NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

November 2004

NWMO BACKGROUND PAPERS
3. HEALTH AND SAFETY

3-5 A RISK-BASED MONITORING FRAMEWORK FOR USED FUEL 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.

A RISK-BASED MONITORING FRAMEWORK FOR USED FUEL MANAGEMENT

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EXECUTIVE SUMMARY

The Nuclear Waste Management Organization (NWMO) has a mandate from the Government of Canada to consult with the public and to recommend an approach for managing Canada's used nuclear fuel. Three main technical methods for managing used fuel are being explored and evaluated by the NWMO:

- disposal in a Deep Geological Repository (DGR);
- reactor-site extended storage (RES); and
- centralized extended storage (CES), either above ground or below ground.

The used nuclear fuel management system, whether a DGR or an extended storage system will require monitoring. The purpose of this study is to develop a risk-based monitoring framework for the used fuel management program. This is being carried out using a step-by-step approach with the following two major steps:

- First, the various management methods are reviewed to estimate potential risks at each stage of their development.
- Second, the results of the review are used to develop, at a conceptual level, a monitoring framework, which focuses on the main areas of potential risk.

STEP 1 - Potential Risks

This review step provides a high-level perspective, based on available information, on what is known regarding potential risk to the public, workers and the environment for the three management methods considered (see Tables ES-1 to ES-3). The risk assessment presented is based on a combination of operating experience at the nuclear sites in Ontario (Pickering, Darlington, Bruce) as well as Canadian and international assessments. The possible effects are not limited to only present-day conditions as risks may also arise in the far future*. Detailed discussions of the risk associated with the various stages of implementation of each option, are given in Appendices attached to the Main Report.

Both routine operating conditions and hypothetical accident scenarios are evaluated considering both radiological and non-radiological (conventional) effects.

* However, since about 98% of the used fuel is natural uranium, as radionuclides decay, the radioactivity in the system will in the long term become similar to that of natural uranium ore bodies found in Canada.

TABLE ES-1 – OVERVIEW OF STAGES IN THE DEVELOPMENT OF DEEP GEOLOGICAL DISPOSAL AND POTENTIAL RISKS

Stage	Non-radiological Effects		Radiological Effects	
	On site worker	Off site resident	On site worker	Off site resident
Siting	Green	Green	Green	Green
Construction	Yellow	Yellow	Green	Green
Operation	Orange	Green	Green	Green
Transportation	Orange	Orange	Green	Green
Extended Monitoring, Decommissioning and Closure	Yellow / Green	Green	Green	Green
Post Closure	Green	Green	Green	Green
Inadvertent Human Intrusion	Green	Green	Purple / Green	Green

TABLE ES-2– OVERVIEW OF STAGES IN THE DEVELOPMENT OF STORAGE AT REACTOR SITES AND POTENTIAL RISKS

Stage	Non-radiological Effects		Radiological Effects	
	On site worker	Off site resident	On site worker	Off site resident
Site Preparation and Construction	Yellow	Green	Green	Green
Operation	Orange	Green	Green	Green
Transportation	Green	Green	Green	Green
Extended Monitoring	Yellow	Green	Green	Green
Facility Repeat	Yellow	Green	Green / Blue	Green / Blue
Repackaging	Green	Green	Green / Blue	Green / Blue
Replacement of Modules and Baskets	Green	Green	Green / Blue	Green / Blue
Extended Long Term Monitoring	Green	Green	Green / Blue	Green / Blue

TABLE ES-3– OVERVIEW OF STAGES IN THE DEVELOPMENT OF CENTRALIZED STORAGE AND POTENTIAL RISKS

Stage	Non-radiological Effects		Radiological Effects	
	On site worker	Off site resident	On site worker	Off site resident
Site Preparation and Construction	Yellow	Green / Yellow	Green	Green
Operation	Orange	Green	Green	Green
Transportation	Orange	Orange	Green	Green
Extended Monitoring	Yellow	Green	Green	Green
Facility Repeat	Yellow	Green	Green / Blue	Green / Blue
Repackaging	Green	Green	Green / Blue	Green / Blue
Replacement of Modules and Baskets	Green	Green	Green / Blue	Green / Blue
Extended Long Term Monitoring	Green	Green	Green / Blue	Green / Blue

LEGEND

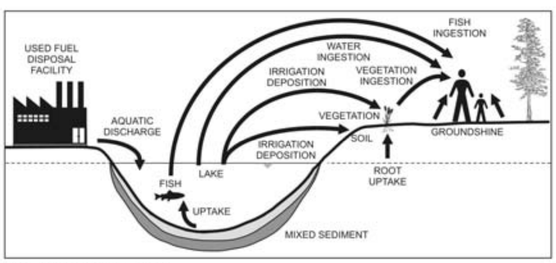
Green	No significant effect; very small risk of injury
Blue	Not assessed in detail
Purple	Potential exposure in the hypothetical and unlikely event of institutional collapse in the near-term and society memory loss of the site. No potential impact from DGR is expected if such a societal collapse occurs in the long term even in the case of human intrusion (because of gradual radioactive decay, see Appendix A).
Yellow	Theoretical potential lost time accident
Orange	Theoretical potential fatality

Brief examples of this evaluation are provided in Tables ES-1 to ES-3. Where emissions are thought to occur, the resulting exposure doses are compared to existing limits, guidelines and background values for perspective. Where there are gaps in current knowledge, these are noted, so that they can be addressed in a future analysis during the implementation of the monitoring program.

Radiological dose rates were estimated for the various stages in the implementation of each of the three types of facilities and for the public, workers and non-human biota (e.g., mammals, birds, fish) in each case.

The dose estimates were made using a comprehensive pathways analysis (see Figure ES-1a, b for pathways being considered). Example results for a deep geological repository and reactor-site extended storage are shown in Figures ES-2 and ES-3, respectively. Other routine and non-routine scenarios are provided in the Main Report and Appendices.

FIGURE ES-1a – KEY EXPOSURE PATHWAYS FOR SURFACE FACILITIES



SOURCE: Adapted from Russell, 1996

FIGURE ES-1a – KEY EXPOSURE PATHWAYS FOR UNDERGROUND FACILITIES

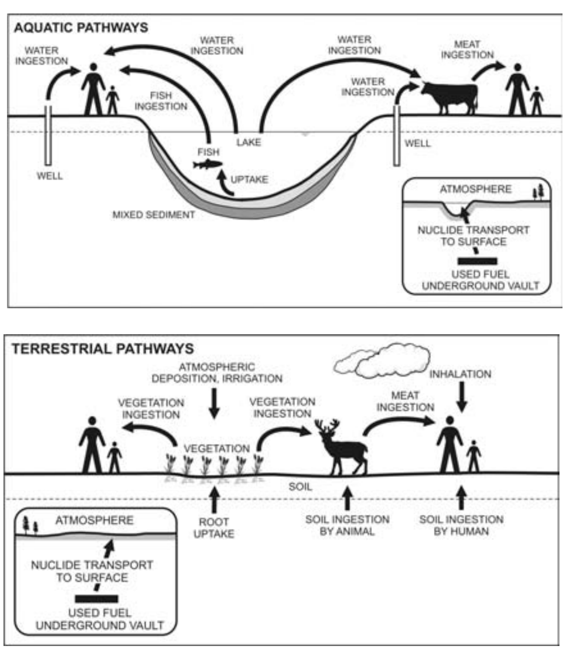
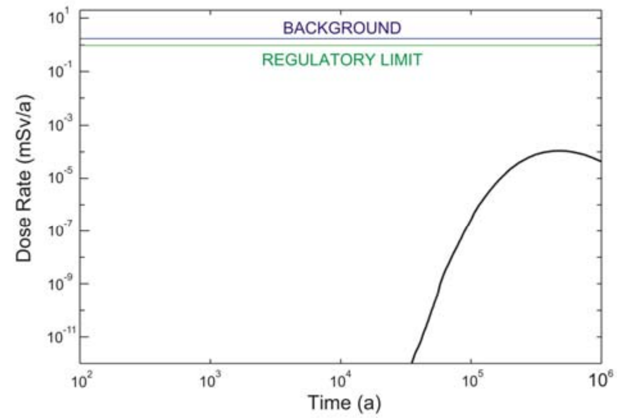
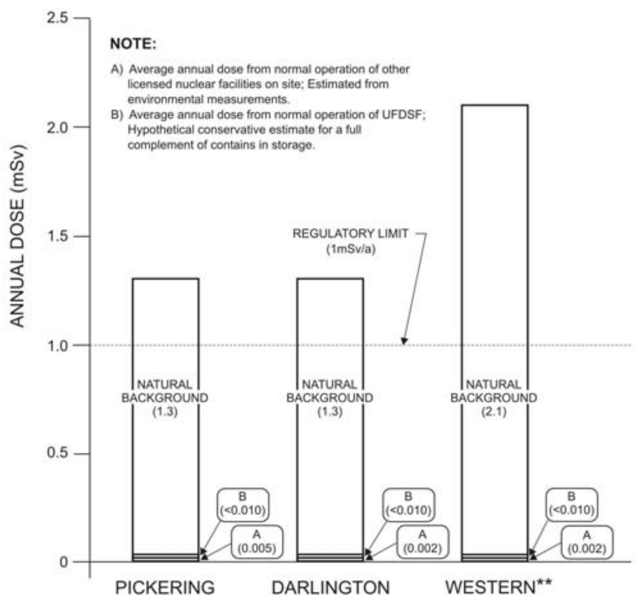


FIGURE ES-2 – DOSE RATE AS A FUNCTION OF TIME FOR THE POST-CLOSURE STAGE OF A DEEP GEOLOGICAL REPOSITORY



SOURCE: Adapted from Garisto et al, 2004

FIGURE ES-3 – ANNUAL PUBLIC DOSE FOR REACTOR-SITE EXTENDED STORAGE: OPERATING CONDITIONS*



* The operating experience from existing facilities has confirmed that the current dose rate to the public at the property boundary is less than 1% of the regulatory limit.

** Western refers to the Western Management Facility at the Bruce Site

The main conclusions from the Step 1 analysis are:

- Under current routine conditions, and based on available information, no significant impacts on human health or the environment, from any of the proposed technical management methods are expected.

- Conventional industrial and/or transportation accidents may occur in the implementation of these methods, as with any large industrial project. Such risks can be mitigated by the implementation of safety programs including worker education, strict implementation of safety procedures, and monitoring of this implementation. Some small differences between the options can be expected regarding risk from conventional accidents. For example, transportation risk is smaller for storage at reactor site than at a centralized facility.

- Overall, except for negligible changes in radiological dose after container failure, the total risk from a Deep Geological Repository decreases with time due to radioactive decay and the inherent passive nature of this disposal method.

- Over the long term, there may be a requirement to relocate the used fuel for the reactor-site extended storage and perhaps centralized extended storage (e.g., for above-ground facilities). This may be due to potential rise in surface water levels caused by climate-change factors such as global warming. Monitoring of climate conditions may be used to warn of the need for used-fuel facility relocation. Also, the impact of a far-future glaciation scenario has not been addressed in existing documentation on reactor-site extended storage and centralized extended storage. The consideration of such a scenario, may result in such facilities having to be relocated, prior to glaciation, to avoid glaciation related impacts.

  The risks associated with the extension of storage time at either reactor sites or a centralized location to very long times has not been studied quantitatively in detail. Such an assessment requires for example, an understanding of risks associated with potential loss of integrity of the fuel bundles (i.e., the cladding and potentially the fuel). However, a specific monitoring program can be developed to focus on this aspect of the performance of storage systems, to determine potential risk and decide on mitigation measures.

- Although radioactivity is often perceived as being a high risk factor associated with used fuel management, the estimated exposure doses for the various options are generally low in comparison to established national and international benchmarks.

- Current information on risks associated with the various options supports the safety of these systems under current conditions. Security risks such as acts of terrorism have not been evaluated in the present study.

- Several gaps in the risk estimates and its documentation were noted. However, none of these are considered to affect the overall conclusions from this study. They include a need:

  1. to update the documentation of risk assessments to ensure that they consider the current reference design concepts and alternatives studied by the NWMO;

  2. to complete the documentation of risk assessment from chemical emissions;

  3. to directly address potential specific human receptors (e.g., a specific documentation of potential risk to Aboriginals would enhance the transparency of the assessment, although most diets assumed in the current assessment encompass those of Aboriginal receptors);

  4. to complete and update the assessment of ecological risk to non-human biota (e.g., mammals, birds, fish).

  5. to re-evaluate the risk from transportation and if necessary, to develop mitigation measures to improve transportation safety.

These gaps will need to be addressed as part of the implementation of the approach selected by the federal Government for long-term management of nuclear fuel waste.

STEP 2 - Risk-Based Monitoring Framework

Monitoring is a set of activities that sample, measure and analyze radiological and chemical substances and physical parameters (e.g., temperature). The objective of monitoring activities is to demonstrate that adequate measures have been taken to protect the environment and to keep radiation doses to members of the public as low as reasonably achievable, social and economic factors taken into account.

A monitoring framework that addresses risks associated with used nuclear fuel management has been developed for the various technical methods relying on the results of risk assessments from Step 1. The proposed approach addresses the unique challenges of used fuel management being implemented in a multi-stakeholder process, including:

(i) The complexity of the facilities, i.e., the need to monitor multiple contaminants and pathways. - *This is addressed by using the results of the pathways analysis and risk assessments to define the main contaminants and environmental compartments that should be considered in the monitoring plans.*

(ii) The need to consider both science-based risk and perceived risk in the monitoring plans - *This is addressed by following a multi-stakeholder process that allows stakeholder input into the planning of risk-based monitoring (see Figure ES-4 and ES-5).*

(iii) The difficulty in conducting "invasive" measurements of sealed systems, particularly over a very long time frame - *This is addressed by developing a program of component-testing and by using monitoring boreholes that are sealed when not in use and periodically unsealed for measurement (see Figure ES-6).*

The above approach implies for example, for Deep Geological Disposal, even if the sealed repository is "out of sight" (because it is located deep underground) it can stay "monitorable".

The development of monitoring plans is an iterative process throughout the life cycle of the project (see Figure ES-5). As gaps in the risk assessment are gradually filled, the monitoring plans can be refined.

FIGURE ES-4 – THE MONITORING PLANNING PROCESS

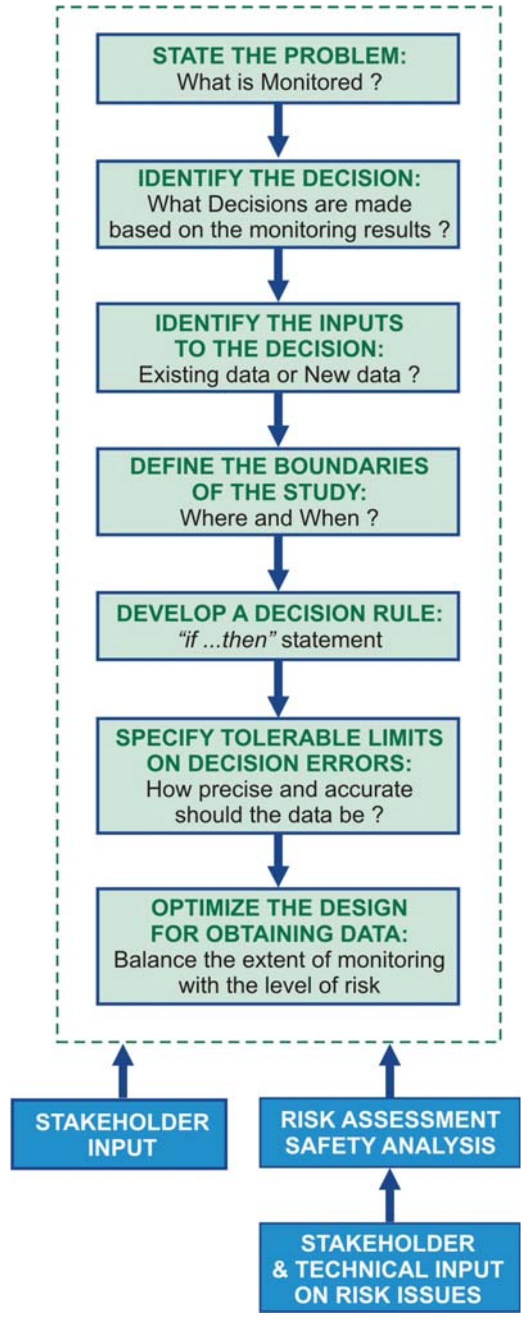
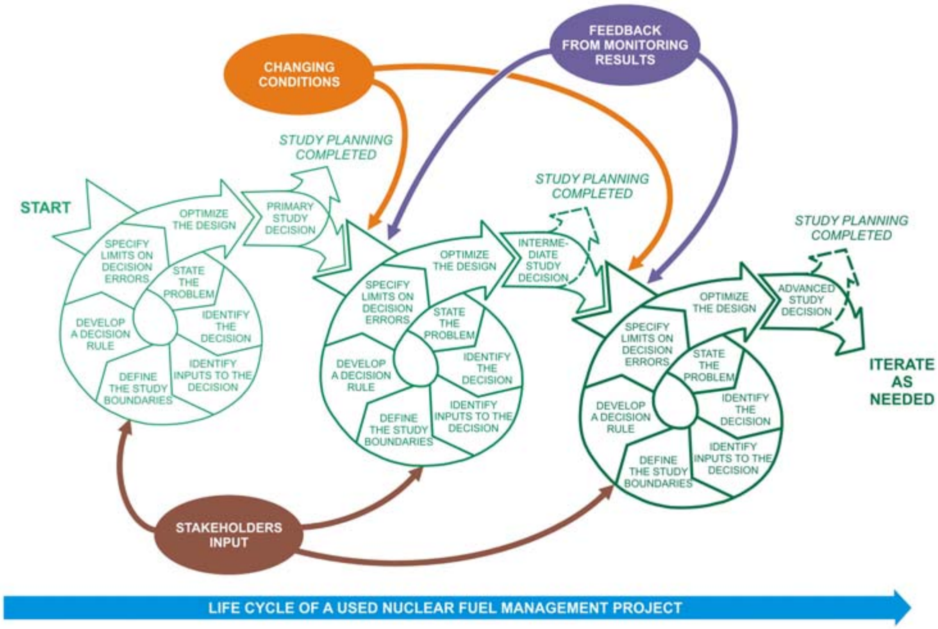


FIGURE ES-5 – REPEATED APPLICATION OF THE MONITORING PLANNING PROCESS THROUGHOUT THE LIFE CYCLE OF A PROJECT



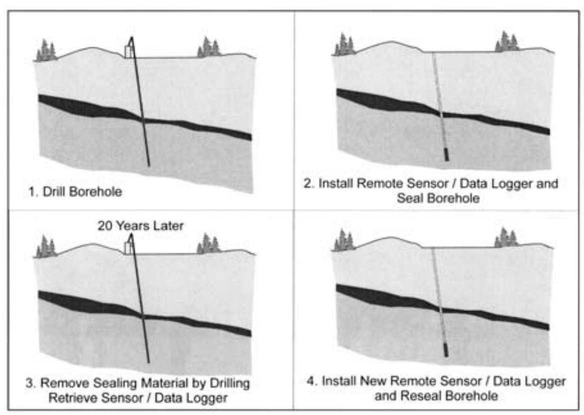
SOURCE: Adapted from U.S. EPA, 2000

Conclusion

Conceptual designs developed for the used-fuel management methods considered by the NWMO would all meet Canadian regulatory safety and environmental requirements. Regulatory compliance, however, does not imply that these concepts can be implemented under zero-risk conditions. Like any major industrial project, a nuclear used-fuel facility may result in a small risk to human health or the environment. This is the case even though all relevant regulations are met and particular care is taken to reduce the risk to as low as practically possible.

Potential risks may occur at different times and through different pathways for the different used-fuel management methods being considered by the NWMO. This report shows how an understanding of these risks can be used to develop a monitoring framework that focuses on the main risk pathways that are expected to affect the performance of the used-fuel management systems. Such a monitoring framework is based on the principle of "more risk => more monitoring" and is expected to complement routine monitoring done to demonstrate regulatory compliance.

FIGURE ES-6 – APPLICATION OF REMOTE DATA LOGGER/SENSOR ASSEMBLY TO LONG-TERM REPOSITORY MONITORING



Source: Extracted from Thompson and Simmons, 2003.

The monitoring framework discussed in this report is systematic, risk driven and iterative. It is based on a multi-stakeholder input process. It is expected that monitoring results will be used not only to determine compliance, but also to determine whether any aspects of the used-fuel management system (including monitoring) need to be modified to improve performance.

The iterative monitoring framework (Figure ES-5) enables the process to adapt to changes in stakeholder needs and in actual facility performance throughout the long life cycle of the project.

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1.0 MONITORING AND RISK

The Nuclear Waste Management Organization (NWMO) has a mandate from the Government of Canada to consult with the public and to recommend an approach for managing Canada's used nuclear fuel. Three main technical methods are being explored and evaluated by the NWMO. These are:

- Disposal in a Deep Geological Repository (DGR);
- Extended storage at nuclear reactor sites (RES);
- Centralized extended storage (CES), either above ground or below ground.

The used nuclear fuel management system (whether a DGR or an extended storage system) will be monitored. The results of environmental monitoring would be used to:

- Establish baseline information;
- Obtain data to assess potential environmental effects;
- Improve understanding of the performance of engineered barriers;
- Determine compliance;
- Determine whether any aspects of the management system need to be modified.

A step-by-step approach is used in this study to develop the monitoring framework:

- First, the various management options are reviewed for potential risks. These would include potential risk to the public, workers and the environment;
- Second, the results of the review are used to develop, at a conceptual level, a monitoring system, which focuses on the areas of potential risk.

Conceptual designs were developed for the used nuclear fuel management options studied by the NWMO (CTECH, 2002; 2003a, b; COGEMA Logistics 2003). All these designs meet regulatory safety and environmental requirements. Regulatory compliance, however, does not imply that these concepts can be implemented under zero-risk conditions. Like any major industrial project, a nuclear used fuel facility may affect the health of project workers and of members of the public living near the site or along affected transportation routes. It is not surprising therefore, that a small risk to human health or the environment would be expected from any of the management options mentioned above. This is the case even though all the relevant regulations are met and particular care is taken to reduce the risk to as low as practically possible.

This report provides a high-level perspective, *based on available information*, on what is known regarding potential risk to the public, risk to workers and risk to the environment for the three options listed above. The possible effects associated with the various management options are not limited to those resulting from exposure to radiation, nor to those experienced by individuals working at, or living near, the facility. Equally, they may not be limited to the period during which the facility is built, filled and sealed, but may arise many centuries in the future.

Potential radiological and non-radiological effects are considered in this report. Furthermore, both routine operating conditions and hypothetical accident scenarios are considered. Where emissions are thought to occur, the resulting exposure doses are compared to existing limits, guidelines and background values for perspective. Where there are gaps in current knowledge, *these gaps are noted*, so they can be addressed in a future analysis, during the step-wise implementation of the approach. Such an analysis will close gaps in the analysis, update the calculations, quantify the risk associated with this option and document the results for communication with the public.

Potential risk occurs at different times and through different pathways for the different options. It is useful to understand these aspects of the performance of the optional systems because an environmental monitoring framework can be developed to focus on the main risk pathways and provide potentially useful information on the performance of the system to interested stakeholders. Such a monitoring program would be based on the principle of **"more risk => more monitoring"** and would complement routine monitoring activities done to meet regulatory requirements**.** It is expected that the results of monitoring programs would be used not only to determine compliance, but also to determine whether any aspects of the management system (including the extent of monitoring) need to be modified to improve performance.

2.0 THE OBJECTIVE OF THE STUDY

The objective of this study is to provide answers to the following questions, based on *currently available information*:

(i) What can we expect, under normal conditions for the three options?

- Are there any potential, significant public health impacts expected?
- Are there any potential, significant workers health impacts expected?
- Are there any potential, significant ecological impacts expected?

(ii) What can hypothetically go wrong for the three options? How likely is it? What are the potential consequences for:

- The public?
- Workers?
- The environment?

(iii) What are the main gaps in these evaluations?

(iv) What are the main contaminants that could lead to potential risk (however small) from the used fuel facility? What are the main potential routes of exposure?

(v) Can risk aspects associated with the three options be used to design an environmental monitoring system? How can a risk-based monitoring system be developed? How can the challenges of very-long term monitoring be met?

3.0 FROM QUESTIONS TO RECOMMENDATIONS: THE STUDY PROCESS

This report uses information on risk from several similar design concepts to assess risk from the conceptual design options being evaluated by the NWMO. It does not provide an updated risk calculation on all the current conceptual design options. For example, the 1994 pre-closure report for DGR by Grondin *et al*. is used to discuss risk from DGR pre-closure stages. That report assumed 10 million fuel bundles whereas the current NWMO conceptual designs assume 3.6 million fuel bundles based on updated estimates (CTECH 2002). The use of the results from Grondin *et al.* (1994) in the present report is therefore conservative. As mentioned above, gaps and areas that require update are noted and will need to be addressed at the appropriate stage of implementation.

The major study steps are described schematically in Figure 3.1. The first step in this study was to review the waste management stages associated with each design option. Such stages include, for example:

- Siting;
- Construction;
- Operation;
- Transportation;
- Extended monitoring;
- Decommissioning;
- Closure; and
- Post closure.

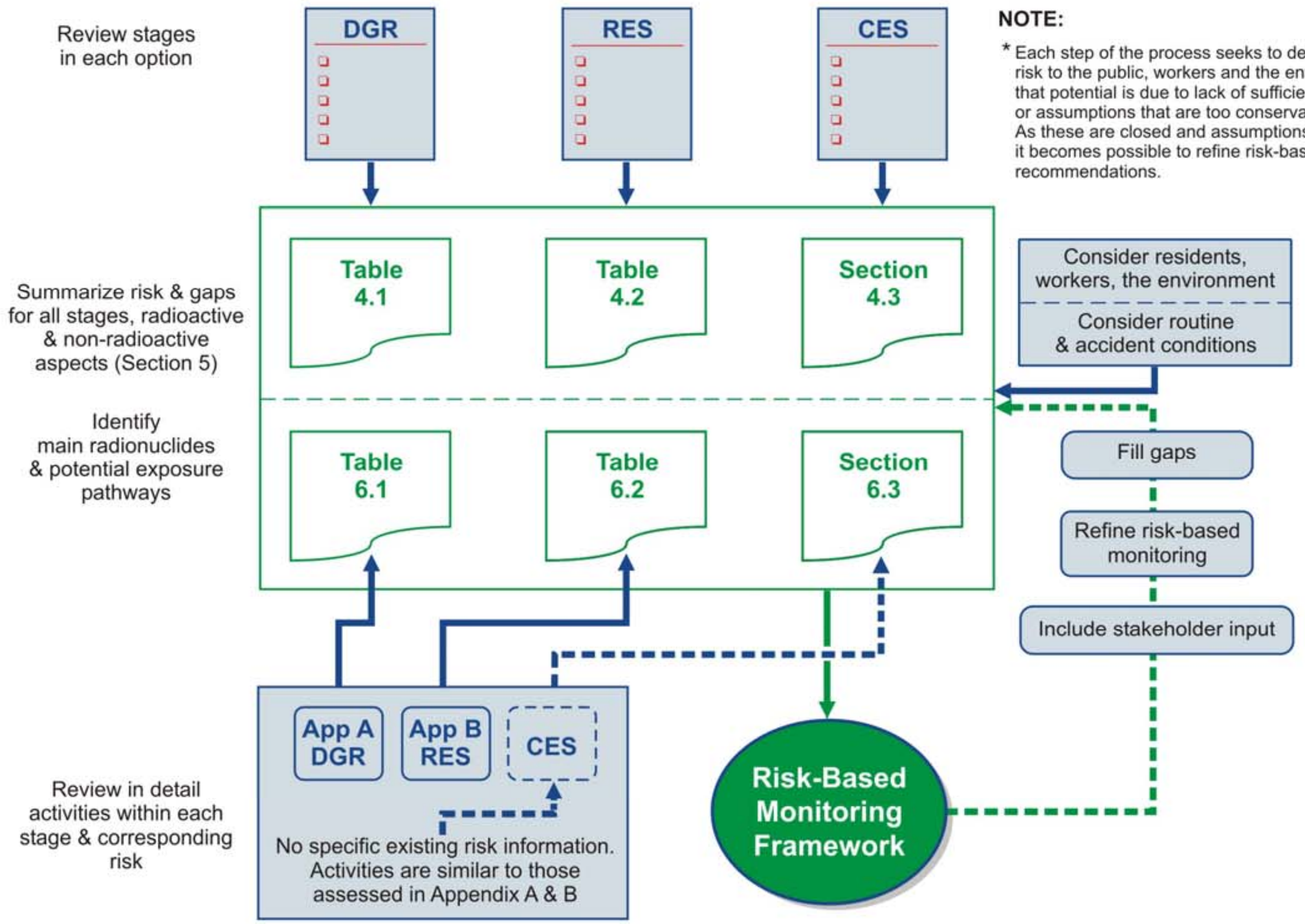
These stages are well established and described in detail in NWMO documents. (See www.nwmo.ca and follow the links to Background Papers, Technical Methods).

Next came a detailed review of all the activities in each of these stages and the risk associated with them. Such a review of DGR and RES is provided in Appendix A and B of this report, respectively. CES is similar to RES except in some aspects (e.g., transportation, option for below ground storage). There is no specific risk information on activities associated with different stages of CES. However, the individual activities are similar to those assessed for DGR and RES. We used this information to address potential CES risk issues.

An *overview* of the activities at each stage of the implementation each option and the associated risk is provided in Section 4 of this report. A more detailed examination of radioactivity issues is provided in sections 5 and 6. In particular, section 6 summarizes the radioactive dose, main pathways and main radionuclides at each stage of each option. It compares the estimated dose to radiological benchmarks (e.g., regulatory limits) and identifies gaps in the analysis.

FIGURE 3.1

STEP-BY STEP: THE PROCESS OF DEVELOPING A RISK-BASED MONITORING FRAMEWORK FOR USED NUCLEAR FUEL MANAGEMENT*



NOTE:

* Each step of the process seeks to determine potential risk to the public, workers and the environment; and whether that potential is due to lack of sufficient information or assumptions that are too conservative. Gaps are identified. As these are closed and assumptions become more realistic it becomes possible to refine risk-based monitoring recommendations.

Appendix C addresses in further detail the concept of risk from exposure to radioactivity. It provides a quantitative discussion of the very small risk that is associated with exposure to low doses of radiation. This conceptual risk analysis will have to be expanded and clearly communicated once a safety case is developed for a particular option.

Based on the analysis described in Section 6, a risk-based monitoring framework is recommended (see Section 7).

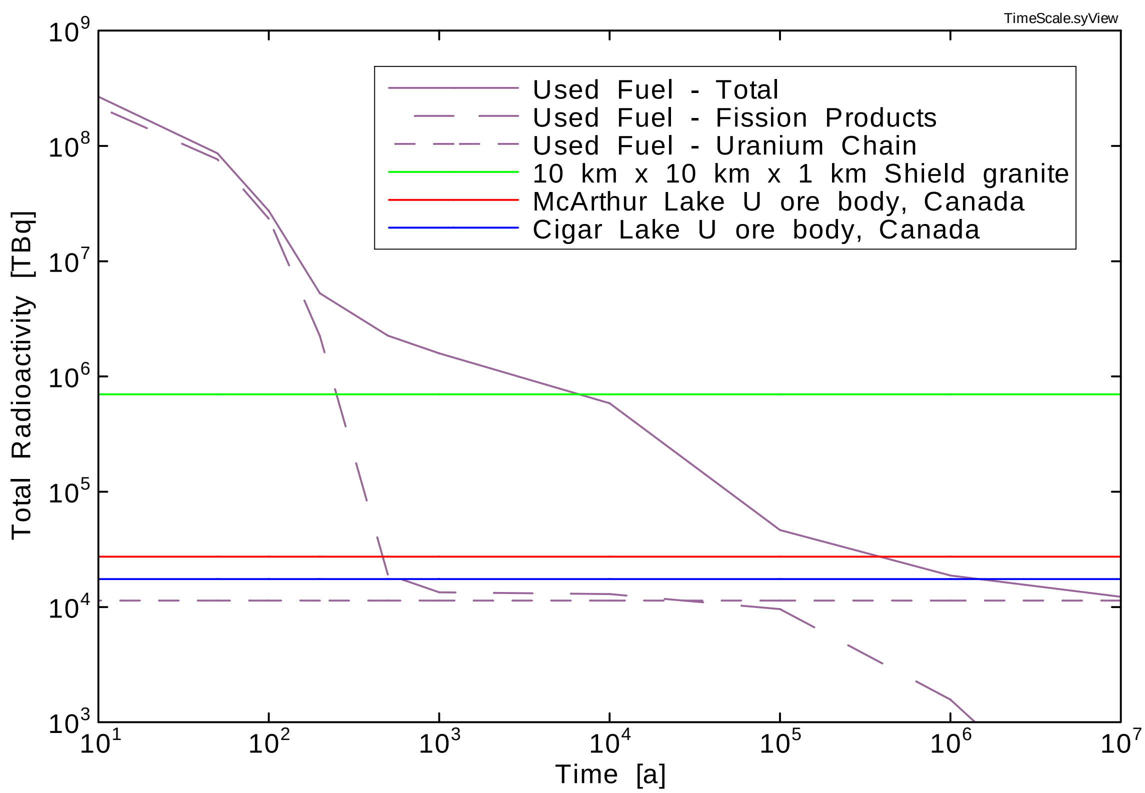
In the future, as gaps are closed and stakeholders input are provided, it should be possible to refine the risk-based monitoring recommendations provided in this report.

4.0 OVERVIEW OF STAGES IN THE DEVELOPMENT OF USED FUEL WASTE MANAGEMENT SYSTEMS AND ASSOCIATED POTENTIAL RISKS

This section provides an overview of stages in the development of Used Fuel Waste Management systems and associated risks. It addresses radiological and non-radiological aspects of Used Fuel Waste Management.

Since about 98% of the used fuel is natural uranium, as radionuclides decay, the radioactivity in the system will eventually become similar to that of uranium ore bodies found in Canada. This occurs on time scales of about one million years (see Figure 4.1).

Figure 4.1
Time Scale for Radioactivity Decay in Repository



The gamma-emitting fission products decay within about 1000 years. The remaining fuel radioactivity becomes comparable to that of the granite in the surrounding watershed after about 10,000 years. On time scales of about 1 million years, the residual used fuel radioactivity is dominated by that of the uranium in the fuel (and its decay chain products), a level that is comparable to natural uranium ore bodies (extracted from Gierszewski *et al.* 2004).

Extensive studies have been conducted on radiological aspects of used nuclear fuel management (see Appendices A, B and C).

There has been less emphasis in past assessments on exposure to non-radioactive contaminants, because they were perceived to be less hazardous than radioactive contaminants. Recent assessments of sites with mixed contaminants developed comprehensive systematic approaches for considering both radioactive and non-radioactive contaminants (e.g., Garisto, 2002). Based on available screening-level information (e.g., Environmental Assessments on the Extension of Storage Sites for Dry Used Fuel Storage), there are no major issues associated with chemical emissions from dry used fuel storage facilities. Similarly, based on Goodwin and Mehta (1994) and Gierszewski *et al.* (2004), it is likely that no exposure to chemical contaminants will occur until containers fail, engineered barriers fail and chemicals gradually disperse into the receiving environment through groundwater transport. An updated analysis of the risk from chemical contaminants will be required as part of the implementation of the approach selected by the federal Government for the long-term management of nuclear fuel waste.

4.1 DEEP GEOLOGICAL DISPOSAL

Disposal in a Deep Geological Repository (DGR) is one approach for the long-term management of used nuclear fuel.

A detailed assessment of the safety of DGR based on existing information is provided in Appendix A. The assessment is based on a series of Canadian and Swedish studies on DGR in Crystalline rock, as well as Swiss and Belgian studies on sedimentary rock. The combined results from the assessment studies that were reviewed illustrate the safety of DGR concepts for several combinations of design and sites.

The information in Appendix A (and references therein) was used to construct an overview table of the type of activities that take place at each stage of DGR and the main risk issues associated with these activities (see Table 4.1). Table 4.2 presents a similar overview for RES.

Table 4.1
Overview of Stages in the Development of Deep Geological Disposal and Potential Risks

	Non-radiological Effects		Radiological Effects	
	On site worker	**Off site resident**	**On site worker**	**Off site resident**
Siting	Site characterization will be in progress. No major activities will take place at existing storage sites. There will be very few health effects.	Activities will be mainly office-based, associated with field research and evaluation studies. They will involve some transportation hazards. Some stress-related symptoms are possible (in areas under consideration for a facility). Otherwise, few health effects are expected.	Some research personnel may have limited exposure to radiation.	Drilling equipment will be transported using radioactive logging devices. Although transport accidents to vehicles carrying radioactive sources may occur, no health effects are likely.
Construction	Vault mining and building construction will take place. Potential lost time due to industrial accidents is possible.	Extensive transport of conventional materials and supplies will take place. There may be transportation accidents.	Some industrial radiography workers will probably have small-scale exposures.	Transportation of gamma sources for industrial radiography may lead to some public concerns.
Operation and Transportation	Transportation of used fuel to the site, loading and sealing of containers, emplacement underground and backfilling of the repository, will be ongoing. Mining of new disposal areas will continue. Over the years, these activities may lead to lost time due to accidents as well as risk of potential fatalities.	Continued transportation of non-radioactive materials will take place. Transportation of used fuel from storage sites will also occur. Transport accidents may occur. Dust releases from the site and modifications of lifestyles after site development may affect members of the nearby community.	Handling of fuel during loading and unloading will lead to occupational exposures. Small exposures of transport workers will also occur. Workers placing used fuel bundles in containers and emplacing these containers underground may also be exposed. Regulatory application of the ALARA principle is expected to keep all doses well below CNSC occupational exposure limits.	Very small exposures of some members of the public will occur during transport procedures. Off –site releases of small quantities of radioactivity from the facility site may also occur. Any resulting public exposures are expected to meet CNSC regulatory requirements, and are not likely to lead to significant health effects. ALARA will be applied to ensure that exposures are as low as reasonably achievable.
Extended Monitoring, Decommissioning and Closure	This phase will mainly involve mining-related activities carried out on site, as well as decontamination and dismantling of all surface structures. These activities may lead to lost-time accidents. Operation-phase effects will gradually diminish.	Transportation of supplies will continue, but on a reduced scale. Operation-phase effects will continue, but will gradually diminish.	Some underground on-site exposures will continue at reduced levels. Workers may be exposed to radiation while dismantling contaminated above-ground facilities. Regulatory application of the ALARA principle is expected to keep all doses well below the CNSC occupational exposure limits.	No further transportation of used fuel will take place. Dismantling and possible transport of above ground facilities will lead to off-site releases of small quantities of radioactivity. Operation-phase effects will therefore continue, but will diminish with time. ALARA will be applied to ensure that exposures are as low as reasonably achievable.

Table 4.1 (Cont'd)
Overview of Stages in the Development of Deep Geological Disposal and Potential Risks

	Non-radiological Effects		Radiological Effects	
	On site worker	**Off site resident**	**On site worker**	**Off site resident**
Post closure	None	None	None. Inadvertent human intrusion could occur in the future, after loss of institutional control and societal memory of the site. The impact from such an unlikely event will diminish with time of intrusion.	None under normal conditions or under assumed scenarios of failed containers. Inadvertent human intrusion could occur in the future, after loss of institutional control and societal memory of the site. The impact from such an unlikely event will diminish with time of intrusion

Legend:

Green	No significant effect; very small risk of injury.
Purple	Potential exposure in the hypothetical and unlikely event of institutional controls collapse in the near-term and society memory loss of the site. No potential impact from DGR is expected if such a societal collapse occurs in the long term (because of gradual radioactive decay, see Appendix A).
Yellow	Potential lost time accident.
Orange	Potential fatality.

The analysis has shown that:

- There are no potentially significant public health and ecological impacts associated with emissions from used fuel waste management facilities.
- As expected for a very large industrial project, some potential worker fatalities and lost time due to conventional accidents are possible during construction, operation and transportation activities associated with DGR. Transportation accidents may also affect off-site residents using the transportation route. The estimates (see Appendix A for details) are considered to be conservative, and are based on Ontario industry statistics. However, it is expected that a disposal facility for used nuclear fuel would achieve a better than industry average for worker safety. For example, no worker fatality was experienced during a 50 million person-hours worked to construct the Darlington Nuclear Generating Station.

Table 4.1 also indicates that there are some radioactive exposures of workers, residents and biota associated with DGR. Radioactivity aspects of DGR were therefore examined in more detail (see sections 5 and 6, below). Risk calculations for these exposures are provided in Appendix A and further discussed in Appendix C.

It should be noted that the evaluation of potential risks during the post-closure stage in Table 4.1, is largely based on the so called Third Case Study (TCS), a recent assessment of DGR in the

Canadian Shield (Gierszewski *et al.*, 2004). However, it is expected that risk and monitoring aspects of the DGR concept in the TCS would be similar to those presented in other suitable geological media, such as sedimentary rock (e.g., NAGRA, 2002). *Nevertheless, the risk assessment will have to be expanded and updated, as part of the development of a safety case during implementation, if the DGR option is selected.*

The TCS provides a qualitative discussion of the consequence of possible long term climate changes (i.e., due to global warming, glaciation). These scenarios are not considered to have a significant effect on DGR.

Similarly, several large-scale external events such as earthquakes, volcanic activity and meteorite impacts were discussed in the TCS. These events are considered to be very unlikely to occur, or they would not have a significant impact (McMurry *et al.*, 2003).

4.2 STORAGE AT REACTOR SITES

The permanent or indefinite storage of used nuclear fuel at dry storage facilities at reactor sites is referred to as RES (Reactor Site Extended Storage). This extended storage requires maintenance and facility refurbishment.

Some of the used nuclear fuel, generated at several nuclear stations in Canada is currently stored in Used Fuel Dry Storage Facilities (UFDSF) at each of the sites. The present report is based on experience with the safety of these operating facilities, as well as recent representative assessments, carried out in support of plans to expand their capacity to accommodate fuel arising in the various stations. Assumptions on the extension of the operation of UFDSF towards long-term storage were based on the projected design lifetime of the various engineered barriers (CTECH, 2003a).

Appendix B provides a detailed summary of potential radioactive exposure aspects of RES under normal and hypothetical accident conditions. Other risk aspects associated with operating Used Fuel Dry Storage Facilities are evaluated in detail in the corresponding Safety reports. Table 4.2 provides an overview of the stages in the development of RES and the main risk issues associated with each stage.

In this table, facility repeats refers to the refurbishment or renewal of the storage complex facilities, which periodically reach the end of their service lives. Fuel bundles will be transferred from one storage structure to another, and the time served storage structure demolished (or refurbished) and replacement structures constructed, within the overall "footprint" of storage complex.

Repackaging refers to the periodic removal of fuel bundles from existing storage containers which have reached the end of their service life. Fuel containers are transferred from the storage complex to a repackaging facility, where fuel bundles are transferred from an existing storage container to another.

Replacement of modules and baskets refers to replacement of modules and baskets used to hold the fuel bundles in the container.

The analysis has shown that:

- There are no potentially significant public health and ecological impacts associated with emissions from RES under current routine conditions
- As expected for very large industrial projects, some conventional industrial accidents may occur and may impact workers. Such risks can be mitigated by the implementation of safety programs.
- The perpetual repeats of the operation assume the availability of institutional controls.
- The impact of the potential loss of institutional controls has not been assessed in existing documentation on RES. Also, the potential impact of a hypothetical human intrusion that may occur far in the future (after the hypothetical loss of institutional controls) has not been addressed in existing documentation.
- The potential impact of long-term climate change factors has not been addressed in existing documentation. Based on current understanding of climate change, there may be a future change in surface water levels due to factors such as global warming. Such scenarios may affect the integrity of RES and require ongoing future maintenance programs and/or relocation. Such activities require ongoing institutional control.
- The impact of a far-future glaciation scenario has not been addressed in existing documentation on RES. The consideration of such a scenario would indicate that RES should be relocated prior to glaciation, to avoid glaciation related impacts.

Table 4.2
Overview of Stages in the Development of Storage at Reactor Sites and Potential Risks

	Non-radiological Effects		Radiological Effects	
	On site worker	**Off site resident**	**On site worker**	**Off site resident**
Site preparation and construction	Building construction will take place. Potential lost time due to industrial accidents is potentially possible.	Potential effect on off-site residents is expected to be minimal.	Workers will have small exposure from other existing on-site nuclear facilities for RES.	Residents will have very small exposures from other existing on-site nuclear facilities.
Operation and Transportation	Operation: potential lost time and risk of fatalities due to industrial accidents is possible. Transportation: Not significant for this option.	Potential effect on off-site residents is expected to be minimal.	Handling of fuel during loading and unloading may lead to small occupational exposures. Regulatory application of the ALARA principle is expected to keep all doses well below CNSC occupational exposure limits. Transportation: Not significant for this option.	Residents may have very small exposures from the operation stage. Transportation: Not significant for this option.
Extended Monitoring	Potential effects are expected to gradually diminish.	Potential risk is smaller than during the operation stage.	Potential risk is smaller than during the operation stage.	Potential risk is smaller than during the operation stage.
Facility repeat	Potential risk is not worse than original operation.	Potential risk is not worse than original operation.	Potential risk is not worse than original operation. Some radioactive decay has occurred by now. The potential effect of loss of institutional controls was not assessed.	Potential risk is not worse than original operation. Some radioactive decay has occurred by now. The potential effect of loss of institutional controls was not assessed.
Repackaging	Potential risk not worse than original operation.	Potential risk not worse than original operation.	Potential risk not worse than original operation. Some radioactive decay has occurred by now. The potential effect of loss of institutional controls was not assessed.	Potential risk not worse than original operation. Some radioactive decay has occurred by now. The potential effect of loss of institutional controls was not assessed.
Replacement of modules and baskets	Potential risk not worse than original operation.	Potential risk not worse than original operation.	Potential risk not worse than original operation. Some radioactive decay has occurred by now. The potential effect of loss of fuel-bundle integrity has not been assessed in detail. However, it can be addressed by monitoring activities and mitigation. The potential effect of loss of institutional controls was not assessed.	Potential risk not worse than original operation. Some radioactive decay has occurred by now. The potential effect of loss of fuel-bundle integrity has not been assessed in detail. However, it can be addressed by monitoring activities and mitigation. The potential effect of loss of institutional controls was not assessed.

Table 4.2 (Cont'd)
Overview of Stages in the Development of Storage at Reactor Sites and Potential Risks

	Non-radiological Effects		Radiological Effects	
	On site worker	**Off site resident**	**On site worker**	**Off site resident**
Extended long term monitoring	Potential risk not worse than original operation.	Potential risk not worse than original operation.	Potential risk not worse than original operation. The potential loss of institutional controls and potential human intrusion scenarios have not been assessed for RES.	Potential risk not worse than original operation. The potential loss of institutional controls and potential human intrusion scenarios have not been assessed for RES.

Legend:

Green	No significant effect
Blue	Inadvertent human intrusion not assessed in detail
Yellow	Potential lost time accident
Orange	Potential fatality

4.3 CENTRALIZED EXTENDED STORAGE

Centralized extended storage (CES) systems are storage facilities and associated systems to store used nuclear fuel in a central location. Alternative CES concepts considered by the NWMO include several variations of dry storage, both above ground and below ground.

CES is similar to RES except:

- Site preparation and construction may also include mining (for below ground options). There is an associated risk of conventional industrial accidents to workers (see Section 4.1).
- Such risk can be mitigated by the implementation of a comprehensive health and safety plan.
- Exposure from other existing nuclear facilities does not occur if the facility is sited away from current nuclear facilities
- Transportation accidents may occur on the route from reactor sites to a centralized storage location. A small fraction of these accidents may result in lost-time to the persons involved. In extreme cases, such accidents may also result in fatalities. The risk from transportation accidents can be reduced by the implementation of mitigation measures.
- Long-term exposure may be associated with potential releases to groundwater pathways (for below ground options).
- Glaciation and/or global warming would likely require CES relocation or a change to RES in the long-term. The need for relocation due to climate change factors is diminished for below ground options such as extended storage in deep rock caverns.

Table 4.3 illustrates stages in the development of CES based on analogies to RES and DGR. This table assumes an underground CES for illustrative purposes.

Table 4.3
Overview of Stages in the Development of Centralized Extended Storage and Potential Risks

	Non-radiological Effects		Radiological Effects	
	On site worker	**Off site resident**	**On site worker**	**Off site resident**
Site preparation and construction	Similar to DGR	Similar to DGR	Similar to DGR	Similar to DGR
Operation and Transportation	Similar to DGR	Similar to DGR	Similar to DGR	Similar to DGR
Extended Monitoring	Similar to DGR	Similar to DGR	Similar to DGR	Similar to DGR
Facility repeat	Similar to RES	Similar to RES	Similar to RES	Similar to RES
Repackaging	Similar to RES	Similar to RES	Similar to RES	Similar to RES
Replacement of modules and baskets	Similar to RES	Similar to RES	Similar to RES	Similar to RES
Extended long term monitoring	Similar to RES	Similar to RES	Similar to RES	Similar to RES

Legend:

Green	No significant effect; very small risk of injury.
Blue	Inadvertent human intrusion not assessed in detail.
Yellow	Potential lost time accident.
Orange	Potential fatality.

5.0 RADIOLOGICAL LIMITS/BENCHMARKS

Estimates of radiological doses associated with the various methods for managing Canada's used nuclear fuel are provided in Appendix A and B. In the present study, we compare these estimated doses to regulatory limits and background values as follows:

Under normal conditions:

- The dose limit for members of the public is 1 mSv/a (the CNSC Radiation Protection Regulations; ICRP 60, 1991).
- A dose constraint of 0.3 mSv/a (ICRP 2000) which accounts for the possibility of exposure to multiple sources is also discussed.
- The dose rate limit for Nuclear Energy Workers (NEWs) is 50 mSv/a in any single year and 100 mSv over 5 years (the CNSC Radiation Protection Regulations; ICRP 60, 1991).
- The Canadian average background dose rate to humans from natural sources is 1.7 mSv/a (Grasty and LaMarre, 2004; see also Appendix C).
- A range of natural background dose rates to humans was reported in various studies and is also discussed (1.41 mSv/a in the Pickering and Darlington Environmental Assessments, 2.1 mSv/a in the Bruce Environmental Assessment (see Appendix B) and 3.0 mSv/a in Neil (1985).

Under upset conditions (abnormal events):

- The consequences to members of the public and the probabilities of accidents are compared to the regulatory compliance limits used for licensing nuclear generating stations (CNSC 1999).
- There is currently no Canadian Nuclear Safety Commission (CNSC) dose limit for Nuclear Energy Workers (NEWs) under accident conditions. The present report compares accident exposure dose to 30 mSv, the value used by OPG for potential accidents at a nuclear station (Grondin *et al.* 1994). A worker exposed to such an accidental dose would not exceed the 50 mSv/a regulatory limit.
- The International Commission on Radiological Protection (ICRP) proposes a maximum dose constraint of 100 mSv for workers in emergency situations (ICRP 2005).

There is some uncertainty at present regarding the selection of appropriate radiation benchmarks for non-human biota. A recent review (Garisto, 2004) derived ranges of radiation benchmarks for various types of biota and recommended a nominal value for use in current assessments. The summary Table from that report, and the corresponding literature sources are

reproduced in Appendix D for completeness. The nominal values from Garisto (2004) are used in the present report to provide perspective on exposure values of non-human biota.
Thus, for non-human biota we use the following nominal benchmarks:

- Terrestrial plants: 2.7 mGy/d
- Mammals : 1 mGy/d
- Birds : 5 mGy/d
- Fish: 5 mGy/d

Doses below these benchmarks are unlikely to cause significant (population-level) ecological impacts.

Table 5.1 summarizes radiological benchmarks considered in this study.

Table 5.1
Summary of Radiological Benchmarks Considered in this Study

	Public	**Worker**	**Non-Human Biota**
Normal	1 mSv/a (CNSC limit) 0.3 mSv/a (ICRP target) 1.7 mSv/a (average Canadian background) 1.4 to 3.0 mSv/a (range of background values)	20 mSv/a (complies with CNSC limit of 100mSv over 5 years) 50 msv/a (complies with 1 year CNSC limit)	Mammal: 1 mGy/d Plants: 2.7 mGy/d Birds: 5 mGy/d Fish: 5 mGy/d
Abnormal	$f^{*}>0.01$ 0.5 mSv $0.01 > f > 0.003$ 5 mSv $0.001 > f > 1x10^{-4}$ 30 mSv $1x10^{-4} > f > 1x10^{-5}$ 100 mSv $f < 1x10^{-5}$ 250 mSv	Nominal value: 30 mSv A maximum dose constraint proposed by ICRP: 100 mSv/a	*No readily-available benchmarks were found.* Comparison to benchmarks for normal conditions was used in the interim for the long term exposure following an accident.

* f = annual frequency.

Health risks associated with exposure to low-levels of radiation are summarized in Appendix C.

6.0 POTENTIAL RADIOACTIVITY EXPOSURE PATHWAYS

This section summarizes the radiological dose associated with the various technical methods which are explored by the NWMO. A dose estimate is based on a pathways analysis which considers all potential routes of exposure (see illustration of exposure pathways in Figure 6.1).

Section 6 is structured as follows:

- Section 6.1 discusses the dose estimate associated with DGR.
- Section 6.2 discusses the dose estimate associated with RES.
- Section 6.3 discusses the dose estimate associated with CES.

6.1 DOSE FROM DEEP GEOLOGICAL REPOSITORY

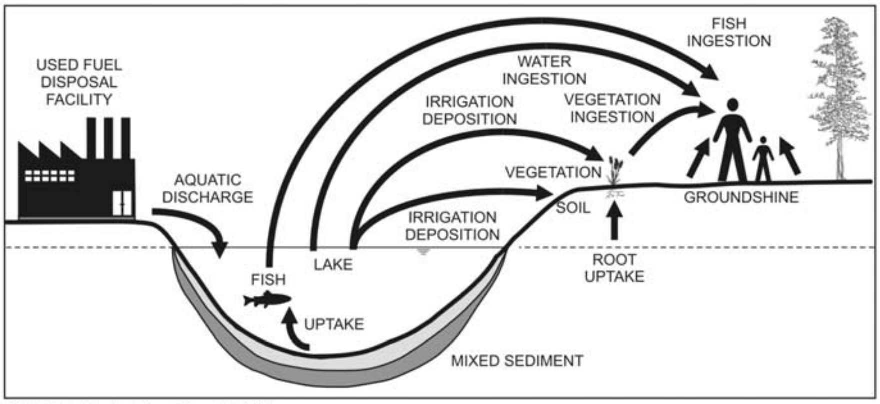
Table 6.1 presents representative radiological dose values associated with the DGR option. The values presented in this table were extracted from safety assessments including Grondin *et. al*. (1994) and Garisto *et. al*. (2004) and are expected to be representative of the DGR option. Several combinations of sites and designs were assessed to demonstrate safety (see Appendix A). The values in Table 6.1 provides illustrations of exposure based on these DGR concepts.

Table 6.1 indicates that

- It is unlikely that DGR will result in significant radiological effects on residents, workers, or the environment under routine conditions
- Conservative estimates of hypothetical unlikely severe accidents may result in fatality of workers from conventional causes for an assumed severe traffic accident. Mitigation measures such as special driver education, avoidance of shipment under bad weather conditions can be implemented to reduce this risk.
- Localized effects on fish cannot be ruled out for hypothetical, unlikely severe traffic accidents that may result in release to water bodies. Uncertainty in the benchmarks for fish is acknowledged (see Appendix D).
- Overall, except for negligible changes in radiological dose if containers fail, the risk from DGR decreases with time due to radioactive decay and the inherent passive nature of this disposal method.

FIGURE 6.1a

KEY EXPOSURE PATHWAYS FOR SURFACE FACILITIES



SOURCE: Adapted from Russell, 1996

FIGURE 6.1b

KEY EXPOSURE PATHWAYS FOR UNDERGROUND FACILITIES

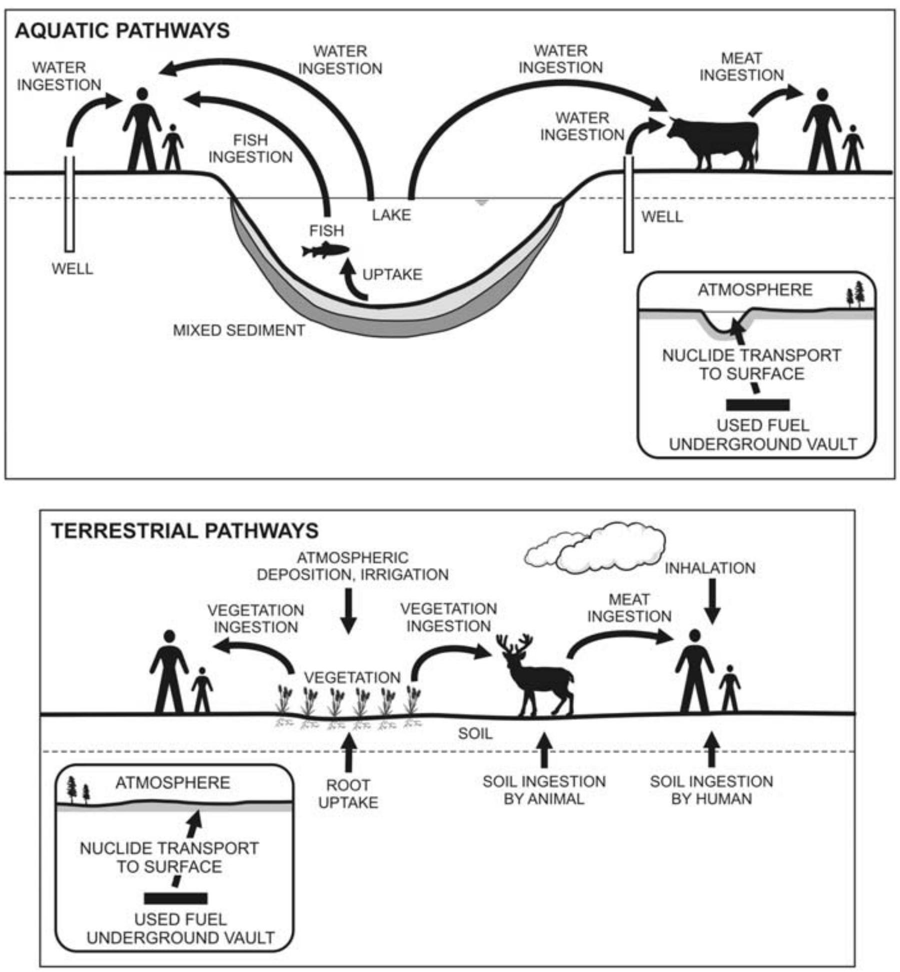


Table 6.1
Illustration of Radiological Exposures at Various Stages of the Development of a Deep Geological Repository. Maximum Doses to Adults and/or Infants are Shown, as Appropriate and as Available

	Public	Workers	Environment
Siting	Not significant	Not significant	Not significant
Construction	Not significant; Release of naturally occurring radon and its progeny to the atmosphere at a small fraction of natural background is expected.	Not significant; Release of naturally occurring radon and its progeny to the atmosphere at a small fraction of natural background is expected. Can be mitigated (e.g., ventilation).	Not significant
Operation normal	Max dose to most exposed individual: 5e-4 mSv/a; Main pathway: emission to water; Main radionuclide: ^{90}Sr.	Max dose to worker: 17 mSv/a estimated for technical staff (operators) and trades (mechanics); Main pathway: external gamma	Fish dose: 2.4e-5 mGy/d; Main pathway: internal; Main radionuclide: ^{134}Cs; Plant dose: 1.8e-5 mGy/d; Main pathway: groundshine; Main radionuclide: 90Sr; Mammal dose: 1.7e-5 mGy/d; Main pathway: groundshine; Main radionuclide: 90 Sr; Bird dose: 1.7e-5 mGy/d; Main pathway: groundshine; Main radionuclide: ^{90}Sr.
Operation accident	For hypothetical accident scenarios, (Grondin *et al.* 1994) max dose: 0.25 mSv at an annual frequency of 3e-4; Doses for other accident scenarios (all lower): are presented in Table 4.2.1-4 in Appendix A; Doses for all accident scenarios were found to be a small fraction of the corresponding dose limits; The main pathway is inhalation; The main radionuclides are ^{3}H and actinides.	For hypothetical accident scenarios, (Grondin *et. al.* 1994) max dose for a surface accident: 17 mSv at an annual frequency of 2.1e-3; Max dose for underground accident: 21 mSv at an annual frequency of 4e-3; The main pathway is inhalation of volatile radionuclides and particulates.	Not assessed
Transportation normal	Very small exposures of some members of the public may occur during transport procedures. Max dose: 0.09 mSv/a. This was estimated to be the dose by road transportation to persons working at a truck stop used by the trucks. Doses for other modes of transportation (all lower) are presented in Table 5.1.1-1 of Appendix A. The dose was due to external radiation.	Small exposures of transport workers will occur. Max driver dose: 11 mSv/a; This was estimated for water transportation. Doses for other modes of transportation (all lower) are presented in Table Section 5.1.2 of Appendix A. The dose was due to external radiation.	Very small exposures of non-human biota are expected, in the vicinity of the cask. Max dose: 2.5e-4 mGy/d; The dose was due to external radiation.

Table 6.1 (Cont'd)
Illustration of Radiological Exposures at Various Stages of the Development of a Deep Geological Repository. Maximum Doses to Adults and/or Infants are Shown, as Appropriate and as Available

	Public	Workers	Environment
Transportation Accident	Extremely low probability accidents are potentially possible. The max short-term dose for hypothetical severe accident conditions was: 10 to 40 mSv, for an infant, for a frequency of 3e-6 per year or less.	Extremely low probability accidents were assessed. The max short-term dose to a worker occurs in a range of potential severe accidents and reach: 190 mSv for rail and water transportation; 65 mSv for road transportation. The corresponding maximum frequency is 3.6e-5 (assuming road shipment of 10.1 million fuel bundles).	Doses to non-human biota were estimated in the vicinity of a potential severe potential accident. Long-term doses were estimated in the range of about 2.7e-2 mGy/d for plants, mammals and birds. These are less than radiation benchmarks.
	This is much less than the limit of 250 mSv for such an accident for nuclear generating stations. The main pathway is inhalation. The main radionuclides are volatiles and particulates.	The assumed hypothetical severe accident may result in a fatal crash for the driver and crew (already addressed in Table 4.1 under conventional non-radiological impacts). Conservative assumptions did not take credit for reduced probabilities due to special driver training, avoidance of bad weather conditions and other risk mitigation measures that can be implemented to prevent such hypothetical extreme collisions. The main hypothetical exposure pathway is inhalation. The main radionuclides are volatiles and particulates.	Doses are estimated at about 2.7 mGy/d for fish, in a localized area in the vicinity of the crash. There is uncertainty in the benchmarks for fish. The conservative exposure estimate exceeds the lower end of this range. It does not exceed the current internationally accepted benchmark of 10 mGy/d for aquatic biota (see Appendix D) or the proposed benchmark on p5-2. The main exposure pathway is water ingestion. The contributors to dose are ^{134}Cs and ^{137}Cs.
Extended Monitoring, Decommissioning and Closure	This phase involves mining-related activities, demolition and decontamination. Dose to members of the public is expected to be extremely small (much less than regulatory limit or exposure from natural background).	Some radiation exposure is expected during dismantling and decontamination operations. The average dose to worker: 0.05 to 0.1 mSv/a.	Potential effects are likely to be less than those during construction and operation.

Table 6.1 (Cont'd)
Illustration of Radiological Exposures at Various Stages of the Development of a Deep Geological Repository. Maximum Doses to Adults and/or Infants are Shown, as Appropriate and as Available

	Public	Workers	Environment
Post closure Normal (Defective Containers Scenario, DCS)	No exposures will occur until containers fail and radionuclides are gradually released. The peak dose of about 1e-4 mSv/a may occur at about 500,000 years after disposal. The analysis assumes that some containers had undetected manufacturing defects (DCS Reference case). The main contributor to dose is ^{129}I followed by ^{36}Cl.	No impact	Estimated future doses to non-human biota are orders of magnitude less than the dose from natural background. The main pathway is future release to groundwater and ingestion of ^{129}I and ^{14}C.
Post closure Inadvertent human intrusion. Assume that this happens 1,000 years after emplacement.	There is an extremely low probability (3e-8) that an on site resident will receive an inadvertent dose of 8 mSv/a from contaminated core that is brought to the surface, if institutional controls and knowledge of the site are lost over the next 1000 years. This dose will decrease with time of intrusion and will reach about 0.5 mSv at 100,000 years and 0.4 mSv at 1,000,000 years (see Figure 6.1).	There is an extremely low probability (4e-8) that a core technician (the most exposed worker) will receive an inadvertent dose of 140 mSv if institutional controls and knowledge of the site are lost over the next 1000 years. This dose will decrease with time of intrusion and will reach about 2 mSv at 100,000 years and 0.3 mSv at 1,000,000 years (see Figure 6.2).	Not assessed

Legend

Green	Exposures are less than radiation benchmarks.
Blue	Not assessed.
Purple	Potential exposure in the hypothetical and unlikely event of institutional controls collapse in the near-term and society memory loss of the site. No potential impact from DGR is expected if such a societal collapse occurs in the long term (because of gradual radioactive decay, see Appendix A).
Yellow	Exposure under very unlikely and very severe accident conditions exceeds lower end of the range of estimated benchmark. Exposures do not exceed current internationally accepted benchmark.
Orange	Potential fatality under extremely unlikely accident conditions that can be further reduced by risk mitigation measures such as special driver education, avoidance of shipments under bad weather conditions, etc.

Detailed calculations and a discussion of these results appear in Appendix A. An example of the estimated dose in comparison to radiological benchmarks, is shown in the following figures. Figures 6.1 and 6.2 shows the time dependence of the estimated dose to a self-sufficient farmer living at the site for a representative post-closure scenario, and for a hypothetical inadvertent intrusion scenario, respectively.

Figure 6.2
Estimated Dose rate as a function of Time for the Post-closure stage of a DGR (Adapted from Garisto *et. al*., 2004)

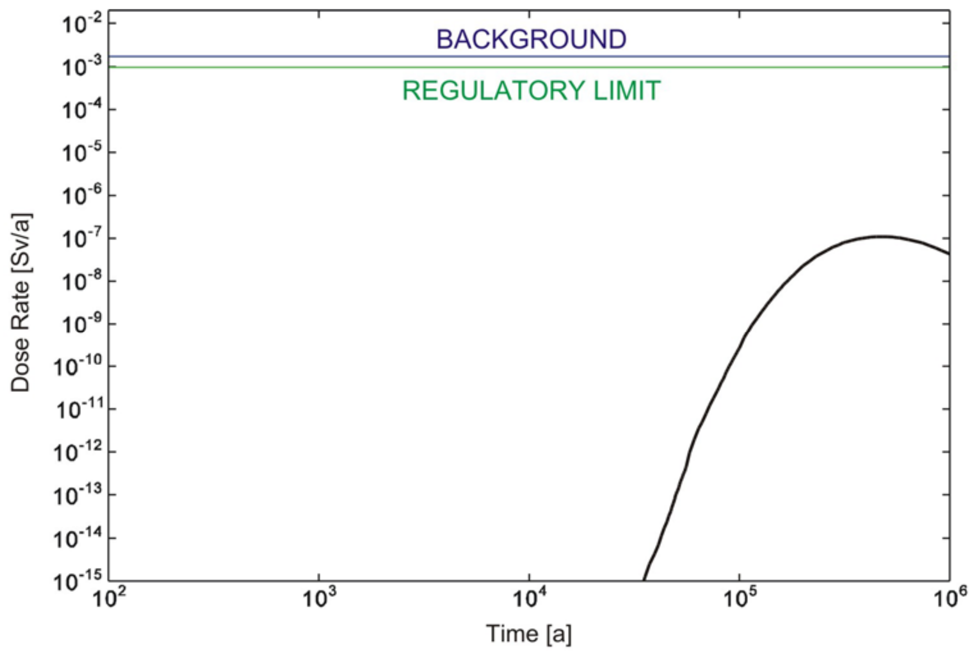
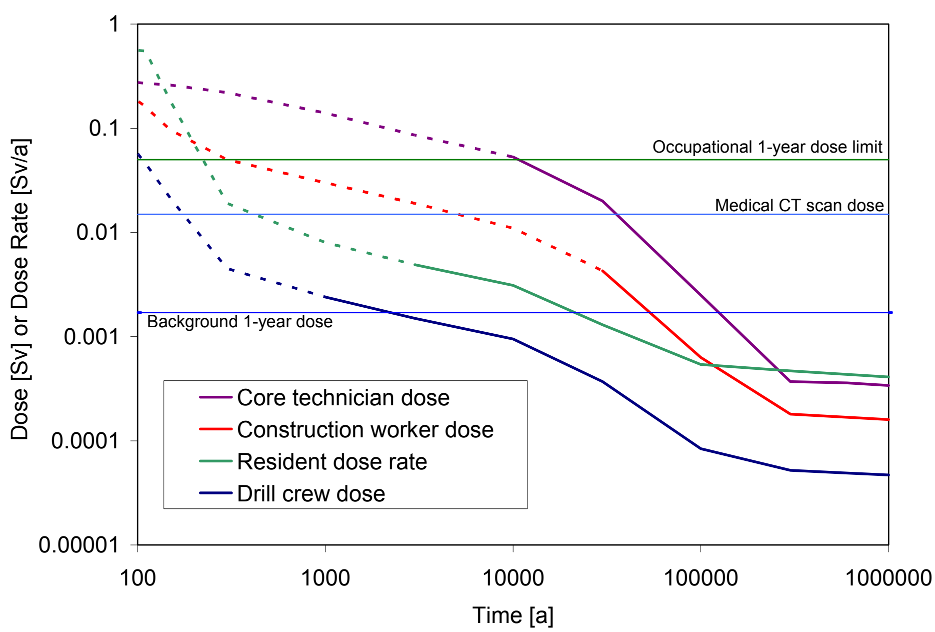


Figure 6.3
Calculated Inadvertent Exposures as a Result of a Borehole Drilled into a Container. The Core Technician, Construction Worker and Drill Crew Receive a One-Time (Acute) Dose, While the Resident Receives a Chronic Dose Rate. Dashed Portions of Each Line have Estimated Probabilities Smaller than One-in-a-Million (Extracted from Gierszewski *et. al*., 2004)



6.2 DOSE FROM EXTENDED STORAGE AT REACTOR SITES

Table 6.2 presents representative radiological dose values associated with the RES option. The values presented in this table are extracted from Appendix B. This appendix is based on operating experience at representative Dry Fuel Storage Facilities in Canada (e.g., at the Pickering, Darlington and Bruce nuclear generating stations). It also addresses projections on the dose associated with the extension of the operation of these facilities to accommodate additional fuel projected to arise from the future operation of these nuclear stations.

Table 6.2
Illustration of Radiological Exposures at Various Stages of the Development of RES. Maximum Doses to Adults and/or Infants are Shown, as Appropriate and as Available

	Public	Workers	Environment
Site preparation	No increased radioactivity in the environment is expected due to site preparation and construction activities.	Not significant; Workers are expected to receive exposures from existing licensed nuclear facilities on site	No increased radioactivity in the environment is expected due to site preparation and construction activities.
Construction	No increased radioactivity in the environment is expected due to site preparation and construction activities.	Not significant; Workers are expected to receive exposures from existing licensed nuclear facilities on site	No increased radioactivity in the environment is expected due to site preparation and construction activities.
Operation normal	Gamma radiation levels from full storage buildings based on recent EAs on expansion of Dry Storage Facilities are expected to be indistinguishable from variations in natural background, at the site boundaries.	Max dose to nuclear energy worker*: 0.5 mSv/a: Main pathway: inhalation. Main radionuclide: tritium.	Max. dose*: 0.008 mGy/d for terrestrial biota. Main pathway: gamma
Operation accident	Doses for all hypothetical accident scenarios were found to be a small fraction of the regulatory limit on annual public dose; The main pathway is inhalation; The main radionuclides are ^{3}H and ^{85}Kr.	Max dose for a surface accident:16.5 mSv. The main pathway is inhalation of volatile radionuclides and particulates.	Doses for all hypothetical accidents were less than 50 mGy. The main pathway is inhalation. The main radionuclide is ^{3}H.
Extended Monitoring;	Dose to members of the public is expected to be extremely small (much less than regulatory limit or exposure from natural background).	Potential risk is smaller than during operation stage.	Potential risk is smaller than during operation stage.
Facility repeat	Potential risk not worse than original operation Some radioactive decay has occurred by now. The potential effect of loss of institutional controls was not assessed.	Potential risk not worse than original operation Some radioactive decay has occurred by now. The potential effect of loss of institutional controls was not assessed.	Potential risk not worse than original operation Some radioactive decay has occurred by now. The potential effect of loss of institutional controls was not assessed.

Table 6.2 (Cont'd)
Illustration of Radiological Exposures at Various Stages of the Development of RES. Maximum Doses to Adults and/or Infants are Shown, as Appropriate and as Available

	Public	Workers	Environment
Repackaging	Potential risk not worse than original operation. The potential effect of loss of institutional controls was not assessed.	Potential risk not worse than original operation. The potential effect of loss of institutional controls was not assessed.	Potential risk not worse than original operation Some radioactive decay has occurred by now. The potential effect of loss of institutional controls was not assessed
Modules and baskets	Potential risk not worse than original operation. The potential effect of loss of institutional controls was not assessed.	Potential risk not worse than original operation. The potential effect of loss of institutional controls was not assessed.	Potential risk not worse than original operation. Some radioactive decay has occurred by now. The potential effect of fuel-bundle disintegration has not been assessed in detail. It can be addressed by monitoring activities and mitigation. The potential effect of loss of institutional controls was not assessed.
Long-term monitoring; Inadvertent human intrusion.	Not assessed	Not assessed	Not assessed

Legend

Green	Exposures are less than radiation benchmarks.
Blue	Not assessed
Yellow	Exposure under very unlikely and very severe accident conditions exceeds lower end of the range of estimated benchmark. Exposures do not exceed current internationally accepted benchmark
Orange	Potential fatality under extremely unlikely accident conditions that can be further reduced by risk mitigation measures such as special driver education, avoidance of shipments under bad weather conditions, etc.

* Based on Darlington Used Fuel Dry Storage Facility, as an example. For other examples, see Appendix B.

Table 6.2 indicates that:

- It is unlikely that RES will result in significant radiological effects on residents, workers, or the environment under routine conditions.
- There are knowledge gaps regarding the risk associated with long-term integrity of the fuel bundles. A monitoring program is required to address this potential risk and indicate whether and when mitigation measures are required.
- There is knowledge gaps regarding the risks associated with inadvertent human intrusion in case of loss of institutional controls.

Detailed calculations and discussion of these results appear in Appendix B. Examples of the estimated dose in comparison to benchmarks are extracted from Appendix B and shown in Figures 6.4 to 6.11.

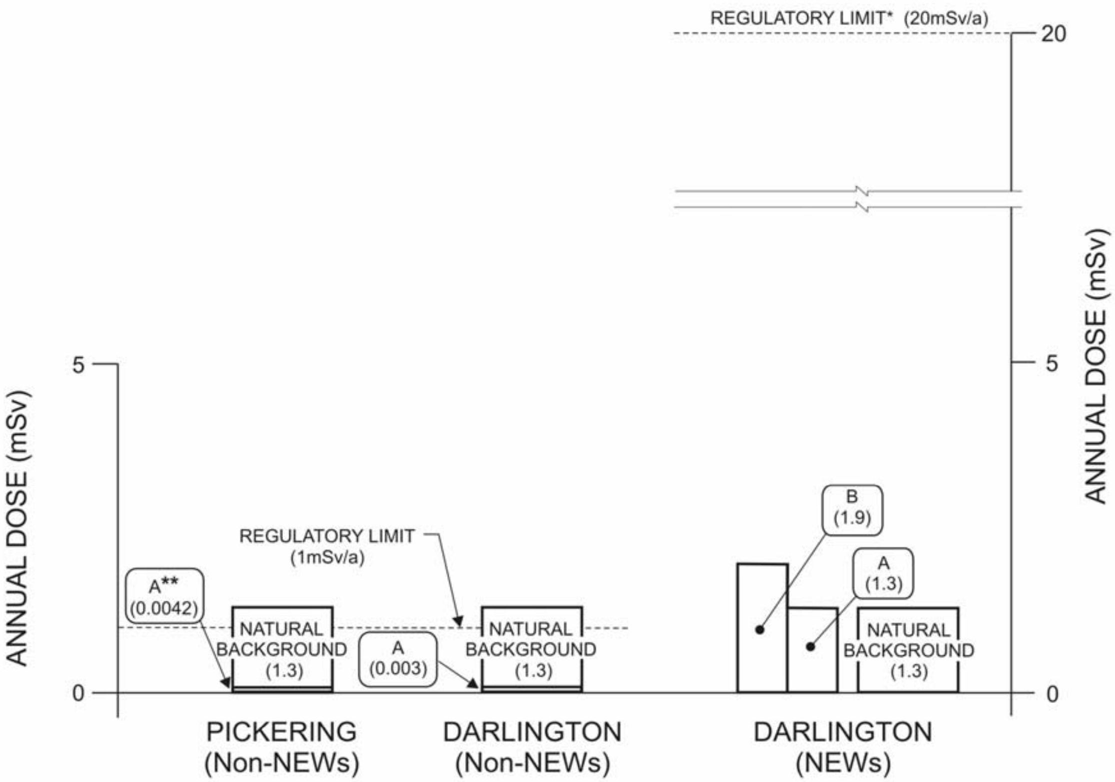
6.3 DOSE FROM CENTRALIZED EXTENDED STORAGE

The dose from above-ground CES could be similar to RES except that there could be exposure from transfers of used fuel along transportation routes in the case of CES. On the other hand, there will be no exposure of Nuclear Energy Workers (NEWs) to radiation from other facilities on site and from used fuel in existing storage pools. Such exposures are accounted for in the dose estimates of RES (see Appendix B).

The dose from below-ground CES would be similar to DGR although there would be differences in the handling of the used-fuel containers and sealing materials underground.

FIGURE 6.4

ANNUAL WORKER DOSE (Construction-Normal)



NOTE:

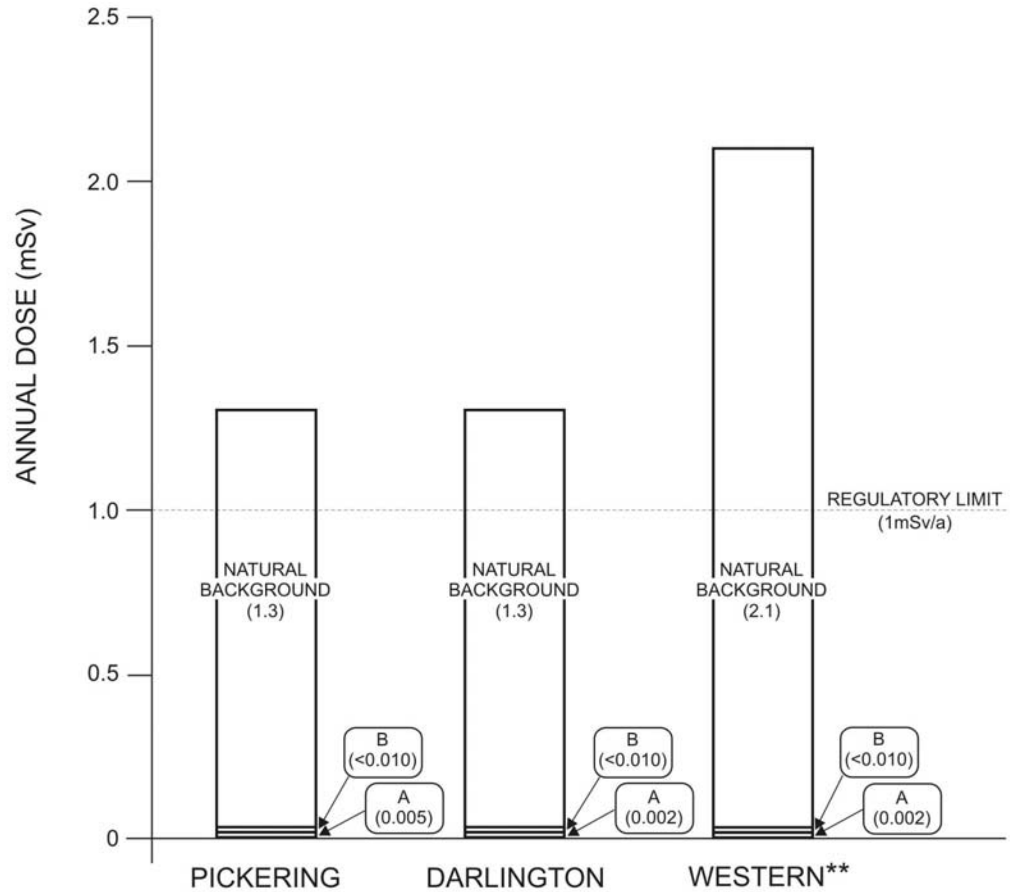
A) Average annual dose from other licensed operations
B) Highest annual dose from other licensed operations

* Regulatory Limits are 100 mSv/ over 5 consecutive calendar years and 50 mSv in any single year

** Phase II only

FIGURE 6.5

ANNUAL PUBLIC DOSE*
(Operation - Normal)



NOTE:

A) Average annual dose from normal operation of other licensed nuclear facilities on site; Estimated from environmental measurements.

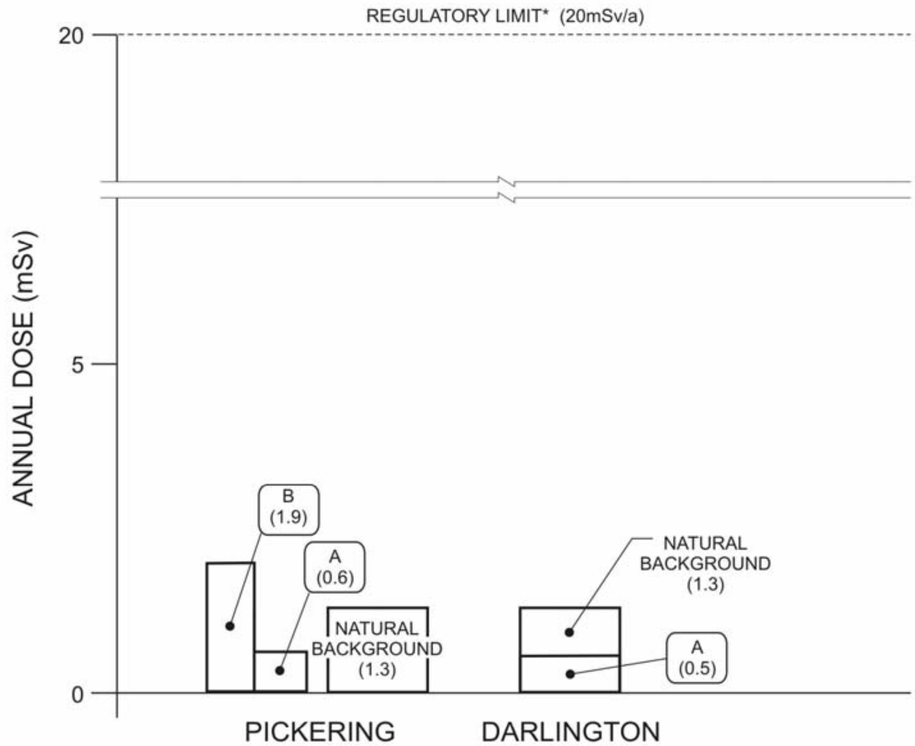
B) Average annual dose from normal operation of UFDSF; Hypothetical conservative estimate for a full complement of contains in storage.

* The operating experience from existing facilities has confirmed that the current dose rate to the public at the property boundary is less than 1% of the regulatory limit.

** Western refers to the Western Management Facility at the Bruce Site

FIGURE 6.6

ANNUAL WORKER DOSE (NEW)
(Operation - Normal)



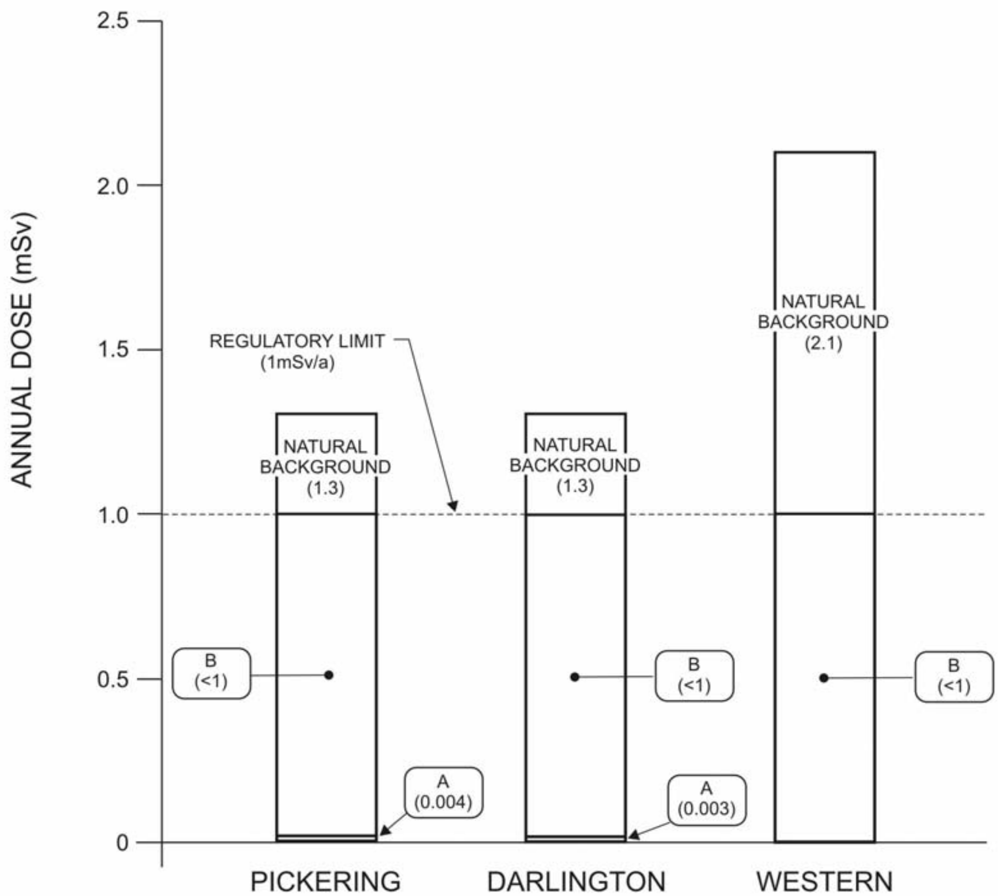
NOTE:

A) Average annual dose from normal operations
B) Highest annual dose from normal operations

* Regulatory Limits are 100 mSv/ over 5 consecutive calendar years and 50 mSv in any single year

FIGURE 6.7

ANNUAL WORKER DOSE (non-NEW) (Operation - Normal)

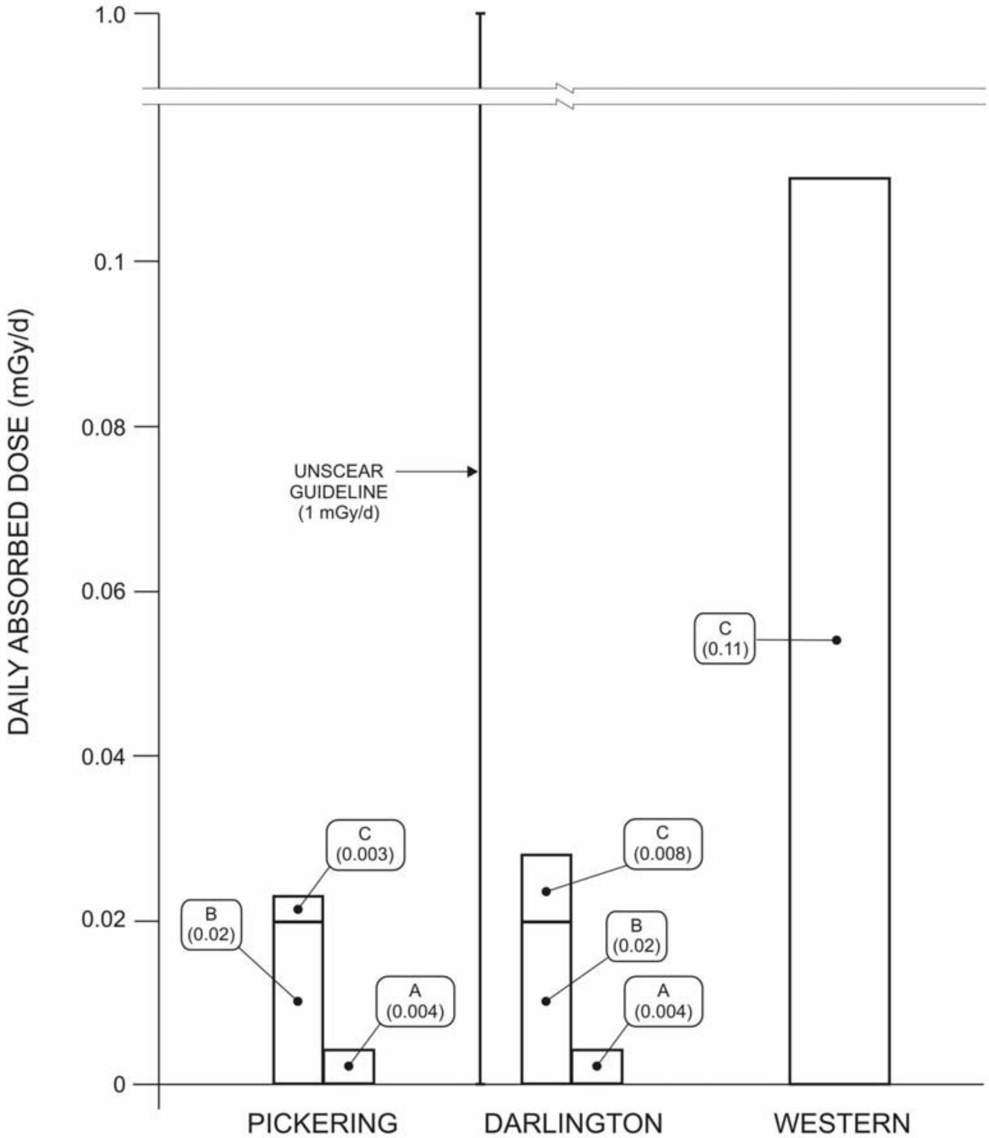


NOTE:

A) Average annual dose from normal operation of other licensed nuclear facilities.
B) Annual dose from normal operation of UFDSFs.

FIGURE 6.8

DAILY DOSE TO NON-HUMAN BIOTA
(Operation - Normal)

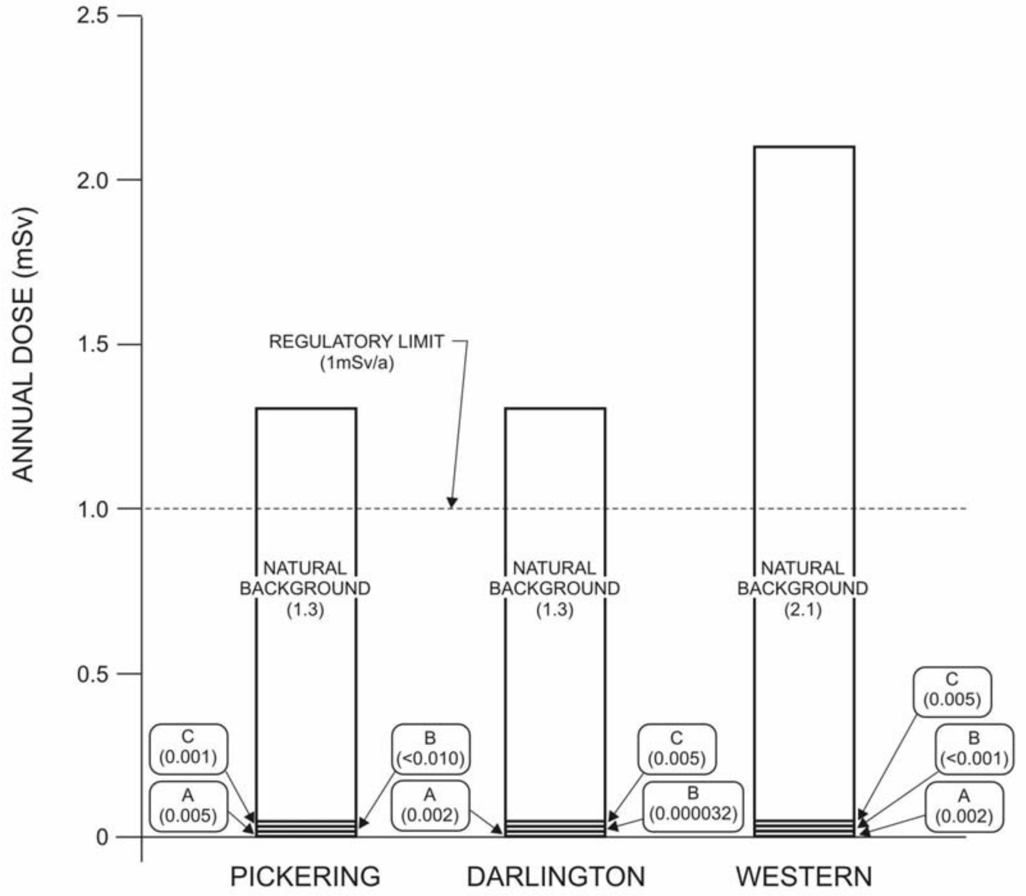


NOTE:

A) Low end of range of daily dose from natural background.
B) High end of range of daily dose from natural background.
C) Average daily dose from normal operation at UFDSF.

FIGURE 6.9

PUBLIC DOSE DURING A HYPOTHETICAL YEAR IN WHICH A BOUNDING MALFUNCTION/ACCIDENT OCCURS AT UFDSF

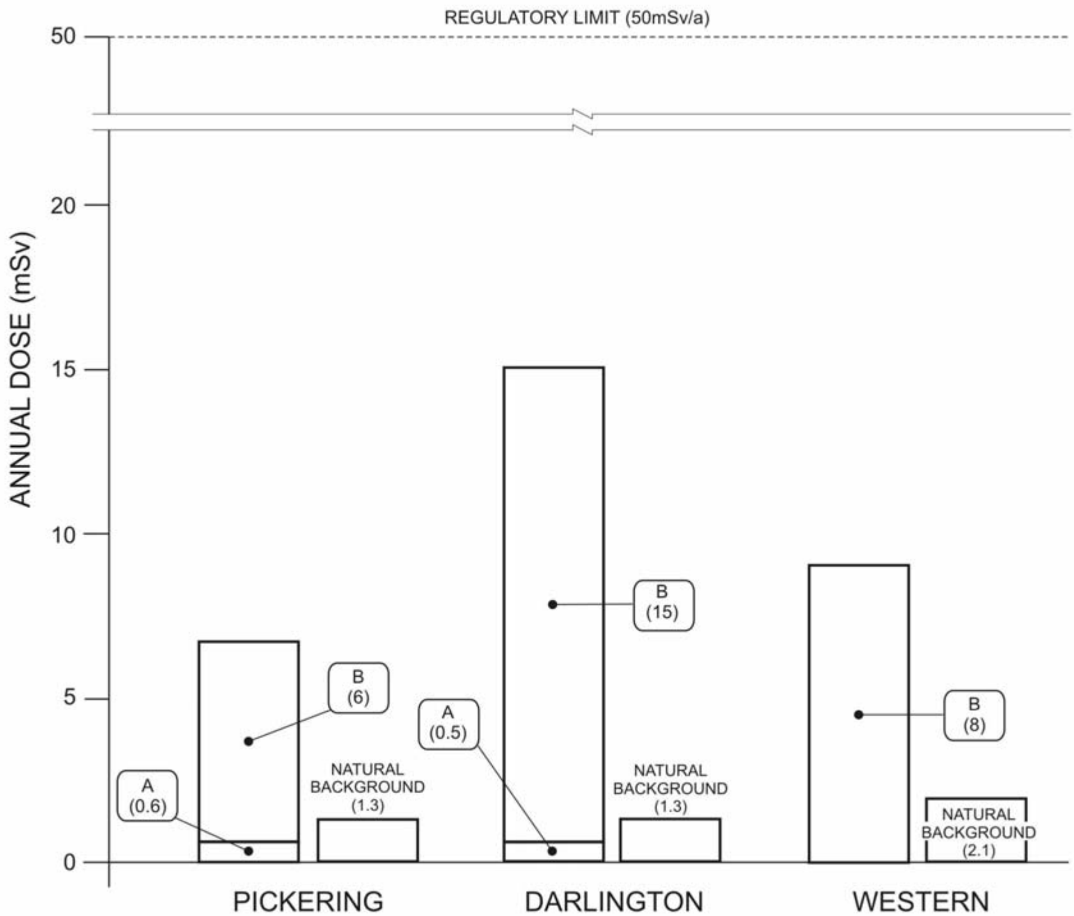


NOTE:

A) Average annual dose from normal operation of other licensed nuclear facilities on site.
B) Dose from normal operation of UFDSF at year end when malfunction/accident occurs.
C) Dose from bounding malfunction/accident at UFDSF.

FIGURE 6.10

WORKER DOSE (NEW) DURING A HYPOTHETICAL YEAR IN WHICH A BOUNDING MALFUNCTION/ACCIDENT OCCURS AT UFDSF

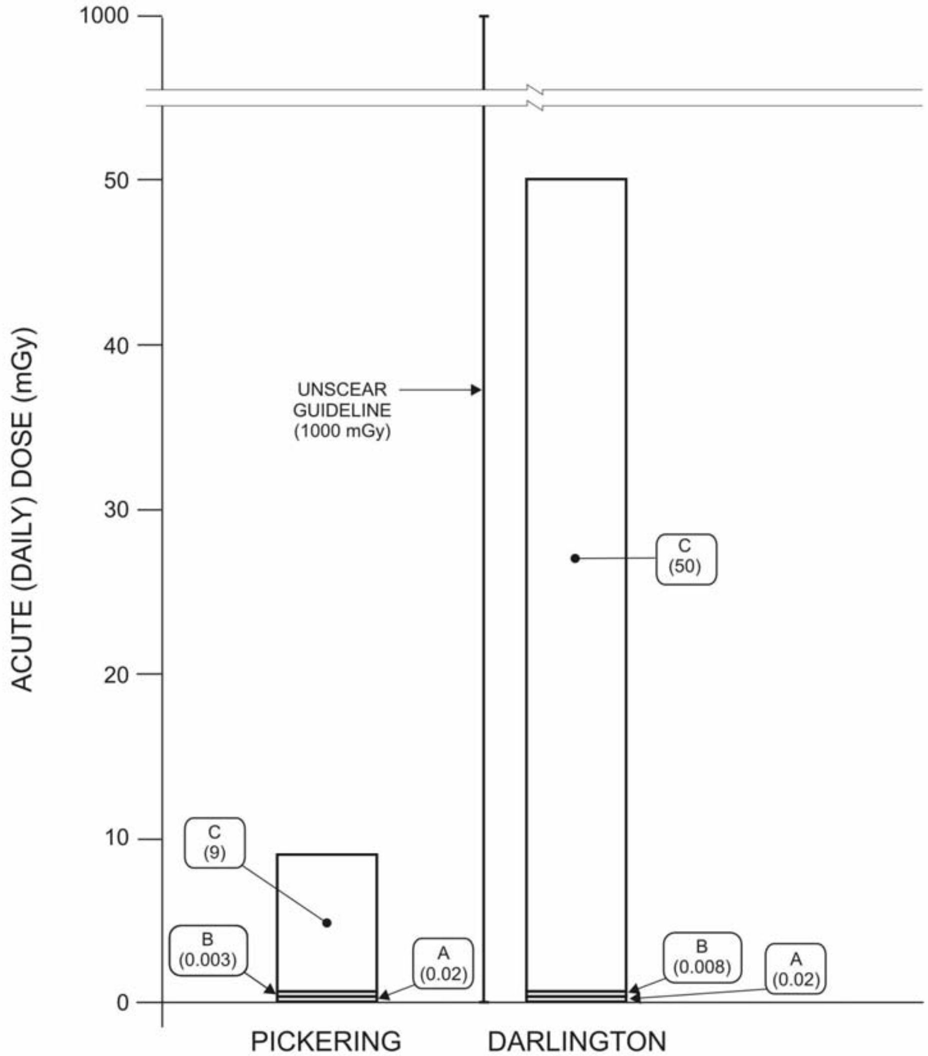


NOTE:

A) Average occupational dose at year end when malfunction/accident occurs.
B) Expected dose from malfunction/accident.

FIGURE 6.11

DOSE TO NON-HUMAN BIOTA
(Hypothetical - Bounding Malfunction/Accident at UFDSF)



NOTE:

A) High end of range of daily dose from natural background.
B) Average daily dose from normal operation at UFDSF.
C) Acute dose from bounding malfunction/accident at UFDSF.

7.0 MONITORING FRAMEWORK

Monitoring is a set of activities that sample, measure and analyze radiological and chemical substances and physical parameters. The objective of monitoring activities is to demonstrate that adequate measures have been taken to protect the environment and to keep potential impacts to members of the public as low as reasonably achievable, social and economic factors taken into account.

Used nuclear fuel management systems are and will be monitored to satisfy regulatory licence conditions. In addition, there may be a need to go beyond the minimal regulatory requirements, and reflect stakeholders concerns and considerations by the implementing organization, to keep high standards of health and environmental protection. Also, parameters such as temperature, groundwater chemistry and rock mass properties may need to be monitored to confirm the expected evolution of the facility.

This section describes a systematic approach towards the development of a monitoring system, which focuses on areas of potential risk and incorporates stakeholders concerns. Such a system would complement core monitoring which is done to comply with regulatory requirements. Initial discussions of monitoring requirements for the various options appear in NWMO documents (e.g., see CTECH, 2002).

In general terms, the purpose of a monitoring program for all used fuel waste management systems is to demonstrate that the facility is operating within the parameters under which it is expected to operate. Environmental monitoring can be regarded as a continuous activity in which:

- Pre-operational baseline monitoring, environmental risk assessments and operational monitoring, all complement each other.
- Decommissioning baseline, decommissioning impact (or recovery) predictions and monitoring, also complement each other.

Monitoring of used fuel waste management facilities faces several unique challenges. These include:

- The complexity of the facilities: the need to monitor multiple contaminants and pathways; this is addresses in section 7.1.
- The need to consider technical risk and perceived risk in the monitoring plans; this is addressed in section 7.2.

- The difficulty in conducting "invasive" measurements of sealed systems, particularly over a very long time frame; this is addressed in section 7.3.

The monitoring framework proposed in this report addresses these challenges as follows.

7.1 HOW TO LINK MONITORING TO RISK?

A risk-based monitoring framework is proposed in this report. This approach implies that, for example, the parameters and frequency in the effluent monitoring program would depend on the results of the risk assessment for the facility. Such a program would include the routine monitoring of core contaminants, as well as periodic characterization of the effluent, whenever a change in process or procedures occurs. The selection of the core contaminants (both radioactive and chemical) would be based on the results of the risk assessment.

The predictions of risk to members of the public, workers and biota are often based on contaminant-transfer models. Pathways confirmation monitoring will also have to take place. The objective of this monitoring would be to confirm that transfer modeling was accurate or conservative. This is achieved by measuring contaminants in the environment for the key media identified in the risk assessment to ensure that they are equal or less than those used in the transfer modeling. Monitoring would focus on contaminants and their transfer pathways that:

- Pose the greatest risk to human receptors or biota;
- Have the greatest uncertainty in their modeling.

For example, such an approach is used by nuclear utilities to plan environmental monitoring around nuclear power stations.

The environmental compartments (media) that are selected for monitoring within a pathway would generally include:

- The initial point of entry to the receiving environment (e.g., air, water, groundwater);
- Environmental compartments with the potential to accumulate contaminants over time (e.g., sediment, where applicable).

Preliminary examples of environmental compartments and radionuclides that would be included in a monitoring program based on the "snapshot" of current understanding of risk summarized in this review, is provided in Tables 7.1 to 7.3. As can be seen in these tables, the major parameters that are monitored change with time. For example, tritium, which is important to monitor during the initial stages of the implementation of RES and CES, decays with a half-life of 12 years and is therefore not monitored in the long term.

In addition to facility monitoring, there will be a need to address monitoring along transportation routes. For example, Grondin *et al.* (1994) advises monitoring at truck stops in the early stages of the program. In the COGEMA Logistics (2003) transportation system design, stops would be only in designated compounds, which would require monitoring.

Table 7.1
Main Expected Pathways for Emission Monitoring for Above Ground RES[1] and CES Facilities

Stage	In air				In liquid	
	H-3	Alpha/beta particulates	Radioactive noble gases	Gamma	H-3	Gross alpha/beta
Siting	-	-	-	-	-	-
Construction	-	-	-	-	-	-
Operation	✓	✓	-	✓	✓	✓
Extended Monitoring	✓[5]	✓	-	✓	✓[5]	✓[5]
Facility repeat (50a)	✓	✓	-	✓	✓[4]	✓[4]
Repackaging (100a)	-	✓[2]	✓[2]	✓	-	✓
Replacement of modules and baskets (300a)	-	✓[2]	✓[2]	✓	-	✓
Long-term monitoring [3]	-	✓	✓	-	-	✓

[1]for RES-monitoring also complies with current monitoring plans of existing facilities.
[2]also important for monitoring fuel bundle integrity.
[3]extent of monitoring depends on results during repeats, repackaging or module/baskets change.
[4]for decontamination, if required.
[5]extent of monitoring depends on initial results

Table 7.2
Main Expected Pathways for Monitoring at the Boundary for Above Ground RES[1] and CES[3]

Stage	In air				In liquid	
	H-3	Alpha/beta particulates	Noble gases	Gamma	H-3	Gross alpha/beta
Siting	-	-	-	-	-	-
Construction	-	-	-	-	-	-
Operation	✓	✓	✓	✓	-	-
Extended[2] Monitoring	-	-	-	-	-	-
Facility repeat (50a)	✓	✓	✓	✓	-	-
Repackaging (100a)	-	✓	✓	✓	-	-
Modules and baskets (300a)	-	✓	✓	✓	-	✓
Long-term[2] monitoring	-	✓	✓	-	-	-

[1]abiotic and biotic sampling of RES – also complies with current monitoring plans of existing facilities.
[2]repeats of extended monitoring conditional on results during repeats, repackaging or modules/baskets change.
[3]transportation monitoring for CES as per transportation packages regulation and along the route.

Table 7.3
Main Expected Pathways for Emission Monitoring for DGR and CES (Underground Rock Cavern Alternative)

Stage	In air				In liquid	
	H-3	Alpha/beta particulates	Radioactive noble gases	Gamma	H-3	Gross alpha/beta
Siting	-	-	-	-	-	-
Construction	-	-	-	-	-	-
Operation	✓	✓	-	✓	✓	✓
Extended Monitoring	✓	✓	-	✓	-	-
Transportation*		✓		✓		
Post closure	-	-	-	-	-	✓ See Section 7.3

*monitoring as per transportation packages regulations.

As the main risk issues identified in Sections 4, 6 are related to worker health and safety, it would be important to keep track that safety procedures are followed and maintain quality assurance and quality control (QA/QC). *It should be noted that all monitoring plans also have to follow regulatory requirements.* Accident monitoring activities per se are not part of the routine monitoring of a system. Risk management and mitigation measures need to be developed for potential accident scenarios. These would include monitoring activities.

7.2 HOW TO DEAL WITH RISK AND PERCEIVED RISK IN A SYSTEMATIC MANNER?

The process of linking risk and monitoring priorities (as described above) is part of the problem formulation stage in a so-called Data Quality Objectives (DQO) process. The DQO process is a multi-stakeholder planning approach, formulated by the U.S. EPA (2000) to develop monitoring plans in support of decision-making. For example, monitoring results can be used to support a decision to continue or modify a given operation. Systematic planning, as described here, is based on a common sense, tiered approach to ensure that the level of detail in monitoring is commensurate with risk and with the importance and intended use of the results. Elements of the DQO process are used in this report to develop a systematic, risk-based approach to monitoring. The proposed framework promotes communication between all stakeholders involved in the program. Through a systematic planning process, a team can develop acceptance criteria for the quality of the data collected and for the quality of the decision made based on these data. A similar process was recently developed by SENES and OPG for the monitoring of potential ecological effects around nuclear generating stations (Wismer *et al*., 2004).
The steps in the systematic monitoring planning process are as follows (see Figure 7.1):

- Step 1: Define the problem.
  This is based on a conceptual model of the potential risks involved (risk assessment, including risk of issues raised by stakeholders, pathways analysis)
- Step 2: Identify the decision.
  This step identifies the key questions associated with the decision that the monitoring study attempts to address and alternative actions that may be taken, depending on the answers to the key questions.
  Examples of key questions include:
  - Does a radionuclide concentration significantly exceed background levels?
  - Does a contaminant pose a human health or ecological risk?

  Examples of alternative actions include:
  - Report levels to the authorities
  - Take no action
- Step 3: Identify information needed for the decision.
  This step identifies the kind of information that is needed to resolve the decision statement and potential sources of information (e.g., new data or existing data).
- Step 4: Identify the boundaries of the study.
  This includes spatial boundaries that define the physical area to be studied and temporal boundaries that describe the time frame that the study will represent and

when the samples should be taken. Practical constraints may be introduced to limit the extent of the study (e.g., potential practical risk, future land use, etc.)

- Step 5: Develop a decision rule (an "*if…then…*" statement).
- Step 6: Specify limits on decision errors.

  In step 6 we face the reality that we do not have perfect information for making decisions based on a set of sample data subject to various errors. Inherent in the use of sample data for making decisions is the fact that those decisions can, and occasionally be wrong. In this step of the systematic process, the probabilities for making decision errors (false positive and false negative) are specified.

For example, if the consequences of decision errors are severe (e.g. risk to human health), it may be necessary to develop a monitoring design that requires large amount of data, analyzed by precise and accurate analytical methods. The balancing of risk of incorrect decisions with the cost of monitoring should be fully explored in the planning stage. This is done in the next step.

- Step 7: Optimize the design for obtaining data.

  This step builds on the previous steps to develop an effective monitoring program that focuses on potential risks.

The development of monitoring plans is an iterative process (see Figure 7.2). As gaps in the risk assessment are gradually filled, the monitoring plans can be refined.

FIGURE 7.1

THE MONITORING PLANNING PROCESS

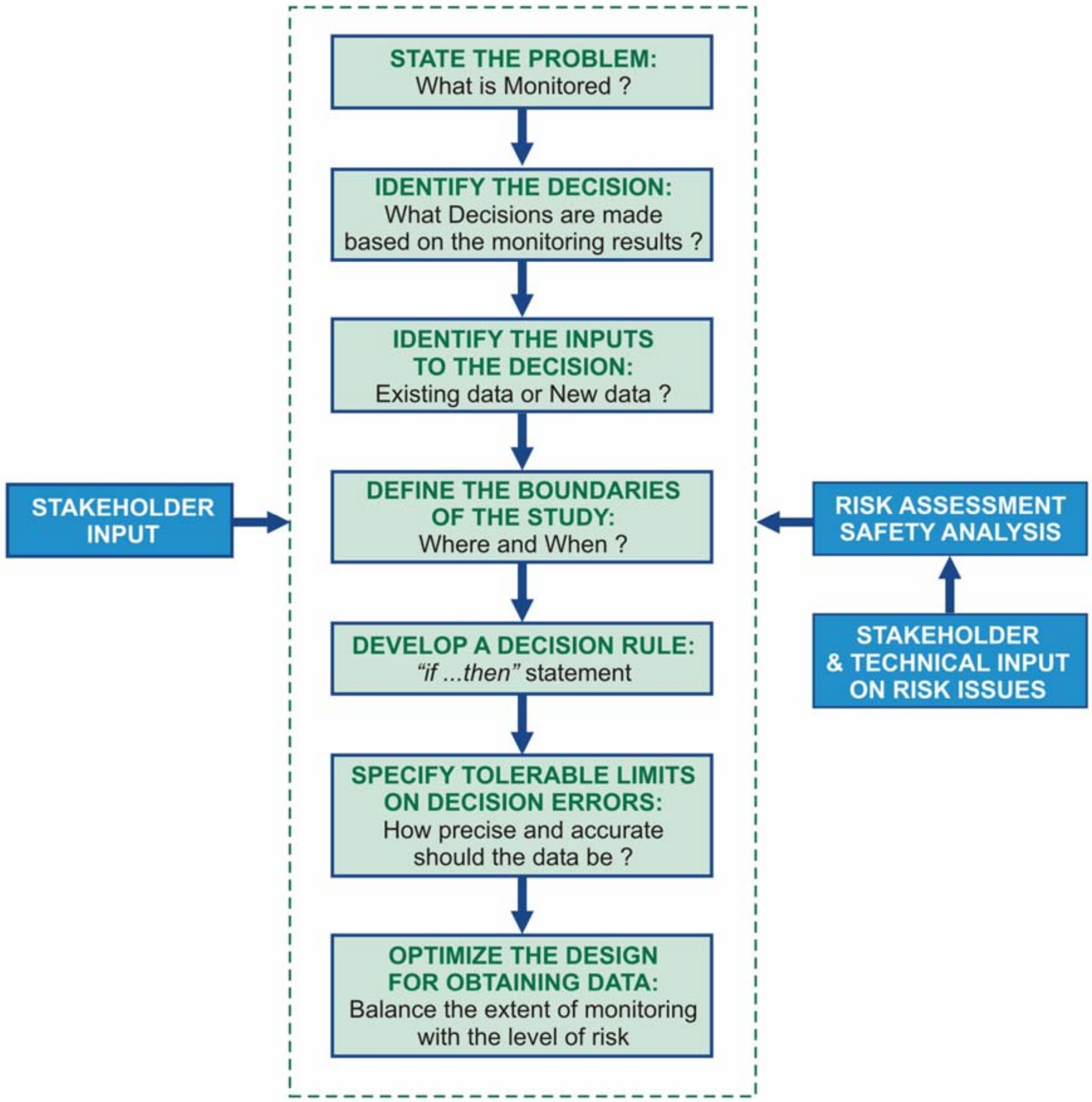
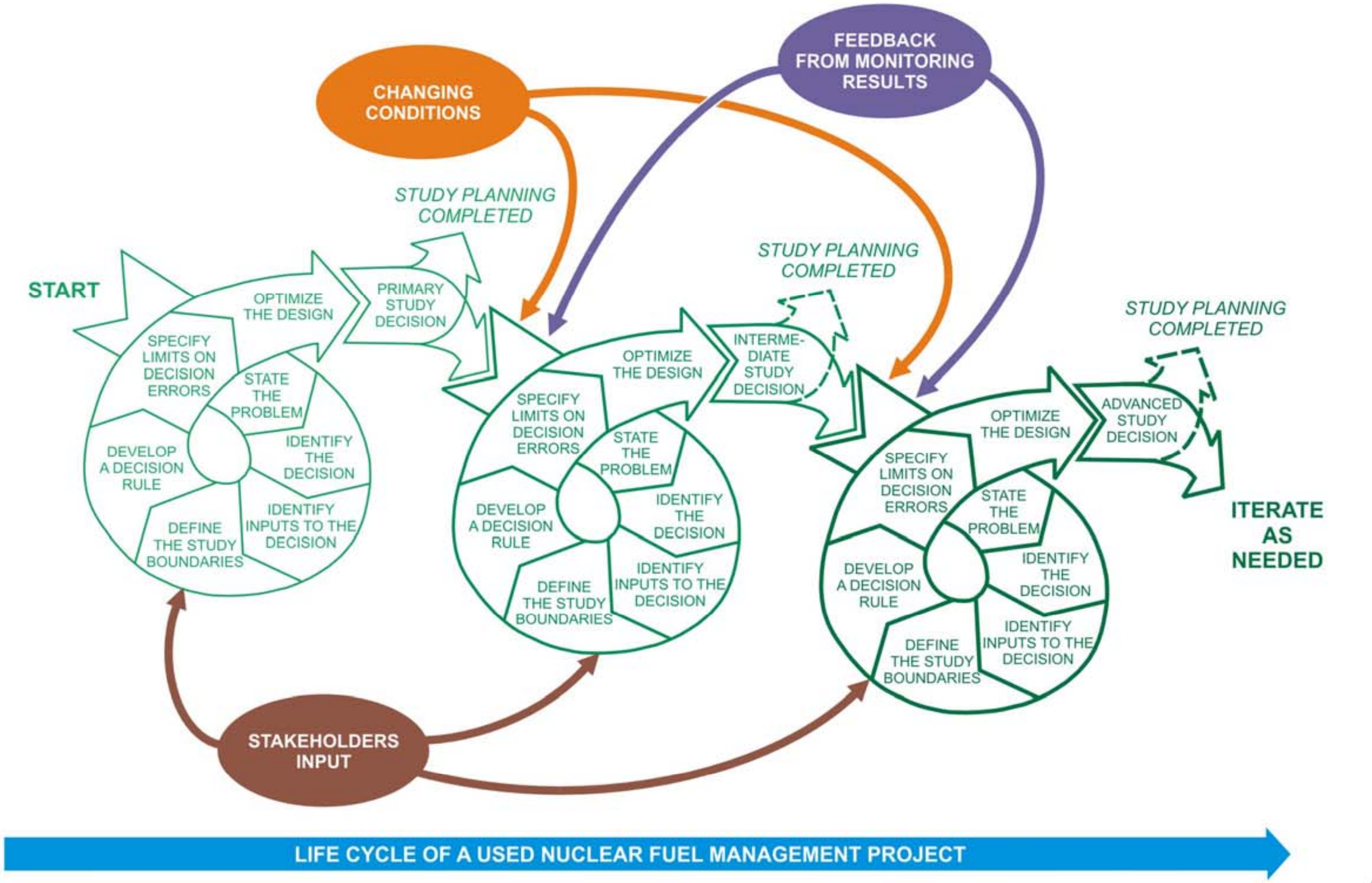


FIGURE 7.2

REPEATED APPLICATION OF THE MONITORING PLANNING PROCESS THROUGHOUT THE LIFE CYCLE OF A PROJECT



SOURCE: Adapted from U.S. EPA, 2000

7.3 How to Deal with Very Long Time Frames and Issues Related to Invasive Measurements of a Sealed System?

An approach to address long-term monitoring issues of DGR was developed by Thompson and Simmons (2003) and is adopted here for DGR and could be used for the long-term monitoring of a deep underground rock-cavern CES facility. (Note that the reference depth in the below-ground option for CES is 50 m (CTECH) 2003b). Here, we consider a potentially deeper CES facility).

In this approach, several parameters were identified as those that can be measured *and* that would be indicative of repository performance, including:

- Temperature;
- Stress changes, rock displacements and acoustic emission; micro-seismic events;
- Groundwater movement and pressure; and
- Groundwater chemistry and radio chemistry.

> The first three of these are expected to show measurable responses to the operation of the repository over relatively short time periods. Responses are expected to be detectable during the period of repository operation. Monitoring of groundwater chemistry is not expected to indicate the occurrence of events, such as waste containers with undetected manufacturing defects, during the period of repository operation.

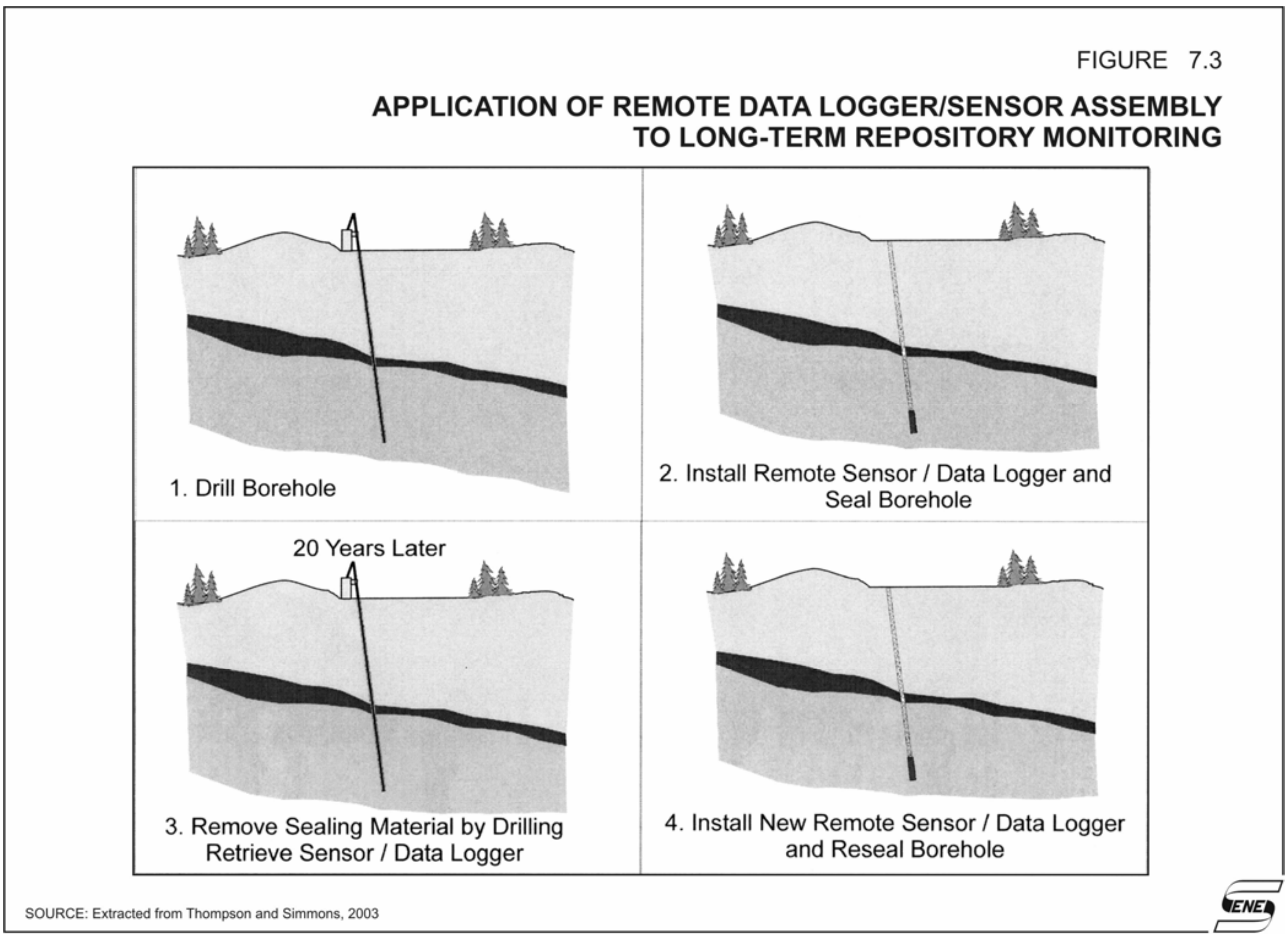
Both non-invasive and invasive methods are proposed to monitor these parameters.

> Non-invasive methods use remote methods or shallow boreholes. Invasive methods require the drilling of boreholes from the surface or from the excavated access shafts or ramps and tunnels. In both methods it is important to minimize the perturbations caused by monitoring installation to the repository system being monitored. However, boreholes drilled close to the outer edge of the repository (within a potential perturbation zone) could compromise the passive safety of a repository. Therefore, invasive monitoring boreholes within this zone need to be backfilled and sealed prior to closure. If such boreholes are used for surface-based post closure monitoring, they can be periodically unsealed for measurements (see Figure 7.3).

The above approach implies that e.g. for DGR, even if the sealed repository is “out of sight” (because it is located deed underground), it can stay “visible” to the monitoring system.

At this point in time, it is not considered prudent to install monitoring systems within the waste emplacement rooms, as these would jeopardize the long-term performance and safety of the repository. Instead, a program of component demonstration testing is proposed, that would begin during underground evaluation of the site and would continue until repository closure. Data on the performance of the container and emplacement room sealing system would be obtained from controlled tests in locations where the containers could later be removed. These component tests would be separate from the emplacement rooms. They would be located either in a single test area, or in strategically- located and spatially distributed test rooms within the repository.

Figure 7.3
Application of Remote Data Logger/Sensor Assembly to Long-Term Repository Monitoring (Extracted from Thompson and Simmons, 2003)



8.0 CONCLUSIONS

Based on the review provided in this report it is possible to make the following comments:

- Under current routine conditions, and based on available information, no significant impacts on human health or the environment, from any of the proposed technical management methods are expected.
- Conventional industrial and/or transportation accidents may occur in the implementation of these methods, as with any large industrial project. Such risks can be mitigated by the implementation of safety programs including worker education, strict implementation of safety procedures, and monitoring of this implementation. Some small differences between the options can be expected regarding risk from conventional accidents. For example, transportation risk is smaller for storage at reactor sites than at a centralized facility.
- Over the long term, there may be a requirement to relocate the used fuel for the RES and perhaps CES (e.g., for above-ground facilities). This may be due to potential rise in surface water levels caused by climate-change factors such as global warming. Monitoring of climate conditions may be used to warn of the need for used-fuel facility relocation. Also, the impact of a far-future glaciation scenario has not been addressed in existing documentation on RES and/or CES. The consideration of such a scenario, may result in RES having to be relocated, prior to glaciation, to avoid glaciation related impacts.

  The risks associated with the extension of storage time at either reactor sites or a centralized location to very long times has not been studied quantitatively in detail. Such an assessment requires for example, an understanding of risks associated with potential loss of integrity of the fuel bundles (i.e., the cladding and potentially the fuel). However, a specific monitoring program can be developed to focus on this aspect of the performance of storage systems, to determine potential risk and decide on mitigation measures.
- Although radioactivity is often perceived as being a high risk factor associated with used fuel management, the estimated exposure doses for the various options are generally low in comparison to established benchmarks.
- Current information on risks associated with the various options *generally supports the safety of these systems* under current conditions. Security risks were not evaluated and were beyond the scope of the present study.
- Several gaps in the risk estimates and its documentation were noted. However, none of these are considered to affect the overall conclusions from this study. They include a need:

1. to update the documentation of risk assessments to ensure that they consider the current reference design concepts and alternatives studied by the NWMO;
2. to complete the documentation of the assessment of chemical emissions;
3. to directly address potential specific human receptors (e.g., although most diets assumed in current assessment encompass those of Aboriginal receptors, specific documentation of potential risk to Aboriginals would enhance the transparency of the assessment);
4. to complete and update the assessment of ecological risk to non-human biota;
5. to re-evaluate the risk from transportation and if necessary, to develop mitigation measures to improve transportation safety.

These gaps will need to be addressed during the implementation of the long-term management approach that is selected by the federal Government.

ACRONYMS USED IN THE REPORT AND APPENDICES

ACES	Advisory Committee on Environmental Standards
ACRP	Advisory Committee on Radiological Protection
AECB	Atomic Energy Control Board
ALARA	As Low As Reasonably Achievable
BEIR	Biological Effects of Ionizing Radiation
CES	Centralized Extended Storage
CNSC	Canadian Nuclear Safety Commission
DDREF	Dose and Dose Rate Effectiveness Factor
DGR	Deep Geological Repository
DNA	Deoxyribonucleic Acid
DNGS	Darlington Nuclear Generating Station
DQO	Data Quality Objectives
DSC	Dry Storage Container
DUFDSF	Darlington Used Fuel Dry Storage Facility
EIS	Environmental Impact Statement
ENEV	Expected No Effect Value
HEPA	High Efficiency Particulate Air
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IFB	Irradiated Fuel Bay
LET	Linear Energy Transfer
LNT	Linear, Non-threshold
MAC	Maximum Acceptable Concentration
MHC	Module Handling Cell
MOE	Ontario Ministry of the Environment
NAS	National Academy of Sciences
NCRP	National Council on Radiation Protection and Measurements
NEW	Nuclear Energy Worker
NGS	Nuclear Generating Station
NRPB	National Radiological Protection Board
NWMO	Nuclear Waste Management Organization
PAL	Protective Action Level
PNGS	Pickering Nuclear Generating Station
PWMF I	Pickering Waste Management Facility I
RES	Extended Storage at Nuclear Reactor Sites
TCS	Third Case Study
UFDC	Used Fuel Disposal Centre
UFDSF	Used Fuel Dry Storage Facility
UFTS	Used Fuel Transportation System
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization
WWMF	Western Waste Management Facility

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