NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

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NWMO BACKGROUND PAPERS
3. HEALTH AND SAFETY

3-1 RADIOLOGICAL PROTECTION AND RADIOACTIVE WASTE MANAGEMENT

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NWMO Background Papers

NWMO has commissioned a series of background papers which present concepts and contextual information about the state of our knowledge on important topics related to the management of radioactive waste. The intent of these background papers is to provide input to defining possible approaches for the long-term management of used nuclear fuel and to contribute to an informed dialogue with the public and other stakeholders. The papers currently available are posted on NWMO's web site. Additional papers may be commissioned.

The topics of the background papers can be classified under the following broad headings:

1. **Guiding Concepts –** describe key concepts which can help guide an informed dialogue with the public and other stakeholders on the topic of radioactive waste management. They include perspectives on risk, security, the precautionary approach, adaptive management, traditional knowledge and sustainable development.
2. **Social and Ethical Dimensions** - provide perspectives on the social and ethical dimensions of radioactive waste management. They include background papers prepared for roundtable discussions.
3. **Health and Safety –** provide information on the status of relevant research, technologies, standards and procedures to reduce radiation and security risk associated with radioactive waste management.
4. **Science and Environment –** provide information on the current status of relevant research on ecosystem processes and environmental management issues. They include descriptions of the current efforts, as well as the status of research into our understanding of the biosphere and geosphere.
5. **Economic Factors** - provide insight into the economic factors and financial requirements for the long-term management of used nuclear fuel.
6. **Technical Methods** - provide general descriptions of the three methods for the long-term management of used nuclear fuel as defined in the NFWA, as well as other possible methods and related system requirements.
7. **Institutions and Governance** - outline the current relevant legal, administrative and institutional requirements that may be applicable to the long-term management of spent nuclear fuel in Canada, including legislation, regulations, guidelines, protocols, directives, policies and procedures of various jurisdictions.

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Summary

Radioactive waste is a by-product of a number of activities, such as electrical power generation, medical treatment, education, research and development, and various industrial/manufacturing activities. The waste produced is potentially hazardous to the public and to the environment if it were to be released in the process of handling, storage or following disposal. To minimize exposure to radiation, radiological protection technologies and operational procedures are put in place at the sites that will handle and store or dispose of radioactive waste.

This paper presents the radiation protection principles, technologies and operational procedures related to radioactive waste that are currently in use or are planned for managing radioactive wastes in Canada, with a particular focus on high-level waste.

The paper begins with an overview of what radiation is and why it is potentially hazardous. The three types of radioactive waste in Canada: high-level waste, low-level waste and uranium mine tailings, are described. The "defence-in-depth" concept and the use of multiple barriers are discussed as provisions for radiation protection when handling, storing and disposing of the various types of radioactive waste. The nuclear fuel cycle is described from the mining and milling of uranium ore to the decommissioning of the power generators that utilize the nuclear fuel. The waste produced at each step in the nuclear fuel cycle is listed with a brief explanation of how the public and the environment are being protected from exposure to the radioactive waste. Radioactive waste produced outside of electrical power generation typically falls into the category of low-level waste. The treatment of low-level waste in terms of radiological technologies and operational procedures are generally similar to those described in the nuclear fuel cycle. The scope of this paper does not include a discussion on naturally occurring radioactive waste (NORM).

A description is provided of the current management options for high-level waste, specifically the wet and dry storage methods. The elements of radiation protection are described as part of the Radiation Protection Programs that are in place at all nuclear facilities.

The long-term management solution for high-level waste in Canada by means of storage or disposal is currently under review. According to the mandate of the NWMO these options: deep geological disposal, centralized storage, and on-site storage, are management options serving different societal needs that will be investigated and are presented in this paper. In addition to these, reprocessing or treatment, and a number of disposal options are also considered and briefly described. A discussion has been included on the radiation protection technologies and operational procedures that may be in place for the long-term solutions to protect the public and the environment.

1 Introduction

Canada has been using nuclear technology for electricity generation for over fifty years, from research facilities and small prototype nuclear reactors in the early years to the present generation of CANDU reactors currently used to produce electricity. In addition, medical uses, educational programs, research and development and many industrial applications have taken advantage of the advances in nuclear technology. One of the by-products of these activities is radioactive waste.

If it is not properly handled, radioactive waste is potentially hazardous to the public and to the environment through the release of ionizing radiation. To minimize exposure to ionizing radiation, well-developed radiological protection principles including technologies and operational procedures are put in place at the sites that manage, handle, store and dispose of the waste.

This paper presents the radiological protection principles, technologies and operational procedures related to radioactive waste that are currently in use or are planned for managing the waste. Emphasis is placed on understanding the radiation protection requirements of the technologies and procedures specific to high-level waste management.

The following items are included in this paper to give the reader a better understanding of radiation protection as it relates to radioactive waste.

- A background on what ionizing radiation is and why it is hazardous (Section 1).
- A description of the types of radioactive waste (Section 1).
- The governing principles for radiation protection in Canada (Section 2).
- An illustration of the nuclear fuel cycle, listing the radioactive waste produced at each step and a brief overview of the radiological protection procedures and technologies in place at each step of the cycle (Section 3).
- Details of radiation protection during handling and storage of high-level waste (Section 4).
- The elements of the Radiation Protection Program that provide protection from high-level waste and are implemented at all nuclear sites (Section 5).
- A discussion on the possible long-term options for high-level waste storage or disposal and the radiation protection technologies and operational procedures associated with each option (Section 6).
- The laws and regulations that govern radiation protection of high-level waste handling and management (Section 7).

1.1 What is ionizing radiation and where does it come from?

"Radiation" is energy and can take the form of high-speed particles or electromagnetic waves.

“Ionizing radiation” is radiation that has enough energy to separate the electrons from the nucleus of an atom, thus “ionizing” the atom. It is released during the process of “radioactive decay”. Radioactive decay happens when an unstable atom spontaneously releases energy from its nucleus causing the atomic nuclei to change to a more stable state. The property of an element that undergoes radioactive decay is called “radioactivity”. An atom or nuclide that exhibits radioactivity is called a “radionuclide”.

Radioactivity is measured in “Becquerels” (Bq). 1 Becquerel equals 1 decay per second.

A common term used to understand the behaviour of a radionuclide is its “half-life”. Half-life is the time required for half the nuclides of a sample of radioactive material to decay. In practical terms, “half-life” is the time required for the radioactivity of a sample to be reduced to half. For example, technetium-99 has a radiological half-life of 6 hours, which means that half the atoms in a sample of technetium-99 will decay in that much time.

We are exposed to ionizing radiation everyday. Radiation is found everywhere; it is in air, soil, and food, inside our houses and even in our own bodies. About 76% of the total is naturally occurring radiation. It comes from cosmic and terrestrial radiation, radon[*], and internal radiation from inside the human body. “Cosmic radiation” is radiation originating from space. Nuclear reactions drive the universe providing the power to make stars shine and give light and warmth to the planets. “Terrestrial radiation” consists of radioactive elements found in all the rocks that make up our planet. These elements have been present since the planet was formed approximately 4.5 billion years ago and were produced and are still being produced in the sun and other stars. The centre of the earth contains heat generated by radioactive elements, specifically uranium, thorium and potassium. “Radon” is a colourless and odourless gas formed from the decay of radium which itself is a decay product of uranium. It is constantly being produced and released from the ground and is always present in the air. “Internal radiation” is inside our own bodies and comes from the intake of potassium and carbon from the food we eat.

The remaining 24% of radiation is man-made radiation, coming from sources like medical x-rays, nuclear medicine, and others. “Others” usually represent consumer products (i.e., colour televisions and smoke detectors), the nuclear power industry, and fallout from nuclear weapons testing. The annual average exposure to radiation differs from region to region or country to country, depending on a multitude of factors, such as the geographical location, and/or the extent of use of man-made radiation for various applications. Figure 1 shows the sources of average annual exposure to radiation in Canada (Reference 1). Table 1 shows a comparison of the radioactivity of various natural and man-made materials.

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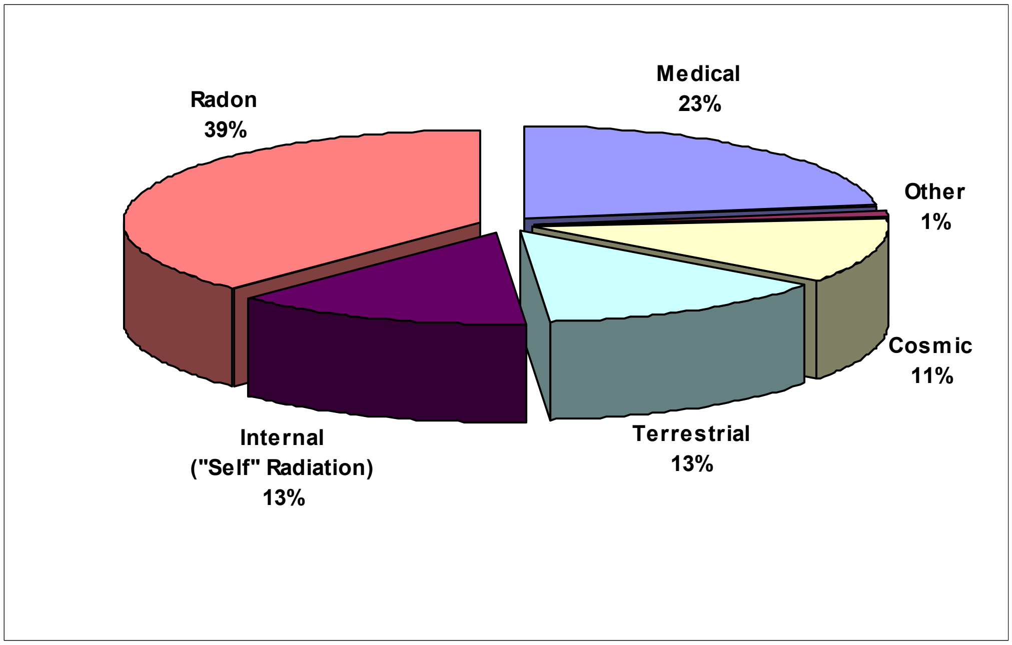
[*] Radon, although of terrestrial origin, is usually mentioned separately to emphasize its significant contribution to the overall background radiation.



Source: Reference 1.

Figure 1 – Sources of Average Annual Radiation Exposure in Canada

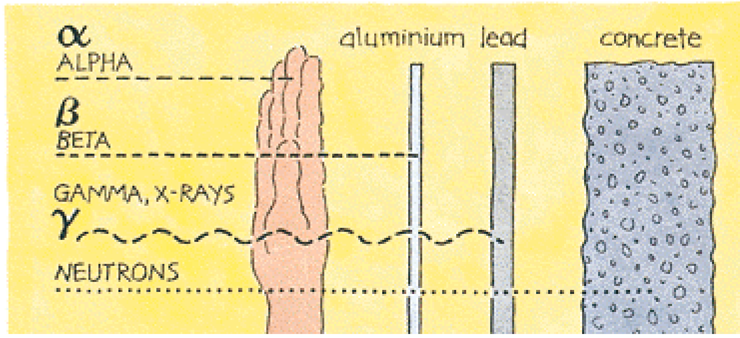
Table 1 - Radioactivity of Some Natural and Other Materials

1 adult human (100 Bq/kg)	7,000 Bq
1 kg of coffee	1,000 Bq
1 kg superphosphate fertiliser	5,000 Bq
1 household smoke detector (with americium)	30, 000 Bq
Radioisotope for medical diagnosis	70 million Bq
Radioisotope source for medical therapy	100, 000, 000 million Bq
1 kg 50-year old vitrified high-level nuclear waste	10, 000, 000 million Bq
1 luminous Exit sign (1970s)	1, 000, 000 million Bq
1 kg uranium	25 million Bq
1 kg uranium ore (Canadian, 15%)	25 million Bq
1 kg low level radioactive waste	1 million Bq
1 kg of coal ash	2,000 Bq
1 kg of granite	1,000 Bq

Source: "Radiation and Life", Uranium Information Centre website; http://www.uic.com.au/ral.htm.

1.2 What are the different types of ionizing radiation and what can they penetrate?

Gamma rays, x-rays, alpha and beta particles, and neutrons are all types of ionizing radiation. Figure 2 shows different types of radiation and what they can penetrate. For example, skin can stop alpha particles and low energy beta particles, whereas a thin aluminum foil will be sufficient to stop beta particles. Neutrally charged and higher energy radiation, such as neutrons, gamma rays, and x-rays will penetrate through the body and will require a lead or concrete shield (a few centimetres thick) to stop them. Once stopped, the radiation energy is converted to heat energy.



Source: "Radiation and Life", Uranium Information Centre website; http://www.uic.com.au/ral.htm.

Figure 2 –Types of Radiation

1.3 How does radiation affect human health?

Exposure to ionizing radiation produces a variety of biological effects depending on the amount of radiation received and the tissue or organs that receive it. Exposure to low amounts of radiation can damage DNA, which the cellular repair mechanisms then fix. If the DNA damage is not repaired the cell may die or malfunction in some manner possibly leading to cancer as well as genetic disorders (Reference 2). The first signs of radiation exposure can be seen as temporary (i.e., reversible) chromosomal changes and temporary changes in white blood cell count. The levels of radiation at which we see these changes are higher than the regulatory limits. Exposure to very high amounts of radiation in a short period of time can result in damaged DNA that cannot be repaired, burns, Acute Radiation Syndrome (ARS) and even death.

Human exposure to ionizing radiation can occur in the following ways:

- Inhalation of radionuclides suspended in the air;
- Ingestion of radionuclides in foods and drinking water;
- Absorption of radionuclides directly through the skin; and
- Direct external exposure from radiation emitted in the immediate environment.

The amount of ionizing radiation, or "dose", received by a person is measured in terms of the energy absorbed in the body tissue. It is expressed in "Gray" (Gy). 1 Gy is 1 Joule deposited per kilogram of mass. The biological effects are different for exposure to different types of radiation, even if the amount of exposure, expressed in Gy, is the same. This is known as the Relative Biological Effectiveness or RBE of the radiation. For example, 1 Gy of alpha radiation (an RBE in humans of approximately 20) will have a greater effect than 1 Gy of beta radiation (an RBE in humans of 1). However, when we talk about radiation effects, we express the radiation as "effective dose", in a unit called "Sievert" (Sv). A Sievert is simply a Gy multiplied by the RBE of the radiation type. Thus, regardless of the type of radiation, 1 Sv of radiation produces the same biological effect in any particular type of tissue.

The amount of radiation each Canadian receives on average, every year, is approximately 2.6 mSv* (Reference 1). This is typically referred to as the “annual background dose”, with 76% or 2.0 mSv coming from natural radioactivity and the rest of about 0.6 mSv from medical and other sources. Commercial aircraft crew, for example, receive 1 to 2 mSv/a from flying. Concorde crew members receive about 2.5 mSv/a from flying (Reference 1). It was estimated that astronauts received a dose of approximately 5 mSv of cosmic radiation in 12 days of space flight (Reference 1).

According to the U.S. Nuclear Energy Institute, the increased dose received in one year while living within 50 miles of a nuclear power plant is approximately equal to the amount of radiation found in one banana. Furthermore, it is estimated that living for one month near the proposed U.S. repository for high-level nuclear waste at Yucca Mountain, would be also equivalent to the radiation received from eating one banana (Reference 3).

1.4 What is radioactive waste and why is it hazardous?

Radioactive waste is gaseous, liquid, or solid material containing radioactive materials that are generated by activities associated with the nuclear power industry, research and education, and by the medical and manufacturing industries, etc. These materials are considered waste when they are no longer useful for their original purpose.

Radioactive waste is potentially hazardous as it may release ionizing radiation; the effects of which were discussed in Section 1.3.

1.5 How is radioactive waste classified?

Radioactive waste can be classified based on different criteria, such as source, physical state, radioactivity levels, half-life of the radionuclides, amount of long lived or short lived radionuclides, intensity of radiation, or toxicity. For example, Environment Canada and the Canadian Nuclear Safety Commission (CNSC) classify radioactive waste according to its radiological hazard, using the following three categories (Reference 4, 5):

1. *High-level waste*: This is recognized internationally as representing used fuel that is removed from a nuclear reactor. A common term for used fuel is “spent fuel”.

2. *Low-level waste*: This includes all forms of radioactive waste that is not spent fuel and is not waste from uranium or thorium mining and milling. Low-level waste is further categorized for the purpose of managing, handling and long-term storage.

3. *Uranium Mine Tailings*: Radioactive waste generated during the mining and milling of uranium ore (Reference 4).

* 1 mSv = 0.001 Sv.

1.6 Where does radioactive waste come from?

Radioactive waste comes from nuclear reactors, hospitals that use radioactive materials for diagnosis and medical therapy, research and development, agricultural, and industrial applications. Figure 3 illustrates all of the major sources of radioactive waste in Canada. Data presented in Figure 3 is further broken down by site in Table 7 in Appendix 3.

Power Generation (Mines, Fuel Production, Nuclear Reactors, Historic Waste)

Radioactive wastes are produced in all stages of power generation. As described in Section 3, the nuclear fuel cycle produces uranium mine tailings during mining and milling and produces low-level wastes during refining, fuel production, nuclear reactor operation, and decommissioning of nuclear reactors and other facilities. High-level waste is produced during nuclear reactor operation. Details on the types of wastes produced from power generation are given in Sections 3.1 through to 3.5. High-level waste from power generation is presently stored in Canada in wet and dry storage facilities at the reactor sites. Low-level wastes are compacted and put into steel containers that are stored in a variety of facilities such as concrete trenches, in bunkers, in the reactor building, and in in-ground and above-ground storage units.

Research and Education

Radioactive waste is produced at reactors operating at various Canadian universities. University of Toronto, McMaster University, Royal Military College, École Polytechnique, Dalhousie University, University of Alberta, and Saskatchewan Research Council have all operated reactors for educational research (Reference 5). Five of the seven reactors used for educational purposes are a reactor design called “SLOWPOKE”. The remaining two reactors are sub-critical assemblies* in which the core sits inside a pool of water. These reactors produce both low-level wastes and high-level wastes as by-products.

In addition to the seven reactors used for educational purposes at the universities, there are two research reactors currently operating at Chalk River Laboratories. One is called the “National Research Universal“ (NRU), and the other is the “Zero Energy Deuterium-2” (ZED-2) (Reference 5). These reactors use high-enriched fuel or low-enriched fuel and produce low-level waste as a by-product. Research reactors that were used in the past and have been decommissioned also have low-level wastes that are being stored. Similar to power generation, the high-level wastes from research reactors are stored in dry storage facilities at the Chalk River site. Low-level wastes are also stored on-site at Chalk River.

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* A sub-critical assembly is one whose geometry does not allow criticality to occur. Criticality refers to the state of a nuclear chain reaction when the reactivity is greater than zero.

Industrial and Agricultural Use

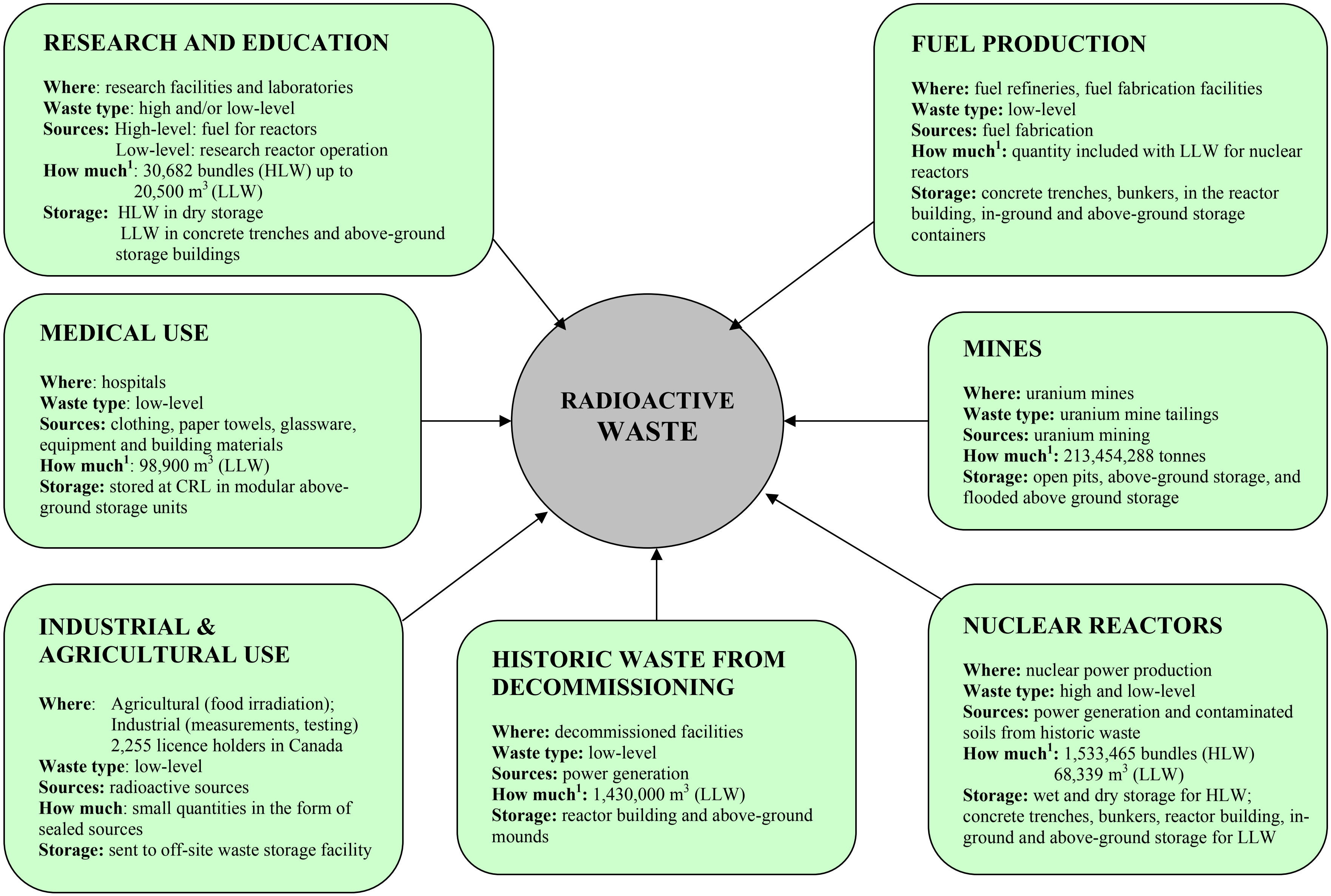
In industrial applications, radiography is used to inspect and test various materials and equipment (i.e., to inspect a pipe weld and ensure there are no cracks in the weld). As well, radioactive waste sources are used by over 2000 licensees.

Food irradiation is performed to kill bacteria and moulds and prevent illness due to contaminated foods. Parasites and micro-organisms are killed or made sterile using commercial food irradiators.

In agriculture, radiation is used to increase disease resistance, improve yields, strengthen plants, and increase winter hardiness in crops. Low-level wastes are produced in agro-industrial use.

Medical Use

The medical field uses radioisotopes for sterilization, cancer therapy, and as tracers for medical research, diagnoses and therapy (Reference 5). Currently MDS Nordion has two small reactors that produce radioisotopes for medical use located at chalk River Laboratories. MDS Nordion also has several accelerators at the University of British Columbia (UBC) where they produce radioisotopes for medical and research purposes and which are sold around the world. The radioactive wastes produced during radioisotope production at Chalk River, UBC and radioisotope use in the medical field are primarily low-level wastes. They consist of clothing, paper towels, glassware, equipment and building materials. The wastes are sorted and compacted into steel containers that are stored in modular above-ground storage units at the Chalk River Laboratories site in Ontario.



1. Quantities are reported to December 31, 2001 for all radioactive wastes.

Figure 3 – Radioactive Waste Sources in Canada

2 Radiation Protection in Canada

Section 1 has provided a background on what radioactive waste is, why the ionizing radiation it releases is hazardous, and the sources that generate the waste. This section will explain the principles that govern the protection of workers, the public and the environment from exposure to radiation from radioactive waste.

In Canada, the principles followed to make sure that the people and the environment are not affected by the radiation from radioactive waste are:

1. Reduce the amount of radiation and radioactive waste (minimize source).

2. Prevent release of radiation or material from source (minimize release).

3. Apply protection to people and environment from the radiation (minimize exposure).

A key element of radiation protection is the setting of exposure limits. That is to say that limits are set on how much radiation a worker and the public may be exposed to. In Canada, there are specific laws and regulations that limit the amount of allowable exposure to ionizing radiation for any person. The government of Canada sets the limits for how much ionizing radiation a worker and the public can be exposed to based on Canadian and international experience on the effects of ionizing radiation exposure. The exposure limits and allowable doses are listed in Section 7.2 of this report. These limits are in agreement with international guidelines provided by the International Commission on Radiological Protection (ICRP, Reference 6) and the International Atomic Energy Agency (IAEA).

Another key element of radiation protection is ALARA, meaning that the dose to workers and the public during nuclear operations is maintained "As Low As Reasonably Achievable". The ALARA principle is internationally accepted and is put in place through radiation protection programs (Reference 5).

The Canadian regulations for radiation protection state that facilities that use or handle radioactive material as well as produce radioactive waste must have a program in place to minimize exposure to the workers, the public and the environment. Program elements that need to be in place at the facilities are (Reference 5):

- management control over work practices;
- personnel qualification and training;
- control of occupational and public exposure to radiation;
- planning for unusual circumstances; and
- knowing the quantity and concentration of any nuclear substance released.

The applicant for a licence must also prepare a plan for what is done to such facilities and sites when they are to be shutdown and dismantled ("decommissioned"). This plan is part of the process for licensing of any nuclear facility including storage facilities in Canada and must be approved prior to the facility receiving a construction licence.

Facilities that currently handle radioactive waste in Canada must have as part of their licensing requirements implemented Radiation Protection Programs to protect the workers, the public and the environment. Details on the Radiation Protection Program and the ways in which protection against ionizing radiation exposure is provided at all nuclear facilities and nuclear waste storage sites are given in Section 5.

2.1 Defence-in-Depth

A useful tool to ensure that the risk from radioactive waste is minimized is to follow a strategy called "defence-in-depth". The defence-in-depth strategy is based on having many nested levels of protection both in design and in operating procedures. In design, the strategy for defence-in-depth is to prevent accidents and, if an accident does occur, to limit its potential consequences. Using the defence-in-depth concept for everyday operations, plans are put in place at the facilities to deal with emergencies or potential accidents in the facility that could cause exposure to radiation. Based on government guidelines, the strategy must also show the most efficient ways in which the operation of the facility will prevent and reduce the effects of accidental releases of nuclear substances.

Defence-in-depth is structured in five levels. The strategy consists of implementing a series of barriers and protective measures such that the risk from a potential accident is minimized. Each barrier or protective measure represents a "level" of protection where if one level fails, the next level comes into play. Each level consists of barriers that are designed to ensure against failure.

Defence-in-depth has two main objectives: accident prevention and accident mitigation (Reference 7).

Accident Prevention

Facilities are designed with an appropriate level of quality assurance (QA) and components are fabricated with quality control consistent with licence requirements. Monitoring and feedback systems are utilized within the facility to continuously provide information on deviations during normal operations, thus preventing accidents by catching deviations before they turn into accidents. Consistent with an approved QA program, equipment and components within the facility are regularly tested and maintained to ensure they continue to function as designed. In some instances, duplicate or redundant components are used so that if one fails, the other will continue to operate. As a back-up to monitoring and feedback, safety systems are used to respond in the case of a deviation from normal operations.

Accident Mitigation

Accident mitigation includes accident management, use of engineered safety systems, and off-site countermeasures. Accident management entails having planned and approved operational practices, and having safety procedures and steps in place to deal with potential accidents. The engineered safety systems are features such as the physical barriers mentioned earlier and ensuring radioactive material is confined.

Figure 4 illustrates the defence-in-depth concept for a nuclear power plant (Reference 7). This illustration can be applied to a nuclear waste facility. The first row of the figure shows the two strategies of accident prevention and accident mitigation. The second row shows the state of the plant and whether the state is normal operation, operation with anticipated occurrences, complex operation (where the plant is being operated close to its design limit), complex operation with potential accidents, and the post-accident situation. Accident prevention is the goal for normal operation. During complex operation both accident prevention and accident mitigation strategies are followed. For more severe accidents and post-accident situations accident mitigation strategies are put in place. The third row of the figure lists the five levels of defence-in-depth relating to each state of plant operation. The objectives that must be achieved at each level are listed in the fourth row. For example, during normal operation the objective is to prevent abnormal operation and failures. The features in place to achieve each objective at the five levels are shown in row five. For example, under level 4 the objective is to control more severe accidents and mitigate the consequences of the accidents, which can be achieved by having accident management in place at the site. The procedures in place to control each level are listed in row six. For example, for level 5, where the plant is in the post-accident state, emergency operating procedures are followed to mitigate the situation.

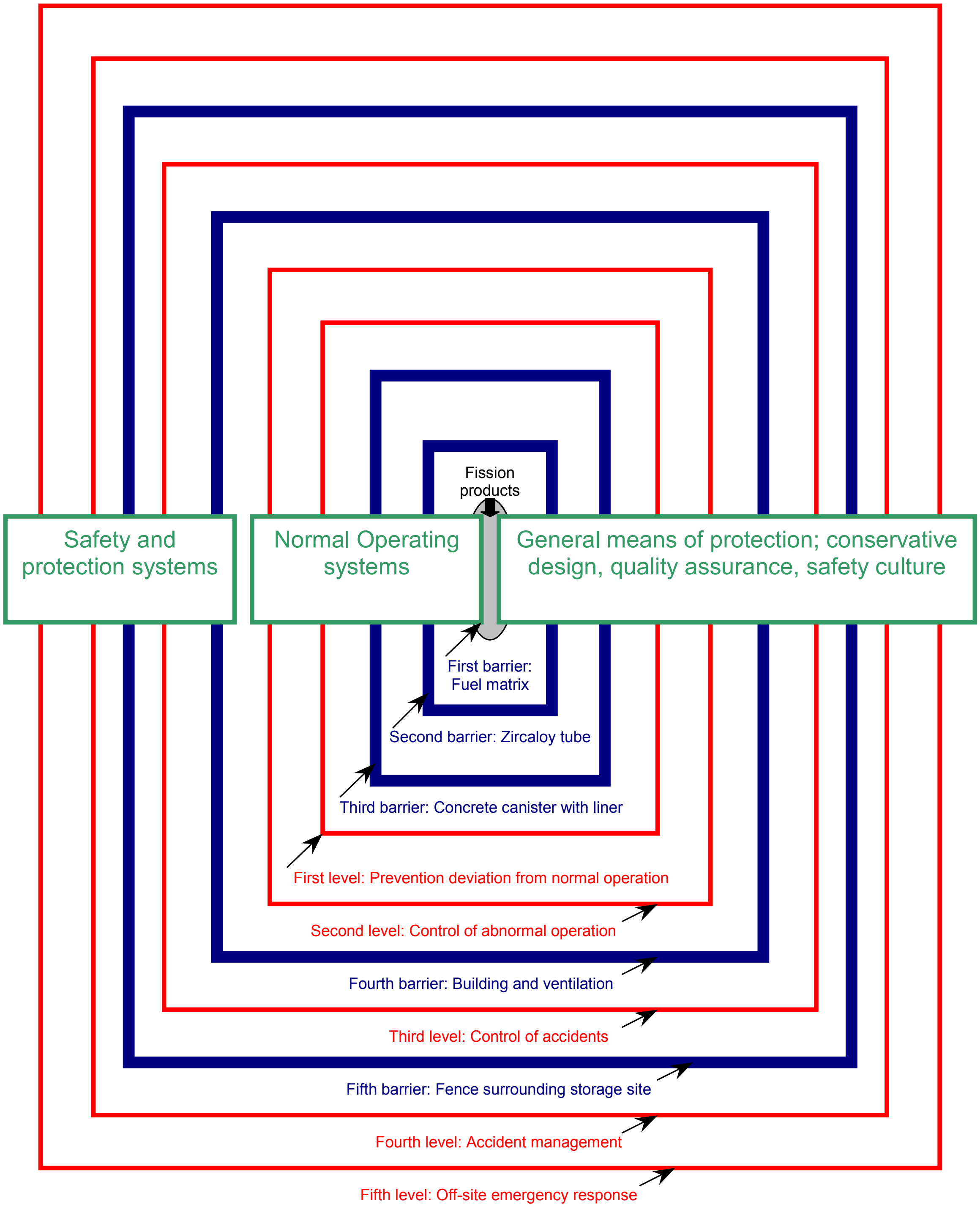
Strategy	**Accident Prevention**			**Accident Mitigation**	
State of the plant	Normal operation	Anticipated operational occurrences	Complex operation	Accidents beyond complex operation	Post accident situation
Level of defence-in-depth	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Objective	Prevent abnormal operation and failures	Control abnormal operation and detect failures	Control accidents	Control more severe accidents and mitigate consequences of accidents	Mitigate radiological consequences of significant releases of radioactive materials
Features	Conservative design and quality in construction and operation	Control, limiting and protection systems, monitoring and feedback systems	Safety features and accident procedures, monitoring and feedback systems	Accidents management	Off-site emergency response
Procedures	Normal operating procedures		Emergency operating procedures	Emergency operating procedures	

Source: Adapted from Reference 7.

Figure 4 – Overview of Defence-in-Depth

2.2 Multiple Barriers

The principle of defence-in-depth is implemented by using a series of barriers that must be breached in turn before harm can occur to people or the environment. These barriers are physical so that radioactive material can be confined. The five levels of defence-in-depth as discussed before are incorporated using multiple barriers. Figure 5 shows the relationship between multiple barriers and the five levels of protection of defence-in-depth for a dry storage facility holding nuclear fuel waste (Reference 7).



Source: Adapted from Reference 7.

Figure 5 – Relationship Between Multiple Barriers and Defence-in-Depth for Dry Storage Sites

At the centre of Figure 5 is the high-level radioactive waste. The fission products are the radioactive material generated as a result of power production. The fuel waste is only a risk if the fission products were to escape into the environment, so the goal is to keep them contained. The first three physical barriers that provide this protection consist of the ceramic material that makes up the fuel matrix, the Zircaloy tubing in which the fuel pellets are encased, and the concrete canister that holds the fuel bundles (see Section 4.3). The first level of protection in defence-in-depth is a combination of conservative design, quality assurance and an overall safety culture at the facility. The second level of defence-in-depth is the control of operation, including response to abnormal operation or indication of systems failures. The fourth physical barrier is the building and the ventilation systems. The first two levels of protection and the four barriers exist as part of the normal operating systems and form the basis of the defence-in-depth strategy, ensuring accident prevention.

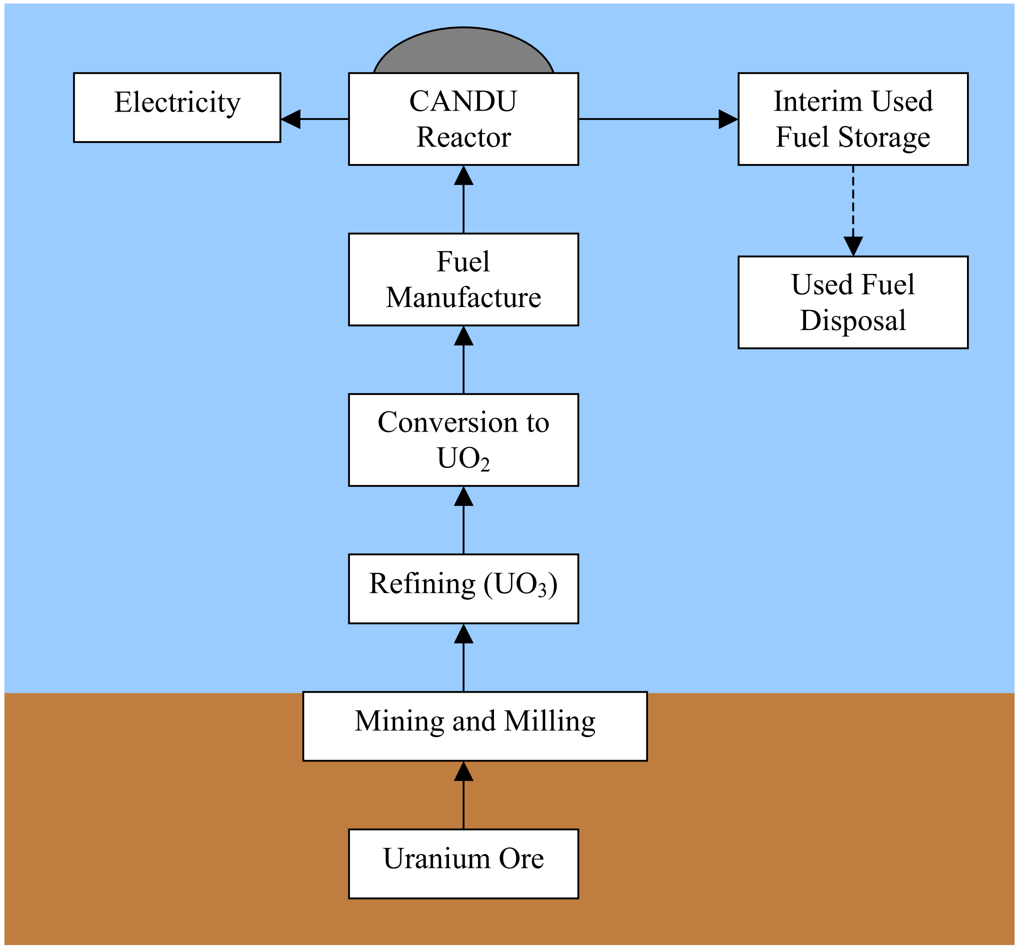
The third level of protection focuses on controlling potential accidents. Systems that have additional safety features to protect against potential accidents are put in place at the facility. A fifth physical barrier to protect during potential accidents that separates the storage facility and keeps it isolated is the fence that surrounds the facility and bounds the protected area. The fourth and fifth levels of protection in defence-in-depth are in place for accident mitigation. Procedures are in place to deal with potential accidents, as well as incidents and emergencies (see Section 5.9).

Section 2 has described the governing principles for radiation protection illustrating the defence-in-depth concept and the relationship between defence-in-depth and multiple barriers. Section 3 will present the nuclear fuel cycle, providing a brief overview of the radioactive wastes produced at each stage in the cycle and the radiation protection technologies and operational procedures in place to protect the workers, the public and the environment.

3 The Nuclear Fuel Cycle

The process of producing electricity from nuclear energy has a number of steps that are followed from the uranium mines to the waste storage sites. The entire process is called the “nuclear fuel cycle”. In Canada, the nuclear fuel cycle begins with the mining of uranium ore from the ground. The ore goes through a mining and milling process, a refining and conversion process and then the uranium is manufactured into nuclear fuel. The fuel is loaded into the reactors where nuclear reactions generate heat which is used to convert water into steam and via steam turbines into electricity. Once the fuel is consumed and can no longer produce electricity, it is removed from the reactor and is stored on-site for a number of years while its radioactivity decays and the resulting heat produced is reduced (Reference 1). Figure 6 illustrates the nuclear fuel cycle in Canada.

Most radioactive wastes are by-products of the nuclear fuel cycle. At every stage of the fuel cycle, radiation protection measures are incorporated in the facilities and procedures are in place to handle and store the radioactive waste, whether it is uranium mine tailings, low-level waste, or high-level waste. An understanding of the nuclear fuel cycle provides a background for understanding why and when various radiological protection technologies and operational procedures are used to protect workers, the public and the environment from exposure.



Source: Adapted from Reference 1.

Figure 6 – The Canadian Nuclear Fuel Cycle

3.1 Uranium Mining and Milling

Uranium ore is mined in Canada through a mining process that uses an open-pit method or an underground mining process with tunnels. The ore is transported to the mill directly or at some of the high grade mines it is crushed, ground and mixed with water to form a slurry that can be pumped to the surface to be transferred to a mill. At the mill, uranium oxide (U_3O_8) is leached from the ore using sulphuric acid and dissolved. The solution is extracted and dried to form a yellow powder (called "yellowcake") that contains 70-82% uranium by weight (Reference 1). The leftover crushed rock and chemical sludges from the mining and milling process are considered radioactive waste and are referred to as "tailings". The waste tailings are put in contained areas, such as excavated underground mine workings or mined out pits, and are allowed to flood to reduce acid generation and the release of gamma radiation and radon gas. Waste rock may also contain low levels of natural radioactivity and is managed appropriately. Systems are put in place at the waste sites to monitor the effluents for chemical and radiation levels. The yellowcake product from the mining and milling is then shipped to a refinery for further processing.

3.2 Refining and Conversion

At the refinery, the yellowcake in order to form fuel for CANDU reactors goes through a process to form uranium trioxide (UO_3). The process involves dissolving the powder in nitric acid to form a solution, removing impurities from the solution, evaporating water from the solution, and then heating the solution to form UO_3 powder. The UO_3 powder is then taken to the conversion plant and dissolved in nitric acid to form UO_2, forming a brown powder. Other yellowcake is converted to a uranium hexaflouride that is shipped off for enrichment for use in light water reactors. The radioactive wastes produced during the refining and conversion processes are low-level wastes consisting of contaminated scrap lumber, pallets, rags, paper, cardboard, rubber, plastic, contaminated air filters, fibreglass, ductwork, floor sweepings, sandblast sand, insulation, sample bottles, scrap metal, anodes and chemical sludge (Reference 8).

In the past, wastes from refineries and conversion facilities were managed by means of direct in-ground burial. This practice was discontinued in 1988. Today, in areas where these facilities still exist, the seepage and runoff water from the waste management facilities where in-ground burial was used is collected and treated prior to discharge. The waste now being produced is drummed and stored in warehouses pending the establishment of an appropriate disposal facility (Reference 8). The sites holding low-level waste are regularly inspected and monitored to ensure hazard levels remain acceptably low and that contaminants are not released to the environment (Reference 5). The volume of waste produced has been greatly reduced by recycling and reuse of the material.

3.3 Fuel Fabrication

The fuel fabrication process begins by sintering UO_2 in a hydrogen atmosphere at 1800°C, forming ceramic cylindrical pellets that are about one centimetre in diameter and two centimetres long. Thirty (30) pellets are placed inside a long tube of Zircaloy metal (often referred to as a “pencil”). The tubes are then assembled into fuel bundles as shown in Figure 7. The radioactive wastes produced during fuel fabrication are low-level wastes consisting of contaminated soils, rags, paper, gloves, oils, oil sludges, equipment, and construction materials (Reference 8). Low-level wastes are decontaminated if possible and reused to reduce waste quantities. For example, the fuel pellets are shaved to create perfectly cylindrical forms and the shavings produced during this process are collected, dried and pressed and sent to the refining and conversion facilities for reuse. Remaining waste is consolidated at waste sites and placed in drums for storage, or into mounds on drainage pads and under filtration covers on access-controlled sites. Protective clothing and equipment is used for handling radioactive wastes (Section 5.6). Workers wear dosimeters (Section 5.4) and have respiratory equipment (Section 5.6) available for use while handling the waste. The fuel fabrication facility has monitoring systems in place to measure radiation levels and take samples of the air (Section 5.5 and 5.11). The sites holding low-level waste are regularly inspected and monitored to ensure hazard levels remain acceptably low and that contaminants are not released to the environment (Reference 5).

Source: CANTEACH website; http://canteach.candu.org/.

Figure 7 – Nuclear Fuel Bundle used in CANDU Reactors

3.4 Power Generation

The fresh fuel used in a nuclear reactor is shipped from the supplier to the nuclear reactor site. The fuel used in CANDU reactors in Canada comes in the form of bundles and is approximately 0.5 m long. A CANDU fuel bundle is shown in Figure 7.

The fresh fuel is shipped and stored until use, in containers that hold multiple bundles. The containers are unloaded from the truck into a new fuel storage area on the nuclear reactor site. As the new fuel has not yet been put into the reactor, it is not highly radioactive and therefore it is safe for humans to handle. Typically, if fuel bundles are handled, there is no radiation protection equipment required, except for gloves, which are necessary to protect the fuel from oils or moisture. The new fuel storage area contains a radiation monitoring system that alarms if the radiation fields rise unacceptably.

The new fuel is remotely loaded into a machine and transported to the reactor. The machine moves through the contained space to where the reactor sits. The contained space has monitoring systems that detect radiation levels. As well, monitoring systems in adjacent rooms (next to or above) have monitors to warn workers of potential exposure. The monitoring systems in place are described in Section 5.5.

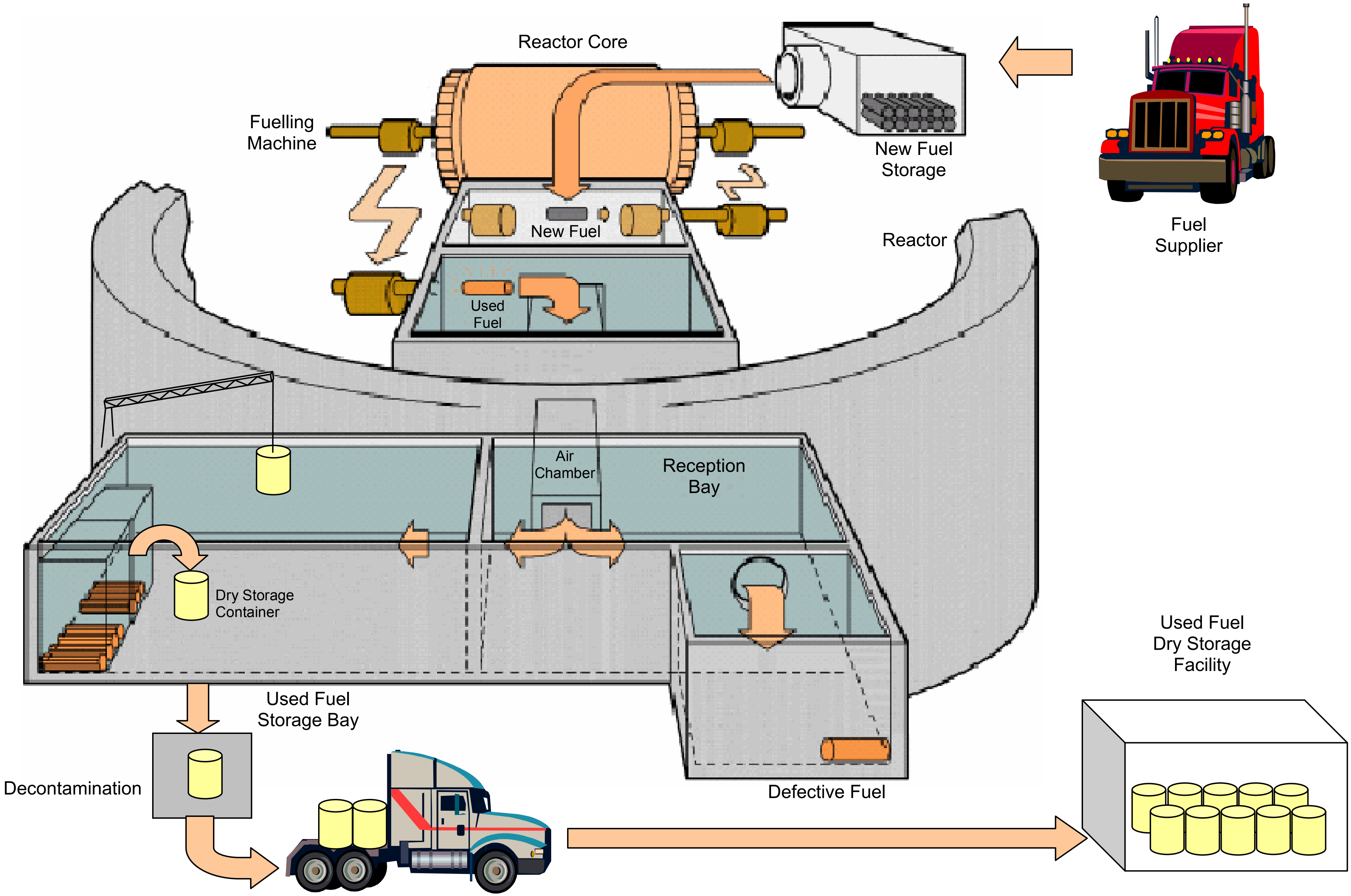


Figure 8 – CANDU Fuelling Process

The machine then loads the fuel into the reactor. While in the reactor the fuel fissions and it is in this process that energy is released. During the loading of fuel into the reactor, the fuel that has been used up is removed from the reactor using the same type of machine connected to the other side of the reactor. The machine that takes out used fuel or “spent fuel” is filled with water to provide fuel cooling, as it is highly radioactive and at a very high temperature.

Figure 8 illustrates the fuelling process in a CANDU reactor.

In addition to high-level waste, power generation also produces low-level wastes consisting of paper, plastic, rubber, cotton, wood, organic liquids, plastic suits, fibreglass, metal pieces, empty drums, filters, light bulbs, cable, used equipment, metals, construction debris, absorbents, ion exchange resins, reactor core components, and retubing wastes (Reference 8).

Low-level waste is either sent to a supplier for reuse, or is sent to a licensed storage facility, such as Chalk River Laboratories in Ontario. Handling of low-level waste is the same as that described in Section 3.3.

High-level waste storage is further discussed in Section 4, with the radiation protection elements described in Section 5 and disposal discussed in Section 6.

3.5 Decommissioning

Once the reactor can no longer be used to produce electricity it is “decommissioned” and dismantled. At this stage only low-level radioactive wastes are generated and they consist of paper, plastic, rubber, cotton, wood, plastic suits, fibreglass, metal pieces, filters, used equipment, absorbents, ion exchange resins, active drain wastes, decontamination solutions, and concrete (Reference 8).

Low-level radioactive wastes resulting from reactor operations are stored in waste management facilities located at reactor sites. Prior to storage, the volume of the wastes may be reduced by incineration, compaction or baling. There are facilities for the decontamination of parts and tools, cleaning protective clothing, and the refurbishment and rehabilitation of equipment (Reference 8).

Atomic Energy of Canada Limited’s (AECL) research facilities at Whiteshell and Chalk River, and at prototype power reactor sites (Douglas Point, NPD, and Gentilly-1), are now partially decommissioned and are in a state of “storage-with-surveillance”. This surveillance period is to allow for the decay of radioactivity in the reactor, thus reducing radiation dose to workers involved in the final dismantlement (Reference 9). University of Toronto has also completed decommissioning its research reactor and sent its radioactive waste to Chalk River Laboratories for storage.

Some uranium mining facilities are also going through the decommissioning phase, like those in the Elliot Lake mining camp including Stanrock and Denison (Denison Mines Limited), the Quirke, Panel and Stanleigh mines (Rio Algom Limited), mines in the Bancroft area including Dyno and Madawaska, and several uranium mining facilities in Northern Saskatchewan including Gunnar, Lorado, Beaverlodge and Cluff Lake.

Decommissioned facilities are monitored and managed for continued safety of the sites.

Radioactive waste collected from the mining and milling facilities prior to 1980 is considered low-level “historic” waste. The federal government has commissioned the Low-level Radioactive Waste Management Office (LLRWMO) to manage the cleanup and long-term storage or disposal of these wastes. In the Town of Port Hope, Ontario, where historic waste associated with refining of uranium and radium resides, the LLRWMO has established temporary holding facilities for radioactive wastes uncovered during routine excavation within the town.

4 High-level Waste Handling and Storage

While a brief overview has been provided of the nuclear fuel cycle and the handling and storage methods used for the radioactive wastes produced as by-products of the cycle, the focus of this paper is on high-level waste. A more detailed discussion regarding handling and storage of high-level waste is presented here.

There is currently no agreed disposal solution for high-level waste. As such, the fuel is transferred using remote handling equipment from the reactor to pools designated for storage of the nuclear fuel. This is considered "wet storage" and the large pools and buildings housing the pools are the "wet storage facilities". After several years in wet storage the fuel has decayed sufficiently to be transferred to a dry storage facility, normally a building containing above-ground dry storage canisters.

The following sections describe the wet and dry storage facilities and the radiation protection measures taken to provide protection to the workers, the public, and the environment during the handling and storage of the waste.

Table 4 and Table 5 in Appendix 1 list the sites that are currently storing high-level waste and the type of waste they are storing.

4.1 Wet Storage

The spent fuel travels in a machine to the "reception bays", where it is unloaded into a large pool of water. Unloading takes place through an "air chamber", where radioactivity levels of the air are measured (see Section 5.11). If the fuel that is used in the reactor is defective it is identified in the air chamber or within the reactor itself using a Gamma Fission Product (GFP) monitoring system. The GFP system checks the radioactivity levels in the coolant in the reactor core. If the radioactivity levels are found to be higher than expected, then the source of the radioactivity is traced and the fuel bundle is removed from the reactor core. Defective fuel bundles are visually inspected at the nuclear facility in part of the main storage bay using underwater cameras. The visual inspection may indicate the need for further inspection at special off site facilities. If offsite inspection is required, the fuel is loaded into a transportation flask and shipped to these facilities. Transportation flasks have thick dense walls to prevent radiation from escaping into the environment. See Section 5.10 for details on packaging and transportation.

The reception bay is a large pool of water that provides cooling for the bundles, as they are hot when they are removed from the reactor, and also provides shielding from the radiation given off by the bundles. While in the reception bay, the fuel is transferred underwater into modules that hold multiple bundles. Once a module is full it is moved remotely into the main storage bay area, referred to as a "wet storage facility". The wet storage facility includes a large pool of water with a mechanical crane above the water, racks in the water and monitors, among other equipment. The water column between the surface and the module provides cooling for the heat generated by the decaying spent fuel and shielding from the radiation given off. The radiation monitoring systems in place include gamma monitoring and air monitoring systems (described in Section 5.5) to monitor the radiological conditions.

Workers can go into the wet storage area as long as they have the proper protective equipment (see Section 5.6), and monitoring devices, such as dosimeters (see Section 5.4), and are qualified to be in that area (see Section 5.8). Typically, workers are required to wear protective boots, hard hats and dosimeters in the wet storage area during normal operation. The pool sits in a big concrete building with a stainless steel liner that is designed to prevent leaking through to the concrete. If there is a leakage in the liner, the pool has a special drainage system that holds the water and traces where it came from so that the liner can be fixed to stop further leakage to the concrete part of the pool. The water in the pool is circulated through a cooling system that also purifies the water to minimize the radiation fields and the amount of radioisotopes in the water.

The defence-in-depth strategy is applied at the wet storage sites by having concrete buildings, a steel liner in the pool, monitored drainage system with a process for repair, ventilation systems, monitoring of radiation levels and the air, protective clothing for workers, radiation protection procedures, and worker training in radiation protection. These barriers protect the workers at the facility and protect the public by minimizing releases to the environment.

4.2 Transfer from Wet to Dry Storage

The bundles stay in the pool for about six to ten years. After this time they are moved to a “dry storage” facility.

The fuel bundles are placed inside of steel-shelled containers, which are then placed inside of large concrete structures, called “canisters”, with walls that are one-metre thick. The dry storage canisters are brought to the wet storage facility, lifted by the crane above the pool, and immersed into the pool. Figure 9 and Figure 10 show dry storage canisters used at the Pickering and Bruce storage sites. The modules are placed inside the canister and the canister is sealed tight. The canister is then pulled out of the pool using the crane and placed in an area next to the pool to be decontaminated of radioactive particles from the pool, and is drained of all water. All of the steps outlined are performed remotely by an operator who controls the equipment from a distance.

The area used for decontamination is equipped with radiation monitoring systems and special contamination control procedures are used in accessing it (see Section 5.5). The following radiation protection elements are considered in the decontamination area:

- Area is monitored and measured (Section 5.5).
- Signs are posted for radiation hazards (Section 5.1).
- Workers are trained and qualified to work in the area and to respond to emergencies (Section 5.8).
- Respiratory and other protective equipment is provided and workers are trained to use it as per monitored and measured conditions (Section 5.6 and 5.8).
- Dosimeters are used to measure exposure (Section 5.4).
- Workers are monitored for contamination when exiting the decontamination area (Section 5.2 and 5.5).

▪ Equipment, including the dry storage canisters, is monitored prior to transfer (Section 5.2 and 5.5).

From here, the canisters are transported to the dry storage facility. The canisters are designed to store fuel for a minimum of 50 years.

Source: Reference 10.

Figure 9 – Dry Storage Canisters at the Pickering Site

Source: Canadian Nuclear FAQ website, http://www.nuclearfaq.ca/drystrge.htm.

Figure 10 – Dry Storage Canisters at the Bruce Site

4.3 Dry Storage

The dry storage facilities have effluent monitoring systems in place to measure the amount of radiation in the air and the liquid effluents, if any (see Sections 5.5 and 5.11). In addition to these, they have gamma radiation monitoring systems (see Section 5.5), canister monitoring programs to check for leak tightness in the baskets and the liners, and an environmental monitoring program (see Section 5.11). The facilities have barriers in place to shield the public and the environment from exposure (see Figure 5). The main protective barriers that are in place are (Reference 11):

- The uranium fuel pellet is a ceramic material that enables it to retain almost all the fission products;
- The tube that holds the uranium pellet is made of Zircaloy, a metal that is similar to steel, and seals the fuel pellets inside;
- The fuel bundles are placed in a stainless steel basket that is leak proof;
- The baskets are placed in a stainless steel leak proof cylinder;
- The cylinders are located inside a concrete vault, which is designed to prevent the spread of radioactivity;
- A fence surrounds the storage site that bounds the protected area;
- The exclusion zone has a radius surrounding the power plant, within which no other construction may be built without the government's authorization.

The dry storage facilities are designed to store spent fuel for up to 50 years. After this time a decision must be made on whether to extend the life of the storage facility, or to transfer the spent fuel to a long-term storage or disposal area. Currently, the Nuclear Waste Management Organization (NWMO) is exploring long-term options for Canada.

5 Elements of Radiation Protection for High-Level Waste

Section 4 discussed the handling and storage processes for high-level waste. For each stage of high-level waste handling and storage, the elements of radiation protection applicable to high-level waste are implemented in the specific Radiation Protection Program that is in place at each nuclear site. These elements are developed and implemented as described below (Reference 12, 13, 14, 15).

The Radiation Protection Program is enforced by the CNSC and the facility operations are assessed against it. The Radiation Protection Regulations incorporated in the Nuclear Safety and Control Act (NSCA, see Section 7) require that the Radiation Protection Program includes the following elements:

(a) classification of work areas and access control to specific areas;

(b) contamination control within the facility;

(c) local rules for each area and supervision of work;

(d) dosimetry and control of exposure;

(e) monitoring of the workplace;

(f) protective clothing and equipment;

(g) work planning and work permits;

(h) training and qualification;

(i) incidents and emergencies preparation;

(j) packaging and transportation;

(k) emissions and environmental monitoring.

5.1 Classification of Work Areas and Access Control

Nuclear facilities are classified into zones based on anticipated radiological hazard levels and on the potential for contamination and exposure. Some areas are "clean" with no radiological hazards and are considered normal public access areas. Some areas that contain the potential for radiological hazards, like the area where spent fuel is transferred to the wet storage bay, are considered radiological zones. Access to radiological zones is restricted to personnel that are qualified and have authorization to enter. This restriction is accomplished using physical access control systems and barriers, as well as procedures.

Zones are clearly posted and have boundaries between them. Boundaries can be in the form of a visible line on the floor, or a wall between areas. Personnel are instructed on the traffic routes that can be taken in the facility and are trained to follow procedures when travelling between zones. Personnel must go through a monitoring process if they move from a radiological zone of a higher probability of contamination to a zone of lower probability. If the monitoring process finds that the person is contaminated then the person must decontaminate and re-monitor before proceeding.

Areas that have radiological hazards are clearly marked with the radiation warning symbol and a written warning sign identifying the hazard (e.g. contamination, radiation fields, etc.). The radiological hazard symbol is shown in Figure 11.

Source: IAEA website, http://www.iaea.org/worldatom.

Figure 11 – Radiological Hazard Symbol

5.2 Contamination Control Within the Facility

The movement and accumulation of all forms of contamination are controlled in the facility. The two types of contamination that are controlled are “surface” and “airborne” contamination. The spread of surface contamination is controlled through monitoring (see Section 5.5), decontamination, access restriction, use of protective equipment (see Section 5.6) and identification and designation of specific areas with an increased risk of contamination. Before moving from areas of higher potential to areas of lower potential for contamination, all personnel and equipment are monitored for surface contamination and are decontaminated.

Ventilation systems are designed to minimize the accumulation of airborne radioactive contamination in areas where personnel are usually working, to reduce the spread of radioactive contamination from any radiological zone to a non-radiological zone and to minimize releases to the environment. Ventilation is designed such that air travels from areas of lower potential to areas of higher potential for contamination. Prior to release air is filtered to minimize releases. Airborne contamination is reduced through the use of high efficiency filtration systems that can retain radiological material from air.

5.3 Local Rules and Supervision of Work

Activities in each zone or area are governed by rules and procedures that depend on hazards present and anticipated. There are rules for exit and entry in the area, for emergency procedures in the area, and for the overall safety and protection of the workers and other persons in the area. Work is performed and supervised by someone who has been trained to work safely in the area and is qualified to supervise the area. All workers who enter a radiological zone are made aware of the radiological hazards and the protective measure required.

5.4 Dosimetry and Control of Exposure

All workers and visitors accessing the radiological zones are monitored for radiation exposure. The measurements are recorded and exposures are controlled to not exceed regulatory limits (Section 7.2) and facility guidelines. The program includes both external and internal dosimetry as described below. Each facility, consistent with ALARA, will have a program for the recording of doses to individuals and collectively to groups of personnel. Each facility will have pre-set guidelines or “administrative dose limits” that help management minimize individual doses as well as collective doses.

5.4.1 External Dosimetry

All personnel that enter a nuclear facility must wear a “dosimeter”. A dosimeter is a device that measures the “external dose” received by the person wearing it. These devices can be badges that are pinned onto clothing, wrist straps, armbands, rings, or disks that can be placed in a pocket or clipped onto clothing. Figure 12 shows various kinds of dosimeters.

Source: National Dosimetry Services, Health Canada, website; http://www.hc-sc.gc.ca/ehp/ehd/rpb/worker/nds/dosimeters.htm.

Figure 12 – Types of Dosimetry Devices

Thermoluminescent Dosimeter (TLD)

A TLD is a type of personal dosimeter in which the gamma and beta radiation energy to which it is exposed is stored in a crystal. The energy is released in the form of light, by heating the crystal. Using a TLD reader, the light intensity can be measured, and related to the amount of energy initially absorbed through exposure to the energy source. By wearing the TLD at the location of interest (e.g. the trunk for the whole body, the finger tips for extremities, etc.) the dose to the individual is measured, where required.

Direct Reading Dosimeter (DRD)

A DRD is a personal dosimeter that also measures gamma radiation but does not require additional processing (as the TLD does) to measure the individual's dose. A DRD contains an ionization chamber that is at a certain voltage. When the chamber is exposed to radiation, the ionization process reduces the voltage. The drop in voltage is a direct measure of the amount of radiation exposure. A common type of DRD is the Personal Alarm Dosimeter (PAD), which can be worn or carried in a pocket and displays the dose reading on a digital display screen. As the name suggests, this device can also be set to alarm if a pre-set dose level is reached.

5.4.2 Internal Dosimetry

In addition to monitoring external dose, internal dose from uptake (ingestion or inhalation) of radionuclides is assessed from time to time by obtaining bioassay samples from personnel who have come out of radiological zones with possible internal contamination. The test results for the bioassays, urine samples, whole body counting, thyroid counting and personal air samplers are used to calculate the dose that an individual could receive as a result of this internal "uptake".

5.5 Monitoring of the Workplace

Nuclear facilities utilize a variety of monitoring systems to check the radiological hazard levels created by the activities in the facility. In the case of the high-level waste handling facilities, the hazards monitoring systems include:

- *Gamma Monitoring Systems:* Some areas, such as the reception bays and wet storage bays, have a gamma monitoring system with an alarm that sounds if an unexpected increase in gamma radiation or radionuclide concentration occurs. The gamma monitoring systems are tested and maintained regularly.

- *Contaminated Air Monitoring System*: This system samples the air on a continuous basis. In the wet storage facility this provides an indication of contamination from failed fuel that may have escaped earlier detection. It provides an indication for further requirements for respiratory equipment and protective clothing. The contaminated air monitors also indicate the need for automatic action regarding facility ventilation to minimize possible releases.

- *Surface and Floor Contamination Monitors*: The Radiation Protection Program includes routine measurements of the contamination level on the floor and surfaces of corridors, rooms, and equipment. As well, measurements are taken prior to and after work activities to verify the conditions in the area. Equipment surfaces are monitored for contamination prior to transfer from an area of higher to lower potential for contamination.

- *Contamination Control for Individuals:* Other personnel monitoring systems include contamination monitors such as whole-body monitors, used to check contamination of the whole body, and hand and foot monitors. Personnel are always monitored when moving from an area of higher to lower potential for contamination.

5.6 Protective Clothing and Equipment

All facilities provide protective clothing and equipment for the workers or visitors to wear or use when entering or working in radiological zones with high probability of contamination.

Gloves are worn if contaminated material is handled (see Figure 13). Special footwear is worn if the work area is, or is likely to become, contaminated. If there are airborne concentrations of hazardous radioactive materials and exposure is likely to exceed the allowable limits, then a protective suit is worn (see Figure 13). The protective suit is ventilated and protects against skin contamination. Respiratory protective equipment is worn when airborne contamination levels exceed or may potentially exceed set limits (see Figure 14). When combining respiratory protective equipment with a ventilated suit, individuals are protected against inhalation of contaminants as well as surface contamination. Each facility has detailed procedures identifying what protective equipment would be required under various conditions.

Source: Lancs Industries website, http://www.lancsindustries.com.

Figure 13 – Protective Suit and Gloves

Source: Lancs Industries website, http://www.lancsindustries.com.

Figure 14 – Respiratory Protective Equipment

Protective clothing and equipment is regularly sent for decontamination and cleaning. If the clothing remains contaminated after cleaning, it is not reused. It is considered low-level waste and it is handled and stored according to the facility's waste management procedures (see Section 3.4).

5.7 Work Planning and Work Permits

All work in the nuclear facility is carefully planned and takes into account the personnel involved in the work, the hardware to be used, the procedures to be followed, the supervision required and the hazards, both industrial and radiological. Work approvals must be given for all projects and tasks and the approvals are given in writing. The level of authorization needed for each task depends on the radiological hazard levels, measured and anticipated, at the work site. Work permits and work plans can only be approved by qualified personnel as defined in Section 5.8.

5.8 Training and Qualification

Each nuclear facility is responsible for training the employees on the potential radiological hazards within the facility. The training program includes qualifying employees who work in controlled areas and radiological zones. Typically, training covers topics such as those listed below (Reference 12). The level of training varies depending on the requirements of the job and the level of qualification required. Table 2 outlines the typical qualification standards for workers used by a particular Canadian nuclear power plant operator (Reference 13).

a. main types of ionizing radiation and their effects;

b. basic quantities and units in radiation protection;

c. basic protection and safety procedures;

d. principles of radiation protection and radioactive waste management;

e. use of protective equipment, including shielding and protective clothing;

f. use of contamination monitors, and individual external and internal monitoring;

g. potential risks associated with operation of a nuclear facility;

h. rules and procedures at the facility;

i. warning signs and alarm signals and information on the appropriate actions to be taken;

j. contamination control, decontamination procedures and reduction of sources of radiation;

k. responsibility to inform designated persons in circumstances that are unexpected where the radiation risks are increased;

l. actions that should be taken if there is a radiological emergency or an accident during transport of radioactive material;

m. regulations for the safe transport of radioactive material on and off site;

n. criticality safety for nuclear fuel;

o. behaviour in controlled areas.

Table 2 – Qualification Standards at Canadian Nuclear Power Plants

Qualification Level	Responsibility for Radiation Protection While Performing Radioactive Work	Access to Radiological Zones
None	May perform radioactive work only when a "full" level person takes responsibility for and directly oversees their radiation protection.	Only when accompanied by individuals holding an approved level of qualification.
Elementary	May perform radioactive work only when a "full" level person takes responsibility for and directly or indirectly (if authorized) oversees their radiation protection	Normally within designated accessible areas.
Intermediate	Can be responsible for own radiation protection, but cannot be responsible for the radiation protection of others.	No restrictions, in accord with facility radiation protection procedures.
Full	Can be responsible for own radiation protection and may be responsible for the radiation protection of others.	No restrictions, in accord with facility radiation protection procedures.

Source: Reference 13, 14, 15.

5.9 Incidents and Emergencies

Nuclear facilities have plans and procedures in place to deal with emergency situations and incidents that are not routine. The emergency plans are in place to control imminent or actual hazards and prevent or mitigate impacts on human health and safety. All employees are trained in the emergency procedures and are aware of the preparations necessary to deal with emergencies, and of the necessary steps that they are to take in the case of an emergency.

The emergency plan includes the following (Reference 13):

a. The type of emergencies it deals with;

b. An outline of the responsibilities for implementing emergency actions;

c. Detailed emergency procedures;

d. Specific responsibilities at each work site affected for interactions with regulatory agencies, approval and communications.

5.10 Packaging and Transport of High-level Waste

Currently, most high-level waste is stored at the nuclear reactor sites in wet storage facilities for up to 10 years and subsequently in dry storage facilities. In some cases, individual spent fuel bundles or individual "pencils" may be sent to Chalk River Laboratories for testing. It is also possible that future long-term waste solutions may require transporting high-level radioactive waste off-site. Both on-site transfers and off-site shipments must follow procedures consistent with the CNSC regulations. Transportation of radioactive materials off-site must meet the transportation packaging regulations under the NSCA and the signage and transport regulations of the Transportation of Dangerous Goods Act (TDGA) (see Section 7 for more details). All shipments of radiological waste and non-waste materials must be recorded and tracked.

For on-site transfer of wastes, permits may be required depending on the radiological hazard involved. Permits may apply to a single transfer of materials or to an entire process that requires the transfer of materials; i.e., when the dry storage units are moved from the wet storage facility to the dry storage facility.

Only single bundles or pencils are transported off-site, and spent fuel is not shipped in bulk. Single bundles of spent fuel are shipped in an Irradiated Material Transportation (IMT) package. This package is licensed based on CNSC and international guidelines. For off-site transport the transport coordinator is responsible for ensuring that all applicable regulations have been followed, and that the off-site facility is properly equipped with radiological protection technologies in place to safely receive the material. Loading of the flatbed trucks with radiological material is monitored. The trucks are equipped with portable instruments to monitor radiation levels. Drivers wear dosimeters (see Section 5.4) and are trained to use the portable monitoring equipment. The routes taken for transport of radioactive material are fixed and are approved by the federal regulator. Response teams along the route, such as the police, are notified of the shipment. An emergency response plan is in place to deal with abnormal occurrences and trained emergency response workers are on hand 24 hours a day, seven days a week. The emergency response workers are equipped with protective clothing, respiratory equipment, and other protective gear as mentioned in Section 5.6.

5.11 Emissions and Environmental Monitoring

- *Emission Monitoring Systems:* Emission monitoring systems are designed to measure any radioactive emissions released from the facility. A monitoring program that uses the information from the emission monitoring systems is in place to ensure that the radioactivity in the fluids and gases released from the facility is within the acceptable limits. These limits are conservatively calculated by assessing the potential public dose from releases from the facility, taking into account the public dose limits (see Section 7), the specific environment surrounding the facility, and the various meteorological, agricultural and social factors. Monitors are located at the point where air exhausts or liquid is released. The measurements are collected by either taking samples or by using the monitoring systems in place. For some instances, measurements are collected using both.

- *Environmental Monitoring Programs:* The facilities have environmental monitoring programs, which measure the change in radiation in various environmental elements (rain water, vegetation, fish, milk, etc.) to determine the potential impact of radiological emissions released from the facility into the environment. The measurements taken are input to programs that calculate potential public dose through the pathways that could lead to human exposure. This indicator is used to assess the safe operation of the facility.

6 Long-term Options for Management of High-Level Waste

Sections 5.1 to 5.11 described the elements of the Radiation Protection Program that are implemented to ensure worker safety during handling and storage of high-level waste and to minimize any impact on the public and the environment. Currently, the facilities that store high-level waste in the short-term, both wet and dry storage facilities, have these elements in place. Solutions need to be found to manage high-level waste in the long-term. The options for long-term waste management must consider the same elements of the Radiation Protection Program and should apply the ALARA principle and the defence-in-depth strategy along with multiple barriers, described in Section 2, to minimize risk to the workers, the public and the environment. This section discusses the long-term options for high-level waste management currently being explored and the radiological protection technologies and operational procedures that are anticipated for these options.

6.1 Long-term Options in Canada

In June of 2002, the Canadian government passed the Nuclear Fuel Waste Act (NFWA), which created the NWMO. The NWMO must submit options for long-term management of spent fuel within three years (by 2005).

The following three methods, outlined in the NFWA, must be presented as long-term management approaches for high-level waste in addition to any other options that the NWMO finds are feasible in Canada:

1. deep geological disposal;
2. storage at nuclear reactor sites; and
3. centralized storage, either above or below ground.

6.1.1 Deep Geological Disposal

Disposal is the permanent placement of spent fuel with no intention of future use. Deep geological disposal involves burying the spent fuel deep underground in one of several types of rock and vault configurations. This is the disposal option that has been perused in many other countries.

The Canadian concept for a deep geological repository consists of encapsulating the spent fuel bundles in a container and burying the containers at a depth of 500 to 1000 m below the surface in the granite rock of the Canadian Shield. The repository would be a network of tunnels and rooms designed to suit the rock structure, groundwater flow and other subsurface conditions at the site. The containers would either be placed in the rooms or in holes drilled into the floor of the rooms (Reference 16).

In addition to burying the waste in granite and hard rock, concepts for deep geological disposal have also been developed for burial within rock salt, sedimentary clay, and tuff. Rock salt burial was the first concept in deep geological disposal explored as it is based on the proven technology and knowledge gained from mining in salt. One of the advantages of using rock salt is its high thermal conductivity, which could allow the heat generating waste to cool down faster. Currently, demonstration activities and tests are being conducted in Germany for the feasibility of a rock salt repository (Reference 17). Transuranic wastes are also being disposed of in the USA in deep salt formations. Sedimentary clay formation as a repository is an option that has recently been investigated. Clay has shown to have a highly efficient barrier against the migration of radioactive material. Similar to granite burial this option would involve an underground network of bore holes where the waste is buried. This option is being explored in countries that have a widespread amount of clay sedimentary formations, such as Italy (Reference 17). Tuff is a substance formed by the accumulation of glassy fragments that have been erupted from a volcano. This is a fairly new option being explored in the USA (Reference 17).

The main way in which there is potential for harm from the high-level waste in the deep geological disposal option, is if contamination from the waste leaches out of the canisters in which it is buried underground. Once leached out, it could possibly be carried by groundwater to the earth's surface where people and the environment may be exposed to it. For the deep geological disposal option, as for others, protection through the use of multiple barriers and the defence-in-depth concept would be expected.

Possible barriers that could be in place to prevent the release of radioactivity include (Reference 1):

- The uranium fuel pellet design, which is a ceramic material that retains almost all the fission products;
- The tube that holds the uranium pellet, being made of Zircaloy, a metal that is similar to steel, seals the fuel pellets inside;
- The waste container: the design of the container and the materials used would be selected to prevent corrosion, prevent cracking, and ensure leak tightness. Fabrication would require approved quality control standards;
- Buffer material surrounding the container to fill gaps in the rooms or holes used for disposal, and
- Site selection: the geologic formation, i.e., granite rock, rock salt, sedimentary clay, tuff; ground water movement; burial depth.

In addition to these barriers the repository would be monitored to confirm that the facility is performing as expected (Reference 16). The monitoring systems in place would be similar to the environmental monitoring systems mentioned in Section 5.11.

Appendix 2 presents a comparison table of the engineered barrier systems that are proposed for the deep geological repository in countries around the world.

6.1.2 Storage at Site

Storage is defined as the safekeeping of spent fuel with the intention of future use or disposal. Site storage is storage of spent fuel at the nuclear site. The waste can be stored above ground, similar to the dry storage facilities currently used or waste can be stored underground, which would simply be a dry storage type facility underground.

The radiological technologies and operational procedures that would have to be in place for underground and above ground storage facilities would be similar to those currently being used for the above ground dry storage facilities. As stated in Section 4.3 and illustrated in Figure 5 a number of barriers will exist between the high-level waste and potential exposure to people and the environment. The barriers for an above ground storage facility would include:

- The uranium fuel pellet design, which is a ceramic material that retains almost all the fission products;
- The tube that holds the uranium pellet, being made of Zircaloy, a metal that is similar to steel, seals the fuel pellets inside;
- The fuel bundles being placed in a stainless steel basket that is leak proof;
- The baskets being placed in a stainless steel leak proof cylinder, which is located inside a concrete vault;
- The vault is designed to prevent the spread of radioactivity; and
- A fence surrounding the storage site bounding the protected area.

The barriers in place for an underground storage facility would be similar to those listed above and protection would also be provided by the overlying rock and inward hydraulic gradients, as long as the facility is maintained dry.

The elements of radiation protection as listed in Section 5, would have to be in place at the storage site.

6.1.3 Centralized Storage

Centralized storage is similar to storage on site, but consists of one main storage facility in one location. For example, Canada could create one location for storage of all of its high-level waste.

The radiological protection technologies and operational procedures for a centralized storage site would be similar to those for storage at site as mentioned in Section 6.1.2.

6.2 Other Long-term Options

In addition to the three options listed above that must be explored in Canada, other long-term options for high-level waste have been investigated.

A 1977 report put together by a group led by Dr. Kenneth Hare (known as the "Hare Report") examined a number of long-term solutions to high-level waste (Reference 18). The other options investigated are listed below. The group also investigated treatment options to reduce the amount of waste. These involve using methods to either reprocess and recycle the waste, or find ways to transmutate the waste into shorter-lived radionuclides.

1. *Disposal Options*

   (a) *Seabed Disposal* – disposing the fuel by placing it on or beneath deep oceanic plains and far from continental margins (i.e., the Pacific coast).

   (b) *Space Disposal* – disposing of used fuel by sending it into space.

(c) *Ice Sheet Disposal* – disposing of used fuel in large ice sheets and glaciers.

2. *Treatment Options*

(a) *Reprocessing and Recycling* – a chemical separation process that separates out uranium and plutonium from the spent fuel. The uranium and plutonium can then be recycled and manufactured into fuels for use in nuclear power plants. Reprocessing and recycling reduces the volume and half-life of high-level radioactive waste.

(b) *Reprocessing and Transmutation* – transmutation is a reprocessing method that transforms some long-lived radionuclides into shorter-lived nuclides.

7 Laws and Regulations for High-level Waste Management and Handling

Section 6 presented the options for dealing with high-level waste in the long-term. This section discusses the laws and regulations that must be followed for high-level waste management and where the responsibility lies for dealing with high-level waste.

It is the responsibility of the "licensee" to ensure the proper radiological protection technologies and operational procedures are in place at the sites dealing with high-level waste. The CNSC has a watchdog function, specifically regulating activities regarding the use of nuclear energy so as not to threaten public health, security, safety and the quality of the environment. The CNSC requires the licensee to abide by all of the laws that govern handling and storage of high-level waste.

7.1 Laws and Regulations

The radiological regulations for high-level waste in Canada fall under the NSCA (Reference 19). The NSCA imposes regulations to ensure protection of the environment, the health and safety of workers and the public, and to uphold Canada's international obligations in the area of nuclear safety and security.

In establishing the regulations and guidelines for management and handling of high-level waste, the following are considered (Reference 5):

- Having radiation dose limits that are consistent with the ICRP recommendations.
- Having laws that govern the transport and packaging of nuclear materials to reduce risks to health and safety or the environment.
- Having enhanced security at nuclear facilities and waste storage facilities.

There are nine regulations that fall under the NSCA:

(1) General Nuclear Safety and Control Regulations,

(2) Radiation Protection Regulations,

(3) Class I Nuclear Facilities Regulations,

(4) Class II Nuclear Facilities and Prescribed Equipment Regulations,

(5) Uranium Mines and Mills Regulations,

(6) Nuclear Substances and Radiation Devices Regulations,

(7) Packaging and Transport of Nuclear Substances Regulations,

(8) Nuclear Security Regulations,

(9) Nuclear Non-proliferation Import and Export Control Regulations.

In addition to the NSCA which governs all nuclear facilities, the Canadian Environmental Assessment Act (CEAA), the TDGA, and the NFWA are acts that must be followed when dealing with radioactive waste.

Canadian Environmental Assessment Act (CEAA)

The CEAA requires federal departments (including Environment Canada), agencies, and crown corporations to conduct environmental assessments for proposed projects within Canada that involve federal funding, permit or license or are located on federal lands. In accordance with this Act all nuclear sites and waste storage facilities must conduct a screening or comprehensive environmental assessment prior to being licensed (Reference 20).

Transportation of Dangerous Goods Act (TDGA)

The TDGA applies to all handling and transporting of dangerous goods including hazardous wastes, by any means of transport. Under the TDGA, Environment Canada conducts inspections to determine compliance with the hazardous waste portion of the regulations and processes notices for the export and import of hazardous wastes. The Act defines the proper handling and safety measures that must be in place for transportation and requires an emergency plan in the case of potential accidents during transportation of hazardous wastes (Reference 21). It should be noted that the TDGA governs the transportation but the packaging for transportation is covered by the Packaging and Transport of Nuclear Substance Regulations.

Nuclear Fuel Waste Act (NFWA)

The NFWA provides a framework to enable the Government to make a decision on the management of nuclear fuel waste based on a comprehensive, integrated and economically sound approach for Canada (Reference 22).

The NFWA requires electricity generating companies which produce used nuclear fuel to:

- Establish a waste management organization to provide recommendations to the Government of Canada on the long-term management of used nuclear fuel;
- Establish segregated trust funds to finance the long-term management of the spent fuel.

The NFWA requires the waste management organization to:

- Establish an Advisory Council whose comments on the waste management organization's study and reports will be made public and;

- Within three years of the legislation coming into force, submit to the Minister of Natural Resources proposed approaches for the management of used nuclear fuel, along with comments of the Advisory Council, and a recommended approach.

7.2 Dose Limits

A key element to reducing exposure to radiation is to set limits on how much radiation a worker and the public can be exposed to. Canada has specific regulations limiting the amount of dose that may be received by a worker or a member of the public. These limits are listed in Table 3 (Radiation Protection Regulations under Reference 19).

Table 3 – Dose Limits

Person	Period	Effective Dose (mSv)
Nuclear energy worker, including a pregnant nuclear energy worker	(a) One-year dosimetry period	50
	(b) Five-year dosimetry period	100
Pregnant nuclear energy worker	Balance of the pregnancy[1]	4
A person who is not a nuclear energy worker	One calendar year	1

Source: Radiation Protection Regulations under Reference 19.
[1] "Balance of pregnancy" is defined as the period from the moment the licensee is informed in writing of the pregnancy to the end of the pregnancy.

Note that the maximum public dose limit is 1 mSv/a. This is the total acceptable dose to a member of the public from all possible industrial sources. If a waste storage facility is located near one or more existing nuclear facilities, the sum of the doses to any member of the public must remain below 1 mSv/a.

Canadian limits are the same as those set internationally by the ICRP (Reference 6). Limits set by other countries may vary.

For example the limits by the US Nuclear Regulatory Commission are identical to Canada for the nuclear energy worker during a one-year dosimetry period and the non-worker, however for a pregnant worker the balance of pregnancy limit is set to 0.5 mSv if the pregnant worker was exposed to 5 mSv up to the time at which the licensee was informed of the pregnancy (Reference 23). In Japan the occupational dose limit is also 50 mSv/a, however it is limited for females to 5 mSv per 3 months (Reference 24). In Lithuania the maximum dose to a worker is less than in other countries and is limited to allow 20 mSv/a (Reference 25). France also has an occupational dose limit of 50 mSv/a (Reference 25).

8 References

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20. “Canadian Environmental Assessment Act”, Department of Justice of Canada, June 23, 1992.

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23. NRC, “Standards for Protection Against Radiation”, Subparts C and D, May 21, 1991.

24. NEA, “Occupational Exposures at Nuclear Power Plants, Eighth Annual Report”, 1998.

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9 Glossary

ARS – Acute Radiation Syndrome: in which damage occurs to cells that are dividing rapidly.

ALARA - a concept meaning that the design and use of sources, and the practices associated therewith, including their disposal, should be such as to ensure that exposures are kept as low as reasonably achievable, economic and social factors being taken into account.

Bioassay – a procedure used to determine the nature, activity, and location of radionuclides in the body.

CANDU - a Canadian nuclear power reactor design using deuterium as moderator and natural uranium as fuel.

Collective Dose – the total radiation dose incurred by a given group or population.

Cosmic Radiation - radiation originating from space.

Decommissioning – the permanent removal of a facility from active service. In the case of a nuclear plant this includes safely closing, and possibly dismantling the existing facilities at the end of their service life.

DNA – Deoxyribonucleic acid (DNA), is a double-stranded helix of nucleotides which carries the genetic information of a cell.

Dose – general term for the quantity of radiation or energy absorbed in a specific mass. The unit used to express dose is the Gray (Gy).

Dosimeter – a device that measures external dose.

Effective Dose – a measure of dose designed to reflect the amount of radiation detriment likely to result from the dose. This value is calculated by multiplying the absorbed dose of radiation with a weighting factor for that type of radiation. The unit used to express effective dose is the Sievert (Sv).

Fission - a nuclear reaction in which an atomic nucleus (e.g. U-235) splits into fragments, releasing energy.

Fusion - a nuclear reaction in which nuclei (e.g. H-2 with H-3) combine to form a more massive nucleus with the simultaneous release of energy.

Internal Radiation – radiation inside our own bodies that comes from the intake of the food we eat, the water we drink and the air we breathe.

Ionizing Radiation - radiation that has enough energy to separate the electrons from the nucleus of an atom.

Licensee - the holder of a current licence.

Nuclear Fuel Cycle – the complete process of producing electricity from nuclear fission, which involves uranium mining, milling, refining, conversion, fuel fabrication, and power generation.

Pencil – when dealing with a CANDU nuclear fuel bundle, a "pencil" is a single Zircaloy tube with fuel pellets in it.

Radiation - energy in the form of sub-atomic particles or electromagnetic waves.

Radioactivity - phenomenon whereby atoms undergo spontaneous random disintegration releasing radiation.

Radioactive Waste - Radioactive waste is defined in the Canadian regulatory documents as any liquid, gaseous or solid material that contains a "nuclear substance". A "nuclear substance" can be any of the following:

(a) deuterium, thorium, uranium or an element with an atomic number greater than 92;

(b) a derivative or compound of deuterium, thorium, uranium or of an element with an atomic number greater than 92;

(c) a radioactive nuclide;

(d) a substance that is prescribed as being capable of releasing nuclear energy or as being required for the production or use of nuclear energy;

(e) a radioactive by-product of the development, production or use of nuclear energy; and a radioactive substance or radioactive thing that was used for the development or production, or in connection with the use, of nuclear energy.

Radioisotope - a naturally occurring or artificially produced radioactive isotope of an element.

Radionuclide – an atom or nuclide that exhibits radioactivity.

Radon - a colourless and odourless gas formed from the decay of radium.

Relative Biological Effectiveness - A relative measure of the effectiveness of different radiation types at inducing a specified health effect.

Sintering - to form a mass by heating without melting.

Spent Fuel - used fuel that is removed from a nuclear reactor.

Terrestrial Radiation - is emitted from radioactive elements found in all the rocks that make up our planet. These elements have been present since the planet was formed approximately 4.5 billion years ago and were produced during fusion reaction in stars.

Transmutation – in relation to waste management, a reprocessing method that transforms some long-lived radionuclides into shorter-lived nuclides.

Tuff – an accumulation of glassy fragments erupted explosively from a volcano. A type of glassy volcanic rock.

Vitrified - to change or make into a glassy substance through heat fusion.

Zircaloy - a stable, corrosion-resistant zirconium alloy.

10 Acronyms

AECL – Atomic Energy of Canada Limited

ALARA - As Low As Reasonably Achievable

ARS - Acute Radiation Syndrome

CANDU – Canada Deuterium Uranium

CEAA – Canadian Environmental Assessment Agency

CNSC – Canadian Nuclear Safety Commission

CRL – Chalk River Laboratories

DNA - Deoxyribonucleic Acid

DRD – Direct Reading Dosimetry

HLW – High-Level Waste

IAEA – International Atomic Energy Agency

ICRP – International Commission on Radiological Protection

LLRWMO – Low-Level Radioactive Waste Management Office

LLW – Low-Level Waste

NFWA – Nuclear Fuel Waste Act

NPD – Nuclear Power Demonstration

NSCA – Nuclear Safety and Control Act

NWMO – Nuclear Waste Management Organization

PAD – Personal Alarm Dosimeter

RBE – Relative Biological Effectiveness

TDGA – Transportation of Dangerous Goods Act

TLD – Thermoluminescent Dosimetry

11 Additional Sources of Information

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11.5 IAEA, "Institutional framework for long term management of high level waste and/or spent nuclear fuel", IAEA-TECDOC-1323, December 2002.

11.6 IAEA, "Spent fuel performance assessment and research", IAEA-TECDOC-1343, March 2003.

11.7 OPG, "Pickering Waste Management Facility", OPG Fact Sheet.

11.8 OPG, "Darlington Used Fuel Dry Storage Project", Draft Environmental Assessment Study Report, Volume 1, November 2002.

11.9 NEA, "Regulatory Control of Radioactive Waste Management in Italy", Rev 1, 2002.

11.10 NEA, "Regulatory Control of Radioactive Waste Management in the United States", Rev 1, 2002.

11.11 NEA, "Regulatory Control of Radioactive Waste Management in the United Kingdom", Rev 1, 2002.

Appendix 1 – High-level Waste Wet and Dry Storage Sites

The following tables list the wet and dry storage facilities for high-level waste that are currently in operation within Canada.

Table 4 – High-level Waste Wet Storage Sites

Storage Facility	Location	Type of Waste
Bruce Nuclear Generating Station A and B	Tiverton, Ontario	Spent fuel from Bruce Nuclear Generating Stations A and B
Darlington Nuclear Generating Station	Clarington, Ontario	Spent fuel from Darlington Nuclear Generating Station
Gentilly-2 Nuclear Generating Station	Gentilly, Québec	Spent fuel from Gentilly-2 Nuclear Generating Station
Pickering Nuclear Generating Station	Pickering, Ontario	Spent fuel from Pickering Nuclear Generating Station
Point Lepreau Nuclear Generating Station	Point Lepreau, New Brunswick	Spent fuel from Point Lepreau Nuclear Generating Station

Source: References 5 and 8.

Table 5 – High-level Waste Dry Storage Sites

Storage Facility	Location	Type of Waste
Chalk River Laboratories	Deep River, Ontario	Spent fuel bundles from Bruce, Pickering, Douglas Point reactor (NPD reactor now shut down), and from The University of Toronto SLOWPOKE research reactor
Darlington Used Fuel Dry Storage Facility	Clarington, Ontario	Will become the dry storage facility for spent fuel from the Darlington Nuclear Generating Station (forecasted for 2007)
Douglas Point Radioactive Waste Management Facility -	Douglas Point, Ontario	Spent fuel from Douglas Point Generating Station that is now shutdown
Gentilly-1 Radioactive Waste Management Facility	Gentilly, Québec	Spent fuel from Gentilly-1 Nuclear Power Station that is now shutdown
Gentilly-2 Radioactive Waste Management Facility	Gentilly, Québec	Spent fuel from Gentilly-2 Nuclear Power Station and spent fuel from Gentilly-1 Nuclear Power Station that is now shutdown
Hydro Québec Used Fuel Dry Storage Facility	Gentilly, Québec	Provides additional dry storage for spent fuel from the Gentilly-2 Nuclear Power Station
Pickering Used Fuel Dry Storage Facility	Pickering, Ontario	Spent fuel from Pickering Nuclear Generating Station
Point Lepreau Solid Radioactive Waste Management Facility	Point Lepreau, New Brunswick	Spent fuel from Point Lepreau Generating Station
Savanah River Site	South Carolina, United States	Spent fuel from McMaster University
Western Used Fuel Dry Storage Facility	Tiverton, Ontario	Spent fuel from Bruce A and B nuclear generating stations
Whiteshell Used Fuel Storage Facility	Pinawa, Manitoba	Spent fuel bundles from research and development of prototype reactors

Source: References 5 and 8.

Appendix 2 – Comparison of Deep Geological Disposal Option with Other Countries

This appendix presents the deep geological disposal option in other countries and compares what is being done elsewhere to what is being proposed in Canada. The comparison focuses on the engineered barrier systems, or multiple barriers that are being proposed for this long-term option.

The "Engineered Barrier System" represents the man-made, engineered materials placed within a repository, including the waste form, waste canisters, buffer materials, backfill, and seals.

The following table has been adapted from Reference 26 and compares the waste types for disposal, a description of the waste matrix, the container or overpack used to dispose of the waste, the buffer or backfill used to fill the empty spaces in the repository, and other specifics on the repository sealing and tube or container design details, within a number of countries that are exploring the deep geological disposal option.

Table 6 – Comparisons of Deep Geological Disposal Option

Country/ programme	Waste type	Waste matrix	Container/ overpack	Buffer/ backfill	Others
Belgium	HLW	Borosilicate glass	304 stainless steel container, 316L stainless steel overpack	FoCa clay, 60% calcium bentonite, 35% quartz sand, 5% graphite	Disposal tube, tunnel lining.
Canada	Spent fuel	UO_2	Carbon steel inner container with a copper outer shell	Bentonite buffer, bentonite/sand buffer, clay/crushed rock backfill	Tunnel and shaft seals
Czech Republic	Spent fuel	UO_2	Steel	Bentonite buffer	Clay seals
Finland	Spent fuel	UO_2	Copper-iron	Bentonite buffer, backfill of compacted crushed rock and bentonite	Bentonite and concrete plugs
France	Spent fuel	UO_2 and MOX	Stainless steel with metal insert	Bentonite buffer with metal disposal tube	Bentonite seals
Japan	HLW	Glass	Carbon steel overpack	Bentonite-sand mixture	Tunnel sealing plugs and grout
Korea	Spent fuel	UO_2	Carbon steel inside, copper or stainless steel outer container	Bentonite or bentonite-sand mixture	-
Spain	Spent fuel	UO_2	Carbon steel	Bentonite	Concrete and bentonite seals
Sweden	Spent fuel	UO_2	Copper-iron	Bentonite	Tunnel backfill
Switzerland	HLW	Glass	Steel	Bentonite	-

Country/ programme	Waste type	Waste matrix	Container/ overpack	Buffer/ backfill	Others
US	Commercial spent fuel	Fuel rods, Zircaloy or stainless steel cladding, UO_2 fuel pellets	Stainless steel inside a Ni-based alloy outer container	None	Titanium alloy drip shield, granular invert.
	Defence spent fuel	250 types, e.g. MOX, ceramic-plutonium, Pu/U alloy	-	None.	
	HLW	Borosilicate glass	-	None.	

Source: Adapted from Reference 26.

Appendix 3 – Inventory of Radioactive Waste in Canada

The following inventory table was compiled based on data found in Reference 5.

Table 7 – Inventory of Radioactive Waste in Canada

	Where	Site	Waste Type	Sources	Quantity[1]	Storage[3]
Research and Education	Research facilities	Chalk River Laboratories	High-level waste	Nuclear fuel for prototype reactor	4,853 bundles	Dry storage
		Whiteshell Laboratories	High-level waste	Nuclear fuel for prototype reactor	360 bundles	Dry storage
		Douglas Point	High-level waste	Nuclear fuel for prototype reactor	22,256 bundles	Dry storage
		Gentilly-1	High-level waste	Nuclear fuel for prototype reactor	3,213 bundles	Dry storage
		Nuclear power facilities	Low-level waste[4]	Research reactor operation	20,500 m^3	In concrete trenches and above-ground storage buildings
Agro-Industrial Use	Agricultural (food irradiation); Industrial (measurement, testing)	Many across Canada	Low-level waste	Radioactive sources	Small quantities in the form of sealed sources	Sent to off-site waste storage facility

	Where	Site	Waste Type	Sources	Quantity[1]	Storage[3]
Medical Use	Hospitals	Nuclear power facilities that produce radioisotopes for medical use	Low-level waste	Clothing, paper towels, glassware, equipment and building materials for radioisotope production and use	98,900 m^3	At CRL[2] in modular above-ground storage units.
Power Generation	Mines	Cluff Lake	Uranium mine tailings	Uranium mining	3,840,000 tonnes	Surface storage
		Key Lake	Uranium mine tailings	Uranium mining	6,015,366 tonnes	Open pit and above-ground
		Rabbit Lake	Uranium mine tailings	Uranium mining	11,640,000 tonnes	Open pit and above-ground
		McClean Lake	Uranium mine tailings	Uranium mining	257,922 tonnes	Open pit
		Beaverlodge	Uranium mine tailings	Uranium mining	10,100,000 tonnes	Above-ground and underground/ mine backfill
		Gunnar	Uranium mine tailings	Uranium mining	4,400,000 tonnes	Above-ground
		Lorado	Uranium mine tailings	Uranium mining	360,000 tonnes	Above-ground
		Port Radium	Uranium mine tailings	Uranium mining	907,000 tonnes	Above-ground
		Rayrock	Uranium mine tailings	Uranium mining	71,000 tonnes	Above-ground

	Where	Site	Waste Type	Sources	Quantity[1]	Storage[3]
		Quirke 1 & 2 – Elliot Lake	Uranium mine tailings	Uranium mining	46,000,000 tonnes	Flooded above-ground
		Panel – Elliot Lake	Uranium mine tailings	Uranium mining	16,000,000 tonnes	Flooded above-ground
		Denison – Elliot Lake	Uranium mine tailings	Uranium mining	63,800,000 tonnes	Flooded above-ground
		Spanish-American Elliot Lake	Uranium mine tailings	Uranium mining	450,000 tonnes	Flooded above-ground
		Stanrock/ CANMET Elliot Lake	Uranium mine tailings	Uranium mining	5,750,000 tonnes	Above-ground
		Stanleigh – Elliot Lake	Uranium mine tailings	Uranium mining	19,953,000 tonnes	Flooded above-ground
		Lacnor – Elliot Lake	Uranium mine tailings	Uranium mining	2,700,000 tonnes	Above-ground
		Nordic – Elliot Lake	Uranium mine tailings	Uranium mining	12,000,000 tonnes	Above-ground
		Pronto – Blind River	Uranium mine tailings	Uranium mining	2,100,000 tonnes	Above-ground
		Agnew Lake Mines – Espanola	Uranium mine tailings	Uranium mining	510,000 tonnes	Above-ground
		Dyno – Bancroft	Uranium mine tailings	Uranium mining	600,000 tonnes	Above-ground
		Bicroft – Bancroft	Uranium mine tailings	Uranium mining	2,000,000 tonnes	Above-ground

	Where	Site	Waste Type	Sources	Quantity[1]	Storage[3]
		Faraday/ Madawaska – Bancroft	Uranium mine tailings	Uranium mining	4,000,000 tonnes	Above-ground
	Fuel Production	All sites	Low-level waste	Fuel fabrication	See low-level waste under "Nuclear Reactors"	Concrete trenches, bunkers, in the reactor building, in-ground and above-ground storage containers
	Nuclear Reactors	Bruce A	High-level waste	Power generation	354,567 bundles	Wet storage
		Bruce B	High-level waste	Power generation	337,637 bundles	Wet storage
		Darlington	High-level waste	Power generation	191,522 bundles	Wet storage
		Pickering A and B	High-level waste	Power generation	479,800 bundles	Wet and dry storage
		Gentilly-2	High-level waste	Power generation	80,525 bundles	Wet and dry storage
		Point Lepreau	High-level waste	Power generation	89,414 bundles	Wet and dry storage

	Where	Site	Waste Type	Sources	Quantity[1]	Storage[3]
		All nuclear reactors	Low-level waste	Power generation	66,633 m^3	Concrete trenches, bunkers, in the reactor building, in-ground and above-ground storage containers
		Partially Decommissioned Facilities	Low-level waste	Power generation	1,706 m^3	Concrete trenches, bunkers, in the reactor building, in-ground and above-ground storage containers
	Historic Waste	Port Hope	Low-level waste	Contaminated soils	495,000 m^3	Above-ground mounds
		Welcome and Port Granby	Low-level waste	Contaminated soils	870,000 m^3	Burial
		Other Locations	Low-level waste	Contaminated soils	65,000 m^3	Above-ground mounds

1. Quantities are reported to December 31, 2001 for all radioactive wastes.
2. CRL – Chalk River Laboratories in Ontario.
3. Storage details were obtained from Reference 5.
4. Low-level waste is also produced at CRL for research operations and the quantity of the waste is included in the inventory presented for “Medical Use” in the table.