Canada's High-Level Nuclear Waste Disposal Concept: The Evaluation Process and a Review of Some Aspects of the Research Work

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The Concept of disposing of high-level nuclear waste in granitic rocks in the Canadian Shield, developed by Atomic Energy of Canada Limited (AECL), is anticipated to undergo a national public review within two years. A document which comprehensively describes the disposal Concept is being prepared as an Environmental Impact Statement (EIS). The process for EIS review and Concept evaluation, including the role of the public, government and the scientific/engineering community, is summarized. A Technical Advisory Committee (TAC) has provided external peer review of the Program since 1979 and its findings are published in annual reports which are publicly available. TAC's current views of certain geologic and geotechnical aspects of the Program are presented along with a description of the safety and performance assessment of the disposal Concept.

Il est prévu que le Concept, développé par Énergie atomique du Canada Limitée (EACL), d'enfouir dans les couches de roc granitique du Bouclier canadien des déchets de combustibles nucléaires fortement radioactifs fera l'objet d'une consultation publique nationale dans les deux années qui viennent. Un document qui expose en détail le Concept d'enfouissement est en cours de préparation sous l'intitulé Étude d'impact environnemental (EIE). Le processus d'examen de l'EIE et d'évaluation du Concept, y compris le rôle du public, du gouvernement et de la communauté scientifique et technique y est résumé. Un Comité technique consultatif (CTC) a fourni une critique du programme par des pairs externes à ce dernier depuis 1979 et ses conclusions sont publiées dans des rapports annuels mis à la disposition du public. Les positions actuelles du CTC sur certains aspects géologiques et géotechniques du Programme sont accompagnées d'une description de l'évaluation de sécurité et de performance du Concept d'enfouissement.

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1. Introduction

The research and development Program to establish appropriate technologies for the safe, permanent disposal of Canada's nuclear fuel wastes was formally initiated in June 1978 by a Federal Government-Ontario Government Agreement (Canada-Ontario, 1978). The resulting Canadian Nuclear Fuel Waste Management Program (CNFWMP) as originally envisaged, is described in a public document (Boulton, 1978) and its course of development up to and including 1985 can be followed through a series of publicly available annual reports (e.g., Lisle and Wright, 1986). The present Program is the product of numerous changes made over the years. While a comprehensive discussion of the Program's development is beyond the scope of this paper, its progress since 1985 may be found in a series of semi-annual reports (e.g., Wright, 1991). In the following sections, we give a general overview of the disposal Concept being presented by Atomic Energy of Canada Limited (AECL). This is followed by a discussion of the advantages and disadvantages of the three-phase approach adopted in the Program. We give some emphasis to the review process that the Concept is undergoing and describe the roles of various participants but highlighting that of the public. In the second part of the paper, we focus on several salient geologic-related issues as raised by the Technical Advisory Committee (TAC) (TAC, 1992). This is followed by a description of the safety and performance assessment methodology applied to the total disposal system. This is heavily dependent on simulation with computers, and consequently, the critical importance of software quality assurance is noted. A concluding summary is added.

2. The Canadian Waste Disposal Concept

The overall objective of the CNFWMP is "to ensure that there will be no significant adverse effect on man or the environment from nuclear waste at any time" (Rosinger and Dixon, 1982). Nuclear fuel waste is defined as either irradiated fuel or high-level radioactive material separated from the used fuel through reprocessing, although there are presently no plans to pursue this latter possibility.

2.1 The Multi-Barrier System

Similar to efforts in several other nations, the Canadian Program of research on deep geological disposal of nuclear waste is based on the concept of isolating wastes with a series of barriers situated in a deep (500m–1000m) underground vault, built in a stable, terrestrial geologic formation such as the granitic rocks of the Canadian Shield.

The bundles of used fuel would be encased in containers with an anticipated life of at least 500 years which corresponds to the period of high fission-product activity. The containers would be designed to withstand hydrostatic and lithostatic pressures and be resistant to corrosion under the temperature, groundwater exposure and radiation fields that could potentially exist at depth. The containers would be emplaced in the vault and surrounded with compacted buffer material such as a mixture of sand and bentonite clay. This candidate material swells upon contact with water, thus acting as a highly impermeable seal against leaching and corrosive agents. It also has a high capacity to absorb chemical species, including most of the significant radionuclides. The vault and the shaft would then be backfilled, probably with a mixture of crushed rock, sand, and bentonite to close any opening to the surface.

The geologic medium in which the underground vault is built acts as yet another barrier to the migration of radionuclides should they escape the vault. Retardation occurs as a result of a number of natural processes taking place at depth, including chemical absorption of radionuclides onto rock surfaces, ion exchange, diffusion into the body of the rock, and the long path lengths to the surface due to the relatively small size and frequency of fractures in the chosen rock. The effectiveness of this natural barrier depends on careful selection of a site which exhibits favourable geochemical, geological and hydrogeological conditions.

Finally, although the biosphere is not generally regarded as a "barrier" in the same sense as those described above, the surface environment, with its large volume of soil and water, has a great capacity to disperse and dilute whatever material which, no matter how unlikely, may reach the surface.

2.2 Components of the Research Program

The research work in support of the disposal Concept is divided into several parts:
1. interim storage,
2. transportation of nuclear fuel wastes,
3. disposal or burial of wastes.

Research and development work on the first two parts is referred to as "preclosure" work and is the responsibility of Ontario Hydro (OH). AECL has the responsibility of implementing research on the "postclosure" work. This work includes the assessment of possible safety and environmental impacts from the disposal vault, both in the time period during its operation and also far into the future after its closure.

The postclosure work comprises research in a multitude of disciplines. Components of the Program may be grouped under four headings: geoscience, engineered barriers, bioscience and performance assessment. Included under the first heading are hydrogeology, geology, geophysics, geomechanics and geochemistry. Work on engineered barriers includes design and development of the underground vault, and the research on containers (composition and design), and buffers and backfill. Under bioscience, studies include radiologic effects, dosimetry, ecological succession, limnology, hydrology, plant uptake, and food chain models. The objective of performance assessment is to process and integrate the results from all of these disparate studies into a comprehensive and comprehensible analysis of the safety of the disposal system.

2.3 Three Phases of the Program

The Canadian Program, unlike disposal research programs of many other countries, is divided into phases. The first, Concept Assessment, involves research which aims to determine whether and to what extent waste disposal in deep, stable, terrestrial geologic formations can be achieved with the stated objective of ensuring human safety and environmental protection. This "generic research and development" phase was formally initiated in 1981 and the results of the ensuing years of research are now being assembled by AECL as the substantive work by which the Concept can be evaluated and judged as to its acceptability. This evaluation process is discussed in the succeeding section.

The second phase, that of Site Selection, involving the actual process of screening, evaluating and finally selecting a suitable site, can only begin if the Concept is deemed acceptable. However, there are two other possibilities. The Concept may be found to be conditionally acceptable, in which case AECL will have to conduct further research or otherwise modify present work to satisfactorily address the deemed inadequacies. Should the Concept be judged unacceptable, then it would be the responsibility of the Federal and Ontario Governments to consider alternatives.

The final phase, assuming success in both of the previous phases, would be the construction and operation of the disposal vault. It may be that a demonstration facility would first be built to provide the engineering and operational experience for the full-scale facility. In either case, this third phase is not envisioned to start until sometime in the next century.

The Canadian Program is unusual among other international programs in its clear distinction between the phases – work in one phase cannot begin until successful completion of the previous phase. This sequential approach has both its advantages as well as its disadvantages. These are manifested in the characteristics of the research program as well as in its evaluation.

The scientific and technical research work as originally envisioned and initiated was "generic" in nature, without reference necessarily to any particular location or site. The biospheric conditions and associated data values were obtained from various sources including different locales in the Canadian Shield, field and laboratory experiments and from the literature. This composite of environmental and biologic information is representative of the Shield conditions in general but does not necessarily portray any particular location.

Although this approach proved to be satisfactory for characterizing the surface environment, it proved less successful when applied to the underground geologic conditions. The very wide range of values and heterogeneous conditions encountered in this domain made the concept of a "generic geosphere" questionable, at least in the Canadian Shield situation. Recognition of this fact during the mid-80s led to a much more focused effort in and around the Whiteshell Research Area (WRA) located near the Manitoba-Ontario border close to the Whiteshell Nuclear Research Establishment (WNRE) site. Most data gathering, fieldwork, laboratory experiments and modelling work are specific to this location, although considerable geologic exploratory work has been carried out in two other research areas, one near Atikokan and the other at East Bull Lake, both in Ontario. The present AECL work, therefore, is based on a hybrid of both generic (mostly environmental conditions) and site-specific (mostly geologic conditions) information.

To a lesser degree, the problems encountered in the geologic case are also applicable to the assessment of socioeconomic impacts which belong in the preclosure studies. Although a generic approach was adopted, the effects of transportation and other activities associated with siting are difficult to assess without reference to a specific site.

Despite these difficulties there is an important advantage conferred by this approach. The clear distinction of the phases also defines what type of work is to be done during each phase and gives guidance on where emphasis is to be placed. During this first phase, for instance, the goal is to assess the Concept of waste disposal in deep, stable, terrestrial geologic formation — to see if, and how, this can be accomplished to meet the regulatory requirements of human safety and environmental protection. As such, the research work is necessarily concerned with technical issues such as the effectiveness of system components (e.g., containers, the vault, the geologic barriers) for long periods of time, the possible failures that may occur at each barrier, the consequences of such failures, etc. In brief, the central and critical question which this phase of the work is to answer is: "Will it be *technically possible* to dispose of high-level nuclear waste safely?" Other considerations associated with disposal such as ethical, social, economic, and political issues, valid as they are, must be treated as secondary considerations at this stage. If it cannot be established that safe disposal is at least technically possible, then clearly all other considerations are irrelevant.

The establishment of technical feasibility, although necessary for the ultimate act of waste disposal, is not sufficient. A satisfactory resolution of non-technical issues such as the ones mentioned above are just as necessary for an eventual successful outcome. It is during the second phase when the process focuses on selecting a specific site, that issues such as equitable treatment, social and economic impacts on a certain region, matters of impact mitigation, compensation, etc. will come to the fore, and properly so. The experiences in other disposal programs show the critical importance of non-technical issues to successful siting. The experiences of the Low Level Waste Siting Task Force (Siting Task Force, 1990), the Ontario Waste Management Corporation and even the present controversy over selection of landfill sites in Southern Ontario all provide valuable lessons and insights on the immense difficulty of siting. Intense and vociferous opposition, characterized by the acronyms NIMBY (Not In My Back Yard) and LULU (Locally Unwanted Land Use) have accompanied recent attempts at siting any type of disposal facility.

It is in this sense that the CNFWMP enjoys an advantage over all other disposal situations — the phased approach clearly separates assessment of the Concept (i.e., judgment of technical possibility and feasibility) from the actual process of site selection where experience has shown that non-technical considerations overwhelm technical issues. This phased approach has allowed the Program to concentrate on doing the necessary technical work without being mired in counter-productive controversies and delays as faced by other disposal programs.

3. Evaluation of the Disposal Concept

3.1 Development of an Evaluation Process

In a joint statement (Canada-Ontario, 1981) the Ontario and Federal Governments defined, in detail, the process for evaluation of the acceptability of the proposed Concept. Public announcement of the joint statement constituted the first step in that process. In that document, the Atomic Energy Control Board (AECB) was originally designated as the lead agency for the regulatory and environmental review of the disposal Concept, and was responsible for the issuance of a final regulatory statement (AECB, 1985) which outlined the basis for such a review.

Since the publication of our previous paper (Sheng *et al.*, 1987) in which this review process was described, a number of significant changes have taken place. First, AECB is no longer the lead agency for the review, and second, the Interagency Review Committee (IRC) originally comprising the AECB, the Ontario Ministry of Environment and the Federal Department of the Environment, no longer exists as a collective entity to conduct the review. Because of the increasing recognition during the eighties that implementation of technological projects, large or small, involves the need to better address the concerns of a democratic society in terms of giving due emphasis to socioeconomic and political issues in addition to the technical ones, it was felt that an independent body with such a mandate would be the most appropriate agent to lead the Concept evaluation. Consequently, in a referral letter (Masse, 1988), the Federal Minister of Energy, Mines and Resources requested that the Federal Minister of the Environment set up an Environmental Assessment (EA) Panel to lead the review under the auspices of the Federal Environmental Assessment Review Office (FEARO). Under this new scheme, AECB will play a consultative role to the EA Panel although its regulatory requirements with respect to nuclear waste disposal as promulgated in R-71 (AECB, 1985), R-104 (AECB, 1987a) and R-72 (AECB, 1987b) must still be met. In addition to these regulations, however, the CNFWMP must also satisfy the requirements of the EA Panel operating under the Environmental Assessment Review Process (EARP). One of the requirements under EARP is that the proponent, AECL in this case, must submit an Environmental Impact Statement (EIS) detailing and explaining its disposal Concept and giving due emphasis to non-technical issues. Another essential requirement is that public hearings must be held as part of the process of evaluating the AECL Concept. The entire process is diagrammatically shown in Figure 1 with dates of past events as well as expected dates of future milestones. The end point of this process is a decision by the governments based on the findings of the EA Panel as to whether the disposal Concept is acceptable, conditionally acceptable, or not acceptable.

3.2 The Environmental Impact Statement

AECL is presently preparing the EIS in accordance with the EA Panel Final Guidelines, the development of which is described in section 3.3 below. The EIS will be based on the research conducted over the last 15 years as summarized in a nine volume set of documents designated as the "Primary References," each with the primary title *The Disposal of Canada's Nuclear Fuel Waste* and a subtitle as follows:

1. *Public Involvement and Social Aspects;*
2. *Site Screening and Site Evaluation Technology;*
3. *Engineered Barriers Alternatives;*
4. *Engineering for a Disposal Facility;*
5. *Preclosure Assessment of a Conceptual System;*
6. *Postclosure Assessment of a Reference System;*
7. *The Vault Model for Postclosure Assessment;*
8. *The Geosphere Model for Postclosure Assessment;*
9. *The Biosphere Model, BIOTRAC, for postclosure Assessment.*

As evident from the titles, each of these nine documents addresses, in detail, a specific aspect or significant component of the Program such as the engineering, preclosure and postclosure work, the details of the vault, geosphere and biosphere models, and social aspects of disposal, etc. Originally this set of documents was to be the EIS submission, but now serves as the primary supporting documentation for what will be a single volume EIS entitled "Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste." In addition, a summary volume of the EIS will be produced for general readership. It is expected that AECL will submit the EIS to the EA Panel sometime in 1994.

3.3 Public Participation and Participant Funding

As shown in Figure 1, the EARP provides many different opportunities during the review process for the public to receive information as well as to provide input. We describe these below.

3.3.1 INFORMATION DISSEMINATION – OPEN HOUSES

The Panel, after its appointment on October 4, 1989, (Minister of the Environment, 1989), scheduled "Open Houses" to be held in major cities in New Brunswick, Quebec, Ontario, Manitoba and Saskatchewan throughout the months of May and June of 1990. Secretariat members of the Panel were available to discuss the review process, the Panel's terms of reference, anticipated review activities and participant funding. As well, AECL and OH staff had displays and distributed literature to inform about, and explain, the disposal Concept. Attendance at the some 20 sessions, held both during the day and in the evening, was generally low.

3.3.2 PUBLIC INPUT THROUGH SCOPING MEETINGS

The Panel held some 23 "Scoping Meetings" during

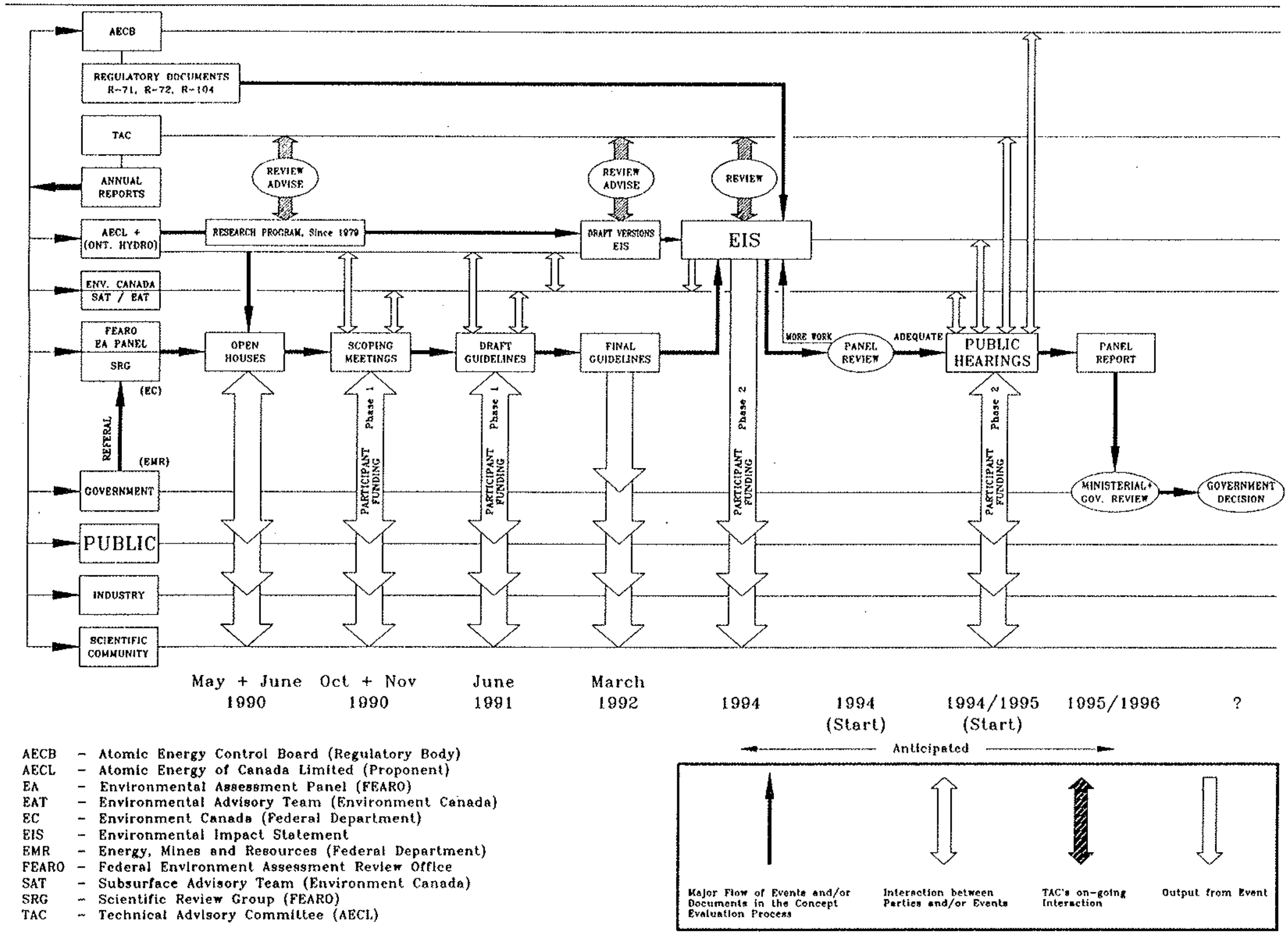

Figure 1: Evaluation of Canadian Nuclear Waste Disposal Concept

the months of October and November of 1990 in the same provinces as for the Open Houses. The intent of these meetings was for members of the general public and any interested parties to present to the Panel their views on what issues should be included in the Panel's guidelines for the preparation of AECL's EIS. More than 100 written and oral presentations were made to the Panel in accordance with a set of procedures announced on November 5, 1990 (FEARO, 1990d). A wide diversity of groups including government agencies, industry, professional, scientific and engineering societies, environmental groups, labour organizations and members of the general public participated in this process. A compilation of the submissions is available from FEARO.

The most salient issues arising out of these meetings include: (1) the need to examine the disposal Concept within the context of the entire Canadian energy policy, (2) the public concern about a "walk-away" Concept, on-going postclosure monitoring being a very high priority in the public mind; (3) the view that ethical and socioeconomic issues are at least as important as technical issues and the difficulty of talking separately about them.

3.3.3 PUBLIC COMMENTS ON THE DRAFT GUIDELINES

From the input provided through the Scoping Meetings, the EA Panel drafted a set of Interim Guidelines for AECL's EIS which was released for public comment. Although the level of response to the Draft Guidelines did not match that of the Scoping Meetings, comments received from some groups, including AECL, were detailed and comprehensive. Modifications were made to the Draft Guidelines as a result of the various responses and the set of Final Guidelines was issued by the EA Panel in March 1992 (FEARO, 1992). A complete compilation of all submissions is available from the FEARO office.

3.3.4 PARTICIPATION THROUGH PUBLIC HEARINGS

The next opportunity for formal input and participation will be during the public hearings which are anticipated to start after AECL submits its EIS (expected in 1994) and after the EA Panel is satisfied of the EIS's compliance with the Final Guidelines. At that time the EIS will be distributed for public review to any interested party. The dates, locations and detailed procedures for the hearings will be announced by the Panel. Although it is difficult to predict how long the hearings will take, it is anticipated that completion would be within a twelve-month period. Upon completion, the Panel will submit a report of its findings and recommendations to the Federal and Ontario governments. It is then the responsibility of those governments to state the acceptability, conditional acceptability or non-acceptability of AECL's proposed Concept. Should the first outcome be realized, the second phase, site-selection, may be initiated. In the second instance, AECL may be required to do further work. In the event of the third outcome, the two governments will have to consider other alternatives.

3.3.5 PARTICIPANT FUNDING

A critical component of the review process is the availability of funding to help the public participate more effectively over the entire process. The $750,000 participant funding, provided by AECL, is administered by a separate Funding Committee set up by FEARO which reviews and allocates funds to successful applicants in accordance with its eligibility criteria (FEARO, 1990a). The Committee had awarded $152,500 to 17 of 33 applicants to assist them in the preparation for, and participation in, the Scoping Meetings and for review and comment on the Draft Guidelines (FEARO, 1990c). The remaining amount has been allocated for Phase 2 which involves the review of the EIS and its related documents, and participation in subsequent public hearings. This amount will be distributed such that full opportunity is provided for participation in both the socioeconomic and technical reviews. However, at least half of the amount will be available to participants wishing to conduct scientific reviews on the technical aspects of the Program. Information about eligibility criteria, deadlines, application forms, and the list of successful applicants from Phase 1 are available from FEARO.

4. Scientific Reviewing Bodies

As well as the overall Concept evaluation process led by the EA Panel as described above, the Concept is presently also being reviewed by three groups with the focus on scientific, technical and engineering aspects of the Program.

4.1 The Technical Advisory Committee (TAC)

The Technical Advisory Committee to AECL, was established in mid-1979, and has provided continuous reviews since then. The purpose of TAC is to act as an independent review body advising AECL on the extent and quality of the CNFWMP. Its responsibilities are to review the content of proposed research projects, to suggest alternatives and additions as deemed appropriate, to review the scientific methods used, to review Program results and assure that conclusions drawn are valid within the limits that are claimed, and to recommend any specific areas of work for which research should be undertaken, either by existing staff or through research contracts. Its autonomy is assured by the form of appointment to TAC of persons independently nominated by professional and scientific societies, by the requirement of reporting in the public domain and by the provision to TAC of full and free access to all aspects of the research Program. The Committee is also provided with resources that allow it to obtain additional specialist advice as it deems fit. TAC's 13 annual reports provide a publicly available documentation of its on-going assessment of the progress and performance within the Program as well as external factors influencing it. A concise summary of TAC's recommendations over the last dozen years is presented in Shemilt and Sheng (1991).

4.2 The Scientific Review Group (SRG)

The SRG was established by the EA Panel in mid-1990 specifically to evaluate and provide advice on the scientific and engineering aspects of the Concept (FEARO, 1990b). Similar to TAC, most of its members are Canadian scientists chosen mostly from universities, although several are from industry and government. The SRG reports directly to the EA Panel and has provided input to the Scoping Meetings as well as comments on the Draft Guidelines.

4.3 The Subsurface Advisory Team (SAT) and Environmental Advisory Team (EAT)

These two teams of consultants were established in 1989-90 by Environment Canada on a contractual basis to provide it with dedicated scientific advice on AECL's disposal Concept, and to develop Environment Canada's position as an intervenor during the public hearings. The SAT is responsible for issues associated with the disposal vault and the geosphere, and the EAT is to review issues associated with the biosphere as well as those involving social, economic and policy aspects of disposal. Both teams have conducted their own "scoping calculations" which are summarized in SAT (1992) and EAT (1992). A concise description of the teams' roles, activities and major findings is given by Pascoe *et al.* (1992).

5. Aspects of TAC'S Review

5.1 The Geoscience Program and Salient Issues

The CNFWMP places considerable importance on the geosphere as a barrier for the long-term containment of nuclear wastes. The objectives of the geoscience program are to develop and refine the technologies for locating and characterizing potential disposal sites, leading to the development of a geosphere model which can be used in performance assessment of a hypothetical vault. The geoscience program is the largest component within the CNFWMP and has undergone many changes since its inception in the late seventies. It is beyond the scope of this paper to trace the history of the program's development and discuss the reasons for the changes. Dormuth *et al.*, (1989) provide a comprehensive overview of the geological considerations for nuclear fuel waste disposal in Canada including the philosophy and goals of the Canadian effort, the rationale and justification for the choice of plutonic rocks in the Canadian Shield as the potential host medium, the most important geotechnical factors to be examined in considering potential sites, the methodology developed and planned to be used in the site characterization process, the methodology developed and being used in the prediction of disposal system performance, and a brief presentation of the case study (based on the Whiteshell Research Area) developed for demonstration of the Canadian Disposal Concept. Our previous paper (Sheng *et al.*, 1987) reviewed some highlights of the then current geologic, geotechnical and performance assessment work, including the Underground Research Laboratory (URL), the geomechanic characterizations taking place there as well as the hydrogeological studies with the associated field investigations. In this paper we focus on several aspects of the geoscience program which we believe to be critical for successful demonstration of the Concept.

The approach being adopted by AECL for the EIS is to present a case study based mostly on the work at the WRA, including the URL, to demonstrate the safety of the Concept. The case study places high reliance on the integrity of the granitic host medium (the Lac du Bonnet Batholith) as the main barrier for the long-term containment of any wastes. This is manifested in the geosphere modelling which simulates the characteristics of the URL and its surroundings within the WRA. The model assumes the existence of a zone of unfractured rock around a hypothetical vault with transport of material across this zone only through diffusion. TAC, in its recent annual report (TAC, 1992), raised several issues of concern related to this approach, as well as on the results of preliminary modelling which indicate that a fracture zone penetrating through the mass of intact rock within 50 meters of a failed container would seriously reduce the effectiveness of the geosphere as a barrier. Furthermore, this reduced effectiveness is most serious for a vault with such an intersecting fracture located in a hydrogeologic discharge area as is the case at the URL site. Based on the above, TAC's specific concerns are summarized by the following points:

1. the existence of a volume of continuously-intact rock necessary to host a disposal vault with an equivalent area of 2 km x 2 km,
2. the ability to characterize the rock mass such that any significant fracture (i.e., any fracture with the characteristics that would violate the diffusion-only transport assumption) within 50 meters of the vault would be detected,
3. the implicit assumption that no such fractures would develop in the future,
4. the inherent disadvantages of placing a vault in an area of groundwater discharge which is the case study being presented at the URL site.

Environment Canada's Subsurface Advisory Team have also carried out scoping studies which explicitly raised the same concerns as in 2. above, as well as the first issue implicitly (SAT, 1992).

In the papers by Pascoe *et al.* (1992) and Raven and Timlin (1992) they state the following as one of a number of issues which they believe "require substantially greater attention by AECL during the presentation of their environmental impact statement" (Pascoe *et al.*, 1992):

> The intact rock surrounding the emplacement room is likely to be the critical feature of the multi-barrier concept developed by AECL. Our scoping calculations indicate that approximately 50m of intact rock of bulk permeability less than 10^{-18} m^2 would be needed to prevent radionuclide releases over a 10,000 year period. Consequently, demonstrated success of the AECL Concept may require reliable characterization of the bulk rock permeability to values of 10^{-19} m^2 or less over scales of 50m surrounding each emplacement room throughout the repository" (Raven and Timlin, 1992).

As noted above, TAC therefore considers that two elements within the geoscience program require particular attention: (1) hydrogeologic characteristics of the site, and (2) long-term geomechanical behaviour of the rock mass.

5.2 *Hydrogeology*

With regard to the former, TAC's advocacy of regional flow system studies and a regional recharge area as a desired site characteristic has been presented in previous TAC reports (e.g., TAC, 1989; 1990), and reiterated in its recent Twelfth and Thirteenth Annual Reports (TAC, 1992; 1993).

In a regional recharge area, groundwater moves away from the land surface and is generally destined to migrate along very long flow paths (possibly tens or even hundreds of kilometres) for very long times (possibly hundreds of thousands of years), thereby contributing to higher amounts of adsorption and radioactive decay of the transported nuclides. TAC continues to hold its previous opinion (TAC, 1989; 1990) that from a groundwater hydraulics point of view, such regional recharge areas have positive characteristics as potential vault locations and therefore that a recharge setting in regional groundwater flow systems should be formally recognized as a highly ranking favourable hydrogeological attribute. Such a consideration could also expedite the process of initial site screening since it can be readily deduced from topographic maps and does not require the use of destructive methods of investigation. Hence the claim by AECL that current knowledge does not justify a search for regional recharge areas is not a position that accords with the above judgment which TAC is reasserting in recent reports (TAC, 1992; 1993).

TAC has noted that the work on regional groundwater flow systems is being maintained by field investigations and monitoring of hydrogeological conditions both at the Atikokan Research Area (ARA) and more extensively at the WRA (especially related to the URL). Hydrogeological maps for both areas are being prepared using general specifications. TAC reaffirms its earlier judgment that the delineation of flow systems and establishing of flow directions should constitute integral components of such mapping. The EIS and its supporting documents, including such fundamental components as hydrogeological maps, should demonstrate both an understanding of all significant conceptual aspects of ground-water flow distribution in the Canadian Shield and an ability to evaluate, characterize and model regional flow paths in several field situations (TAC, 1992).

5.3 Geomechanics

Geomechanical research in the NFWMP is being carried out to gain an adequate understanding of the response of rock mass to stresses imposed by the range of disturbances associated with the construction, operation and long-term existence of a deep disposal vault. One of the most important ultimate goals of the CNFWMP is to demonstrate the ability to predict, from a limited amount of data, the short- and long-term behaviour of rock masses surrounding the vault when they are subjected to changes of stress, temperature, humidity and other time-dependent factors (TAC, 1990). Although this is clearly a well-defined objective, at this stage in the Program and on the basis of presently available data on vault rock and rock mass constitutive behaviour, TAC considers that the ability to simulate the behaviour of rock mass around the projected vault for any hypothetical site, including one similar to the URL site, and to check its short- and long-term stability has not yet been sufficiently demonstrated. Further, although good experimental work has been done in connection with ground stress determination, more attention to addressing the problem of understanding the behaviour of the host rock would seem to be needed. As noted below, the planned Mine-by Experiment, being carried out in the URL, promises to be a valuable source of information concerning this problem.

These aspects have continued to be stressed by TAC. However, with currently available information, it is still difficult to model adequately for stresses induced by the vault and the possible development of short- and long-term failure zones. Through existing AECL documents, the useful, but fragmentary, information on the host rock mechanical behaviour at small scale, and the small amount of data available at a large scale have yet to be put in a form appropriate for use in vault modelling and design. What is needed is a 3D constitutive model of the rock which hosts the vault, and which includes both existing and potential fracture zones. This would enable simulation of the rock behaviour around the planned vault at both short- and long-term, and at both small- and large-scale, taking into account all imposed time, space and environmental constraints (TAC, 1992). It is noted that the first results of a 3D near-field structural analysis of the vault have just become available.

The value in reaching such an overall understanding of the rock behaviour around the planned vault is demonstrated by the propagation of damage zones encountered during experimental water-jet cutting of a typical emplacement borehole in the URL, and during the Mine-by Experiment in the URL. This problem may be expected to occur on a much larger scale in a real situation if in-floor emplacement of containers is adopted. The renewed emphasis on in-room emplacement (Wright, 1991) appears most justified in this respect (TAC, 1992).

Some positive steps towards obtaining additional and much needed information on rock mass behaviour are presently being taken (Wright, 1991). A number of outside rock mass modelling experts are participating in the prediction and back-analysis of rock response in the URL Mine-by Experiment. In that study, various more-or-less complex constitutive models will be used. At the end, an independent review will be done to assess which of the models may be the most suitable for predicting the behaviour of elastic-brittle rock masses around a vault. TAC supports this approach (TAC, 1992).

TAC emphasizes the importance of selecting future sites within geological units that are not located in an unusually high lateral stress field, as is the case in a portion of the URL. Engineering technology is capable of overcoming differential stress during the preclosure phase of a vault in order to maintain safety. Highly stressed rock is more likely to develop fractures in the future during the postclosure phase. Such fractures could provide new pathways to the surface although it is possible to minimize such an eventuality for a vault sited in a hydrogeologic recharge zone.

5.4 Performance Assessment

In order to assess adequately the long-term environmental impact of the disposal Concept, it is necessary to invoke methodologies that will both encompass the large number of variables inherent in the system and predict effects over extensive time periods. The possible consequences, over both time and space, will be measured against criteria that are set by regulatory agencies, as discussed immediately below. A common approach to assessment is to apply probabilistic analysis (Sheng and Shemilt, 1990). This methodology and its application is briefly described below.

5.4.1 DOSE, RISK AND OTHER CRITERIA

The criteria for judging nuclear waste disposal safety has been established by AECB, the regulatory body in Canada which has responsibility for matters dealing with radioactive substances. The regulatory document R-104 (AECB, 1987a) contains specific radiobiological and risk criteria as well as other requirements. In brief, AECB requires that: (a) burdens placed on future generations be minimized, (b) the environment must be protected, and (c) human health must be protected, for which the risk criterion of less than 10^{-6} (or one in a million) serious health effects per year is imposed. This risk figure is associated with a dose of 0.05 mSv/yr which is equivalent to approximately 2.5% of the annual dose received by the general population in Canada from natural background radiation.

5.4.2 SYSTEM VARIABILITY ANALYSIS

There are two unique characteristics associated with the permanent disposal of nuclear waste: (a) no precedents exist for such an endeavour and (b) the very long time-span over which the multi-barrier system must remain effective. To deal with the inherent uncertainties involved in predicting possible future outcomes under this latter condition and reflecting the system complexity, a method known as "system variability analysis" was adopted (Wuschke *et al.*, 1981). It takes into account, systematically, the effects of imprecise data (i.e., parameter values that cannot be precisely specified as single point values).

In this approach, uncertainties in the data gathered through research, and the variation of conditions through space and time are taken into account by assigning a distribution of values (rather than specifying a single value) to the parameters used to model or describe the disposal system. The distributions (e.g., normal, lognormal, exponential, uniform, etc.) are selected to cover the credible range of values for the parameters and are characterized by the likelihood of occurrence of chosen values in the specified range. The distributions thus represent observed or theoretical variability, subjective uncertainty, or a combination of both. Simulation studies using these data are performed by sampling values from each parameter distribution to generate a range of possible outcomes and their corresponding frequency of occurrence.

5.4.3 THE SYVAC SIMULATION

This method is implemented with a computer program, SYVAC (SYstems Variability Analysis Code) (Wuschke *et al.*, 1981) and is illustrated in Figure 2. System simulations are performed by linking a set of three submodels representing the three major constituents of the disposal system: the vault, the geosphere, and the biosphere. Significant processes and conditions within each are characterized by sets of equations. These are, in effect, mathematical statements of the current state of knowledge about the disposal system and the phenomena that influence it.

Initial data input consists of the inventory of radionuclides placed in the vault. This is in the form of the used fuel bundles packed in a structurally supported container of titanium or copper. The processes of container failure and of leaching and transporting by groundwater within the vault, together with the reaction of these radionuclides with engineered barriers such as buffers and backfill, and the final movement out of the vault are simulated. The output terms (i.e., integrated flux of radionuclides) from the vault serve as the input terms for the geosphere model. Examples of parameters which are taken into account in the estimation of radionuclide movement through geologic media include groundwater velocity, effective path length, chemical retardation factors including sorption, etc. In the third and last model, the biosphere, the analysis involves the estimation of radionuclide movement leaving the geosphere and travelling through shallow groundwater surface water, soil, plants, animals and, finally, to humans.

SYVAC treats the three submodels in sequence and produces for a particular run (i.e., the situation defined by one particular set of values derived from the stochastic selection of one value from each parameter probability distribution), an estimate of the maximum dose to an individual in the most exposed group within a given time after disposal.

The maximum dose is termed the "consequence" for that run. Estimates of maximum dose from a large number (typically 1000) of such stochastically constructed simulation runs are plotted to show the frequency of occurrence of any particular consequence. A theoretical risk figure can then be calculated by summing the product of each pair of consequence (maximum dose)-versus-frequency values.

5.4.4 THE SYVAC COMPUTER CODE

The SYVAC computer code is a large and complex FORTRAN computer program consisting of over 370 software modules (or FORTRAN subroutines). It has over 30,000 executable FORTRAN statements and, over 100,000 statements (including comment statements) in total. More than 7000 parameters characterize the disposal system and describe the behaviour of more than 90 radionuclides and chemically toxic elements. With respect to execution time, SYVAC (Version 3.07) requires almost three full days of dedicated execution time to complete a 1000 run case on a SUN Sparcstation 1+ Workstation (12 - 15 MIPS). A 5000 run case requires almost two weeks to complete. Version 3.8 requires considerably more execution time, possibly an increase by a factor of 10.

5.4.5 SYVAC AND QUALITY ASSURANCE (QA)

The critical nature of the conceptual models as well as the size and complexity of the SYVAC computer code necessitates a rigorous program of quality assurance. TAC in its annual reviews and evaluation of the Canadian Program has continually emphasized the critical importance of code verification (i.e., the process of ensuring that the software is doing what was intended of it) and recommended the use of software tools and adoption of well-established software engineering practices to minimize program errors. Examples of such tools and techniques are described in Ören *et al.* (1985), Ören and Sheng (1988), Ören and Sheng (1990), and Sheng and Ören (1991).

Another critical, but more difficult, issue is that of model validation which is concerned with how closely or relevantly the conceptual models describe real-world processes. There is as yet no agreed-upon methodology for tackling

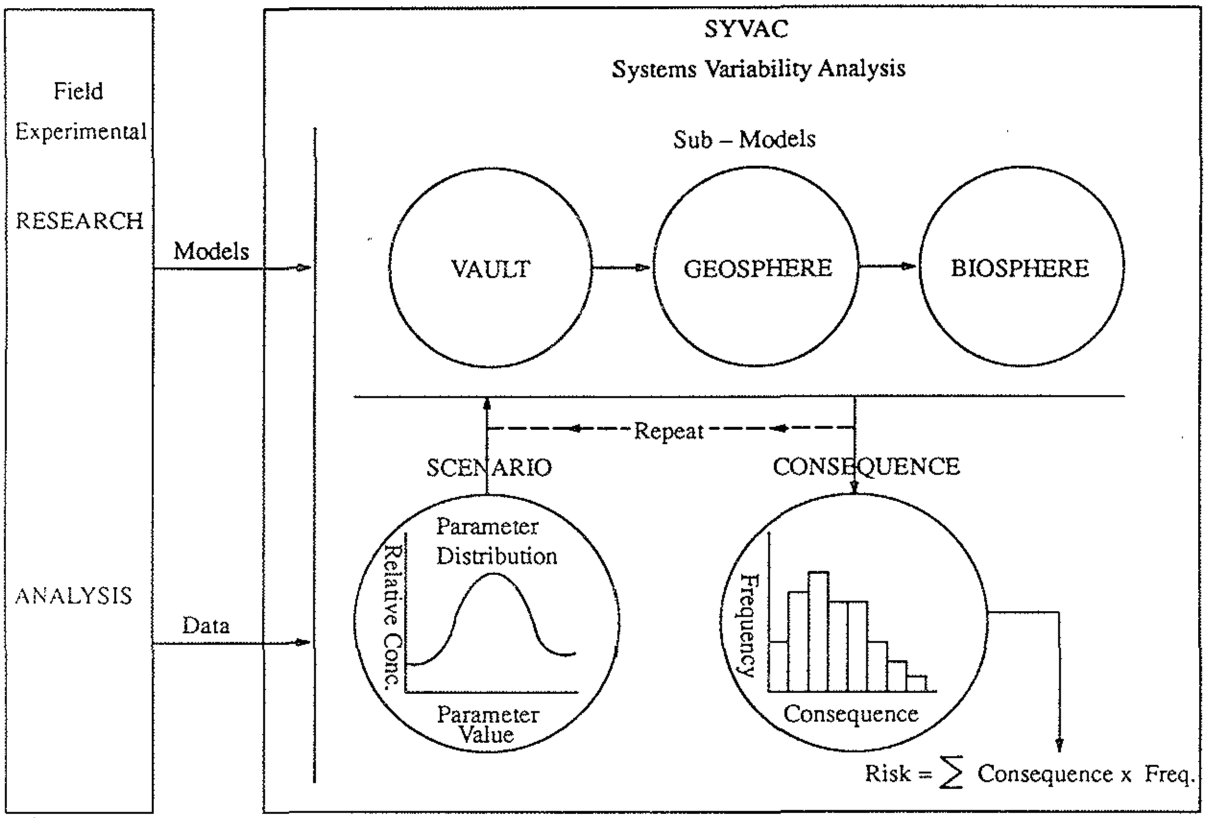

Figure 2: Systems Variability Analysis

this very difficult problem although Sheng *et al.* (1994) outline a possible approach that is rigorous, systematic and based on systems theory.

6. Concluding Summary

Based upon the extensive laboratory and field research conducted within the Canadian Program over the past 15 years, AECL is currently preparing a series of primary reference documents to support the Concept of deep geological disposal. An environmental impact statement will be prepared to summarize this work and will be presented for environmental assessment under federal jurisdiction and established procedures. These include public hearings as well as extensive scientific and technical review. The overall process has been initiated and an Environmental Assessment Panel established by FEARO has issued final guidelines for the EIS which must also give due emphasis to non-technical issues. Continuing scientific reviews are being made of the research conducted by AECL to date. TAC's evaluation, as presented in its annual reports, include observations and recommendations on several geological-related issues. These centre on the establishment of favourable hydrogeologic characteristics for any future disposal site, including location in regional groundwater recharge areas, as well as on advanced geomechanical knowledge of rock mass characteristics.

One of the primary reference documents to be issued by AECL will be a report on postclosure assessment of a waste disposal facility. This will provide the documentation for the performance (safety) assessment of such a facility, including the details of the vault, geosphere and biosphere models, and the application of SYVAC to one or more case studies which will incorporate the extensive research data available. Such documentation should be available in 1994 for independent external evaluation. The scientific and engineering communities in Canada can perform service to the nation by direct participation in such evaluation.

Acknowledgements

The authors wish to express their appreciation to Mel Kliman and two anonymous referees for their helpful comments on a draft of this paper. Thanks are due also to Guido Bendrich and Peter Bewer for their assistance in preparing the figures, and to Rita Donaldson for the preparation of the manuscript.

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