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ATOMIC ENERGY
OF CANADA LIMITED

L'ENERGIE ATOMIQUE
DU CANADA, LIMITEE

SECOND INTERIM ASSESSMENT OF THE CANADIAN CONCEPT FOR NUCLEAR FUEL WASTE DISPOSAL

VOLUME 2: BACKGROUND

DEUXIEME EVALUATION INTERIMAIRE DU CONCEPT CANADIEN D'EVACUATION DES DECHETS DE COMBUSTIBLE NUCLEAIRE

VOLUME 2: ETAT DE LA QUESTION

P. A. Gillespie, D. M. Wuschke, V. M. Guvanasen, K. K. Mehta,
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Whiteshell Nuclear Research Establishment

Etablissement de recherches nucléaires de Whiteshell

Pinawa, Manitoba R0E 1L0

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DEUXIÈME ÉVALUATION INTÉRIMAIRE DU CONCEPT CANADIEN
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RÉSUMÉ

Le concept d'évacuation des déchets de combustible nucléaire retenu à des fins de développement et d'évaluation au Canada intéresse le stockage de conteneurs anticorrosifs de déchets dans une enceinte située à grande profondeur dans la roche plutonique du bouclier canadien. À mesure du développement du concept et des outils d'évaluation, on effectue des évaluations périodiques afin de permettre l'analyse de la méthodologie et d'assurer un retour d'information à ceux qui développent le concept. Le but ultime de ces évaluations consiste à prédire l'impact qu'aurait le système d'évacuation si le concept était mis en oeuvre.

La deuxième évaluation a eu lieu en 1984 et est documentée dans les suivants:

Deuxième évaluation intérimaire du concept canadien d'évacuation des déchets de combustible nucléaire
Volume 1: Sommaire
Volume 2: État de la question
Volume 3: Évaluation avant fermeture
Volume 4: Évaluation après fermeture

Dans le présent volume, intitulé État de la question, on examine les déchets de combustible nucléaire du Canada et les caractéristiques souhaitables d'une méthode d'évacuation des déchets. On décrit plusieurs options d'évacuation actuellement à l'étude dans un certain nombre de pays, dont l'option retenue à des fins de développement et d'évaluation au Canada. On décrit les systèmes d'évacuation de référence supposés être adoptés pour la deuxième évaluation et on traite brièvement du mode d'évaluation du concept.

L'Énergie Atomique du Canada, Limitée
Établissement de recherches nucléaires de Whiteshell
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ABSTRACT

The nuclear fuel waste disposal concept chosen for development and assessment in Canada involves the burial of corrosion-resistant containers of waste in a vault located deep in plutonic rock in the Canadian Shield. As the concept and the assessment tools are developed, periodic assessments are performed to permit evaluation of the methodology and provide feedback to those developing the concept. The ultimate goal of these assessments is to predict what impact the disposal system would have if the concept were implemented.

The second assessment was performed in 1984 and is documented in

Second Interim Assessment of the Canadian Concept for Nuclear Fuel Waste Disposal
Volume 1: Summary
Volume 2: Background
Volume 3: Pre-Closure Assessment
Volume 4: Post-Closure Assessment

This volume, entitled Background, discusses Canadian nuclear fuel wastes and the desirable features of a waste disposal method. It outlines several disposal options being considered by a number of countries, including the option chosen for development and assessment in Canada. The reference disposal systems assumed for the second assessment are described, and the approach used for concept assessment is discussed briefly.

Atomic Energy of Canada Limited
Whiteshell Nuclear Research Establishment
Pinawa, Manitoba ROE 1LO
1984 December

AECL-8373-2

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF METRIC UNITS

The units used in this volume conform to the standard specified in the Canadian Metric Practice Guide (Canadian Standards Association 1979), which is a guide for the application of the International System of Units. In this report, negative powers are used to express compound units formed by division. For example, $mSv.a^{-1}$ means millisievert per year.

SYMBOL	UNIT NAME
a	year
Bq	becquerel
cm	centimetre
Gg	gigagram
GJ	gigajoule
GW	gigawatt
GW(e)	gigawatt electric
Gy	gray
h	hour
J	joule
kg	kilogram
kg(U)	kilogram of uranium
km	kilometre
m	metre
man-Sv	man-sievert
Mg	megagram
Mg(U)	megagram of uranium
mm	millimetre
mSv	millisievert
MW(e)	megawatt electric
Sv	sievert
W	watt

CONVERSION FACTORS

1 Bq = 2.7×10^{-11} curies
1 Gy = 100 rads
1 Sv = 100 rems

FOREWORD

The Canadian Nuclear Fuel Waste Management Program was established in 1978 to develop storage and disposal concepts which, if implemented, would ensure that nuclear fuel waste would not have any significant adverse effects on man or the environment. To achieve this goal, research is being conducted by Atomic Energy of Canada Limited; Ontario Hydro; Energy, Mines and Resources Canada; Environment Canada; scientists at Canadian universities; and consultants in the private sector. Most of the research involves developing, and assessing, the concept of isolating containers of nuclear fuel waste in a vault located deep in plutonic rock in the Canadian Shield.

The second interim assessment was performed in 1984 and is documented in a four-volume report, of which this is Volume 2. The other volumes in the report are:

Volume 1: Summary (Gillespie et al. 1984)
Volume 3: Pre-Closure Assessment (Johansen et al. 1984)
Volume 4: Post-Closure Assessment (Wuschke et al. 1984)

The major supporting documents are

Preliminary Environmental Assessment of the Canadian Nuclear Fuel Waste Management Concept: Pre-Closure Phase (Gee et al. 1983)

Nuclear Fuel Waste Management Concept: Preliminary Safety Assessment of the Pre-Closure Phase (Nathwani 1983)

Reference Environment for Pre-Closure Environmental and Safety Assessments (Gee 1983)

Radiological Pathway Analysis for Chronic Radioactive Emissions and Normal Transport of Irradiated Fuel for the Nuclear Fuel Waste Disposal Centre: Pre-Closure Phase (Green and Donnelly 1983)

Preliminary Social Impact Assessment of a Nuclear Fuel Waste Management Centre - Concept Assessment (Stevenson 1983)

Preliminary Social Impact Assessment: Transportation Component of a Long-Term Irradiated Fuel Management Program (Rogers and Hardy 1983)

Preliminary Occupational Safety Assessment Relating to the Nuclear Fuel Waste Management Program (Velshi 1981)

SYVAC2 - A Systems Variability Analysis Code for Assessment of Nuclear Fuel Waste Disposal Concepts (Sherman 1985)

Vault Submodel for the Second Interim Assessment of the Canadian Concept for Nuclear Fuel Waste Disposal: Post-Closure Phase (LeNeveu 1984)

Geosphere Submodel for the Second Interim Assessment of the Canadian Concept for Nuclear Fuel Waste Disposal: Post-Closure Phase (Heinrich 1984)

Biosphere Submodel for the Second Interim Assessment of the Canadian Concept for Nuclear Fuel Waste Disposal: Post-Closure Phase (Mehta 1984a)

LIMCAL: A Comprehensive Food Chain Model for Predicting Radiation Exposure to Man in Long-Term Nuclear Waste Management (Zach 1982)

Confidence Bounds on an Empirical Cumulative Distribution (Andres 1984)

Proposed Risk Acceptance Criterion for Nuclear Fuel Waste Disposal (Mehta 1984b)

The first assessment was performed in 1981 and was documented in the following report:

Environmental and Safety Assessment Studies for Nuclear Fuel Waste Management
Volume 1: Background (Lyon et al. 1981)
Volume 2: Pre-Closure Assessment (Johansen et al. 1981)
Volume 3: Post-Closure Assessment (Wuschke et al. 1981)

A third assessment is scheduled for 1986. A fourth assessment of the concept will be completed in 1988, at which time it will be reviewed by regulatory and environmental agencies, and later at a public hearing.

Comments on this document, and inquiries concerning the Canadian Nuclear Fuel Waste Management Program may be directed to The Director, Waste Management Division, Whiteshell Nuclear Research Establishment, Pinawa, Manitoba ROE 1LO.

1. INTRODUCTION

In Canada, nuclear reactors are currently being used to produce heat for the generation of electricity at stations in Ontario, New Brunswick, and Quebec. When used fuel is removed from these reactors, it is stored at the reactor sites in monitored facilities. These facilities provide cooling, radiation shielding, and containment for the used fuel.

At present, used fuel is not considered a waste because it contains plutonium, which can also be used as a reactor fuel. If a decision is made to recycle used fuel, the plutonium, and probably the uranium, would be removed, leaving fuel recycle waste. If a decision is made not to recycle the fuel, then the used fuel would be considered as a waste.

These two kinds of waste, collectively known as nuclear fuel waste, would be radioactive for thousands of years, far longer than social and institutional stability can be assumed to continue. Therefore, it is considered that monitored storage is only an interim waste management approach; it must eventually be followed by permanent disposal, that is, isolation of the waste from man and the environment with no intention of retrieval, so that future generations will not be burdened with the reponsibility for monitoring and maintenance.

The disposal concept receiving most of the research effort in Canada involves the burial of corrosion-resistant containers of nuclear fuel waste in a vault located deep in plutonic rock in the Canadian Shield. As defined by Atomic Energy of Canada Limited (AECL), adequate development of this concept and preparation for its formal evaluation will require the development of four basic capabilities:

(1) the capability to construct a disposal vault designed to protect man and the environment from the harmful effects of nuclear fuel wastes;

(2) the capability to reliably predict disposal vault performance, contaminant migration, and potential hazard, by using computer models of the vault and the various pathways to man;

(3) the capability to maximize the benefits and minimize the adverse effects of the environmental and social impacts of the disposal system in the pre-closure period; and

(4) the capability to ensure the safety of the workers and the public during the pre-closure period.

To develop these capabilities, AECL coordinates and participates in an extensive generic research and development program that is directed from its Whiteshell Nuclear Research Establishment in Manitoba. The program involves the study of fundamental processes and the development and assessment of a generic disposal concept. This means that data from several locations are used, and a range of design options is considered. Research results are reviewed by government regulatory and environmental agencies, independent scientists, and interested members of the public. Moreover, the entire research program is continuously reviewed by the Technical Advisory Committee to Atomic Energy of Canada Limited on the Nuclear Fuel Waste Management Program (Technical Advisory Committee 1980, 1981, 1982, 1983, 1984), whose members are distinguished Canadian scientists nominated by their respective professional societies.

Both the generic research and the external review will continue until the four basic capabilities have been developed. At that time, AECL will prepare a formal concept assessment document (as distinct from the present, interim, documents) that will describe the proposed concept, present evidence of sufficient capability in the four areas listed above, and provide an assessment of the concept to indicate the impacts it might have on man and the environment if it were implemented; this document is expected to be ready for review by 1988.

Evaluation of the concept is expected to proceed in three stages. During the first stage, the formal concept assessment document will be analyzed by the Atomic Energy Control Board (AECB), in consultation with the Interagency Review Committee, whose members are representatives of the AECB, Environment Canada, and the Ontario Ministry of the Environment. The AECB will determine whether the concept meets all the regulatory guidelines and criteria, and its analysis will be made available to the public, as well as to governments. During the second stage, a public hearing will be held, which will result in recommendations to the AECB on the acceptability of the concept and the concept assessment. The third stage will comprise a decision by governments, based on the AECB's, recommendations, on the acceptability of the concept. Only if the concept is accepted by governments would selection of a disposal site be considered.

As part of the preparation for concept evaluation, interim assessments are performed to permit evaluation of assessment tools and skills, and to provide feedback to the research and developoment program. Two such assessments have been performed, and they are included in the reports listed in the Foreword. This volume is part of the documentation for the second assessment. Comments on the first assessment were recorded, along with the actions that resulted. Comments on the second assessment are invited, and will be recorded and acted upon in a similar way.

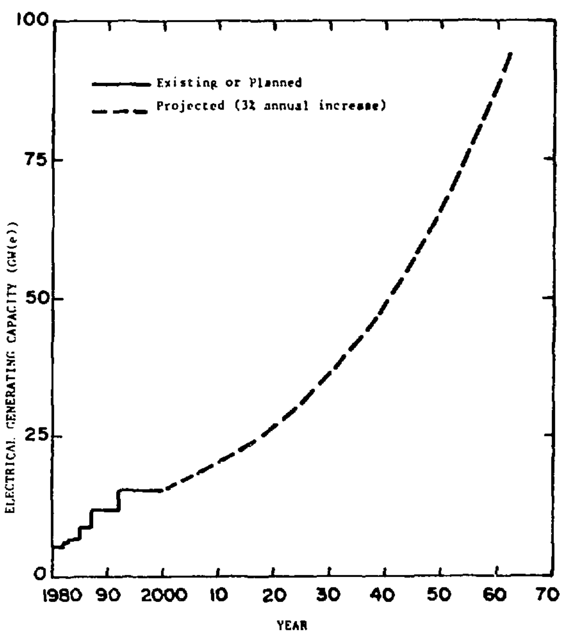
This background volume describes Canadian nuclear fuel waste and the desirable features of a waste disposal method. It outlines several disposal options being considered by a number of countries, including the option chosen for development and assessment in Canada: disposal in plutonic rock. The reference disposal systems assumed for this second assessment are described, and an overview of the concept assessment process is given. Technical terms are defined in the Glossary.

2. NUCLEAR FUEL WASTE

2.1 USED FUEL

2.1.1 Production and Storage of Used Fuel

In 1962, nuclear energy was first used to generate electricity in Canada at the Nuclear Power Demonstration (NPD) station at Rolphton, Ontario. Since then, three more nuclear power stations have been built in Ontario and one each in New Brunswick and Quebec, bringing the current nuclear-electric generating capacity in Canada to about 8000 MW(e). Three additional nuclear power stations now under construction in Ontario will be in operation within the next ten years. The generating capacity of these Canadian stations is listed in Table 1. If, as planned, no further nuclear power stations are built before the year 2000, and if the annual growth rate of nuclear electricity is 3% thereafter, then the nuclear capacity in Canada between 1970 and 2060 would be as shown in Figure 1.



Nuclear energy provides the province of Ontario with about 35% of its electricity and is projected to contribute 60 to 70% by the end of the century. By this time, Canada's net nuclear electrical generating capacity (provided mostly by Ontario stations) is planned to be about 15 GW, which would constitute approximately 20% of the electricity required in Canada. If the nuclear electric generating capacity in Canada increases annually by 3% after the year 2000, then it would approximately double by the year 2025 and would reach about 75 GW by the year 2055. Such projections aid in predicting the amount of fuel waste that will have to be disposed of.

FIGURE 1: Canada's Net Nuclear Electrical Generating Capacity

TABLE 1

CANADIAN NUCLEAR POWER STATIONS

Name	Location	Net Power* (MW(e))	In-Service Date
NPD	Ontario	(20)+	1962
Douglas Point	Ontario	(210)+	1967
Pickering A	Ontario	520 x 4 = 2 080	1971-73
Bruce A	Ontario	740 x 4 = 2 960	1977-79
Point Lepreau	New Brunswick	630	1982
Gentilly 2	Quebec	640	1983
Pickering B	Ontario	520 x 4 = 2 080	1983-85
Bruce B	Ontario	760 x 4 = 3 040	1984-87
Darlington	Ontario	880 x 4 = 3 520	1988-92
Total Nuclear Power by the year 2000+		14 950	

*Net power is approximately equal to gross power/1.05.
+Power from the NPD and Douglas Point reactors is not included in the total, because of plans to decommission these reactors during the 1980's.

The reactor developed and used in Canada for electricity production is called the CANDU (CANada Deuterium Uranium) because its moderator is heavy water (water in which hydrogen is replaced by deuterium) and its fuel is natural uranium. The fuel is in the form of uranium dioxide pellets that are sealed inside Zircaloy tubes, which are assembled into a fuel bundle (see Figure 2). A typical bundle for a Pickering reactor contains about 20 kg of uranium (Canadian Nuclear Association 1976).

When bundles of used fuel are removed from the reactors, they are stored in water-filled bays at the reactor sites. These bays have reinforced concrete walls approximately 2 m thick, and are lined with stainless steel or fibreglass-reinforced epoxy paint (Boulton 1978). The water provides both cooling and shielding for the fuel. Continual monitoring and surveillance are maintained to ensure that there is no hazard to man or the environment. This storage method is used around the world, and has been used at research and power reactor sites in Canada for over 30 years (Boulton 1978).

The core of a CANDU reactor contains uranium fuel in the form of uranium dioxide pellets that are encased in bundles of Zircaloy tubes. The amount of uranium in the core varies with the power of the reactor. In a Pickering reactor, there are about 92 Mg of uranium in approximately 4700 fuel bundles. A typical fuel bundle stays in the reactor for about 585 days. While in the reactor, it produces about 13 000 GJ of energy.

FIGURE 2: CANDU Fuel Bundle

Another interim storage method involves the containment of used fuel in concrete canisters constructed above ground. This method has been used at the Whiteshell Nuclear Research Establishment since early 1976 (Ohta 1978). It is an economical way of storing used fuel after a five-year preliminary cooling period in water, because it generates less secondary waste and requires less maintenance than wet storage. As this dry storage method is still being tested, it is not yet being used at any nuclear power stations in Canada.

Table 2 lists the rate of accumulation and inventory of used fuel in storage bays at Canadian nuclear power stations as of 1983 January 1, and the predicted inventory at 2000 January 1. The used fuel generated by research reactors and by the Gentilly-1 reactor are not included in Table 2, as it comprises, at present, only about 1% of the total, and this fraction will decrease with time.

TABLE 2

USED FUEL IN CANADA

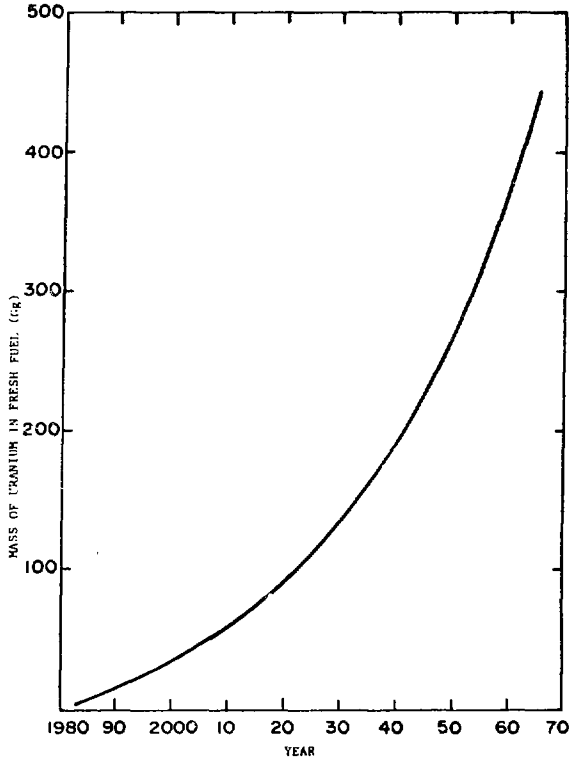
Nuclear Power Station	Rate of Accumulation $(Mg(U).a^{-1})$*	Mass Accumulated by 1983 Jan.1 (Mg(U))*	by 2000 Jan.1 (projected) (Mg(U))*
NPD**	negligible	80	100
Douglas Point**	20	250	300
Pickering A**	260	2 800	7 200
Bruce A**	440	2 000	9 300
Point Lepreau***	80	0	1 300
Gentilly 2***	80	0	1 300
Pickering B**	270	0	4 100
Bruce B**	430	0	6 000
Darlington**	460	0	4 300
	2 040	5 130	33 900

* Used fuel inventory in terms of initial uranium in fuel.

** Estimates based on unpublished data of Ontario Hydro, Toronto.

*** Estimates based on the ratio of rate of accumulation to installed capacity for other CANDU reactors.

Figure 3 shows the projected cumulative used fuel in Canada to the year 2065, starting with the inventory of about 5100 Mg uranium that was in storage on 1983 January 1. The data given in Table 2 and Figure 3 are based on the same assumptions used in calculating the planned and projected nuclear capacities of Figure 1.



At the end of 1982, the used fuel inventory in Canada was approximately 5100 Mg. The projected inventory of used fuel is based on the planned and projected nuclear electrical generating capacity shown in Figure 1. On this basis it is estimated that there will be more than 100 Gg of used fuel in Canada by the year 2025, and more than 300 Gg by the year 2060. Such predictions assist in determining capacity requirements for a disposal vault.

FIGURE 3: Projected Cumulative Used Fuel in Canada

2.1.2 Properties of Used Fuel Bundles

Nuclear fuel bundles change very little in appearance while in the reactor; both the fuel pellets and the Zircaloy tubes retain their solid forms. Almost 99% of the original uranium is unchanged, but significant changes do occur in the remaining 1%. These changes are due to neutron absorption, which results in the production of a large variety of radionuclides. These fall into two categories: actinides and fission products. Small amounts of radionuclides are also produced in the fuel bundles by neutron activation of fuel impurities, Zircaloy fuel sheaths, and other bundle components.

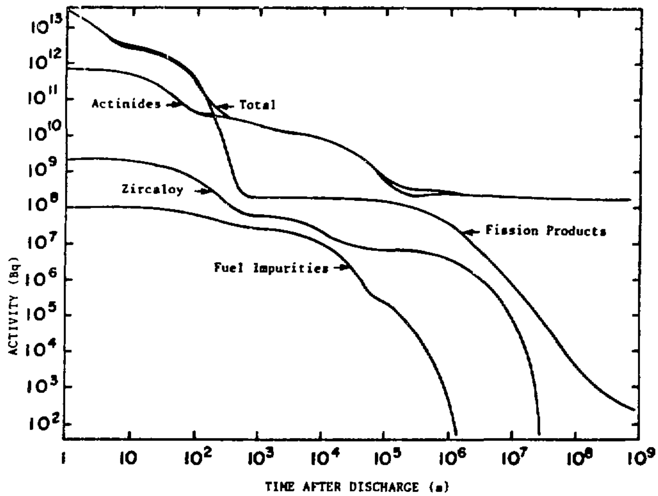
Table 3 lists the quantities of naturally occurring uranium, other actinides, and fission products in typical CANDU fuel bundles. Quantities of activation products arising from Zircaloy and fuel impurities are also listed. A more complete description, including the amount of each radionuclide present in used fuel, is given by Mehta (1982).

TABLE 3
COMPOSITION OF A TYPICAL PICKERING FUEL BUNDLE

Constituent	Grams per Kilogram of Initial Uranium Fresh Fuel	Grams per Kilogram of Initial Uranium Used Fuel*
Naturally Occurring Uranium		
^{238}U	992.9	985.5
^{235}U	7.1	2.3
^{234}U	0.05	0.04
Other Actinides		
^{239}Pu	0.0	2.6
Other Pu isotopes	0.0	1.2
^{236}U	0.0	0.7
Other elements	0.0	0.04
Fission Products		
Stable	0.0	6.5
Active	0.0	1.1
Zircaloy Activation Products	0.0	0.07
Activation Products of Fuel Impurities	0.0	0.0004

*Assuming a burnup of 650 $GJ.(kg(U))^{-1}$ and a cooling time of 0.5 a.

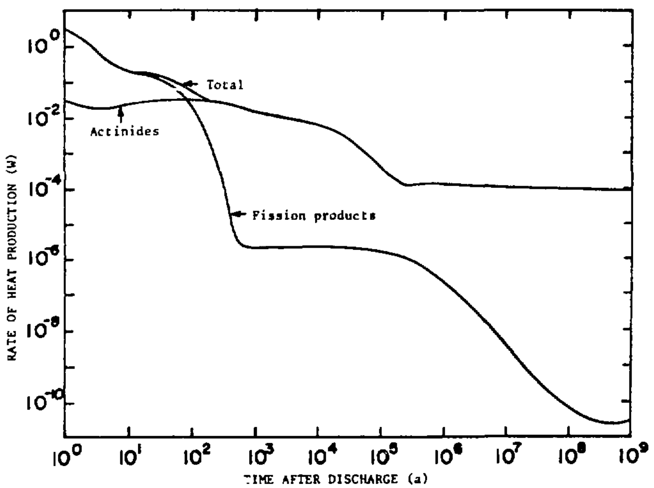
The fuel is intensely radioactive when it is discharged from the reactor, but decay causes the activity to decrease by a factor of 50 in the first year, 500 in 10 years, and 50 000 in 300 years (Clegg and Coady 1977). Most of this initial radiation is produced by the fission products, the majority of which have short half-lives. After 300 years, most of the radiation is produced by the actinides with long half-lives (see Figure 4).



When a fuel bundle is discharged from a reactor, it is intensely radioactive. Two major groups of radionuclides contribute to this radioactivity: the long-lived actinides, which are largely alpha emitters, and the shorter-lived fission products, which are largely beta emitters. Minor contributors are the activation products of Zircaloy (fuel sheath and bundle structural material) and the activation products of the fuel impurities. Radioactivity decreases rapidly during the first few hundred years, when fission products are the major contributors, and decreases more slowly thereafter, when the actinides are the major contributors.

FIGURE 4: Radioactivity of Pickering Used Fuel per Kilogram of Initial Uranium

Radioactive decay produces heat in used fuel, but the rate of heat production decreases by a factor of 30 in the first year and continues to decrease thereafter (see Figure 5).



Radioactive decay produces heat in used fuel bundles. The radioactivity of used fuel, and thus the rate of heat production, decrease with time and eventually reach a steady value about 1 000 000 years after discharge.

FIGURE 5: Rate of Heat Production in Used CANDU Fuel per Kilogram of Initial Uranium (from data produced by the revised CANIGEN code (Clegg and Coady 1977))

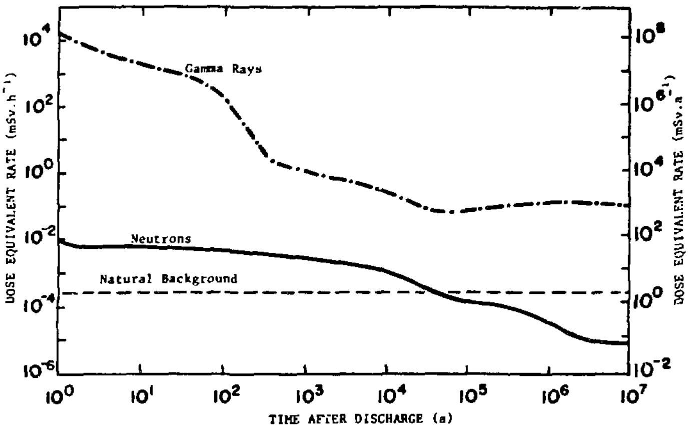
Radionuclides eventually decay into stable nuclides, some of which are chemically toxic. These include isotopes of lead and barium, arsenic, selenium, silver, cadmium, and antimony, whose inventories in used fuel are given by Mehta (1982).

2.1.3 Potential Hazards of Used Fuel

Used fuel emits ionizing radiation, which is potentially harmful to living organisms. A very large dose of this radiation to the whole body in a short time could destroy so many cells that death would result. A large dose to a localized area could cause damage leading to scarring or illness. Even small amounts of ionizing radiation could result in harmful effects many years after the time of exposure. If radiation damages the parts of a cell that control its growth or behavior, the cell may multiply out of control and cancer may develop. If radiation damages a sperm or egg cell that later develops into a fetus, hereditary defects may occur. According to the International Commission on Radiological Protection (ICRP), about 12 to 13 cancer deaths and a similar number of future genetic defects are produced by a radiation dose of 1000 man-Sv (ICRP 1977a, ICRP 1977b). About four of the genetic defects are produced in the first two generations (ICRP 1977a).

The dose equivalent that could potentially be received from the radionuclides in used fuel would depend on the level of radioactivity, the type of radiation emitted (alpha, beta, gamma, or neutron), and on whether the radioactive source was inside or outside the body. Alpha particles are only hazardous if ingested or inhaled, and beta particles are most hazardous when the source is internal. Both gamma rays and neutrons are hazardous to man whether their source is inside or outside the body.

The dose from an external source also depends on the distance from the source and the amount of shielding. The undamaged Zircaloy tubing of used fuel bundles stops the alpha and most of the beta particles, so only gamma rays and very small amounts of neutrons emerge from the bundles. At a distance of 36 cm from the bundle, these give rise to the dose equivalent rates shown in Figure 6. For comparison, the natural background dose equivalent rate of about 1.8 $mSv.a^{-1}$ (equivalent to about 2×10^{-4} $mSv.h^{-1}$) is shown.



Almost all alpha particles and a large majority of beta particles emitted by used fuel are stopped within the bundle itself. However, gamma radiation and neutrons emerge from fuel bundles and can cause an external radiation dose. As the radioactivity of the bundle decreases, the dose rates also decrease. These rates can be compared with that due to natural background radiation, which is caused by natural sources such as cosmic rays and naturally occurring radionuclides in the earth's crust, in the air, and in the body.

FIGURE 6: External Dose Equivalent Rate from a Pickering Fuel Bundle at a Distance of 36 cm in Air (McKean 1978)

The dose from an internal source depends on whether the source was ingested or inhaled, the path of assimilation in the body, the distribution among and within different organs, and the rate of elimination from the body.

2.2 FUEL RECYCLE WASTE

2.2.1 Production of Fuel Recycle Waste

In Canada, used fuel is not presently reprocessed for recycling. If recycling is adopted in the future, it would involve separating plutonium, and probably uranium, from the used fuel, and using the plutonium, mixed with natural uranium or thorium, to produce fuel bundles for use in nuclear power stations. The remainder of the used fuel would be classified as fuel recycle waste. A decision has not yet been made regarding the suitability of depleted uranium for recycling; for the present assessment it is not considered a component of the fuel recycle waste, as it is a naturally occurring substance.

An isotope of plutonium, ^{239}Pu, is a fissile nuclide that is produced via neutron capture in ^{238}U while a fuel bundle is in the reactor. Although the fission of ^{239}Pu accounts for nearly half the power produced by a CANDU fuel bundle at the time it is removed from the reactor, there is still a net accumulation of fissile plutonium, as indicated in Table 3.

Plutonium and uranium can be separated from used fuel by chemical processes. Table 4 lists the quantities of the resulting separation products for typical CANDU fuel.

TABLE 4

SEPARATION PRODUCTS OF PICKERING FUEL*

Separation Product	Grams per Kilogram of Initial Uranium
Separated Uranium	983.6
Separated Plutonium	3.8
Fuel Recycle Waste	12.7

*Assuming burnup of 650 $GJ.(kg(U))^{-1}$ and reprocessing after 10 a of cooling.

2.2.2 Properties of Fuel Recycle Waste

Fuel recycle waste comprises the fission products from used fuel, the actinides other than plutonium and uranium, and the small amounts of activation products of fuel impurities and of Zircaloy bundle components. Because of the nature of the separation process, 0.5% of the plutonium and 0.5% of the uranium may also remain in the waste. Table 5 lists the quantities of the components of fuel recycle waste.

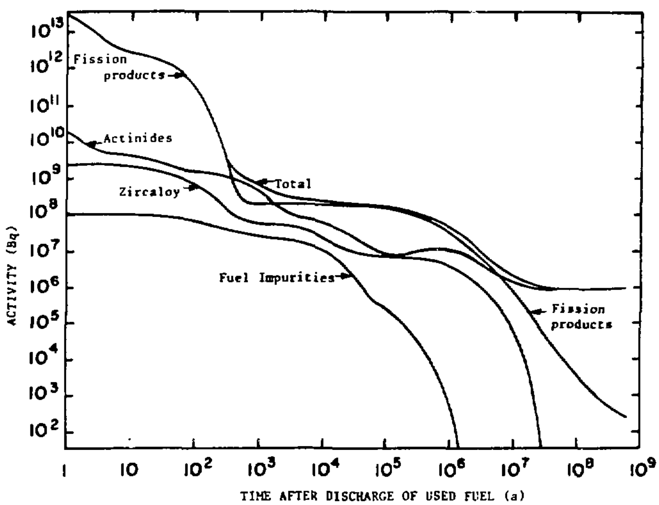
TABLE 5

COMPONENTS OF FUEL RECYCLE WASTE*

Component	Grams per Kilogram of Initial Uranium
Fission Products	7.63
Uranium	4.94
Plutonium	0.02
Other Actinides	0.04
Zircaloy Activation Products	0.07
Activation Products of Fuel Impurities	negligible
Total	12.70

*From Pickering fuel with burnup of 650 $GJ.(kg(U))^{-1}$.

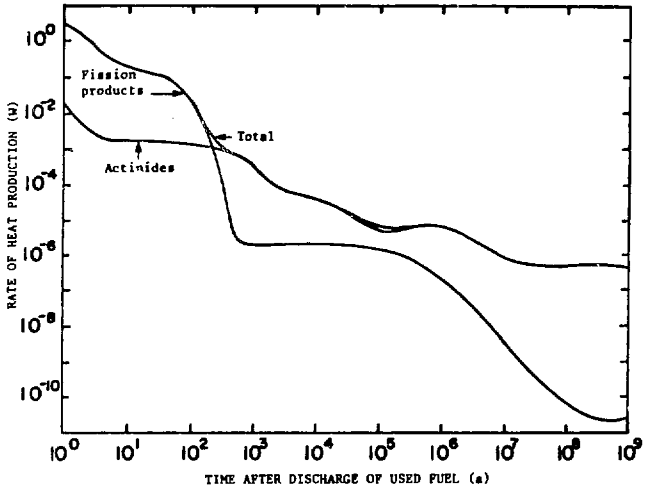
The activity of the fuel recycle waste decreases with time as shown in Figure 7. For the first few hundred years, almost all the activity is due to the fission products, and they continue to be the major contributor for most of the first million years, despite the fact that their activity decreases by a factor of 25 000 in the first 300 years.



As is the case for used fuel, the activity of fuel recycle waste decreases with time. The four contributors to the total radioactivity are the same as those in used fuel. However, their relative contributions are different (see Figure 4), because there are much lower amounts of actinides (uranium and plutonium) in fuel recycle waste than in used fuel. Therefore, the fission products in fuel recycle waste are the major contributors to radioactivity for the first million years.

FIGURE 7: Radioactivity of Fuel Recycle Waste per Kilogram of Initial Uranium

The rate at which decay heat is produced by fuel recycle waste is shown in Figure 8. For the first few hundred years, almost all the heat is produced by the fission products, but after about 300 years, most is produced by the actinides.



Radioactive decay produces heat in fuel recycle waste. The rate of heat production is lower than in used fuel (see Figure 5) when compared on the basis of equal amounts of initial uranium.

FIGURE 8: Rate of Heat Production in Fuel Recycle Waste per Kilogram of Initial Uranium (from data produced by the revised CANIGEN code (Clegg and Coady 1977))

2.2.3 Potential Hazards of Fuel Recycle Waste

The potential hazards arising from ingestion of radionuclides in fuel recycle waste are in general similar to those for used fuel. However, fuel recycle waste has a much smaller inventory of actinides (see Figures 4 and 7), which are alpha emitters, so its ingestion dose equivalent is less than that of used fuel. The external radiation hazards of fuel recycle waste are similar to those of used fuel, but depend somewhat upon the waste form and the shielding it provides.

3. NUCLEAR FUEL WASTE DISPOSAL OPTIONS

3.1 DESIRABLE FEATURES OF A WASTE DISPOSAL SYSTEM

There are many possible ways to dispose of nuclear fuel waste, but not all the options would be suitable for implementation in Canada. A suitable system for Canada should have the potential to be

(1) safely implemented: For any activities associated with implementation of the system the conventional and radiological risks to the workers and the public should be no greater than those normally acceptable to society. It is assumed that radiological safety criteria will be specified by regulatory agencies (see Section 5.2.1), based on information on acceptable levels of risk developed by the International Commission on Radiological Protection (ICRP 1977a).

(2) environmentally and socially benign: Any adverse impacts on man and the environment should be limited. Regulatory agencies will specify criteria that define acceptable levels of such impacts.

(3) robust: The system should be safe and environmentally sound for as large a range of environmental conditions as possible.

(4) technically feasible: Implementation of the system should be possible using existing Canadian technology or straightforward extensions of that technology.

(5) economically feasible: Implementation of the system should be possible at a reasonable cost compared with the other costs involved in electrical power generation.

(6) capable of implementation in the near future: The responsibility for nuclear waste disposal should not be left to future generations.

(7) capable of implementation using Canadian resources: The physical and human resources required to implement the system should be available in Canada.

(8) acceptable to the public: At the completion of a formal public hearing, the Canadian public should be satisfied that the waste disposal system is suitable.

These features largely determine the suitability of the various disposal options for Canada. The options are described in the following section, their suitability for Canada is evaluated, and their status in Canada and in other countries is discussed.

3.2 DESCRIPTION AND STATUS OF WASTE DISPOSAL OPTIONS

3.2.1 Transmutation to Short-Lived Radionuclides

Transmutation is the transformation of one nuclide species into another by bombardment with neutrons or other high-energy particles, or radiation. Selected radionuclides in nuclear fuel waste could be treated in this way, so that the long-lived and most hazardous ones would be transformed into stable nuclides or into radionuclides that decay in a relatively short time, say a few hundred years.

Since high neutron fluxes are present in nuclear reactors, most transmutation schemes involve recycling selected radionuclides in fuel waste through a nuclear reactor. It would not be practical to recycle all the waste in a power reactor, since fission products absorb neutrons, which would severely reduce reactor efficiency. The feasibility of transmuting the long-lived and most hazardous fission products, such as ^{129}I and ^{99}Tc, has been studied, but methods for quantitatively separating out these nuclides have yet to be developed (Battelle Pacific 1976).

It is considered feasible to transmute the actinides to products of shorter half-life, by first separating them from used fuel, then combining them with uranium and plutonium, fabricating this product into fuel, and recycling it in a reactor. Although conceptually simple, there are practical difficulties. The International Atomic Energy Agency coordinated a four-year research program to evaluate the merits of partitioning and transmuting actinides (IAEA 1982). It was found that the chemical separation of the waste actinides is much more difficult than the separation of uranium and plutonium, and is yet to be demonstrated on other than the laboratory scale.

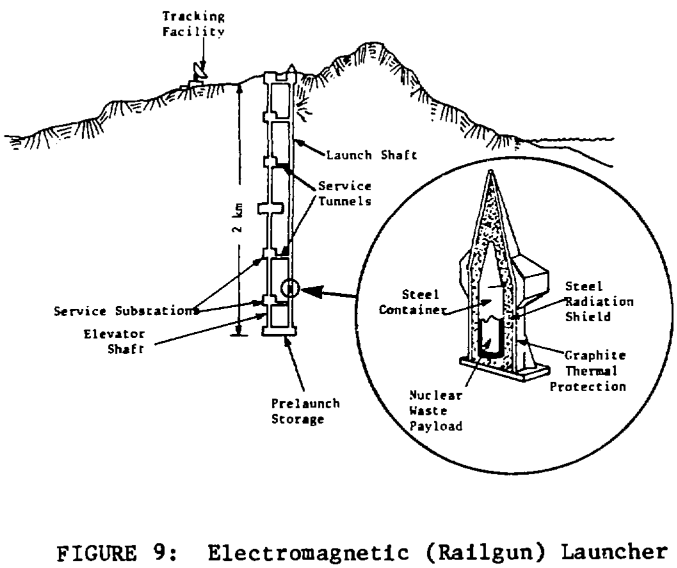
It was also found that the recycled actinides in the fuel would require repeated irradiation in successive batches of fuel to achieve a worthwhile degree of conversion. Additional chemical processing would produce an increase in the radiation dose to man in the short term. The general conclusion of the research program (IAEA 1982) was that implementation would be an immense undertaking, providing at best a small reduction in the long-term radiological hazard. Thus, since transmutation would be neither technically adequate nor economically advantageous, it is not considered a suitable option for Canada.

3.2.2 Extraterrestrial Disposal

The objective of extraterrestrial disposal is to remove selected nuclear wastes from the earth and its atmosphere permanently . In the United States, preliminary studies have been carried out on a number of concepts for disposal in space (NASA 1974, Burns et al. 1978). These concepts include launching into deep space, into the sun, or into a solar orbit. Two types of launching method are undergoing feasibility assessment.

The more conventional method (Rice et al. 1982a, Boeing Aerospace Company 1982) would involve transport by a modified space shuttle. The reference system calls for fuel recycle waste to be disposed of in metallic, spherical containers covered with graphite-and-steel tiles. Two such containers mounted on a support structure would constitute a waste payload. This payload would be launched into a low Earth orbit aboard a modified space shuttle, and an orbit transfer system would be launched into the same orbit aboard a cargo launch vehicle. Then the waste payload would be transferred to the orbit transfer system, which would transfer it to an orbit around the sun about half-way between Venus and Earth. Part of the orbit transfer system would be recovered by the space shuttle in low Earth orbit, and then the shuttle would return to Earth.

An alternative launching method would be to use an electromagnetic railgun (Rice et al. 1982b). Containers would be shot out of a shaft extending 2 km into the ground. Along the inside of the shaft would be two rails, and armature built into each container base would conduct an electric current from one rail to the other. This would create a magnetic field and a wave of high-pressure gases (see Figure 9). The container would be shot out of the shaft at a velocity more than sufficient for escape from the earth's gravitational field and eventual escape from the solar system. Such a launcher could be in operation in about 40 years, if research and development proceed, and are successful.



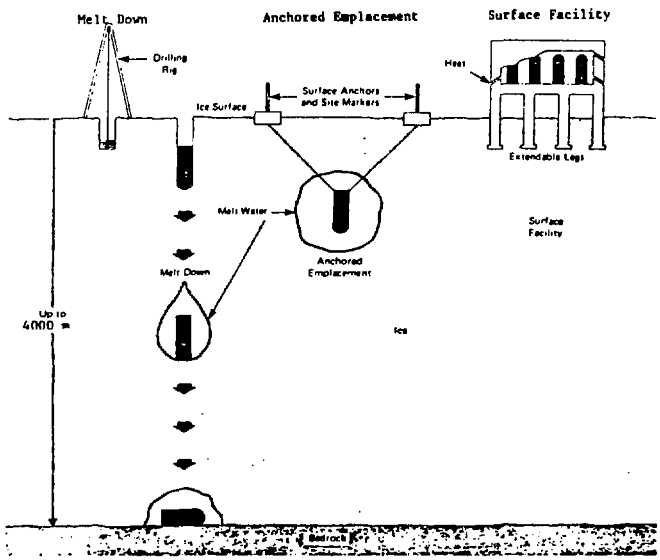
This space disposal concept involves the use of an electromagnetic launching shaft extending 2 km into the ground. Within it, a pulsed electric current would create a magnetic field and a wave of superheated gases, which would launch the waste from the earth at such a speed that it would eventually leave the solar system.

FIGURE 9: Electromagnetic (Railgun) Launcher (after Rice et al. 1982b)

Extraterrestrial disposal by either of these launching methods would require a financial committment of billions of dollars. Also, it could not be implemented using present Canadian technology or straightforward extensions of that technology, and at the present time Canada has no plans to acquire this technology from the U.S.

3.2.3 Ice-Sheet Disposal

It was proposed by the U.S. Department of Energy (1980) that nuclear fuel wastes could be disposed of in continental ice sheets. These cover 11% of the earth's land surface, and ice is an attractive disposal medium because it is a slowly changing environment, free of living organisms. Containers of waste could be allowed to melt to the bottom of an ice sheet, due to their own heat generation, or could be anchored by cables that would keep them suspended at a specified depth, thus permitting retrieval. Alternatively, the containers could be placed in a central storage facility that would eventually melt into the ice sheet (see Figure 10).



The concept of ice disposal could be implemented in three ways: (1) by placing each container of waste in a shallow hole and allowing it to melt to the bottom of the ice sheet due to its own heat generation; (2) by anchoring each container and allowing it to melt as far as the cables permit; or (3) by placing the containers in a storage facility that would slowly melt into the ice sheet.

FIGURE 10: Ice-Sheet Emplacement Methods (U.S. Department of Energy 1980)

At present, there would be little likelihood of human intrusion at a disposal site in a continental ice sheet; in the future, however, intrusion could occur during exploration for resources. Another factor to be considered is cost, which would likely be higher than for underground disposal (U.S. Department of Energy 1980), because of the high cost for the research and development that would be required.

No studies have been carried out on container degradation and radionuclide migration in ice. Few site-selection criteria have been developed. To determine the feasibility of ice-sheet disposal, an extensive geological and hydrogeological study would be needed. However, transportation is severely limited in ice-sheet regions, and the climate is harsh for both personnel and machines. Also, no site is currently available for research and development of ice-sheet disposal technology.

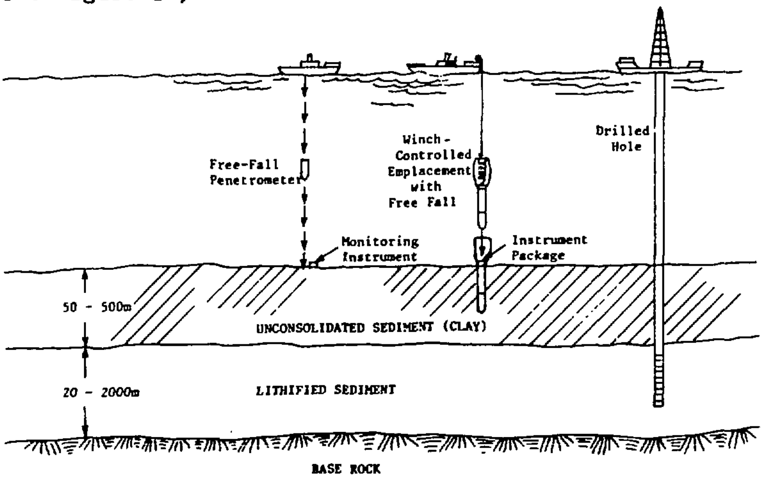
Thick ice sheets exist in Greenland and Antarctica, but, according to Schneider and Platt (1974), disposal in Antarctica is specifically prohibited by the Antarctic Treaty of 1959. Only thin ice sheets exist in Canada, so this alternative does not warrant serious consideration as a disposal option for Canada (Aikin et al. 1977).

3.2.4 Subseabed Disposal

Subseabed disposal would involve burying containers of radioactive waste within the ocean sediments. The waste form, container, and sediments would provide containment for the radionuclides, while the seawater would ensure dilution and dispersion of any that escaped. According to Hinga et al. (1982), an ocean depth of 5000 m would be sufficient for this purpose. The ocean would also be the primary barrier to intrusion by man.

Site-selection criteria developed by the U.S. (Laine et al. 1981) and by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD/NEA Seabed Working Group 1982) suggest that geological and climatic stability are primary requirements, and that uniform sedimentation over wide areas, and lack of economic potential, are also essential features of a suitable subseabed disposal site. Areas of the ocean floor in the North Atlantic and North Pacific Oceans are presently under investigation.

Studies by the U.S. (Hinga et al. 1982) and by the OECD/NEA Seabed Working Group (1982) recommend that the containers of waste be placed at least 30 m deep in the ocean sediment. Emplacement might be achieved by releasing the containers at a sufficient height above the sediment, so that after falling freely they would penetrate to the required depth. Other emplacement methods being considered are winch-controlled injection, and drilling (see Figure 11).



Nuclear fuel waste could be emplaced in the seabed by (1) encasing it in a penetrometer (a torpedo-shaped container) and dropping the penetrometer from a ship; (2) using a winch to control the fall of a penetrometer; or (3) drilling a hole in the sediments and placing the waste within it.

FIGURE 11: Subseabed Emplacement Methods

Research on subseabed disposal is coordinated by the OECD/NEA Seabed Working Group, which was formed in 1975. Of the 10 member countries, the U.S. has the largest program for the study of subseabed disposal, followed by the U.K. and France. Canada is also a member.

Research and development work in the U.S. involve

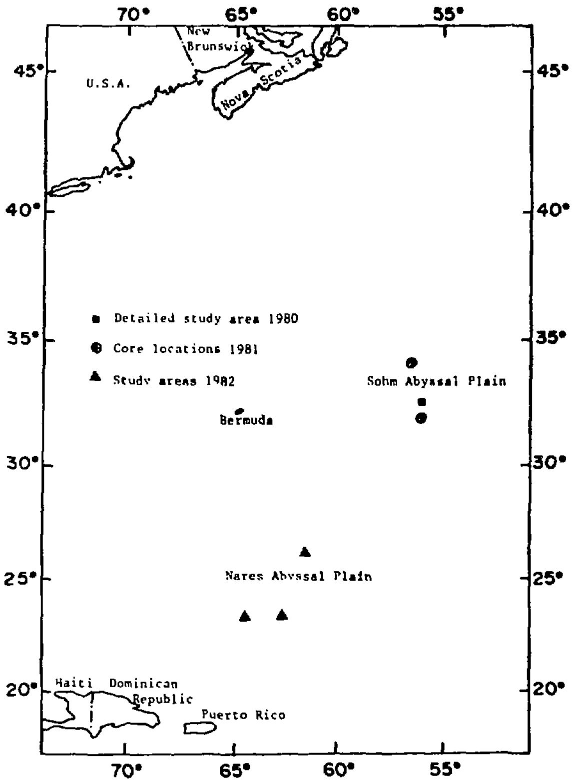
- the study of physical and biological oceanography to determine pathways to man, and potential environmental effects;
- the development of predictive mathematical models, with input parameters to be determined by laboratory and field test data;
- the assessment of emplacement methods by using predictive models and scale testing;
- the identification of reference sites in the North Atlantic and North Pacific Oceans; and
- the determination of regulatory and institutional requirements.

The U.K. has initiated studies on ocean sediment as a barrier to radionuclide migration, corrosion in the marine environment, ocean circulation, radionuclides in ocean waters, and container emplacement methods. France is studying the sorption and migration of radionuclides in North Atlantic sediments, as well as the physical and chemical behavior of actinides in seawater and marine sediments.

Canada has a small-scale research program involving feasibility studies on the disposal of nuclear fuel waste in the seabed. The program is managed by the Atlantic Geoscience Centre, Geological Survey of Canada. Canada's deep-sea investigations began in 1980 with a survey and sampling experiment on the northern Nares Abyssal Plain located southeast of Bermuda (see Figure 12). Seismic data were obtained for sediments to a depth of 200 m (OECD/NEA Seabed Working Group 1980). Subsequent deep-sea cruises indicated sediments thicker than 370 m on the nearby Sohm Abyssal Plain, where sediment samples were collected and analyzed (OECD/NEA Seabed Working Group 1981). The 1982 survey of the Nares Abyssal Plain included investigations of radionuclide behavior in biological processes in the deep ocean, and sampling to determine the organisms present (OECD/NEA Seabed Working Group 1982).

Another Canadian contribution to the OECD/NEA Seabed Working Group has been to demonstrate how the AECL-developed computer code SYVAC could be used to do a probabilistic analysis of the radiological impact of subseabed disposal (Wuschke et al. 1983).

Considerable research remains to be done before the technical feasibility and environmental acceptability of subseabed disposal can be demonstrated. Also, a detailed economic feasibility study of this option has not been performed. Until such studies have been completed, a decision cannot be made concerning the suitability of this option for Canada.



Canada has done some deep-sea investigations to help determine the feasibility of disposing of nuclear fuel waste in the seabed. Research areas in the North Atlantic Ocean are near Bermuda.

FIGURE 12: Location of Seabed Study Areas (OECD/NEA Seabed Working Group 1982)

3.2.5 Underground Disposal

3.2.5.1 General Features of Underground Disposal

Underground disposal would involve the placement of waste in a conventionally mined vault deep within a geological formation on Earth. Desirable features of deep geological formations are their capacity to absorb and disperse heat and their ability to provide containment. This ability is evidenced by the retention of ore deposits and of the remains of the natural reactor at Oklo (IAEA 1978). If developed at an appropriate site, a deep underground disposal vault would have a low probability of being breached by erosion, volcanism, meteorite impact, or other natural events. Also, underground locations with little economic potential would have low probability of future intrusion by man.

Transport by groundwater is the most important mechanism for the potential transfer of radionuclides from an underground vault to man's environment. This could be limited by the careful choice of a host formation, as well as by a series of engineered barriers within the vault. Engineered barriers could include the waste form, its container, a buffer material surrounding the container, and backfill and sealing materials. Desirable features of a host formation are homogeneity, integrity, low permeability, and sufficient size and depth to ensure isolation of the waste.

Many geological formations are being considered worldwide as host media for the disposal of nuclear fuel wastes. Five of these are discussed in the sections that follow.

3.2.5.2 Disposal in Clay and Shale

Clay is a sediment having a soft, plastic consistency, and is composed primarily of fine-grained particles known as clay minerals. These minerals are hydrous aluminum silicates derived from the weathering and decomposition of feldspar and quartz. Clay is generally plastic when wet, so fractures self-seal and seismic disturbances are absorbed. Other properties that make clay an attractive medium for the disposal of nuclear fuel waste include its low permeability, which limits groundwater movement, and its high sorptive qualities, which retard radionuclide migration. Clay formations are also widespread and often hundreds of metres thick.

Shale is a sedimentary rock formed by the deposition of clay minerals under water. As the layers of clay built up they were compacted under their own weight, and pore water was squeezed out. A characteristic of shale is the well-marked separation between its layers. Shale differs from clay in that it is non-plastic and more permeable, and some varieties of shale may disintegrate when immersed in water. Other properties of shale are similar to those of clay.

Italy and Belgium are investigating clay as a disposal medium (OECD/NEA 1982). In Italy, site selection is underway, and research on the properties of clay is concentrating on heat dissipation characteristics, on corrosion characteristics for waste forms and packages, and on geochemical retardation of radionuclides. At the Nuclear Energy Research Centre, Mol, Belgium, construction of an experimental shaft and gallery has begun. Because of the plasticity of the clay and of the unconsolidated nature of the overlying layers, a ground-freezing technique was adopted during construction of the shaft (OECD/NEA 1982). In Canada, disposal in clay has not been investigated.

Shale has not been studied extensively as a potential disposal medium, although Japan is still considering it, along with other host media. The United States has performed preliminary heating tests in shales in Tennessee and Nevada (Klingsberg and Duguid 1980). In Canada, Ontario Hydro has recently completed a preliminary review of shale as a nuclear waste disposal medium (Heystee 1982). Certain shales located in southwestern Ontario were identified as the most suitable in the province, and subsurface data have been compiled for the area. However, shaft construction would be difficult, as shale deforms readily. Also, these formations have commercial value: since 1958, over 50 000 oil and gas wells have been drilled in the area, and the oil shales located there may be developed in the future (Heystee 1982). This option is not being considered seriously in Canada at present.

3.2.5.3 Disposal in Tuff

Tuff is a rock formed of compacted volcanic ash particles, generally smaller than 4 mm in diameter. It varies from being a soft and relatively unconsolidated, highly porous material, to more compacted and less porous forms. It is sometimes welded, as a result of its high temperature on deposition. The permeability of the more consolidated tuffs is low, and they exhibit high sorptive capacities. Tuff is a stronger material than clay, but does not have such good sealing properties.

Significant tuff deposits exist in North America and Italy, but the United States is the only OECD country presently investigating this material for geological disposal (OECD/NEA 1982). Drilling is underway on Yucca Mountain at the Nevada Test Site, where welded and non-welded tuffs extend thousands of metres deep. The volcanic history of this area indicates a low probability for renewed volcanism and minimal consequences for emplaced waste in the unlikely event of such activity (U.S. Department of Energy 1982). Although occurring in Western Canada, tuff deposits in this country are much less extensive than those in the U.S. Disposal in tuff has not been investigated in Canada, principally because tuff does not occur in Ontario.

3.2.5.4 Disposal in Basalt

Basalt is a hard, fine-grained, dark volcanic rock formed from lava flows. It is widespread within the Earth's crust, but thick slabs are limited in occurrence at depths required for a nuclear waste disposal vault. Basalt frequently exhibits columnar structures produced by shrinking while cooling.

Basalt is normally fractured in a regular joint pattern, and since a basalt formation comprises many layers, there is great potential for horizontal groundwater movement in the more porous upper zones of individual layers. The degree of homogeneity of basalt is very site-specific. Favorable characteristics displayed by basalt include the following: low permeability, high sorptive qualities, high structural strength, moderate thermal conductivity, high melting temperature, and resistance to weathering.

As a result of past volcanic activity, basalt occurs in some abundance in the northwest U.S., Nova Scotia, British Columbia, and the Canadian Shield. The potential for renewed volcanic activity in basaltic regions is a disadvantage, although the likelihood of such renewed activity is low.

At the present time, the U.S. is the only country actively investigating basalt as a disposal medium for nuclear waste (Atomics International Division 1980). The area being investigated is the U.S. Department of Energy's Hanford Reservation in the state of Washington. Hydrogeological testing of wells to acquire data on deep water-bearing formations has narrowed the area of interest to the Cold Creek Syncline and has allowed identification of a preferred site for an exploratory shaft. Seismic activity is being monitored near this proposed site. The shaft will be constructed during the period 1983 to 1985. Investigations at depth will continue until 1990 to characterize the host rock and its hydrogeology, and to provide the basis for selection in 1987 of a site for the first waste repository in the U.S. in either basalt, tuff, or salt (OECD/NEA 1982).

Canada has identified areas of basalt flows but has not actively investigated any of these regions for nuclear waste disposal.

3.2.5.5 Disposal in Salt

Large salt deposits occur in several European countries and on the North American continent. They exist as stratified bedded salt and as more localized salt-dome formations extruded from deeper bedded layers. Salt deposits have existed as such for millions of years, indicating isolation from aquifers in which salt is readily soluble. Salt formations also offer the advantages of negligible permeability, high thermal conductivity, and plasticity that increases with increasing temperature. Mining in salt is also cheaper than mining in other geological media.

Disadvantages of salt are that it does not provide the sorptive qualities of other rock types, and metals have a low corrosion resistance in it. Salt deposits often occur in association with deposits of potash or hydrocarbons; this increases the likelihood of human intrusion into such areas in the future.

In the U.S. both bedded and dome salt formations have received more attention than other geological formations as host media for nuclear wastes. A bedded salt site in southeast New Mexico has been proposed as the location for a Waste Isolation Pilot Plant. The plant's primary function will be the receipt of actinide-contaminated wastes from defence operations (Hill 1980). Oriented towards commercial wastes, the National Waste Terminal Storage program was created in 1976. Within this program, investigations of salt formations are presently directed towards two bedded salt areas in Utah and four salt domes in Texas, Louisiana, and Mississippi (OECD/NEA 1982).

In Europe, investigations are underway to identify suitable disposal sites in salt-dome formations in the Federal Republic of Germany, Denmark, Spain, and off-shore from the Netherlands on the continental shelf (OECD/NEA 1982).

In 1975 the Geological Survey of Canada, with financial and manpower assistance from AECL, commenced a three-phase program for assessing the suitability of Canadian salt formations for nuclear fuel waste disposal. The first two phases, completed in 1979, were confined to appraisal of data generated from geological, geophysical, and hydrogeological studies. Field studies were to be undertaken in the third phase. Three bedded salt areas were identified for future geological research. These are located in southwest Ontario, in Nova Scotia, and at Lloydminster, Saskatchewan. The concluding phase of the program has not yet begun, although potential research areas could be identified if and when approval were forthcoming to initiate this phase (Sanford 1982).

3.2.5.6 Disposal in Plutonic Rock (Granite, Gabbro)

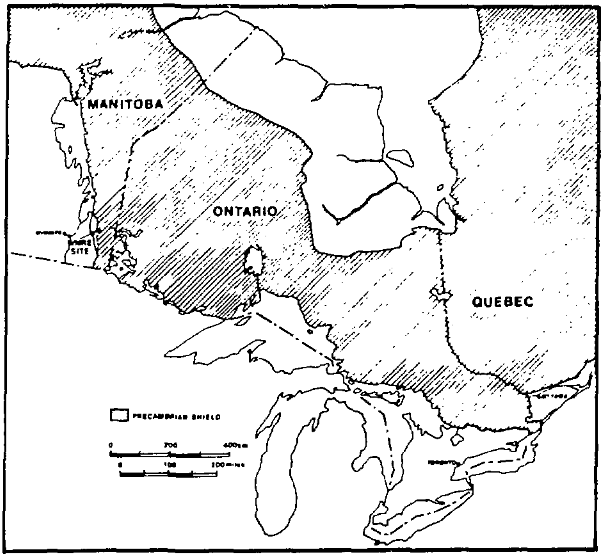
Granite is a widespread plutonic rock consisting predominantly of alkali feldspar and quartz. It is light-colored, coarse-grained, and relatively uniform in structure and composition. During periods of intense tectonic activity, granitic liquids from deep within the earth intruded into surface rocks, where they cooled and solidified to form dome-like masses, called plutons. These masses vary in size, reaching 100 km in width and many kilometres in depth. They normally do not contain significant concentrations of valuable minerals.

Gabbro is a plutonic rock consisting mainly of basic plagioclase with slightly smaller amounts of pyroxene, olivine, or hornblende. Gabbro is generally dark grey or greenish in color, coarse grained, and fairly uniform in structure. It is considered to have formed by crystallization of gabbroic magma. Gabbroic plutons are generally smaller in size than granitic plutons.

Like basalt, plutonic rock has structural strength and resistance to erosion. However, it normally contains minor joints and fractures through which groundwater flows. Owing to the action of groundwater, the mineralogical composition of plutonic rock can be changed by surface mineral modification and by deposition of sediment in fractures.

Underground disposal in plutonic rock is the option that receives most of the research effort in Canada. Underground disposal was chosen for investigation because it was considered to offer the greatest promise for development with available technology (Scott 1979). A specific rock type was chosen for investigation because all possible rock types could not be studied simultaneously (Scott 1979).

The choice was narrowed to formations occurring in Ontario, since Ontario is anticipated to be the area of Canada experiencing the most growth in the use of nuclear power (Scott 1979). The choice was further narrowed to the Canadian Shield of Ontario (Figure 13), because its relative stability for hundreds of millions of years suggests that it will remain stable for further millions of years, since it takes that long for the geological regime to change from stable to active (Aikin et al. 1977). In the Canadian Shield of Ontario, there is an abundance of relatively homogeneous bodies of plutonic rock (McCrank et al. 1981, Brown et al. 1982), so this type of rock is being studied to determine its suitability as a host medium for a nuclear fuel waste disposal vault.



To date, some 1365 plutonic bodies have been identified in the Ontario segment of the Canadian Shield. Nearly three quarters are granitic.

FIGURE 13: The Canadian Shield of Ontario

Underground disposal in plutonic rock, particularly granite, is the option receiving most attention internationally, although disposal in salt is being studied almost as much (see Table 6). Disposal in granite receives most of the research effort in Finland, France, Sweden, and Switzerland, as well as in Canada. It is also being investigated in Japan, the United Kingdom, and the U.S. (OECD/NEA 1982).

The research in these countries involves field and laboratory experiments and the development of computer models. Field experiments include exploratory drilling to obtain geological and hydrogeological data, as well as measurements of heat transfer. Supporting laboratory studies include the investigation of the heating effects of waste on the surrounding rock. Other topics being studied are rock mechanics, radionuclide sorption, and waste immobilization. The mining technology is already proven, but other technologies are being developed: the design of containers, and the design, production, and installation of buffer, backfill, and grouting materials. Computer models of radionuclide transport in geological media are being developed by most OECD/NEA member countries, including Canada (OECD/NEA 1982).

Other countries exchange information on waste disposal research with Canada. A summary of the disposal research activities underway in Canada and of the information exchange between Canada and other countries is given in the Guide to the Canadian Nuclear Fuel Waste Management Program (Rosinger et al. 1983).

TABLE 6

STATUS OF DISPOSAL OPTIONS IN SELECTED COUNTRIES

(derived from OECD/NEA 1982)

	Belgium	Canada	Denmark	Fed. Rep. of Germany	Finland	France	Italy	Japan	Netherlands	Spain	Sweden	Switzerland	U.K.	U.S.A.
Transmutation														
Extraterrestrial Disposal														4
Ice-Sheet Disposal														
Subseabed Disposal		4		3		3		3	3			3	2	2
Underground Disposal:														
in Clay	1						1					3	3	4
in Shale		4						2						4
in Tuff														1
in Basalt								2						1
in Salt		4	1	1					1	1				1
in Plutonic Rock		1			1	1		2			1	1	2	3

Legend:
1 - Highest priority, intensive effort.
2 - High priority, substantial effort.
3 - Low priority, moderate effort.
4 - Lowest priority, minimal effort.

4. CANADIAN REFERENCE WASTE DISPOSAL SYSTEMS

4.1 INTRODUCTION

The disposal option receiving most of the research effort in Canada is underground disposal in plutonic rock. The Canadian concept involves the burial of corrosion-resistant containers of nuclear fuel waste in a vault located deep in plutonic rock in the Canadian Shield. To assess the impacts that would occur during and after the implementation of this concept, it is necessary to define a reference system in enough detail to provide the information required.

To assess the impacts that would occur during operation of the waste disposal facility, the reference system used was the conceptual design of a disposal system for used fuel, prepared by Acres et al. (1980a). To assess the impacts that would occur after the vault was closed, two reference systems were used: one for the disposal of used fuel bundles, and the other for the disposal of immobilized fuel recycle waste. These two reference systems are based on the conceptual designs by Acres et al. (1980a and 1980b), with two major modifications, made as a result of information obtained after the conceptual designs were documented. The first modification involved going from a single type of filling material in the vault to two: buffer and backfill. The second modification involved using Grade-2 titanium (commercial purity 99.2%) as the container material, rather than stainless steel.

The following descriptions of the reference systems are summaries of the reports by Acres et al. (1980a and 1980b), with the changes noted above. However, not all the new information was incorporated into these reference systems, because the aim was to use reference systems as similar as possible to the only documented designs of complete disposal systems for Canadian conditions. All the new research results will be considered during the development of new conceptual designs, which should be complete by 1988. Some of the changes that may be made are discussed in Section 4.4. When reading the descriptions that follow, it should be borne in mind that the reference systems used for this assessment do not reflect all recent research findings, and that further changes will be made in the future.

4.2 REFERENCE SYSTEM FOR THE DISPOSAL OF USED FUEL

4.2.1 Overview

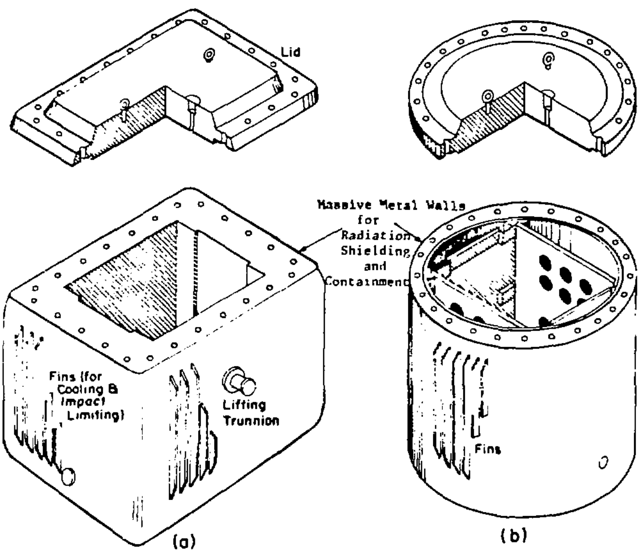
This reference system comprises the facilities and operations required to transport and dispose of used fuel bundles. After removal from the reactor, the bundles would be cooled for a minimum of 10 years at an interim storage facility. This facility, generally located at the reactor site, is not considered to be part of the reference disposal system. After interim storage, the bundles would be transported to the disposal facility, which would include surface facilities, shafts, a vault, and the equipment and materials required to handle the waste underground, and to fill and seal the excavation. At the disposal facility specified in the Acres et al. (1980a) design, about 580 000 bundles (11 000 Mg(U)) per year could be immobilized in containers that would subsequently be emplaced in rooms in the vault. When all the rooms were filled with containers, the vault would be backfilled and sealed, and the surface facilities would be decommissioned.

4.2.2 Transportation to the Disposal Facility

For transportation from the interim storage facility to the disposal facility, used fuel bundles would be loaded into transportation casks. These casks would conform to the safety and performance standards set by the International Atomic Energy Agency (IAEA 1979). These standards require that transportation casks provide adequate shielding against radiation and contain the radioactive gases given off by the waste, even if an accident resulted in severe stresses due to impact, fire, or immersion in water.

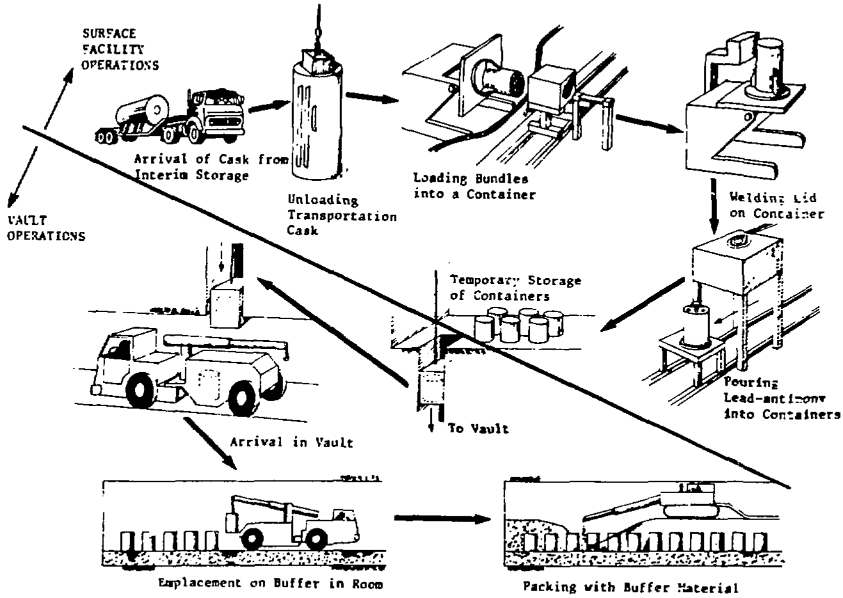
Appropriate cargo handling facilities would be designed and built to ensure the safety of the general public and of the crews loading and unloading the casks. Transportation routes would be chosen carefully to limit any adverse effects on the public (Nathwani 1983). Casks would be transported by truck, train, or barge, depending upon the safety, cost, and feasibility of each method (Missio 1982).

Because of load limitations, a road cask would contain only one 96-bundle module and weigh 36 Mg (Figure 14), while a rail cask would probably be larger, containing three or four such modules and weighing about 65 Mg (Gee et al. 1983). A barge could transport either of these casks, so it could be used in conjunction with either road or rail transportation.



Transportation casks are designed to reduce the radiation from the waste to a safe level outside the cask, and to provide protection and containment of the waste in the event of any credible accident. Details of the size, shape, and materials used will vary with the mode of transportation to be employed.

FIGURE 14: Examples of Road Transportation Casks: (a) rectangular, (b) cylindrical (after Oberth (1982))



Used fuel bundles would be unloaded from the transportation cask, stored temporarily, and then immobilized in disposal containers. After a period of temporary storage, the containers of waste would be lowered into the vault, emplaced in a room on a bed of buffer material, and then surrounded with more buffer material. The room would then be backfilled.

FIGURE 15: Activities at a Disposal Centre for Used Fuel (Acres et al. 1980a)

4.2.3 Surface Facility Operations

The major activities at the surface facilities (see Figure 15) would involve

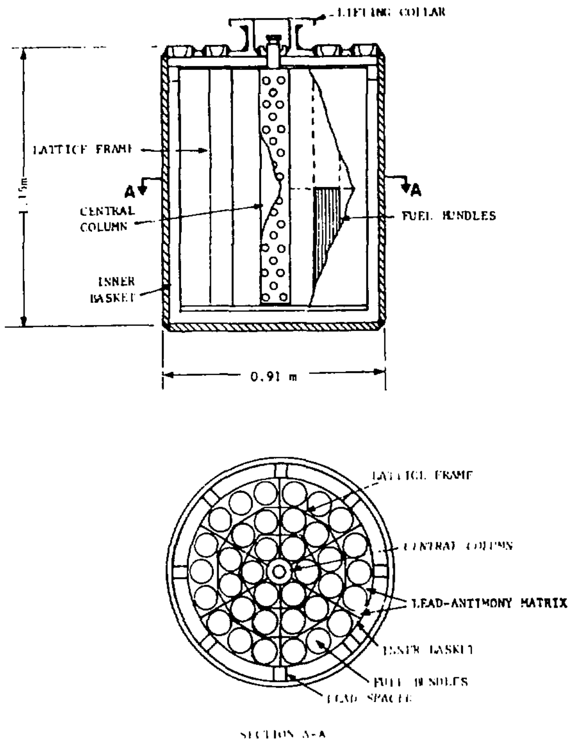
(1) receiving the shipping casks,
(2) unloading the used fuel bundles,
(3) storing the bundles temporarily,
(4) immobilizing the bundles, a process that would include
- loading 72 bundles into each supported-shell disposal container (see Figure 16),
- welding on a lid with fill and vent holes,

- inspecting the welds,
- pouring molten lead-antimony into the container,
- inspecting the casting,
- welding the fill and vent holes, and
- inspecting the welds,

(5) storing one year's throughput of containers so that vault operations would not be affected by interruptions in the preceding operations,

(6) transferring the containers to the waste-lowering shaft, and

(7) decontaminating the shipping casks and returning them to the interim storage facility.



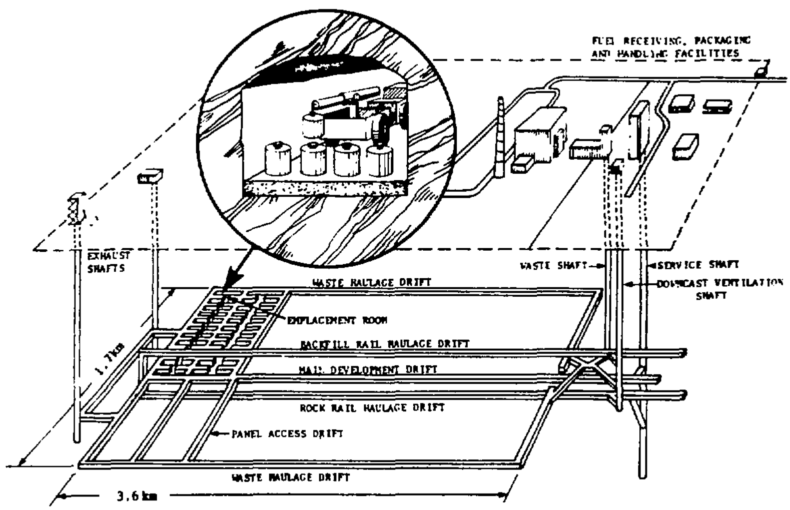
The reference container is an enclosed cylindrical vessel made of titanium. Each container would hold 72 bundles of used fuel stacked in two levels of 36 bundles each. The bundles would be immobilized in the container with a matrix of cast lead-antimony. The mass of a container of immobilized fuel would be about 8000 kg.

FIGURE 16: Reference Disposal Container for Used Fuel Bundles (Acres et al. 1980a)

These activities would be part of an integrated handling system that would also include the underground handling of the containers. This system would be designed to ensure the safety of operators and the public from radiation exposure. Because the equipment in the system would operate in a radioactive environment, it would be designed for high reliability and easy maintenance.

4.2.4 Vault Operations

The vault would be built on a single level at a depth of 1000 m. Exhaust shafts would be sunk at one end, and a waste-lowering shaft, intake ventilation shaft, and service shaft at the other (see Figure 17). Underground passageways, called drifts, would be excavated to connect these shafts and to permit the removal of excavated rock, containers of waste, and fill materials. Further excavation and the emplacement of waste would be carried out on a modular basis, starting at the end near the exhaust shafts and working toward the waste-lowering shaft. Excavation and emplacement operations would be kept separate by the use of separate drifts for construction traffic and for nuclear fuel waste transport.



During vault construction, about 9 000 000 m^3 of rock would be excavated, half of which would be returned to the vault as part of the backfill. An area at the surface would be required for storage of rock and other materials. An additional area would be designated as an exclusion zone, so the total surface area required for the disposal centre would be about 27 km^2. The area of the vault itself would be about 7 km^2.

FIGURE 17: Layout of Disposal Facilities (Acres et al. 1980a) (Drawings not to scale. Only a fraction of the rooms off the panel drifts are shown)

The completed vault would be 3600 m long and 1700 m wide. Besides the drifts, it would consist of 16 panels, each containing 52 rooms. Each room would accommodate 300 containers, which would be arranged in 75 rows of four. Thus, the completed vault would contain almost 18 000 000 bundles (about 334 000 Mg(U)) of used fuel, which is the amount that will have been produced by about the year 2055, according to the projections given in Section 2.1.1.

Vault operations directly related to the waste (see Figure 15) would involve

(1) transferring the containers underground by hoist,
(2) transferring the containers to underground interim storage,
(3) transferring the containers to an excavated room, using a shielded flask,
(4) emplacing the containers on a 1-m bed of buffer material,
(5) packing buffer material between the containers and to a height of 1 m above them, and
(6) backfilling the rest of the room to a depth of 3 m.

The buffer material surrounding the containers would be primarily intended to retard the movement of groundwater and radionuclides. It would consist of a clay-sand mixture, possibly with additives to modify chemical conditions in the vault. Additives could be used to further retard the movement of selected radionuclides, or to reduce container corrosion by controlling the pH and electrochemical potential (Bird and Cameron 1982).

The backfill material would fill the remainder of the vault, the shafts, and the exploratory boreholes. Its major component would be crushed rock or sand, or a mixture of the two, with enough clay added to achieve the desired low permeability. Pneumatic packing methods would be used to emplace the backfill.

4.2.5 Vault Closure and Decommissioning of the Surface Facilities

The vault would be closed in stages. To permit short-term retrieval of the used fuel, the rooms would not be backfilled until 20 years after all containers were embedded in buffer. After the rooms were filled, the drifts would be completely backfilled, and the shafts and exploratory boreholes would be backfilled, except where seals were required. The seals would probably be low-permeability clay, or concrete plugs (Lopez et al. 1983). The rock surrounding the shafts would be grouted, as required.

After all the waste has been emplaced in the vault, the surface facilities would be decommissioned. The site would be made safe for the public, and could be returned as closely as possible to its original condition or used for some other purpose.

4.3 REFERENCE SYSTEM FOR THE DISPOSAL OF FUEL RECYCLE WASTE

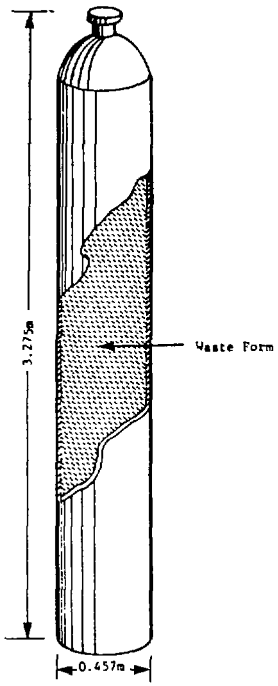
4.3.1 Overview

This reference system comprises the facilities and operations required to immobilize, transport and dispose of fuel recycle waste. Most of the fuel recycle waste would be immobilized in glass, though other waste forms would be required for some components. Figure 18 shows the reference container for fuel recycle waste. After being filled, each container would be sealed and inspected. These operations would be carried out at a reprocessing facility, but are considered part of the reference disposal system.

From the reprocessing facility, the containers would be transported in casks to the disposal facility. There they would be placed in boreholes drilled in the floor of each room in the vault. The vault rooms would be successively backfilled and sealed and finally the shafts and boreholes would be filled and plugged and the surface facilities decommissioned.

4.3.2 Transportation to the Disposal Facility

The procedures for transporting immobilized recycle waste from the reprocessing facility to the disposal facility would be similar to those described in Section 4.2.2 for used fuel. However, the transportation casks would likely be of a different design to those for used fuel, although they would be required to meet the same high standards of safety and reliability.



The reference container is a cylindrical vessel made of titanium. The mass of a container filled with the glass waste form would be 1675 kg.

FIGURE 18: Reference Disposal Container for Fuel Recycle Waste (Acres et al. 1980b)

4.3.3 Surface Facility Operations

The major activities at the surface facilities (see Figure 19) would involve

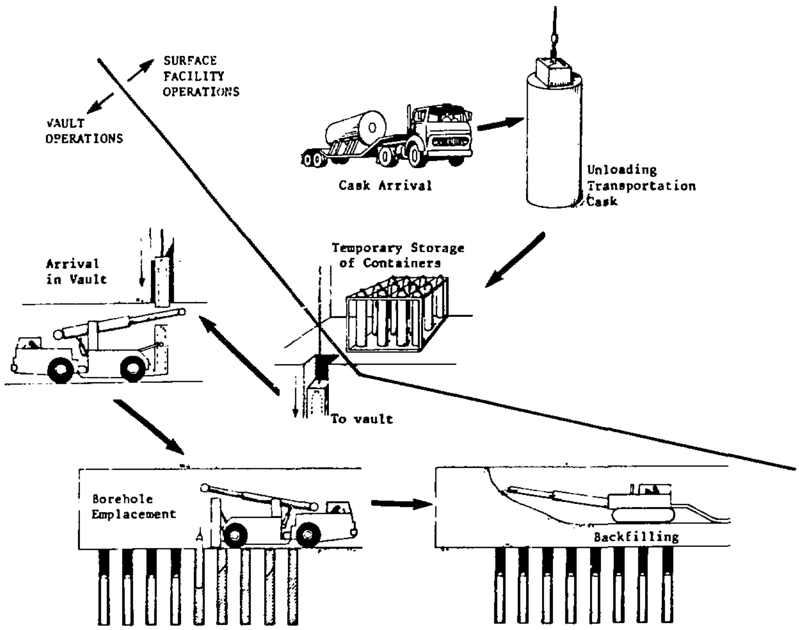
(1) receiving the transportation casks,

(2) unloading the containers of fuel recycle waste from the casks,

(3) storing the containers temporarily, and

(4) transferring the containers to the waste-lowering shaft.

These activities would be part of an integrated handling system, much the same as that described in Section 4.2.3 for used fuel.



Containers of fuel recycle waste would be unloaded from the transportation cask, stored temporarily, and then lowered into the vault, where they would be emplaced in boreholes lined with buffer material. More buffer would be packed on top of the containers and the room would then be backfilled.

FIGURE 19: Activities at a Disposal Facility for Fuel Recycle Waste (Acres et al. 1980b)

4.3.4 Vault Operations

The construction and operation of a disposal vault for fuel recycle waste (see Figure 19) would be similar to those activities for used fuel (described in Section 4.2.4), except for the emplacement method. The conceptual design for the disposal of fuel recycle waste (Acres et al. 1980b) specifies emplacement in boreholes drilled in the floor of each room in the vault. The reference system is based on this design, but it substitutes buffer for backfill as the fill material around the container in the borehole. The thickness of the buffer between the container and the borehole wall would be about 0.1 m, and the thickness of the backfill in the room would be 5 m.

The completed vault would be 3600 m long and about 900 m wide. Besides the drifts, it would consist of 15 panels, each containing 24 rooms. The floor of each room would have 480 boreholes, arranged in 120 rows of four. One container would be emplaced in each borehole. Thus, the completed vault would contain the waste derived from about 13 000 000 bundles (about 270 000 Mg(U)) of used fuel, which is the amount of used fuel that will have been produced by about the year 2050, according to the projections given in Section 2.1.1.

4.3.5 Vault Closure and Decommissioning of the Surface Facilities

These operations for fuel recycle waste would be the same as those described in Section 4.2.5 for used fuel.

4.4 POTENTIAL CHANGES TO THE REFERENCE DISPOSAL SYSTEMS

The reference systems for both the first and this second concept assessment were based on the conceptual designs of Acres et al. (1980a and 1980b) because they are the only documented designs of complete disposal systems for Canadian conditions. However, since they were developed, results obtained in the Canadian Nuclear Fuel Waste Management Program have led to the consideration of several possible changes. Those deemed useful will be incorporated in new conceptual designs, which will be completed by 1988.

Some of the changes being considered are discussed below:

(1) The projected rate of fuel arisings reported in Section 2.1.1 may be used instead of the higher estimate on which the conceptual designs (Acres et al. 1980a and 1980b) were based. If the lower rate is

adopted, several aspects of the reference systems would be affected. For example, the surface facilities could be scaled down, and the shipping rates reduced from those specified in the Acres reports.

(2) Longer cooling times for nuclear fuel waste will be considered if research shows that it would be advantageous to further reduce the heat and radiation emitted by the waste before disposal.

(3) New container designs are being investigated (Cameron 1982). For example, the TEC-II design specifies a geometry suitable for both in-room and borehole emplacement. Also, a stressed-shell design is being considered as an alternative to the supported-shell design. Potential construction materials for stressed-shell containers include stainless steel, Inconel, and titanium. Very-long-lived containers made of copper or ceramics are also being considered.

(4) Because lead is both valuable and toxic, it may not be the most suitable material for filling the voids in a supported-shell container for used fuel bundles. One alternative being considered is the use of an inert particulate material, such as 1-mm diameter glass beads (Teper 1982).

(5) For each of the waste packages, other emplacement options are being considered (Baumgartner and Simmons 1982). For example, as an alternative to the in-room emplacement of used fuel, borehole emplacement is being considered. The design would be as shown in Figure 19 for fuel recycle waste, and would necessitate the use of a container different from the reference container shown in Figure 16.

(6) Materials suitable for buffer, backfill, seals, and grouts are being developed and assessed (Bird and Cameron 1982), as well as the processes to prepare and install them.

(7) Underground waste handling systems are being developed and assessed (Baumgartner and Simmons 1982).

Two other studies are being carried out to evaluate other system options, but they are not expected to lead to changes in the reference design. These are

(1) an assessment of alternative vault designs, such as a multilevel vault, or vault rooms in which long boreholes are drilled so that each borehole can accommodate several containers (Baumgartner and Simmons 1982);

(2) a study by Ontario Hydro of the characteristics of reinforced concrete containers that could be used for temporary storage, transportation, and disposal, without further handling or repackaging of the used fuel (Burnett 1982, Freire-Canosa 1982).

5. OVERVIEW OF CONCEPT ASSESSMENT

5.1 INTRODUCTION

The assessment of the Canadian concept for nuclear fuel waste disposal is divided into two major parts: pre-closure assessment and post-closure assessment. This division is made because the approach to predicting the impact of pre-closure activities is different from that used to predict the impact of post-closure processes and events.

The pre-closure activities include the following operations needed to implement the disposal system described in Section 4: transporting the nuclear fuel waste to the disposal facility, constructing and operating the disposal facility, closing the vault, and decommissioning the surface facilities. The pre-closure assessment is being performed by Ontario Hydro, and the methods and results to date are summarized in Volume 3 of this document (Johansen et al. 1984). Current results are for the disposal of used fuel, but future studies will assess fuel recycle waste as well.

The post-closure phase begins after the vault has been closed and the surface facilities have been decommissioned. The process of interest during this phase is the migration of radionuclides and other toxic substances from the vault to man's environment. The post-closure assessment is being performed by AECL, and is described in Volume 4 of this document (Wuschke et al. 1984). The consequences of disposing of both used fuel and fuel recycle waste were determined.

The general approach for each of these assessments is described in the remaining sections of this volume.

5.2 THE APPROACH TO PRE-CLOSURE ASSESSMENT

5.2.1 Basis for Pre-Closure Assessment Objectives

Regulatory agencies, such as Environment Canada and the Ontario Ministry of the Environment, have developed guidelines and regulations by which to judge the acceptability of proposed industrial projects (Canada. Federal Environmental Assessment Review Office 1979, Ontario. Legislative Assembly 1971). These are designed to ensure that the social, economic, and environmental concerns of the people affected by such projects are taken into account; these guidelines and regulations will be followed by AECL.

Because it would involve nuclear materials, a disposal system for nuclear fuel waste must also meet the specifications given in the Atomic Energy Control Regulations (Canada. Privy Council 1974). Additional specifications, currently being developed, will define the practices to be employed in the design, construction, and operation of a disposal system, and the standards of performance and safety to be met throughout its operating life.

5.2.2 Objectives and Scope of Pre-Closure Assessment

The objectives of the second pre-closure assessment are to

(1) determine, evaluate, and describe the potential impacts that the pre-closure activities would have on man and the environment;

(2) determine and describe how to optimize these impacts, that is, how to maximize the benefits and minimize the adverse effects; and

(3) determine the degree of safety of the facility workers and the public during the pre-closure period.

The scope of the pre-closure assessment includes the consideration of two types of impacts: the conventional impacts that would arise from the establishment of a new industrial centre, and the impacts that would result from the involvement of radioactive materials in its operation.

5.2.3 Overview of Pre-Closure Assessment Methods

Over the past few decades, general procedures have been developed and used to analyze the environmental, social, and radiation-safety-related impacts of industrial projects (see, for example, Lang and Armour (1981)). The pre-closure assessment was performed using these methods, which are outlined below. It is assumed that all activities would conform to federal and provincial codes specifying conventional industrial safety practices, so these are not discussed in detail in this assessment.

To determine environmental impacts, it is necessary to

(1) identify all environmental features and processes potentially affected by the proposed project, establishing initial conditions and evolutionary trends;
(2) predict the range, magnitude, and probability of potential environmental effects, distinguishing between direct and indirect effects, and between immediate and long-term changes;
(3) assess the relative importance of these effects, recognizing possible changes in conditions and mitigative measures; and
(4) evaluate the overall acceptability of the proposed project with respect to its impact on the environment.

To determine social impacts, it is necessary to

(1) record the existing social conditions in the potentially affected area, establishing initial conditions and trends;
(2) project the social changes that are likely to occur, noting their distribution in the affected population;
(3) assess the relative importance of the anticipated changes for the affected groups, recognizing present and possible future social conditions and mitigative measures; and
(4) evaluate the overall acceptability of the proposed project with respect to its impact on social conditions.

To determine radiation-safety-related impacts, it is necessary to

(1) describe the system to be analyzed;
(2) identify events that may lead to releases of radionuclides and estimate the probability of their occurrence;
(3) characterize the radioactive materials likely to be involved in the release;
(4) establish the mechanisms by which a release may be effected; and
(5) assess the radiological doses likely to be involved, noting any safety measures and their mitigating effects, and compare these with existing regulatory dose limits and industrial norms.

The implementation of these methods is discussed in Volume 3 of this document (Johansen et al. 1984).

5.3 THE APPROACH TO POST-CLOSURE ASSESSMENT

5.3.1 Basis for Post-Closure Assessment Objectives

Insofar as they are applicable to the post-closure phase, the regulatory specifications mentioned in Section 5.2.1 must be met. One of the most detailed specifications for evaluating the acceptability of the concept will be a regulatory policy statement by the Atomic Energy Control Board (AECB). A draft of this statement has been issued, as a Consultative Document (Canada. Atomic Energy Control Board 1984).

Radiological protection criteria for the disposal of radioactive waste are being developed by expert groups engaged by organizations such as the International Commission on Radiological Protection and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development. The consensus that appears to be emerging from the work of these groups is that both dose and the probability of its occurrence should be considered when developing criteria. It is anticipated that this approach will be taken by the AECB.

5.3.2 Objectives and Scope of Post-Closure Assessment

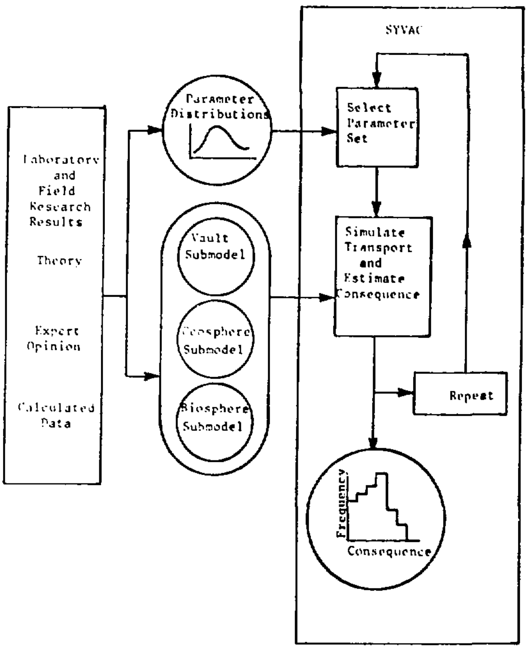
The major objective of the second post-closure assessment is to demonstrate the methodology that has been developed to obtain a probabilistic estimate of the individual dose equivalent to man due to radionuclide migration from a disposal vault. The migration mechanism being studied is that in which groundwater penetrates the vault, corrodes the containers, dissolves the radionuclides in the waste, and carries them to the surface environment, where they could disperse or concentrate and deliver a dose of ionizing radiation to man. It is also necessary to analyze the extent to which human activities, such as intrusion, and natural phenomena, such as glaciation, uld influence these processes or otherwise allow radionuclides to reach man. In this second post-closure assessment, the potential impact of migration of chemically toxic substances from the vault is also evaluated.

5.3.3 Overview of Post-Closure Assessment Methods

Research information is obtained from laboratory and field studies, from scientific theories, from the opinions of experts, and from simulation studies. This information is used to develop mathematical submodels that represent the relevant processes in three physical regions: the vault, the geosphere, and the biosphere. These submodels are linked by the executive program SYVAC (Sherman 1985), and the resulting computer code models the release of toxic substances from the containers and their migration through the vault, geosphere, and biosphere. In the case of radionuclides, the consequence calculated is the maximum radiation dose equivalent to man. For chemically toxic substances, it is their maximum concentration in soil, and water.

The system to be modeled is characterized by the system parameters, whose values are used as input to the computer program. The values of many of the system parameters are specified as probability distributions. This is done to permit consideration of a range of sites, to account for the natural variability at a single site, and to account for possible errors in measurement. To obtain parameter values from the probability distributions, SYVAC randomly selects a single value from each distribution for each computer simulation. Many simulations are performed, constituting a Monte Carlo approach (Dormuth and Quick 1981). Thus SYVAC can incorporate the variability and uncertainty present in the real system to estimate a range of possible consequences.

An overview of the post-closure assessment method is shown schematically in Figure 20. The implementation of this method is discussed in Volume 4 of this document (Wuschke et al. 1984).



Laboratory and field research results, theory, expert opinion, and calculated data are used to develop the submodels and data used in SYVAC. The vault, geosphere, and biosphere submodels represent the release and transport of toxic substances. Some of the SYVAC input is in the form of probability distributions, from which single values are selected for each simulation. Many simulations are performed, and the results give a range of possible consequences.

FIGURE 20: Post-Closure Assessment Process

5.3.4 Quality Control in the Post-Closure Assessment Process

Ideally, a computer model should be verified by comparison of its predictions with events in the real world. The total real system that SYVAC submodels is not accessible, and so the assessment cannot be verified in this way. However, SYVAC and its submodels provide the means for assimilating information from many sources, by using them to provide input data. These sources include the results of other computer codes that model parts of the system in detail. Many of these results can be validated by comparison with real-world measurements. The laboratory and field data that also provide input to SYVAC are derived from direct observations of the real world, and as such are implicitly verified.

What then remains is to establish confidence in the process of assimilation. This can be done by a two-fold process. First, the process of assimilation must be thoroughly specified and described in clear, concise documentation such that the approach taken, the analysis, and the intended computations can be subjected to critical review by regulatory agencies and by the scientific community. Second, every effort must be made to avoid faulty logic, mistakes in data transcription, and numerical errors. Adequate quality control of model formulation and implementation will ensure that error due to these sources is minimized. The techniques used are discussed in Volume 4 of this document (Wuschke et al. 1984).

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GLOSSARY

ABSORBED DOSE: The amount of energy, from ionizing radiation, absorbed per unit mass of material. The SI derived unit of absorbed dose is the GRAY.

ACTINIDE: An element with an atomic number from 89 (actinium) to 103, inclusive. All are radioactive. Examples are uranium and plutonium.

ALPHA PARTICLE: A positively charged particle composed of two protons and two neutrons and emitted from a nucleus during RADIOACTIVE DECAY. It is identical in all measured properties with the nucleus of a helium atom. An example of a RADIONUCLIDE that emits alpha particles is ^{239}Pu. Alpha particles cannot penetrate the body's outer layer of skin.

BACKFILL: The material used to refill the excavated portions of a VAULT, after waste and BUFFER have been emplaced. Current plans call for a mixture of clay, sand, and perhaps gravel and crushed rock.

BECQUEREL (Bq): The SI derived unit of activity (radioactive), equivalent to the disintegration of one radioactive atom per second.

BETA PARTICLE: An electron or positron emitted by a nucleus during RADIOACTIVE DECAY. It can penetrate body tissue to a depth of 1 to 2 cm. An example of a RADIONUCLIDE that emits only beta particles is ^{90}Sr.

BIOSPHERE: The life-zone of the earth including the surface of the earth, the plants and animals, the regions below the land surface (to the limit of biological activity), the lower part of the atmosphere, and surface water bodies such as lakes, rivers, and oceans and their bottom sediments. It includes the human habitat or environment in the widest sense.

BUFFER: A barrier surrounding the waste CONTAINER, intended to control the movement of water, the rates of CONTAINER corrosion and fuel dissolution, and RADIONUCLIDE migration. Current plans call for a clay-sand mixture.

<u>CANISTER</u>: A receptacle used for the above-ground storage of NUCLEAR FUEL WASTE.

<u>CASK</u>: A receptacle used for transporting NUCLEAR FUEL WASTE from an interim storage facility to the waste DISPOSAL FACILITY.

<u>COLLECTIVE DOSE EQUIVALENT</u>: The sum of the products of the individual DOSE EQUIVALENTs and the number of individuals in each exposed group in a population. The SI derived unit of collective dose equivalent to a population is the man-sievert.

<u>CONCEPT, WASTE MANAGEMENT</u>: A basic idea from which a waste management method may be developed.

<u>COMPUTER MODEL</u>: The mathematical representation of a system, coded in computer language.

<u>COMPUTER SIMULATION</u>: The use of a computer to determine the behavioral characteristics of a system represented by a COMPUTER MODEL.

<u>CONTAINER</u>: A durable, sealed receptacle used for enclosing NUCLEAR FUEL WASTE. It will provide radiological shielding during the disposal process, and will serve as a barrier between the waste form and groundwater until failure by corrosion.

<u>DECOMMISSIONING</u>: The work required for the planned permanent retirement of a nuclear facility from active service, including decontamination of the site.

<u>DISPOSAL CENTRE</u>: A DISPOSAL FACILITY, the associated surface storage areas, and the surrounding exclusion zone.

<u>DISPOSAL FACILITY</u>: Surface facilities, shafts, a VAULT, and the equipment and materials required to handle the fuel waste underground, and to fill and seal the excavation.

DISPOSAL SYSTEM: A DISPOSAL CENTRE and the transportation facilities needed to bring NUCLEAR FUEL WASTE from interim storage sites.

DOSE EQUIVALENT: A measure of the biological effect of radiation received by exposed tissue. It is the product of ABSORBED DOSE, a quality factor, and a modifying factor. The quality factor expresses the biological effectiveness of different kinds of radiation. The modifying factor takes account, for example, of ABSORBED DOSE rate and fractionation. The SI derived unit of dose equivalent is the SIEVERT.

EFFECTIVE DOSE EQUIVALENT: The weighted sum of the DOSE EQUIVALENTs received by several organs from an intake of RADIONUCLIDEs and/or external irradiation. The weighting is carried out in such a way that the effective dose equivalent would give rise to the same risk of induction of fatal cancer or serious genetic defects as a numerically equal whole body dose equivalent resulting from uniform irradiation (i.e., an effective dose equivalent of 5 mSv would give rise to the same risk as a DOSE EQUIVALENT of 5 mSv to the whole body from uniform irradiation).

ENVIRONMENT: (i) The surroundings (ii) All the conditions and influences surrounding an organism, human or otherwise, that affect its life, survival, and development.

FISSION PRODUCT: A NUCLIDE produced either by nuclear fission, or by the subsequent RADIOACTIVE DECAY of a RADIONUCLIDE produced by fission. Nuclear fission is the splitting of an atomic nucleus into two approximately equal parts, with the release of a large amount of energy.

FUEL RECYCLE WASTE: Waste resulting from fuel REPROCESSING.

GAMMA RAY: A quantum of electromagnetic radiation emitted by a nucleus during RADIOACTIVE DECAY, as a result of a transition from one of its excited energy levels to a lower level. Gamma rays have a shorter wavelength than X-rays, and easily penetrate body tissue.

GEOSPHERE: The upper, rigid part of the Earth's crust. It is assumed that a vault would be located in a section of the geosphere.

GRAY (Gy): The SI derived unit of ABSORBED DOSE. (1 Gy = 1 $J.kg^{-1}$).

IMMOBILIZATION: (i) In the case of USED FUEL, encapsulation of the fuel bundles by placing them in CONTAINERs and filling the remaining space with a MATRIX MATERIAL (ii) In the case of FUEL RECYCLE WASTE, incorporation of the waste in a MATRIX MATERIAL followed by encapsulation in CONTAINERs.

IONIZING RADIATION: Any radiation capable of displacing electrons from atoms or molecules, thereby producing ions. Examples are alpha, beta, and gamma radiation. Ionizing radiation may produce skin or tissue damage.

ISOTOPE: One of two or more NUCLIDEs that have the same number of protons in their nuclei. Different isotopes of an element have the same atomic number (number of protons) but different numbers of neutrons, hence different mass numbers.

MAN-SIEVERT (Man-Sv): The unit of COLLECTIVE DOSE EQUIVALENT to a population.

NATURAL BACKGROUND RADIATION: Radiation from natural sources which include cosmic rays (from outside the solar system and from the sun) and naturally occurring RADIONUCLIDEs in the Earth's crust, in the air, and in the body.

NUCLEAR FUEL WASTE: Includes USED FUEL and FUEL RECYCLE WASTE.

NUCLIDE: A species of atom characterized by its mass number, atomic number, and energy state.

PLUTONIC ROCK: A body of igneous rock that has formed beneath the surface of the Earth by consolidation from magma.

RADIOACTIVE DECAY: A spontaneous nuclear transformation in which particles or gamma radiation are emitted, or X-radiation is emitted following orbital

RADIONUCLIDE: A NUCLIDE that undergoes RADIOACTIVE DECAY.

RADIONUCLIDE MIGRATION: The movement of RADIONUCLIDEs through a medium by fluid flow and/or diffusion.

RECYCLING: The reuse of fissionable material, such as plutonium, after it has been recovered by chemical processing from USED FUEL.

REPROCESSING: The processing of USED FUEL to recover components, typically uranium and plutonium, that have further use as a fuel.

SI UNITS: Le Systeme International d'Unites. An internationally accepted coherent system of units based on the metric system.

SIEVERT (Sv): The SI derived unit of DOSE EQUIVALENT. ($1\ Sv = 1\ J.kg^{-1}$).

TRANSMUTATION: Nuclear conversion, transforming one NUCLIDE into another, naturally or artificially, (i) as a result of bombardment with IONIZING RADIATION or nuclear particles, or (ii) by RADIOACTIVE DECAY if the original NUCLIDE is radioactive.

USED FUEL: Nuclear fuel that has been used in a nuclear reactor and become highly radioactive.

VAULT: An underground excavation and its contents of immobilized USED FUEL or FUEL RECYCLE WASTE in CONTAINERs that are surrounded by BUFFER and BACKFILL.

ZIRCALOY: A trade name for a family of alloys containing zirconium as the main constituent. Zirconium is used to form the structural components of fuel bundles.

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