced and reference MOX fuel characteristics

	Advanced MOX-fueled Bruce-A station		Reference MOX-fueled Bruce-A station	
Fuel bundle geometry	CANFLEX 43-element design		Existing Bruce 37-element design	
Pellet material composition (percentage based on weight of HM in fuel)	Ring 4 (21 pins) Ring 3 (14 pins) Ring 2 (7 pins) Ring 2 (1 pin) All rings have 0.2% U^{235}	2.6% plutonium 4.6% plutonium 15% dysprosium 15% dysprosium	Ring 4 (18 pins) Ring 3 (12 pins) Ring 2 (6 pins) Ring 2 (1 pin) All rings have 0.2% ^{235}U	1.6% plutonium 3.1% plutonium 15% dysprosium 15% dysprosium
Bundle material composition (fuel material only)	Plutonium ^{235}U ^{238}U dysprosium O_2 TOTAL:	0.47 kg 0.04 kg 17.22 kg 0.63 kg 2.97 kg 21.33 kg	Plutonium ^{235}U ^{238}U dysprosium O_2 TOTAL:	0.33 kg 0.04 kg 17.92 kg 0.51 kg 2.53 kg 21.33 kg
Average burnup	17,000 MWd/MT		10,000 MWd/MT	
Maximum burnup	28,000 MWd/MT		15,500 MWd/MT	
Bundle/FPD	8.8		15.0	
Fuel management scheme	2 bundle shift		2 bundle shift	
Maximum channel power	7,000 kW		7,000 kW	
Maximum bundle power	800 kW		780 kW	
Moderator/coolant purity	97.00%		97.00%	
LOCA void reactivity	–4.5 mk		–5.0 mk	

Table 2.39. Actinide inventory for CANFLEX and reference MOX fuel bundle (g/bundle)

	New		Exit burnup	
	CANFLEX MOX	**Reference MOX**	**CANFLEX MOX 17,000 MWd/MT**	**Reference MOX 9,700 MWd/MT**
^{235}U	34.7	36.0	18.8	22.2
^{238}U	17218.8	17923.6	17088.1	17831.1
^{239}Pu	443.4	313.8	173.2	172.9
^{240}Pu	27.4	19.4	101.8	69.3
^{241}Pu	1.7	1.2	20.9	13.1
^{242}Pu	0.1	0.1	6.7	2.9

302.6 g of plutonium at discharge burnup. The corresponding values in the reference MOX fuel bundle are 334.5 and 258.2 g, respectively.

Reactor Power Distribution—Figure 2.22 compares the radial power distribution between the advanced MOX core and the reference MOX core across the central row of fuel channels. Figure 2.23 shows the axial bundle power distribution along a high-power channel in the advanced MOX core and in the reference MOX core. The fuel management scheme in the advanced MOX core has been designed to give channel and bundle power shapes comparable to those in the reference MOX core.

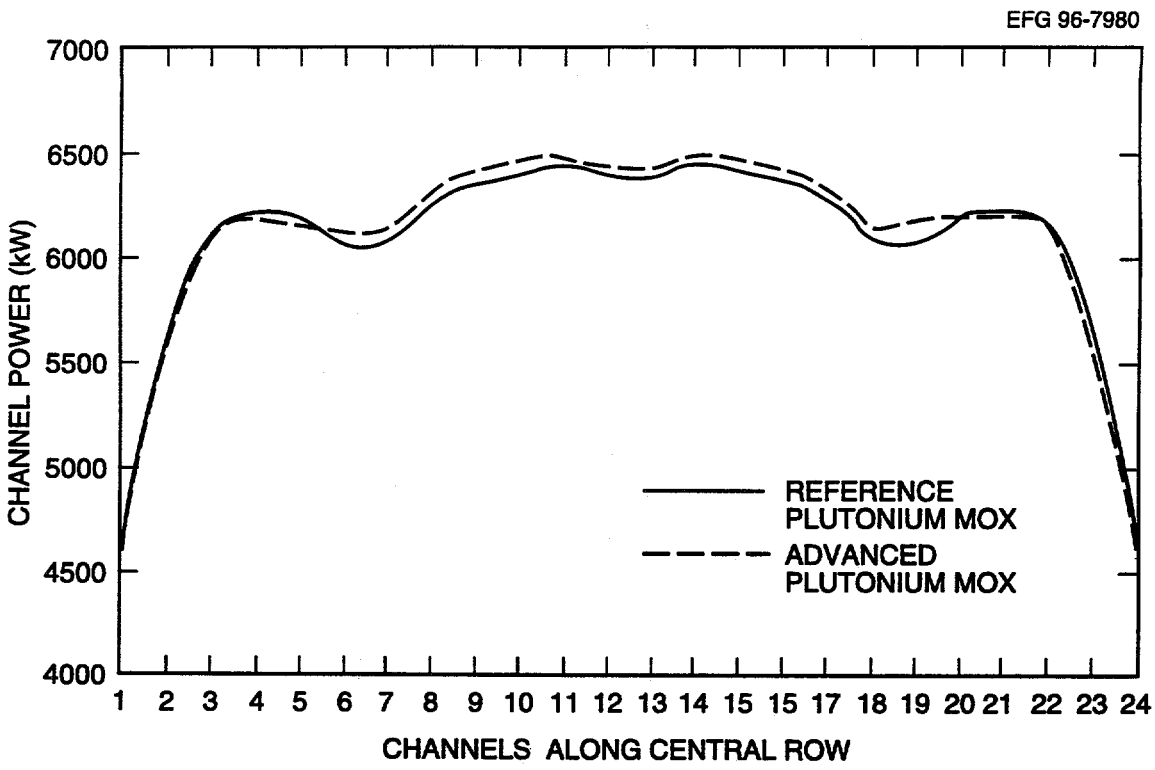


Figure 2.22. Radial power distribution advanced fuel design vs reference MOX fuel

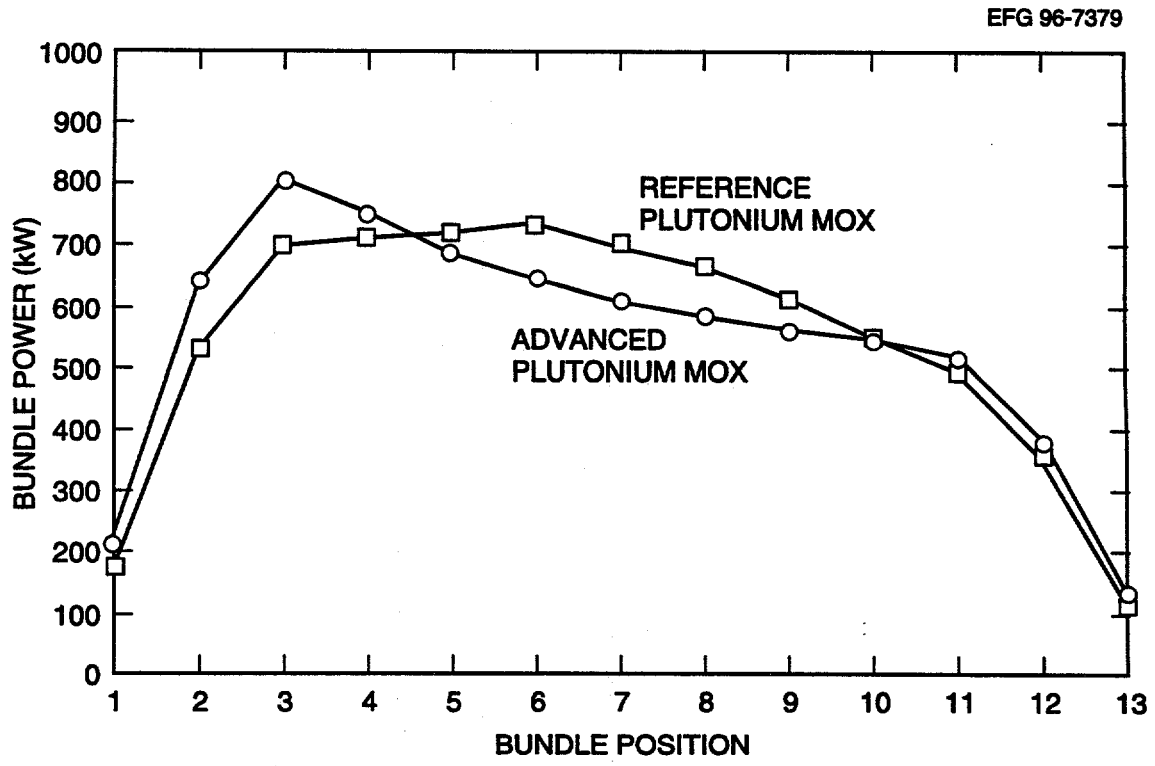


Figure 2.23. Axial power distribution advanced fuel design vs reference MOX fuel

Fuel performance data are extracted from a rippled core calculation using a random fuel burnup distribution designed to simulate the advanced MOX core at equilibrium. Time-dependent refueling simulations have not been carried out for the advanced MOX core; however, based on the results obtained from the 100 full-power days refueling simulation in the reference MOX core, the power boosting effect from refueling in the advanced MOX core is not expected to be a critical factor.

Control—Table 2.40 gives the reactivity worths of the control and safety reactivity devices in Bruce-A for the advanced MOX fuel core and the reference MOX fuel core. Equilibrium xenon load, average reactivity from refueling a single channel, and full core void reactivity are also given for both cases. The control and safety reactivity device worths in the advanced MOX core are typically 10% lower than those in the reference MOX core. This reduction in reactivity device worth is caused by the increase in the absorption cross section of the advanced MOX fuel lattice. Based on the stability analyses carried for the reference MOX core, this small decrease in controller reactivity worth is not expected to significantly affect the control of the advanced MOX core.

Kinetics—Table 2.41 gives the kinetics data for the advanced MOX core and the reference MOX core at equilibrium conditions. Because of the higher plutonium content in the advanced MOX fuel core, the delayed neutron fraction and the prompt neutron lifetime are slightly lower than those in the reference MOX core. This indicates that the power transients in the advanced MOX core will be slightly faster than those in the reference MOX core.

Table 2.40. Reactivity effects in Bruce-A CANFLEX and reference MOX cores

	CANFLEX MOX core (mk)	Reference MOX core (mk)
14 zone controllers inserted	–3.4	–3.5
30 SORs inserted	–12.4	–13.3
28 SORs inserted (2 best pins missing)	–10.9	–12.1
4 MCAs inserted	–2.8	–5.5
One channel refueled	+0.2	+0.1
Full core voided	–4.5	–5.0
Equilibrium xenon load	–19.0	–20.0

Table 2.41. Delayed neutron data for equilibrium CANFLEX and reference MOX fuel

	CANFLEX plutonium-MOX fuel		Reference MOX fuel	
Group	Delayed neutron fraction (β)	Time constant (s^{-1})	Delayed neutron fraction (β)	Time constant (s^{-1})
1	0.202×10^{-3}	0.462×10^{-3}	0.207×10^{-3}	0.470×10^{-3}
2	0.779×10^{-3}	0.312×10^{-1}	0.788×10^{-3}	0.311×10^{-1}
3	0.649×10^{-3}	0.132×10^{-0}	0.622×10^{-3}	0.132×10^{-0}
4	0.136×10^{-3}	0.327×10^{-0}	0.139×10^{-2}	0.327×10^{-0}
5	0.464×10^{-3}	0.136×10^{2}	0.474×10^{-3}	0.135×10^{1}
6	0.138×10^{-3}	0.355×10^{1}	0.144×10^{-3}	0.357×10^{1}
Total	0.359×10^{2}		0.366×10^{-2}	

Note: Prompt neutron lifetime = 0.00046 s (CANFLEX) = 0.00047 s (reference)
Fuel temperature coefficient = –2.0 μk/°C (CANFLEX) = –2.9 μk/°C (reference)
Full core void reactivity = –4.5 mk (CANFLEX) = –5.0 mk (reference)

2.4.4.3 CANDU Reactor Facility Operations Schedule

After completion of the preoperational phase, the CANDU reactors will be ready to accept reference MOX fuel in February 2002; however, the U.S. MOX fuel fabrication facility will not produce a sufficient supply of fuel bundles until June 2007. At this time, two reactor units at Bruce-A will start operating with reference MOX fuel and will operate with this fuel for 5 years. At the end of the 5-year period, the first two units fuel and two additional units will be switched to irradiating CANFLEX fuel. These four reactors are loaded with CANFLEX fuel for 7.2 years. The CANDU reactor facility operational schedule is shown in Table 2.42 and in Fig. 2.24.

2.4.4.4 CANDU Reactor Facility Operating Cost

Category 13 of Table 2.43 shows the costs for the additional staff and materials needed for the MOX mission above the normal staffing and materials for operation on natural uranium. DOE-FMDP is assumed to reimburse the Canadian utility for these costs. AECL estimates that only 14–15 total additional staff (half direct and half indirect assumed) will be needed in the following areas: fuel receiving and storage, fuel loading, in-reactor staff, and common services and training. The cost of the additional staff and a minimal amount of materials is costed in category 13 at $1.1M/year. The AECL has projected that no DOE funds are needed for categories 15–19 because of the simplicity of the fuel cycle (categories 15 and 16) and institutional differences vis-a-vis the United States and Canada (categories 17–19). D&D of the reactors (category 19) is the responsibility of the Canadian utility at the end of the lives of the reactors and involves no U.S. funds. Because the reactors are not owned by the U.S. government, no revenues accrue, and zero is shown in category 21. The incentive fee to the Canadian utility (category 22) is calculated on the formula used for the other reactor alternatives, that is, $25M/year/reactor pair for the first 5 years followed by $10M/year for the remaining years (7.2 years in this case). This incentive fee does not represent a negotiated amount, but rather is based only upon informal discussions by the cost estimating group and is included only for completeness. This incentive fee was assumed to be zero in the TSR. Approximately $2M/year in transportation costs has been calculated for transportation of MOX bundles from the U.S. MOX fuel fabrication facility (assumed to be located in the southeastern United States) to the Bruce NGS A site.

If the fee and transportation are included, the reactor part of the CANDU MOX mission will cost $25M/year. This is the same as the annual costs for using existing LWRs and is much lower than the $200+M/year needed if DOE-FMDP owns the reactors.

Operations duration. The 12.2-year operation duration represents the time from the first MOX fuel facility loading to the last MOX fuel loading for a given reactor. In reality MOX fuel will still be in the reactors for 1.2 years after the last fuel load. It is assumed that operations costs and payment of a fee accrue only for the 12.2-year period.

Table 2.42. CANDU facility operations schedule

Task ID	Task name	Duration (months)	Start	Finish
4.	**MOX Facility Lead Time**	6	12/2006	6/2007
11.	**Preoperational Phase**	3	12/2002	2/2003
13.	**Reactor Facility Operation**	161	6/2007	10/2020
14.	Units 1 and 2 Reference MOX Loading Duration	60	6/2007	6/2012
15.	Units 1–4 CANFLEX Loading Duration	86	6/2012	8/2019
16.	Irradiation of last CANFLEX Bundles	15	8/2019	10/2020
17.	**Spent Fuel Storage**	274	10/2014	7/2037
18.	First MOX in Spent Fuel Pool	120	8/2008	8/2018
19.	Last CANFLEX	120	11/2020	11/2030

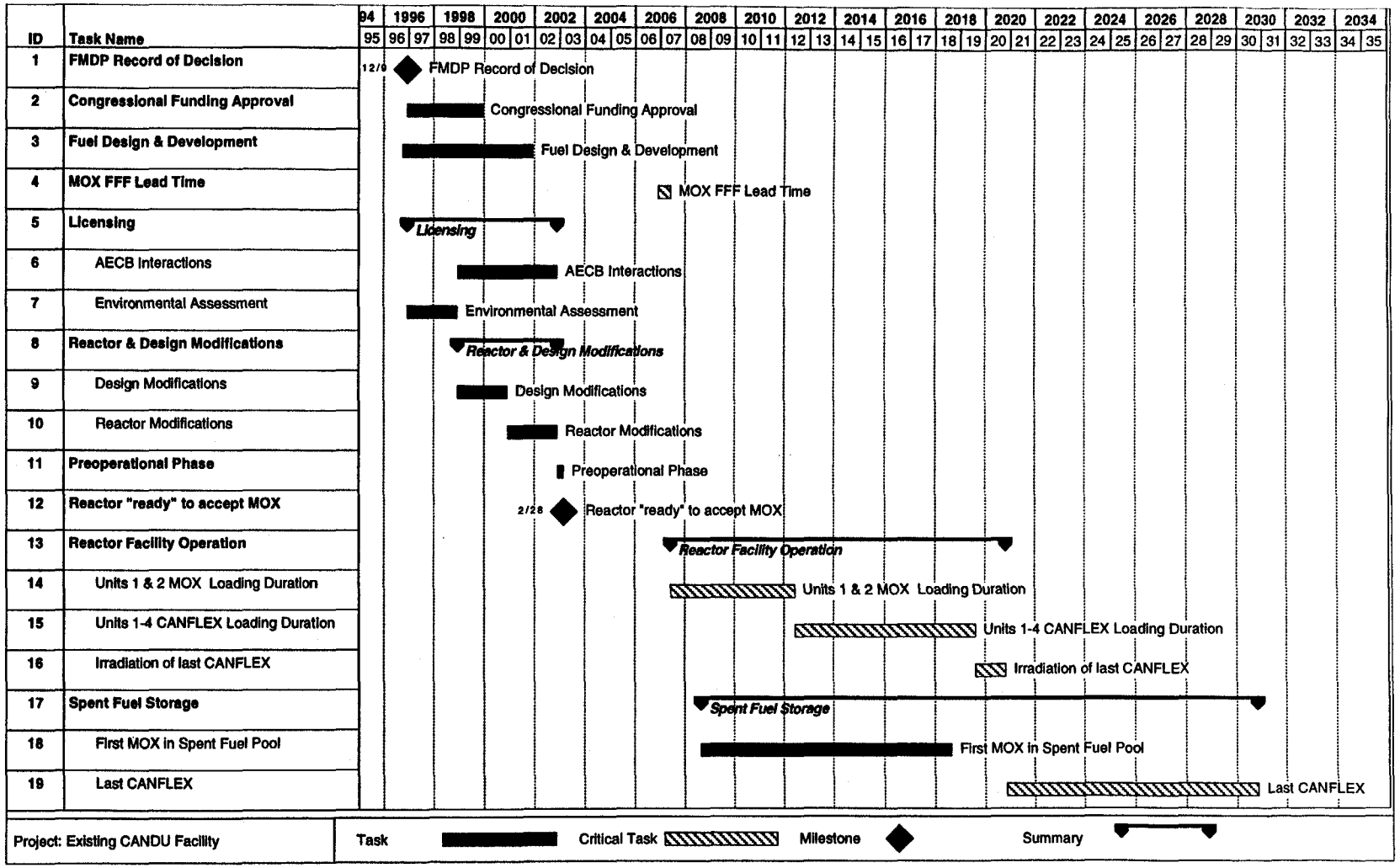


Figure 2.24. CANDU HWR facility schedule summary

Table 2.43. Recurring and other LCCs for CANDU reactor facility

Category	Cost category description	Cost		Basis
		Lump sum ($M)	Annual ($M/year)	
	Other LCCs for 2 followed by 4 units: Campaign length = 12.2 years			
13	O&M staffing			
	Incremental staff size (headcount) 14 persons for CANDU facility			
	Staffing cost	12	1.0	Based on AECL data
14	Consumables (including utilities) (14 years)	0		Small amount included in category 13
15	Major capital replacements or upgrades	0		Negligible incurred costs per AECL
16	Waste handling and disposal			Negligible incurred costs per AECL
17	Oversight	0		Included in category 13
18	M&O contractor fees	0		N/A
19	PILT to local communities (14 years)	0		Not applicable in Canada
	TOTAL REACTOR RECURRING COSTS	12	1.0	
20	D&D (sinking fund approach)	0		N/A
21	Revenues	0		N/A
22	Incentive fee to utility	269	22.0	See discussion in Sect. 2.4.4.4
23	Transportation of plutonium forms to facility: ORNL T&PD group (12.2 years)	26	2.1	Transportation of bundles from MOX fuel fabrication facility to Bruce NGS A
24	Storage of plutonium at existing 94-1 site facility	N/A	N/A	N/A
	TOTAL OTHER LCC	307	25.1	

2.4.5 CANDU Reactor Facilities Schedule Summary

The overall CANDU facility implementation schedule is summarized in Table 2.44 and shown in Fig. 2.24. The facility schedule is also shown in the discussion of the overall alternative schedule in Sect. 2.6.

2.4.6 CANDU Reactor Facilities Cost Summary

Table 2.45 shows a summary of the CANDU facility LCCs in the 24-category format. All anticipated reactor-related costs from FY 1997 forward are included in this table. Chapter 3 compares these constant-dollar LCCs (along with the discounted LCCs) with those for other facilities needed for the overall program.

2.4.7 CANDU Reactor Facility Technical Viability

DOE has identified five items the consideration of which constitutes a qualitative assessment of the technical viability of a concept: a definition of the technological maturity of a process; the specification of the technical unknowns for the process and the technical risk associated with the application of the process; research and engineering development needs of the process, the condition, capacity, and reliability of the infrastructure; and, lastly, the regulatory and licensing requirements associated with the process. The first three of these items are discussed in this section. The infrastructure is discussed within the facility description and design and construction sections. The licensing item is discussed in a separate section for each facility.

Table 2.44. CANDU HWR facility schedule summary

Task ID	Task name	Duration (months)	Start	Finish
1.	**FMDP Record of Decision**			12/1996
2.	**Congressional Funding Approval**	36	12/1996	12/1999
3.	**Fuel Design and Development**	62	10/1996	11/2001
4.	**MOX Facility Lead Time**	24	12/2006	11/2008
5.	**Licensing and Permitting**	72	12/1996	11/2002
8.	**Reactor & Design Modifications**	48	12/1998	11/2002
11.	**Preoperational Phase**	3	12/2002	2/2003
12.	**Reactors "ready" to accept MOX**			2/2003
14.	Units 1 and 2 Reference MOX Loading	60	6/2007	6/2012
15.	Units 1–4 CANFLEX Loading Duration	86	6/2012	8/2019
16.	Irradiation of Last CANFLEX Bundles	15	8/2019	10/2020
17.	**Spent Fuel Storage**	266	8/2008	11/2030

Technological Maturity—Judging the maturity of the technologies employed in plutonium disposition facilities requires an assessment of the current level of development of each stage of the fuel cycle. Technologies can be categorized as being at the conceptual design stage, the laboratory or bench-scale testing stage (demonstrating scientific feasibility), the prototype stage (demonstrating engineering feasibility), or the industrialization/commercialization stage. Even if a significant domestic development base does not exist, a foreign experience base may be available.

The technologies present in the reactor facility are:

1. methods of fuel receipt, inspection, and accountability;
2. methods of new fuel storage;
3. method of new fuel transfer to reactor and of fueling the core;
4. reactor operation to consume plutonium;
5. balance of plant operation not related to fuel handling;
6. method of fuel discharge from core and spent fuel transfer;
7. method of wet spent fuel storage;
8. method of fuel transfer to spent fuel cask; and
9. method of dry, spent fuel storage.

The first seven technologies correspond to physical operations involved in the placement of MOX fuel in differing areas of the plant, while the last two technologies relate to transfer of fuel from the plant to the final spent fuel waste repositing.

Assessment of the development level of these technologies requires evaluations based on one or more of the following engineering analyses:

1. Steady-state analysis
   i. Thermal-hydraulics
   ii. Reactor physics
   iii. Reactivity control
   iv. Fuel chemistry and thermodynamics
   v. Fuel structural mechanics
2. Transient analysis
   i. Reactor transient response
   ii. Accident analysis

Research and development needs to support these engineering analysis areas follow:

- validation of reactor neutronics and thermal-hydraulic codes;
- performance of experiments to support neutronics and thermal-hydraulic code validation;
- performance of a CANFLEX fuel qualification test program consisting of research reactor irradiations and in-reactor irradiations of a limited number of bundles in a Bruce-A reactor;

Table 2.45. Summary of LCCs for CANDU reactor facilities

Category	Cost category description	Cost [lump sum ($M)]
	Preoperational or OPC up-front costs:	
1	R&D	35
2	NEPA, licensing, permitting	18
3	Conceptual design	1
4	QA, site qualification, S&S plans	2
5	Postconstruction start-up	4
6	Risk contingency	7
	TOTAL OPC	67
	Capital or TEC up-front costs:	
7	Title I, II, III engineering, design, and inspection	0
8	Direct and indirect construction/modification	32
9	Construction management (percentage of category 8)	0
10	Initial spares (technology dependent)	0
11	Allowance for indeterminates (AFI) (percentage of categories 7–10)	0
12	Risk contingency	0
	TOTAL TEC	32
	TOTAL UP-FRONT COST (TPC)	99
	Other LCCs: (12.2-year loading campaign)	
13	O&M staffing	12
	Incremental staff size 14 persons	
14	Consumables including utilities	0
15	Major capital replacements or upgrades	0
16	Waste handling and disposal	0
17	Oversight	0
18	M&O contractor fees	0
19	PILT to local communities	0
20	D&D	0
21	Revenues	0
22	Government subsidies or fees to private-owned facilities[a]	269
23	Transportation of plutonium forms to facility	26
24	Storage of plutonium at existing 94-1 site facility	N/A
	TOTAL OTHER LCC	$307
	GRAND TOTAL ALL LCC	$406

[a]The incentive fee to the Canadian utility is not included in the estimate provided in Table 4.1 of the TSR.

- development and updating of CANDU fuel thermal and mechanical performance computer codes for CANFLEX fuel; and
- performance of accident analysis to update the Bruce-A Safety Report, including fuel criticality analysis.

1. Fuel Receipt, Inspection, and Accountability—Fuel receipt will occur at the new fuel storage building. Inspection will occur at the new fuel-loading room. Full compliance with IAEA requirements for safeguarding and accountability will be implemented for new fuel handling.

   Because only additional analyses are required, and considering Ontario Hydro's experience with meeting IAEA requirements, the technologies are judged to be at the *commercialized* stages of development.

2. Method of new fuel storage—Upon receipt at the reactor facility, fuel will be stored in the secure dry storage vault of the new fuel storage building.

Validation of criticality analysis will be required. However, this technology is judged to be at the *commercialized* stage of development.

3. Method of new fuel transfer to reactor and fueling the core—Fuel will be transferred from the new fuel storage building to the new fuel-loading room in shielding sleeves. Transfer from the shielding sleeve to the fueling machine head will be via a simple remote/manual tool. Since this tool has not been designed, it is judged to be at the *prototypic* stage of development. All other new fuel transfer and core loading methods are at the *commercialized* stage of development. Note that CANFLEX fuel is designed to be compatible with fuel handling for the existing 37-element bundle design.

4. Reactor operation to consume plutonium—No modifications to the reactor have been identified. Operation within the existing operating envelope for the Bruce-A reactors currently operating with natural uranium fuel is predicted. Confirmation of this will be performed through the fuel qualification (load test assembly) program and by conducting detailed reactor response and accident analysis.

   Based upon the confirmatory engineering analysis and supporting experimental programs, and the fact that there are no CANDU reactors operating with full MOX cores and none operating with CANFLEX fuel, this technology is judged to be at the *prototypic* stage of development.

5. BOP operations not related to fuel handling—There are no impacts on the balance of plant operation due to MOX fuel utilization. Therefore, this technology is judged to be at the *commercialized* stage of development.

6. Method of fuel discharge from core and spent fuel transfer—The existing Bruce-A fueling machines will be employed without modification for either reference MOX or CANFLEX fuel. Therefore, this technology is at the *commercialized* stage of development.

7. Method of wet spent fuel storage—Spent fuel storage will be in existing water storage pools utilizing spent fuel storage modules based upon the Darlington station design. This technology is judged to be at the *commercialized* stage of development.

8. Method of fuel transfer to spent fuel cask and dry storage—This method of transfer has been demonstrated in connection with Ontario Hydro's dry storage and transportable cask, and there is not a strong dependency on the type of cask. Therefore, these technologies are judged to be at the *commercialized* stage of development.

Technical Risks—Certain technologies have associated technical unknowns. Generally these unknowns are parameters whose values for certain "reference" fuel cycles are known but whose behavior for MOX fuel cycles is unknown or poorly known. Consequently there are risks associated with the application of the technologies based on these parameters.

Assuming that implementation of any activity not currently operational involves some minimal degree of risk (technical, financial, regulatory, and/or scheduling), risk is herein quantified as minimal, low, medium, or high for each of the technologies. All of those technologies determined to be commercialized either domestically or internationally have only minimal implementation risks as discussed in the following.

The technological risks associated with the previously identified noncommercial technologies in the Technical Maturity section are summarized as follows:

1. Methods of fuel receipt, inspection, and accountability—Based upon both the international experience with MOX fuel and Ontario Hydro's significant experience with implementing technologies to meet IAEA requirements, there is low risk associated with these technologies.

2. Method of new fuel storage—The technologies associated with the provision of secure storage facilities for MOX fuel are well established. The risk associated with adapting these technologies to MOX fuel storage at Bruce-A are minimal.

3. Method of new fuel transfer to reactor and fueling the core—These operations involve existing fuel-handling systems at Bruce-A with a simple and minor modification for transferring bundles from a shielding sleeve to the fueling machine head. The risks associated with these technologies are minimal.

4. Reactor operation to consume plutonium—Both MOX fuel designs are based upon use of the burnable poison dysprosium in the central seven

elements of a bundle. The use of this material in bundles with low enrichment has been investigated by AECL for other fuel designs. In addition, a natural uranium-based CANFLEX fuel design is already being tested. New Brunswick Power's Point Lepreau and Korea Electric's Wolsong 1 are considering the use of natural uranium CANFLEX fuel within the next 3 to 4 years. Based upon past operational experience, the ongoing work on natural uranium CANFLEX fuel, and the predicted MOX fuel performance envelope being within the existing natural uranium fuel operating envelope, a low risk is associated with MOX fuel performance. The fuel qualification program will confirm this expectation.

Impurities in plutonium, particularly gallium and americium, are not considered to be major issues primarily due to the much lower burnup rates as compared to LWR fuel..

The MOX fuel design will result in a change in coolant void reactivity feedback from positive to negative. Since CANDU reactors have been designed to accommodate rapid positive reactivity changes associated with positive coolant void in natural uranium fuel, this is not judged to be a major issue. Accident analysis will confirm this.

Due to the longer residence time in the core and consequent higher burnup of the fuel, the fission product inventory in the CANFLEX core at equilibrium will be significantly greater than that present in the reference fuel. This higher fission product inventory will impact, in some unquantified fashion, the severe accident analysis results for the CANFLEX cycle as compared to the reference cycle. However, since the power density in the two fuels is essentially the same, the inventory of fission products with short half-lives—generally those that pose the greatest health hazard—will be essentially the same for the two fuels. Accident analyses must be performed to assess the magnitude of the difference between reference and CANFLEX cycles relative to severe accident sequences.

Therefore, although issues do exist with reactor operation, they are all considered to be manageable and do not add significant risk to the overall mission.

R&D Needs—Previously, various parameters of this alternative were identified as unknown or poorly known for. The research and/or engineering development necessary to address each of these technology development needs is presented subsequently. Cost and scheduling data for these needs are presented elsewhere.

The engineering development and R&D necessary to address each of the previously identified technologies in the Technical Maturity and Technical Risk sections are summarized as follows:

1. Methods of fuel receipt, inspection, and accountability—Minimal development is foreseen in this area.

2. Method of new fuel storage—Minimal development to adapt existing technologies to CANDU fuel is foreseen.

3. Method of new fuel transfer to reactor and fueling the core—Minor development of a tool for transferring bundles from a shielding sleeve to the fueling machine head is required. This is of the nature of well-established mechanical design and poses no difficulties.

4. Reactor operation to consume plutonium—Completion of the CANFLEX fuel design and testing of both reference and CANFLEX fuel bundles are necessary. The fuel and physics qualification program for the MOX fuel entails experimental demonstration that is necessary to qualify the fuel for large-scale implementation in Bruce-A. This development work consists of the following elements:

   Design confirmation—This involves demonstrating that the fuel design meets all the requirements for normal operating conditions. Included are the irradiation of elements and bundles in the NRU research reactor and postirradiation examination (PIE) of irradiated elements to confirm acceptable irradiation behavior; reactor physics experiments in a research reactor to confirm the physics parameters; critical heat flux (CHF) tests in a full-scale water test facility to demonstrate that the design provides acceptable margins for the shutdown system trips; and mechanical integrity tests to confirm acceptable in-reactor mechanical performance.

Prototype irradiation in Bruce-A—Approximately 20 to 50 bundles would be involved in a prototype irradiation in a Bruce-A reactor to confirm fuel performance prior to full core implementation of MOX fuel.

5. Balance of plant operations not related to fuel handling—No development is foreseen in this area.

6. Method of fuel discharge from core and spent fuel transfer—No development specific to MOX fuel utilization is foreseen in this area.

7. Method of wet spent fuel storage—Spent fuel storage will be in existing water storage pools utilizing spent fuel storage modules based upon the Darlington station design. The development necessary for this technology is minimal, involving adaptation of an existing system.

8. Method of fuel transfer to spent fuel cask—No development specific to MOX fuel utilization is foreseen in this area.

2.4.8 CANDU Reactor Facilities S&S Summary

This section covers the S&S requirements for BNPD focusing on the specific need to carry out the mission of dispositioning excess weapons-grade plutonium. For the reference case, (37-element MOX fuel bundle), the S&S requirements are addressed under the following headings:

- Bases of Study,
- Existing Site Security Arrangements,
- Additional Site Security Requirements, and
- Additional Site Safeguards Requirements.

The advanced fuel design case has also been reviewed to identify any significant changes to the S&S plans developed for the existing 37-element fuel design.

2.4.8.1 Bases of Study

For the reference case of 37-element CANDU MOX fuel, the bases of study are that the fuel will be delivered to the Bruce site in convoys of the DOE SSTs. These deliveries are expected to be consistent with the fueling requirements of the CANDU reactors assigned to this mission. It is also presumed that the SNMs that are being shipped have undergone an IAEA safeguards accountancy and sealing procedure at the reference fuel fabrication site, FMEF Hanford, prior to shipping. It is further presumed that the packaging has received approvals from both the appropriate U.S. government and Canadian government authorities. (These issues are addressed in the Packaging and Transportation Sections and in the Security and Safeguards Overview Section.)

2.4.8.2 Additional Site Security Requirements

Basic security systems required for this facility would include four levels of access control such that an individual requiring access would have to be accompanied by at least one other authorized individual (the two-person rule), have a valid access control card and personal identification number, and be further authorized by a biometric security device such as hand geometry or retinal scan. The facility itself would be monitored by external motion detection and video surveillance.

The security requirements, built-in delay factors, and fuel bundle storage schemes have been evaluated using guidelines developed for such facilities by DOE and the IAEA.[2]

Fencing, barriers, and motion detection and alarm systems would be installed in strategic areas to ensure coverage and provide early warning of intrusion attempts. The evaluation indicated that a delay time of 90 minutes would be sufficient to allow an initial armed emergency response team to arrive at the site. The tactical response units would be at the site within 2 hours.

Current commercially available security devices and systems have been used for the purposes of estimating the costs associated with the study. It would be prudent, however, to specify the devices and systems to be used closer in time to the actual construction of the facility to take advantage of any technological advances.

The transfer to the new fuel-loading room could be effected via a tunnel or an overhead bridge, both of which can be hardened and secured to prevent any unauthorized access. The transfer route will be chosen on the basis of least disruption to Bruce station operations. While the transfer of one container at a time of new MOX fuel could technically be classified as a category 2 movement, there are advantages to maintaining the category 1 requirement throughout the transfer process to reduce the risk of diversion of the material. Thus the entire process of receiving, storing,

transferring, and eventually loading the new MOX fuel will be carried out in a category 1 facility.

The new fuel-loading area will require some engineering work to seal off potential unauthorized access points that currently exist. The main entryway to this room would have to be modified to include the four levels of access control described earlier for the receiving and storage facility. This would entail the construction of a vestibule that would serve as a man-trap and ensure the integrity of the category 1 requirement for the new fuel-loading room. A more detailed description of the new fuel-loading room is presented in Sect. 2.4.

Another change required for this mission would be to obtain the appropriate security clearances for personnel authorized for access to the MOX fuel-receiving and storage facility as well as the new fuel-loading room. The personnel clearances would have to include any employees who would be handling existing natural uranium fuel for the other two reactors, as the two types of fuel would share the same room for fuel loading. This is a cost that would be incremental to the existing activities. The approximate time to obtain such a clearance is 10–12 months.

It is anticipated that there would be a need for five additional security personnel to support this mission and five fuel-handling personnel for the handling of the MOX fuel.

2.4.8.3 Additional Site Safeguards Requirements

The existing full-scope safeguards regime at the Bruce facility have been put in place by the IAEA. These safeguards consist of an accounting scheme that identifies and tracks the natural uranium fuel from reception through loading into the reactor, through the on-power cycle, and subsequent discharge to the spent fuel storage bays. A spent fuel bundle counter (SFBC) counts the spent fuel bundles as they are discharged into the spent fuel storage bays. Once in the spent fuel storage bays, the fuel comes under an IAEA containment/surveillance system that records all movements of spent fuel. Some spent fuel has been put in specially designed cages that have an IAEA tamper-indicating seal as a closure.

The safeguards associated with the new mission of dispositioning the weapons-grade plutonium as MOX fuel will require several significant changes to the existing regime. On delivery of the MOX fuel via the transport system selected for the mission, the IAEA will verify that the seals placed on each container by the IAEA at the shipping site are intact. A device currently in use in Japan, and developed by LANL, will then be used to verify that the container did indeed contain the right amount of MOX fuel. Two of these devices, based on passive neutron counting,[3] will be required. The second device will be used in the new fuel-loading room prior to insertion into the new fuel-loading magazine to ensure that no diversion has occurred. These measurements can be integrated with the accountancy program to ensure tracking of fuel bundles and assays.

Because Bruce is a multiunit station, and this mission is dedicated to the disposition of weapons-grade material, the IAEA will want to augment the current arrangement of relying only on SFBCs and will require the installation of core discharge monitors (CDMs) to reconcile the gap between actual core discharge of fuel and possible diversion prior to discharge to the spent fuel bay. These devices have been installed in the latest generation of CANDU multiunit reactor station. There may be a requirement to have the CDMs made capable of distinguishing between spent natural uranium fuel and spent MOX fuel. This may be an area for further study.

2.4.8.4 Advanced Fuel Design

No significant changes to the S&S regime are anticipated with the introduction of the advanced fuel. Current evaluations do not identify any parameters that indicate that new approaches be adopted or that any new assay equipment may be required. It is anticipated that recalibration of the assay equipment will be required. The procedures and protocols put in place for the reference fuel may have to be modified somewhat, but the impacts on costs are expected to be negligible.

2.4.8.5 S&S Costs

The estimates for costs associated with the S&S aspects of the dispositioning of plutonium at the BNPD site are based on having four Bruce units dedicated to the mission, with MOX fuel arriving on a monthly basis in sufficient quantities to meet fueling requirements and have an additional float supply of 1 month's fuel. They are also based on the use of DOE SSTs for the transportation of the MOX fuel. All mission costs are inclusive of start-up costs.

The costs associated with the new MOX fuel-receiving and storage facility at the Bruce site as presented

here are exclusive of construction costs, which are covered elsewhere and are inclusive of delay systems, access control and sensing equipment, and alarm systems as well as licensing costs associated with a category 1 facility.

The safeguards needs for this facility are expected to include material accountancy systems and plutonium assay equipment, along with handling tools and inspection activities. The total S&S costs for the new MOX fuel-receiving and -storage facility are anticipated to be $3.6M for the initial startup phase and $1.8M/year for O&M. The new fuel-loading room estimates are exclusive of construction "hardening" costs but inclusive of access control systems, surveillance systems, and alarm systems.

The safeguards associated with the new fuel-loading area include the installation and use of plutonium assay equipment, an accounting system station, containment and surveillance systems, and inspection. The total S&S costs for the new fuel-loading room are anticipated to be $1M for the initial startup phase and $0.2M/year for O&M.

The safeguards associated with in-reactor operations include the installation of DMs, refurbishment of spent fuel bundle counters, and inspection. The cost of the system has been annualized at $0.2M/year to reflect the fact that it must be periodically replaced because of the high radiation field.

BNPD site central security services associated with the disposition project would require additional staff, additional communications equipment, and additional security monitoring room equipment for the primary and secondary security control rooms. Other cost items identified are the development and delivery of training programs, operational protocols, response strategies, and liaison with other security forces. These costs are anticipated to be $1.1 M in the startup phase and $0.5M/year for O&M.

The existing infrastructure will be used for safeguards requirements. Additional costs associated with the dispositioning of plutonium are covered in the areas identified above.

To summarize, the costs for the S&S measures identified in this section are anticipated to total about $5.7M during startup and $2.7M for O&M costs for the overall mission. These have been included in the Bruce-A modification costs and the overall O&M costs.

Although it is recognized that many activities need to be carried out prior to committing the reactors to this mission, the overall schedule for the mission is dependent on the earliest production of MOX fuel to supply reactor operations. As a consequence, all the S&S measures must be in place for receipt of the MOX fuel. The longest lead-time factor governing the S&S requirements dealt with in this section is the construction, commissioning, and licensing of the category 1 fuel-receiving and storage facility. The preliminary design and subsequent detailed design should start as early as possible to ensure that all the appropriate S&S measures are addressed for this facility.

2.5 CANDU Alternative HLW Repository Facility

2.5.1 CANDU Alternative HLW Repository Description

The following paragraphs are provided for information only because the FMDP will not have any responsibility for the Canadian HLW repository.

Facility diagrams and descriptions—The layout for the proposed Canadian HLW repository facility is shown in Figs. 2.25 and 2.26. None of the activities associated with this repository will affect the duration nor the cost of the FMDP mission.

The repository consists of two facilities: a surface facility for the receipt and handling of wastes and a subsurface facility for permanent isolation of the wastes from the accessible environment. The surface facilities include a container fabrication plant, a used-fuel packaging plant, a concrete mixing plant, a rock crushing plant, and shaft head frame. Disposal is on a single level at a depth of 1000 m.

Facility and process station sizing criteria and constraints—The Canadian concept for disposing of irradiated fuel from CANDU reactors is based on disposal in plutonic rock of the Canadian Shield. Developed as part of the Nuclear Fuel Waste Management Program (NFWMP), the disposal concept and the associated technologies are currently being reviewed under a federal government review process. Conceptual repository design studies were undertaken as part of the NFWMP to demonstrate how the concept could be implemented and to produce reference designs for performance assessment studies. The schematic surface

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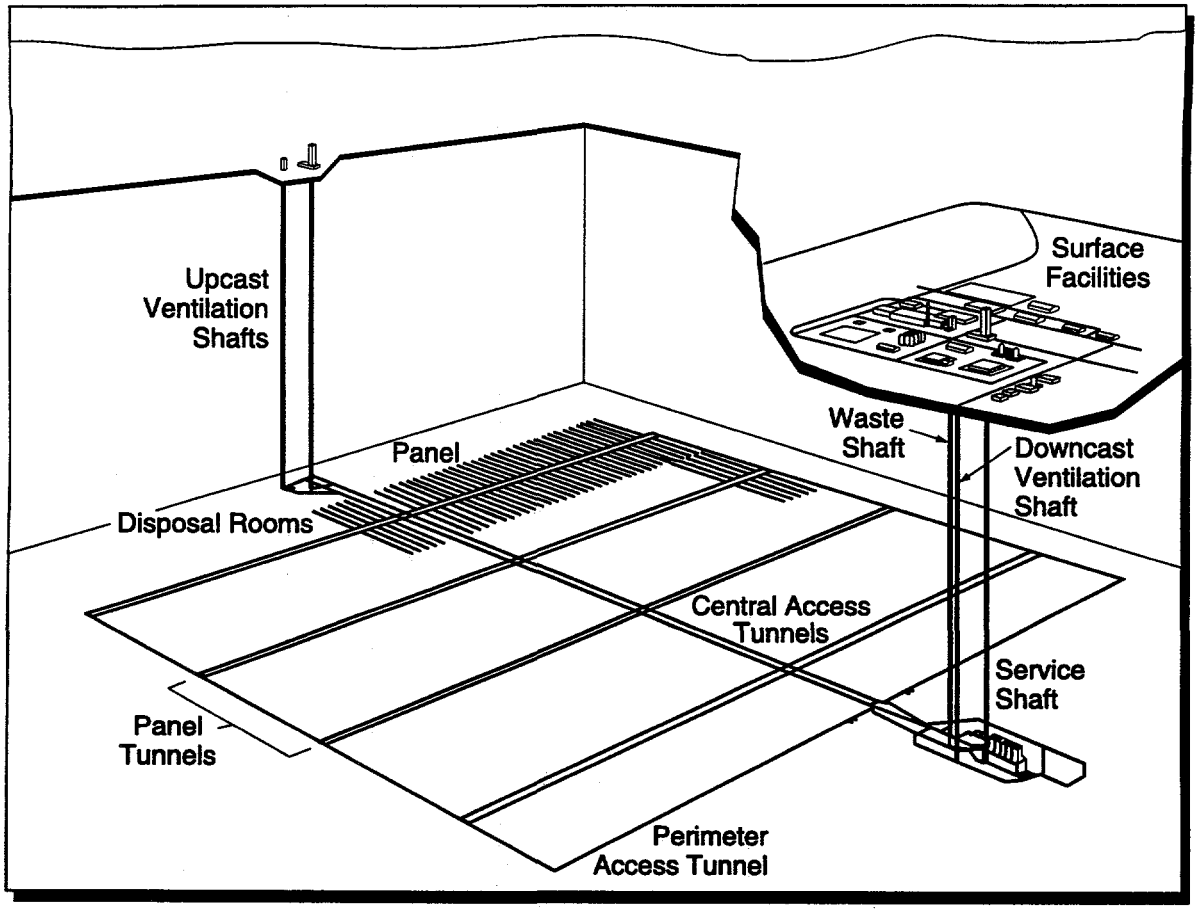

Figure 2.25. Surface layout of HLW repository

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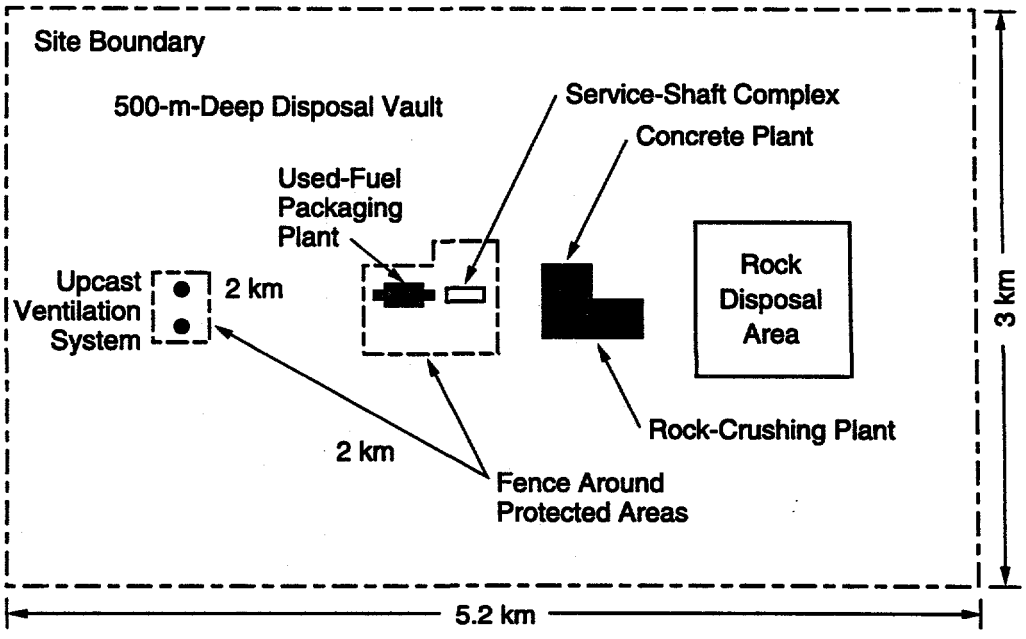


Figure 2.26. Schematic underground layout of reference repository based on conceptual design engineering

and underground layouts are based on these conceptual studies. A final repository layout would depend, among other factors, on the characteristics of a disposal site.

Process Operation Descriptions—The key elements are outlined in the following, based on conceptual engineering studies carried out in the NFWMP.

Surface activities:

- Transport of irradiated fuel from reactor storage to repository facility.
- Removal of fuel storage modules from the transportation cask.
- Transfer of fuel bundles into disposal containers, and container sealing.
- Transfer of fuel disposal containers to the surge-storage pool.
- Transfer of containers to the facility transportation cask.
- Transfer of the transportation cask to the waste shaft headframe.

Underground activities:

- Arrival of transportation cask at shaft bottom.
- Emplacement of containers in disposal rooms.
- Backfilling and sealing of disposal rooms and tunnels.
- Backfilling and sealing of facility shafts.

2.5.2 CANDU Alternative HLW Repository Facility Schedule

The Canadian HLW repository facility is scheduled to open in 2025. The duration and path of design and construction activities are based upon information from AECL. Licensing and permitting activities are estimated to begin in 2002 and take 10 years to complete. The reference MOX and CANFLEX fuel delivery schedule is listed in Table 2.46 and shown in Fig. 2.27.

2.5.3 CANDU Alternative Spent Fuel Repository Facility Technical Viability

DOE has identified five items the consideration of which constitutes a qualitative assessment of the technical viability of a concept: a definition of the technological maturity of a process; the specification of the technical unknowns for the process and the technical risk associated with the application of the process; research and engineering development needs of the process, the condition, capacity, and reliability of the infrastructure; and, lastly, the regulatory and licensing requirements associated with the process. The first three of these items are discussed in this section. The infrastructure is discussed within the facility description and design and construction sections. The licensing item is discussed in a separate section for each facility.

Table 2.46. CANDU alternative HLW repository facility schedule

Task ID	Task Name	Duration (months)	Start	Finish
27.	**Licensing and Permitting**	120	1/2002	1/2012
28.	**Design Activities**	120	1/2004	1/2014
28.	**Siting Issues and Construction**	324	1/1998	1/2025
	Repository Opening Date			1/2025
	Delivery of MOX & CANFLEX Fuel	71	1/2025	11/2030
	Transportation of first MOX to Repository	1	1/2025	1/2025
	First MOX bundle arrives			1/2025
	Transportation of last CANFLEX	1	11/2030	11/2030
	Last CANFLEX bundle arrives			11/2030

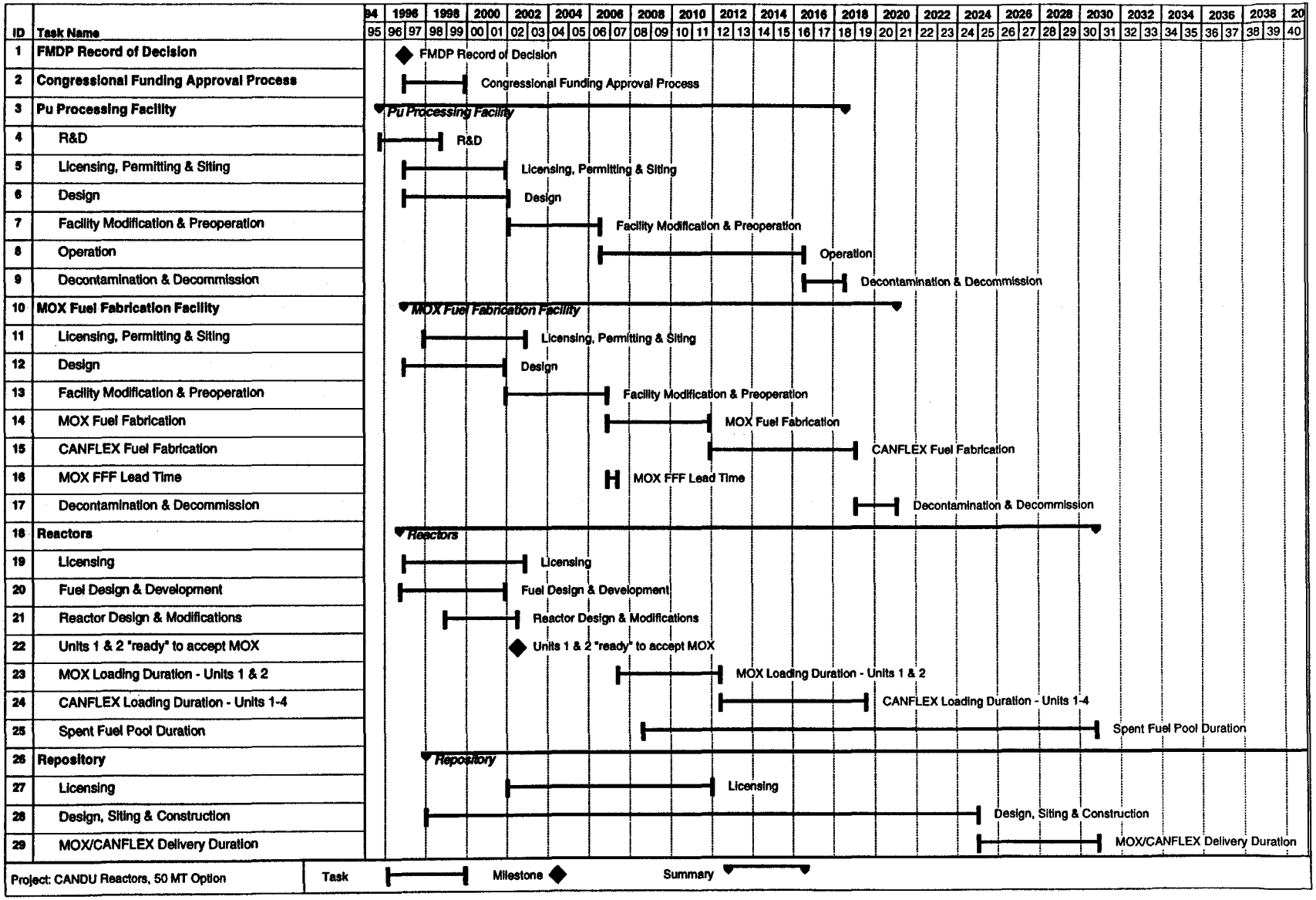


Figure 2.27. CANDU alternative schedule summary (base case)

2.5.3.1 Technological Maturity

Judging the maturity of the technologies employed in plutonium disposition facilities requires an assessment of the current level of development of each stage of the fuel cycle. Technologies can be categorized as being at the conceptual design stage, the laboratory or bench-scale testing stage (demonstrating scientific feasibility), the prototype stage (demonstrating engineering feasibility), or the industrialization/ commercialization stage. Even if a significant domestic development base does not exist, a foreign experience base may be available.

The primary technological basis for the repository facility has been developed over the past seventeen years in the Canadian NFWMP. The program objective has been to assess the concept of deep disposal of nuclear fuel waste from CANDU reactors in plutonic rock of the Canadian Shield and to develop the associated technologies. The following summarizes some of the key technologies developed and their state of maturity.

Conceptual Design of Repository Facility—Several conceptual repository design studies have been completed. The most comprehensive was to develop a reference design for the disposal of 10 million CANDU fuel bundles in a single level repository at a depth of 1000 m. The reference design assumed a titanium disposal container emplaced in boreholes drilled in the floors of disposal rooms. The study examined the life cycle activities including repository siting, design, construction, operation, decommissioning, and closure.

Disposal Container Technologies—Several disposal containers have been developed to the conceptual level. Half- and full-scale prototypes of three container designs have been fabricated and their short-term mechanical performance evaluated in handling tests and hydrostatic tests. Container closure (welding) and inspection techniques have been evaluated and demonstrated on the prototypes and in large-scale simulations.

Site Characterization Technologies—Extensive field work at several field research sites, together with complementary laboratory studies, has developed the process and techniques required to characterize the geological properties of potential repository sites. These technologies have been developed and applied most comprehensively in studies at the Whiteshell Research Area in Manitoba. The work has allowed development of a detailed understanding of the geological and hydrogeological characteristics of the Research Area from which models for contaminant transport have been developed and tested.

Underground Construction and Operation—As part of the NFWMP, an underground research laboratory (URL) has been constructed as a development and testing facility for the technologies required in a repository. The URL has two operating levels (240 and 420 m) and has provided considerable information and experience in construction techniques and operating procedures that can be applied to an actual repository. DOE has been an active participant in the URL project. The experimental program in progress at the URL includes large-scale testing of various aspects of the engineered and natural components of a repository.

2.5.3.2 Technical Risks

Given the knowledge base developed in the NFWMP, and internationally, with regard to the technologies for geological disposal, it is considered that the technical risks in applying the technologies are small.

2.5.3.3 Research and Engineering Development Needs

Both R&D and engineering development are required to fully develop the technologies for disposal of spent MOX fuel. Only a few of these are specific to the disposal of MOX fuel. The large majority are developments required to dispose of spent CANDU fuel for which the addition of MOX fuel to the disposal concept leads to no significant design changes. Discharge fissile fractions for both reference and CANFLEX fuels are less than that of the typical LWR MOX discharged fuel assembly. The technology needs for MOX fuel disposal are noted here only where significant changes are considered necessary.

The R&D and engineering development needs to implement disposal of spent fuel include the following:

1. *Refinement of characterization tools for siting*—Detailed evaluation of rock bodies is essential to determine geological and hydrogeological characteristics that are suitable for locating a repository. These tools (geophysical, hydrogeological, and hydrogeochemical techniques) are well established but require further refinement to increase confidence that suitable blocks of low-permeability rock can be found in which to locate a repository.

2. *Disposal facility design and construction*—A conceptual design study has been completed for disposal of spent CANDU fuel. The study indicates that no major developments in technology are required to implement disposal. For the disposal of MOX fuel, it would be necessary to reevaluate the reference design to consider the somewhat higher thermal output of the MOX fuel. This is likely to lead to a slightly larger spacing between containers in the repository. An additional consideration would be the somewhat higher neutron emissions for MOX fuel, which could necessitate some modifications in shielding design.

3. *Engineered barrier system design*—Various design concepts for containers have been developed for disposal of spent CANDU fuel. The reference MOX fuel for a CANDU reactor has approximately the same burnup and identical bundle geometry. The disposal container concepts for CANDU fuel are thus directly applicable to disposal of MOX fuel. Criticality calculations for disposal containers saturated with groundwater would have to be performed to determine if design modifications are needed to prevent criticality. Criticality calculations for fuel storage bays, however, indicate that CANDU MOX fuel modules for unirradiated MOX fuel are subcritical; this would also be the case for disposal containers.

   A program of research would be required to evaluate the leaching and dissolution characteristics of MOX fuel and include the effects of radiolysis to develop source-term models for performance assessment calculations.

4. *Pilot-scale facilities and in situ experiments*—A program of in situ experiments involving a variety of issues including geological and hydrogeological characterization, excavation response in highly stressed rock, and repository sealing is in progress at the AECL's URL. Significant issues include the development of models to describe coupled thermal, hydrologic, and mechanical phenomena in repositories; development of repository sealing designs and criteria; and the validation of models to describe groundwater and contaminant migration in crystalline rock.

Pilot-scale repository and fuel encapsulation facilities will need to be developed. Again, these involve largely generic issues that are common to disposal of all types of oxide fuel, and it is unlikely that disposal of MOX fuel will create special technological challenges that are not already being evaluated.

2.6 Existing CANDU Reactor Alternative Base Case Summaries (50SFC2-4)

2.6.1 CANDU Alternative Base Case Schedule Summary

The CANDU HWR alternative schedule is a combination of the individual facility schedules discussed earlier in this chapter. The overall schedule is summarized in Table 2.47 and shown in Fig. 2.27. The plutonium disposition mission begins when the first reference MOX fuel is loaded into the CANDU reactors in June 2007 and is complete after the last CANFLEX bundles are fully irradiated in October 2020. The overall mission duration is 13.3 years and starts 10.5 years after ROD.

The critical path for the alternative is the licensing, design, and construction of the MOX fuel fabrication facility. The CANDU reactors are ready to accept the reference MOX fuel 5 years before the fuel is available. If the preoperational schedule for the MOX fuel fabrication facility is shortened by more than 3 months, the unavailability of PuO_2 from the PuP facility will affect the MOX fuel fabrication facility operation.

The schedule risk for the PuP facility and MOX fuel fabrication facility are the same as for the other reactor-based alternatives. The schedule risk for modifying the existing CANDU reactor facility is the same as for modifying existing LWR facilities for MOX fuel.

2.6.2 CANDU Alternative Base Case Cost Summary

Table 2.48 shows the LCC for all facilities associated with the CANDU base case alternative using the 24-category format. Of the $871M in investment costs (total up-front costs) for all facilities, the MOX fabrication facility cost dominates at $450M. This 141 MTHM/year facility (weighted average of reference and CANFLEX production modes) is larger in heavy metal (HM) capacity than the LWR MOX plants (typically 47–107 MTHM/year); therefore, a higher capital expenditure of about $100M over the

Table 2.47. CANDU HWR base case alternative schedule summary

Task ID	Task name	Duration (years)	Start	Finish
1.	**FMDP Record of Decision**			12/1996
2.	**Congressional Funding Process**	3	12/1996	12/1999
3.	**Plutonium Processing Facility**	22.8	10/1995	7/2018
4.	R&D	3	10/1995	9/1998
5.	Licensing, Permitting and Siting	5	12/1996	12/2001
6.	Design	5.1	12/1996	1/2002
7.	Facility Modification and Preoperation	4.5	1/2002	7/2006
8.	Operation	10	7/2006	7/2016
9.	Decontamination and Decommissioning	2	8/2016	7/2018
10.	**MOX Fuel Fabrication Facility**	24.1	4/1996	1/2021
11.	Licensing, Permitting and Siting	6	12/1996	12/2002
12.	Design	5	12/1996	11/2001
13.	Facility Modification and Preoperation	5	12/2001	12/2006
14.	Reference MOX Operation	5	12/2006	12/2011
15.	CANFLEX Operation	7.2	12/2011	2/2019
16.	MOX Facility Lead Time	0.5	12/2006	6/2007
17.	Decontamination and Decommissioning	2	2/2019	1/2021
18.	**Reactors**	34.1	9/1996	11/2030
19.	Licensing	4	6/1998	5/2002
20.	Fuel Design and Development	5.2	9/1996	11/2001
21.	Reactor Design and Modifications	3.6	12/1998	7/2002
22.	Units 1 and 2 "ready" to accept MOX			7/2002
23.	MOX Loading Duration—Units 1 and 2	5	6/2007	6/2012
24.	CANFLEX Loading Duration—Units 1–4	7.2	6/2012	8/2019
	Last CANFLEX bundles irradiated for 1.2 years			10/2020
25.	Spent Fuel Pool Duration	22.2	8/2008	11/2030
26.	**Repository**			
27.	Licensing	10	1/2002	1/2012
28.	Design, Siting, and Construction	27	1/1998	1/2025
29.	MOX/CANFLEX Delivery Duration	5.9	1/2025	11/2030

Table 2.48. CANDU base case alternative cost summary

Costs (1996 dollars)		PuP facility		MOX fuel fabrication facility		Existing CANDU reactors		Canadian repository		Total lump sum ($M)
	Cost type	Lump sum ($M)	Annual ($M)	Lump sum ($M)	Annual	Lump sum ($M)	Annual	Lump sum ($M)	Annual	
	Years of operation	10		12.2		12.2		0		
	Preoperational or OPC:									
1	R&D	81		21		35		0		137
2	NEPA, licensing, permitting	6		35		18		0		59
3	Conceptual design	3		2		1		0		6
4	QA, site qualifications, S&S plans	1		1		2		0		3
5	Postconstruction startup	50		41		4		0		95
6	Risk contingency	10		0		7		0		17
	SUBTOTAL OPC	151		100		67		0		318
	Capital or TEC:									
7	Title I, II, III engineering, design, and inspection	17		56		0		0		72
8a	Capital equipment	34		175		0		0		209
8b	Direct and indirect construction/modification	32		60		32		0		123
9	Construction management	4		0		0		0		4
10	Initial spares (technology dependent)	3		14		0		0		17
11	Allowance for indeterminates (AFI)	25		45		0		0		70
12	Risk contingency	56		0		0		0		57
	SUBTOTAL (TEC)	171		350		32		0		553
	TOTAL UP-FRONT COST (TPC)	322		450		99		0		871
	Other LCCs:									
13	O&M staffing	785	79	309	25	12	1	0		1106
14	Consumables (include utilities)	0	0	611	50	0		0		611
15	Major capital replacements or upgrades	0	0	242	20	0		0		242
16	Waste handling and disposal	66	7	101	8	0		0		167
17	Oversight	10	1	12	1	0		0		22
18	M&O contractor fees	17	2	25	2	0		0		43
19	PILT to local governments	9	1	13	1	0		0		21
20	D&D	169		70		0		0		239
21	Revenues from MOX sales	0		–320	–26	0		0		–320
22	Government subsidies of fees to privately owned	0		0		269	22	0		269
23	Transportation of plutonium forms to facility	35	4	18	1	26	2	0		79
24	Storage of plutonium at existing 94-1 site facility	0		0		0		0		0
	PuP facility at LANL	1		0		0		0		1
	TOTAL OTHER LCC	$1092	$92.2	$1081	$82.9	$307	$25.1	0		$2480
	GRAND TOTAL ALL LCC	$1414		$1531		$406		0		$3351

other alternatives is anticipated. It should be noted that a common set of algorithms was used to calculate the LCCs for both LWR and CANDU fuel fabrication facilities that may not take into account that the much smaller size of the CANDU bundles, and therefore the size and amount of equipment needed for the MOX fabrication facility, may be less expensive than the amount shown.

Figure 2.28 shows the comparative costs of the three facilities. Note that there are no costs associated with a spent fuel repository facility as this cost will be covered by the Canadian utility. It should be noted that the $269M incentive fee paid by the U.S. government to the Canadian utility (item 22) has been shown separately from its higher level category, O&M and other LCCs. This has been done to allow comparison with other reactor options. The modification cost for the CANDU reactors is much lower than for the U.S. existing LWR cases. The investment cost for PuP of $322M is the same as for the other reactor options and is based on a plant capacity of 5 MT plutonium/ year. The recurring cost or O&M plus other LCCs total is also large for the CANDU MOX fuel fabrication facility compared to the other alternatives, again, because of the higher HM throughput. The incremental operating cost (without incentive fee) for the CANDU reactor MOX mission is very low at only slightly over $1M per year. It should also be noted that the U.S. government will sell MOX fuel to the Canadian utility in the same manner as it does for U.S. utilities. This price of the MOX fuel is computed at the energy-equivalent price of natural uranium fuel normally used by CANDU reactors. This accounts for the $320M credit (item 21)to the U.S. government. This credit is about one-third that amount credited from U.S. LWR utilities, which reflects the much lower unit cost of natural uranium fuel compared to LEU fuel.

The LCCs for all facilities combined are shown in Fig. 2.29. The total D&D cost of $259M for the PuP and MOX facilities is shown on this chart. The U.S. government is not responsible for any D&D of the CANDU reactors. Unlike the U.S. reactor options, no repository cost is shown. The Canadian utilities will be responsible for HLW repository disposal of the spent MOX fuel.

Figure 2.30 shows the annual constant dollar cash flow to the U.S. government for this alternative. These costs rise rapidly about 10 years after ROD because of the cost to modify existing facilities for plutonium processing and MOX fuel fabrication. The effect of the offsetting fuel displacement credit (MOX sales revenue) is also shown.

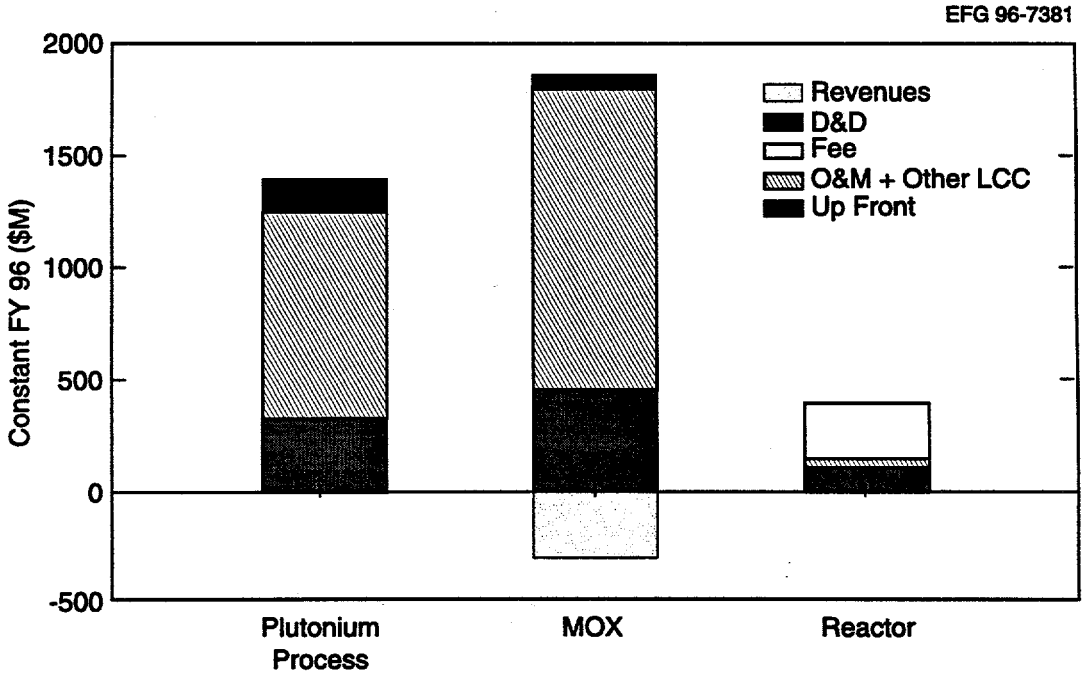
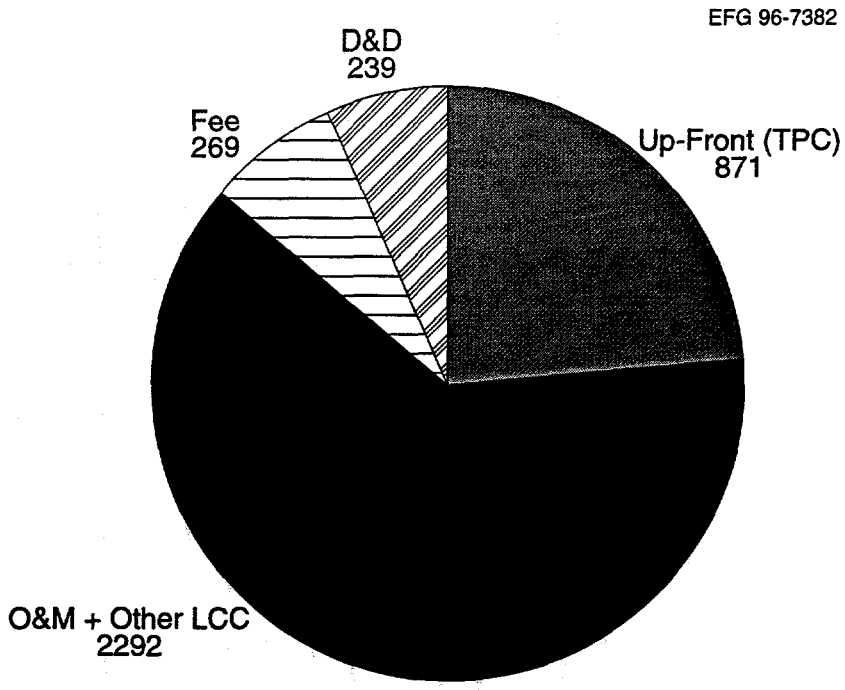


Figure 2.28. CANDU reactors, cost/revenues by facility



Revenue from the sale of MOX = $320M
Total cost = $3671M
LCC = cost – revenue = $3351M

Figure 2.29. CANDU reactors (base case)

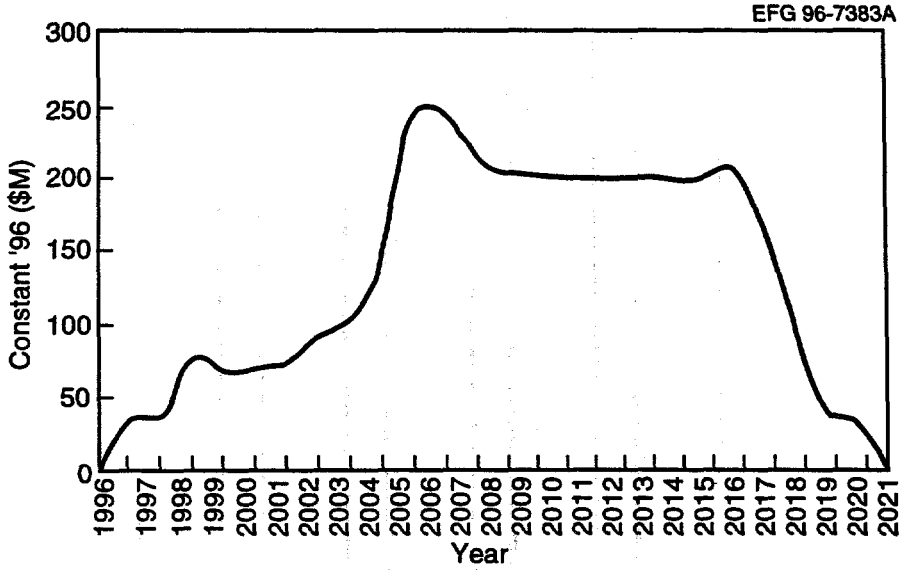


Figure 2.30. Annual cash flow for base case CANDU reactor

Tables 2.49 and 2.50 show summaries of the undiscounted and discounted LCCs as they appear in the TSR for each facility and for the project as a whole. Discounted costs are based upon a 5% real discount rate.

Table 2.51 shows how the undiscounted and discounted LCCs estimates for CANDU base case, which include the incentive fee, compare to those provided in the TSR.

Table 2.49. Undiscounted LCC summary for the CANDU reactor alternative

LCCs to U.S. government	Facility ($M)			Total all facilities ($M)
Cost category (1996 dollars)	Plutonium processing	MOX	Reactor and repository	
Up-front (TPC)	322	450	99	871
LEU fuel cost (government reactor)			0	0
Nonfuel operations and maintenance including government transportation and nuclear waste fee	923	1362[a]	38	2323
Fee to utility owner or operator (reactor)			0	0
D&D (including government payments to sinking fund for reactor)	169	70	0	239
MOX revenues to government at LEU equivalent		0	0	0
Power revenues or subsidy	0	–320	0	–320
Sale of reactor to utility			0	0
TOTAL COST (TSR)	$1414	$1562	$137	$3113

[a]The TSR MOX plant schedule was longer than that in Table 2.19; thus, O&M cost in the TSR is $31M higher.

Note: 1. Basis for Table 4.1 of TSR.
2. Operating costs in Table 4.1 of TSR include D&D cost. All operating costs in Table 4.1 of TSR are rounded to nearest $10M.

Table 2.50. Discounted LCC summary for CANDU alternative

LCCs to U.S. government	Facility ($M)			Total all facilities ($M)
Cost category discounted	Plutonium processing	MOX	Reactor and repository	
Up-front (TPC)	240	319	69	628
LEU fuel cost (government reactor)				0
Nonfuel operations and maintenance including government transportation	460	616	18	1094
Fee to utility owner or operator (reactor)			0	0
MOX purchase (private fabrication only)				0
Power subsidy (privately owned new reactor only)			0	0
D&D (government)	62	22	0	84
MOX revenues at LEU equivalent (private reactor)	0	–145	0	–145
Power revenues (government-owned reactor only)	0	0	0	0
Sale of reactor			0	0
TOTAL COST	$762	$812	$87	$1661

Note: 1. Basis for Table 4.1 of TSR.
2. Operating costs in Table 4.1 of TSR include D&D cost. All operating costs in Table 4.1 of TSR are rounded to

Table 2.51. Comparison of RASR and TSR LCCs for the CANDU alternative

Cost category	Undiscounted ($M)	Discounted ($M)
Total LCC (TSR)	3113	1661
Addition of incentive fee to CANDU utility	269	123
MOX facility schedule revision cost effects	–31	–14
TOTAL LCC (TSR)	$3351	$1770

Note: Values in Table 4.1 of the TSR were rounded to $3110M and $1660M, respectively.

A comparison of the different existing reactor alternatives shows that both the RASR and TSR discounted LCCs for the CANDU alternative fall in the upper part of the range for the discounted costs for the all existing reactor alternatives (between $1.0B and $1.6B). The lower fuel displacement credit for natural uranium used by CANDU reactors as compared to low-enriched uranium (LEU) fuel used by U.S. reactors and the higher LCCs for the MOX fabrication facility are the main reasons for the higher LCCs for the CANDU alternative as compared to other existing reactors.

2.6.2.1 Cost-Related Advantages and Disadvantages of the CANDU Reactor Alternative

Advantages

- Compared to the partially complete and evolutionary reactors, the cost and schedule advantages are substantial because the licensing and construction for the reactors has already been accomplished and the reactors are known performers.
- The spent fuel remains in Canada, thus avoiding any possible incremental repository costs in the United States to handle a fuel form that is currently not qualified for U.S. repository disposal.
- If the United States and other G-7 nations finance all or part of a Russian plutonium-disposition program, this option may be one of the economically attractive options if the Russian material is dispositioned in tandem with the U.S. plutonium.
- Because only minor modifications are required for the CANDU reactors, these units can be ready to accept MOX fuel about 5 years prior to the fuel being available from the MOX fabrication facility. This early readiness makes it worthwhile to consider fabrication of CANDU MOX fuel in Europe until the U.S. MOX fuel fabrication facility is completed.

Disadvantages

- The fuel displacement credit to the U.S. government is lower than for U.S. LWRs.
- The MOX plant investment and operating costs are larger than for LWRs.
- Unlike U.S. LWRs, the CANDU facilities could not be used for a tritium production mission.

Potential for Privatization

It is possible that the MOX fabrication facility or equipment could be privately owned. The private fabricator, such as Zircatec, could recover their capital and operating costs, plus the returns to their investors, in the price they charge the U.S. government for the MOX fuel. Privatization of a facility on an existing DOE reservation could introduce complex negotiable business relationships that are beyond the scope of this report.

2.6.3 CANDU Alternative Base Case S&S Summary

DOE and its predecessor agencies have successfully managed S&S of SNMs for several decades. DOE maintains an impeccable record of providing adequate measures to ensure against theft or unauthorized access to SNMs. These measures include physical security, material accountability, inventory safeguards, and other technologies. These measures have been applied to SNMs in a variety of material forms, ranging from bulk SNM powders and solutions to pits.

An assessment has been performed to identify critical vulnerabilities that might exist in operations or

processes that make up the reactor disposition alternative. The purposes of the assessment were to (1) determine whether any inherent vulnerabilities exist that represent unique or novel threats to maintaining adequate measures against theft or unauthorized access and (2) identify any threats in the reactor disposition alternative operations that will require particular attention by facility designers to ensure that potential vulnerabilities are properly addressed.

This section discusses the vulnerabilities to theft and unauthorized access intrinsic to the material forms and processing environments in the plutonium processing facility. In the sense employed here, a "risk" is a set of conditions that require specific measures to ensure proper physical control of SNMs. These risks should *not* be interpreted as the overall risk that the material will be subject to in the as-built facilities. The overall risk in the as-built facility is driven to very small values by the S&S measures incorporated in the design and operation of the facility.

Facilities that handle large quantities of bulk material, have high throughputs, and involve very complex operations are assigned a greater risk that material can be diverted. The PuP and MOX fuel fabrication facilities that are part of this alternatives are such facilities. In these facilities the material is relatively accessible, and measurement uncertainty may mean that diversion of a quantity of material may be likely. As the material is made into items (e.g., fuel assemblies), the likelihood for diversion decreases. After the fuel has been irradiated, the radiation barriers along with the location and mass of the assemblies make diversion and/or retrieval less likely. Before the material is made into fuel assemblies, it is generally in a form that makes it attractive and possible for reuse. As the material is made into fuel assemblies, it becomes a much less attractive target. The increased number of handling steps involved with the transport operations increases the risk for diversion.

It is assumed that all facilities will be designed and modified to meet necessary S&S requirements and that appropriate protective measures will be taken to adequately protect SNM. The PuP facility has the highest risk, and the repository has the lowest. The risk remains relatively high until the MOX fuel has been irradiated. For the CANDU reactor alternative the more complex reactor operations and the smaller fuel assemblies increase the risk slightly in comparison to the LWRs. There is also an increased risk associated with the greater number of trips and miles for SST transport between the fuel fabrication facility and the CANDU reactors.

There are no unique or novel threats represented by the reactor disposition alternative that would jeopardize DOE's ability to ensure control of SNMs. Similar or identical processing operations have been successfully accomplished in the DOE complex during the last 40 years. On the other hand, several critical vulnerabilities have been identified that will require proper attention in facility design and operations. Most of the vulnerabilities relate to handling large amounts of SNM in attractive bulk form, a set of conditions that require more extensive, obtrusive, and sophisticated measures to ensure proper safeguards against theft or unauthorized access. In all cases, the overall risk of theft or unauthorized access to material will be very low.

2.6.4 CANDU Alternative Base Case Technical Viability Summary

MOX fabrication for CANDU CANFLEX fuel should be simpler than for LWR fuel but more complicated than for reference CANDU MOX fuel because of criticality and shielding concerns. The small size of CANDU bundles (10-cm diam, 50-cm length compared to the 366-cm length of LWR fuel pins) should result in simpler fuel pin fabrication procedures and equipment. Because the burnable poison for CANDU fuels is not an integral part of the MOX fuel, the fuel development program is much simpler than that for LWR cycles employing integral burnable absorbers.

The fissile content of the CANDU CANFLEX fuel is similar to that of existing LWR fuel but less than that of evolutionary LWRs. This higher fissile content relative to reference CANDU fuel will result in a more restrictive MOX facility design relative to the reference CANDU case. Issues related to reactor performance are similar to those for LWRs. However, transitioning an on-line refueled reactor from a uranium cycle to a MOX cycle or from reference fuel to CANFLEX fuel would likely be more operationally difficult than for any of the existing LWRs and has yet to be defined. The proposed Canadian repository appears to be at a similar state of development as the U.S. repository.

Some of the risk involved with this alternative is due to scheduling uncertainty which, in turn, leads to an associated economic risk. There is no question that the

technologies are feasible. However, the time to implement, and even the need to implement certain technologies, is uncertain. In this context, the CANFLEX cycle is riskier than the reference CANDU, but possible benefits may make the risk acceptable.

Use of MOX fuel in CANDUs enhances the safety of the reactor concept by changing the sign of the coolant void coefficient from positive to negative. Though the risk associated with the current operation of CANDUs is considered acceptable, use of MOX fuel may actually lower the risk of operation.

Most R&D items are concerned with assessment of fissile material throughput or provision of regulatory certification of the proposed fuel cycle. Throughput items include determination of process reliability, process optimization, and cost reduction. R&D items for the PuP facility are the same as for the LWR cases. In the MOX facility, fewer issues exist for CANDU MOX fabrication than for the LWR fabrication cases. CANFLEX fuel will require more criticality and shielding constraints as compared to reference MOX CANDU fuel. Reactor R&D consists of concept certification and is similar to that required for LWRs.

2.6.5 CANDU Alternative Base Case Transportation Summary

Multiple facilities are required for disposition of approximately 50 MT of excess weapons-usable plutonium as MOX fuel in a CANDU HWR. Between each facility are a series of sequential movements of the plutonium from its present locations (storage vaults at a number of DOE facilities) through the various processing, fabrication, and reactor facilities and, ultimately, emplacement as spent fuel at a Canadian HLW repository. Figure 2.2 provides a simplified flowchart of the transportation segments associated with the Canadian HWR disposition alternative. Actual U.S.-based processing and fabrication facility locations will be determined by DOE following the ROD. For transportation analysis purposes, it has been assumed that the excess plutonium is in interim storage at many locations within the DOE weapons complex. This material is first packaged and transported to a PuP facility (assumed for transportation analysis purposes to be located at the SRS), where the material is converted to PuO_2. The PuO_2 is then repackaged and transported to the MOX fuel fabrication facility plant (assumed for transportation analysis purposes to be constructed in an existing building elsewhere on the SRS). Once fabricated, the fresh MOX fuel is packaged and transported to the Bruce-A reactor in Ontario, Canada. Spent fuel disposal is intended to be at a Canadian HLW repository and is beyond the scope of the present analyses.

2.7 References

1. National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, National Academy Press, 1994.
2. ITC 10, *IAEA Course on Physical Protection of Nuclear facilities and Materials*; Vol. 2, "Designing a Physical Protection System."
3. H. O. Menlove et al., *CANDU MOX (CMOX) Counter Design and Operation Manual*, LA-12101-M (ISPO-336), Los Alamos National Laboratory, October 1991.

3. Existing CANDU Reactor Alternative Hybrid Case (33SFC2)

3.1 Introduction

Definition of the hybrid case assumes that 32.5 MT of plutonium is available from surplus plutonium for disposition as reactor fuel and that 17.5 MT is available for disposition by an alternate means such as one of the immobilization options. The hybrid case for the CANDU reactor alternative is to complete plutonium processing of 32.5 MT of feed material and MOX fuel fabrication at U.S. facilities, irradiation in Canada, and disposal of the reactor fuel bundles at a Canadian HLW repository. No discussion of the facilities required to disposition the remaining 17.5 MT of surplus plutonium is provided in this report. See the separate alternative reports for a discussion of the immobilization options.

The top-level flow diagram (Fig. 3.1) shows the flow paths proposed for disposition using this option.

The PuP facility would be a government-owned facility located at an existing federal site. This facility would use the ARIES process for development of PuO_2 for use as reactor fuel and the aqueous process for development of plutonium oxides that would be disposed of by other means.

The MOX fuel fabrication facility would be a GoCo facility located in an existing building at an existing federal site. MOX fuel assemblies would be fabricated to Canadian specifications and packaged into fuel bundles to be irradiated in Canadian reactors.

The Canadian reactors are located at the Bruce NGS near Kincardin, Ontario. All spent nuclear fuel would be handled by the Canadians for some period of time in the spent fuel pool at the reactor site and eventually transferred either to a Canadian HLW repository or to dry storage. No material would be returned to the United States.

It must be understood that the power rating of the reactor chosen for the plutonium disposition mission, coupled with the reactor core design, establishes the plutonium throughput for the reactors. This value, in turn, establishes the throughput for all upstream operations to support fuel fabrication.

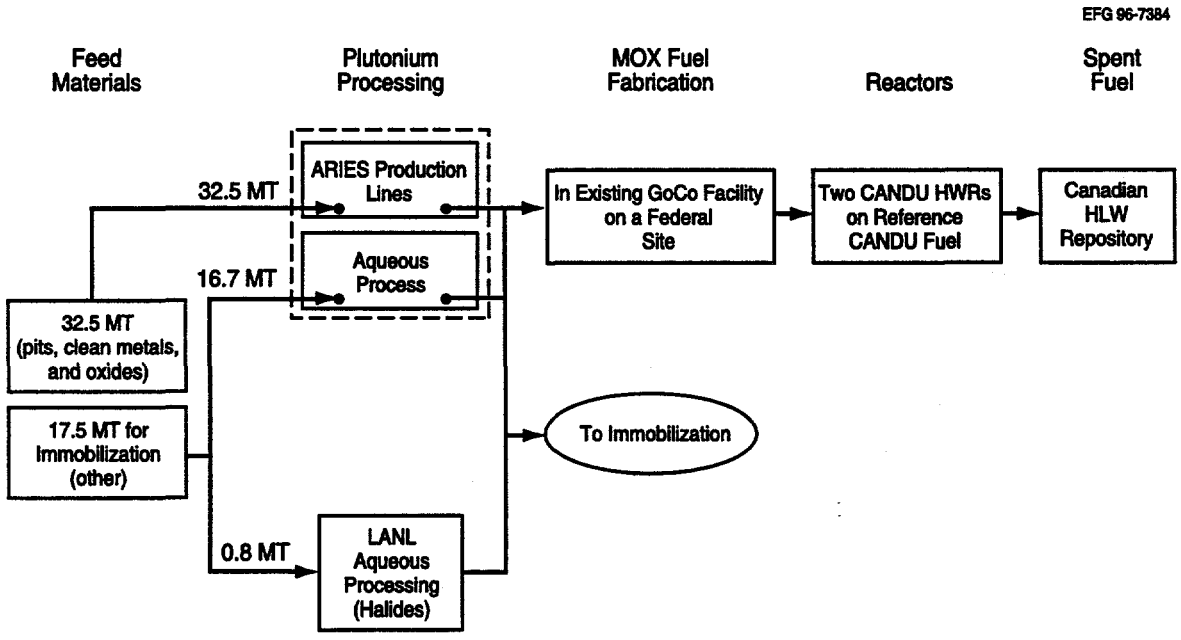


Figure 3.1. 50-MT hybrid plutonium disposition flow diagram

The reactors will use reference MOX fuel containing pins with 1.6 and 3.1 wt % plutonium in two Bruce reactors. Loading of fresh MOX fuel would continue for 10.9 years or until the inventory of PuO_2 available for reactor disposition is exhausted.

Only two CANDU reactors are used with the reference fuel because the HM throughput required from the MOX fuel fabrication facility for four reactors would make the plant uneconomically large and would exceed the 5-MT capacity limit of the PuP facility.

3.1.1 Summary Description of Hybrid CANDU Reactor Alternative Disposition Facilities

The facilities included in this hybrid case are as follows:

PuP Facility. It is proposed that the PuP facility be located in an existing facility at a federally owned site. The plutonium pits and clean metal (~33 MT plutonium) would be processed by the ARIES HYDOX dry processing procedure, and the other feed material (~17 MT plutonium) would be processed by one of the immobilization options. A small amount (~800 kg) of halide-contaminated plutonium feed material is proposed to be processed at available facilities at LANL. The end product of the PuP facility is plutonium oxide, PuO_2. The PuP facility will be subject to external review by the DNFSB.

MOX Fuel Fabrication Facility. The MOX fuel fabrication facility will receive the PuO_2 from the PuP facility, pin and bundle components from Canada, depleted UO_2 from Canada, and additives for fabrication of MOX fuel; perform the assembly of fuel bundles; and ship the fuel to the Bruce station in Canada. This facility will be NRC licensed.

CANDU Reactors. Two Bruce CANDU reactors will irradiate the MOX fuel for 12.1 years (final fuel load plus 15 months), until it reaches scheduled burnup and achieves the characteristics defined in the FMDP SFS.[1] Then fuel will be unloaded to the spent fuel pool, bundled in trays, and stored on site for 6 to 10 years before being moved to the Canadian HLW repository.

Canadian HLW Repository. The Canadian HLW repository will receive the spent fuel in large canisters, transfer the inner sealed canister to disposal casks, and move the casks underground for permanent disposal.

Transportation. Plutonium is packaged and transported from its present locations (i.e., post-DNFSB 94-1 interim storage) to the PuP facility using SSTs operated by the DOE TSD. Following conversion to PuO_2, SSTs are again employed to transport canisters with the PuO_2 derived from pits and clean metals to the MOX fuel fabrication facility and other PuO_2 to the immobilization facility.

Following fabrication as MOX fuel, the fresh fuel bundles are packaged and transported by SSTs to the Bruce station reactors. After irradiation and a suitable cooling time, the spent fuel is transported to the Canadian HLW repository.

In addition to dispositioning plutonium, the FMDP is responsible for packaging and transport of all feed materials (plutonium, uranium oxide, etc.) and transport, packaging, and disposal of process waste materials from the PuP and fuel fabrication facilities. Operation of the reactors and the repository will be covered by the Canadian utility. Transportation of the fresh MOX CANDU fuel into Canada will be by SSTs operated by DOE personnel escorted by Canadian security guards.

3.1.2 Description of Facility Interfaces

Multiple facilities are required for CANDU HWR disposition alternatives. Between each facility is a series of sequential movements of the plutonium from its present locations (storage vaults at a number of DOE facilities) through the various processing, fabrication, and reactor facilities, and ultimately, emplacement as spent fuel at a Canadian HLW repository. Figure 3.2 provides a simplified flow chart of the transportation segments associated with the CANDU HWR disposition alternative. Actual U.S.-based processing and fabrication facility locations will be determined by DOE following the ROD. For analysis purposes, it has been assumed that the excess plutonium is in interim storage at many locations within the DOE weapons complex. This material is first packaged and transported to a PuP facility (assumed for analysis purposes to be located at SRS), where the material is converted to PuO_2. The PuO_2 for the reactor option is then repackaged and transported to the MOX fuel fabrication facility plant (assumed for transportation

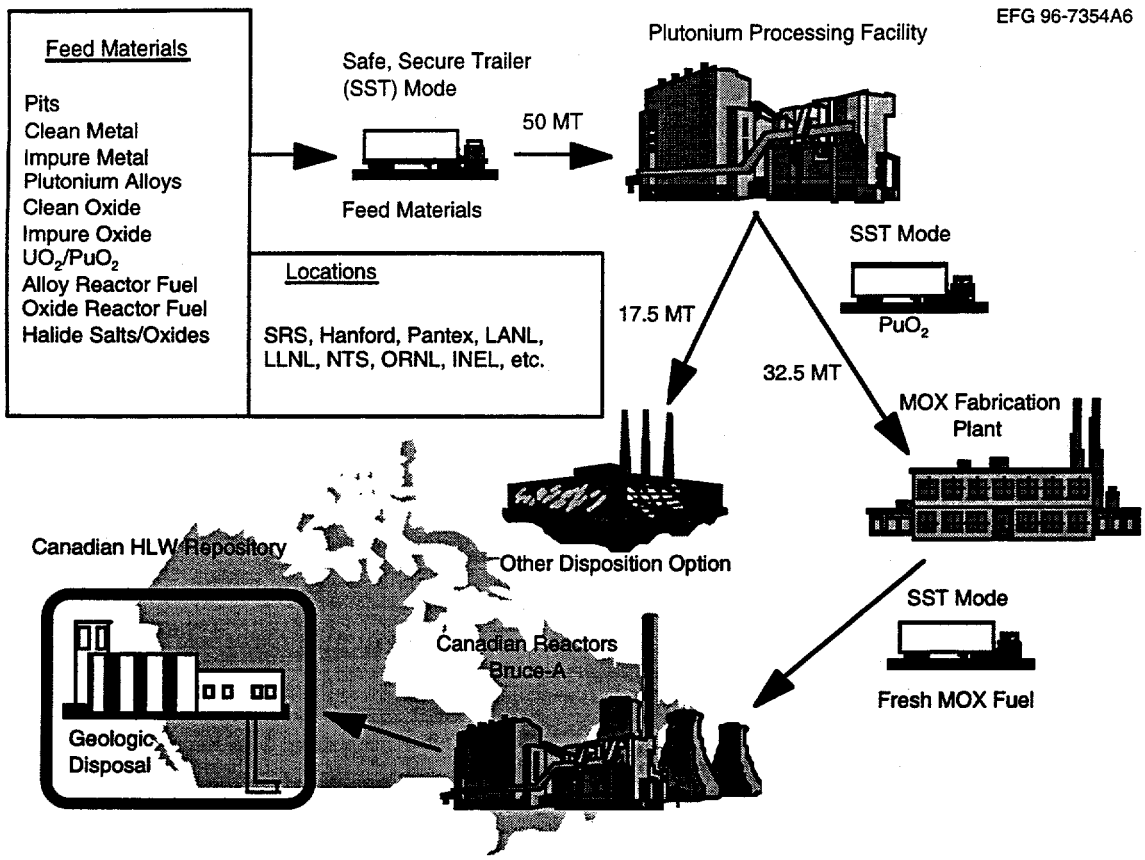


Figure 3.2. Simplified flow chart showing transportation segments for the CANDU HWR alternative

analysis purposes to be constructed in an existing building elsewhere at SRS). Once fabricated, the fresh MOX fuel is packaged and transported to the Bruce-A reactors in Ontario, Canada. Spent fuel disposal is the responsibility of the Canadian utility and is beyond the scope of the present analyses.

3.1.3 General Assumptions

- The inventory of surplus plutonium is 50 MT. Of this, 32.5 MT is from pits and clean metals and 17.5 MT comes from other sources such as impure metals, oxides, and unirradiated reactor fuels.
- Alternatives are designed to address the entire inventory. This does not mean necessarily that all material will ultimately channel through the same set of operations, only that any alternatives have to provide a disposition path for all surplus material.
- Disposition of the plutonium will begin within approximately 10 years and be completed within approximately 25 years after the ROD.
- Authorization for initiation of the line item funding process coincides with the ROD.
- All necessary operations to implement a disposition alternative (e.g., design, construction, licensing, operations, D&D, storage, transportation, S&S, inspections, and packaging operations), from the inception of the program until disposition to the spent fuel standard, must be included.
- Adequate funding will be available, when required, to support the design and construction of the chosen disposition alternatives.
- Facilities will comply with applicable U.S. federal, state, and local laws and regulations, DOE orders, and Canadian laws and regulations (as applicable).
- Schedules presume legislation is available to support implementation of the alternatives. In all cases, some legislation will be required to enable a disposition alternative to be implemented.
- Prior to disposition as reactor fuel, the plutonium must meet the *Stored Weapons Standard,* as the term was coined by the NAS and as specified in DOE orders and guides.

- All operations involving surplus plutonium will be performed under IAEA safeguards, except those involving classified parts, shapes, and information.
- WIPP will be available to accept small amounts of TRU wastes generated in the PuP facility operations.
- Waste minimization and pollution control principles consistent with DOE policy will be applied in the design considerations of each technology.

3.2 PuP Facility

3.2.1 PuP Facility Description

The PuP facility receives surplus material from the various sites in the DOE complex and converts it into a form suitable for feed to the MOX fuel fabrication facility. Surplus fissile materials to be processed include pits, clean and impure metal, plutonium alloys, clean and impure oxides, uranium/plutonium oxides, unirradiated plutonium alloy reactor fuels, unirradiated oxide reactor fuels, and halide salts. Pits and clean metal will be converted to PuO_2 using the ARIES (HYDOX) process. A large fraction of the gallium will be removed, if necessary, using a thermal process, and the resulting oxide will be packaged, assayed, and stored awaiting shipment to the MOX fuel fabrication facility. If thermal processing proves to be inadequate for reducing gallium concentration to acceptable levels, aqueous processing will be used. The remaining feed materials are destined for disposition via an immobilization option, which is discussed in a separate alternative report.

It is assumed that the PuP facility will be located in an existing building on one of several existing federal sites. One such candidate is Building 221-F, located at SRS in the F-canyon area. Approximately 21,000 ft^2 of space has been identified in this building which could be adapted for the plutonium disposition mission.

An additional location for possible use would be the FMEF on the Hanford reservation in Washington state. This facility has approximately 85,000 ft^2 of space and much of the needed equipment available. It was initially designed to support the FFTF for the production of MOX fuel. An extensive study of conversion of this facility to support the CANDU fuel fabrication process was conducted for DOE by AECL. Use of this facility for plutonium processing is equally feasible. Additional federal sites will also be considered for the PuP facility location.

3.2.2 PuP Facility Design and Construction

3.2.2.1 Design and Construction Schedule

The duration and path of the design and construction tasks for the hybrid CANDU option are assumed to be the same as in Sect. 2.2.2.1.

3.2.2.2 PuP Facility Design and Construction Cost

The cost estimates for the hybrid CANDU option are assumed to be the same as those presented in Sect. 2.2.2.2 until a better design description of the facility is available.

3.2.3 PuP Facility Oversight and Permitting

Oversight and permitting activities, schedule, and cost are assumed to be the same as those described in Sects. 2.2.3, 2.2.3.1, and 2.2.3.2.

3.2.4 PuP Facility Operations

Operation of the hybrid PuP facility is projected to be the same as described in Sect. 2.2.4 and Sects. 2.2.4.1 through 2.2.4.4.

3.2.5 PuP Facility D&D

The D&D activities for the hybrid CANDU option will be the same as those discussed in Sects. 2.2.5, 2.2.5.1, and 2.2.5.2.

3.2.6 PuP Facility Schedule Summary

The overall PuP facility implementation schedule for the 32.5-MT case is the same as that presented for the 50-MT case in Sect. 3.2.

3.2.7 PuP Facility Cost Summary

Due to the 5-MT plutonium/year limitation on the PuP facility capacity, two CANDU reactors operating on reference fuel have been specified for the hybrid option. The cost effect on the PuP facility is yet to be accurately determined pending better design definition from LANL.

3.2.8 PuP Facility Technical Viability

Technical viability discussion for the hybrid CANDU option will be the same as described in Sect. 2.2.8.

3.2.9 PuP Facility S&S Summary

The S&S activities for the hybrid CANDU option PuP facility will be the same as those described in Sect. 2.2.9.

3.3 MOX Fuel Fabrication Facility

3.3.1 MOX Fuel Fabrication Facility Description

The MOX fuel fabrication facility converts the PuO_2 from the PuP facility to MOX fuel to supply the reactors. The MOX fuel fabrication facility will be federally owned and separate from the PuP facility although the two facilities could be collocated.

The MOX fuel fabrication facility receives PuO_2 from the PuP facility and other feed materials (such as UO_2, additives, fuel pins, and bundle components) from offsite and produces fuel bundles. The feed oxide is received, stored as needed, purified if required, milled, screened, and blended into lots. It is then fabricated into pellets; the pellets are inserted into pins, and the pins assembled into bundles. The bundles are then stored on site to await shipment to the BNPD.

The overall generic facility size for the annual throughput rate of 2.9 MT of plutonium [138 MTHM (metric tons heavy metal)/year] will depend on the existing building ultimately chosen at a federal site with a plutonium-handling infrastructure. The MOX fuel fabrication facility output is based on planned reactor consumption. The MOX fuel fabrication facility receiving area is sized to receive up to 15 MT PuO_2 for storage from the PuP facility. The remaining PuO_2 will be stored at the PuP facility or at another vault that is part of the DOE complex until needed for fuel fabrication.

Since the CANDU reactors will not, in this hybrid option, shift to the advanced CANFLEX fuel after five years, the MOX facility will continue to produce reference CANDU fuel for the entire mission.

3.3.2 MOX Fuel Fabrication Facility Design and Construction

Design and construction of the MOX fuel fabrication facility will be only slightly affected by the hybrid case. Since the heavy metal throughput would be reduced from 141 MT/year (the average used for the base case) to 138.1 MT/year (the actual throughput required for two CANDU reactors on reference fuel), the amount of capital equipment and floor space required would be slightly reduced. Design and construction would not be affected.

3.3.2.1 MOX Fuel Fabrication Facility Design and Construction Schedule

The schedule for design and construction would be the same as the base case described in Sect. 2.3.2.1.

3.3.2.2 MOX Fuel Fabrication Facility Design and Construction Cost

Costs associated with design and construction would be the same as the base case described in Sect. 2.3.2.2.

3.3.3 MOX Fuel Fabrication Facility Licensing and Permitting

Licensing and permitting of the hybrid case will not be different from the base case fuel fabrication facility described in Sect. 2.3.3.

3.3.4 MOX Fuel Fabrication Facility Operations

Operation of the hybrid case fuel fabrication facility will differ from the base case described in Sect. 2.3.4 only that slightly fewer operating personnel will be needed and the facility will operate for 10.9 years instead of 12.2 years.

3.3.4.1 MOX Fuel Fabrication Facility Shipping and Storage

There will be no change in the shipping and storage activities from the base case described in Sect. 2.3.4.1.

3.3.4.2 MOX Fuel Fabrication Facility Operations Process

The process used to operate the hybrid case fuel fabrication facility will be the same as described in Sect. 2.3.4.2.

3.3.4.3 MOX Fuel Fabrication Facility Operations Schedule

The schedule for operating the hybrid case fuel fabrication facility will decrease from 12.2 years to 10.9 years.

3.3.4.4 MOX Fuel Fabrication Facility Operating Cost

Operating staff for the hybrid case fuel fabrication facility would only be reduced by one direct FTE. The greater effect, from a cost standpoint, will be the reduction in operating time by 1.3 years. The estimated effect of these changes will be to reduce the fuel fabrication facility total LCC by $114M. The 24-category cost breakdown for this facility is presented in Table 3.1.

3.3.5 MOX Fuel Fabrication Facility D&D

D&D activities for the hybrid case fuel fabrication facility will be the same as those for the base case discussed in Sects. 2.3.5, 2.3.5.1, and 2.3.5.2.

3.3.6 MOX Fuel Fabrication Facility Schedule Summary

The overall MOX fuel fabrication facility design, construction, licensing, and permitting schedules for the 32.5-MT cases are the same as those presented for the 50-MT case in Sects. 2.3.2 and 2.3.3. The MOX fuel fabrication facility will operate for 10.9 years and will produce reference MOX fuel for only two reactors.

3.3.7 MOX Fuel Fabrication Facility Cost Summary

The CANDU MOX fuel fabrication facility is designed for a production rate of 138 MTHM/year and will operate for 10.9 years. This size is very close to the two feed rates required for the base CANDU MOX fuel fabrication facility, which will produce reference CANDU fuel followed by CANFLEX fuel after 5 years. (The hybrid CANDU MOX fuel fabrication facility will need to produce reference fuel for only two Bruce units.) An anticipated LCC savings of $114M could be realized as a result of the shorter operating campaign for the hybrid MOX facility as compared to the CANDU base case facility. For this 138-MTHM/year MOX fuel fabrication facility, the staffing will be nearly identical to that of the CANDU base MOX fuel fabrication facility at 64 direct FTEs and 260 indirect FTEs for a total of 324 FTEs, compared to a total of 325 total FTEs for the base case facility with an average (reference fuel and CANFLEX fuel) capacity of 141 MTHM/year.

3.3.8 MOX Fuel Fabrication Facility Technical Viability

There will be no difference in technical viability for design and construction from the base case described in Sect. 2.3.8.

3.3.9 MOX Fuel Fabrication Facility S&S Summary

No changes in S&S for the hybrid case fuel fabrication facility will be evident from those discussed for the base case in Sect. 2.3.9.

3.4 Existing CANDU Reactor Facility

3.4.1 CANDU Reactor Facility Description

The reactor facility description is the same as Sect. 2.4.1 except that only two Bruce-A reactors will be used with reference CANDU fuel for the entire mission.

3.4.1.1 Process Stream Identification and Quantification

Table 3.2 lists the batch characteristics of each processing section of the reactor portion of the CANDU hybrid alternative.

Information concerning the plutonium disposition rate for the reactors for this alternative is shown in Table 3.3. Fuel cycle characteristics for the reactors are shown in Table 3.4. The plutonium dispositioned and number of assemblies moved through the facilities are displayed in Figs. 3.3 and 3.4. For the reference MOX fuel, the annual disposition of plutonium per reactor would be 1.45 MT. The annual reference MOX fuel bundle disposition would be 4525 MOX fuel bundles per reactor at a burnup of 9700 MWd/MT.

Since CANDU HWRs operate on a continuous refueling program, there are no planned shutdowns for

Table 3.1. CANDU hybrid alternative, MOX fabrication facility costs

Category	Cost category description	Lump sum (in 1996 $M)	Annual ($M/year)
	Years of operation = 10.9		
	Preoperational or OPC up-front costs:		
1	R&D	21	
2	NEPA, licensing, permitting	35	
3	Conceptual design	2	
4	QA, site qualification, S&S plans	1	
5	Postconstruction start-up	41	
6	Risk contingency	0	
	SUBTOTAL OPC	100	
	Capital or TEC up-front costs:		
7	Title I, II, III engineering, design, and inspection	56	
8a	Capital equipment	175	
8b	Direct and indirect construction/modification	60	
9	Construction management	0	
10	Initial spares (technology dependent)	14	
11	AFI (percentage of categories 7–10)	46	
12	Risk contingency	0	
	SUBTOTAL TEC	350	
	SUBTOTAL UP-FRONT COST	450	
	TOTAL UP-FRONT COST(TPC)	450	
	Other LCCs:		
13	O&M and staffing	275	25.2
14	Consumables (including utilities)	533	48.9
15	Major capital replacements or upgrades	212	19.5
16	Waste handling and disposal	88	8.1
17	Oversight	11	1
18	M&O contractor fees (2% of categories 13–16)	22	2.1
19	PILT to local communities	11	1
	TOTAL RECURRING COSTS	1152	105.8
20	D&D (percentage of capital or dollar estimate)	70	
21	Revenues (if applicable)	–273	–25
22	Government subsidies or fees to private-owned facilities	0	
23	Transportation of plutonium forms to facility	18	1.8
24	Storage of plutonium at existing 94-1 site		
	Plutonium processing at LANL (halides)	0	
	TOTAL OTHER LCC	$967	$82.6
	GRAND TOTAL ALL LCC	$1417	

Table 3.2. Reactor facility batch process data

Process box	Process cycle data	Data (average)[a]
Fresh MOX fuel storage and handling	Batch size	2986 kg of plutonium
	Cycle time[b]	360 days
	Plutonium input form	MOX bundles
	Plutonium output form	MOX bundles
Irradiation in reactor	Batch size One full reactor load	2059 kg of plutonium
	Cycle time	450 days
	Plutonium input form	MOX bundles
	Plutonium output form	MOX bundles
Fuel storage pool (postirradiation)	Batch size	7.92 kg of plutonium per tray
	Cycle time	10.0 years
	Plutonium input form	24 MOX bundles in trays
	Plutonium output form	60 MOX bundles in storage baskets
Dry storage of spent fuel	Batch size	19.8 kg of plutonium/basket
	Cycle time[c]	10.0 years
	Plutonium input form	60 MOX bundles in storage baskets
	Plutonium output form	Undetermined

[a]Data given are for two reactors on reference fuel.
[b]Fresh MOX fuel could reside in the fuel storage and handling facility for up to one full fuel cycle (450 days).
[c]Assumes that dry storage of the spent fuel is needed for the reactors for at least 10 years.

Table 3.3. Plutonium disposition rate, CANDU hybrid case

Plutonium disposition rate	
Parameter	**Reference MOX (two reactors)**
Plutonium per bundle, kg	0.33
Plutonium disposition per year, MT	2.90
Plutonium dispositioned during phase of program, MT	32.5

Table 3.4. Fuel cycle characteristics, CANDU hybrid case

Fuel cycle characteristics		
Parameter	**Reference MOX**	
	One reactor	**Two reactors**
Reload batch size, bundles/year	4525	9050
Average discharge exposure (burnup), MWd/MT	9700	9700

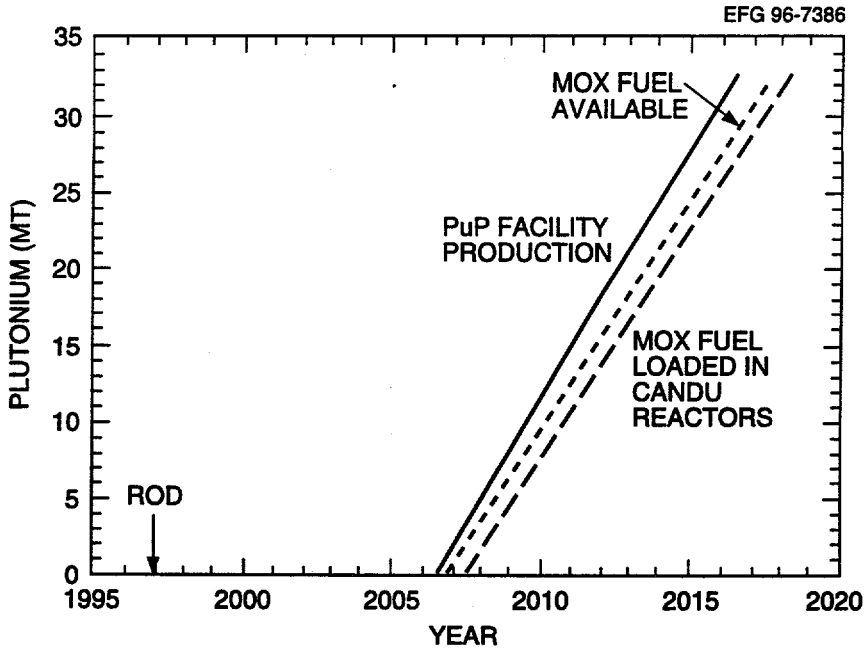


Figure 3.3. Plutonium disposition schedule

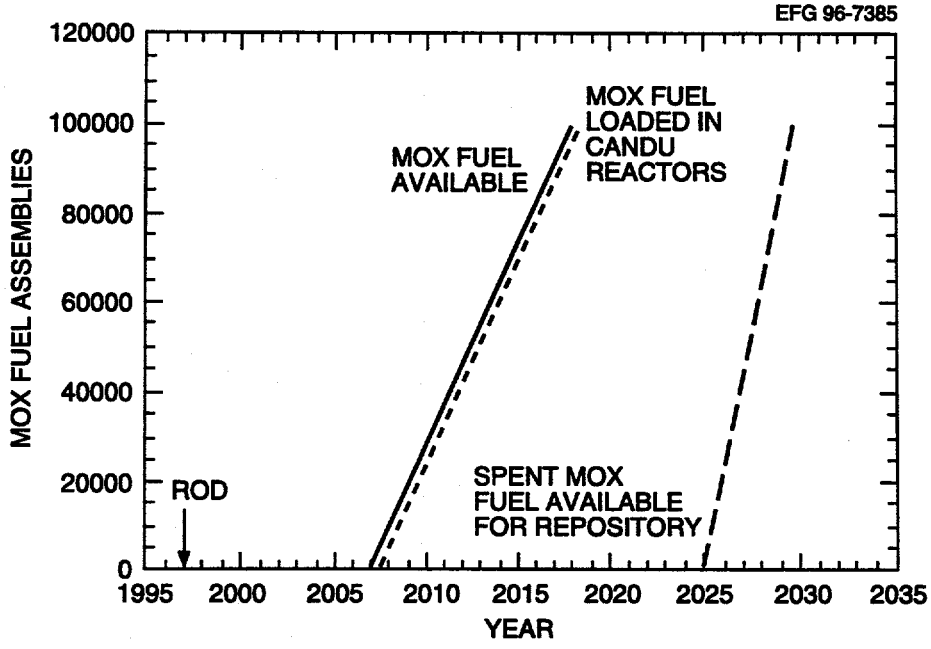


Figure 3.4. Fuel assemblies use schedule

refueling as in LWRs. Periodic outages are planned for maintenance purposes; however, these downtimes are accounted for in the 80% capacity factor used to determine throughputs, etc.

The MOX fuel loading schedule for the entire mission is shown in Table 3.5 for the hybrid case.

3.4.2 CANDU Reactor Facility Design and Construction

Engineering changes in the existing CANDU reactor plants that may be required to receive, store, and handle the MOX fuel are the same as those discussed in Sect. 2.4.2 with the exception of the use of CANFLEX fuel.

3.4.2.1 CANDU Reactor Facility Design and Construction Schedule

The duration and path of the design and construction tasks are the same as those presented in the CANDU reactor alternative base case. After approval of intermediate line item funding, the project begins with completion of the required design and reactor facility modifications and construction of the new fuel storage building.

3.4.2.2 CANDU Reactor Facility Design and Construction Cost

The design and construction costs for the reactor facility are for the modification of two CANDU reactors to burn reference MOX fuel only. Since additional design and construction costs were not required in the base case (50SFC2-4) to shift from reference to CANFLEX fuel, these costs for the hybrid option will remain the same as in Sect. 2.4.2.2.

3.4.3 CANDU Reactor Facility Licensing and Permitting

These activities will be essentially the same as described in Sects. 2.4.3, 2.4.3.1, 2.4.3.2, and 2.4.3.3.

3.4.4 CANDU Reactor Facility Operations

Operation of the Bruce-A reactors will be same as described in Sect. 2.4.4 except that the shift to CANFLEX fuel will be omitted.

3.4.4.1 CANDU Facility Shipments and Storage

Approximately 98,485 CANDU MOX fuel bundles will be fabricated from the 32.5 MT of PuO_2. The MOX fuel bundles will be shipped from the MOX fuel fabrication facility to the Bruce-A CANDU reactor facility in Ontario, Canada. The MOX fuel fabrication facility, in providing fuel bundles for each reactor reload, must have the capacity to store completed bundles until they are needed. In addition, each reactor provides sufficient storage capacity to continue operations while additional fuel bundles are shipped to the reactor.

Table 3.6 provides estimates of the number of shipments required to transport the fresh MOX fuel from the fuel fabrication facility to the Bruce-A CANDU reactors.

3.4.4.2 CANDU Reactor Facility Operations Process

The Bruce-A reactors will be operated the same as that described in Sect. 2.4.4.2 except that there will be no shift to CANFLEX fuel after 5 years nor will two additional reactors be used. The hybrid case mission will be completed by two Bruce-A reactors on reference fuel.

3.4.4.3 CANDU Reactor Facility Operations Schedule

The overall CANDU HWR design, construction, licensing, and permitting schedules for the 32.5-MT cases are the same as those presented for the 50-MT case in Sects. 2.4.2 and 2.4.3. Only two CANDU reactors will be used for this alternative. Reference MOX fuel will be loaded into these two reactors for 10.9 years.

3.4.4.4 CANDU Reactor Facility Operations Cost

The CANDU reactors operating costs due to implementation of the hybrid option will be reduced by $94M from those shown in Sect. 2.4.4.4. The hybrid case costs are shown in Table 3.7.

3.4.5 CANDU Reactor Facility Schedule Summary

The CANDU reactor facility schedule will be the same as for the base case discussed in Sect. 2.4.5 up to the

Table 3.5. MOX fuel charging/discharging schedule

Time from MOX load in first reactor (years)	Assemblies loaded in reactor[a]			Cumulative plutonium loaded (MT)	Cumulative HM loaded (MT)	Cumulative assemblies discharged
	1	2	Cumulative			
0.0	4,525	4,525	9,050	2.9	138.1	
1.0	4,525	4,525	18,100	5.9	276.2	9,050
2.0	4,525	4,525	27,150	8.9	414.3	18,100
3.0	4,525	4,525	36,200	11.9	552.4	27,150
4.0	4,525	4,525	45,250	14.9	690.5	36,200
5.0	4,525	4,525	54,300	17.9	828.6	45,250
6.0	4,525	4,525	63,350	20.9	966.7	54,300
7.0	4,525	4,525	72,400	23.8	1,104.8	63,350
8.0	4,525	4,525	81,450	26.8	1,242.9	72,400
9.0	4,525	4,525	90,500	29.8	1,381.0	81,450
10.0[b]	4,525	3,460	98,485	32.5	1,502.8	90,500
11.0						98,485

[a]Entire mission: Plutonium enrichment = 2.2% average
Plutonium per CANDU bundle = 0.33 kg
HM per CANDU bundle = 15.25 kg
Average burnup = 9700 MWd/MT
Reload batch size = 15.5 bundles per day
Plutonium throughput = 1.45 MT/year per reactor
HM throughput = 138.1 MT/year (two reactors)

[b]Remainder of 32.5 MT plutonium charged to Unit 2. At 10.9 years, Unit 1 begins transition to natural uranium fuel as MOX fuel reaches 9700 MWd/MT.

Table 3.6. Parameters for fresh MOX fuel transport leg

Maximum material per package	Quantity of plutonium per campaign (MT)	Estimated number of packages to be shipped	Number of SST shipments per campaign
Seven MOX CANDU fuel bundles	32.5	14,488	604

fifth year of operation when the hybrid case will continue to operate on reference fuel instead of shifting to CANFLEX fuel. Operation on reference fuel will continue until the last bundles are loaded in July 2019 and then continue for another 15 months until the bundles are replaced by natural uranium bundles.

3.4.6 CANDU Reactor Facility Cost Summary

The reactor facility cost summary is shown in Table 3.7. The only items that change are the reduction in fees to the Canadian utility and transportation, both of which are due to the shorter operating period.

3.4.7 CANDU Reactor Facility Technical Viability

Based upon current experience, the ongoing work on CANFLEX fuel, and the predicted MOX fuel performance envelope being within the existing natural uranium fuel operating envelope, a low risk is associated with reference CANDU MOX fuel performance. The fuel qualification program, which is included in the schedule for the CANDU option, will confirm this expectation.

3.4.8 CANDU Reactor Facility S&S Summary

There are only slight differences between this alternative and the base case described in Sect. 2.4.8. The assemblies would contain slightly less plutonium and therefore would be a slightly less attractive target. The reduced number of fuel bundles would decrease the risk.

3.5 Canadian HLW Repository Facility

No changes in this facility other than minor schedule improvements discussed in Sect. 3.4.5 are anticipated.

3.5.1 CANDU Spent Fuel Repository Description

The repository used for the hybrid case will be the same as described in Sect. 2.5.1.

3.5.2 Canadian HLW Repository Facility Schedule

The overall Canadian HLW Repository design, construction, licensing, and permitting schedules for the 32.5-MT case are the same as were presented for the 50-MT case in Sects. 2.5.2 and 2.5.3. Spent reference MOX fuel is scheduled to be delivered to the facility starting in 2025 and continuing for 4.6 years.

3.5.3 CANDU Spent Fuel Repository Technical Viability

Technical viability for the hybrid case repository is the same as described in Sect. 2.5.3.

3.6 CANDU Reactor Alternative Hybrid Case Summaries (33SFC2)

3.6.1 CANDU Reactor Hybrid Case Schedule Summary

The overall schedule for the CANDU HWR 32.5-MT alternative is summarized in Table 3.8 and shown in

Table 3.7. CANDU hybrid alternative, reactor facility costs

Category	Cost category description	Lump sum (in 1996 $M)	Annual ($M/year)
	Years of operation = 10.9		
	Preoperational or OPC up-front costs:		
1	R&D	35	
2	NEPA, licensing, permitting	18	
3	Conceptual design	1	
4	QA, site qualification, S&S plans	2	
5	Postconstruction start-up	4	
6	Risk contingency	7	
	SUBTOTAL OPC	67	
	Capital or TEC up-front costs:		
7	Title I, II, III engineering, design, and inspection	0	
8a	Capital equipment	0	
8b	Direct and indirect construction/modification	32	
9	Construction management	0	
10	Initial spares (technology dependent)	0	
11	AFI (percentage of categories 7–10)	0	
12	Risk contingency	0	
	SUBTOTAL TEC	32	
	SUBTOTAL UP-FRONT COST	99	
	TOTAL UP-FRONT COST(TPC)	99	
	Other LCCs:		
13	O&M and staffing	12	1.1
14	Consumables (including utilities)	0	0
15	Major capital replacements or upgrades	0	0
16	Waste handling and disposal	0	0
17	Oversight	0	0
18	M&O contractor fees (2% of categories 13–16)	0	0
19	PILT to local communities	0	0
	TOTAL RECURRING COSTS	12	1.1
20	D&D (percentage of capital or dollar estimate)	0	
21	Revenues (if applicable)	0	
22	Government subsidies or fees to private-owned facilities	184	16.9
23	Transportation of plutonium forms to facility	17	1.6
24	Storage of plutonium at existing 94-1 site		
	Plutonium processing at LANL (halides)	0	
	TOTAL OTHER LCC	$213	$19.6
	GRAND TOTAL ALL LCC	$312	

Table 3.8. CANDU HWR 32.5-MT alternative schedule summary

ID	Task name	Duration (years)	Start	Finish
1	**FMDP Record of Decision**			12/1996
2	**Congressional Funding Process**	3	12/1996	12/1999
3	**Plutonium Processing Activities**	22.8	10/1995	7/2018
4	R&D	3	10/1995	9/1998
5	Licensing and Permitting	5	12/1996	12/2001
6	Design	5.1	12/1996	1/2002
7	Facility Modification and Preoperation	4.5	1/2002	7/2006
8	Operation	10	7/2006	7/2016
9	Decontamination and Decommissioning	2	8/2016	7/2018
10	**MOX Fuel Fabrication Facility**	24.1	4/1996	1/2021
11	Licensing and Permitting	5	12/1997	12/2002
12	Design	5	12/1996	11/2001
13	Facility Modification and Preoperation	5	12/2001	12/2006
14	Operation	10.9	12/2006	10/2017
15	MOX Facility Lead Time	0.5	12/2006	6/2007
16	Decontamination and Decommissioning	2	10/2017	10/2019
17	**Reactors**	32.8	9/1996	7/2029
18	Licensing	4	6/1998	5/2002
19	Fuel Design and Development	5.2	9/1996	11/2001
20	Reactor Design and Modifications	3.6	12/1998	7/2002
21	Units 1 and 2 "ready" to accept MOX			7/2002
22	MOX Loading Duration	10.9	6/2007	4/2018
	Last MOX bundles irradiated for 1.2 years			7/2019
23	Spent Fuel Pool Duration	20.9	8/2008	7/2029
24	**Repository**			
25	Licensing	10	1/2002	1/2012
26	Design and Construction	27	1/1998	1/2025
27	MOX Delivery Duration	4.6	1/2025	8/2029

Fig. 3.5. The plutonium disposition mission begins when the first reference MOX is loaded into the CANDU reactors in June 2007 and is complete after the last reference MOX bundles are fully irradiated in July 2019. The overall mission time is 12.1 years and starts 10.5 years after ROD.

The critical path for the alternative is the licensing, design, and construction of the MOX fuel fabrication facility. The CANDU reactors are ready to accept the reference MOX fuel 5 years before the fuel is available. If the preoperational schedule for the MOX fuel fabrication facility is shortened by more than 3 months, the unavailability of PuO_2 from the PuP facility will affect the MOX fuel fabrication facility operation.

The schedule risk for the PuP facility and MOX fuel fabrication facility are the same as for the other reactor-based alternatives. The schedule risk for modifying the existing CANDU reactor facility is the same as for modifying existing LWR facilities for MOX fuel.

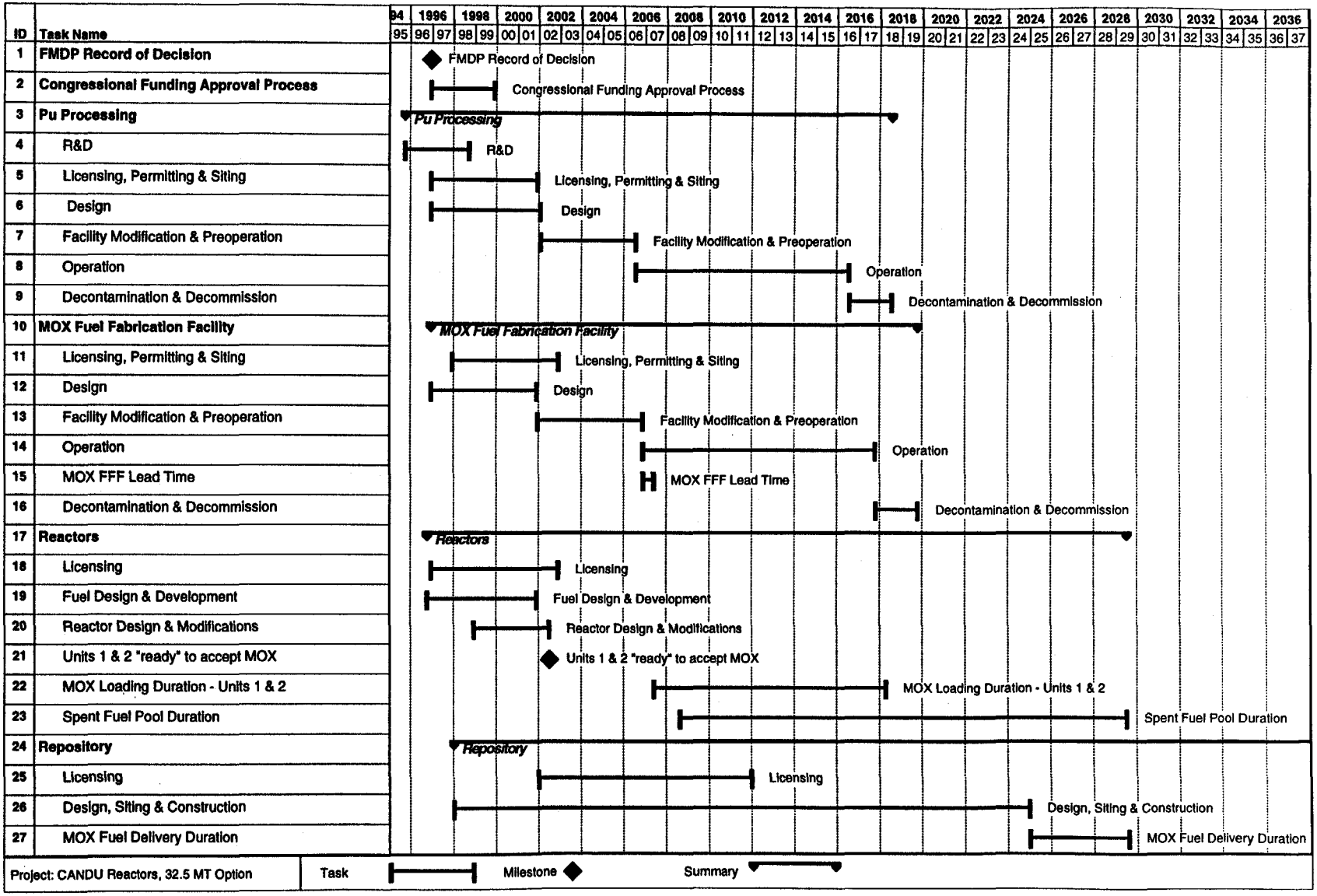


Figure 3.5. CANDU alternative schedule summary (hybrid case)

3.6.2 CANDU Reactor Hybrid Case Cost Summary

It has been suggested that the CANDU reactor option could handle 32.5 MT of the total 50 MT of plutonium (the pits and other clean metal or oxides) and that an immobilization technology could simultaneously handle the remaining 17.5 MT of residues and impure metals and oxides. Use of the hybrid option would reduce the LCCs of the MOX fabrication and reactor facilities. (The cost effect on the PuP facility is yet to be accurately determined, pending better design definition.) It is anticipated that the MOX fabrication facility LCCs would be reduced by $114M. The LCCs of the reactor facility would reduce by $94M since the shift to the advanced CANFLEX fuel would not be necessary and the mission would be completed on two CANDU reactors with reference fuel. Therefore, the irradiation schedule would be reduced by 1.3 years from the base case. The 5-MT/year PuP facility could accommodate the annual feed requirements for both the MOX fuel plant and the other selected disposition facility. However, costs for any additional equipment at the PuP facility and at the other disposition facility would have to be added to those facility capital costs to obtain the total costs for the hybrid mission.

3.6.3 CANDU Reactor Hybrid Case S&S Summary

For S&S there are no significant differences between this alternative and the base case. Obviously, the decreased amount of plutonium means that the proliferation risks integrated over the disposition period would be less.

The final disposition form of the reactor alternatives meets the spent fuel standard. The CANDU reactor alternatives may have slightly greater transportation S&S risks than the LWR alternatives because of the increased trips and the change of custody of the material from the United States to Canada. The PuP facility and MOX fuel fabrication facility, which are common to all alternatives, have the highest risk. Once the fuel is irradiated, the risk is reduced significantly. Since the radiological barrier is time dependent, this attribute will decrease over a period of time. For CANDU reactors it is necessary to place several bundles together in order to achieve self-protection. In Table 3.9 the potential risks are presented. This assessment is based on available data and on the inherent risk for each of the measures.

The values presented in Table 3.9, as was the case in the base case alternative, should not be interpreted as the overall risk for this process or activity when it is in place. These risks represent a set of conditions that require particular measures to be taken, such as the design of the facility and its security systems, which will ensure proper physical control of SNM.

3.6.4 CANDU Reactor Hybrid Case Technical Viability Summary

Technical viability for the hybrid case is the same as for the base case with the exception that the uncertainty associated with the CANFLEX fuel will be removed. The overall hybrid option technical viability is indeterminate until better facility descriptions are provided.

3.6.5 CANDU Reactor Hybrid Case Transportation Summary

Multiple facilities are required for disposition of approximately 32.5 MT of excess weapons-usable plutonium as MOX fuel in a CANDU HWR. Between each facility is a series of sequential movements of the plutonium from its present locations (storage vaults at a number of DOE facilities) through the various processing, fabrication, and reactor facilities, and ultimately, emplacement as spent fuel at a Canadian HLW repository. Actual U.S.-based processing and fabrication facility locations will be determined by DOE following the ROD.

Table 3.9. Potential risks for theft, diversion, and retrieval

	Plutonium conversion	Transit	MOX fuel fabrication	Transit	Reactor	Transit	Repository
Threat							
Covert threat (domestic)	High	Medium	High/medium	Medium	Medium/low	Low	Low
Overt threat (domestic)	Medium high	Medium	Medium high/ medium	Medium high	Medium/low	Low	Low
Diversion (international)	High	Medium	High/medium	Medium high	Medium/low	Low	Low
Criteria 1							
Material form	High	High	High/medium high	Medium	Medium high/low	Low	Low
Environment	High	Medium	High/medium	Medium high	Medium high/medium	Medium	Medium low
Safeguards and security	High	Medium	High/medium	Medium	Low/low	Low	Low
Criteria 2							
Detectability	High	High	High/medium	Medium	Medium/low	Low	Low
Irreversibility	High	Medium	High/medium	Medium	Medium/low	Low	Low

3.7 Reference

1. National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, National Academy Press, 1994.

4. Existing CANDU Reactor Alternative—Other Benefits

4.1 Reduction of Plutonium Inventory by Reactor-Based Disposition Alternatives

Four different classes of reactor-based disposition alternatives are under consideration: (1) existing LWRs, (2) existing CANDU HWRs, (3) partially completed LWRs (completed and operated for the plutonium disposition mission), and (4) new ELWRs. All reactor alternatives offer two important advantages for plutonium disposition. First, a portion of the initial 50 MT of surplus plutonium is consumed in the reactor (converted by fission to energy, which is in turn converted to electricity). Second, the plutonium that remains is converted from weapons grade (isotopic purity of 94% fissile ^{239}Pu) to reactor grade (fissile fraction of ^{239}Pu between 55 and 65%). Of the four classes of reactor-based disposition options noted previously, it is important to note that use of existing reactors (LWRs or CANDU HWRs) offers the additional advantage of displacing uranium-based fuels from these reactors that would otherwise have resulted in creation of additional reactor-grade plutonium. Table 4.1 shows a summary of plutonium inventories before and after reactor-based disposition. On average, all reactor alternatives convert the 50 MT of surplus plutonium into roughly 35 MT of reactor grade plutonium contained within the spent fuel (see Fig. 4.1). Existing reactor alternatives (LWR or CANDU) have the added benefit of avoiding the creation of between 12.5 and 14.7 MT of plutonium from their operation on an LEU or a natural uranium fuel cycle, for a net reduction of plutonium in the inventory of between 26 and 30 MT. Clearly, the reduction of overall plutonium inventory is a favorable outcome of the reactor-based alternatives that is not achievable by immobilization or deep borehole disposition alternatives.

4.2 Beneficial Use of Depleted Uranium

This alternative involves the use of approximately 1700 MT of depleted uranium in the manufacture of MOX fuel. The current inventory of DOE-owned depleted uranium is about 375,000 MT and exists in the form of UF_6 that is stored within canisters at DOE reservations in Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio. These canisters are stored on concrete pads exposed to the weather, and concerns about potential canister corrosion and UF_6 releases have been raised by many sources. DOE's

Table 4.1. Plutonium inventory reduction for reactor-based disposition alternatives

Alternative	Without reactor disposition (MT)			After reactor disposition (MT)			Plutonium inventory reduction (MT)
	Weapons-grade plutonium	Reactor-grade plutonium[a]	Total	Weapons-grade plutonium	Reactor-grade plutonium	Total	
Existing LWRs	50	14.7	64.7	0	35.0	35.0	29.7
CANDU HWRs	50	12.5	62.5	0	36.9	36.9	25.6
PCLWRs	50	0	50	0	36.8	36.8	13.2
ELWRs	50	0	50	0	36.4	36.4	13.6

[a]Reactor-grade plutonium that would be produced from UO_2 fuels in the mission reactors during the mission period if a nonreactor disposition alternative were employed.

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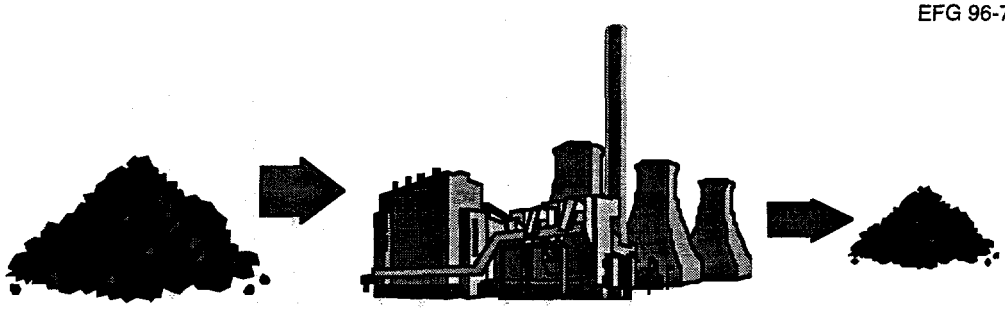

50-MT Weapons-Grade Plutonium in Fresh Fuel

~35-MT Reactor-Grade Plutonium in Spent Fuel

Figure 4.1. Depiction of consumption of plutonium by reactor alternatives

Office of Nuclear Energy, Science and Technology, is currently studying disposition alternatives for the existing inventory of depleted uranium. Disposal of depleted uranium in near-surface or subsurface facilities is a primary option, but beneficial uses for depleted uranium are being sought as a way to avoid the costs and long-term radiological emissions associated with classifying the depleted uranium as waste.

Disposal costs of the depleted uranium, once it has been converted to a uranium oxide form, have been estimated to be in the range of $5/kg to $25/kg.[1] Thus, the beneficial use of depleted uranium in MOX fuel may avoid waste disposal costs totaling $8.5M to $42.5M. These cost benefits are not included in the overall financial summaries of the alternative because of the uncertainties associated with the future strategy for depleted uranium disposition.

4.3 Influences on Russia and Other Countries

In view of the current political and economic instability in Russia, it is essential that disposition activities in the United States set appropriate standards and promote timely implementation of secure monitoring regimes and ultimate disposition of nuclear materials in Russia and other countries. An important element of the U.S. disposition program is to work jointly with the Russians to study issues and develop solutions that are appropriate for each country. Agreements for secure, safeguarded management and disposition of fissile materials from dismantled nuclear weapons could demonstrate that the nuclear powers are fulfilling their disarmament obligations under Article VI of the Nonproliferation Treaty.

Separate from the FMDP efforts with Russia regarding safeguarding and disposition assistance, Ontario Hydro and AECL have been negotiating to provide assistance to Russia for conversion of surplus plutonium to PuO_2, construction of a MOX fuel fabrication facility in Russia, and manufacturing of CANDU MOX bundles. These bundles would then be shipped to the Bruce station in Ontario, Canada, and irradiatiated.

4.4 Reference

1. National Academy of Sciences, *Affordable Cleanup? Opportunities for Cost Reduction in the Decontamination and Decommissioning of the Nation's Uranium Enrichment Facilities*, Academy Press, 1966.

Appendix A
Summary Description of Plutonium Disposition Reactor Alternatives and Variants

As described in Chap. 1, five basic reactor-based plutonium disposition alternatives survived the screening process (Table A.1).

Regardless of the reactor alternatives (LWRs, CANDUs, etc.) under consideration, multiple process or facility variations are possible at several points in the material flow (Fig. 1.1). Each of these end-to-end process and facility chains or "variants" constitutes a unique approach to the plutonium disposition mission. Thus, an "alternative" is a group or class of variants that share a generic reactor type (existing LWRs, CANDUs, etc.).

The number of potentially viable variants for any one of the four reactor alternatives was too large for individual analysis of each combination (Table A.2). To limit the scope of the study to a tractable level, a "base" or "reference" case was selected for each of the four reactor alternatives. The base cases were defined simply to be reasonable initial cases to facilitate the analysis. Other variants within the alternative were considered for analysis only if they were perceived to be significantly different from the base case and to have some advantage over it. Quantitative criteria or "variant discriminators" were required to implement this definition and to select the variants to be analyzed for each reactor alternative. Five "variant discriminators" were ultimately adopted by the RxAT (Table A.3). A variant was analyzed if it was anticipated that any one of these five criteria would be met, with the exception of the hybrid alternatives.

A.1 Introduction of Options

Based on the variant selection approach outlined above, ten reactor-based plutonium disposition scenarios were initially selected for further analysis. One of these options (EuroMOX) was eventually deemed to be unworkable (see next section). The current alternative/variant set (Tables A.4 and A.5) consists of

Table A.1. Plutonium disposition reactor alternatives

Alternatives	Plutonium processing/ MOX fabrication facility	Type of reactors	Number of reactors	Integral neutron absorbers
Existing LWRs, existing facilities	Existing facilities on DOE site	PWR	5	No
Existing LWRs, new facilities	New collocated PuP facility and MOX fabrication plant	BWR[a]	4	Yes
Partially complete LWRs	Existing facilities on DOE site	PWR	2	Yes
Evolutionary LWRs	Existing facilities on DOE site	PWR	2	Yes
Existing CANDUs	Existing facilities on DOE site	CANDU	Two for 5 years on reference fuel, then four reactors on advanced fuel (CANFLEX)	No

[a]BWRs could also be implemented using existing facilities and without integral neutron absorbers. The facility combinations considered were done only for the purpose of producing bounding scenarios. The decision at ROD would not down select between PWRs and BWRs if the existing reactor alternative is selected.

Table A.2. Deployment approaches for LWRs

Parameter	Range of possible choices	Comments
PuP facility	• Greenfield—new facility at a new site • New facility at a DOE site • Existing facility at a DOE site	All three options could also be done either in conjunction with (cofunctional, collocated facilities) or separate from a MOX fuel fabrication facility.
MOX fuel fabrication facility	• Ownership—Privately owned domestic; government-owned domestic; existing European facilities • Siting—Greenfield, new facility at a DOE site, or an existing facility at a DOE site	Except for the European cases, all options could also be done in conjunction with or separate from a plutonium processing facility. (It is likely that plutonium processing would remain government owned.)
Type of reactor	PWRs and BWRs	Even for a specific type of reactor, many designs are available. Both types could operate with or without integral neutron absorbers.
Number of reactors	Two to five[a]	Two is the minimum number of reactors. The maximum number of reactors is limited by the number of reactors available.
Core design approaches	• Amount of MOX per core—full core with neutron absorbers; full core without neutron absorbers; partial MOX cores • Irradiation—from 10,000 to 45,000 MWd/MT HM (approximately) • Fuel cycle length—12, 18, and 24 months	

[a]Five PWRs is similar to four BWRs for environmental impacts.

Table A.3. Reactor variant discriminators

Variant discriminator	Description
1	The *start time* for plutonium disposition for the proposed variant decreases by 3 or more years from the base case.
2	The *duration* of the plutonium disposition mission decreases from that of the base case by 5 or more years.
3	The *investment cost* before initial plutonium disposition for the proposed variant is at least $500M less than the base case.
4	The *discounted life cycle* cost for a proposed variant is at least $500M less than the base case.
5	The proposed variant involves *facilities in a foreign nation.*

Table A.4. Reactor alternatives and variants—50-MT cases

ID	Category	Description
50SFL5	Existing LWR Base case	• 50 MT plutonium • Plutonium processing – Halide plutonium processing at LANL – Modified existing 221-F plutonium processing facility (ARIES and new aqueous lines) at the SRS • MOX fabrication – Domestic, federally owned, GoCo fuel fabrication facility located in existing building on existing federal site • Reactors – Five privately owned domestic PWRs – *No* integral neutron absorbers in fuel • Spent fuel to HLW repository in United States
50SPL5	Existing LWR Variant 1	Same as 50SFL5 except: • Privately owned MOX fabrication facility located in a new building on an existing federal site
50COL4	Existing LWR Variant 2	Same as 50SFL5 except: • Federally owned, collocated plutonium processing and MOX fabrication facility located in a new building on an existing federal site • Four privately owned BWRs • *With* integral neutron absorbers in fuel
50QSL5	Existing LWR Variant 3	Same as 50SFL5 except: • Plutonium available from ARIES demonstration and prototype operation • Early MOX fabrication in existing European commercial facilities • Lag storage facility added for fresh MOX fuel
50SFP2	Two partially complete LWRs	Same as 50SFL5 except: • Two partially complete federally owned PWRs are completed and employed for mission • *With* integral neutron absorbers in fuel
50SFE2	Two new evolutionary LWRs	Same as 50SFL5 except: • New federally owned reactors located on an existing federal site • *With* integral neutron absorbers in fuel
50SFC2-4	CANDU Base case	Same as 50SFL5 except: • Two CANDU units operated on reference CANDU fuel for 5 years followed by • Four CANDU units operated on CANFLEX fuel for remainder of mission

Table A.5. Reactor alternatives and variants—33-MT hybrid cases

ID	Category	Description
33SFL3	Hybrid LWR	Same as 50SFL5 (LWR base case) except: • 32.5 MT of plutonium • 3 PWRs
33SFC2	Hybrid CANDU	Same as 50SFC2-4 (CANDU base case) except: • 32.5 MT of plutonium • Use two CANDU units operated on reference fuel for the entire mission

the existing LWR base case, three variants, and a hybrid case; the CANDU case and one hybrid case; a partially complete LWR case; and an evolutionary LWR case.

Table A.6 provides summary information of the plutonium throughput characteristics for each reactor alternative and variant.

[Note: It is very important to recognize that none of these reactor-based plutonium disposition alternatives have been optimized in terms of cost, schedule, or any other characteristic.]

The analyses discussed in this report include the evaluation of site-specific issues (such as transportation costs, etc.). It was necessary to associate each facility with a geographical site to facilitate these analyses. The selection of these "surrogate" sites should in no way be interpreted as a prediction or a recommendation for the actual site of these facilities.

A.1.1 Existing LWR Alternatives

The existing LWR alternative employs existing domestic LWRs for irradiation of the surplus plutonium. The actual number and type of reactors potentially available for the plutonium disposition mission in the United States are varied and extensive. The U.S. commercial reactor population consists of several different vintages/models of reactors, produced by four different reactor vendors. The base case (50SFL5) chosen by the RxAT consists of five Westinghouse PWRs.

50SFL5 – Existing LWR Base Case—This case is for the disposition of 50 MT of plutonium. The PuP facilities consist of two federally owned facilities, one for halide plutonium processing at LANL and one using ARIES and aqueous plutonium processing at SRS. MOX fuel is fabricated in a federally owned facility located on a federal site in an existing building. Five existing privately owned PWRs are used to transform the MOX fuel to a form meeting the SFS. Spent fuel is sent to an HLW repository. Fuel does *not* contain integral neutron absorber.

50SPL5 – Existing LWR Variant 1—This case is identical to Case 50SFL5 except that the MOX fuel fabrication facility is a privately owned new building on an existing federal site.

50COL4 – Existing LWR Variant 2—This case is identical to Case 50SFL5 except that the plutonium processing and MOX fuel fabrication facilities are federally owned, cofunctional, collocated facilities located in a new building on an existing federal site. Fuel with a maximum plutonium loading and integral neutron absorbers is loaded into four privately owned BWRs.

50QSL5 – Existing LWR Variant 3—This case is identical to Case 50SFL5 except that plutonium is made available from the ARIES demonstration and prototype operations. Early MOX fuel (before the domestic MOX fuel fabrication facility is operational) is provided by European commercial MOX facilities. A lag storage facility is needed for fresh MOX fuel.

33SFL3 – Hybrid LWR—This case is identical to Case 50SFL5 except that three existing privately owned PWRs are used to transform 32.5 MT of plutonium in the form of MOX fuel to a form meeting the SFS. This "hybrid" approach consists of the use of three LWRs in conjunction with another disposition technology (vitrification or deep borehole technology) to disposition the entire inventory of surplus plutonium. Vitrification or deep borehole technology is used to disposition the remaining 17.5 MT of surplus plutonium.

A.1.2 CANDU HWR Alternative

50SFC2-4 – CANDU—This case is identical to the existing LWR base case 50SFL5 except that the reactors are two CANDU units operated on reference CANDU fuel for 5 years, followed by four CANDU units operated on CANFLEX (extended burnup) fuel for the remainder of the mission. This case utilizes existing CANDU reactors at the Bruce-A site in Ontario, Canada.

33SFC2 - Hybrid CANDU—This case is identical to Case 50SFC2-4 except that two CANDU units operated on reference CANDU fuel are used to disposition 32.5 MT of plutonium. This "hybrid" approach consists of the use of two CANDU reactors in conjunction with another disposition technology (vitrification or deep borehole technology) to disposition the entire inventory of surplus plutonium. Vitrification or deep borehole technology is used to disposition the remaining 17.5 MT of surplus plutonium.

Table A.6. Summary of throughput characteristics for plutonium disposition reactors

ID	Reactors	Loading time[a]	Plutonium in HM (%)	Initial loading (MT)		Plutonium throughput (MT/year) Average[c]	MOX (HM) throughput (MT/year) Average[d]	Burnup MWd/MT
				Plutonium	HM[b]			
50SFL5	Five PWRs	9.8	4.3	1.5	35.4	5.0	118.2	45,000
50SPL5	Five PWRs	9.8	4.3	1.5	35.4	5.0	118.2	45,000
50COL4	Four BWRs	16.6	3.0	0.9	31.2	3.0	98.8	33,700
50QSL5	Five PWRs	13.1	4.3	0.5	10.6	5.0	118.2	45,000
50SFP2	Two partially complete PWRs[e]	15.7	4.5	3.2	105.8	3.0	67.7	32,500
50SFE2	Two CE System 80+ PWRs	13.3	6.8	6.7	98.2	3.5	52.2	42,600
50SFC2-4	Two Bruce-A CANDUs for 5 years, then four Bruce-A CANDUs with CANFLEX for 7.2 years	12.2	2.2[f] 3.4[f]	2.9	138.1	2.9 5.0	138.1 149.9	9,700 17,100
33SFL3	Three PWRs	10.5	4.3	1.5	35.4	3.0	69.5	45,000
33SFC2	Two Bruce-A CANDUs	10.9	2.2[f]	2.9	138.1	2.9	138.1	9700

[a]The loading time is the period (years) between the initial MOX loading into the first reactor and the final MOX loading into the last reactor.

[b]Since options 50SFP2, 50SFE2, 50SFC2-4, and 33SFC2 initial loads are full core, plutonium and HM throughputs represent full core load.

[c]The average throughput is the mass of plutonium loaded after the initial loading of the first reactor divided by the loading time.

[d]The HM throughput is the plutonium throughput divided by the plutonium in HM.

[e]The partially complete reactor schedule is represented by the throughput for two CE System 80 reactors. It should be noted that the initial cores for this case employ a 3.0% plutonium enrichment.

[f]For CANDU and CANFLEX, the listed plutonium enrichment is the weighted average for the pins that contain plutonium.

A.1.3 Partially Complete LWR Alternative

50SFP2 – Partially Complete LWR—This case is identical to the existing LWR base case 50SFL5 except that the reactors are two newly completed, federally owned PWRs (currently partially complete). Fuel contains integral neutron absorbers.

A.1.4 Evolutionary LWR Alternative

50SFE2 – Evolutionary LWR—This case is identical to the existing LWR base case 50SFL5 except that the reactors are two newly completed, federally owned evolutionary reactors constructed on an existing federal site. Fuel contains integral neutron absorbers.

A.1.5 EuroMOX—The Elusive Option

The EuroMOX alternative involves the preparation of PuO_2 at a GoCo plutonium processing facility to be built in the United States, and transportation of the oxide to Europe, where it would be fabricated into MOX reactor fuel assemblies (Table A.7) and utilized as full-core MOX fuel loading in existing reactor facilities in one or more European countries. Final disposal of the spent fuel assemblies would be within one or more HLW repositories in Europe.

During the course of this study, it became clear that none of the existing European MOX fuel fabricators would be willing to act as an entry point for American weapons-grade MOX into the European commercial MOX economy. Thus, an immediate and seemingly insurmountable obstacle to implementation of this alternative is apparent. Additionally, the desire for timely disposition of the weapons-grade plutonium would require either the relicensing of two or more foreign reactors for full-MOX cores, or the use of several foreign reactors with partial-MOX cores. It is possible that multiple reactors in more than one European country would be required to implement this alternative. The combination of the MOX fabricator's unwillingness to participate in this endeavor, combined with the political and institutional difficulties associated with its implementation, effectively eliminates EuroMOX from consideration as a viable alternative.

A.2 European Fabrication of MOX Fuel

As shown in Table A.7, MOX fuel fabrication capacity is growing rapidly in Europe. The increased capacity will help bring the European civilian plutonium inventories in balance such that the supply of plutonium from spent reactor fuel will match the demand for plutonium for use in fabricating MOX fuel. It is estimated that MOX fuel demand will match fuel supply capacity after 2005. There is, however, sufficient uncertainty in anticipated MOX fuel demand that no definite statements about future civilian plutonium balance in Europe can be made at this time. Given this fact and the fact that all of the reactors being considered for the disposition of plutonium could operate on European MOX fuel, two conditions are clear:

- Excess MOX fuel fabrication capacity will persist in Europe until at least 2005. This excess capacity could be utilized by the FMDP plutonium disposition mission.
- Sufficient MOX fuel fabrication capacity cannot be assumed to be available to ensure completion of the U.S. plutonium disposition program. Therefore, the need for a domestic MOX fuel fabrication facility is required to ensure completion of the plutonium disposition mission.

Table A.7. Current and anticipated European MOX fuel fabrication capacity

Owner/facility/location	Current MOX fabrication capacity (MTHM/year)	Anticipated MOX fabrication capacity in 2000 (MTHM/year)
Belgonucleaire/P0/Dessel	35	35
COGEMA/MELOX/Cadarache	30	30
COGEMA/MELOX/Marcoule	80	210
COGEMA/MELOX/La Hague	0	50
BNFL/MDF/Sellafield	8	8
BNFL/SMP/Sellafield	0	120
TOTALS	153	453

Appendix B
Schedule Analysis Approach

B.1 Introduction

The NAS labeled the existing international regime for surplus plutonium to be a "clear and present danger" and urged that actions be initiated to effect the disposition of surplus plutonium without delay. Thus, timeliness should be a primary determinant for the selection of approaches for plutonium disposition. The FMDP RxAT interprets timeliness to comprise three performance attributes:

- **Time to start disposition:** For the partially complete and evolutionary reactor options, the mission begins when the first reactor begins operating at full power using a full MOX core. For the existing LWR options, the mission begins when the first reactor is loaded with MOX fuel, after the lead use assemblies (LUAs). For the CANDU options, the mission begins when the first reactors are loaded with MOX fuel.

- **Time to complete:** For all of the reactor options, the mission is complete after the final load of MOX fuel has been irradiated for a specified time in the reactor. For the existing and partially complete LWR options, the mission is complete after the first irradiation cycle of the last core load containing MOX fuel assemblies. For the CANDU options, the mission is complete after the final reference MOX or CANFLEX fuel bundles have been discharged from the reactors. In the evolutionary LWR case, the ABB-CE System 80+ loading schedule assumes a single 3.75-year irradiation cycle for each core load with three reshuffles of the core load. The mission is complete after the first reshuffle of the last core load which contains MOX fuel assemblies.

- **Schedule certainty:** A full uncertainty analysis of the implementation schedules was considered too premature for the analysis presented in this document. A qualitative assessment of the schedule certainty has been included in the facility schedule sections.

The schedule estimates were generated by the RxAT presuming a moderate national priority for plutonium disposition, as opposed to the very high national priority associated with the Manhattan Project or the Apollo Project. Similarly, the team assumed no protracted delays with funding, licensing, or technical problems.

B.2 Schedule Elements

Each deployment schedule has been developed by combining the schedules for each of the individual facilities involved in the alternative. The major elements for each of these schedules include:

- project definition and approval;
- siting, licensing and permitting;
- research, development, and demonstration;
- design;
- facility modification or construction, procurement and preoperational activities;
- operation; and
- decontamination and decommissioning.

The completion of each of these facility elements must be sequenced properly with the other facilities. For example, the MOX fuel fabrication facility needs to have a sufficient supply of PuO_2 to operate. Similarly, the reactors require a sufficient supply of fuel to meet the reload schedule.

In defining the schedule elements for a large government project, a number of activities required for federal projects may not apply or are less important for a private sector project. These complications are reflected in the schedules and include the following elements:

- congressional line item approval and funding authorization,
- compliance with the NEPA, and
- special procurement and vendor selection rules and regulations.

B.3 Schedule Assumptions and Bases

- Some research and demonstration projects are currently under way.
- The project officially starts with the issuance of the programmatic ROD. After ROD, the following tasks begin:
  - line item funding approval process,
  - conceptual design of the PuP and MOX fuel fabrication facilities, and
  - DNFSB review of the use of existing DOE facilities.
- The line item funding approval process has been assumed to take three years and to proceed in two phases. After completion of the first phase, intermediate line item funding approval, several activities begin: contract negotiations with M&O contractors, vendors, and utilities; site selection for the new reactors; and Title I design work. After completion of the second phase, final approval of line item funding, Title II design work begins.
- The facility licensing assumptions are as follows:
  - For the PuP facility, a 5-year oversight review period by the DNFSB is assumed.
  - For the MOX fuel fabrication facility, a 5-year licensing duration is used. This duration is based on analysis by Fluor Daniel, Inc., with the full discovery period and hearing process durations shortened after further discussions with the NRC.
  - For all of the LWR facilities, the licensing processes are based on analyses by Fluor Daniel, Inc. For the existing LWRs, the license modification process is assumed to take 4.25 years for the PWR options which do not have integral neutron absorbers in the MOX fuel assembly and requires 5.25 years for the existing BWR option which includes integral neutron absorbers in the MOX fuel assembly. For all of the existing LWR options, the initial reload permit for MOX fuel is not granted until after the LUAs have been irradiated for two cycles. This two-cycle period allows a full irradiation cycle for confirmatory testing of the new fuel design from a new fuel fabrication facility prior to the reload permit review.
  - For the CANDU HWR facility, the licensing process is based on analyses by AECL and Ontario Hydro and has been estimated to require 4 years.
- Plutonium availability and PuP facility assumptions are as follows:
  - The schedules assume sufficient plutonium will be available for the fuel development work before the PuP facility is operational.
  - For all of the options except 50QSL5, the PuP facility operates for 10 years.
  - For option 50QSL5, the existing PWR option with some MOX fuel fabrication in Europe, the plutonium will be processed in a staged start. This alternative requires PuO_2 feed before the PuP facility could provide it. For this alternative, it is expected that a sufficient quantity of PuO_2 will be available from the ARIES prototype, which is being developed to demonstrate the ARIES process and for design support for the production facility. Using the prototype ARIES line to process some of the mission material also shortens the operational duration of the production facility to 9.1 years.
- The MOX fuel fabrication facility assumptions are:
  - For most of the reactor options, the MOX fuel fabrication facility will be located in an existing building on an existing federal site and will be GoCo. The exceptions are as follows. The existing PWR option which has an early start, 50QSL5, uses fuel fabricated in Europe before fuel fabricated in the domestic facility is available. The MOX fuel assemblies for the existing BWR option are assumed to be fabricated in a new building on an existing federal site. This new building will also contain the PuP facilities. The last exception is the existing PWR option which assumes a privately owned facility located in a new building on an existing federal site. However the implementation schedule is the same as the federally owned facility for two reasons. First, the time required to select the M&O contractor in the federal option is assumed to be of the same duration as selecting the private owner for the facility. Second, the construction time for modifying an existing facility is assumed to be the same as building a new facility on an existing federal site.

— For the existing LWR options, the initial assemblies will be used as LUAs; full mission fuel production will begin 6 months later.

— The operational schedules for the MOX fuel fabrication facility in each option is based on the fuel assembly production schedule shown in Table B.1.

- The reactor facility assumption is:
  — The assumptions for the design, construction and operation of the various reactor facilities are discussed in their respective volumes.
- The HLW repository facility assumptions are:
  — For the LWR options, it has been assumed that the licensing for the HLW repository facility will begin in March 2002 and be completed in August 2010. The construction of the facility will begin in March 2005 and be completed in 2010. The facility will be ready to accept the spent MOX fuel assemblies after the assemblies have cooled in the spent fuel cooling pool for 10 years.
  — For the two CANDU options, it has been assumed that the Canadian HLW repository facility will be opened in 2025. Spent MOX and CANFLEX fuel, which has cooled in the spent fuel pools for 10 years prior to the opening of the facility, may be stored in dry cask storage until the repository is opened.

Table B.1. MOX fuel fabrication facility production schedule

Alternative	Fuel assembly output/year	Total number of mission assemblies	Plutonium throughput (MT/year)	Average throughput (MTHM/year)	Mission operation (years)
50SFL5, 50SPL5	280	2,756	5	118	9.8
50QSL5 European	85	375	1.5	35.8	4.5
Domestic	280	2,381	5	118	8.5
50COL4	602	9,416	3.2	107	15.6
33SFL3	170	1,819	3.0	71.7	10.7
50SFP2	157	2,692	2.9	69	17.1
50SFE2	129	1,807	3.6	53	14
50SFC2-4	9,050	4,5250	3.0	138	5
	10,500	75,279	5	150	7.2
33SFC2	9,050	98,485	3.0	138	10.9

Appendix C
Cost Analysis Approach

C.1 Introduction

A goal of the FMDP is to minimize the incremental cost impact on the government and taxpayers. Although the national security benefits clearly outweigh the costs involved, significant budget pressures are projected throughout program execution. Timing and allocation of costs were assessed. The following cost-related performance factors were considered to evaluate the extent to which a particular variant is cost-effective.

- **Investment and start-up cost**: Investment and start-up cost refers to research and development, construction, retrofit, and program infrastructure costs that are incurred early in the program. In government accounting, they are known as Total Project Costs (TPCs).

- **Discounted life cycle cost**: Discounted life cycle cost (DLCC) is defined as the net present value of all "cradle to grave" government cash flows including those in the TPC. DLCC includes adjustments for revenues that may be produced by electric power production but does not include the sunk (pre-FY 1997) costs of existing facilities or other costs that would be incurred whether or not any action is taken.

For large government projects, such as the FMDP, there is the need to consider not only the costs to design and construct the project, but also the costs to operate the facilities over their lives and safely D&D them. For this reason the total life cycle costing (TLCC) approach is used for cost estimating to obtain the true "cradle to grave" costs. This costing methodology also makes comparison of competing plutonium-disposition alternatives more meaningful. Many of the alternatives being considered have different operating lifetimes, and the TLCC concept allows schedule differences to be correctly reflected in overall costs.

Early in the FMDP evaluation process, a set of cost estimating guidelines and a 24-life-cycle category (Table C.1) estimating format were supplied to the alternative teams for each technology. This was done to ensure comparability between estimates and assist the decision-making process. The alternative teams were responsible for preparation of the LCCs, which were then reviewed by the Systems Analysis Team for completeness and adherence to the guidelines. In the case of the reactor estimates, much of the cost data came from 1993 and 1994 plutonium-disposition feasibility studies by reactor vendors, reactor cost data bases at ORNL, DOE plutonium-handling sites such as SRS, and the two weapons research laboratories [Lawrence Livermore National Laboratory (LLNL) and LANL] and their AE subcontractors. The FMDP multilaboratory Systems Analysis Team had the role of "levelizing" the cost data, i.e., ensuring their comparability. It should be noted that the focus in these studies is the LCC to the federal government, and specifically those costs that will be borne by FMDP. Costs to private concerns such as utilities, fuel suppliers, etc., are not considered in this study; however, they may have been used during the estimating process to calculate costs that are ultimately passed on to the federal government. (An example would be the cost of MOX fuel from a privately owned facility specifically built to meet government plutonium-disposition needs.)

C.2 Major Cost Categories

The 24 LCC categories can be rolled into three higher-level categories: investment cost, recurring costs, and D&D costs. Each category includes the following items:

- **Investment Costs**: This cost is essentially the sum of the "up-front" costs needed to bring a facility into full-capacity operation and includes planning, research and development, ES&H studies (including NEPA), site qualification, quality assurance planning, permitting, safety analysis, design, construction, project management, initial spare equipment items, facility start-up, staff training, and manual preparation.

- **Recurring Costs**: These costs are incurred during normal facility operation after start-up and include plant staffing cost (including fringe benefits and taxes), costs of process consumables and

Table C.1. 24-category format for LCC estimates

Category	Costs (1996 dollars)
	Preoperational or OPC up-front costs:
1	R&D
2	NEPA, licensing, permitting
3	Conceptual design
4	Implementation plans: QA, site qualification, S&S
5	Postconstruction start-up
6	Risk contingency
	SUBTOTAL (OPC)
	Capital or TEC up-front costs:
7	Title I, II, III engineering, design, and inspection
8a	Capital equipment
8b	Direct and indirect construction/modification
9	Construction management
10	Initial spares (technology dependent)
11	Allowance for indeterminates (AFI) (percentage of category 7–10)
12	Risk contingency
	SUBTOTAL (TEC)
	TOTAL UP-FRONT COST(TPC)
	Other LCCs:
13	O&M staffing
14	Consumables including utilities
15	Major capital replacements or upgrades
16	Waste handling and disposal
17	Oversight
18	M&O contractor fees (2% of categories 13–16)
19	PILT to local governments (1% of categories 13–16)
	TOTAL RECURRING COSTS
20	D&D (20% of TEC)
21	Revenues (if applicable)
22a	Revenue from sale of reactor
22b	Government subsidies or fees to privately owned facility
23	Transportation of plutonium forms to facility (or T&PT)
24	Storage of plutonium at existing 94-1 site facility
	TOTAL OTHER LCC
	GRAND TOTAL ALL LCC (1996 $M)

- maintenance materials, utility costs, administrative and plant overheads, transportation costs for nuclear materials, oversight costs, fees to the facility management contractor, capital replacement items, waste-handling costs, and payments-in-lieu-of-taxes to local communities. [In many of the charts this category is also called "O&M (Operations and Maintenance) and Other LCCs."]

- **D&D Costs**: These are the costs incurred at facility end-of-life to decontaminate and remove process equipment and to decontaminate any process buildings to a safe or "habitable" state where no adverse human health or environmental consequences result from their continued existence on the site.

A special category is that of revenues. For some reactor alternatives the federal government may benefit from the sale of the following items:

— Electricity: If the government owns the nuclear power plant, electricity will be sold.

— MOX fuel: If the government owns the MOX fuel and sells it to a private utility reactor owner, the fuel would probably be sold at a price close to that of an energy equivalent amount of LEU or natural uranium fuel.

— Reactor power plant: If the government owns the power plant during the duration of the plutonium disposition campaign, it may wish to sell the plant to a utility at the end of the campaign, thus removing the government/FMDP from the business of selling electricity.

C.3 General Cost Assumptions for the CANDU and CANDU Hybrid Reactor Cases

- All costs are reported in constant 1996 dollars.

- For the CANDU base case, LCCs are reported for three facilities:

  — the PuP facility: a federally owned facility assumed located in an existing facility SRS;

  — the MOX fabrication facility: a federally owned facility assumed located in an existing building at a DOE site with plutonium-handling infrastructure; and

  — the two to four existing CANDU HWRs: utility-owned power plants assumed located at the Bruce site in the Canadian province of Ontario.

- For the hybrid case (assuming an immobilization option is chosen), two additional facilities are needed: the vitrification facility located in the existing facility at SRS, and the U.S. repository to handle the glass logs produced there (CANDU spent fuel stays in Canada).

- 50 MT of plutonium is dispositioned over a 12.2-year irradiation campaign in the two to four CANDU HWRs in the base case. 32.5 MT of plutonium is dispositioned over 10.9 years in two CANDU units for the hybrid case.

- Plutonium-processing LCCs and MOX-fabrication LCCs are based mainly on data from LLNL, LANL, and SRS. Reactor LCCs are based on data from AECL, Ontario Hydro, and ORNL.

- U.S. repository costs for the glass logs from the vitrification process are based on a disposal fee of $500K per log.

- Total discounted dollar cost is calculated by spreading the constant-dollar cash flows in a manner consist with the project schedule, and then discounting these cash flows at 5% real discount rate as prescribed by the Office of Management and Budget. This discount rate is consistent with the federal government's costs of borrowing.

- Government-owned facilities are assumed to be operated and managed by private corporations or utilities on a fee basis. The contractors' annual fee for the plutonium processing and the MOX fabrication facility is calculated as 2% of the annual recurring costs. The CANDU reactor operator receives a fee of $25M per reactor pair per year for the first 5 years, followed by $10M per reactor pair per year thereafter. This is consistent with the assumptions made for other reactor options. These fees were not included in the CANDU alternative cost analysis presented in Table 4.1 of the TSR.

- Comparison with cost information in the *Technical Summary Report (TSR) for Surplus Weapons-Usable Plutonium Disposition:* In the TSR, costs or benefits for negotiable or business-related cost

categories were assumed to be zero. In this report, however, these categories are costed; a table comparing the TSR CANDU-reactor case and this case (CANDU-RASR base case) will be presented. The one category so treated is the following:

— The fee to a utility for MOX operations in a private facility, or to an O&M contractor for MOX operations at a GoCo facility. (Table 2.51 shows a comparison of the RASR and TSR costs related to this fee.)

Appendix D
Safeguards and Security Analysis Approach

D.1 Introduction

S&S concerns are of two basic types. The first concern has to do with the potential for theft and diversion of materials by disgruntled employees, "unauthorized" groups such as terrorist and subnational organizations, and aspiring nuclear states. The second concern has to do with the threat that the "host" nation (presumably the United States or the Russian Federation) might retrieve the dispositioned plutonium form, extract the plutonium, and reuse the material for weapons production.

D.2 Resistance to Theft or Diversion by Unauthorized Parties

Evaluation Criteria—This metric was developed to address the risk of theft of weapons-usable nuclear material primarily during transportation, storage, and processing, as well as the risk of theft after disposition is completed. The threat was presumed to be theft by terrorists, subnational groups, or aspiring nuclear states, in addition to potential theft by disgruntled employees. This threat can be reduced by minimizing the handling and processing of the material and applying effective S&S measures. Important characteristics included the inherent attractiveness of the weapons-usable material, the number of transportation steps and sites involved, and the number and characteristics of the processing steps that influence the effectiveness of standard S&S practices. The transportation, storage, and processing of the material must meet the Stored Weapons Standard[1] and the condition after disposition must meet or exceed the proliferation resistance of SFS.[2] Factors considered when applying this criterion were the following:

- **Low inherent attractiveness**: This factor favored alternatives that minimize the attractiveness of the physical, chemical, or isotopic makeup of the nuclear material during processing, transportation, or storage. The risk of theft (or weapons use) is reduced if material is available only in small quantities and/or is in a physical and chemical form that makes recovery difficult.

- **Minimization of transportation and number of sites**: The more complex the logistics, the more opportunities there are for theft. Disposition scenarios that involve very complex logistics with many transfers and storage locations, with attendant transportation requirements, were considered to be more vulnerable to theft.

- **S&S assurance**: The effectiveness of the S&S protection depends on the form of the fissile material and the characteristics of the processes and facilities involved in the storage and disposition activities.

Applicable S&S Requirements and Measures—The S&S requirements for this alternative are primarily driven by the attractiveness of the material as defined in DOE Order 5633.3B (Table 2.8) and/or 10 CFR Parts 73 and 74. Every facility in this alternative (e.g., PuP, MOX fuel fabrication, and reactors) except the repository will be a Category I facility. Information about the flow of plutonium through this alternative and a description of the material and its attractiveness level are provided in Chap. 2. A number of different forms are received by the PuP facility (IB to IID). This material is converted into PuO_2 (IC), which is sent to the MOX fuel fabrication facility. At the MOX fuel fabrication facility the PuO_2 is made into fuel, but the attractiveness level (IC) remains the same. A single fuel assembly contains more than 6 kg of plutonium and therefore meets the criteria for Category I. The presence of fresh MOX fuel is the primary factor that will affect S&S areas for the reactor facilities. Once the MOX fuel has been irradiated, the S&S requirements/procedures should not be significantly different from what is currently required at existing reactors. Highly irradiated MOX fuel (e.g., a radiation dose rate in excess of 100 rem/h at a distance of 3 ft) will be considered as Category IVE and will be

[1] The Stored Weapons Standard was selected by NAS to mean that, to the extent possible, the high standards of security and accounting applied to the storage of intact nuclear weapons should be maintained for these materials throughout dismantlement, storage, and disposition.

[2] The SFS was defined by NAS to mean that alternatives for the disposition of plutonium should seek to make this plutonium as inaccessible or unattractive for weapons use as the much larger and growing stock of plutonium in civilian spent fuel.

exempt from certain requirements in 10 CFR 73 for SNM (10 CFR 73.6). If after a period of time the irradiated MOX fuel no longer meets the above radiation dose criteria, then it may be considered as Category IID, depending on the quantity of SNM present. Protection against radiological sabotage should likewise not be significantly different for MOX fuel. In order to meet the requirements for protection of the more attractive fresh MOX fuel, it may be necessary for reactors to upgrade their facilities, procedures, and personnel qualifications.

Category I and/or strategic SNM must be used or processed within an MAA. Material that falls under attractiveness levels IB to IC must be stored, at a minimum, in a vault-type room. To protect against radiological sabotage, reactors have both a protected area and vital area but would not normally have an MAA or equivalent protection. The requirement for an MAA and vault-type storage room means that certain physical protection enhancements may be required beyond those currently present at existing reactors (e.g., beyond 10 CFR 73.55). At least three barriers must protect strategic SNM, with the physical barriers at the protected area consisting of two barriers with an intrusion detection system placed between them. The protected area boundary must also provide for a barrier from vehicle penetration. The access control points into the protected area must be made of a bullet-resistant material. Duress alarms will be necessary at all manned access points. There will be enhanced entrance/exit inspections of personnel, vehicles, and hand-carried items. MAA/protected area portals will typically have metal detectors, SNM detectors, and perhaps X-ray machines for hand-carried items. If Category I SNM is to be stored, the storage area must meet the criteria of a vault-type room, which means an area with enhanced barriers, access control, and motion sensors to detect penetration.

Possible Diversion, Theft, or Proliferation Risks—This criterion evaluates the system resistance to theft by an outsider and/or an insider and retrieval after final disposition by outside groups. Theft or diversion of material refers to both overt and covert actions to remove material from the facility. This is perpetrated by unauthorized parties including terrorists, subnational groups, criminals, and disgruntled employees. Protection of the material and information from these parties is a domestic responsibility, not an international one. It is internationally recognized that protection against these threats is a state's right and obligation. For this criterion the primary concern is that of theft of fissile material by a subnational group. There are a number of possible adversary groups with different motivations and capabilities. The actions could be overt such as a direct attack on a facility, or they could involve covert measures that might utilize stealth and deception as well as possible help from an "insider." It is assumed that all facilities will meet the necessary S&S requirements and that existing measures will help mitigate any risks. Still the threats to facilities will be different, depending on the form of the material, the activities at the facility, and the barriers to theft (both intrinsic to the material and also to the facility).

Criterion Measures—The measures identified for this criterion are the environment, material form or characteristics, and S&S. These measures are briefly described below. The analysis is qualitative based on available data and will be refined later in the decision process.

Environmental Conditions—The logistics, physical location, throughput, inventory, and the state during processing, transportation, or storage affect the opportunities for theft. The more complex the operations (e.g., large operations, number of steps, transfers, or processes), the more opportunities there are for theft. The more inaccessible the physical location (e.g., storage locations), the fewer the opportunities for theft. Throughput is particularly important for operations involving bulk operations. When the material is in discrete items, this factor is less important. For transport operations the number of trips and distances traveled (particularly for off-site moves involving SSTs) are important.

Material Form—Attractiveness is based on physical, chemical, or nuclear (isotopic and radiological) makeup of the nuclear material during processing, transportation, or storage. The risk of theft for weapons use is reduced if material is available only in small quantities, is in a physical and chemical form or matrix that makes recovery difficult, or is isotopically unattractive. The DOE attractiveness table found in DOE Order 5633.3B is the primary basis for evaluating the material form. The presence of other fissile nuclear material, particularly in a separated form, will affect opportunities for possible diversion of plutonium.

S&S Assurance—The effectiveness of S&S protection depends on the form of the material, the physical protection characteristics of the processes, facilities involved in the storage and disposition activities, and the material measurement systems being applied.

Ability to Achieve the SFS—The "SFS" means that the material is comparable to existing spent fuel at commercial reactors with respect to its environment, material form, and S&S. The plutonium in MOX spent fuel is as difficult to divert or steal as plutonium in commercial spent fuel. In fact, since the origin of the MOX fuel is from weapons material, there is a good chance that this material may have increased visibility with respect to safeguards. *The final disposition form for this alternative meets the SFS.* Both significant extrinsic (facility) and intrinsic (related to the material form) safeguards exist. Since the radiological barrier is time dependent, this attribute will, over a long period of time, decrease and the material will not be self-protecting. Before the irradiation of the fuel assemblies, the material does not meet the SFS, and therefore, protection commensurate with its attractiveness level must be provided.

S&S Transportation-Related Issues—Transportation of SNM such as plutonium exposes the materials to threats of theft and diversion outside the controlled areas of secured nuclear facilities. These threats are addressed by DOE and the United States. The NRC, through implementation of requirements for administrative controls on transportation planning, preparations, activities, and oversight, and through the use of advanced technologies for payload security and shipment monitoring, has established regulations in 10 CFR 73.37 requiring implementation of measures to ensure that shipments of SNM are secured from theft and diversion during transport. The measures include provisions for specially equipped transportation vehicles that become immobile if subjected to a diversion threat, frequent and planned communications between an in-transit shipment and the shipper facility, location monitoring and reporting of shipments every 2 h, armed escorts, security-cleared vehicle operators and escorts, and route planning approved in advance by the NRC.

Safeguarding and security for DOE shipments of weapons-usable materials, such as plutonium, are governed by DOE Order 5632.2B. This order specifies the levels of security that are required for varying quantities and types of materials that are shipped. SST vehicles are to be used for the shipment of all materials classified as Category I materials (weapons assemblies, pure products, and high-grade materials). Category II materials, which are all materials that could be used with little technological effort to produce a nuclear weapon (weapons-usable materials), are also required to be transported in SSTs unless these materials have been provided with diversion resistance. Plutonium materials associated with the RxAT alternatives, except spent nuclear fuel, are believed to all fall into the Category I or II classifications, thus requiring SST level of transportation security. The technical features of the SST system are necessarily classified to protect its effectiveness in preventing theft or diversion of materials that are shipped. In general, however, SSTs provide an extremely resistant barrier to intrusion into the vehicle's closed cargo area where packages of plutonium materials will be carried. Minimizing the number and/or duration of the transport steps is desirable.

D.3 Resistance to Retrieval Extraction and Reuse by the Host Nation

International safeguards—The IAEA is the primary agency for international safeguards (ISGs). ISGs also comprise two subsystems: (1) nuclear materials accountancy and (2) materials containment and surveillance (C/S) required to satisfy international inspection agreements. The focus is on the independent verification of material use through material accountancy programs and containment and surveillance systems. IAEA inspections are conducted to verify the facility's declared nuclear inventory values. Nuclear measurements play an important role in verifying material accountability and measurement accuracy and differences from "book" values and holdup are particularly important for high-throughput processes. C/S provides continuity of knowledge during inspector absences and provides supplemental information to assure inventory values when measurement inaccuracies might lead to the conclusion of an inventory discrepancy. Classified information (e.g., as in the PuP facility) will need to be protected before IAEA safeguards can be applied. It is assumed that all facilities except the PuP facility will be subject to IAEA safeguards. IAEA safeguards are designed to detect in a timely manner the diversion of nuclear material. The safeguards requirements for this alternative are based on IAEA INFCIRC documents and negotiated facility attachments. Nuclear material for this alternative falls under the IAEA categories of unirradiated direct use (e.g., plutonium metal and compounds, MOX powder and pellets, MOX fuel rods and assemblies) and irradiated direct use (e.g., MOX fuel in the reactor core, spent MOX fuel). Some of the other fissile materials in the FMDP are not considered by the IAEA.

Applicable S&S Requirements—The S&S requirements for this alternative are primarily driven by the

attractiveness of the material as defined in DOE Order 5633.3B and/or 10 CFR 73 and 74. Every facility in this alternative (e.g., PuP, MOX fuel fabrication, and reactors) except the repository will be a Category I facility. A number of different forms are received by the PuP facility (IB to IID). This material is converted into oxide (IC) which is sent to the MOX fuel fabrication facility. At the MOX fuel fabrication facility the oxide is made into fuel, but the attractiveness level (C) remains the same. The presence of fresh MOX fuel is the primary factor which will affect S&S areas for the reactor facilities. Once the MOX fuel has been irradiated, the S&S requirements/procedures should not be significantly different than what is currently required at existing reactors. Highly irradiated MOX fuel (e.g., a radiation dose rate in excess of 100 rem/h at a distance of 3 ft) will be considered as Category IVE and will be exempt from certain requirements in 10 CFR 73 for SNM (10 CFR 73.6). If after a period of time the irradiated MOX fuel no longer meets the above radiation dose criteria, then it may be considered as Category IID, depending upon the quantity of SNM present. Protection against radiological sabotage should likewise not be significantly different for MOX fuel. In order to meet the requirements for protection of the more attractive fresh MOX fuel, it may be necessary for reactors to upgrade their facilities, procedures, and personnel qualifications.

Category I and/or strategic SNM must be used or processed within an MAA. Material which falls under attractiveness levels IB to IC must be stored, at a minimum, in a vault-type room. To protect against radiological sabotage, reactors have both a protected area and vital area but would not normally have an MAA or equivalent protection. The requirement for an MAA and vault-type room storage means that certain physical protection enhancements may be required beyond what currently is present at existing reactors (e.g., beyond 10 CFR 73.55). At least three barriers must protect strategic SNM with the physical barriers at the protected area consisting of two barriers with an intrusion detection system placed between them. The protected area boundary must also provide for a barrier from vehicle penetration. The access control points into the protected area must be made of a bullet-resistant material. Duress alarms will be necessary at all manned access points. There will be enhanced entrance/exit inspections of personnel, vehicles, and hand-carried items. The MAA/protected area portals will typically have metal detectors, SNM detectors, and perhaps X-ray machines for hand-carried items. If Category I SNM is to be stored, the storage area must meet the criteria of a vault-type room, which means an area with enhanced barriers, access control, and motion sensors to detect penetration.

Threat—The threat for this criterion is the host nation. This criterion evaluates the system resistance to diversion of material before final disposition by the host nation, retrieval of material after final disposition by the host nation, and conversion of the material back into usable form by the host nation. This refers to covert attempts to remove material from the system by the host nation or state. Although the host nation may choose to use overt measures to obtain material and/or weapons design information, the greatest concern is with covert attempts. The table in Sect. 2.6.3 summarizes the threat for diversion for the various alternative facilities. The highest threat is at the plutonium processing and MOX fuel fabrication facilities, where there are large throughputs of very attractive bulk material and diversions can be masked by small uncertainties in the accountancy measurements.

Evaluation Criteria—One goal of the program is to make it unlikely that the surplus weapons-usable materials could be reused in weapons. High resistance to retrieval would provide other nations with the confidence that a relatively large resource expenditure (cost and time) would be required to reconstruct the stockpile from dispositioned material. Barriers to reuse result from the form of the material, physical location of the material, and institutional controls (such as IAEA safeguards). A goal of disposition is to reduce reliance on institutional controls.

Modification of the weapons-usable material to make it as difficult to use for weapons production as plutonium contained in spent commercial reactor fuel would make the proliferation and rearmament threat associated with the surplus weapons-usable materials no greater than the threat resulting from plutonium in spent fuel. When modified, the surplus weapons-usable materials would not require a unique level of domestic and international safeguards.

The following factors were considered when applying these criteria:

- **Difficulty of retrieval, extraction, and reuse**: This factor addresses the difficulty (reflected by cost and time) of retrieval of surplus weapons-usable material and its reuse in weapons.

- **Assurance of detection of retrieval and extraction**: This factor primarily deals with how

difficult the material would be to retrieve and extract in a clandestine manner, which depends on the resultant material location and form.

Applicable Safeguards Requirements and Measures—The safeguards requirements for this alternative are based on INFCIRC 288, 66, 153 and the IAEA safeguards inspection criteria 1990-11-21. This criterion evaluates the system resistance to diversion of material before final disposition by the weapons state itself, retrieval of material after final disposition by the weapons state itself, and conversion of the material back into usable form by the weapons state. This refers to covert attempts to remove material from the system by the host nation or state. Again the material form, environment, and safeguards are particularly important for detecting the diversion, retrieval, and extraction activities. In addition, the irreversibility of the material form is important for assessing its reuse in nuclear devices. Nuclear material for this alternative falls under the IAEA categories of DUU (e.g., plutonium metal and compounds, MOX powder and pellets, MOX fuel rods and assemblies) and direct use irradiated (DUI, e.g., MOX fuel in the reactor core, spent MOX fuel). Some of the other fissile material in the FMDP is not considered by the IAEA. The only existing world-wide inspection regime that exists to address this threat is the IAEA. One mission of the IAEA is timely detection of the diversion of nuclear material from declared nuclear activities. An important measure used by the IAEA is the "significant quantity (SQ)" measure, which for plutonium is 8 kg for 1 SQ. Since the state owns and operates the physical protection and material control and accountancy measures, the IAEA does not rely on these systems to fulfill their obligations. The IAEA does independent verification of the data from the state's system of material control and accountancy. The IAEA, in performing its safeguards inspection activities, audits the facility records and makes independent measurements of selected samples of each kind of nuclear material in the facility. To help them fulfill their responsibilities, this verification is coupled with C/S which is designed to provide "continuity of knowledge" during inspector absence. Much of the C/S equipment used by the IAEA is very similar in technology and in some cases nearly identical to the seals and surveillance equipment used by national authorities in physical protection functions. Although the technologies may be the same, the objectives are different. For example, for domestic requirements optical surveillance is generally monitored in or near real time by security forces, whereas for the IAEA the unattended surveillance monitors activities over 1–3 months. The philosophies and implementation of international safeguards (commonly referred to as IAEA safeguards) are substantially different from domestic S&S (as DOE and NRC practice). These activities will quite likely require additional accountability verification (e.g., identification, weighing, sampling and analysis, and NDA, as well as increased inventories and item checks); C/S measures installed throughout the facilities (e.g., surveillance, seals, monitors, tags); space for inspectors; and equipment for independent measurements by international inspectors. In addition, classified information will need to be protected beyond what might currently be necessary. This is an issue for the PuP facility where some of the material input to this facility is pits, and perhaps other classified matter that under current laws cannot be divulged to IAEA inspectors (e.g., disclosure of weapons design information violates the Atomic Energy Act and the 1978 Nuclear Nonproliferation Act). Therefore, at least part of this facility will not be under international safeguards, and therefore, verification by the IAEA is not possible until agreements between the IAEA and the United States can be accomplished. A number of different options are being considered which address this problem. They include processing weapons-related components and material and, after the material has been converted into a declassified form, making it available for the IAEA and the use of modified IAEA safeguards until the material is unclassified.

Possible Diversion, Reuse, and Retrieval Risks—As mentioned above, the threat for this criterion is the host nation. Although the host nation may choose to use overt measures to obtain material and/or weapons design information, the greatest concern is with covert attempts. Because the state has responsibility for physical protection and materials control and accounting (MC&A), the IAEA will seek to independently verify material accounting. C/S complements the material accountability measures. The vulnerability to diversion is dependent on the environment, material form and safeguards measures, and the ability to retrieve and convert the material into a weapons-usable form. Therefore, if we were to evaluate each of the facilities for this alternative, there may be some differences. Because of inherent limitations on the accuracy of NDA measurements, there is increased risk for diversion at high-throughput facilities. This is where C/S plays an important role in assuring material accountability. Existing protective measures will help mitigate these risks.

Criterion Measures—Again the measures of the environment, material form, and safeguards and security measures contribute to this criterion. Thus, the information found in Table 2.11 is applicable; however, the capabilities of the adversary (e.g., the host nation) must be considered when this information is analyzed. The primary measures are the irreversibility of the material forms (e.g., the ability to convert the material back into weapons-usable form) and the ability to detect diversion, retrieval, and conversion, which is dependent on material form, the environment, and safeguard measures. The performance measures that would demonstrate effectiveness in this area are in terms of the following:

- **Difficulty of Diversion, Retrieval, Extraction, and Reuse**—The difficulty of retrieval of surplus plutonium and its reuse in weapons establishes the timeliness and irreversibility criteria and the level of safeguards required. The material form and location are particularly important measures.
- **Assurance of Detection of Retrieval and Extraction**—The difficulty of detection or diversion of a significant quantity of material depends on material form, environment, safeguards, and the following factors:
  - ability to measure material, which includes processing that is under way, accuracy of applicable NDA techniques, the presence of waste streams, and classification issues that may prohibit measurement, and whether item accountancy instead of bulk accountancy methods can be applied
  - C/S systems
  - timeliness of detection

Ability to Achieve the SFS—The final disposition form for this alternative meets the SFS. Both significant extrinsic (facility) and intrinsic (related to the material form) safeguards exist. Since the radiological barrier is time dependent, this attribute will, over a long period of time, decrease, and the material will not be self-protecting. Before the irradiation of the fuel assemblies, the material does not meet the SFS, and therefore, protection commensurate with its attractiveness level must be provided.

S&S Transportation-Related Issues—For all Category I material, SSTs will be used to move the material between facilities. A secure unloading area must be available to receive and verify the material and send it to the storage area. Only after the MOX fuel has been irradiated will the requirement for SST movement be removed. IAEA safeguards can be applied for SST transportation of plutonium materials. Tamper-indicating devices/seals can be applied to packages containing excess plutonium materials, and the cargo compartments of SST vehicles provides an extremely resistant security barrier. Use of welding to attach seals to an SST would not be permitted because it would compromise security. Inspection of SST loading and unloading that does not require access to design features of the vehicle would also be permitted. Since the characteristics of the SST design must be protected to ensure its mission effectiveness, inspections that use instruments, in particular equipment that uses radiative power, would be prohibited. However, inspections of tamper-indicating devices/seals and other approved international safeguards devices would be permitted. Monitoring of SST payloads would also be permitted under the condition that such monitoring would not compromise security through tracking of a vehicle's geographic location. Shipment route data and other sensitive data that must be classified to protect the secure operations of SSTs would not be available for IAEA inspection. Inventorying of payloads before shipment and following receipt would be allowed except under conditions that the excess fissile material contains restricted data.

Appendix E
Quantitative Technical Viability Assessment

An early plutonium disposition study by Omberg[1] contained a proposal for a technical readiness scale. This scale was deficient in four areas: It assumed that scientific feasibility of a concept had been demonstrated. It did not include the final phase of development, which is commercialization. It did not include the possibility that experimental work and analyses may be required in order to satisfy safety and/or regulatory requirements. It appeared to have been based on the assumptions that there were no time lags between various stages of development; and no allowances were made for the loss of corporate memory due to schedule delays.

Omberg's[1] scale was modified to include stages related to the demonstration of scientific feasibility; that is, the process under consideration has been demonstrated in the laboratory. Scientific phenomena have been confirmed, and all principles governing the behavior of the process are believed to be known.

Another modification to Omberg's[1] scale was the addition of two final stages to designate that the process has been commercialized. These stages are the achievement of "final application in the proper operating environment."

To account for the requirements imposed by the need for regulatory approvals, a six-level regulatory status scale is postulated in Table E.1. Since the NRC has never licensed a PuP facility or a MOX fuel fabrication facility, phases of the NRC approval are difficult to establish. The regulatory procedure for a geologic disposal facility, while formulated, has never been carried to completion. Studies of Canadian geologic disposal conducted to date have not included site-specific factors. For reactor certification, the Canadian regulatory process has been less litigious than the United States system and has been perceived to rely on consensus-building between petitioner and regulator. For these reasons, the scale shown in Table E.1 is not linked to specific NRC procedures.

In Table E.2, the regulatory status scale has been combined with the modified scale from Omberg[1] to form the reactor alternatives technical viability scale. The utility value reflects the degree of viability of a process. A value of one indicates low viability. A value of 12 reflects the highest degree of viability, that of a currently operating process.

Table E.1. Regulatory assessment scale

Regulatory status level	Definition
1	No contact with a regulatory agency
2	Discussions initiated with a regulatory agency
3	Continuing discussions; experiment/analyses programs defined
4	Continuing discussions; experiment/analyses programs under way
5	Continuing discussions; experiment/analyses programs complete
6	Final approval received from a regulatory agency

A subtle but important point is that the scale in Table E.2 is based on the assumption that success is possible. If a process is viable at the laboratory level but could not be developed into a prototypic process (e.g., the process is not scaleable to an industrial level), the process does not remain at a utility value of four. Instead, the function to be fulfilled by the process or facility must be degraded to a utility value of one. The scale in Table E.2 is applicable only to processes or facilities for which it is possible to progress up the scale.

An assumption of plausibility with respect to other assessment criteria is necessary for technical viability studies to be conducted independent of other assessment criteria such as safeguards or economics (i.e., in order to study technical viability, not overall viability, of a concept). In performing the technology level

Table E.2. Technical viability scale

Maturity level	Designation	Regulatory status scale	Comment
1	Conceptual	1	Basic principles of the concept, function, and potential application have been proposed.
2	Lab-1	1	Some scientific investigations (calculations and/or experiments) have been conducted.
3	Lab-2	1	Scientific investigations (calculations and/or experiments) are currently under way.
4	Lab-3	1	Scientific feasibility has been demonstrated.
5	Prototype-1	1	A basic engineering system has been defined to implement technology principles and determine if the system can perform the function in the specific application of interest.
6	Prototype-2	2	Critical functions to the performance of the engineering system have been identified and verified with applicable computer codes or general experimental data.
7	Prototype-3	3	Design trade-offs for the engineering system have been identified to establish a reference design configuration. Initial collection of safety-related data is being performed. Existing technologies are available but have not been applied to this application.
8	Prototype-4	4	The system design is complete. The technology development process begins transition into a technology demonstration. Data gathering continues to support licensing.
9	Prototype-5	4	The technology development process has progressed to integrated system demonstration. Collection of safety-related data is complete. Safety-related analyses continue.
10	Prototype-6	5	A final design is approved or approval is pending with no outstanding issues of significance. An integrated system has been demonstrated at a scale relevant to the final application in the proper operating environment. Safety-related analyses are complete.
11	Commercial-1	6	A facility or process is operational but lacks capacity to perform the mission or has been operational at the desired scale or throughput but is not currently in operation.
12	Commercial-2	6	A facility or process is operational and available.

assessments needed for selecting a utility value from Table E.2, one must assume that there are no impediments to technological development due to other criteria. This assumption is believed valid as the "screening process" used to select the reactor options.

E.1 Derivation of a Technical Viability Index

Each facility in each reactor alternative is composed of processes, and each process is at some stage of development. These processes are identified previously in this report and are listed in Table E.3. For each process in each reactor alternative, the degree of technical viability is assessed, based on the categories defined in Table E.2. Each process is evaluated under the assumptions that preceding processes are accomplished successfully (i.e., each process is evaluated independently from all other processes that form the alternative).

Table E.3. Technical viability rankings for components of the CANDU HWRs alternative (50SFC2-4)

Process	Weight function	Maturity level	Reason not lower	Reason not higher
Plutonium processing—shipping to plutonium processing	1.00	11	Pantex is receiving material at the desired rate.	There is no surplus facility capacity to do this for the front end.
Plutonium processing—receiving	1.00	7	A receiving facility exists at the SRS.	A receiving process used previously at Rocky Flats was not adequate. The item accounting which was used did not account for radioactive decay and lead to unacceptably large inventory differences. A new receiving process must be specified which will require measurement of all materials received.
Plutonium processing—pit and metal processing	0.65 for 50-MT option, 1.0 for 33-MT option	6	The technical viability reported is the average for the component process (gas sampling, bisection, plutonium removal, and HEU decontamination). Although some of the subprocesses have been done at Rocky Flats at the desired scale (gas sampling) and can be given a high technical viability rating, other processes are under development.	The bisection system has not been specified for all components. Parting bisector and lathe will be tested as a part of the ARIES program to establish final system design. The scientific feasibility of the hydride/dehydride process has been demonstrated during the FY95. Experiments are underway to optimize operating parameters and system hardware design. The HYDOX system has not been demonstrated or proven, but will be tested as a part of ARIES. The baseline Rocky Flats process for oralloy decontamination generates an unacceptable amount of aqueous waste. A new nearly waste-free system has been demonstrated during FY94 and FY95 and shown to be scientifically feasible. The hydride/dehydride process can also be used to purify metal.
Plutonium processing—gallium removal	0.65 for 50-MT option, 1.0 for 33-MT option	7	Experiments to determine process parameters are currently being conducted.	System design is not complete.

Table E.3. Technical viability rankings for components of the CANDU HWRs alternative (50SFC2-4) (cont.)

Process	Weight function	Maturity level	Reason not lower	Reason not higher
Plutonium processing—U/PuO_2 processing	0.05 for 50-MT option, 0.0 for 33-MT option	5	Hydrochloric acid separation, rating by facility lead.	Assessment by facility lead.
Plutonium processing—halide salts/oxides processing	0.05 for 50-MT option, 0.0 for 33-MT option	5	Salt distillation laboratory scale only.	Assessment by facility lead.
Plutonium processing—oxidelike materials processing	0.05 for 50-MT option, 0.0 for 33-MT option	5	Hydrochloric acid dissolution, assessment by facility lead.	Assessment by facility lead.
Plutonium processing—alloy reactor fuel	0.05 for 50-MT option, 0.0 for 33-MT option	11	Done commercially at INEL, however, there could be difficulties with the plutonium processing which could reduce this to a maturity level of 7.	Sufficient capacity not available.
Plutonium processing—impure metal, and plutonium alloys	0.05 for 50-MT option, 0.0 for 33-MT option	5	Hydrochloric acid dissolution, assessment by facility lead.	Assessment by facility lead.
Plutonium processing—clean oxide, impure oxide, and oxide reactor fuel	0.10 for 50-MT option, 0.0 for 33-MT option	12	No processing required.	No processing required.
Plutonium processing—shipping	1.00	7	Assessment by facility lead.	Assessment by facility lead
Fuel fabrication—plutonium receiving and storage	1.00	9	Facilities for plutonium oxide storage have been built and approved by DOE.	A final design has not been generated.
Fuel fabrication—nonplutonium receiving and storage	0.20	11	Similar facilities exist and are operating, size or scale not a concern.	Facility for this specific purpose is not available.

Table E.3. Technical viability rankings for components of the CANDU HWRs alternative (50SFC2-4) (cont.)

Process	Weight function	Maturity level	Reason not lower	Reason not higher
Fuel fabrication—PuO_2 purification	1.00	6	Critical functions have been identified with experimental data.	Reference design not fully established.
Fuel fabrication—feed materials preparation	1.00	7	Technology available but not applied, design trade-offs have been done.	System design not complete, needed safety data identified but data collection not initiated.
Fuel fabrication—fuel pellet fabrication	1.00	7	Trade-off studies done, existing technology available for nonpoisoned MOX, needed safety data identified.	Technology demonstration (remote fabrication) not available, needed safety identified but data collection not initiated.
Fuel fabrication—fuel rod fabrication	1.00	8	System design (rod materials, diameter, pitch) complete; prototypic pellets have been fabricated.	Integrated technology demonstration not available.
Fuel fabrication—fuel bundle assembly	1.00	9	With suitably decontaminated rods, bundle assembly should be the same as for natural uranium.	Final approval has not been received from regulatory authority.
Fuel fabrication—materials recycle	0.50	7	Existing technologies are available but not all have been applied, reference design envisioned, considerable safety data exist.	System design is not complete.
Fuel fabrication—waste management	0.50	9	Similar systems have been demonstrated.	A final design is not approved, waste content will depend on source plutonium impurities.
Fuel fabrication—bundle shipping	0.20	8	System design complete.	Collection of safety-related data may not be complete.
Reactor—fresh MOX storage	1.00	8	CANDU natural uranium technology applicable, available on same scale as needed, some safety-related data available.	Collection of safety-related data may not be complete.
Reactor—fuel storage pool	1.00	12	Existing facility designed for natural uranium fuel should be applicable for MOX with few or no changes.	Existing facility designed for natural uranium fuel should be applicable for MOX with few or no changes.
Reactor—core configuration	8.125 for 50-MT option, 8.30 for 33-MT option	8	No changes proposed to existing BRUCE core configuration.	Collection of additional safety-related data believed needed.
Reactor—spent fuel storage pool	1.000	12	Existing facility designed for natural uranium fuel should be applicable for MOX with few or no changes.	Existing facility designed for natural uranium fuel should be applicable for MOX with few or no changes.

Table E.3. Technical viability rankings for components of the CANDU HWRs alternative (50SFC2-4) (cont.)

Process	Weight function	Maturity level	Reason not lower	Reason not higher
Reactor—dry spent fuel storage	1.000	12	Existing facility designed for natural U fuel should be applicable for MOX with few or no changes.	Existing facility designed for natural U fuel should be applicable for MOX with few or no changes.
Reactor—shipping	0.200	8	System design complete.	Collection of safety-related data may not be complete.
Repository—surface, security	0.0625	11	No difference from existing technology.	Sufficient capacity does not exist.
Repository—surface staging area	0.0625	8	System design advanced but additional safety data/analyses likely needed.	Collection of safety data/analyses not complete.
Repository—surface receiving bay	0.0625	8	System design advanced but additional safety data/analyses likely needed.	Collection of safety data/analyses not complete.
Repository—surface, handling cells	0.1250	8	System design advanced but additional safety data/analyses likely needed.	Collection of safety data/analyses not complete.
Repository—surface, welding	0.1250	8	System design advanced but additional safety data/analyses likely needed.	Collection of safety data/analyses not complete.
Repository—surface, decontamination	0.0625	8	System design advanced but additional safety data/analyses likely needed.	Collection of safety data/analyses not complete.
Repository—surface, vault	0.1250	8	System design advanced but additional safety data/analyses likely needed.	Collection of safety data/analyses not complete.
Repository—surface, transfer area	0.1250	8	System design advanced but additional safety data/analyses likely needed.	Collection of safety data/analyses not complete.
Repository—surface, cask maintenance	0.0625	8	System design advanced but additional safety data/analyses likely needed.	Collection of safety data/analyses not complete.
Repository—surface, waste treatment	0.0625	8	System design advanced but additional safety data/analyses likely needed.	Collection of safety data/analyses not complete.
Repository—subsurface, emplacement	0.1250	8	System design advanced but additional safety data/analyses likely needed.	Collection of safety data/analyses not complete.
Repository—geologic facility postclosure isolation and safety	7.125 for 50-MT option, 7.30 for 33-MT option	7	Transition to technology demonstration is in progress, system design believed complete.	Integrated system demonstration not achieved, collection of safety-related data not complete.

Table E.3. Technical viability rankings for components of the CANDU HWRs alternative (50SFC2-4) (cont.)

Process	Weight function	Maturity level	Reason not lower	Reason not higher
Sum[a]	32.50 for 50-MT option, 33.20 for 33-MT option	320 for 50-MT, 277 for 33-MT		
Weighted sum[a]		262.66 for 50-MT, 267.09 for 33-MT		
Unweighted viability factor		8.21 for 50-MT, 8.39 for 33-MT		
Weighted viability factor[b]		8.08 for 50-MT, 8.04 for 33-MT		

[a]Sum does not include processes which have a weighting function value of zero.
[b]Viability factor = weighted sum/sum of weights. A value of 12.0 means the alternative is commercialized; a value of one means that the alternative exists only on paper.

The overall figure-of-merit or technical viability index for each alternative/variant is derived by summing, over all processes from all facilities, the product of the technical maturity values (from Table E.2) assigned to the processes and the weighting or "importance" function values. This sum is then divided by the summation of the weighting function values for all processes. The resulting quotient is the desired figure of merit. Consequently, the highest possible figure of merit for an alternative is 12. The lowest possible value is 1.0.

Several of the subjective weighting values listed in Table E.3 differ from unity. Justifications for all nonunity assignments are provided subsequently.

The nonunity plutonium processing weight functions were defined on the basis of the relative quantities of material expected to be received at the processing facility. That is, 65% of the material is expected to be in the form of metal; 35%, in other forms. Only the metal materials will require removal of gallium. For the hybrid option, only the metal pits will be processed for reactor fuel. The other plutonium-bearing forms will be prepared for immobilization. Consequently, for the hybrid option, the weights for plutonium metal processing and gallium removal were set at one, and the weights for the other processes in the plutonium processing facility were set at zero to reflect their absence from the reactor fuel preparation process.

The fuel fabrication nonplutonium receiving and storage functions were judged to be equivalent in function and difficulty of design as existing facilities and were assigned a weight less than one. The fuel fabrication materials' recycle and waste management processes were judged less important than the other fabrication processes because problems or delays in performing these functions could occur without necessarily interrupting the fabrication of MOX fuel. The assignment of 0.5 reflects that these are lesser but still important functions. Shipping of fresh fuel to the reactor and spent fuel from the reactor were judged to be relatively simple items to commercialize and were assigned a weight of 0.2.

The reactor core configuration was assigned a large weight (25% of the sum of all weights) because it is *the process* by which the weapons-usable plutonium characteristics are modified to be similar to spent fuel from commercial reactors. All reactor processes except core design were assigned lower weights because of a judgment that the qualification of the balance of plant was considerably easier to accomplish than the core design.

The sum of the weights for all surface repository processes was set equal to one because of the simplicity of these operations as compared with other processes in the alternative. Certain surface functions were judged by the facility manager to be simpler operations than others, and their weights were reduced accordingly. The repository cask maintenance and waste treatment process values were reduced relative to other surface processes because problems or delays in performing these functions could occur without necessarily interrupting the storage of spent fuel. The subsurface portion of the repository was assigned a large weight (25% of the sum of all weights less the sum of the repository surface processes) because recovery from failure of this process would be more difficult than recovery from the failure of other processes.

Though not considered in the current work, a different weighting for the subsurface portion of the repository would be required for other plutonium disposition options (immobilization or storage in a borehole) being studied by DOE. Whereas the reactor core design process achieves the goal of transforming weapons-usable plutonium for the reactor options, plutonium/fission product vitrification and subsurface storage are the principal processes for achieving the disposition goal for the immobilization and borehole options, respectively.

E.2 Reference

1. R. P. Omberg and C. E. Walter, *Disposition of Plutonium from Dismantled Nuclear Weapons: Fission Options and Comparison*, LLNL, UCRL-ID-113055, February 1993.

Appendix F
Description of Surplus Plutonium Feed Materials

The surplus weapons-usable plutonium is currently stored at multiple sites across the DOE complex, as shown in Fig. F.1. DOE is currently working on a PEIS to make long-term storage and disposition policy decisions for excess plutonium. While long-term disposition of plutonium is not expected to start for 10 to 15 years, DOE is actively implementing recommendations of the DNFSB (DNFSB Recommendation 94-1) involving immediate and near-term stabilization and repackaging of plutonium at a number of DOE facilities. Table F.1 shows a breakdown of plutonium inventories (by site and form) that are excess to national security needs. Figure F.2 shows a graphical representation of the breakdown of (a) weapons-grade, and (2) reactor- and fuel-grade plutonium by form. Storage options under consideration include (1) upgrading all present plutonium storage facilities, (2) consolidating all excess plutonium at a single location, and (3) consolidating excess plutonium at multiple storage locations (while closing some present locations).

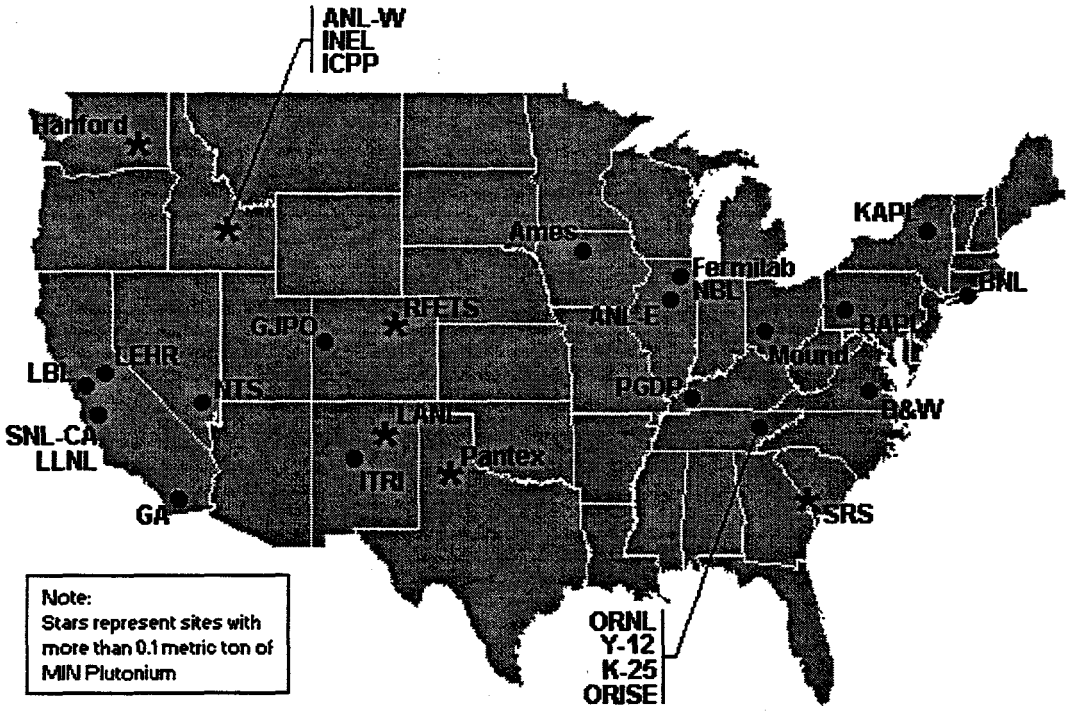

Figure F.1. Geographic distribution of DOE sites storing surplus plutonium. *Source:* U.S. Department of Energy, *Taking Stock: A Look at the Opportunities and Challenges Posed by Inventories from the Cold War Era*, DOE/EM-0275, January 1996

Table F.1. Plutonium inventories (in metric tons) excess to national security needs[a] by site and form

Site	Weapons grade						Reactor and fuel grades			Total plutonium inventory
	Metal	Oxide	Unirradiated fuel	Spent nuclear fuel	Other	Total	Separated (all forms)	Spent nuclear fuel	Total	
Pantex plus planned dismantlements	21.3					21.3				21.3
Rocky Flats	5.7	1.6			4.6	11.9				11.9
Hanford Site (PNL and Hanford)	<0.1	1		0.2	0.5	1.7	2.9	6.4	9.3	11
Los Alamos National Laboratory	0.5	<0.1	<0.1		1	1.5	0.3		0.3	1.8
Savannah River Site	0.4	0.5		0.2	0.2	1.3	0.4	0.1	0.5	1.8
INEL (INEL, ICPP, and ANL-W)	<0.1		0.2	0.2	<0.1	0.4	3.6	0.4	4	4.4
Other sites	<0.1			<0.1	<0.1	0.1	0.2		0.2	0.3
TOTAL	27.8	3.1	0.2	0.6	6.4	38.2	7.5	6.9	14.4	52.6

[a]Includes plutonium in spent nuclear fuel and small amounts of plutonium that are in use in nonnational security programs.
[b]PNL = Pacific Northwest Laboratory, INEL = Idaho National Engineering, ICPP = Idaho Chemical Processing Plant, ANL-W = Argonne National Laboratory–West.
[c]Totals may not add due to rounding.
Sources: (1) DOE Openness Initiative February 6, 1996, p. 88; and (2) DOE, *Taking Stock: A Look at the Opportunities and Challenges Posed by Inventories from the Cold War Era*, DOE/EM-0275, January 1996.

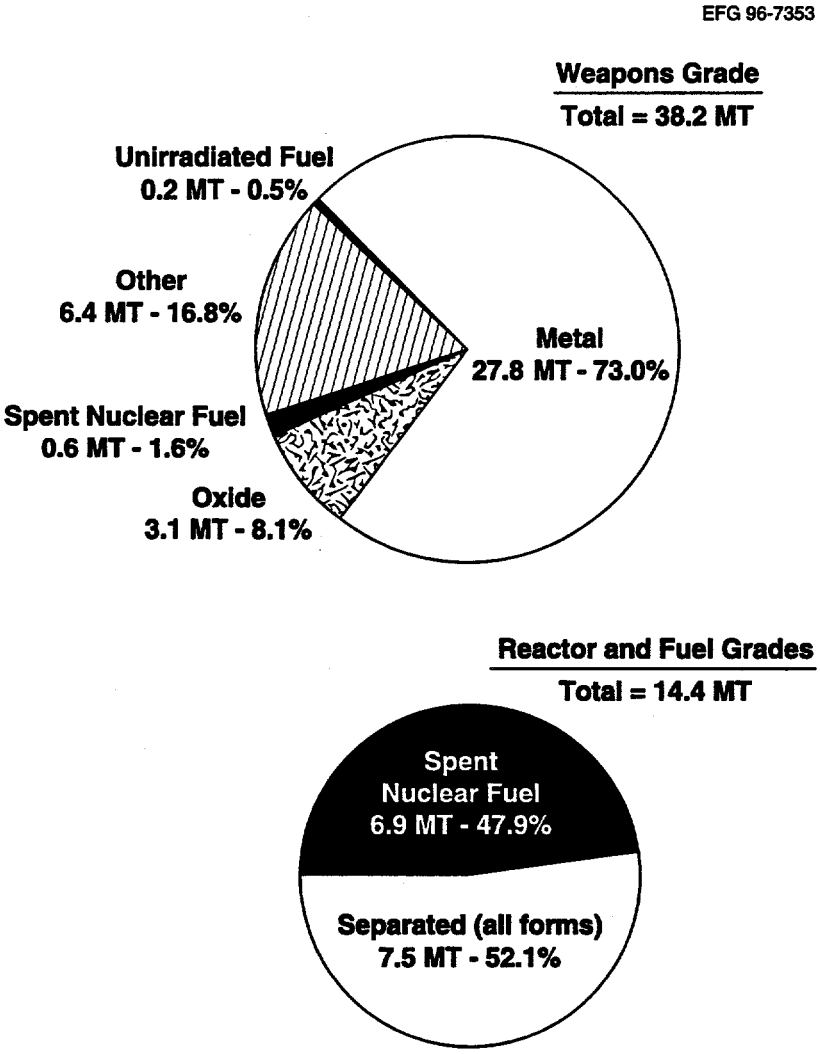

Figure F.2. Unclassified surplus plutonium by form. *Source:* U.S. Department of Energy, *Taking Stock: A Look at the Opportunities and Challenges Posed by Inventories from the Cold War Era*, DOE/EM-0275, January 1996

Appendix G
Transportation and Packaging of Plutonium Material Forms

G.1 Overview

Disposition of 50 MT of excess weapons-grade plutonium will require a series of sequential movements of the plutonium from its present locations (storage vaults at a number of DOE facilities) through the various processing, fabrication, and disposition facilities, and ultimately, emplacement as spent fuel at a Canadian HLW repository and HLW in a U.S. repository. Figure G.1 provides a simplified flow chart of the transportation segments associated with a Canadian reactor disposition alternative. Actual facility locations will be determined by DOE following the ROD. For analysis purposes, it has been assumed that the excess plutonium is in interim storage at many locations within the DOE weapons complex. This material is first packaged and transported to a PuP facility (assumed to be located at SRS), where the material is converted to PuO_2. The PuO_2 is then repackaged and transported to the MOX fuel fabrication plant (assumed to be constructed in an existing building elsewhere at SRS). Different amounts of PuO_2 will be fabricated into reactor fuel, depending upon the option chosen. Once fabricated, the fresh MOX fuel is packaged and transported to the Bruce-A CANDU reactors in Ontario, Canada. Spent fuel discharged from each reactor is first stored in spent fuel pools or dry storage at each reactor for a number of years.

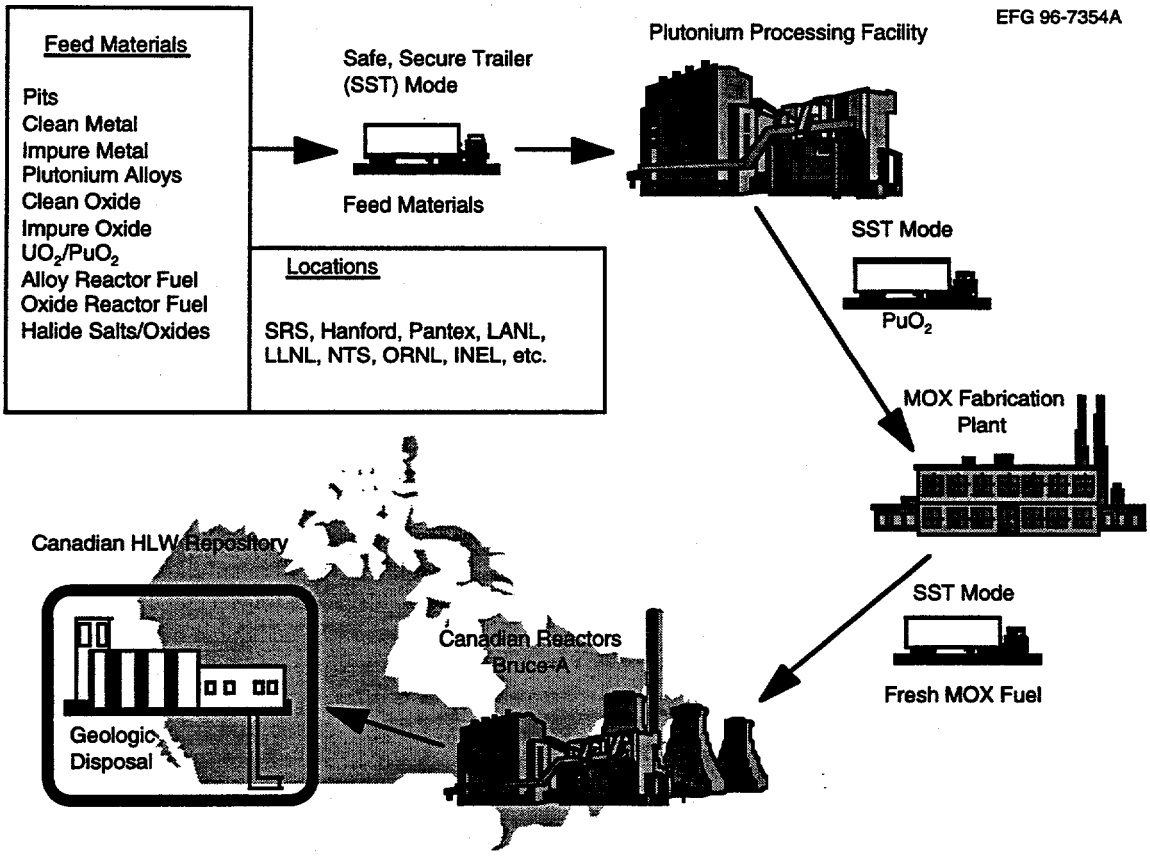

Figure G.1. Simplified flow chart showing transportation segments for Canadian reactor alternatives

Ultimately, the spent fuel is packaged and transported to a Canadian HLW repository. Waste produced at U.S. facilities will be transported to a U.S. repository.

Packaging and transportation of radioactive materials within the U.S. (e.g., plutonium, spent nuclear fuel, and associated radioactive wastes) are subject to the regulations of the DOT, the NRC, and the DOE. Similarly, transportation of radioactive materials in Canada are subject to regulations of the Canadian AECB and Transport Canada. In addition, international shipments of radioactive materials are made in accordance with Safety Series No. 6, IAEA Safety Standards, "Regulations for the Safe Transport of Radioactive Materials, 1985 Edition" (as amended 1990).

The following sections discuss applicable radioactive material transportation regulations and the safety of packaging and transporting radioactive materials. Finally, each transport leg associated with the reactor alternative is described in terms of the packaging needed and the number of shipments to occur over the duration of the alternative.

G.2 Regulations

Packaging and transportation of even low levels of radioactive materials are strictly regulated by the DOT and the NRC. The DOE also controls packaging and transportation of radioactive under its control through a series of DOE orders. The FMDP has assumed that most existing DOE facilities will continue their compliance under DOE orders, with the DNFSB as the reviewing agency. New facilities, however, would be licensed by the NRC.

NRC regulations establish requirements for the packaging and transportation of radioactive materials (10 CFR Part 71), including the preparations and procedures for shipment of licensed nuclear materials, procedures and standards for obtaining NRC certification of packaging. In the case of weapons-grade plutonium, a quantity in excess of ~25 mg (8.8×10^{-4} oz) constitutes a Type B quantity per 10 CFR Part 71. Therefore, all conceivable plutonium shipments with the FMDP program must utilize, at a minimum, a Type B package. 10 CFR Part 71 incorporates by reference DOT regulations 49 CFR Parts 170–189.

Additional NRC regulations pertain to the physical protection of nuclear materials at facilities and during transport operations (10 CFR Part 73). The DOE also requires physical protection and control of nuclear materials per DOE Order 5633.3B. Security requirements for the transport of nuclear materials by DOE are provided in DOE Order 5632.1C, as provided by DOE's Transportation Safeguards System. Off-site transport of radioactive materials requirements are prescribed in DOE Order 460.1 or 5610.12, depending on the type of material. To provide security for shipment of special nuclear materials and weapons components, DOE's Transportation Safeguards Division operates SSTs that provide additional protection for special nuclear materials while in transit. Figure G.2 shows a picture of a typical SST and tractor operated by the DOE. SSTs are accompanied by armed escort vehicles. The design of the SST and operation of the SST fleet by DOE has been judged to significantly exceed the NRC's requirements for the physical protection of nuclear materials in transit, embodied in 10 CFR Part 73.

Although 49 CFR Part 173.7(b) provides the so-called national security exemption from the regulations in Parts 170–189 of Title 49 for shipments of radioactive materials made by or under the direction or supervision of the DOE or the Department of Defense (DoD), and which are escorted by personnel specifically designated by or under the authority of those agencies for the purpose of national security, it remains the DOE's policy to comply with all DOT over-the-road requirements for which no overriding safety or security imperative exists. As noted in 49 CFR 173.7(d), "notwithstanding the requirements of sections 173.416 and 173.417 of this subchapter, packagings made by or under the direction of the U.S. Department of Energy may be used for the transportation of radioactive materials when evaluated, approved, and certified by the Department of Energy against packaging standards equivalent to those specified in 10 CFR Part 71. Packagings shipped in accordance with this paragraph shall be marked or otherwise prepared for shipment in a manner equivalent to that required by this subchapter for packagings approved by the NRC." In simplest terms, DOE maintains full compliance with packaging certification requirements and greatly exceeds NRC's physical protection requirements. DOE's SSTs, however, are exempted from placarding requirements required for hazardous materials shipments. However, additional safety, in the unlikely event of an accident involving an SST, is provided through the use of shipment monitoring and communication from a central control center.

Figure G.2. Safe, secure trailer (SST) and tractor operated by DOE

G.3 Transportation Safety

Over the past two decades, the nuclear energy industry has safely transported more than 45 million packages of radioactive materials across the nation's highways and rail lines. Fewer than 3500 packages (0.008%) have been involved in accidents. Because of stringent regulations covering the packaging, only a few released any radiation. In every case, exposure levels were so low that there was negligible hazard to the public.

Every year, about 100 million packages of hazardous materials are shipped in the United States. Most contain materials that are flammable, explosive, corrosive, or poisonous. Only about 3% contain radioactive materials used for medical, research, and industrial purposes, mostly medical isotopes. For the most dangerous materials, high-level radioactive wastes and spent nuclear fuel, fewer than 100 shipments are made each year.

Safety from radioactive materials during transport is provided by using containers that meet strict requirements. Even low levels of radioactive materials are packaged for shipment in strong, tight containers to protect the radioactive contents under a variety of transportation and accident conditions. Even more stringent requirements are imposed on shipments of highly radioactive materials, such as spent nuclear fuel. Spent fuel must be shipped in thick, stainless steel containers that can withstand the most severe accident conditions. Determination of the type of container needed is a function of the quantity and identity of the radionuclides to be shipped. For shipments containing radionuclides in quantities that exceed the Table of A_1 (for special form) or A_2 (for normal form) values (49 CFR 173.435 or 10 CFR 71, Appendix A), a Type B package is required. Spent fuel casks are Type B packages. For fissile materials, such as plutonium, many different acceptable Type B packages have been certified.

Type B packages are carefully reviewed from design to fabrication before certification for use by either the NRC or DOE. Before certification, the container must meet rigorous engineering and safety criteria and pass a sequence of hypothetical accident conditions that create forces greater than container will experience in actual accidents. Accident tests for Type B packages, administered in sequence, include:

- a 9-m (30-ft) free fall onto an unyielding surface (which is equivalent to a crash into a concrete bridge abutment at 120 mph), followed by
- a puncture test allowing the package to free-fall 1 m (40 in.) onto a steel rod 15 cm (6 in.) in diameter, followed by
- a 30-min exposure at 800°C (1475°F) that engulfs the entire package, followed by
- submergence of that same container under 0.9 m (3 ft) of water for 8 h.

A separate, undamaged container is also subjected to immersion in 15 m (50 ft) of water for 8 h. For certification, a package must not release any of its contents during the hypothetical accident testing.

Figure G.3 shows the accident tests used for Type B packages. Many different containers have been successfully certified as Type B packages for radioactive materials. Each design provides considerable protection from the accidental release of radioactivity. To demonstrate that Type B packages (such as the robust packages used to transport spent nuclear fuel) can withstand a severe accident, DOE has performed a number of accident tests to simulate severe conditions. Figure G.4 shows the results of a severe accident involving crashing a tractor trailer carrying a package prototype into a massive concrete wall at 81 mph. While the truck was totally destroyed, damage to the package was external and superficial. The package remained intact, not releasing any of the material contained within the package. Analyses have shown that the hypothetical regulatory tests simulate literally all the mechanical and 99% of all thermal conditions that could realistically be experienced in the field. And since these hypothetical tests are performed in sequence, it is felt that the maximum level of conservatism has been achieved.

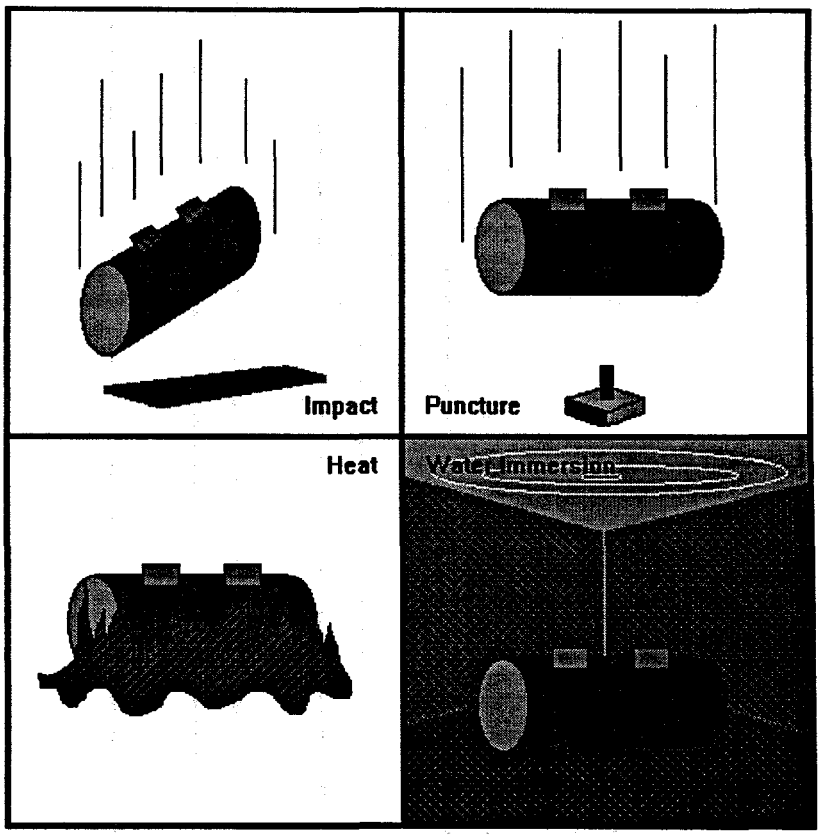

Figure G.3. Accident testing of Type B packages

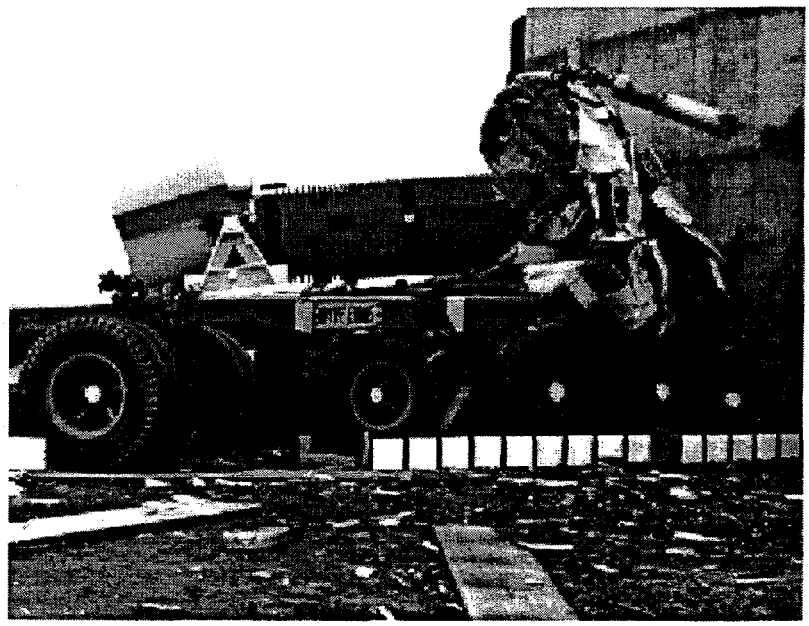

Figure G.4. Spent fuel cask—results of crash testing

G.4 Transportation System

The transportation system, as described below and previously shown in Fig. G.1, will require extensive use of DOE's SST fleet for the transport of all plutonium materials prior to their irradiation in the reactor. The quantity of plutonium to be shipped, in whatever form, has been determined to exceed the definition of strategic special nuclear materials (or Category I). Category I quantities of SNM require the highest level of transport security, using special armored transport vehicles and other measures to ensure security (as specified in 10 CFR Part 73). At present, DOE's SSTs, which exceed the requirements of 10 CFR 73, are the only available capability existing in the U.S. The following sections describe shipment requirements on a leg-by-leg basis.

G.5 Feed Materials Transport Leg

As shown in Fig. G.1, excess fissile materials located at various DOE facilities include pits, clean metal, impure metal, plutonium alloys, clean oxide, impure oxide, U/PuO_2, alloy reactor fuel, oxide reactor fuel, and halide salts and oxides. Due to the variety of materials involved, no single Type B package design is appropriate. Therefore, DOE will utilize a number of different package designs.

Packages. Excess pits from dismantled nuclear weapons under the FMDP will be stored and transported in the Model FL or the newer AT-400A container. The various pits can utilize these containers by using different internal containers. The remaining (nonpit) weapons-grade plutonium is assumed to be in storage at the various DOE facilities. This material is assumed to be stored in a form and storage container that meet the requirements of DOE-STD-3013, *Criteria for the Safe Storage of Plutonium Metals and Oxides*. The criteria state that all plutonium metal and oxides (excluding pits) shall either (a) be sealed in a material container nested in a boundary container (until a primary containment vessel can be used) or (b) sealed in a boundary container nested in a primary containment vessel (PCV). The design goal for the boundary container (like the traditional crimp-sealed "food can") and the PCV storage package is that the entire package should be maintenance free and be either compatible with a common transport package or transportable without additional repackaging.

Historically, DOE has utilized many different configurations of the DOT Specification 6M packages for the transport of plutonium (nonpit) materials. Such configurations, as specified in the *User's Guide for Shipping Type B Quantities of Radioactive and Fissile Material, Including Plutonium, in DOT 6M Specification Packaging Configurations,* DOE/RL-94-68,

September 1994, were approved for use by DOE. The DOT Specification 6M, as defined in 49 CFR 178.354, when used with a DOT Specification 2R inside containment vessel (per 49 CFR 178.360), as a "Specification Package" under DOT regulations is not required to undergo the formal certification process for new package designs. A typical Specification 6M package is shown in Fig. G.5. Figure G.6 shows a schematic of typical Specification 2R inner containers for the 6M package. Under NRC regulations, special requirements for plutonium shipments specify [per 10 CFR 71.63(b)] that plutonium shipments in excess of 20 Ci (approximately 30 g for weapons-grade plutonium) must be shipped as a solid and must be shipped in an separate inner container that is placed within the outer packaging. The separate inner container must be demonstrated to be leak tight (not releasing its contents to a sensitivity of 10^{-6} A_2/h), where values of A_2 are defined in Table A.1 of 10 CRF 71 or the table of A_1 and A_2 values for radionuclides contained in 49 CFR 173.435. Reactor fuel elements and metal or metal alloy forms of plutonium are exempt from this requirement. In terms of the Specification 6M package (including its Specification 2R inside containment vessel), the NRC regulations impose the additional requirement that for dispersible forms of plutonium, such as plutonium oxide, a "double containment" package is required.

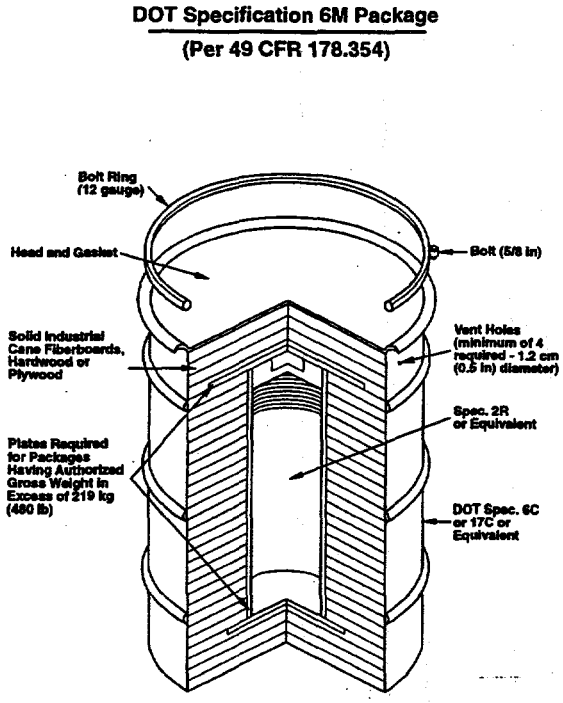

Figure G.5. Schematic of typical DOT Specification 6M package

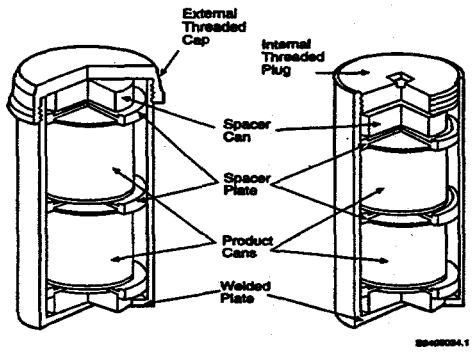

Figure G.6. Schematic of typical 2R inner containers for a Specification 6M package

Many new package designs, utilizing either single and double containments, have been certified for use, or are under development. Figure G.7 shows a cross-section view of the 9975 Package, a double-containment plutonium package developed by Savannah River. The 9975 Package is just one of many new-generation packages that have been developed to provide the double containment necessary for nonmetal or nonalloy plutonium materials. Identification of the actual packages needed to ship the various plutonium materials (feed materials) from the various DOE storage locations to the PuP facility will be performed at some point following the completion of DOE's implementation of the DNFSB's Recommendation 94-1 to stabilize the plutonium materials presently in storage.

G.6 PuO_2 Transport Leg

Following conversion to PuO_2, the PuO_2 will be repackaged (utilizing many of the same packages previously identified above), and shipped to the MOX fabrication plant or to an immobilization or borehole facility depending on whether a hybrid option is chosen. The MOX fabrication plant will operate on a schedule similar to the reactor operation schedule (between 10 and 18 years in most cases). This will require that some of the PuO_2 be placed in a lag storage vault, since the PuP facility is scheduled to operate for only 10 years. The lag storage vault could be accommodated in the design of the MOX fabrication plant design, or DOE could choose to utilize excess vault capacity at another DOE site that would be available.

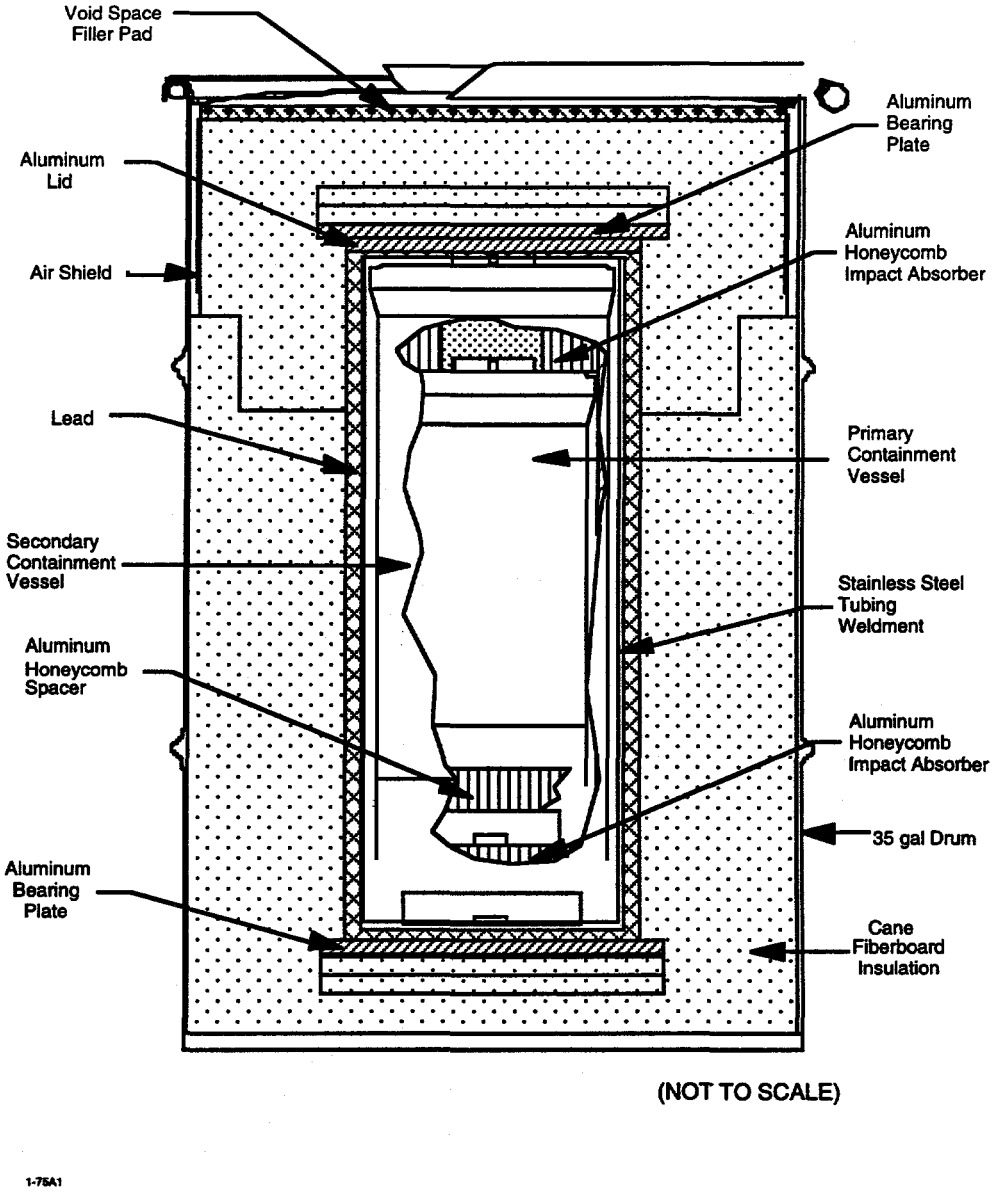

Figure G.7. Cross-section view of 9975 package

Packages. Double-containment plutonium packages would be utilized for shipment of the PuO_2 from the PuP facility to the MOX fuel fabrication facility.

G.7 Fresh MOX Fuel Transport Leg

Over 100,000 CANDU MOX fuel bundles will be fabricated from the 50 MT of PuO_2. The MOX fuel bundles will be shipped from the MOX fuel fabrication facility to the reactor site.

Packages. The CANDU MOX fuel bundles will be shipped in a redesigned and recertified version of the AECL Model 4H package [Certificate of Compliance CDN/4212/B(U)F]. The current Model 4H package holds four MOX CANDU bundles in a stainless steel 55-gal drum. An updated design is assumed to carry seven bundles per package. It is assumed that

24 packages are transported per SST, based on limitations of net payload.

G.8 Spent MOX Fuel Transport Leg

Although beyond the scope of the FMDP, Canadian spent fuel is first stored at the reactor in the spent fuel pool, as shown in Fig. G.8. Later (after approximately 6 to 10 years in wet storage), the spent fuel bundles may be placed in dry storage canisters, as shown in Fig. G.9. Finally, the CANDU spent fuel is loaded into disposal canisters for disposition in the proposed Canadian geologic repository. A representation of the disposal canister is show in Fig. G.10.

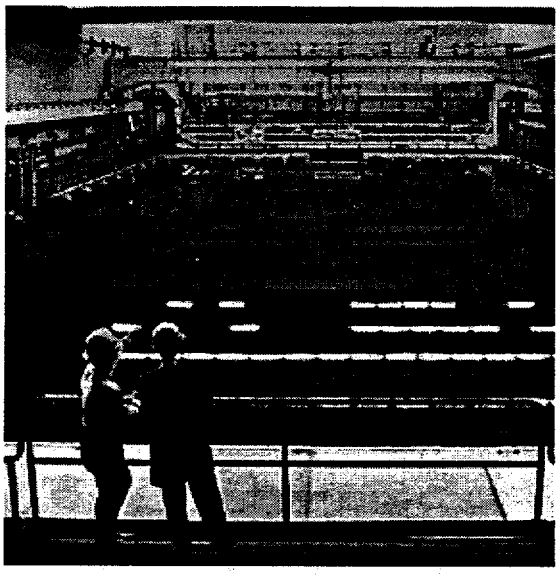

Figure G.8. CANDU wet storage

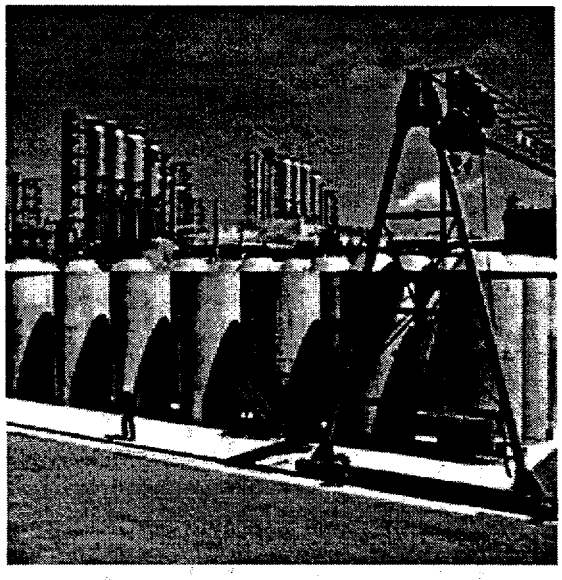

Figure G.9. CANDU spent fuel dry storage canisters

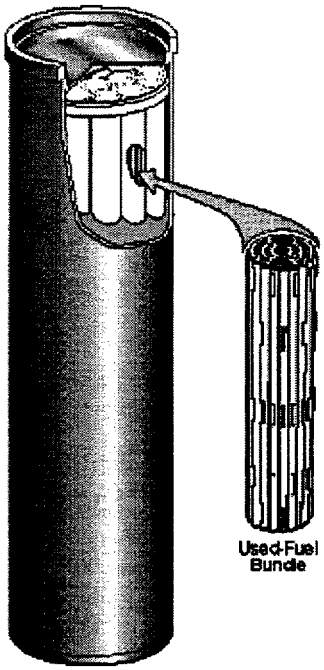

Figure G.10. Representation of Canadian spent fuel disposal container

Appendix H
Glossary

Within DOE, there are many words used in documents that have meanings specific to certain projects or programs. The sources of abbreviations referenced in this glossary are as follows:

ECCDO	"Preliminary Evaluation Criteria for Control and Disposition Options," April 30, 1993, Draft, Surplus Fissile Material Control and Disposition Program Decision Analysis and Development Team
OTA	"Dismantling the Bomb and Managing the Nuclear Materials," OTA-O-572, September 1993, U.S. Congress, Office of Technology Assessment
TI	Defined by Technical Integration, Department 5321, SNL/CA
RAND	"Limiting the Spread of Weapon-Usable Fissile Material"; ISBN: 0-8330-1468-4; 1993; Chow, Brian G., and Solomon, Kenneth A.; RAND's National Defense Research Institute.
NSC	"Agreed Definitions," memorandum from Daniel Poneman, Special Assistant to the President and Senior Director for Nonproliferation and Export Controls, February 18, 1994
GFS	DOE Glossary Fact Sheet, August 29, 1994, Storage & Disposition of Weapons-Usable Fissile Materials
PMBOK	Project Management Institute, Project Management Body of Knowledge, March 28, 1987

Actinides: Radioactive elements with atomic number larger than 88 (i.e., 89 or higher). (Source: OTA)

Alternative: A term used during FMDP Phase II to define a group of pathways through a baseline set of facilities. Currently "alternative" is defined by reactor type. (Source: TI)

Aqueous Process: An operation involving chemicals dissolved in water. (Source: ECCDO)

Architect and Engineering Contractor (AE): The organization responsible for incorporating process and manufacturing technology requirements into the design of facilities. (Source: TI)

Attribute: A measurable relevant characteristic of an option, such as public acceptability or technical risk. (Source: TI and ECCDO)

Boiling Water Reactor (BWR): BWR is a type of LWR whose primary coolant is permitted to boil. The primary loops are typically under about 1000 psi of pressure.

Burn: To consume fissile materials in a reactor through fission. (Source: ECCDO)

Canyon: A remotely operated, heavily shielded plutonium or uranium processing facility. (Source: ECCDO)

Construction Contractor: The organization responsible for construction of new or modified facilities. (Source: TI)

Conversion: An operation for changing material from one form, use, or purpose to another. (Source: ECCDO)

Criticality: Pertaining to a critical mass (the least amount) of fissionable material that can achieve self-sustaining nuclear chain reactions. (Source: OTA)

Curie: A unit of radioactivity equal to that emitted by 1 g of pure radium. (Source: OTA)

Deuterium: An isotope of hydrogen used in the fusion reaction of a nuclear weapon. (Source: OTA)

Disassembly: The process of taking apart a nuclear warhead and removing the subassemblies, components, and individual parts. (Source: OTA)

Discard: To dispose of material as waste. (Source: ECCDO)

Dismantlement: The process of taking apart a nuclear warhead and removing the subassemblies, components, and individual parts. (Source: OTA)

Disposal: The process of placing waste in an interim or final repository. (Source: ECCDO)

Disposition: A process of use or disposal of materials that results in the remaining material being converted to a form that is substantially and inherently more proliferation-resistant than the original form. (Source: GFS)

Dissolution: The chemical dispersal of a solid throughout a liquid medium. (Source: ECCDO)

Fissile: The term "fissile" refers to nuclear materials that are fissionable by both slow (thermal) and fast neutrons. Fissile materials include ^{235}U, ^{233}U, ^{239}Pu, and ^{241}Pu. Materials such as ^{238}U and ^{232}Th, which can be converted into fissile materials, are called fertile materials. It should be noted that ^{232}Th, ^{238}U, and all plutonium isotopes are fissionable by fast neutrons but not by thermal (slow) neutrons. They are not called fissile materials but may be called fissionable materials. The term fissile also refers to material that is able to support nuclear detonation. (Source: RAND and ECCDO)

Fission: Fission occurs when a neutron bombards the nucleus of an atom and causes it to split into fragments and release energy. (Source: RAND)

Fissionable Material: Material whose nuclei fission when bombarded by neutrons. (Source: RAND)

Formerly Restricted Data: Classified information, defined in the Atomic Energy Act, that is shared by DOE and DoD and is related to the military utilization of nuclear weapons or energy. Decisions to declassify such data must be agreed upon by both agencies. (Source: OTA)

Fuel Grade: Plutonium with a plutonium concentration of 7 to 19%. (Source: ECCDO)

Hazardous Material: A substance that poses a risk to health, safety, and property.

Hazardous Waste: Waste that includes toxic materials, reactives, corrosives, flammables, and explosives. These materials can damage living tissue; they can pose a variety of health hazards and cause a wide range of effects.

Heavy Metal: Heavy metal refers to all the isotopes of Th, U, Np, Pu, Am, and Cm. (Source: RAND)

High-Level Waste (HLW): Highly radioactive waste material from the reprocessing of spent nuclear fuel (including liquid waste produced directly in reprocessing and any solid waste derived from the liquid) that contains a combination of transuranic waste and fission products in concentrations requiring permanent isolation. DOE is responsible for disposing of all HLW in the United States. HLW is highly radioactive and must be handled from behind heavy protective shielding. (Source: OTA)

Highly Enriched Uranium (HEU): Uranium enriched in the isotopic content of ^{235}U to greater than 20%, a concentration range usable for nuclear weapons. (Source: OTA and ECCDO)

Interagency Working Group on Plutonium Disposition (IWG): An interagency group established by the president to conduct a comprehensive review of the options for disposing of surplus plutonium from nuclear weapons activities of the United States and the former Soviet Union.

Interim Storage: Safe, controlled, inspectable storage facilities and conditions that will be established in the near term and will remain in effect until the long-term storage or disposition actions are implemented.

Light-Water Reactor (LWR): There are two types of LWRs. One is a pressurized-water reactor (PWR) and the other is a boiling-water reactor (BWR). Both are thermal reactors. All commercially operating reactors in the United States and most commercial reactors worldwide are LWRs. (Source: RAND)

Light-Water Reactor (Full MOX Fuel): An LWR with full MOX fuel is fueled with fuel rods, each containing a mixture or blend of UO_2 and PuO_2. Traditional programs of using plutonium in LWRs use partial, not full, MOX fuel. (Source: RAND)

Light-Water Reactor (Partial MOX Fuel): An LWR with partial MOX fuel contains some fuel rods that are blended with UO_2 and PuO_2 and some that are just UO_2. The blended uranium and plutonium oxides typically account for one-third of the total number of fuel rods. (Source: RAND)

Low-Enriched Uranium (LEU): Naturally occurring uranium contains only about 0.7% ^{235}U and almost all of the rest is ^{238}U. LEU is enriched in the isotopic content of ^{235}U, greater than 0.712% but less than 20% of the total mass, for use as LWR fuel. (Source: OTA, ECCDO, and RAND)

Low-Level Waste (LLW): Radioactive waste not classified as high-level waste, transuranic waste, spent nuclear fuel, or by-product material. (Source: OTA)

Management and Operating (M&O) Contractor: The organization responsible for production of weapons material, components, or assembly operations. (Source: TI)

Metal: Plutonium ingots or buttons that have not been fabricated into parts. (Source: ECCDO)

Mixed Oxide (MOX): MOX refers to a physical blend of UO_2 and PuO_2. (Source: RAND)

Mixed Waste: Waste that is a combination of radioactive and hazardous materials. DOE production of materials for nuclear weapons has generated both radioactive and hazardous waste and often contaminated the production facility or site.

More specifically, the Federal Facility Compliance Act (FFCA) of 1992 defines mixed waste as containing both hazardous waste and source, special nuclear, or by-product material subject to the Atomic Energy Act. Therefore, the term "mixed waste" does not include all hazardous waste containing radionuclides. For example, it does not include hazardous waste containing naturally occurring or accelerator produced radioactive material.

Natural Uranium: Uranium with ^{235}U concentration of 0.711%, the average concentration of ^{235}U in uranium in the natural, pre-enriched state. (Source: ECCDO)

Neutron Absorber: The excess reactivity (and hence the number of control rods), which must be included in a reactor to obtain a desired lifetime, can be reduced by the use of a neutron absorber. This is an isotope having a large-absorption cross section, which is converted to an isotope of low-absorption cross section as the result of neutron absorption. The increase in reactivity due to the burnup of this neutron absorber compensates to some extent for the decrease in reactivity due to fuel burnup and the accumulation of fission-product poisons.

Operations Office: The on-site DOE organization responsible for management and oversight of production facilities, M&O contractors, and DOE laboratories. (Source: TI)

Option: Term used during FMDP screening process to define a group of related alternative pathways through a specific set of facilities that takes surplus fissile material to complete disposition. (Source: TI) See Alternative.

Oxidation: A chemical reaction in which, typically, an oxide is formed. (Source: ECCDO)

Oxide: A compound in which an element (such as plutonium) is bonded to oxygen. (Source: ECCDO)

Plutonium Pit: The core element of a nuclear weapon's "primary" or fission component. Pits are made of weapons-grade plutonium, principally ^{239}Pu, and surrounded by some type of casing. (Source: OTA)

Plutonium: Man-made element produced when uranium is irradiated in a reactor. Plutonium-239 is the most suitable isotope for constructing nuclear weapons. (Source: OTA)

Pressurized-Water Reactor (PWR): A PWR is a type of LWR whose primary coolant is not permitted to boil. The primary loops are typically under about 2000 psi of pressure. (Source: RAND)

Process: To extract, separate, or purify a substance by physical or chemical means (e.g., to remove actinides). (Source: ECCDO)

Proliferation: The spread of nuclear, biological, and chemical capabilities and the missiles to deliver them. (Source: NSC)

Rad: Radiation absorbed dose, a basic unit of absorbed dose of ionizing radiation representing an amount of energy absorbed per unit of absorbing material, such as body tissue. (Source: OTA)

Radioactive Waste: Any waste material or combination of waste materials (solid, liquid, or gaseous) that contain radionuclides regulated under the Atomic Energy Act.

Radionuclide: Certain natural and man-made atomic species with unstable nuclei that can undergo spontaneous breakup or decay and, in the process, emit alpha, beta, or gamma radiation. (Source: OTA)

Reactor-Grade: Plutonium with a ^{240}Pu concentration greater than 19%. (Source: ECCDO)

Recast: The process of melting metal and casing into a mold. (Source: ECCDO)

Record of Decision (ROD): A concise public document, issued no sooner than 30 d after completion of a final environmental impact statement or programmatic environmental impact statement, stating the agency's decision on the proposed action evaluated in the document. The ROD is not considered to be an environmental document since the decision may consider other factors in addition to environmental ones.

Rem (roentgen equivalent, man): Unit of biological dose equivalent. The dose equivalent in "rem" is numerically equal to the absorbed dose in "rad" multiplied by necessary modifying factors. (Source: OTA)

Reprocessing: The chemical separation of spent reactor fuel into uranium, transuranic elements, and fission products. (Source: GFS)

Residue: Recoverable by-product from a manufacturing or purification process. (Source: ECCDO)

Restricted Data: Classified information defined by the Atomic Energy Act. Restricted Data are born classified, regardless of source. (Source: OTA)

Special Nuclear Materials (SNM): As defined in the Atomic Energy Act," 'special nuclear materials' means (1) plutonium, uranium enriched in the isotope U^{233} or in the isotope U^{235}, and any other material which the Commission . . . determines to be special nuclear material, but does not include source material . . ." (Source: OTA)

Spent Fuel Standard (SFS): A disposal standard whereby weapons-usable plutonium is made as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in spent fuel from commercial reactors. (Source: FMDP)

Spent Fuel: Irradiated reactor fuel that is no longer useful as fuel. (Source: ECCDO)

Stabilize: To convert a compound, mixture, or solution to a nonreactive form. (Source: ECCDO)

Staging: An interim storage or gathering of items awaiting use, transportation, consumption, or other disposition. (Source: ECCDO)

Storage: Any method of keeping items while awaiting use, transportation, consumption, or other disposition. (Source: ECCDO)

Stored Weapon Standard: A level of security and accountability that is equivalent to that afforded a stored nuclear weapon. (Source: TI)

Technology: A specific technical component that is a subset of a facility (e.g., glass melter and feed preparation technology might fall under vitrification of plutonium in borosilicate glass). (Source: ECCDO and TI)

Transparency: Exchange of information, access to facilities, and cooperative arrangements undertaken to provide ready observation and verification of defense or other activities. (Source: OTA)

Transuranic: Any element whose atomic number is higher than that of uranium. All transuranic elements are produced artificially and are radioactive. (Source: OTA)

Treatment: An operation necessary to prepare material for disposal. (Source: ECCDO)

Tritium: A radioactive gas, an isotope of hydrogen, that serves as a booster for the fusion reaction in the secondary component of a nuclear weapon. (Source: OTA)

Variant: Term used to define a different specific set of facilities within a baseline alternative.

Vitrification: Process of immobilizing radioactive material by encapsulating it into a glasslike solid. (Source: OTA)

Warhead: Explosive part of a nuclear weapons system. Warheads consist of nuclear materials, conventional high explosives, and related firing mechanisms. (Source: OTA)

Waste: A discardable residue from a manufacturing or purification process. (Source: ECCDO)

Weapons-Grade: Plutonium with a ^{240}Pu concentration less than 7%. (Source: ECCDO)

Weapons-Usable Fissile Materials: A specific set of nuclear materials that may be utilized in making a nuclear explosive for a weapon. Weapons-usable fissile materials include uranium with ^{235}U isotopic content of 20% or more, ^{235}U, plutonium of any isotopic composition, and other special nuclear materials. The term "weapons-usable fissile materials" does not include the fissile materials present in spent nuclear fuel or irradiated targets from reactors.

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