Agence canadienne
d'évaluation environnementale

An Evaluation of the

Environment Impact Statement on Atomic Energy of Canada Limited's Concept for the Disposal of Canada's Nuclear Fuel Waste

An Addendum to the Report

of the Scientific Review Group

Advisory to the Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel

September 16, 1996

Canada

Canadian Environmental Assessment Agency

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[redacted]

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September 13, 1996

Mr. Blair Seaborn
Chairman
Nuclear Fuel Waste Review Panel
Canadian Environmental Assessment Agency
Fontaine Building, 13th Floor
200 Sacré-Coeur Blvd.
Hull, Québec, K0A 0H3

Dear Mr. Seaborn:

On behalf of the Scientific Review Group (SRG), I am pleased to submit this Addendum to our Final Report on Atomic Energy of Canada Limited's concept for geologic disposal of Canada's nuclear fuel waste.

The Addendum comprises a critical assessment, from a scientific and engineering point of view, of the additional information that has been presented in the public hearings or published by Atomic Energy of Canada Limited between mid-1995, when we wrote our Final Report, and July 12, 1996.

A major objective of this Addendum is to provide the SRG's overall integrated assessment of AECL's generic multiple-barrier disposal concept as further outlined and documented by the new information made available by AECL following the release of the EIS. The addendum supplements, but does not replace, the analyses, comments, and conclusions presented in our Final Report dated October 6, 1995.

Respectfully,

R A Price

Raymond A. Price
Chairman
Scientific Review Group

Attachment

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EXECUTIVE SUMMARY

This document is an addendum to the October, 1995 Report of the Scientific Review Group (SRG) on AECL's multiple-barrier concept for the disposal of Canada's nuclear fuel waste. It has been prepared at the request of the CEAA Panel that is reviewing the disposal concept. The addendum is based on the SRG's review and appraisal of the new information presented to Panel since the completion of the SRG Report, including AECL presentations to the Panel during its public hearings, and new reports and scientific papers that have been published, released, or referenced by AECL.

A major objective of this addendum is to provide the SRG's overall integrated assessment of AECL's generic multiple-barrier disposal concept as further outlined and documented by the new information made available by AECL following the release of the EIS (1994). The addendum supplements, but does not replace, the analyses, comments, and conclusions presented in the SRG Report dated October, 1995.

Full implementation of the disposal concept, which will include, in particular, a decision to close a disposal vault, will require a reliable quantitative assessment of the long-term risks associated with a specific disposal site and with the engineering design that is developed for that site. The risks associated with the generic concept, which is not site-specific, also should be amenable to quantitative analysis; but AECL's postclosure performance assessment of the concept, using its SYVAC technology and hypothetical reference case studies that are based on the Whiteshell Research Area, is unreliable and cannot be used to determine whether the generic concept is safe or is not safe. There are a number of fundamental shortcomings in AECL's methodology for assessing the long-term safety of the disposal concept, but among the foremost is that it relies upon an inadequate conceptual model of the geosphere in the Whiteshell Research Area.

In spite of the lack of a reliable quantitative assessment of the long-term safety of the generic disposal concept, the SRG concludes that, in principle, the concept could be implemented safely and effectively. The rationale for this conclusion is the SRG's judgement, based on the available information, that:

- **Waste disposal containers can be designed and manufactured so as to confine practically all of the contaminants for many tens of thousands of years.**

- **Bodies of sparsely fractured, low-permeability plutonic rock containing very old saline groundwater have been found at the Whiteshell Research Area. Such bodies should provide a natural barrier that could potentially inhibit transport of contaminants from a disposal vault to the surface for more than 10,000 years. It is plausible, although not documented, that similar bodies of low-permeability rock may also exist at other sites in the Canadian Shield.**

- **A vault with long-term mechanical stability and integrity can be designed and constructed, even under relatively high *in situ* differential stress.**

- **A buffer-backfill-vault seal system can be designed and constructed to significantly inhibit contaminant transport from the vault.**

To establish that favourable conditions do in fact exist in the Canadian Shield, screening and evaluation of potential sites should begin, but the performance assessment methodology must be improved before a reliable quantitative probabilistic performance assessment can be done at the site evaluation stage.

Computer-based, probabilistic safety assessment of the entire disposal system should be deferred

until the site evaluation stage, when actual, site-specific field and laboratory data can be used to develop and apply a realistic geosphere model, and a more representative and relevant biosphere model. It also will be necessary to ensure that conceptual models used in the safety assessment receive broad input and review from a wide variety of stakeholders. The conceptual models must be robust and well accepted before proceeding to quantitative analysis. Furthermore, it will be necessary to take advantage of newer, more flexible and more powerful technologies to replace the computational components of AECL's probabilistic risk assessment methodology.

THE SRG CONFIRMS AND REITERATES ITS CONCLUSION THAT AECL'S MULTIPLE-BARRIER CONCEPT FOR THE DISPOSAL OF CANADA'S NUCLEAR FUEL WASTE IS POTENTIALLY ACCEPTABLE AND APPLICABLE, BUT THIS NEEDS TO BE DEMONSTRATED FOR EACH INDIVIDUAL SITE. THEREFORE THE SITE SELECTION PROCESS SHOULD BEGIN.

1. INTRODUCTION

This document is an addendum to the October, 1995 Report of the Scientific Review Group (SRG) on AECL's multiple-barrier concept for the disposal of Canada's nuclear fuel waste. It has been prepared in response to a request on June 28, 1996 from the CEAA Panel that is reviewing the disposal concept.

The purpose of the Addendum is to describe and explain any significant changes in the SRG's conclusions that have emerged as a result of its review and appraisal of the new information that has been presented to the Panel by AECL and others. The Addendum is based on the SRG's review and appraisal of new information, including reports and scientific papers that were prepared by AECL since the original EIS was submitted.

The SRG has been instructed specifically, in its terms of reference:

(a) to "*... review and comment on the acceptability and applicability of AECL's high-level nuclear fuel waste disposal concept from a scientific and engineering point of view;*"

(b) to "*... review and comment on the choice of predictive techniques, the underlying assumptions and the validity of the results of the predictive techniques used to assess the long-term performance and safety of the disposal concept;*" and

(c) to "*... provide advice on other issues when requested by the Panel.*"

The Addendum is focused on the two principal conclusions in the SRG's October 1995 report, which were:

(1) AECL's generic multiple-barrier deep geological disposal concept is, in principle, applicable and acceptable for the disposal of Canada's nuclear fuel wastes, because an integrated system of engineered barriers could be designed and constructed, and a site with suitable natural barriers could be selected to provide an acceptable disposal system that will contain and isolate the nuclear fuel waste effectively and safely for more than 10,000 years.

(2) The results of AECL's postclosure performance assessment of the multiple-barrier deep geological disposal concept are unreliable, and AECL has not developed and demonstrated (to the extent reasonably achievable in a generic research program) the methodology to evaluate the safety of a disposal system against established safety criteria, guidelines and standards.

This Addendum also attempts to provide an overall integrated assessment of AECL's generic multiple-barrier disposal concept in which the various strengths and weaknesses in AECL's description and documentation of the concept, and of AECL's assessment of the long-term safety of the concept, are considered in the context of their relationship to the overall applicability and acceptability, and long-term safety of the concept.

There are four main sections in this document:

(1) a review and assessment of new information bearing on the applicability and acceptability of AECL's generic disposal concept, which comprises a system of multiple engineered and natural barriers that are intended to isolate and contain the nuclear fuel waste for more than 10,000 years;

(2) a review and assessment of new information bearing on AECL's methodology for postclosure assessment of the safety of the disposal concept, and the result of AECL's postclosure (safety) assessment of the concept;

(3) a review and assessment of new information bearing on AECL's site screening and site evaluation technology and methodology; and

(4) a summary of general conclusions concerning the overall applicability and acceptability and long-term safety of the concept.

2. REVIEW AND EVALUATION OF AECL'S GENERIC DISPOSAL CONCEPT

The new information strengthens the SRG's conviction that an integrated system of engineered and natural barriers could be designed and selected to provide an acceptable disposal system that would contain and isolate nuclear fuel waste effectively and safely for more than 10,000 years; and therefore, that the multiple-barrier deep geological disposal concept is applicable and acceptable, and would provide the required margin of safety.

The function of each component of the multiple-barrier system is defined in the SRG report (SRG Report 1995: p.6), "*the multiple-barriers can be designed to operate in sequence. A body of sparsely-fractured, low-permeability plutonic rock in which the disposal vault is excavated is the first barrier. It controls the rate of flow of groundwater into the disposal vault. It also controls the rate of saturation of the backfill and the buffer in the vault, and thereby the performance of these barriers, and also the chemical environment around the container. The backfill, seals and buffer retard the movement of groundwater toward the container. The container itself is a fundamental barrier because it isolates the fuel waste from the groundwater. Until the container fails, no radioactive or other toxic contaminants will be released into the groundwater flow system. If a container fails, most of the contaminants that are released are expected to be sorbed by the buffer, backfill and enclosing plutonic rock, and transport of the remaining contaminants will be impeded by the buffer, backfill and enclosing low-permeability rock. Each atom of contaminant must pass through one barrier before it can proceed to the next barrier*".

2.1 The Disposal Container

The function of the container is to isolate the nuclear fuel waste from the groundwater. The essential requirements for the design of a container are resistance to mechanical failure and to corrosion-induced failure.

New information presented by AECL reinforces the opinion of the SRG that a chemically and mechanically stable nuclear fuel waste container can be designed and manufactured. On the basis of this new information, the SRG is confident that copper would perform satisfactorily as the primary barrier to release of radionuclides and other contaminants. This opinion is based on the following considerations:

- The new data provided by AECL indicate that a copper container will provide effective containment of nuclear fuel waste, and will survive in the vault environment for a period exceeding a million years (Wikjord et al. 1996). Similar conclusions have been reached in other national programmes (Safety Assessment Management 1996).

- AECL has performed a thorough and valuable study of copper as an alternative container material. This study convincingly shows that, if copper is used as a container material, the release rates of radionuclides would be negligible, in the absence of either manufacturing defects or mechanical failure in combination. AECL's data on subsurface environments in the Canadian Shield that are analogues for a waste disposal vault environment provide compelling evidence that containment for at least a million years is feasible.

- In support of the selection of copper as a material of construction for nuclear waste containers, AECL has presented a well-reasoned mechanism for the corrosion of a copper alloy in an environment similar to that anticipated in a disposal vault during the transitional phase, where the environment is changing from oxidizing to reducing (King 1995). AECL also has provided a convincing mathematical model for uniform and pitting corrosion with decreasing oxygen concentrations in the anticipated vault environment (King and Kolar 1995). According to this model, the wall penetration of copper containers by corrosion only reaches 5 micrometres before corrosion is totally arrested, and localized corrosion by pitting does not exceed 6 millimetres in depth. Thus a 25 millimetre copper wall would resist corrosion indefinitely in a vault environment.

- In the new case study (Wikjord et al. 1996; Johnson et al. 1996), which postdates the EIS (1994), AECL states that there would be no corrosion-induced failures of copper containers, and that the only failure mechanism would be undetected fabrication defects such as a "pin-hole" in the closure welds. This is a "critical" case study from the point of view of selection of container materials. Both general corrosion and localized corrosion, including microbially induced corrosion and stress corrosion cracking, are addressed appropriately. This case study indicates that the disposal concept could be implemented safely with copper containers, provided that the container environment does not become oxidizing, and that the containers are not subjected to mechanical failures.

- AECL has provided a detailed description of the construction of a copper container and has demonstrated that current fabrication technologies are adequate to produce containers that will withstand the mechanical loading that can be expected in a vault after closure (Baumgartner et al. 1996). Some concern has been expressed with regard to increased stresses due to future glaciation but, if calculations should indicate that such stresses might cause mechanical failure of solid copper containers, carbon steel inner shells could be inserted for additional structural support (Garroni et al. 1996).

- AECL's assumption that one container in 5000 will be ineffective because of undetected manufacturing defects is excessively conservative. Even the manufacturing technology, manufacturing quality assurance procedures, and detection techniques for weld defects that are available now, in the 1990s, would ensure a lower failure rate. In the unlikely event of an incompletely sealed weldment, radionuclide transport would nevertheless be delayed, since water ingress into the container through a "pin-hole" defect would be slow, and transport of contaminants out of the container would be unlikely until the container was filled with water.

2.2 The Nuclear Fuel Waste

The nuclear fuel waste form, which would be either CANDU fuel or solidified high-level waste from reprocessing (if Canada should decide to reprocess its waste fuel), **would have sufficiently low solubility to retain most of the radioactive and chemically toxic contaminants indefinitely in the chemically reducing environment that can be expected below the water table in the Canadian Shield.** When a container fails, some of the contaminants that are not held in the uranium dioxide crystals will be released from the fuel waste into the groundwater. The available evidence (Vandergraaf et al. 1992) shows that most of those contaminants would be sorbed and retarded by the buffer and the clays in the backfill. The contaminants most likely to pass through the buffer and the seals are primarily those that form anionic species, notably ^{14}C, ^{36}Cl, ^{129}I, and possibly ^{99}Tc.

The new case study involves changes to several of the ambient conditions in the vault (Wikjord et al. 1996). These changes, which provide improved safety of the concept because of their effect on the release and migration of the radionuclides and their ultimate transfer to humans, are as follows:

- The use of copper containers means that the emergence of all radionuclides will be markedly delayed. This will effectively eliminate the short-lived isotopes ^{137}Cs and ^{90}Sr-^{90}Y from the list of radionuclides of concern.

- The ultimate effect on humans of the two highly mobile radionuclides ^{36}Cl and ^{129}I will be substantially reduced by isotopic dilution because they will mix with non-radioactive isotopes of the same elements in the vault, in the geosphere and the surface environment (Amiro and Dormuth 1996).

- The very low oxygen content of the very old saline groundwater (Gascoyne 1996) will alleviate concern about the dissolution of UO_2, which has very low aqueous solubility under anoxic conditions (R-Vault 1994: p.138), and will relieve concern about the possible migration of technetium, as an anion TcO_4- under more oxidizing conditions (R-Vault 1994: p.144).

2.3 The Disposal Vault Design and Stability

The function of the vault is to contain and protect the nuclear fuel waste containers and the surrounding buffer and backfill throughout the lifetime of the system. The vault comprises the excavation and the surrounding rock that will be damaged during excavation.

The basic requirements for the vault are long-term mechanical stability and integrity which will protect waste containers and prevent the formation of new fractures that might breach the engineered barriers or the geosphere barrier.

The new information presented by AECL has provided adequate evidence that a vault with long-term mechanical stability and integrity can be designed and constructed, even under relatively high *in situ* differential stress. This conclusion is based on the following:

- The results of the Mine-by Experiment (Martin and Kaiser 1996; Read and Martin 1996) provide more reliable design criteria for excavation of the vault and for analysis of thermal-mechanical loading of the vault (Baumgartner et al. 1996; Baumgartner et al. 1995).

- The choice of an in-room design instead of an in-floor design for the emplacement of waste containers, which is described and evaluated in the new reference case study (Wikjord et al. 1996; Baumgartner et al. 1996), eliminates the problem of fracturing of the rock webs between in-floor holes, and also contributes to the overall mechanical stability and integrity of the vault.

- The choice of an appropriate elliptical-cross-section design for tunnels provides increased mechanical stability and substantially reduces the extent of the damage in the surrounding rock during excavation (Baumgartner et al. 1995).

- The design values of the *in situ* stress has made the vault design analysis much more realistic in high *in situ* stress environments (Baumgartner et al. 1996: p.87, Table 4).

- Analysis of mechanisms of fracture propagation and of stress-induced displacements on pre-existing fractures in the surrounding rock (Fairhurst et al. 1996) confirms that in all areas tested the risk of significant displacement on pre-existing fractures is very small, and that the possibility of generating significant displacement on new fractures is even smaller.

2.4 The Buffer, Backfill and Other Vault Seals

The function of the buffer is to form a low-permeability barrier around the containers, to retard corrosion of the containers, dissolution of the waste, and transport of contaminants, by inhibiting the movement of groundwater, by modifying the chemistry of the groundwater, and by sorbing contaminants that may escape from the fuel waste (SRG Report 1995).

The purpose of the backfill is to fill the space in the disposal rooms, tunnels and shafts, to retard radionuclide and contaminant migration by both slowing groundwater flow and enhancing sorption, and to chemically condition the groundwater to reduce the container corrosion and to limit solubility of the fuel waste (SRG Report 1995).

The other vault seals include bulkheads, plugs, grouts and other exploration borehole seals. Their purpose is to retard movement of contaminants by inhibiting groundwater movement in the vault and to restore the hydraulic integrity of the rock where it has been disrupted by the boreholes and vault construction (SRG Report 1995).

AECL has studied in detail the container emplacement design (Baumgartner et al. 1996) **in which the containers are placed horizontally end to end within an excavated room rather than in holes drilled in the floors of the rooms. This improved design makes the buffer and the backfill more effective. It provides for a thicker shell of buffer around the containers and it ensures that groundwater moving to and from the containers must pass through the buffer and the backfill.** The use of precompacted buffer in the disposal rooms and to seal tunnels also is a significant design improvement.

The proposal to design a torus-shaped seal in the excavation-damaged zone of tunnel walls is an innovative and potentially effective solution to the problem of possible contaminant transport along the vault axis in the excavation-damaged zone (Martin et al. 1996). This would inhibit any advective transport along the excavation-damaged zone in the tunnel walls.

2.5 The Geosphere

The function of the geosphere in the multiple-barrier disposal system is to protect the waste, the container, and the vault seals from natural disruptions and human intrusion, and to restrict the rate at which contaminants from the waste could move from the vault to the surface. The geosphere comprises the body of low-permeability, sparsely fractured rock containing the disposal vault, the surrounding more highly fractured and permeable rocks, the sediments below the water table that overlie the rocks, and the groundwater flow system. The dominant means by which the radionuclides and other contaminants can move from the vault toward the surface are by advective and dispersive-diffusive transport in the groundwater. Accordingly, a sound understanding of the groundwater flow system, and of the processes, features, and events that control the transport of contaminants in and through groundwater is critical to the concept and to the selection of a disposal site (SRG Report 1995).

The main requirements of the geosphere as a host for a disposal vault are the presence of suitable bodies of sparsely fractured rock of low permeability which would provide long, slow migration pathways (i.e. tens of thousands of years) from the vault to the ground surface, as well as long-term mechanical stability. Plutonic rocks generally contain extensive fracture zones of relatively high permeability and masses of moderately fractured rock which are also relatively permeable; thus, a key concern of the SRG has been the lack of convincing documentation for the existence of blocks of sparsely fractured or unfractured rock of sufficient size (depth and lateral extent).

The SRG concurs with AECL's expert panel (Domenico et al. 1995) in acknowledging that AECL possesses state-of-the-art field-testing technologies for local rock characterization. **New information that has been published or**

presented at the Panel hearings by AECL (Stevenson et al. 1996a; Stevenson et al. 1996b) **provides increased confidence that suitable blocks of sparsely fractured rock do exist at the WRA and can potentially be found at other sites.** The analysis of several boreholes (Stevenson et al. 1996a: Figure 9; Stevenson et al. 1996b: Figure 15) shows long intervals of sparsely fractured rock within which the pore pressure is substantially higher than hydrostatic, and which contain highly saline waters. The high pore pressure in the interior of these sparsely fractured rock bodies must be a remnant of some former (long-past) geological condition, and the highly saline pore water is likewise probably very old geologically (Gascoyne et al. 1996). Values of equivalent fresh water hydraulic head in the fracture zones and in the moderately fractured rock masses are much lower than those within the sparsely fractured rock bodies, and moreover, values of hydraulic head in fracture zones and moderately fractured rocks located at various depths encountered in some boreholes are commonly very nearly equal.

This pattern of high and low hydraulic head strongly suggests that the sparsely fractured rock bodies form blocks embedded within a more-or-less hydraulically and geometrically interconnected (horizontally and vertically) network of relatively permeable moderately fractured rocks and fracture zones. Water within this interconnected regional network of relatively permeable rocks is at or near dynamic equilibrium, or steady state. On the other hand, the steep hydraulic gradients found within the blocks of sparsely fractured rock imply that water within the blocks is under a nonsteady-state, or transient, flow regime. This transient regime is local, pertaining to individual blocks, each of which drains into the surrounding permeable network independently of other blocks. Pressures within the blocks are dissipating slowly (probably on time scales of tens of thousands of years, past and future) through leakage of water and salts out of the blocks, into the surrounding network of more permeable material. This slow dissipation, and leakage, suggest that the blocks do indeed have very low permeability. On the other hand, the permeability and gradients within them are large enough so that the dissipation, and leakage, occur primarily by advection and only to a minor extent by diffusion, as demonstrated in a recently reported AECL field experiment at the URL (Gascoyne et al. 1996). This is contrary to AECL's EIS, according to which diffusion is the dominant transport mechanism within the sparsely fractured "waste exclusion zone" that surrounds the vault. The lateral extent of the blocks of low-permeability sparsely fractured rock is still poorly defined, but on the basis of the high but transient pore pressures observed in the borehole profiles, it can be expected that at least some of the blocks measure hundreds of metres. It is plausible, but thus far not documented, that similar bodies of low-permeability rock may also exist at other sites in the Canadian Shield.

Thus the new information provided by AECL indicates that groundwater flow in the geosphere at the Whiteshell Research Area comprises two systems: a very slowly moving component in the sparsely fractured low-permeability rock that is driven by relict pressure gradients, and a relatively fast component in the surrounding higher-permeability fractured-rock network that is driven by present-day topographic gradients. This dual flow system mechanism in the geosphere, as well as the potential implications of advective transport in the sparsely fractured rock, have not yet been recognized nor analyzed by AECL. Before designing a repository, it will be necessary to formulate an appropriate conceptual model and to develop a fundamental understanding of the controlling mechanisms of flow and transport in this type of system. In particular, it will be necessary to understand the effect of the vault excavation and the heat source on the long-term transient pore pressure profile and the transport of the saline water, as well as the combined effects of these processes on the potential migration of radionuclides under the advective transport regime apparently prevailing in the sparsely fractured rock.

Qualitatively, contaminant migration velocities by advection and diffusion through the sparsely fractured rock can be expected to be very low because the state of transient high pore pressure in the blocks evidently has persisted for a very long time (greater than 10,000 years). Thus, if a vault were emplaced in a low-permeability block of sufficient size, the rock should potentially provide an effective barrier to contaminant migration. The documented occurrence of blocks of low-permeability rock containing old saline groundwater under abnormally high pressure at the WRA gives confidence that suitable blocks having the required characteristics to host a vault can be found in the Canadian Shield. However, the actual existence of a suitable host rock will have to be proven by field exploration at each site under consideration.

2.6 Surface Environment

The surface environment is where people and most other living things live. It obviously is subject to change over the lifetime of the disposal system, and this change can be directly affected by human behaviour. Unlike the disposal container or the disposal vault, the surface environment cannot be designed or engineered to restrict or contain radioactivity. It must be selected through the choice of an appropriate site for the waste repository (SRG: Roots, presentation to the Panel at public hearings in Toronto, June 17, 1996: transcript p. 89).

The SRG has expressed concern that AECL's definition of the scope of the biosphere is too restrictive. Two important aspects that were missing or given very cursory treatment are microbial activity and the effects of human activities on the biosphere.

Important new information from AECL on naturally occurring microbial activity has included studies of the variability as well as the location of microbial populations within the vault, and has addressed microbially induced corrosion of both the fuel (Johnson et al. 1996) and of a copper container (Johnson et al. 1996). These studies have suggested that microbial populations will not adversely affect the disposal concept. However, there is still the need at the conceptual level for an examination of the degree of stimulation of microbial activities as a result of changes in the impacted environment due to intrusions resulting from the installation of the disposal vault. Additionally, the potential role of the subsurface biosphere in the bioaccumulation, retention and transport of radionuclide needs further examination at the conceptual level.

The robustness of the concept needs to be demonstrated in terms of its ability to accommodate a wide range of scenarios. The EIS and new case studies may give the impression that AECL has looked at a wide range of scenarios and therefore has addressed the concerns expressed in the SRG Report. However, the types of scenarios required for concept development include situations such as extreme lifestyle habits in terms of diet, transitional processes, and the bioaccumulation of radionuclides in food (plant, fish).

The new information provided by AECL includes an investigation of the potential effects of climate change on radiological doses (Amiro 1995) and a consideration of continental glaciation on nuclear fuel waste disposal (Sheppard et al. 1995) and this addresses some of the SRG concerns about the limited scope of AECL's performance assessment. These new studies also give assurances that the AECL's approaches and assessment procedures are sufficiently flexible to accommodate and be improved by new information on environmental conditions or processes, biosystems sensitivities or different scenarios of human actions.

If present estimates of rates and effects of radionuclide transfer processes are to be extrapolated, with confidence, to ten thousand years, a coherent comprehensive conceptual model of the biologically related processes is required. It should include the best information on biomass distribution in various living and non-living compartments, the end points or boundaries of the system being modelled, and mass and energy flows along the various pathways. However, the nature of the surface environment does not have a major effect on the disposal concept if the nuclear waste is placed in well-sealed copper containers in a well-engineered vault surrounded by sparsely fractured low-permeability rock.

3. REVIEW AND EVALUATION OF AECL'S POSTCLOSURE PERFORMANCE ASSESSMENT

The basic purpose of a postclosure performance (or safety) assessment of the disposal system is to get a reliable quantitative estimate of how successful the system will be over its design life span of more than 10,000 years, in containing and isolating the waste to satisfy the relevant regulatory safety requirements.

At the concept assessment stage, when a generic concept is being assessed, if comprehensive actual field observations are not available, simple scoping calculations can be much more informative and reliable than a complex, comprehensive probabilistic analysis that is not based on appropriate models, nor supported by actual data. **The AECL postclosure performance assessment attempts to provide a comprehensive probabilistic analysis of the long-term safety of the disposal concept, but parts of it are not based on appropriate models, nor supported by actual data. Therefore, AECL's postclosure performance assessment is unreliable. This does not mean that the multi-barrier nuclear fuel waste disposal concept is unsafe, but it does mean that AECL has not succeeded in its attempt to use its probabilistic safety analysis technology (SYVAC-CC3) to demonstrate that the disposal concept is safe.**

AECL has reiterated (AECL Response 1996: p.11) that its "*postclosure assessment case study was carried out for two principal reasons (EIS page 273). The first reason was to demonstrate the postclosure assessment methodology by applying it to a realistic system in order to illustrate its effectiveness and that it could be applied to a future real disposal system. The second reason was to illustrate that the concept could be implemented to provide safe disposal of Canada's nuclear fuel waste.*"

AECL chose to conduct its evaluation of the long-term safety of its disposal concept in terms of a probabilistic risk assessment using its SYVAC computer modelling technology and a hypothetical reference case study that is based on the URL and WRA. However, the Atomic Energy Control Board (AECB) guidelines for meeting its regulatory objectives and requirements concerning the disposal of radioactive wastes (AECB R-104) do not require probabilistic risk assessments, or the development and application of a SYVAC-type modelling technology (AECB R-104; AECB: Bragg, presentation to the Panel at the public hearings in Toronto, June 11, 1996: transcript p. 150).

The SRG's review of the new information has reinforced its conviction that AECL's choice of, and continuing commitment to, a probabilistic risk analysis and the SYVAC technology has adversely influenced the orientation and emphasis of its research into the long-term safety of the disposal concept. Although AECL's field data are now more extensive and of better quality than in the EIS, and the design of the engineered barriers is sound, the basic task of characterizing, documenting, and assessing the fundamental implications of the pertinent attributes of the natural barriers, particularly the geosphere barrier, and of developing appropriate conceptual models, has been overshadowed by the task of implementing a computer-based probabilistic risk analysis with SYVAC.

Full implementation of the disposal concept, which will include, in particular, a decision to close a disposal vault, will require a reliable quantitative assessment of the long-term risks associated with a specific disposal site and with the concept design that is developed for that site. The risks associated with the generic concept, which is not site-specific, also should be amenable to quantitative analysis; but AECL's postclosure performance assessment of the concept, using its SYVAC technology and hypothetical reference case studies that are based on the Whiteshell Research Area, is unreliable and cannot be used to determine whether the generic concept is safe or is not safe. There are a number of fundamental shortcomings in AECL's methodology for assessing the long-term safety of the disposal concept, but among the foremost is that it relies upon an incorrect conceptual model of the geosphere in the Whiteshell Research Area.

In spite of the lack of a reliable quantitative assessment of the long-term safety of the generic disposal concept, the SRG concludes that, in principle, the concept could be implemented safely and effectively. The rationale for this conclusion is the SRG's judgement, based on the available information, that:

- **Waste disposal containers can be designed and manufactured so as to confine practically all of the contaminants for many tens of thousands of years.**

- **Bodies of sparsely fractured, low-permeability plutonic rock containing very old saline groundwater have been found at the Whiteshell Research Area. Such bodies should provide a natural barrier that could potentially inhibit transport of contaminants from a disposal vault to the surface for more than 10,000 years. It is plausible, although not documented, that similar bodies of low-permeability rock may also exist at other sites in the Canadian Shield.**

- **A vault with long-term mechanical stability and integrity can be designed and constructed, even under relatively high *in situ* differential stress.**

- **A buffer-backfill-vault seal system can be designed and constructed to significantly inhibit contaminant transport from the vault.**

AECL has developed a new revised conceptual geosphere model of the Whiteshell Research Area which includes all the available data accumulated between 1977 and 1994 (Stevenson et al. 1996a; Stevenson et al. 1996b; Ophori et al. 1996). The new field data that are presented appear to be of excellent quality, and the array of experimental techniques described is state-of-the-art. The use of 3D flow system modelling to identify locations within the regional groundwater flow system that have the longest possible travel paths to the surface is commendable.

AECL's interpretation of the data, however, is problematic. The conceptual model developed and calibrated by AECL on the basis of these data is fundamentally flawed because it misinterprets the data in a serious way by failing to recognize the apparent dual and locally transient character of the groundwater flow system. As discussed in Section 2.5, the new data suggest that the groundwater flow system comprises a relatively fast component, which is driven by topographic gradients and controlled by a network of interconnected moderately fractured rock and fracture zones, and a slow transient component, which exists within blocks of sparsely fractured rock embedded within this network, and which is driven apparently by relict (geological) pressure gradients. It is this latter component, unrecognized by AECL, that is critical to the safe, long-term containment of the radionuclides and other contaminants in the nuclear fuel waste.

The AECL conceptual model overrepresents the continuity of the sparsely-fractured rock and underrepresents the hydraulic communication between high-permeability moderately fractured rock and fracture zones that is clearly evident in AECL's own data. It incorrectly assumes that transport in the sparsely fractured rock is diffusive, while the data clearly suggest that saline water, under the influence of high pressure gradients, is moving advectively out of the blocks of low-permeability, sparsely fractured rocks in all directions, albeit at a very slow rate. Evidence of advective outflow of saline water from sparsely fractured rock into boreholes drilled into the rock, and of the subordinate role of diffusion, was also found experimentally (Gascoyne et al. 1996). In calibrating the conceptual model with respect to equivalent freshwater head (Ophori et al. 1996), the high pressure gradients within the sparsely fractured rock were ignored and, in order to obtain a fit that was considered acceptable by AECL (but is poor in the view of the SRG), salinities of up to 200 g/l were assumed. In reality, the only experimental determination of salt concentration in the pore fluid (Gascoyne et al. 1996) showed a maximum of about 90 g/l.

The AECL conceptual model assumes that fracturing decreases with depth, when in fact the data presented by AECL indicate that fractures may occur at all depths that were investigated (Stevenson et al. 1996a: Figures 7 and 8; Stevenson et al. 1996b: Figure 3). In general, the AECL permeability data given in these documents show considerable scatter that may be qualitatively interpreted either as no significant trend below 200 m, or as only a very weak trend of permeability decreasing with depth. The data base itself is too small to allow any meaningful statistical inferences. The permeability trend line assumed by AECL generally underestimates permeability, both for the sparsely-fractured rock and for the fracture zones, sometimes by several orders of magnitude.

AECL has also modelled the performance of the geosphere barrier in its new case study (Stanchell et al. 1996). Contrary to the revised conceptual geosphere model for the WRA which is based on actual field observations (see above), the geosphere for the new case study is not based on actual data and the resulting conceptual model, therefore, has no practical relevance within the context of a viable multiple-barrier system.

In order to provide the capability to perform a credible quantitative performance assessment of the disposal concept, a realistic conceptual model of the geosphere that reflects actual conditions as indicated by AECL's borehole data should be developed. Such a model will be required in the later stages of a site selection program when a site must be evaluated with respect to contaminant travel times from the vault to the surface, as well as in the final performance assessment of a site once it has been chosen.

Although it is not known whether the geologic and hydrologic conditions observed at the WRA site prevail at other sites in the Canadian Shield, the conceptual model must be sufficiently flexible to accommodate any conditions that might be expected. AECL has recognized that flexibility and ease of adaptability to different site conditions are important requirements of a conceptual geosphere model, and Stevenson et al. describe a procedure for the iterative refinement of the conceptual model (Stevenson et al. 1996a: Figure 2). Although this iterative procedure is sound in principle, the SRG doubts that the basic components of the methodology available to AECL at this time are adequate for the task, for the following reasons.

The main components of the AECL performance assessment methodology for the geosphere are the computer codes MOTIF, GEONET, and SYVAC. The role of MOTIF is to simulate groundwater flow and associated processes in the geosphere. On the basis of what is now known about the geosphere (see above), these processes must include local transient flow, the transport of saline water, the transport of radionuclides, and the effect of vault heat on these flow and transport processes. Although MOTIF can in principle handle these processes and had previously been judged by the SRG (SRG Report 1995) to have been adequately validated, a new document released by AECL (Ophori 1996), which reports on an unsuccessful attempt to test the density-dependent flow option of MOTIF against a well-known benchmark problem, raises serious doubts about the validity of MOTIF. Moreover, the application of MOTIF to the extended Whiteshell Research Area site (Ophori et al. 1996), reveals errors in the application itself (incorrect application of elements) as well as doubtful results (unrealistic velocities), while the application to the new case study (Johnson et al. 1996: p. 99) in connection with the new vault model (see discussion below) reveals behaviour inconsistent with physical reality (oscillations in the solute concentrations, negative mass fluxes). Furthermore, the application to the extended WRA site was severely constrained in the level of detail that could be represented because of the inherent limitations in the capacity of the code. These factors raise further doubts about the appropriateness, accuracy, and efficiency of MOTIF for the performance assessment of a real site. Finally, the rapid redesign and adjustment of large grids within the context of the performance assessment of a future real site will require efficient automatic grid generation techniques that are not available with MOTIF. **For all of these reasons, even though MOTIF has been a valuable development tool that has played a key role in the evolution of the Canadian nuclear fuel waste management program, its usefulness in the future, which will present different and more stringent requirements, is in doubt.**

As for GEONET, this code is fundamentally unsuited for use in a credible geosphere performance assessment because it is strictly limited to steady-state flow. Although the flow in the sparsely fractured blocks of rock may be slow enough to be considered essentially steady-state over a time scale of a few years, it is definitely not steady-state over the time scale of the life of the multiple-barrier disposal system, as is clearly revealed by the new data presented by AECL. The rationale for using GEONET was the limited capacities of computers of the 1980s; this rationale no longer exists. Therefore GEONET should be abandoned.

A major concern of the AECL performance assessment methodology, as presented in the EIS (1994), has been the overly simplified one-dimensional vault model which unrealistically assumed that, under the in-floor container emplacement scenario, all radionuclides and other contaminants pass sequentially through the buffer and backfill. New information provided by AECL (Johnson et al. 1996; Kolar and LeNeveu 1995; LeNeveu and Kolar 1996; LeNeveu 1996) addresses this concern. The new cylindrical vault model closely approximates the elliptical cross-section of the new vault design based on in-room placement of the containers. The model includes the buffer (diffusive transport only), the backfill (diffusive and advective transport), the excavation-damaged zone, and the surrounding undamaged rock mass, and represents these components by nested concentric cylinders. These cylinders conserve the design volume of the buffer and backfill but not necessarily their thickness, which is a critical factor with respect to contaminant travel time. The total contaminant mass flux passed on to the geosphere is claimed to be conservatively estimated by the vault model.

Although the new cylindrical vault model represents a substantial improvement over the previous 1D layered model, problematic aspects remain. Because the model is formulated on the basis of radial symmetry (i.e. flow is the same all around a cylinder) and flow is assumed to be constant within each cylinder and discontinuous between cylinders, the fundamental requirement of mass conservation between the cylinders, and between the vault and the geosphere, cannot be satisfied. Furthermore, the structure of the vault model is inconsistent with that of the geosphere model (MOTIF), and it is not clear how the two models are linked in a physically meaningful way. For these reasons, the theoretical basis of the model has doubtful validity, even though AECL claims that the total mass output to the geosphere calculated by the model is conservative in the regulatory sense.

The rationale for developing the new vault model appears to have been the requirements of the SYVAC methodology to perform large numbers of one-dimensional simulations. Without the artificial and unnecessary constraint of the SYVAC framework, a three-dimensional vault model that is both mass conservative and consistent with a three-dimensional geosphere model could have been developed.

The new information provided by AECL reinforces the conviction of the SRG that AECL's performance assessment methodology has been driven by the requirements of SYVAC which is programmed to perform thousands of simplified simulations with parameter values selected from probability distribution functions that are of questionable significance. As is evident from the above discussion, this commitment to a probabilistic assessment has led to the use of a structurally flawed and incorrect geosphere model, and therefore, to results that are unreliable. Moreover, the results are misleading because they impart a false impression of precision in the quantification of uncertainty. As pointed out above, the SYVAC approach is unnecessary and should not have been used at the concept assessment stage.

New state-of-the-art tools for the analysis of complex groundwater systems have recently been developed or are now being developed in other countries. For example, a highly sophisticated automatic 3D finite element grid generation code (Gable et al. 1995), which is specialized for complex geologic environments, including wells and tunnels, and which is optimized for numerical computations, has been developed within the context of the U.S. Yucca Mountain project. A highly efficient multigrid numerical technique for saline groundwater systems, which is especially designed for handling millions of nodes in complex grids, is being developed in Germany. These or similar technologies, which may contain the capabilities that are needed to carry the Canadian disposal concept to its conclusion, should be closely examined.

AECL's biosphere model is BIOTRAC. The SRG is of the opinion that, if the BIOTRAC model is to be used to make plausible predictions about the impact on the surface biosphere over the next ten thousand years of contaminant release from a disposal vault, it should at least be able to examine a wide range of potential human situations and human-instigated activities that might affect the environment. It must also be modified so that it can accommodate variable rates with time, feedbacks, and multiple paths. The SRG understands that some work toward those modifications is underway.

In the new case study, several important changes were made to BIOTRAC, particularly to the food-chain and dose submodels for humans and non-human biota. These changes include: addition of radionuclides ^{36}Cl, ^{137}Cs, ^{239}Np and ^{243}Am; animal inhalation pathway; ICRP 60/61 human internal dose conversion factors; all of the postclosure assessment nuclides in the dose calculations for non-human biota; groundwater dose limits for ^{14}C, ^{36}Cl, and ^{129}I for non-human biota to parallel these limits for humans. AECL has also reviewed and changed several parametric values, including evasion rates of gaseous nuclides from soil and release fractions of various nuclides from domestic water, and has incorporated changes that affect the geosphere-biosphere interface model. The introduction of fractional factorial Latin cube designs is seen as an advance, inasmuch as it permits the extraction of simulations with common features.

The BIOTRAC model treats the movement of radionuclides through the biosphere as a purely physical process, ignoring the fact that the distinguishing feature of the biosphere is that it is alive and capable of responding and adapting to changes in the immediate environment. Over the protracted time under consideration, non-linear biologically-influenced processes are most likely to be significant. The assumption that the movement of radionuclides along the various pathways and through biosystems is considered, for modelling purposes, to be exclusively unidirectional, which remains in the new case study, is still a matter of concern.

Furthermore, because the safety assessment provided by the new case study essentially uses the same performance assessment tool (i.e. SYVAC) as was used in the EIS reference case study, the SRG's concerns about the flexibility and robustness to convincingly demonstrate safety have not been addressed. AECL has still modelled the radionuclide transport in the surface environment under the assumption that no major changes in topography are likely to occur during 10,000 years, that changes in climate, surface water flow patterns, and soils will be negligible, and vegetation types will be within the range observed at present.

The SRG reaffirms, on the basis of its assessment of the new information presented by AECL, that the results of AECL's postclosure performance assessment of its multiple-barrier deep geological disposal concept are unreliable (i.e. they do not provide a logical basis for determining the long-term safety of the disposal concept), and that AECL has not developed and demonstrated (to the extent reasonably achievable in a generic research program) the methodology to evaluate the safety of a disposal system against established safety criteria, guidelines and standards.

The SRG concludes that the probabilistic safety assessment of the entire disposal system should be deferred until the site evaluation stage, when actual, site-specific field and laboratory measurements can be used to develop and apply a realistic geosphere model, properly linked with an equally realistic vault model to allow feedback between the two. A specific site will also provide actual data on the surface environment (topography, watercourses, soils, biota) that will allow the development of a more representative and relevant biosphere model. At that stage, it will be necessary to ensure that conceptual models used in the safety assessment receive broad input and review from a wide variety of stakeholders. The conceptual models must be robust and well accepted before proceeding to quantitative analysis. The SRG also believes that it will be necessary to take advantage of newer, more flexible and more powerful technologies to replace the computational components of its probabilistic risk assessment methodology. Some state-of-the-art computational technologies that are available now may be suitable, and newer technologies most certainly will become available in the future.

4. SITING METHODOLOGY AND CRITERIA

AECL's site screening and site evaluation technology and methodology are state-of-the-art, but evidently most of these capabilities would not play a significant role in site screening because the AECL strategy for site selection is to reject only those potential sites for which it is not possible to secure the agreement of the local community, or within which the seismic ground motion hazard is too high.

The geosphere barrier is an essential component of the multiple-barrier nuclear fuel waste disposal system. Those attributes of the geosphere that control its effectiveness as a barrier must be included in the site screening and the site evaluation processes. Accordingly, it is necessary to establish and specify site evaluation exclusion criteria concerning those properties of the geosphere that control its effectiveness as one of the essential components in the multiple-barrier system at a potential disposal site.

5. CONCLUSIONS

A major objective of this addendum is to provide the SRG's overall integrated assessment of AECL's generic multiple-barrier disposal concept as further outlined and documented by the new information made available by AECL following the release of the EIS. The addendum supplements, but does not replace, the analyses, comments, and conclusions presented in the SRG Report dated October, 1995.

Full implementation of the disposal concept, which will include, in particular, a decision to close a disposal vault, will require a reliable quantitative assessment of the long-term risks associated with a specific disposal site and with the engineering design that is developed for that site. The risks associated with the generic concept, which is not site-specific, also should be amenable to quantitative analysis; but AECL's postclosure performance assessment of the concept, using its SYVAC technology and hypothetical reference case studies that are based on the Whiteshell Research Area, is unreliable and cannot be used to determine whether the generic concept is safe or is not safe. There are a number of fundamental shortcomings in AECL's methodology for assessing the long-term safety of the disposal concept, but among the foremost is that it relies upon an inadequate conceptual model of the geosphere in the Whiteshell Research Area.

In spite of the lack of a reliable quantitative assessment of the long-term safety of the generic disposal concept, the SRG concludes that, in principle, the concept could be implemented safely and effectively. The rationale for this conclusion is the SRG's judgement, based on the available information, that:

- **Waste disposal containers can be designed and manufactured so as to confine practically all of the contaminants for many tens of thousands of years.**
- **Bodies of sparsely fractured, low-permeability plutonic rock containing very old saline groundwater have been found at the Whiteshell Research Area. Such bodies should provide a natural barrier that could potentially inhibit transport of contaminants from a disposal vault to the surface for more than 10,000 years. It is plausible, although not documented, that similar bodies of low-permeability rock may also exist at other sites in the Canadian Shield.**
- **A vault with long-term mechanical stability and integrity can be designed and constructed, even under relatively high *in situ* differential stress.**
- **A buffer-backfill-vault seal system can be designed and constructed to significantly inhibit contaminant transport from the vault.**

To establish that favourable conditions do in fact exist in the Canadian Shield, screening and evaluation of potential sites should begin, but the performance assessment methodology must be improved before a reliable quantitative probabilistic performance assessment can be done at the site evaluation stage.

Computer-based, probabilistic safety assessment of the entire disposal system should be deferred until the site evaluation stage, when actual, site-specific field and laboratory data can be used to develop and apply a realistic geosphere model, and a more representative and relevant biosphere model. It also will be necessary to ensure that conceptual models used in the safety assessment receive broad input and review from a wide variety of stakeholders. The conceptual models must be robust and well accepted before proceeding to quantitative analysis. Furthermore, it will be necessary to take advantage of newer, more flexible and more powerful technologies to replace the computational components of AECL's probabilistic risk assessment methodology.

THE SRG CONFIRMS AND REITERATES ITS CONCLUSION THAT AECL'S MULTIPLE-BARRIER CONCEPT FOR THE DISPOSAL OF CANADA'S NUCLEAR FUEL WASTE IS POTENTIALLY ACCEPTABLE AND APPLICABLE, BUT THIS NEEDS TO BE DEMONSTRATED FOR EACH INDIVIDUAL SITE. THEREFORE THE SITE SELECTION PROCESS SHOULD BEGIN.

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