Canadian Geoscience Council

Published for the Council
by the Geological Survey of Canada as
Paper 79-10

Disposal of high-level radioactive waste: The Canadian Geoscience Program

Prepared by The Canadian Geoscience Council

Edited by C.R. Barnes

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

GEOLOGICAL SURVEY
PAPER 79-10

DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE: THE CANADIAN GEOSCIENCE PROGRAM

PREPARED BY
THE CANADIAN GEOSCIENCE COUNCIL

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C.R. BARNES

1979

Available in Canada through

authorized bookstore agents and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Hull, Québec, Canada K1A 0S9

and from

Geological Survey of Canada
601 Booth Street
Ottawa, Canada K1A 0E8

A deposit copy of this publication is also available for reference in public libraries across Canada

Cat. No. M44-79/10
ISBN -0-660-10210-2

Canada: $5.00
Other countries: $6.00

Price subject to change without notice

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DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE:

THE CANADIAN GEOSCIENCE PROGRAM

PART I

COMMENTARY

The Problem

The problem of the disposal of high level radioactive waste is perceived by the Canadian Geoscience Council to be one of the major problems facing both the geoscience community and Canadian society. Because of the high technology of the nuclear power program, the immense costs involved, and the high toxicity of the irradiated fuel waste, the issue is of acute concern to all, and can generate fears that lead to illogical reasoning. The problem is not a simple one to discuss and perhaps because of this open discussions of all the problems are infrequent. The Canadian Geoscience Council (CGC), therefore, organized a Forum in Toronto on October 24, 1978 to consider the Canadian geoscience program as related to this issue. The formal papers presented and the edited versions of the discussions are published in this volume, for which this commentary has been prepared by the Council.

Cheap energy has been a fundamental driving force in industralized societies. With the rapid depletion of the world's oil and gas supplies, the role of electrical energy will increase, particularly that produced by nuclear power. In 1976, Canada's total installed nuclear capacity was 4000 megawatts and this is expected to rise to about 60000 to 75000 megawatts by the 2000 – an amount approximating to the world's capacity in 1975. If the nuclear power program expands as predicted, there will be 50000 tonnes of irradiated fuel in temporary surface storage by the year 2000, with waste accumulating at about 10000 tonnes per year. The volume of this waste can be accommodated in one repository mine as shown in the paper by R.W. Barnes (Paper 5).

Canada embarked on a program of nuclear power many years ago and until recently has not seriously faced the question of permanent waste disposal. Storage of waste, at least until the end of this century, can be accommodated in water-filled bays at

STOCKAGE DES DÉCHETS TRÈS RADIOACTIFS

PROGRAMME CANADIEN DES SCIENCES DE LA TERRE

PARTIE I

COMMENTAIRE

Le problème

Le Conseil national des Sciences de la Terre perçoit le stockage des déchets très radioactifs comme étant l'un des principaux problèmes de la communauté géoscientifique et de la société canadienne. À cause des techniques avancées du programme d'énergie nucléaire, des dépenses considérables qu'il faut y engager et de la toxicité des déchets du combustible irradié, la question du stockage préoccupe tout le monde au plus haut point et peut engendrer des craintes qui mènent à des raisonnements illogiques. Le problème est loin d'être simple et c'est peut-être pour cela qu'il y a si rarement des discussions ouvertes à ce sujet. Le 24 octobre 1978, le Conseil canadien des Sciences de la Terre (C.C.S.T.) a donc tenu un colloque, à Toronto, pour étudier le programme canadien des Sciences de la Terre en fonction de cette question de stockage. Les documents officiels présentés et les versions définitives des discussions sont publiés dans ce volume pour lequel le Conseil a préparé le présent commentaire.

L'énergie à bon marché a joué un rôle moteur essentiel dans les sociétés industrialisées. L'épuisement rapide des réserves mondiales de pétrole et de gaz rendra plus important le rôle de l'énergie électrique, surtout celle qui est produite par l'énergie nucléaire. En 1976, la capacité nucléaire totale installée au Canada était de 4000 mégawatts. Vers l'an 2000, cette capacité augmentera vraisemblablement jusqu'à environ 60000 à 75000 mégawatts, chiffre presque égal à la capacité mondiale en 1975. Si le programme d'énergie nucléaire prend de l'espansion, comme prévu, il y aura, d'ici l'an 2000, 50000 tonnes de combustible irradié stockées provisoirement en surface, les déchets s'accumulant à un rythme de 10000 tonnes par année. Cette quantité de déchets peut être logée dans une mine cimetière comme l'indique l'exposé de R.W. Barnes.

Il y a bon nombre d'années, le Canada se lançait dans un programme d'énergie nucléaire, mais ce n'est que récemment qu'il s'est attaqué sérieusement à la question du stockage définitif des déchets. Ils peuvent être stockés au moins d'ici la fin du siècle dans

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The Geological Survey of Canada of the Department of Energy, Mines and Resources is pleased to publish the text of the Symposium on Disposal of High-Level Radioactive Waste, which was sponsored by the Canadian Geoscience Council and held in Toronto in October, 1978, but it must not be construed that it necessarily associates itself with the recommendations contained in the introductory Commentary.

Il est agréable à la Commission géologique du Canada du ministère de l'Energie, des Mines et des Ressources de publier le texte du colloque intitulé «Storage des déchets très radioactifs». Ce colloque, organisé par le Conseil canadien des Sciences de la Terre, eût lieu à Toronto en octobre 1978. A noter, la Commission n'est pas nécessairement d'accord avec les recommandations émises à la partie du texte titrée «Commentaire».

power plant sites. However, because of the volume of waste accumulating, the increasing annual supply, and the hazardous toxicity, it has become essential to demonstrate that the waste can be disposed of safely and permanently.

Simple disposal in sealed surface containers presents problems in controlling the emission of toxic substances, such as radon gas. Furthermore, such repositories could not readily be protected against terrorist attacks or nuclear strikes which, however unlikely, could have horrifying consequences.

The Canadian waste disposal program is based on a concept of multiple barriers: waste dilution and solidification; its containment in an inert canister; this container than surrounded by special backfill material and sealed in an excavation created 1000m or deeper in the geological subsurface environment. Thus, each barrier should provide a degree of containment should leaching of the waste occur. Several papers discuss current research aimed at finding appropriate methods of waste solidification/treatment (e.g. vitrification), the types of long-term containers (e.g. copper, corundum ceramics), the nature of impermeable backfill and sealing materials (e.g. bentonite clays), the most desirable rock type, and the optimum depth of burial. Wallach and Poliscuk (Paper 1) note that it is assumed that leached radionuclides will eventually be released, hence the disposal system must be designed so that any leakage to the biosphere is so slow or minimal that it does not exceed acceptable levels. Rothschild and Barraud (Paper 4) acknowledge that should major leaks occur to the biosphere, no actions are known at present that could correct the situation. Thus, the solution to the disposal problem for high level radioactive wastes is to verify the concept that deep disposal is safe, secure and desirable.

The Uncertainties

The solution to this problem is complicated by the presence of uncertainties relating to policy, technology, politics, and public acceptance.

A major policy uncertainty is whether the waste should be eventually reprocessed to recover additional potential energy, but with the resultant production of plutonium and toxic liquid waste. If reprocessing is accepted, wastes must be retrievable from the deep repository; if not, the wastes can be permanently sealed in the repository. The handling of the waste, nature of the containers, and design of the repository are all affected by this current uncertainty.

Radioactive wastes generate high temperatures unless diluted in the solidification process which in turn results in an increased volume of material to be buried. Relatively undiluted wastes may achieve temperatures of up to 400°C, whereas diluted wastes may be maintained in the 60°-100°C range. High initial temperatures could also be accommodated through interim shallow storage, with permanent deep storage after significant cooling. Uncertainty in the actual burial temperatures in turn produces many uncertainties in the composition of the canister, composition of the backfill

des bassins remplis d'eau situés près des centrales. Toutefois, à cause des quantités de déchets qui s'accumulent, de la production annuelle de déchets qui augmente et des dangers de toxicité, il est devenu essentiel de prouver que les déchets peuvent être stockés définitivement et en toute sécurité.

Le simple stockage en surface dans des réservoirs scellés pose des problèmes parce qu'il est difficile de contrôler les émissions de substances toxiques comme le radon. De plus, ce genre de cimetière offre peu de protection contre les attaques terroristes ou nucléaires qui, bien que peu probables, pourraient avoir des conséquences désastreuses.

Le Programme canadien de stockage des déchets se base sur le concept des barrières multiples: diluer et solidifier les déchets; les confiner dans des contenants en matière inerte, entourer ces contenants d'un remblai spécial, les sceller dans des excavations creusées à 1000 mètres ou plus sous terre. Ainsi, s'il y avait infiltration des déchets, chaque barrière, devrait fournir un certain degré de confinement. Plusieurs exposés traitent des travaux qui sont faits actuellement pour trouver des méthodes appropriées de solidification et de traitement de ces déchets (par exemple, la vitrification). Ils traitent également des types de contenants pour le stockage à long terme (par exemple, en cuivre, en corindon, en céramique), de la nature des remblais et des matériaux de scellage imperméables (par exemple, l'argile bentonite) ainsi que du genre de roches et de la profondeur d'enfouissement qui conviennent le mieux. MM. Wallach et Poliscuk notent qu'il est considéré comme admis que les radionucléides lixiviées seront libérées tôt ou tard. La méthode de stockage doit donc être conçue de façon que toute fuite vers la biosphère soit si lente ou si minime qu'elle ne dépasse pas les quantités acceptables. MM. Rothschild et Barraud soulignent qu'à l'heure actuelle il n'existe aucun moyen de remédier à une fuite majeure vers la biosphère. Ainsi, pour solutionner le problème du stockage des déchets très radioactifs, il reste à prouver que le stockage en profondeur est sûr, fiable et souhaitable.

Les incertitudes

La solution à ce problème est compliquée par les incertitudes en matière de programmes et de techniques nucléaires, de considérations politiques et d'approbation publique.

Une question largement controversée reste à régler, soit celle de décider si les déchets devraient éventuellement être retraités pour en récupérer de l'énergie supplémentaire, et cela malgré tous les déchets liquides toxiques et la production de plutonium qui en résulteraient. Si le retraitement est accepté, il faudra pouvoir récupérer les déchets des cimetières profonds; sinon, les déchets peuvent être scellés définitivement dans ces cimetières. La manutention des déchets, le genre des contenants et la conception du cimetière sont tous touchés par cette controverse.

Les déchets radioactifs produisent une chaleur élevée sauf s'ils sont dilués durant leur solidification, ce qui augmente ainsi le volume de matière à enfouir. Les déchets relativement non dilués peuvent aller jusqu'à 400°C. Toutefois, lorsqu'ils le sont, leur température peut se maintenir entre 60° et 100°C. Les déchets à haute température initiale pourraient également être stockés provisoirement à faible profondeur, et après un refroidissement considérable, être mis en stockage permanent en profondeur. Les incertitudes quant aux températures réelles d'enfouissement en-material, and influence on rock stresses, permeabilities, and groundwater flow systems.

Many technological uncertainties arise from those related to repository depth, nature and properties of the host rock, character of the backfill material, and the type of canister, as discussed by Fyfe and Haq (Paper 9). Variations in the nature and design of one barrier may profoundly influence those of an adjacent barrier. In some instances the problem can clearly be overcome with appropriate study and design, for others fundamental questions have yet to be answered and currently defy the logic of a strict timetable for the Canadian program.

Uncertainties of a political nature relate to the geographical location of the repository, which appears destined for Ontario, and to the level of funding to resolve the problems, as deemed sufficient by government agencies and utilities. Uncertainties in the degree of public acceptance and awareness cause problems in restriction on field studies, future site selection procedures, and their influence on government decisions that concern funding levels, environmental safety requirements, and the actual timetable.

The Organization of the Canadian Program

The first five papers in this volume indicate the different roles and projects undertaken by government agencies: the Atomic Energy Board of Canada (AECB; the regulatory body), Atomic Energy of Canada Limited (AECL; the agency with responsibility for the federal nuclear power program and waste disposal), the Department of Energy, Mines and Resources (EMR; subcontracted by AECL to undertake much of the geological work in waste disposal), the Department of Fisheries and Environment (DFE; subcontracted by AECL to undertake hydrogeological and hydrogeochemical work in waste disposal; also with responsibilities for environmental protection), and Ontario Hydro and other provincial utilities whose plants generate both the electricity and the waste. Many of these government agencies have been gradually providing external contracts to individuals/groups from universities and the private sector to undertake specific projects.

Only very recently has there been a greater integration of research and development both between these agencies and with external groups. It is essential that, with the urgency of the problem, efforts be made to identify and fully utilize all the expertise in Canada, with external support where necessary. There should be openness in the administrative systems and decisions, with peer review an integral part of all major funding programs. A constant system of review and debate is essential, with ready access to published and unpublished data. The Council welcomes two recent events of this nature: 1) the establishment of an Advisory Subcommittee by the Geological Survey of Canada (GSC) to investigate its Radioactive Waste Program and 2) the creation of a Technical Advisory Committee by AECL comprised of external specialists. The Canadian Environmental Advisory Council of DFE is also able to function as a critic of DFE activities and to investigate perceived problems.

gendrent à leur tour un grand nombre de questions sur la composition du contenant et du remblai et sur l'influence de cette chaleur sur les contraintes souterraines, les perméabilités et l'écoulement des eaux de la nappe aquifère.

La profondeur du cimetière, la nature et les propriétés de la roche encaissante, les caractéristiques du remblai et le genre de contenant soulèvent nombre de questions techniques qui ont été discutées par MM. Fyfe et Haq. Des variations dans la nature et la conception d'une barrière peuvent grandement influencer celles de la barrière adjacente. Dans certains cas, le problème se résoud simplement par une étude appropriée et une conception adéquate. Dans d'autres cas, certaines questions fondamentales restent toujours sans réponse et défient, à l'heure actuelle, la logique d'un calendrier rigoureux des travaux du Programme canadien.

Les questions en suspend de nature politique se rapportent à l'emplacement géographique du cimetière, vraisemblablement l'Ontario, ainsi qu'au degré de financement que les organismes gouvernementaux et les services publics jugent suffisant pour résoudre les problèmes. Le public est plus ou moins sensibilité à la question nucléaire et plus ou moins d'accord avec ses applications, ce qui impose des restrictions sur les études sur le terrain et le choix des emplacements futurs. Cette situation influence les décisions gouvernementales quant au financement, aux exigences de protection de l'environnement et au calendrier réel des travaux.

Structure du programme canadien

Les cinq premiers exposés de ce volume indiquent les divers rôles et projets des organismes gouvernementaux: la Commission de contrôle de l'Énergie atomique (C.C.É.A., organisme de réglementation), l'Énergie atomique du Canada, Limitée (E.A.C.L., organisme responsable du programme fédéral d'énergie nucléaire et du stockage des déchets), le ministère de l'Énergie, des Mines et des Ressources (E.M.R., sous-contractant de l'E.A.C.L. pour traiter de l'aspect géologique du stockage des déchets), le ministère des Pêches et de l'Environnement, (M.P.E., sous-contractant de l'E.A.C.L., responsable des travaux hydrogéologiques et hydrogéochimiques pour le stockage des déchets ainsi que de la protection de l'environnement) et l'Hydro-Ontario et les autres services publics dont les centrales produisent à la fois de l'électricité et des déchets. Un grand nombre de ces organismes donne graduellement à contrats des projets déterminés à des personnes ou des groupes universitaires ou privés.

Ce n'est que depuis très peu de temps qu'il y a meilleure intégration de la recherche et du développement entre ces organismes et avec ces groupes externes. À cause de l'urgence du problème, il est essentiel de trouver et d'utiliser à fond toutes les compétences du pays, et même de recourir à une aide extérieure si nécessaire. Il faudrait introduire une certaine largeur d'esprit dans les systèmes et les prises de décision de nature administrative pour qu'une vérification par des pairs fasse partie intégrante de tous les principaux programmes de financement. Un système permanent de vérification et de discussion est essentiel et doit donner facilement accès aux données publiées ou non. Le Conseil constate avec plaisir deux récents événements de cette nature, soit la création par la Commission géologique du Canada (C.G.C.) d'un sous-comité consultatif chargé d'étudier son propre programme de déchets radioactifs, et la mise sur pied par l'E.A.C.L. d'un comité consultatif technique composé de spécialistes venant de l'extérieur. Le Conseil consultatif canadien de l'environnement du M.P.E. agit également en qualité de critique des activités de ce ministère et enquête sur les problèmes perçus.

It is evident that AECB and AECL have mandates that are fundamentally different, requiring both agencies to play discrete roles in the waste disposal issue. The number of particular specialists within certain government agencies is relatively small and there has been and is a tendency for one department (e.g. EMR, DFE) to firstly propose a project, secondly to conduct the work under contract, and thirdly to make final recommendations to another government agency (e.g. AECL, AECB). In the open discussion period at the Forum, the potential conflict-of-interest that can develop was raised by Professors G.F. West and R.A. Freeze. The latter, in particular, advocated more of an adversary system with the energy producers clearly separated from the regulatory body and with a more equal funding of research and development from both agencies to provide adequate checks and balances.

This proposal appears to be valid and could indeed by strengthened. The CGC proposes that AECB maintain complete independence as a regulatory body, with its budget increased to allow more funding of research in areas deemed critical for its regulatory role. The agencies with responsibility for energy production (AECL, Ontario Hydro and other provincial utilities) must primarily fund the program to dispose of the waste. It seems strange that the provincial utilities have spent so little in this area in comparison to Sweden where they are funding virtually all of the waste program. As energy producers, these agencies are now actively seeking a solution to the Canadian waste problem. However, their own vested interest must be recognized. Their objectives, methods, and timetable may not be that selected by an environmentalist charged with the same task.

Many papers in the volume caution that public acceptability is crucial. It seems evident that in order for the protection to be seen to be truly protective another independent agency should be involved in these investigations. The most appropriate is DFE with its mandate for general environmental protection. To be effective, it must have substantially increased funding to engage in research and development and to provide external contracts related to the critical environmental aspects of waste disposal. DFE should use such funds to build up a capability and expertise to check the results of research conducted by AECL and provincial utilities. Furthermore, in order to be fully independent DFE should cease to conduct major research programs for AECL; these could be contracted externally. The role of EMR, universities, and the private sector would largely be to conduct research and development for either or both of the energy producers and the environmental protectors. Thus, AECB would periodically receive submissions from different constituencies rather than largely a single dialogue and negotiation with AECL.

Il est évident que la C.C.E.A. et l'E.A.C.L. ont des mandats fondamentalement différents qui leur demandent d'agir avec discrétion dans la question du stockage des déchets. Le nombre de spécialistes donnés au sein de certains organismes gouvernementaux est relativement peu élevé. Les ministères (par exemple, l'E.M.R. et le M.P.E.) ont tendance à proposer un projet, à donner ensuite des contrats pour les travaux et enfin à faire des recommandations finales à un autre organisme gouvernemental comme l'E.A.C.L. et la C.C.E.A. Au colloque, durant la période de discussion générale, MM. G.F. West et R.A. Freeze ont soulevé la question des conflits d'intérêts possibles qui peuvent résulter de cette situation. M. R.A. Freeze plus particulièrement, est en faveur d'un système contradictoire où les producteurs d'énergie et l'organisme de réglementation seraient totalement indépendants l'un de l'autre et où le financement que les deux organismes fédéraux accordent à la recherche et au développement serait du même ordre afin d'assurer des freins et contrepoids adéquats.

Cette proposition semble valable et pourrait être plus étoffée. Le Conseil canadien des Sciences de la Terre propose que la C.C.E.A. conserve une indépendance totale en tant qu'organisme de réglementation et que son budget soit augmenté pour financer davantage la recherche dans les domaines jugés d'une importance capitale pour l'exécution de ses fonctions. Les organismes responsables de la production d'énergie (l'E.A.C.L., l'Hydro-Ontario et les autres services publics provinciaux) doivent tout d'abord financer le programme de stockage des déchets. Il semble étrange que les services publics aient dépensé si peu dans ce domaine alors qu'en Suède, ce sont ces services qui financent presque en totalité ce programme de stockage. Ces organismes, en tant que producteurs d'énergie, cherchent activement la solution au problème des déchets au Canada. Toutefois, il faut reconnaître qu'ils ont des intérêts acquis. Leurs objectifs, méthodes et calendrier des travaux peuvent différer de ceux d'un spécialiste de l'environnement chargé de la même tâche.

Dans ce volume, de nombreux auteurs nous avertissent que l'approbation publique est d'une importance capitale. Il semble évident qu'un autre organisme indépendant devrait s'occuper des enquêtes pour que le public considère que les mesures de protection sont vraiment valables. Le ministère des Pêches et de l'Environnement est l'organisme tout désigné car son mandat concerne la protection générale de l'environnement. Pour fonctionner de façon efficace, le Ministère a besoin d'une augmentation substantielle de fonds pour entreprendre des travaux de recherche et de développement et engager des sous-contractants qui s'occuperont des aspects environnementaux cruciaux du stockage des déchets. Il devrait utiliser ces fonds pour obtenir les services de techniciens et de spécialistes dont il a besoin pour vérifier les résultats des recherches menées par l'E.A.C.L. et les services publics provinciaux. De plus, afin d'être totalement indépendant, le M.P.E. devrait cesser d'entreprendre de grands programmes de recherches pour le compte de l'E.A.C.L.; ces programmes pourraient être donnés à contrats. Le rôle de l'E.M.R., des universités et du secteur privé serait principalement de faire de la recherche et du développement, soit pour les producteurs d'énergie ou pour les organismes chargés de la protection de l'environnement, soit pour les deux. Ainsi la C.C.E.A. recevrait périodiquement des requêtes de divers groupes plutôt que d'entreprendre des discussions et des négociations uniquement avec l'E.A.C.L.

Research Priorities and Problems

Most research in the waste program has been conducted in-house by government agencies. As Dr. J.O. Wheeler has noted in the Discussion, all expertise must be marshalled. More external contracts must be provided to make full use of nongovernment specialists.

Some areas require only time, funds and effort to achieve the required barrier design as indicated, for example, by Charlwood et al. (Paper 8) for the engineering design of the repository. In sharp contrast, Cherry and Gale (Paper 7) and also Witherspoon (in Part III) argue that in fracture hydrology and hydrogeochemistry, especially the dating of groundwaters, fundamental questions have still to be answered. A ten-year hydrogeological program is advocated that clearly is in conflict with the overall program schedule described by Scott (Fig. 3.2) and other authors. It is doubtful whether appropriate geophysical or geochemical systems are yet devised to adequately monitor the waste disposal and barrier systems during and after waste emplacement and after the sealing and decommissioning of the repository. Strangway (Paper 10) argues for adequate funding to develop the new technologies required and Witherspoon strongly advocates refined monitoring systems to check for leakage over the decades following decommissioning.

Nearly all of Canada's effective waste program is concerned with the hard rock (granite pluton) option. This may be wise for economic and geographic reasons, but perhaps not for scientific and political reasons. If the hard crystalline rocks are shown to be too fractured to be sufficiently impermeable, it may be an embarassment and perhaps too late sociopolitically to seek an alternative repository in soft rocks. The CGC advocates that an effective program be mounted to examine sedimentary rocks as a potential repository host. Many of the fracture hydrology and hydrogeological problems will be similar to those of hard crystalline rock, but the effects of thermal loading will be more severe, and hence, significant. Although salt has been investigated extensively in the U.S.A., little attention has been given to argillaceous rocks.

A major component in the Swedish waste program has been the use of underground experiments at the Stripa mine in central Sweden. These are discussed briefly by Brotzen, Cherry and Gale, Fyfe, and Witherspoon. The tests have been most valuable, but it must be cautioned that they were undertaken in a disturbed environment produced by the past mining excavations. Cherry and Gale and Witherspoon bring convincing arguments for the construction of a test facility to conduct fundamental experiments. Witherspoon has estimated its cost at $50 million over 10 years. This may seem a substantial expenditure but it must be remembered that (a) this is a small fraction of the total waste program, (b) government test drilling has to be suspended in 1977 and 1978

Problèmes et priorités de la recherche

Des organismes gouvernementaux ont effectué eux-mêmes la plupart des recherches sur les déchets nucléaires. M. J.O. Wheeler (C.G.C., discussions) souligne que toutes les compétences techniques doivent être mises à contribution. Plus de contrats doivent être accordés afin d'utiliser pleinement les connaissances des spécialistes non gouvernementaux.

Comme l'indique Charlwood et al. par exemple, certains secteurs n'ont besoin que de temps, de capitaux et d'efforts pour réaliser le type de barrière nécessaire à la conception technique d'un cimetière. MM. Cherry, Gale et Witherspoon soutiennent au contraire que dans le domaine de l'hydrologie et de l'hydrogéochimie des fractures, plus particulièrement celui de la datation des nappes aquifères, certaines questions fondamentales sont encore sans réponse. Certains soutiennent un programme hydrogéologique de 10 ans qui entre nettement en conflit avec le calendrier général du programme décrit par M. Scott (fig. 2) et d'autres auteurs. Il n'existe probablement pas encore de bons systèmes géophysique ou géochimique pour surveiller adéquatement les méthodes de stockage des déchets et les barrières durant et après l'enfouissement des déchets et après le scellage et la mise hors de service du cimetière. M. Strangway insiste sur un financement approprié en vue de la mise au point des nouvelles techniques nécessaires et M. Witherspoon recommande fortement des systèmes perfectionnés de surveillance des fuites pouvant se produire pendant les dizaines d'années qui suivront la mise hors de service.

La quasi-totalité du Programme canadien des déchets en vigueur actuellement, favorise l'option de stockage dans la roche dure (pluton granitique). Cette solution est peut-être censée du point de vue économique et géographique, mais elle ne l'est pas pour des raisons scientifiques et politiques. Si les roches dures cristallines sont trop fracturées pour être suffisamment imperméables, il serait très embarrassant, et peut-être trop tard sociopolitiquement, d'opter pour le stockage dans la roche tendre. Le C.C.S.T. insiste sur la mise sur pied d'un programme efficace pour étudier la possibilité d'utiliser les roches sédimentaires comme cimetières. Un grand nombre des problèmes de l'hydrologie et de l'hydrogéologie des fractures seront semblables à ceux de la roche dure cristalline. Toutefois, les effets de la charge thermique seront plus graves, et ainsi, plus importants. Même si le stockage dans le sel a été étudié soigneusement aux États-Unis, on a accordé peu d'attention aux roches argileuses.

Les expériences souterraines effectuées dans la mine Stripa au centre de la Suède ont constitué un élément important du programme des déchets de ce pays. M.M. Brotzen, Cherry, Gale, Fyfe et Witherspoon en parle brièvement. Ces essais ont beaucoup de valeur, il est toutefois nécessaire de mentionner qu'ils ont été faits dans un environnement perturbé par les anciens forages de puits de mines. MM. Cherry, Gale et Witherspoon apportent des arguments convaincants en faveur de la construction d'installations pilotes pour réaliser des expériences fondamentales. M. Witherspoon en a évalué les coûts à 50 millions de dollars échelonnées sur 10 ans. Cette dépense, peut sembler considérable mais il ne faut pas oublier a) qu'il ne s'agit que d'une petite because of adverse public reaction to a potential pilot repository (rather than a test facility that would never become a repository), (c) drilling is currently restricted to AECL property at Pinawa, Manitoba, and Chalk River, Ontario, where geological conditions are not typical for a desirable hard rock repository, and (d) it is essential to fully demonstrate the safety aspects, of which groundwater transport of radionuclides is one of the most critical factors. Thus, the CGC advocates serious consideration of such a test facility rather than a pilot repository. This would probably overcome public reaction and allow adequate demonstration of some key aspects of safety in the waste program.

Funding

Funding levels for the Canadian radioactive waste program have been insignificant compared to other parts of the nuclear power program. After continued efforts, AECL finally succeeded in receiving a substantial increase in the budget of the waste program, doubling to $9.9 million for 1977-78. In the period 1973-1978 Ontario Hydro contributed just $1.8 million. Of these amounts, only a fraction was devoted to primary geoscience research. These costs are a small fraction of the costs of building nuclear power plants or heavy water plants. Yet the waste issue has become the Achilles heel of the industry. Canada's activity has been small compared to that of some other countries. For 1977-78, the U.S.A. program received about $80 million and the Swedish program has been funded at about $20 million for the initial 18 months of research and development and such expenditures in the forseeable future will be about $5 million annually.

For the required advances in fundamental knowledge and for applied research and development, adequate funding is essential. For a $50 million test facility to be developed over 10 years, additional funds are required. The waste problem has been largely ignored in the past and to ensure a relatively rapid solution, significantly increased budgets are mandatory. The CGC can only emphasize that the scale of the problem is probably proportional to certain other phases of the nuclear power program such as the construction of a power plant, and the priorities of utilities and governments seem strangely misplaced in terms of funding. CGC must ask why the utilities are not contributing a larger share to the solution of the problem. S.R. Hatcher (Part IV) indicated that the total construction cost for the commercial repository would only represent 0.02-0.04 cents per kilowatt hour; the actual construction cost is likely to be in the order of $500 million.

Timetable

The timetable for the Canadian program has been discussed by Wallach and Poliscuk, Hatcher, and Scott (Papers 1, 2 and 3).

fraction du programme global des déchets, b) qu'en 1977 et 1978, le gouvernement a dû suspendre le forage d'essai parce que le public voyait d'un mauvais oeil l'installation d'un cimetière pilote (plutôt qu'une installation d'essai qui ne serait jamais utilisé comme cimetière), c) que le forage est actuellement restreint aux terrains de l'E.A.C.L. à Pinawa (Manitoba) et à Chalk River (Ontario) où les conditions géologiques ne sont pas représentatives de l'installation souhaitable d'un cimetière dans de la roche dure et d) qu'il est essentiel de bien démontrer les aspects sécuritaires de la question, dont le transport des radionucléides par la nappe aquifère représente l'un des facteurs les plus cruciaux. Le C.C.S.T. recommande donc fortement que l'on songe sérieusement à une installation d'essai plutôt qu'à un cimetière pilote. Cette décision pourrait calmer l'opinion publique et permettre de prouver certains aspects clés de la sécurité du programme des déchets.

Financement

Comparé aux autres parties du programme d'énergie nucléaire, le degré de financement du programme canadien des déchets radioactifs a été plutôt minime. Après des efforts continus, l'E.A.C.L. a finalement réussi à faire doubler, pour 1977-1978, les fonds budgétaires alloués au programme des déchets, soit un nouveau montant de 9,9 millions de dollars. De 1973 à 1978, l'Hydro-Ontario a seulement contribué 1,8 million de dollars. Une fraction seulement de ces montants a été allouée à la recherche géoscientifique primaire et cette fraction ne représente à son tour qu'une petite partie de ce qu'il en coûte pour construire les centrales nucléaires et les usines d'eau lourde. Malgré cela, la question des déchets est devenu le talon d'Achille de l'industrie. Les réalisations du Canada en ce domaine sont bien faibles si on les compare à celles de certains autres pays. Pour 1977-1978, le programme des États-Unis a reçu environ 80 millions de dollars et celui de la Suède a été financé à environ 20 millions de dollars pour les 18 premiers mois de recherche et de développement et, dans un avenir prévisible, de telles dépenses seront d'environ 5 millions de dollars chaque année.

Il faut absolument trouver des fonds suffisants pour l'acquisition de connaissances essentielles et pour la recherche et le développement appliqués. Pour que l'on puisse mettre sur pied en 10 ans une installation d'essai de 50 millions de dollars, il faut obtenir d'autres fonds. Dans le passé, le problème des déchets a été grandement négligée et il est impératif que les budgets soient largement augmentés pour régler rapidement la question. Le Conseil ne peut qu'insister sur le fait que cette question est probablement aussi importante que certaines autres étapes du programme d'énergie nucléaire telles que la construction des centrales et juge que les priorités des services publics et des gouvernements semblent étrangement déplacées lorsqu'il s'agit de financement. Le Conseil demande donc pourquoi les services publics ne participent pas plus activement à solutionner ce problème. M. S.R. Hatcher (discussion) a indiqué que la construction d'un cimetière commercial ne représenterait au total que 0,02 à 0,04 cent par kilowatt/heure; le coût réel de construction sera vraisemblablement de 500 millions de dollars.

Calendrier des travaux

MM. Wallach, Poliscuk, Hatcher et Scott ont parlé du calendrier des travaux du programme canadien. Le concept de stockage

Verification of the concept of deep subsurface disposal is estimated to be completed by 1982, with site selection for a pilot repository being completed by 1986. CGC views these estimated dates with considerable concern. If fundamental hydrogeological problems have yet to be answered and with research having only recently started, it seems unlikely that the concept verification can be attained by 1982. Further, the problem will predictably arise that scientists will be viewed as having failed or that the concept verification is not possible. Thus, the public and the politicians may not understand why target dates have not been met and may draw unwarranted conclusions. A realistic timetable is only possible when the fundamental questions have been answered and the remaining work is primarily applied science. The time required to find fundamental scientific solutions cannot be confidently predicted. Nor can the attitudes of the public be readily estimated, as seen by the recent collapses of government in Sweden and Austria on the nuclear power issue. Dr. Kühn admirably requested politicians to try to understand the problems of the scientists and not to view these long-term problems within the span of half-lives of government.

The CGC acknowledges the difficult problems associated with high-level radioactive waste disposal and also the scientific challenges and opportunities it presents. Geoscientists, unlike the public, are trained to understand long-term phenomena. There is no doubt that such wastes, unless properly disposed of, represent a major problem to be passed on to future generations. Given the appropriate support, it is likely, though not yet proven, that the disposal problem can be solved.

Summary of Recommendations

The following recommendations from CGC arise from this commentary:

- *that efforts be increased to involve all expertise both inside and outside the government agencies in an integrated attack on the disposal problem.*
- *that the integrity, independence and regulatory power of the Atomic Energy Control Board be made manifest and that the Department of Fisheries and Environment be given an expanded role of examining, conducting and funding research on the waste disposal problem from the viewpoint of environmental protection. AECL and the public utilities, the energy producers, should continue to investigate the feasibility of waste disposal from both the engineering and social aspects. The funding of both AECL and DFE should be in a more reasonable balance. AECB must also have sufficient funds to assure necessary research for decision making, based on the AECL and DFE submissions.*
- *that the responsibility for the waste disposal lies primarily with the waste producers, i.e. AECL and the public utilities. Funding levels must be substantially increased for research and development. These are presently small compared to some other countries and certainly when compared to construction and operating costs of the nuclear power plants generating the waste. Much of the additional funding could come from provincial utilities or governments that have adopted nuclear power.*
- *that particular research emphasis must be placed on those technical areas where fundamental scientific questions remain unanswered.*

souterrain en profondeur sera vraisemblablement vérifié d'ici 1982 et le choix d'un endroit pour la construction d'un cimetière pilote sera fixé d'ici 1986. Le Conseil voit le choix de ces dates d'un oeil très sceptique. Si les problèmes fondamentaux d'hydrogéologie ne sont pas encore résolus et que la recherche ne fait que commencer, il semble peu probable que la vérification de ce procédé puisse être terminée d'ici 1982. De plus, il est fort possible que ce retard crée l'impression que les scientifiques n'ont pas réussi ou que la vérification de ce concept est impossible. Ainsi, le public et les politiciens peuvent ne pas comprendre pourquoi le délai n'a pas été respecté et ainsi tirer des conclusions injustifiées. Un calendrier réaliste des travaux n'est possible que lorsqu'il ne reste plus de problèmes fondamentaux à résoudre et que le restant des travaux se rapportent avant tout à la science appliquée. Le temps nécessaire à la solution des problèmes scientifiques fondamentaux ne peut être prédit avec certitude, pas plus que ne peuvent l'être aisément les réactions du public, comme nous le démontre la défaite récente des gouvernements de Suède et d'Autriche sur la question nucléaire. M. Kuhn s'est adressé admirablement bien aux politiciens pour leur demander d'essayer de comprendre les difficultés auxquelles se heurtent les scientifiques et de ne pas s'attendre à ce que soient trouvées des solutions rapides à des problèmes qui ne peuvent se régler qu'à long terme.

Le C.C.S.T. reconnaît qu'il y a des difficultés associées au stockage des déchets très radioactifs, avec tout ce que cela comporte de défis et de possibilités dans le domaine scientifique. Contrairement au public en général, les spécialistes des sciences de la terre sont habitués à comprendre les phénomènes qui s'échelonnement sur de longues périodes. Il ne fait aucun doute que si ces déchets ne sont pas stockés de façon adéquate, les générations futures hériteront d'un grave problème. Même si rien n'est encore prouvé, il est probable qu'avec l'aide nécessaire, ce problème de stockage soit résolu.

Résumé des recommandations

Suite au présent commentaire, le Conseil canadien des Sciences de la Terre recommande:

- *qu'il y ait recrudescence des efforts pour réunir tous les spécialistes des organismes gouvernementaux et d'ailleurs qui s'attaqueront ensemble au problème du stockage;*
- *que l'intégrité, l'indépendance et les pouvoirs de réglementation de la Commission de contrôle de l'énergie atomique soient manifestement établis et que le ministère des Pêches et de l'Environnement se voit accorder un plus grand rôle, du point de vue de la protection de l'environnement, pour l'étude, la réalisation et le financement de la recherche en matière de stockage des déchets. Les producteurs d'énergie, l'E.A.C.L. et les services publics devraient poursuivre les études de faisabilité du stockage des déchets du double point de vue technique et social. Le financement de l'E.A.C.L., et du M.P.E. devrait être mieux équilibré. La C.C.E.A. doit également disposer de fonds suffisants pour faire la recherche nécessaire à la prise de décisions basée sur les présentations de l'E.A.C.L. et du M.P.E.;*
- *que les producteurs de déchets, c'est-à-dire l'E.A.C.L. et les services publics, aient la responsabilité première en matière de stockage des déchets. Le financement de la recherche et du développement doit augmenter considérablement, les montants actuellement alloués étant faibles comparés à ceux d'autres pays et sûrement s'ils sont comparés aux coûts de construction et d'exploitation des centrales nucléaires qui produisent ces déchets. Les fonds supplémentaires pourraient venir en grande partie des services publics ou des gouvernements provinciaux qui ont optés pour l'énergie nucléaire;*
- *que soit accentuée la recherche dans les domaines techniques où les questions scientifiques fondamentales sont toujours sans réponse. L'hy-*

Fracture hydrology, hydrogeochemistry and geophysical monitoring systems are examples of such areas.

- *that an effective program be mounted to examine sedimentary rocks as a potential repository host, in addition to the current hard crystalline rock program.*
- *that a test mine be developed as soon as possible for research and development, rather than as a pilot repository with the potential for a full-scale repository. This would ensure excellent scientific results and offset local public concerns of the location of a final repository in their area.*
- *that the timetable for concept verification and site selection be made more flexible to accommodate the present scientific uncertainties. With fundamental problems still unresolved, scientists cannot be held accountable for failure to meet such deadlines. The recent restrictions on drilling alone probably mean that the schedules should be extended.*
- *that a major problem is seen to be the low level of public knowledge of the nuclear waste program. The waste problem must be tackled with openness, appropriate speed, and priority to allow the verification of the concept. Politicians must recognize the long-term aspect of much of the research and development in the program.*
- *that nuclear wastes should be viewed as part of a larger Canadian problem of disposal of all kinds of toxic wastes.*
- *that the waste disposal issue be seen in the perspective of the energy requirements of Canadian society.*

Published with the approval of the Canadian Geoscience Council after preparation by the Executive Commitee:

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drologie des fractures, l'hydrogéochimie et les systèmes de surveillance géophysique sont des exemples de ces domaines;

- *qu'un programme efficace soit mis sur pied pour étudier les formations de roches sédimentaires comme cimetière possible, et cela en plus du programme actuel des roches dures cristallines;*
- *qu'une mine pilote soit aménagée, dès que possible, en installation de recherche et de développement et non en cimetière pilote pouvant servir ultérieurement de cimetière. Ceci donnerait des résultats scientifiques excellents et calmerait les inquiétudes des habitants de la région au sujet de l'établissement, sur leur territoire, d'un cimetière définitif;*
- *que le calendrier des travaux de vérification des concepts et de sélection des emplacements soit plus flexible, pour tenir compte des incertitudes scientifiques actuelles. Certains problèmes fondamentaux n'étant pas encore résolus, les scientifiques ne peuvent être tenus responsables si les délais ne sont pas respectés. À elles seules, les récentes restrictions sur le forage signifient probablement qu'il faudra reporter les délais;*
- *qu'un des principaux problèmes est le peu de sensibilisation du public au programme de déchets nucléaires. Il faut que le problème soit traité ouvertement, aussi rapidement que possible et en toute priorité si la vérification du procédé doit se faire. Les politiciens doivent admettre que la plupart des travaux de recherche et de développement du programme doivent s'échelonner sur une longue période;*
- *que le problème des déchets nucléaires doit être vu comme faisant partie d'un problème beaucoup plus vaste, celui du stockage de toutes sortes de déchets toxiques au Canada;*
- *que la question du stockage des déchets soit vue dans l'optique des besoins énergétiques de la société canadienne.*

Publié avec l'approbation du Conseil canadien des Sciences de la Terre d'après une rédaction du Comité exécutif composé des personnes suivantes:

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PART II
INTRODUCTION

H.R. Wynne-Edwards[1]
Moderator

On October 24, 1978 in Toronto the Canadian Geoscience Council organized a forum on the "Disposal of High-Level Radioactive Wastes: The Canadian Geoscience Program". The formal papers and edited discussions that were generated are presented in this volume.

The occasion was the joint annual meetings of the Geological Association of Canada, the Mineralogical Association of Canada, and the Geological Society of America. The forum was a first-ever review of the Canadian radioactive waste management program before an audience of professional peers. Perhaps the most impressive aspect of it was that 600 people came and stayed throughout a 5-hour afternoon session. The geological profession is plainly deeply concerned and anxious to gain information and insight into a critical responsibility that has come its way.

The developed world went nuclear after World War II in the search for peaceful uses of the Atom. The "big" physics and chemistry of the war effort was ready to concentrate on the science and technology involved in developing the capacity to harness first fission and then fusion as controlled energy-producing reactions. The success of the fission reactor is a matter of record, and the technology is now ready to provide a major new energy option for a world population concerned with dwindling and politically vulnerable conventional fuel supplies.

The exercise of the nuclear fission option however, will depend less on the "hardware" of the nuclear power generator than on the "software" that surrounds the question of environmental and resource management. Adequate nuclear fuel supplies, mine and mill waste containment, safe transportation systems, safeguarded reprocessing techniques, and above all satisfactory radioactive waste handling, storage, and disposal will determine the extent to which it is feasible to adopt nuclear power as a major alternative energy source. The scene and the responsibility has thus shifted abruptly from physics and chemistry to the environmental, the social and the earth sciences. The people who participated in this forum are representative of this new generation of policy advisors and specialists addressing a momentous question, not only for individual governments but for Man in general. They must provide unequivocal answers to "Can it be done?".

The current examination of the management of high-level radioactive waste will have a huge impact on the course of the human future. There are parallel programs of research and development on these issues in many countries. High-level radioactive waste disposal requires engineering and design on the scale of geological time. The integrity and stability of the structures involved must be ensured for tens or hundreds of thousands of years, or perhaps in some cases for millions of years.

Unlike most forms of waste management, the problem is containment rather than disposal. Unlike most forms of engineering, the time scale is far beyond a human lifespan. If nuclear power goes ahead, the waste disposal sites must be the most enduring monuments of our civilization.

The geoscience profession is facing several difficulties. Perhaps the greatest is that there is a rooted public impression that to dispose of something in this world, one need only dig a hole in the ground. If the something is particularly noxious or toxic, one need only dig a deeper hole, and fill it up again. Whereas the public is well aware of the enormous complexity and technological difficulty of, for example, nuclear power plants or satellites, it is extremely difficult to persuade people that a hole in the ground may be just as complicated and just as technically challenging. But it is.

Geology is one of the few sciences concerned with "both sides of the street". If objectivity is lost, the profession could split into proconservation and prodevelopment camps. We are involved with the enhancement of our technological *capability* to do things and with the *desirability* of doing so in the light of environmental and other assessments. Both kinds of effort need to be made objectively and not emotionally. Unfortunately science is rarely value-free and the possibility of a split in the ranks is, in my view, a real possibility.

We geoscientists have a responsibility in this world, to ensure the adequacy of the resource supply of the thirteen billion tons of solid materials extracted from the crust of the Earth every year, and to see that the uses to which these materials are put and the manner in which they are disposed of are fully satisfactory. These two activities should go hand in hand, but as one places a constraint on the other, this may not happen. It is a problem our profession needs to recognize and face.

Some of the authors of the papers in this volume, are from government agencies and carry major responsibility for the Canadian nuclear waste management program and others are specialists involved in the assessment of the physical, chemical and dynamic properties of the waste itself, the geological materials that will surround it, the groundwater flow patterns, and the interactions that go on among these. There are also edited contributions from the large and participating audience, members of a profession suddenly in the public eye, required to discharge an awesome public responsibility.

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[1] Ministry of State for Science and Technology, Ottawa, Ontario

The papers in this volume, as presented orally at the CGC Forum, belong in several groups. First, there are contributions from representatives of government agencies who are designing the waste management program in Canada. The next group of papers are largely from specialists from universities or the private sector and are concerned with the major technical problems to be overcome in nuclear waste disposal. Following these are comments from foreign specialists from countries which are at a similar or comparable stage of examining their own waste disposal possibilities (USA, Sweden, Germany). The main points made during an hour of general discussion are also included together with the responses of the panelists (authors).

1. THE REGULATORY ROLE IN THE DISPOSAL OF RADIOACTIVE WASTE IN BEDROCK

J.L. Wallach[1] and V.E. Poliscuk[1]

Introduction

From the regulatory point of view, the objective for all radioactive wastes is that the ultimate form of management will be disposal. The concept of disposal involves a method of management which does not rely for its integrity on the continued need for institutional controls. Furthermore there is no intention of retrieval. Where disposal is practiced by techniques such as emplacing the waste in bedrock, it is acknowledged that radioactive waste cannot be absolutely isolated from the biosphere. It is assumed, therefore, that the material will eventually be released, but that its return to the biosphere will be at an acceptable rate.

Canada is one of several countries concerned with finding a suitable method of effecting disposal. To date there is no official policy in Canada which specifies the manner of disposal although a method under serious consideration is that of emplacing the waste in bedrock deep beneath the earth's surface. A working agreement now exists between the Federal government and the government of Ontario that proposes to verify that burial in plutonic rock is "safe, secure and desirable."

By virtue of the Atomic Energy Control Act of 1946, the Atomic Energy Control Board (AECB) has the authority to provide for the control and supervision of the development, application and use of atomic energy in Canada. Included among the many facets of this authority is the development of guidelines for a radioactive waste repository. As presently conceived the guidelines will initially be general in nature for the following reasons. First of all technology is not sufficiently advanced to permit the development of specific guidelines. Secondly, although plutonic rocks are currently thought to be the preferred generic rock type in Canada in which waste is to be emplaced, there is, as yet, no firm commitment to them. Thus, at some future date Canadian researchers may decide to abandon plutonic rocks in favour of some other host such as salt or argillaceous rocks.

Besides issuing guidelines the AECB will also publish the rationale behind the guidelines to improve public awareness and to provide information about the regulatory role in waste management. Publication of the rationale will not only inform the public of the Board's requirements, it should also point out that the guidelines are the result of careful consideration rather than a product of some arbitrary processes or decisions. It is hoped that the public will be assured that the safety of the biosphere is paramount when applications to license a repository are evaluated.

Regulatory Procedures

In Canada, before a nuclear facility can be constructed and permitted to operate, the applicant must obtain, in sequential order from the AECB, site approval, construction approval and an operating license. For the waste disposal program it is proposed that site approval and construction approval be retained, but that they be followed by a license to emplace the waste and authorization which will permit closure of the facility (Fig. 1.1, 1.2). Although these discrete phases can be observed, all factors (subject areas) germane to establishing and operating a nuclear facility will have to be identified during the period leading to site approval. Each should continue to be addressed throughout the program until by virtue of the granting of an appropriate approval or license, no further information on that factor (subject area) would be required. Prior to the conclusion of each phase a complete assessment of the individual and combined factors is required. If the Board's evaluation is favourable then the applicant will receive approval or a license (Fig. 1.1). If, on the other hand, the evaluation is unfavourable then the license will be denied unless the applicant can provide information to the Board's satisfaction.

Because all factors related to a nuclear facility are identified in the early stages and then carried through to the appropriate license or approval, the entire licensing procedure can be thought of as a continuum. Before the onset of each phase in the licensing procedures, certain factors are identified by the Board as priority items which should receive the greatest emphasis during that phase (Fig. 1.2). However all other factors should still be addressed, though with less emphasis, during that phase. As the program proceeds from one phase to the next, the level of attention required for each factor either increases to an intermediate or maximum level or is reduced to zero. This concept is illustrated in Figure 1.2 for a radioactive waste repository. For example in the site approval phase, sociopolitical and regional and site geological, geographical, meteorological and other environmental factors are top priority items which should receive the highest level of attention whereas the remaining factors would be studied less intensively. In the phase leading to the issuance of construction approval, all factors, except those already mentioned, become higher priority items with designs of waste, repository and backfill subjected to the highest level of attention while the others are receiving only an intermediate level of attention. From the Board's point of view the regional and site investigations, along

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[1] Atomic Energy Control Board, Ottawa, Ontario (AECB Report 1140)

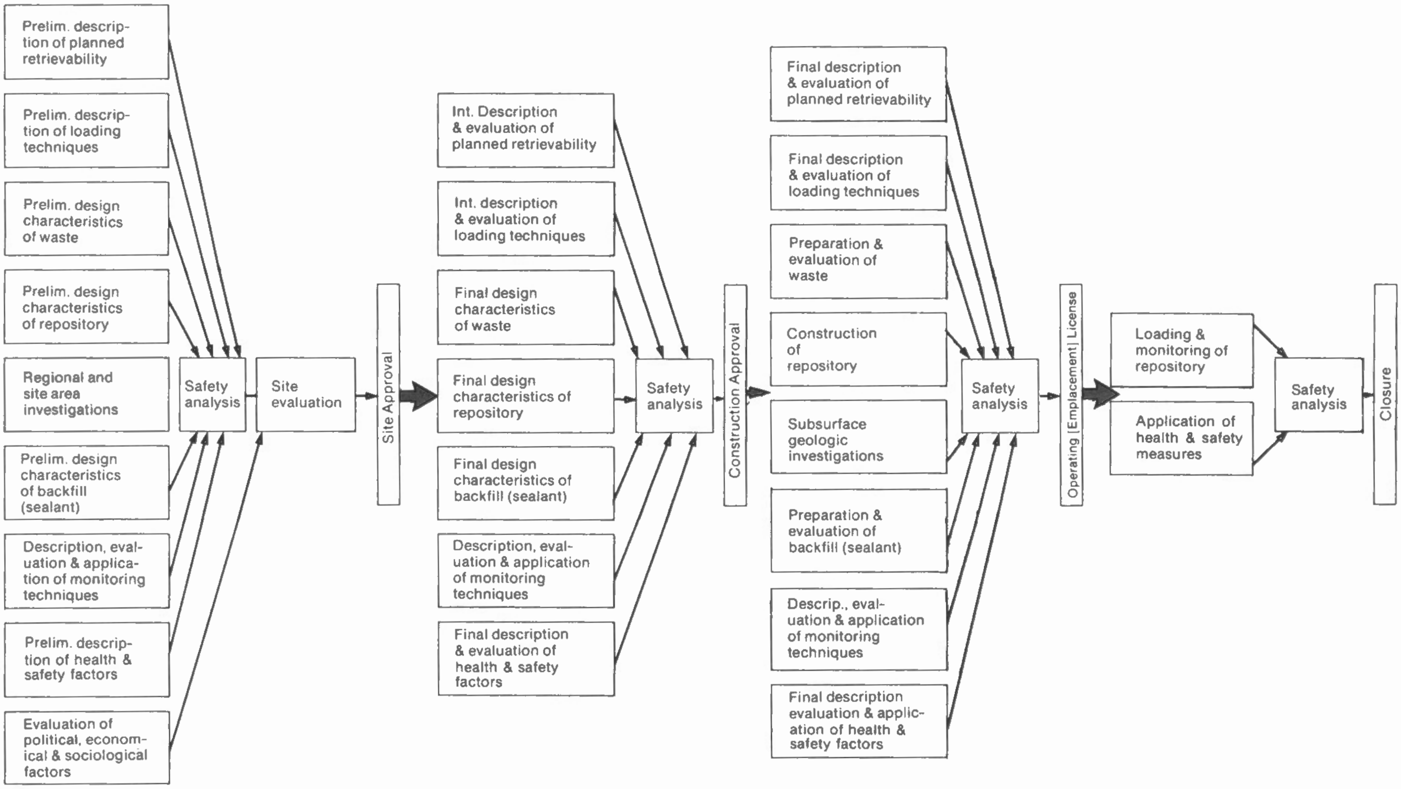

Figure 1.1 Flow diagram illustrating licensing procedures for radioactive waste disposal.

with the sociopolitical factors, should theoretically have been completed during the site approval phase and therefore need not be considered in the application for construction approval. Before a license for emplacement is issued, underground geological investigations within the constructed repository will be required and will be designated as a top priority item along with all other factors noted in Figure 1.2. The phase leading to the authorization for closure of the repository will feature three areas of concern, all of which should be considered as high priority items (Fig. 1.2).

Since site approval is the first formal step in the licensing procedures it is critical that the guidelines for this phase be established first. Among the most important aspects of this phase are the geological factors, which will be considered throughout the remainder of this paper except for the last section which presents a tentative schedule for the issuance of guidelines.

Geological factors

The objective of guidelines concerned with the geological factors of waste management will be to direct the applicant to seek a site possessing natural conditions which will ensure that if migration to the biosphere takes place it will be at an acceptable rate. An ideal setting would be in an isotropic host rock situated in a seismically stable area that is totally free of fluids. Since this situation is unlikely to exist, careful analyses will be necessary to determine that, despite the deviations from the ideal, the conditions that do prevail will, nonetheless, fulfill the regulatory objectives for the disposal program. In order to effect these analyses, regional investigations as well as site-specific studies are recommended.

Regional studies

General statement

A well documented knowledge of the regional geology is imperative for several reasons. First of all it is necessary to ensure that all phases of the work have been carefully conceived and executed. Any apparent oversight in any portion of the study may cast doubts upon the rest of the work and will not aid in gaining and/or retaining confidence of the regulatory agencies or the public. Thus, even though geologically old events, such as folding, may have no apparent impact on present day site selection, knowledge of these events and the conditions under which they formed will help convince the public of the thoroughness and care with which the work has been performed. Secondly, it permits first order selection of potential sites from which a final choice may be made. Thirdly, a regional study provides a more complete picture of the geological framework than a study restricted to a site. This is because any region is characterized by geological features which may be well preserved and clearly understood at some locations, but which may be absent, imperfectly preserved or poorly understood elsewhere. A potential site may be plagued by these problems, thereby rendering a proper comprehension and assessment of the geological setting at the site difficult if not impossible. Lastly, since the length of faults is an important parameter in estimating earthquake potential, the true lengths of faults must be determined which, for many, would necessitate tracing within the region.

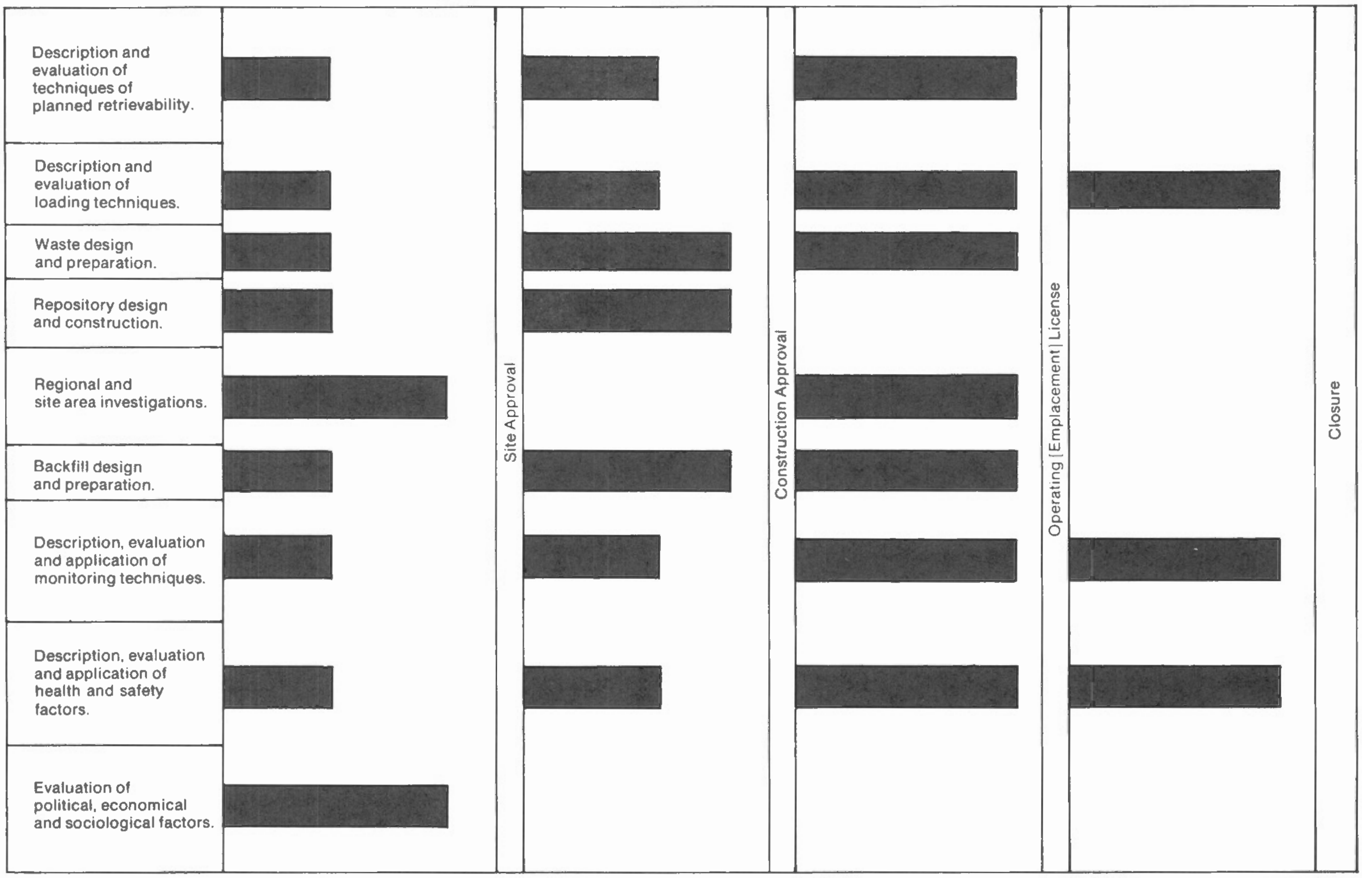

Figure 1.2 Relative priority of subject areas as a function of the regulatory phase.

Structural geology and geomorphology

Much of the regional work essentially revolves around locating major faults and fractures and identifying their characteristics. A comprehensive study of these structures is essential because their characteristics may cause a rejection of a site for two reasons. Firstly, they serve as potential pathways for groundwater movement and secondly, they may be reactivated, resulting in seismic activity. Understanding the evolution, or paleotectonic function(s), of faults and fractures is an important first step in assessing the probability of future earthquake activity along them. In this regard it would be advisable in evaluating a site for waste disposal to attempt to determine the age of the latest fault movements. The reason is that if it can be demonstrated that no movements have occurred in recent geological time then a good possibility exists that natural tectonic processes will not disrupt the satisfactory retardation of radionuclides to the biosphere.

If there is no way to date structures at a site, an understanding of the relationship of such structures to others, which may occur in the region, will help to establish relative or absolute ages. This is illustrated in a simplified example. If the age of an orogeny is known and if the site structures are geometrically, kinematically and dynamically compatible with structures known to have resulted from this orogeny, then the age of the site structures may be interpreted as being geologically the same as that of the orogeny. Furthermore it might appear that the site structures have not been rejuvenated since they were formed, although caution must be exercised when making this interpretation. However, if no evidence to the contrary were uncovered, then, in this very simple example, the age of last movement could be interpreted as being the age of the orogeny.

Another pragmatic aspect of understanding the evolution of the faults lies in attempting to establish the periodicity of faulting. The capability to do this may also be very important in trying to assess the likelihood of future crustal instability in the site areas and its effect on the return rate of radionuclides to the biosphere.

One significant problem, which is all too common in most regions, is that many major lineaments are concealed beneath vegetation thereby hindering a complete understanding of their nature and evolution. However, examinations of faults and fractures on an outcrop scale may prove invaluable in interpreting the larger scale structures. Geomorphic features may also be extremely useful in this context because they can provide a means of assessing the tectonic influence (or lack of same) in an area despite the presence of overburden and vegetation. For example, valleys and ridges can outline folds, scarps and sag ponds are good indicators of recent fault movements, and entrenched meanders may imply differential vertical movements. Furthermore, it may be possible to correlate terrace levels or unconsolidated stratigraphic units across known or suspected faults to detect, within limits, the presence or absence of fairly recent vertical separation.

Seismicity

In addition to knowing the locations of faults and their paleotectonic functions, it is also important to determine whether they are currently generating, or may potentially generate, earthquakes.

Although it seems logical that the effects of seismicity would not be nearly as profound on a sealed underground repository as they would be on surficial structures such as buildings, dams, and nuclear power plants they may, nonetheless, have some influence on the integrity of the repository. They may also change the direction of groundwater flow which, as described below, constitutes the principle envisaged means of transporting waste to the biosphere. Thus, it is recommended that a potential site be located in an area historically, and presently, characterized by no, or only low level, seismicity.

If a site is to be located in an area presently assumed to be either aseismic or characterized by only low level seismicity a seismic network may not exist for that area. Questions concerning, among other things, the presence of seismicity, the magnitudes, peak accelerations, location of foci, focal mechanisms, and potential effects at a site will need to be answered and this is obtained through a seismic network. A network that is both regional and site specific in scope is recommended because regional context and implications are as important in assessing seismic conditions as they are in establishing the overall geological framework and history.

Regional limits

A region within which geological and seismological investigations are to be conducted may theoretically be "limitless" in size. The guidelines, therefore, will attempt to generically define a study area of sufficient size to permit an assessment of all seismic conditions which may directly or indirectly impact on a site. The concept of tectonic or seismotectonic provinces is presently being considered by the AECB as a possible means of achieving this objective. Briefly, a tectonic province is an area marked by an assemblage of tectonic characteristics that distinguishes it from adjacent areas. If seismic activity occurs over all, or a portion of, that tectonic province then the entire province may be described as a seismotectonic province. If a belt or zone of seismic activity crosses juxtaposed portions of two or more adjacent provinces then all of these tectonic provinces may collectively be referred to as a single seismotectonic province. Recognition of distinctive characteristics leading to reliable definitions of such areas may prove to satisfactorily delimit the region enclosing an intended site.

Site specific studies

General statement

In the site selection process site specific studies should be similar to those undertaken in the region except that concentration should be placed on the characteristics of the host rock and the hydrogeological regime.

The host rock and the hydrogeological regime along with the waste, canisters, and backfill constitute an integrated, highly complex system herein referred to as the repository system. Since this system is integrated it should be treated as a unit. For ease of presentation in this paper, however, the naturally occurring components of the system, host rock and hydrogeology, will be treated separately.

Host rock

Many different rock types have been identified as potential hosts for a radioactive waste repository. Each possesses various capabilities for providing an acceptable retardation rate of long-lived radionuclides to the biosphere, yet each seems to have drawbacks as well. No matter what rock type is selected there may always be the nagging thought that a better choice could have been made. For example, plutonic rocks are being considered because they have low permeabilities and many occur in tectonically quiescent environments. Furthermore, they are all strong so there would be little or no tendency for the rock to creep into the excavation during the interval from construction to closure. Despite these positive attributes plutonic rocks are brittle and may be so highly fractured, even at the depths of the repository, that the fracture permeability may be too high to insure a sufficiently low migration rate of presumably dissolved radionuclides. Also in these competent rocks, at depth, there is the threat of rockbursts which could endanger the safety of workers.

Salt is favoured because it is ductile at shallow depths beneath the earth's surface and has the potential to flow and tightly seal the repository. Salt also has a high thermal conductivity. Furthermore, by virtue of its presence, this highly soluble rock indicates that there is no circulating groundwater. Nonetheless because of its ductility salt may creep during the construction, emplacement and observation phases disrupting the underground procedures. Also salt may be interlayered with argillaceous rock or may contain fluid inclusions which, if too voluminous, could release significant quantities of water that could, in turn, dissolve the salt and render the waste vulnerable to transport. Lastly, salt is an economic commodity which may be the object of future exploration.

Argillaceous rocks are potential hosts because they are generally considered to be impermeable. Certain clay minerals, such as montmorillonite, have good sorptive properties. Thus, in argillaceous rocks groundwater circulation may be adequately impeded but, if not, the presumably dissolved radionuclides may be fixed by the clay minerals in the host rock, which would assist in minimizing the return rate of radionuclides to the biosphere. On the other hand, argillaceous rocks may contain significant quantities of both connate and bonded water. Shale, defined here as a fissile, argillaceous, sedimentary rock with clay-sized grains, has a directional permeability parallel to the fissility. Thus, the potential exists for an unacceptable radionuclide migration rate from an argillaceous medium to the biosphere.

In summary, it appears that all rock types, which are commonly considered as possible host rocks for a repository, have the potential to satisfy the objective of geological disposal, yet none has been shown to be unequivocally acceptable. It is therefore clear that a complete understanding of all properties of the host rock such as mineralogy, chemistry, texture, etc. is extremely important in arriving at a final decision.

Hydrogeology

The hydrogeology of the region and the site area is one of the most important factors in the site selection process, because groundwater is considered to be the principle medium by which the radionuclides can be transported to the biosphere.

Ideally, a radioactive waste repository should occur in an area with little or no circulating groundwater. However, the occurrence of groundwater should not necessarily remove an area from

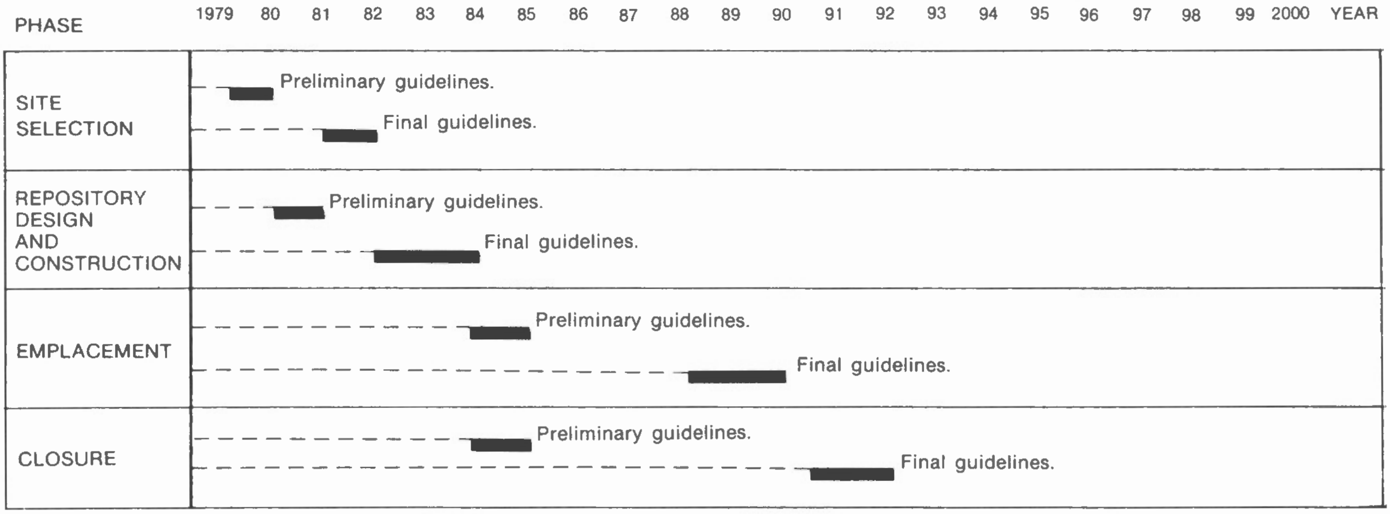

Figure 1.3 Tentative AECB schedule for radioactive waste disposal in bedrock.

consideration as a potential site if the collective capabilities of all other hydrogeological parameters are judged to be acceptable barriers to waste migration. To ascertain acceptability it is important to understand regional hydrogeological conditions, as well as having detailed and thorough comprehension of site area aquifers, their locations, sizes, and recharge and discharge areas. In this regard assessing flow rates and flow paths is critical and calls for a knowledge of the permeability, porosity, hydraulic conductivity and storage capacity of the host rock and the hydraulic gradients of the aquifers. In addition, both the age and the chemical properties of the water need to be considered. If the age can be reliably determined it should be a good indicator of the stability or activity of the hydrogeological regime; this, in turn should provide a means of estimating whether or not the objective of disposal can be met. Knowledge of the water chemistry is important in order to evaluate the potential of the water to dissolve or react with the other components of the repository system. If the waste is dissolved it will presumably be transported back to the biosphere unless it is "fixed" by either the host rock or backfill. If the radionuclides react with the solution to form precipitates their migration rate will be greatly reduced.

Safety analysis

Determining paleogeologic and existing geological conditions is generally the task of geoscientists and can be, and quite often is, frustrating. Yet geoscientists are now required to enter a totally different realm, that of attempting to predict future geological episodes. Not only must there be some attempt to predict the likelihood of events but an attempt should be made to assess their effects on the entire waste disposal system. Natural phenomena to be considered are seismicity, glacial activity and volcanism. Following is a sample of the questions which need to be addressed in order to evaluate the capability of the selected environment to satisfy the objective of disposal in bedrock. Is it conceivable that one or more earthquakes would be capable of either rupturing a repository or generating new fractures which would greatly facilitate water flow to the repository and ultimately to the biosphere? Could an earthquake change the hydrogeologic flow regime? Would the pathway to the biosphere be shortened? What would be the effects of glaciation? Would it change the hydrogeologic flow regime? Is it likely to remove enough overlying bedrock to significantly shorten the vertical distance from the repository to the biosphere? Would the weight of the superincumbent ice load induce further fracturing in the bedrock?

Tentative schedule for publication of guidelines

In establishing a schedule for the issuance of guidelines for the radioactive waste disposal program it is clear that the guidelines should be available before the actual work on the program is underway. According to the joint Canada-Ontario agreement on nuclear waste management, released June 5, 1978, the site selection process is intended to take place between 1981 and 1983. Since this process constitutes the initial step in the disposal program, the tentative AECB schedule for the publication of guidelines (Fig. 1.3) is based on this. However, if for some reason the AECB schedule cannot be maintained as presently envisaged, it will be revised as required.

The order in which the AECB guidelines are to be issued is the same as the order in which each phase of the licensing procedures is to be carried out thus guidelines for site selection will precede those for repository construction, etc. Preliminary guidelines will be published for each phase and will be subjected to a critical review. Following this review, final guidelines will be published.

As presently conceived, the preliminary guidelines for site selection are estimated to be issued by the end of 1980 and the final guidelines will appear by the end of 1982. Final guidelines for the repository design and construction will be issued between 1982 and 1984, those for waste emplacement are planned for 1988 to 1990 and final guidelines for closure are expected to be available by 1991 to 1992.

2. OVERVIEW OF THE CANADIAN FUEL WASTE MANAGEMENT PROGRAM

S.R. Hatcher[1]

Introduction

The objectives of the fuel waste management program are:

Safety – to manage radioactive by-products and wastes so that the potential hazards of the material are negligible.

Responsibility – to manage radioactive by-products and wastes in such a way that the trouble and concern to future generations in keeping them safely will be minimized or eliminated.

There are several steps to the management of irradiated fuel, and a quick review of these will put the disposal requirement into perspective and show the interaction between the different technologies (Fig. 2.1). Irradiated fuel discharged from the reactors is first put into storage so that it can be effectively cooled and shielded to protect man and the environment from the radiation emitted. The universal method of storage is in water-filled pools. These have been proven over several decades to be safe, convenient and economic. Such storage can be technically and economically feasible for many decades and Ontario Hydro is building and using additional pool facilities at the Pickering and Bruce Generating stations.

The important feature of storage is the recognition that the material will be retrieved for further treatment at some time in the future. In view of the responsibility objective it is desirable to eventually dispose of radioactive waste safely, with no intent to handle it further. However, in addition to waste, irradiated fuel still contains nuclear fuel materials with an enormous energy potential, so there are two options at this point. First, the potentially useful materials such as plutonium and uranium could be separated and recovered, while the true wastes – the fission products and some other actinides – could be disposed of. The second option is to discard the energy content of the irradiated fuel by disposing of it in entirety. In either case there is a requirement to make sure that the material going into disposal is immobilized in such a way that both objectives are met.

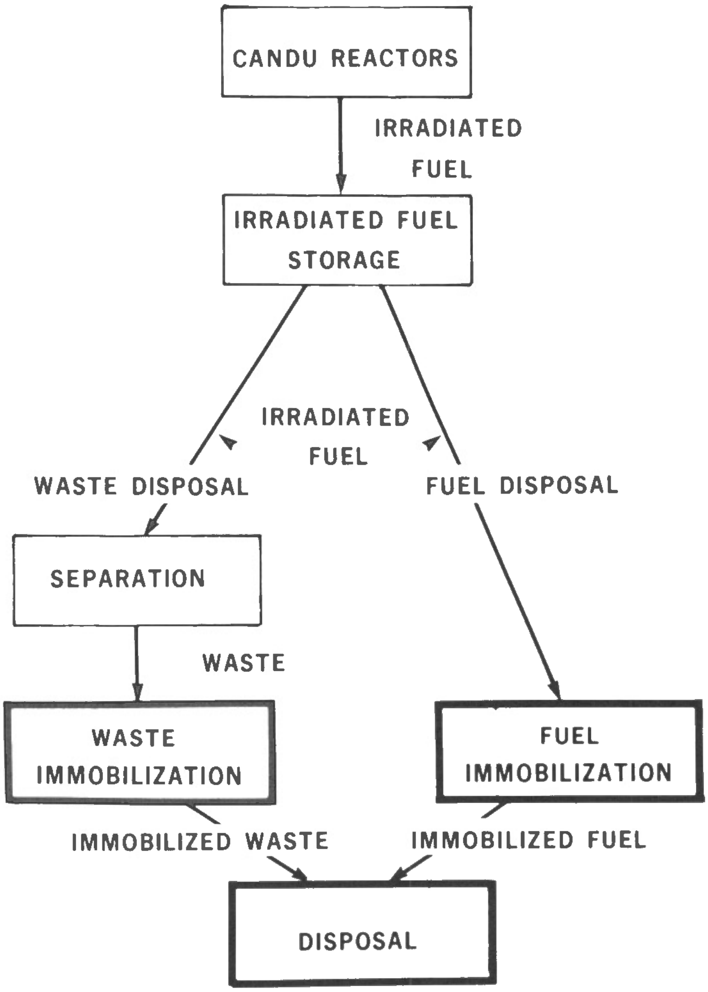

Figure 2.1 Management of irradiated CANDU fuel.

About 20 years ago Atomic Energy of Canada Limited (AECL) pioneered work on the immobilization of separated wastes using a vitrification method. Monitoring of some immobilized wastes buried in wet sand at Chalk River has given valuable long term information on the leaching of radionuclides from the glass (Merrit, 1976). Other countries have continued the work and made improvements to both the process and the matrix. Very little has been done on the immobilization of fuel since it has been assumed by most countries that the residual fuel materials will first be recovered through reprocessing. Meanwhile the consistent Canadian philosophy has been to store irradiated fuel retrievably until the decision on its ultimate disposition is necessary or desirable.

With the storage technology in hand and with the feasibility of waste immobilization demonstrated, AECL turned its attention to optimization of the disposal technology in the early 1970s. Discussions with the Geological Survey of Canada (GSC) led to

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the conclusion that while many types of geology would likely be suitable for disposal, igneous rock formations in the Canadian Shield offered a particularly attractive approach for Canada. Accordingly, GSC proposed a program with major emphasis on plutonic rock and a smaller backup program to identify potential salt formations in Canada.

Within recent years there have been several studies by international interdisciplinary groups of scientists who have reached the conclusion that deep geological disposal is feasible in a variety of geological formations (IAEA/NEA, 1976; Flowers, 1976; Kenny, 1977; Polvani et al., 1977; Hebel, 1978). Most countries with significant nuclear power programs are now mounting major programs along these lines. Co-operation between these programs is very active and Canada is contributing to and benefiting from this exchange in its own program. Last year the Minister of Energy, Mines and Resources commissioned a study by a small group under the chairmanship of Professor F.K. Hare of the Institute of Environmental Studies at the University of Toronto to review the management of Canada's nuclear wastes. Their report (Aikin et al., 1977) gave general endorsement to the Canadian program and recommended an acceleration of the research and development effort. By the end of 1977 the federal government had approved the first phases of the program and authorized acceleration of the work.

Program approach

It is clear that there is a need for proof of the safety of deep geological disposal and for the further development and demonstration of the technology for immobilization of fuel, the immobilization of waste, and disposal. The long-term safety of the system will rely upon a defense-in-depth principle, which is achieved by a series of man-made or natural barriers or impediments to the transport of radionuclides from the emplaced waste to man and the environment. The important factors include the stability and low solubility of the immobilized materials, the flow rates and chemistry of groundwater, the sorption of radionuclides by emplaced and natural mineral surfaces, the length of the pathways to the biosphere, the rate of transport of radionuclides through the biosphere and ultimately their effect upon man and the environment. On the basis of qualitative and semiquantitative studies there is international consensus that there are good prospects for the safety of deep geological disposal in formations of hardrock, salt, clay, and shale. However considerably more research and development will be necessary to provide a detailed quantitative safety assessment for specific sites. This work will involve the construction and verification of theoretically sound mathematical methodology for the pathways analysis, together with collection of detailed physical data and transfer coefficients for the types of geological disposal sites to be considered. This pathways analysis and the resulting safety assessment is crucial for the license application for a potential site and for the technical community to be able to assure the general public that the proposed method and location is safe.

Consequently the disposal program (Boulton, 1978) has been divided up into four phases, reflecting the gradual evolution from research and development to full-scale industrial operation.

Phase 1 Concept Verification
Phase 2 Site Selection and Acquisition
Phase 3 Demonstration Repository
Phase 4 Full-Scale Operation

Each phase will include an active public interaction program which will seek to:

- provide full details of the program to the public as effectively as possible,
- provide ample opportunity for public discussion of the details of the program, and
- accommodate the program to specific community and group interests wherever possible.

Phase 1 – Concept Verification

It is expected that many rock formations and locations will be found to be technically suitable for disposal. Therefore, an important objective is to keep open a wide range of alternatives for all investigations and for the eventual process of site selection.

Verification of the concept of deep underground disposal will involve much theoretical, laboratory, and field work. Painstaking geotechnical evaluations will be required for perhaps six to ten formations, chosen so that they cover a spectrum of rock types and gross fracture patterns. The data obtained from these investigations and from laboratory studies of immobilized fuel and wastes will be used in the pathways analysis. It is expected that the pathways analysis will show that the radioactive materials will have decayed to harmless daughter products long before they could reach the biosphere. There is a good deal of general evidence from the behaviour of natural radioactive materials to support this expectation but specific information is required on the physical, chemical, and hydrological properties of the candidate rock types to prove it. The analyses will also identify which types of geological formation are likely to be suitable for disposal and which are not.

Phase 2 – Site Selection

It is expected that by the end of Phase 1 a large number of sites, perhaps 50 to 100, will have been identified as potentially suitable from a technical point of view. The next task will be to select a site for the proposed waste management centre. Communities in the vicinities of technically suitable sites will be kept up-to-date on the progress and those which express continuing interest in the prospect of the centre will be included on a list of potential sites. Meanwhile governments will decide on the mechanisms by which a specific site will be selected and acquired. If no community shows an interest in having the facility, governments could select a site remote from existing communities and establish there the facility and a new community.

When a reference site has been so designated, detailed environmental and geotechnical evaluations will be required to confirm its suitability. If the site cannot be technically confirmed, it will be abandoned and effort will be concentrated on another site.

Following approval and licensing, the necessary land will be acquired for the repository and its associated surface facilities.

Phase 3 – Demonstration Repository

Once the site has been acquired and serviced, a pilot scale repository will be built. It will be similar in design to a conventional hard rock mine. At a working level of 500 to 1000 m rooms will be excavated for test purposes. The initial testing will include chemical and physical characteristics at both ambient and elevated temperatures but will not involve radioactive waste.

When the results of these tests are considered satisfactory by both experimenters and licensing authorities some radioactive wastes will be emplaced in holes in the floor of the room. This waste will be prepared in the immobilization pilot plants at AECL's laboratories. An extensive sampling program will be established to determine if there is any movement of radioactive materials, and a wide range of other measurements will be taken to confirm predictions of repository behaviour.

Provided the performance continues to be satisfactory, the repository will be expanded to a larger scale demonstration involving several rooms, and the tests continued for a period of perhaps ten to fifteen years.

Although it is not expected that it will be necessary to recover wastes from the repository at any time, the design and operation will be such that the materials can be recovered if the ongoing assessments indicate that the wastes will not be retained for their hazardous lifetimes. If recovery were necessary the wastes would be returned to an interim storage facility where they could be held safely pending investigation of other geological formations.

Phase 4 – Full-Scale Repository

Provided the results from the pilot and demonstration scale operations confirm that the site is suitable, the repository could then be expanded for full-scale operation by building horizontal drifts off the vertical shafts with a number of disposal rooms off each of the drifts. It is anticipated that one repository of this type could handle all the radioactive materials likely to be produced in Canada during the next 50 years.

Progress to date

Approval by the federal government of the Research and Development (R and D) program has allowed AECL to accelerate the work and increase both the breadth and depth of the program by the involvement of expertise from government departments, consultants and the universities, as well as by the expansion of its own effort.

In June 1978 the Minister of Energy, Mines and Resources for Canada and the Minister of Energy for Ontario jointly announced that agreement had been reached on co-operation between the two governments in this program and that AECL and Ontario Hydro would participate as the technical agencies.

The program is under the direction of the Vice-President and General Manager of AECL's Whiteshell Nuclear Research Establishment (WNRE). Much of the work on immobilization of fuel and of separated waste is being done in these laboratories, and research contracts are in effect or under negotiation with a number of universities. Most of the geological work is being undertaken by various branches of the Department of Energy, Mines and Resources (EMR), again with several university research contracts in effect or under negotiation. Prime responsibility for the hydrogeological progam is with the Department of Fisheries and Environment (DFE), reinforced by university contracts. Acres Consulting Services Limited are under contract to WNRE for conceptual studies on the design of the deep underground repository. The pathways and safety assessment incorporating all this other work is being done at WNRE.

Other papers in this volume report in some detail on various aspects of the Canadian nuclear waste management program, and in particular on those segments of the disposal program which are of particular interest to the geotechnical community. We are pleased with recent developments and there has been significant technical progress during the past year. EMR has completed the massive task of compiling, from the literature, a list of all known plutons in Ontario, and is presently preparing maps which will display this data. A high temperature, high pressure triaxial test unit has been put in service at Elliot Lake. Geophysical surveys at Chalk River and Whiteshell have provided us with evidence that one can indeed learn a great deal about a rock mass without riddling it with drillholes. DFE hydrogeologists, in co-operation with AECL staff and Canadian industry, have developed equipment and techniques for downhole measurements which are, we believe, at least as advanced as any in the world today.

In waste immobilization various glass compositions are being evaluated using simulated wastes to determine the effect of waste content on glass properties. Bench scale equipment is being assembled to conduct experiments using active wastes and during the next year composition-property relationships of these active glasses will be studied. Fluid bed and rotary-spray type calciners are also being studied. During the next year a bench nonactive facility will be designed to study on an integrated basis the operations of calcination, vitrification and off-gas clean-up.

The fuel immobilization program is becoming well defined, and work is underway on simple containers and multiple barrier containers for intact fuel bundles. Conceptual design studies have been started for a small scale plant to demonstrate the technology and to provide immobilized fuel for emplacement in the demonstration repository.

The safety assessment, which puts all this together, is going well and the paper by Lyon and Rosinger (Paper 6) provides more detail.

With a broad program involving such a wide range of disciplines, it is most important that we take advantage of the best technical expertise within the country and that the progress of the programs have the benefit of peer review. This approach has the concurrence of the Canadian Geoscience Council who have agreed to help set up an external advisory committee to provide this peer review.

Summary

Canada is now launched on a well-defined, long range research and development program on the immobilization and disposal of radioactive fuel waste. This program is consistent with the broad international consensus which is now developing on the suitability of deep geological disposal. Through international contacts Canadian scientists are well aware of advances being made in other countries and are themselves contributing to this important technology. This year has seen the rapid expansion of the program, the involvement along with AECL of government departments and agencies at both the federal and provincial level, and the growing involvement of universities and private contractors. We particularly value the interest of the Canadian Geoscience Council as expressed through the Forum and this resulting volume, through the direct participation of its members in the technical program, and through its willingness to help provide an on-going peer review system.

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3. EMR PROGRAM FOR GEOLOGICAL DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTES

J.S. Scott[1]

Introduction

The current program of the Department of Energy, Mines and Resources (EMR) for geological disposal of high-level radioactive wastes has evolved over the past five years from an initial request, early in 1973, by Atomic Energy of Canada Limited (AECL) to EMR for geoscience advice on geological disposal. AECL's request arose from the requirements of their continuing responsibility for, and research in, nuclear waste management which has been an integral part of the Canadian nuclear power program initiated in the early 1950s.

Throughout the course of this nuclear power program the interim nature of surface storage facilities for management of nuclear wastes was recognized fully, as was the need for eventual long-term disposal of these wastes. Among the various schemes that have been proposed for long-term disposal, such as burial in ice caps or transport to outer space, the mined-cavity concept was considered to offer greatest promise for development with available technology.

EMR was requested specifically to: (a) identify factors for consideration in the concept of geological disposal of high-level radioactive waste; (b) evaluate the proposal of the United States for high-level, radioactive waste storage in salt (then the preferred rock type in the United States) in relation to geological criteria; (c) determine the extent to which Canadian salt deposits meet the geological criteria; and (d) examine the suitability of other geological formations in Canada for disposal of radioactive wastes. This latter task was considered to be the largest and one of particular significance as a complement to the extensive development work done on salt both in the United States and elsewhere.

Throughout 1973 and 1974, EMR responded to the request from AECL through information exchange, on a formal and informal basis, between scientific staff of EMR and AECL and through the work of an EMR committee drawn from the relevant branches (Geological Survey, Earth Physics, Canada Centre for Minerals and Energy Technology (CANMET)) of the Science and Technology (S&T) Sector of the Department. During this period a preliminary list of factors for consideration in the selection of a rock type and repository site was prepared (Table 3.1), a review of American reports on salt was completed, and an initial assessment was made of the potential within Canada for geological disposal in rock types other than salt. It was recognized that the diversity of Canadian geology, physiography, and demography afforded a wide range of choice of rock types as an alternate to salt. However, choice of alternate rock types was also conditioned by the fact that the Province of Ontario was, and is anticipated to be, the major area for growth in nuclear power in Canada and that all possible alternate rock types could not be studied simultaneously. Therefore, the decision was taken to direct the geoscience activities to the study of igneous rock types prevalent within the extensive area of the Canadian Shield in Ontario and to examine further the potential within various regions of Canada for salt as a disposal medium.

Early in 1975, EMR scientific staff prepared proposals and budgets for geoscientific activities to be included in the AECL program. These activities were: further evaluation of factors for consideration, preliminary examination of igneous rock masses in Ontario, case history studies of engineering structures and mines in crystalline rock with reference to the occurrence and distribution of discontinuities, evaluation of exploration techniques for determination of the structural integrity of igneous rock masses, compilation of data on thermal and mechanical properties of igneous rocks, and an evaluation of salt deposits in western, central and eastern Canada. All of these activities were incorporated in the program and were supported with resources provided by AECL and EMR. Thus, 1975 became the first year of a substantive program which was developed further in subsequent years to form the current program being conducted by EMR in concert with AECL and other agencies including industrial and university contractors as shown in Figure 3.1.

During the formative years of the program the need for public information on the objectives and scope of the program was recognized. Thus, as field work expanded in 1976 to various areas in Ontario to evaluate exploration methodologies and techniques and to accumulate basic geological and geophysical data on the petrological and structural characteristics of igneous rock masses, press releases describing the scope and purpose of the program were issued by both AECL and EMR. However, by late 1976 and early 1977 it was apparent that the program was encountering concern from some sectors of the public through misunderstanding of the objectives and by others through opposition to all aspects of nuclear power development. In view of these concerns, and in consideration of the then preliminary state of planning for a joint Canada/Ontario agreement on nuclear waste management, a decision was taken by AECL to suspend field operations planned for Ontario during 1977. Throughout the balance of that year activities were confined to office and laboratory studies and to minor field work on igneous rocks underlying the AECL facility at Chalk River, Ontario. In 1978 the restriction on field work in Ontario remained in effect, thus all current field activities have

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[1] Geological Survey of Canada, Ottawa, Ontario

TABLE 3.1. FACTORS FOR CONSIDERATION

A. Site and Environmental

1. Accessibility
2. Distance from population and waste land centres
3. Distance from restricted use land
4. Buffer zone availability
5. Topography
6. Hydrology and hydrogeology
7. Overburden
8. Mining and drilling history
9. Mine waste disposal
10. Seismicity
11. Geothermal environment
12. Future geological events e.g. glaciation
13. Risk of external-source hazards

B. Legal and Political

1. Tenure of property rights
2. Alternate use conflicts
3. Population density
4. Site security
5. Anticipated demographic patterns
6. Public acceptance

C. Rock Mass and Rock Substance Characteristics

1. Economic value
2. Structural geology
3. Underground opening stability
4. Rock substance characteristics
5. Erosional stability
6. Thermal properties
7. Stress resistance
8. Moisture migration under hydraulic and thermal gradients
9. Chemical stability
10. Radiation stability

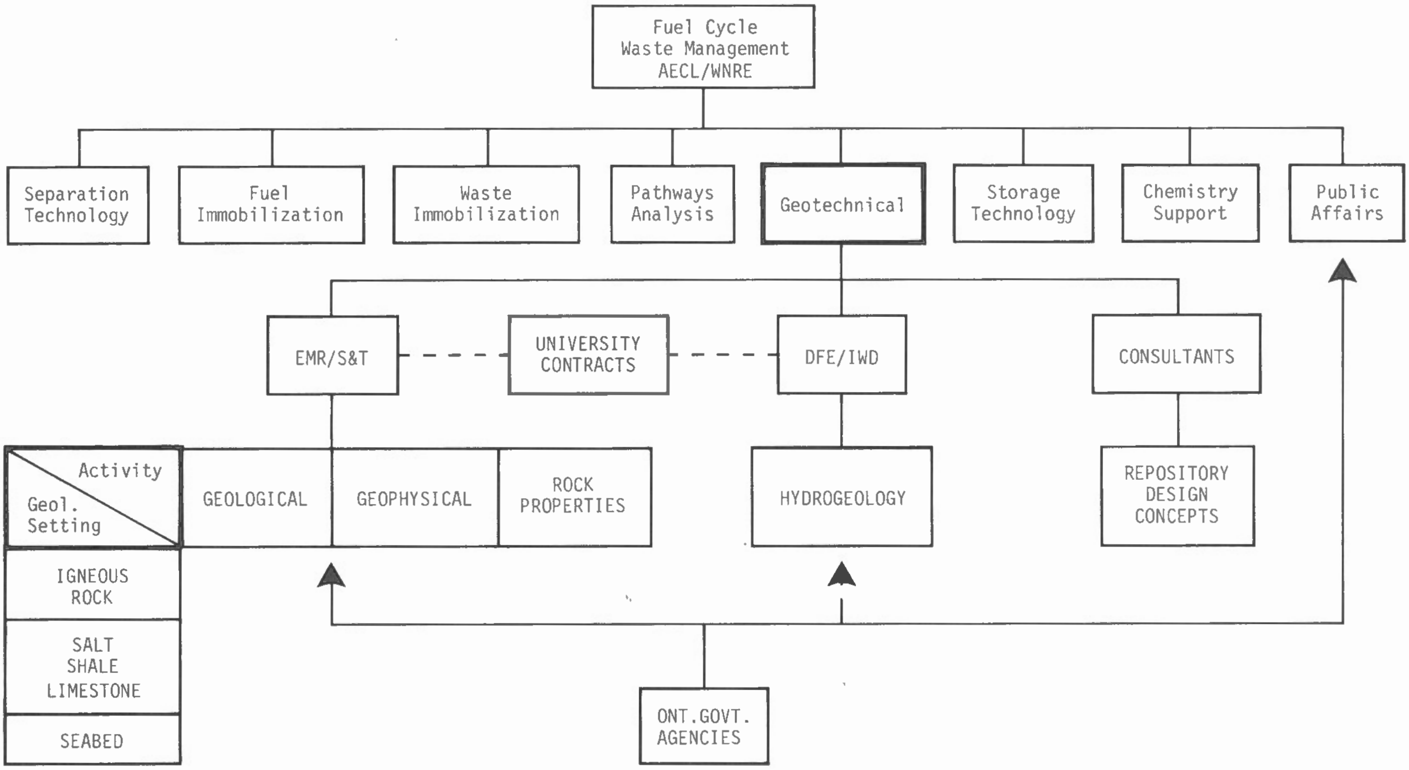


Figure 3.1 Components of fuel cycle waste management program.

been confined to AECL properties at Chalk River, Ontario and Pinawa, Manitoba.

Within the context of the Nuclear Waste Management Program (Fig. 3.1) the part pertaining to geological disposal has evolved such that it comprises four phases, viz., 1. Concept Verification; 2. Site Selection; 3. Pilot Scale Demonstration Repository; and 4. Commerical Repository. Each of the phases is sequential in time as shown in Figure 3.2.

All of EMR's activities within the program are presently being directed toward the Concept Verification phase. However, geoscience activities conducted for Phase 1 of the program and information obtained therefrom will both have direct applicability to later phases.

Current EMR program

The objectives of the current program are: to determine the suitability of igneous rock masses for geological disposal of nuclear wastes, with specific reference to those of the Canadian Shield in Ontario; to evaluate further the potential for geological disposal afforded by salt, limestone, and shale; and to maintain a watching brief on international research and development in seabed disposal. Thus, the program comprises three geological settings with emphasis, both in terms of resource allocations and tasks, placed upon igneous rock studies.

To provide a rational basis for the ultimate selection of an igneous rock type for the development of a demonstration repository, attention is being focused on four principal rock types, viz. granite, anorthosite, syenite, and gabbro in combination with structural settings ranging from highly to weakly fractured.

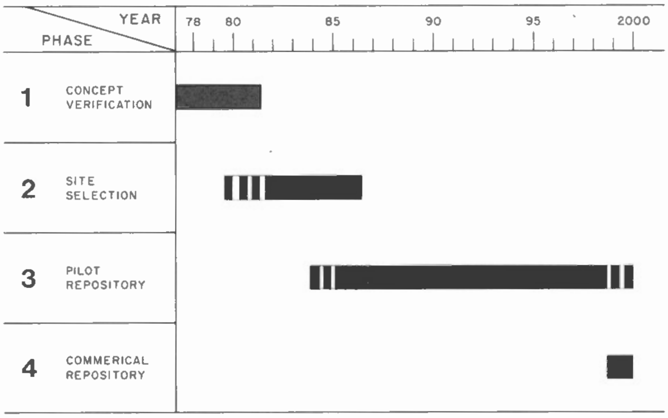
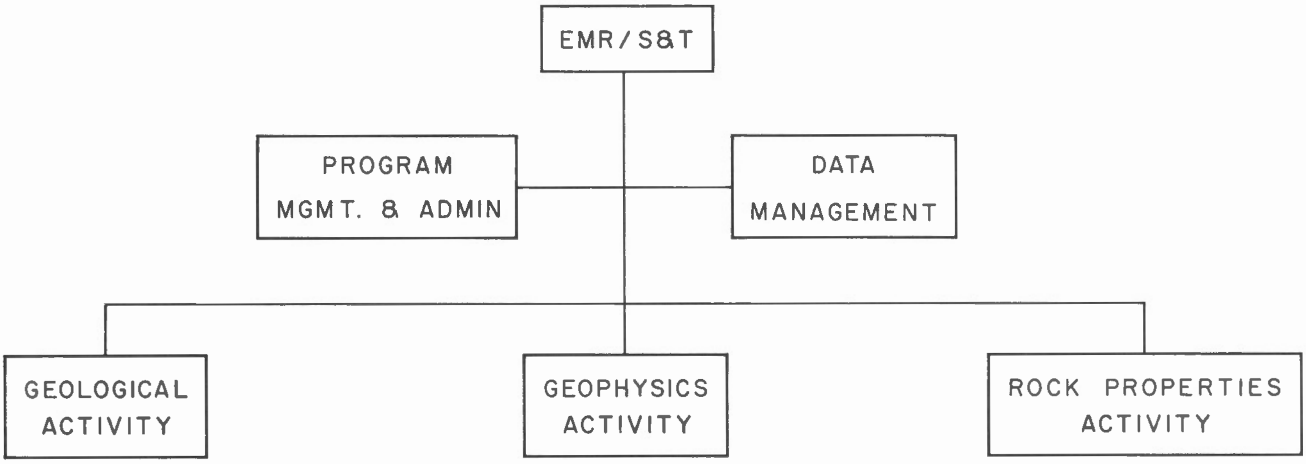


Figure 3.2 Schedule for overall program for geological disposal of radioactive waste.

The program is organized in an Activity/Task structure as shown in Figures 3.1 and 3.3 in which discipline-oriented tasks are grouped for program management purposes. Each of the activities and many of the individual tasks are interrelated as are the major components of the Geotechnical Program.

An Activity manager, provided by the appropriate branch of EMR, is responsible for a group of task leaders. These managers and the program director form the management team which,



TASKS

- GEOLOGY-FIELD/OFFICE
- DRILLING, CORE LOGGING
- BOREHOLE TELEVISION (TV) LOGGING
- GLACIAL EROSION

TASKS

- AIRBORNE SURVEYS-ELECTROMAGNETIC
- AEROMAGNETIC (GRADIOMETER)
- GRAVITY SURVEYS
- MAGNETOTELLURIC SURVEYS
- SURFACE ELECTRICAL SURVEYS
- SURFACE SEISMIC
- SEISMIC LATERAL BOREHOLE
- ELECTRICAL AND STANDARD BOREHOLE SURVEYS
- SEISMIC DOWNHOLE
- GEOTHERMAL LOGGING
- REGIONAL AQUIFER STRAIN
- BOREHOLE RADAR
- BOREHOLE GAMMA-RAY
- TOPOGRAPHIC MAPPING
- SEISMIC RISK EVALUATION

TASKS

- THERMAL PROPERTIES
- MAGNETIC PROPERTIES
- MECHANICAL PROPERTIES
- ELECTRICAL AND DYNAMIC ELASTIC PROPERTIES
- ROCK CRACK PROPERTIES
- UNDERGROUND HEATER
- BOREHOLE AND SHAFT SEALING

Figure 3.3 EMR program — igneous rock tasks.

through co-ordination with AECL and other agencies contributing to the program, collectively provide management for the EMR program.

Geological Activity

Objectives

The Geological Activity (Fig 3.3) as it relates to the several geological settings, has as its primary objectives the identification and evaluation of the physical, structural, and petrological attributes of rocks and related geological materials of significance to geological disposal. These overall objectives are defined further for each of the geological settings under consideration in the program.

From an international perspective of geological disposal, igneous rocks have not received the level of research accorded salt. Thus, the primary objective of igneous rock studies is to establish whether or not intrusive rock masses possess the requisite structural and petrological characteristics such that a demonstration and eventual commercial repository could be constructed within them.

The objectives of studies on salt and other sedimentary strata such as shale and limestone are to identify those areas in Canada possessing suitable basic geological characteristics that would warrant their consideration for geological disposal and to identify, within these areas, locations that would warrant, on scientific and technical grounds, further examination as a potential repository site.

As a maritime nation Canada has an interest in the international work being done on seabed disposal. Through membership on the OECD/NEA Working Group on Seabed Disposal, through contact with United States' scientists involved in research on seabed disposal and through ongoing marine geological and oceanographic research, the Atlantic Geoscience Centre of the Geological Survey of Canada (EMR) maintains a watching brief on seabed disposal research with the aim of being able to provide objective commentary on this aspect of geological disposal.

Since the current program is oriented primarily toward studies of igneous rock, the descriptions of the following tasks, within the Geological Activity and those of the Geophysics and Rock Properties Activities, all pertain to igneous rock.

Office and field investigations

To develop a rationale for the selection of field research areas; to investigate various plutonic (igneous) bodies with particular emphasis on determining the orientation and spacing of fracturing and faulting and the interpretation of the geological history; and to assess and differentiate igneous rock types and structural geological settings to provide a geoscientific basis for repository site selection.

Core drilling

To provide subsurface information on the petrological and structural characteristics of igneous rocks; to develop field and laboratory techniques for analysis of structural geological information obtained from drill cores; to provide subsurface access for in situ geotechnical, geophysical, and hydrogeological measurements; and to provide samples of subsurface materials for various analyses within the Rock Properties Activity.

Borehole television (TV) logging

To provide a photographic record of structural discontinuities within the borehole as basic data for the calculation of discontinuity orientation and spacing in relation to permeability; to establish a data system for storing, processing, and analyzing structural geological and related field data.

Glacial erosion studies

To define and summarize methods of quantifying rates, depths, and volumes of glacial erosion; to identify and evaluate parameters of significance to the control of glacial erosion on the Canadian Shield; to measure the extent of glacial erosion in selected field areas; and to evaluate the evidence underlying published differences of opinion on the extent of glacial erosion on the Canadian Shield.

Geophysics Activity

Objectives

The primary objectives of the Geophysics Activity (Fig. 3.3) are to assist in the establishment of criteria that must be met to validate the concept of geological disposal for igneous rocks and to provide appropriate exploration methodology that can be applied in the search for sites which meet those criteria. The Geophysics Activity thus supports and extends geological and other studies directed toward the concept verification phase and will contribute to the exploration methodology required for the subsequent site selection phase. In order that the Activity contribute effectively and efficiently to the program, various tasks within the Activity are integrated fully, both within the Geophysics Activity and among the tasks of the Geological, Rock Properties, and Hydrogeology activities.

The main tasks within the Geophysics Activity program are summarized below.

Airborne surveys (Electromagnetic, Aeromagnetic (Gradiometer))

To provide interpreted electromagnetic and aeromagnetic maps for the purpose of complementing and extending geological information on the structural characteristics of igneous rock masses.

Gravity surveys

To conduct surveys and provide interpretation of gravity fields of research areas and adjacent areas for the purpose of providing information on the three-dimensional shape of igneous rock bodies and their variation in density; and to determine the extent of isolation of the igneous rock body of specific interest.

Magnetotelluric surveys

To provide interpreted electrical resistivity depth profiles at intervals across igneous rock structures to assist in the identification and delineation of structural discontinuities, and to assist in the characterization of igneous rock masses with respect to their hydrogeological properties.

Surface electrical surveys

To provide maps and profiles of the distribution of apparent electrical resistivity and charge storage capabilities of near-surface materials; to provide further detail of geophysical information on anomalies detected by airborne surveys; to determine the presence of other anomalous structures; and to provide electrical characterization of igneous rock bodies as a means for parametric comparison.

Surface seismic refraction surveys

To provide maps and profiles of the configuration of overburden and to identify anomalous structures within the igneous rock body.

Seismic lateral borehole surveys

To determine anisotropy and estimates of rock quality through the measurement of velocities of seismic body and surface wave as a function of azimuth around boreholes.

Electrical and standard borehole surveys

To provide detailed logs of standard borehole parameters, acquired in industry-accepted formats, as reference for evaluation of their application to experimental work in igneous rock masses; to conduct and evaluate experimental electrical surveys within boreholes for the purpose of determining bulk electrical resistivity and identifying structural features in the rock mass surrounding the borehole.

Seismic downhole borehole surveys

To provide an estimate of rock quality and structural integrity through measurement of seismic velocity distribution throughout the wall rocks of drillholes.

Geothermal logging

To detect the flux of groundwater through micro-temperature measurements at appropriate intervals and to determine the temperature/depth gradients in rock masses.

Regional aquifer strain investigation

To determine regional pore pressure and fluid diffusion coefficients and to detect possible tectonic activity associated with structural discontinuities through measurement of the response of water levels in boreholes to periodic strain at earth-tide frequencies.

Borehole radar surveys

To develop equipment and interpretation methodologies to permit studies of structural features and discontinuities within a range of approximately 50 m from the hole. The experimental state of this method is such that measurements presently are limited to a depth of 150 m. However, it is expected that further development will enable routine surveying to a depth of 1000 m thus enabling acquisition of rock quality information throughout the full depth range required by the program.

Borehole gamma-ray spectrometer surveys

To provide gamma-ray spectral logs of drillholes for the purpose of determining concentrations of radioactive elements (potassium, uranium, and thorium) in wall rocks of the holes. Concentration of these elements and their concentration ratios may be diagnostic of certain structural discontinuities within the wall rocks. At present this survey technique is in the development stage.

Topographic mapping

To provide topographic base maps of research areas at appropriate scales as required for geological and geophysical surveys.

Seismic risk evaluation

To assess regional and local seismic risk at research sites through evaluation of existing information and through the establishment of microseismic networks as required.

Rock Properties Activity

Objectives

The primary objectives of this Activity are to develop and construct equipment, develop techniques, and apply methodologies arising therefrom for the testing of rocks under the thermal and mechanical stress conditions required by the program; to provide appropriate comparative rock-property data required for concept verification; to provide quantitative data on strength, deformation, and thermo-physical properties of igneous rocks for repository design purposes; and to provide such additional rock property data as may be required by the Geological, Geophysics, and Hydrogeology activities. Tasks within this Activity, as with those of other activities, are fully integrated both internally and with the other component tasks of the program.

Thermal rock properties

To obtain data on the thermal properties of various igneous rocks for parametric comparison within the Concept Verification phase of the program; to obtain preliminary data on thermal properties for repository design purposes; to investigate the effects of elevated temperature, confinement, and porosity on thermal properties of rocks, to obtain measurements of thermal conductivity, thermal diffusivity, density, and porosity of drill core specimens and to relate these thermal characteristics to the petrographic and petrofabric character of rocks; and to collate data derived from existing information and field investigations for the analysis of heat flow in areas of interest to the program.

Magnetic rock properties

To measure magnetic properties of drill core specimens for the purpose of providing depth control for surface and airborne magnetic surveys and for comparison with seismic, optical, and other assessments of anisotropy of rock fabrics.

Mechanical rock properties

To obtain data on the mechanical properties of various igneous rocks for parametric comparison within the Concept Verification Phase and for repository design purposes.

Electrical and dynamic elastic properties

To obtain data on electrical and seismic properties of drill core specimens to assist in the interpretation of surface and borehole geophysical surveys; and to provide complementary information on hydrogeological, self-healing, and leachability characteristics of igneous rocks.

Rock crack properties

To measure crack content, rock fabric parameters, and related properties of drill core and surface rock samples as a basis for interpretation of rock properties derived from seismic, electrical resistivity, and porosity measurements; to assist in the assessment of such properties as permeability and shear strength; and to provide a basis for estimating the behaviour of rock masses at elevated temperatures and pressures.

Underground heater experiment

To develop equipment, experimental techniques, and interpretation methodology to permit the evaluation of repository design concepts; and to provide information on the performance of igneous rocks under field conditions at elevated temperatures.

Borehole and shaft sealing

To review and establish appropriate technologies and materials required for the filling and sealing of boreholes, shafts, and underground openings associated with the exploration for and development of an underground nuclear waste repository.

The EMR program thus comprises a spectrum of interrelated tasks designed to evaluate rock mass and rock substance attributes at both field and laboratory scales of investigation. Some of the tasks, particularly several within the Geophysics and Rock Properties activities, involve considerable research and development prior to their application as standard techniques. Others are either direct applications or modifications of existing exploration and laboratory techniques having direct relevance to the program. As may be expected, analysis, interpretation, and synthesis of the large amounts of data arising from even the current level of activity constitute a major task. Therefore, efforts are being directed toward the development of a user-oriented data management system that will permit use of the data and information in the most effective and efficient manner.

Within the Concept Verification phase a primary purpose of the various tasks is to establish a rational basis for the selection of a combination of rock type and structural setting that will provide a suitable geological environment for a repository. In the larger scope of the nuclear waste management program these task data will provide a significant and essential input to the pathways analysis, which will be used to examine the interrelations between and effectiveness of the various components of the entire waste disposal system.

Progress of Research

A complete summary of progress covering each of the tasks within the program is beyond the scope of this paper. Accordingly, the following examples have been chosen to illustrate results of research which have a direct bearing upon the present and future directions of the program.

One of the background studies (Raven and Gale, 1979) carried out during the early part of the program was a survey of the geological structure and groundwater conditions occurring in a number of operating mines and in several large civil engineering subsurface projects. Study sites located in Precambrian Shield areas of Manitoba, Ontario, Quebec, and Labrador were examined. Results of this survey, as shown in Figure 3.4, show that the principal zones of seepage are located within depths ranging from 300-350 m. Zones of seepage were encountered below depths of 350 m; however, seepage from these zones commonly was not continuous and diminished rapidly with time. A major conclusion from this study was that the undisturbed rock mass is saturated at depth and that a lack of water in the deeper mine workings is due primarily to low hydraulic conductivity rather than to a dry rock mass.

One of the primary geological factors for consideration in the study of igneous rocks is an evaluation of the extent of occurrence of fractures and related structural discontinuities within the rock mass. Analysis of aerial photographs and other remotely sensed imagery in concert with surface mapping provides a means for relatively rapid assessment of these structural features particularly in areas of relatively extensive outcrop. However, these methods provide information only on the surface expression of structural discontinuities; thus, a method is required to correlate this

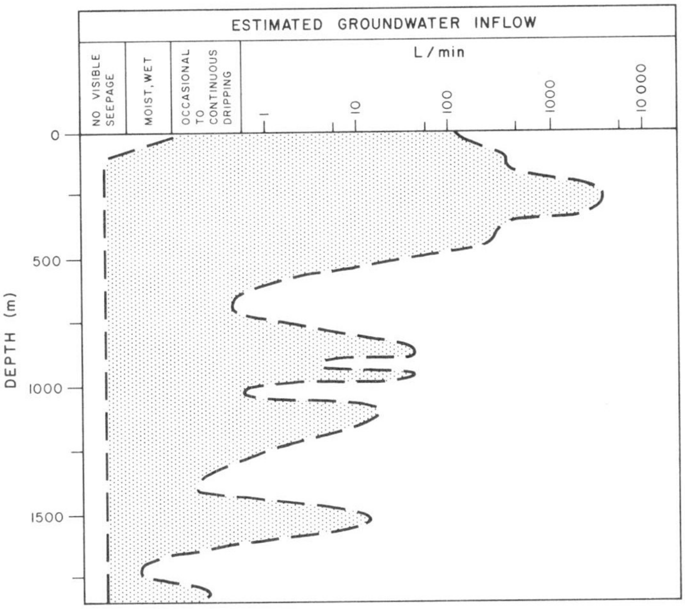


Figure 3.4 Range of groundwater seepage with depth from observations in mines (after Raven and Gale, 1977).

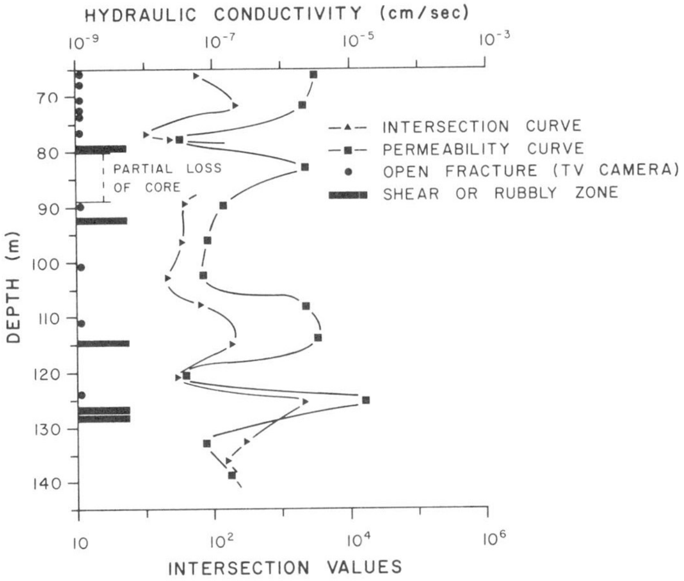


Figure 3.5 Comparison of fracture intersect (I) values and hydraulic conductivity (from Brown, in prep.).

information with that obtained from the subsurface. A detailed study (Brown, in prep.) of the occurrence of structural discontinuities in the igneous rocks underlying the AECL facility at Chalk River where core drilling has been done indicates that the concepts of fracture number (FN)[1] and number of intersections (I)[2] can be used to effect the required depth correlations.

A calculation of fracture intersects for 5 m intervals of core obtained from boreholes at Chalk River plotted against values of hydraulic conductivity obtained from packer tests in these holes shows a high degree of correlation over the depth examined (Fig. 3.5). It is possible that further analysis of the fracture data, including measurement of fracture apertures, may yield a closer correlation with hydraulic conductivity values. Further development of this correlation would enable the use of surface fracture data for the prediction of structural and hydrogeological conditions at depth.

The recent development at the Geological Survey of Canada (Hood *et al.*, 1976) of an inboard digital recording vertical gradiometer system for high resolution aeromagnetic surveying has been opportune for the geological disposal program. Although developed primarily as a technique for mineral exploration, the system, comprising two vertically separated tail boom magnetometers with ancillary data recording and analysis equipment, has a demonstrated capability for detecting short wave length, near-surface magnetic anomolies produced by both petrological and structural features. As shown in Figure 3.6 delineation of structural features, as interpreted from a measured vertical gradient map, is a useful complement to structural geological information obtained from surface examination and from remotely sensed sources.

Contract magnetotelluric surveys (Redman and Strangway, 1979) have been conducted at Chalk River, Ontario using thunderstorms and VLF transmitter sources producing frequencies of from 12 to 20 000 Hz. These surveys have shown that the igneous rock complex at Chalk River has resistivities of a few thousand ohm-metres indicative of a substantial content of fluid within the bedrock. This interpretation is confirmed by other geological and hydrogeological investigations at this site.

Both the depth penetration and resolution capabilities of this geophysical survey method are such that it provides a useful exploration tool for preliminary field surveys.

Through the co-operation of the International Nickel Company, the Canada Centre for Minerals and Energy Technology (CANMET) has been able to acquire access to Creighton Mine, in the Sudbury Basin, for the purpose of conducting an *in situ* heater experiment at the 700 m level (Larocque *et al.*, 1979). Rock at the test site is a medium-to coarse-grained quartz biotite gabbro that has been subject to shear deformation.

In preparation for the installation (initially a single 30 cm diameter, 6.1 m long heater to be placed vertically beneath the floor of the test chamber) testing of the thermal and mechanical properties of the test chamber rocks has been carried out, *in situ* stress measurements have been made, and sensor designs and emplacement arrays have been completed. The experiment is expected to provide such basic information as temperature and stress distributions and the influence of thermal gradients on groundwater movement and will provide a field check on theoretical calculations of temperature and stress distributions.

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[1] Fracture Number (FN) — the average number of parallel or subparallel fractures in a given set per linear distance measured in a linear direction normal to the fracture plane.

[2] Intersections (I) — number of fracture intersections calculated for a unit volume of rock on the basis of the number of fracture sets and frequency of occurrence of fractures within a set.

Task leaders have the responsibility for preparing periodic reports of progress of their work as contributions to the ongoing documentation of the program. While much of the documentation is in a preliminary form and is thus internal to EMR and AECL, the need for wider distribution of this information to the geoscience community and to the public is clearly recognized. Therefore, attempts are being made to establish a documentation handling system that will permit prompt external release of reports of work done under the program.

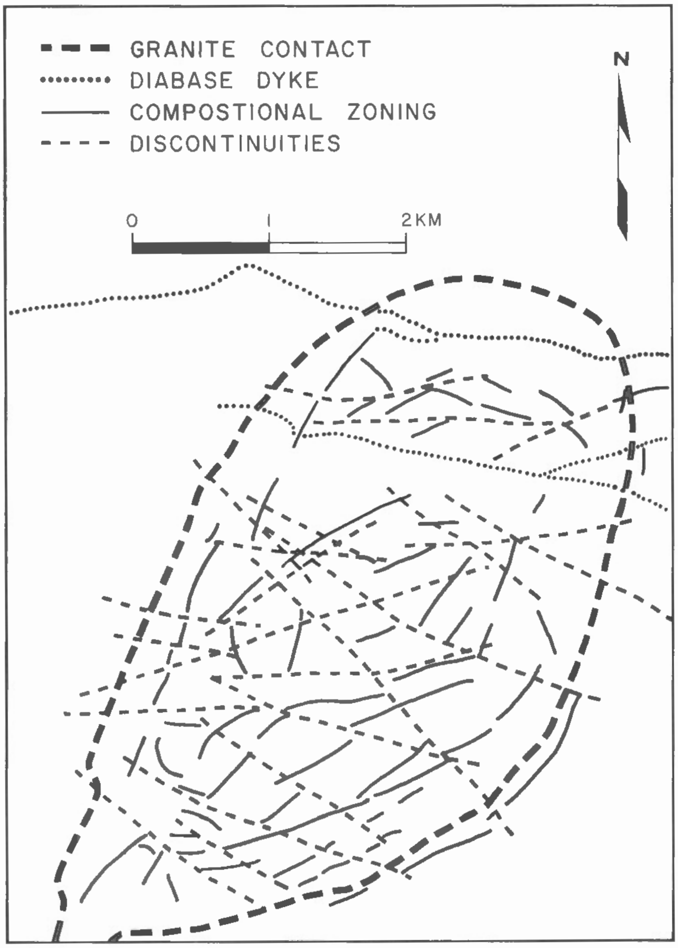

Figure 3.6 Geological features interpreted from airborne gradiometer survey (from Hood et. al., 1976).

Future Directions of the EMR Program

In the immediate future the program will be focused primarily on studies of igneous rock as continuing contributions to the Concept Verification Phase of the nuclear waste management program. Studies will continue-on the evaluation of salt, limestone, and shale, and the seabed at essentially the present levels of activity.

A major task, currently under development within the Rock Properties Activity but which as yet to attain a fully integrated status, is geochemistry. Inclusion of a geochemical task to complement geochemical studies being undertaken by AECL thus will complete the spectrum of tasks for which EMR has both expertise and program responsibility.

The program is faced with a number of internal and external constraints which will affect the ability of those involved in the program to attain program objectives by a specified date. Internally, some of the program tasks are, of necessity, sequential whereas others may be carried out in parallel. Further, all tasks are subject to the need for rigorous data analysis and interpretation which resist acceleration. Externally, the EMR program is subject to the overall schedule of the nuclear waste management program and to the conditions of the Canada/Ontario agreement on nuclear waste management which, as yet, have not been fully formulated. However, the most critical external factor affecting the program is that of public relations as no field work can be undertaken in the absence of acceptance of such field research by the communities involved.

Given such public acceptance and sufficient resources such that the Canadian geoscience community can become fully involved in the program, Canada, as a nuclear nation, can proceed to contribute significantly, both nationally and internationally, toward the development of a safe method for disposal of radioactive wastes.

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4. THE DFE PROGRAM IN ENVIRONMENTAL IMPACT OF THE DISPOSAL OF HIGH-LIGHT RADIOACTIVE WASTE IN GEOLOGICAL FORMATIONS

H.C. Rothschild[1] and C. Barraud[1]

The disposal of high-level radioactive waste material in geological formations encompasses a challenge involving a variety of technical and scientific expertise, as well as an area where many branches of government have an expressed interest and responsibility or even some degree of jurisdiction. The activities of the Department of Fisheries and Environment Canada (DFE) in this area involve the participation of two services: the Environmental Management Service (EMS) and the Environmental Protection Service (EPS). EMS is supporting applied research in hydrogeology and groundwater geochemistry for eventually determining the transport/retardation mechanisms in the deep underground environment. EPS is evaluating the long-term physical and chemical stability of granitic rocks of plutonic origin and also the efficiency of the geological barrier in containing long-lived radionuclides.

The EMS program has the following long-term objectives:

- To assess and develop methodology for collection and analysis of field data for the purpose of determining the hydrogeological parameters relevant to groundwater flow and radionuclide transport from deep underground disposal zones;
- To develop, and encourage development of, field and laboratory testing techniques which will provide information concerning the origin, age, subsurface flow path, and hydrogeochemical evolution of groundwaters in deep underground zones; and
- To assess the possibility of providing a hydrogeological monitoring capability for the physical and hydrogeochemical evaluation of potential groundwater migration paths.

The proposed hydrogeology program for fiscal year 1978-79 can be essentially subdivided into three main components; (1) physical aspects, (2) hydrogeochemical aspects and (3) computer modelling.

The elements relating to the physical aspects component are concerned with obtaining and assessing the reliability of field measurements of fluid potential, hydraulic conductivity, storage coefficients and groundwater velocity, as well as a laboratory investigation of the fundamental nature of the stress-hydraulic conductivity relationship. The laboratory investigation will assist in the interpretation of field hydraulic conductivity tests as well as provide information on the nature of the stress-hydraulic conductivity relationship which could be of use in future modelling work.

The elements relating to the hydrogeochemical aspects are concerned with *in situ* measurements of groundwater chemical parameters and obtaining water samples which have not undergone changes due to degassing or water column effects. A borehole geochemical probe and pressure sampling apparatus has been designed which can be used either in open 3-inch boreholes or in the permanently installed multi-level monitoring device. The probe and samplers will be used to assist in deducing the *in situ* hydrochemical conditions in the deep subsurface and to provide samples for laboratory age dating and chemical and isotopic analysis. A laboratory based study will be undertaken to investigate what mineral equilibria reactions tend to control groundwater geochemistry in the Precambrian Grenville gneiss of the Chalk River area, Ontario. The experimental study on one of the cores from the Chalk River borehole will hopefully be integrated with field sampling of groundwater from various depths in a similar borehole, which should serve as a test for the applicability of the experimental data and methodology.

During the fiscal year 1978-79, the hydrogeological program will be directed towards investigating two boreholes drilled at Chalk River and three boreholes drilled at the Whiteshell Nuclear Research Laboratory, Manitoba. The two adjacent boreholes at Chalk River are 1000 and 500 feet in depth and two of the boreholes at Whiteshell are 1500 and 500 feet in depth. The third Whiteshell borehole will be air-drilled to a depth of 500 feet with a specially designed multilevel sampling system for the purpose of comparing hydrogeochemistry and shut-in pressure tests with the open, diamond-drill boreholes.

The elements concerned with computer modeling of groundwater systems are very preliminary in nature, in fact a prime objective in this fiscal year is to establish what types of models may be required at various stages of the overall deep underground disposal program. A continuous groundwater flow model will be adopted for the purpose of investigating the effect of the natural geothermal gradient and the effect of the repository on groundwater flow patterns.

EPS interest is to develop a methodology that will permit the evaluation of the long term physical integrity, chemical stability and isolation capability of deep underground nuclear waste repositories following backfilling and decommissioning. There are two major reasons for undertaking such an evaluation: (1) there will be limited possibility to monitor the site after sealing the repository, (2) in case of future release of radionuclides into the biosphere in quantities higher than acceptable, no known actions

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[1] Environmental Protection Service, Department of Fisheries and the Environment, Ottawa, Ontario

to correct the situation are presently available. It is thus mandatory that the efficiency of the host rock and of the backfill material to contain the radionuclides be thoroughly assessed before deep rock disposal can be considered safe and environmentally suitable.

To achieve this goal, the long-term objective of EPS is to develop thermodynamic models that, in conjunction with hydrogeological data, will permit the forecast of:

- any potential mineralogical modifications of the host rock after sealing of the cavity, especially along rock discontinuities such as faults, joints and fractures;
- any potential chemical destabilization of the backfill material following abandonment, and the nature of new materials or minerals likely to be formed;
- the sorptive properties of minerals and materials that will be in direct contact with the groundwater flow, e.g. backfill materials and minerals lining the rocks discontinuities.

At first, emphasis will be given to granitic rocks considering the actual Canadian waste disposal program. In a second step, the models will be modified for applicability to other rock types, especially the high sorptive argillaceous rocks.

Ultimately, in conjunction with other concerned organizations, results and conclusions drawn from these studies are intended to lead to the identification of the rocks type(s) that will offer the maximum reliability for predicting and evaluating long-term isolation capability.

For this fiscal year, the EPS program will focus on the qualitative evaluation of potential modifications in the minerals lining the fractures of the host rock due to pertubation in the groundwater flow system following the excavation and the backfilling of the repository. The nature of the backfill material, its chemical equilibrium with host rocks, its potential sorptive properties and the sealing mechanisms will also be investigated. Verification of the preliminary results and conclusions of the above qualitative studies will be verified by the development of the thermodynamic models mentioned earlier. Work done in EPS and by outside contracting firms are considered for this model development.

5. THE MANAGEMENT OF IRRADIATED FUEL IN CANADA

R.W. Barnes[1]

Introduction

The nuclear power program in Canada has been, until recently, relatively modest. Most of the effort by the organizations involved has been concentrated on establishing a safe, viable, economic industry. However, the point has been reached where Canada, like other industrial nations, is looking to nuclear reactors to provide a basic source of economic energy.

In Ontario, nuclear electric stations generate 4500 MWe with a further 9000 MWe in various stages of construction planned to be in service by the late 1980s. During 1977, 26.7 per cent of the electrical energy generated in the province of Ontario was by nuclear electric generating stations. Nuclear-electric stations are under construction in Quebec (638 MWe) and New Brunswick (633 MWe) and these will begin operation in the early 1980s.

Recent estimates by the federal Department of Energy, Mines and Resources for installed nuclear-electric generating capacity in Canada, suggest 60 000 MWe by the year 2000. This would amount to approximately one third of Canada's estimated electrical generating capacity at that time.

Experience has shown that nuclear energy is safe, reliable and economical for generating electricity. In 1977, the average overall capacity factor for units of the Pickering generating station was 90.7 per cent. The cost of producing the electricity was significantly less than the equivalent cost of comparable coal-fired generation. Other benefits from nuclear electric power include security of fuel supplies (particularly for Ontario), low environmental impact, potential for future development and overall benefit to the provincial and Canadian economies.

Reactor system

The reactor that forms the basis of the commercial nuclear power generation is the CANDU-PHW (Pressurized Heavy Water) reactor. This reactor consists of horizontal tubes which hold the fuel bundles. The heavy water coolant which flows through the tubes removes the fission heat from the bundles and transfers it by heat exchangers to a secondary circuit of light water. The steam produced in the secondary circuit is used to drive the turbine-generator system.

The reactor is moderated with heavy water and natural uranium is used in the fuel bundles. The basic unit of fuel for the CANDU reactor is the 50 cm long bundle shown in Figure 5.1. The elements in the bundle are thin zircaloy sheaths containing high density natural UO_2. Zircaloy end plates hold the elements together. Spacers are brazed to the sheaths to provide separation between elements.

Canadian power reactors are designed for on-power fuelling. The fuelling is carried out by two co-ordinated machines which lock onto each end of a horizontal tube. The operation is controlled from the station control centre. New fuel is inserted into a magazine, remotely transferred to the fuelling machine and from there into the reactor. Irradiated fuel is discharged from the fuelling machine to a transfer mechanism which in turn transfers the fuel to underwater storage in the station irradiated fuel storage bay.

Nature of irradiated fuel

The irradiated fuel discharged from the reactors contains more than 99.999 per cent of the radioactivity produced by the nuclear station. The radioactive nuclides in irradiated fuel may be considered as two main groups. The first group, called fission products, consists of those materials produced as a direct result of the fission process. The second group, called actinides, is produced by various nuclear reactions such as neutron capture that result in heavy elements such as plutonium, curium, americium, etc. Many of these nuclides continue to emit radiation after being discharged from the reactor and in doing so, undergo the process known as radioactive decay.

Essentially the highest levels of radioactivity in the early life of discharged fuel are associated with decay of the fission products. The radioactivity of the fission products decreases relatively rapidly and after several hundred years the actinides become the dominant source of radioactivity in the irradiated fuel.

Radiation emitted by irradiated fuel constitutes a potential hazard and methods of management of the fuel must provide protection against this hazard.

Heat is generated by the radioactive decay process and cooling of the irradiated fuel is necessary. A Pickering irradiated fuel bundle generates approximately 60 watts of heat after being out of the reactor one year. This decreases to about 6 watts in the next four years as the level of radioactivity also decreases.

Irradiated fuel storage bays

The station irradiated fuel bays are thick walled, reinforced concrete structures, lined on the inside with stainless steel or fiberglass reinforced epoxy paint. The water in the bays is generally about 9 m deep in the fuel storage areas and a little shallower in fuel transfer and handling areas. A cross section through the auxiliary irradiated fuel bay at Pickering GS is shown in Figure 5.2.

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[1] Ontario Hydro, Toronto, Ontario

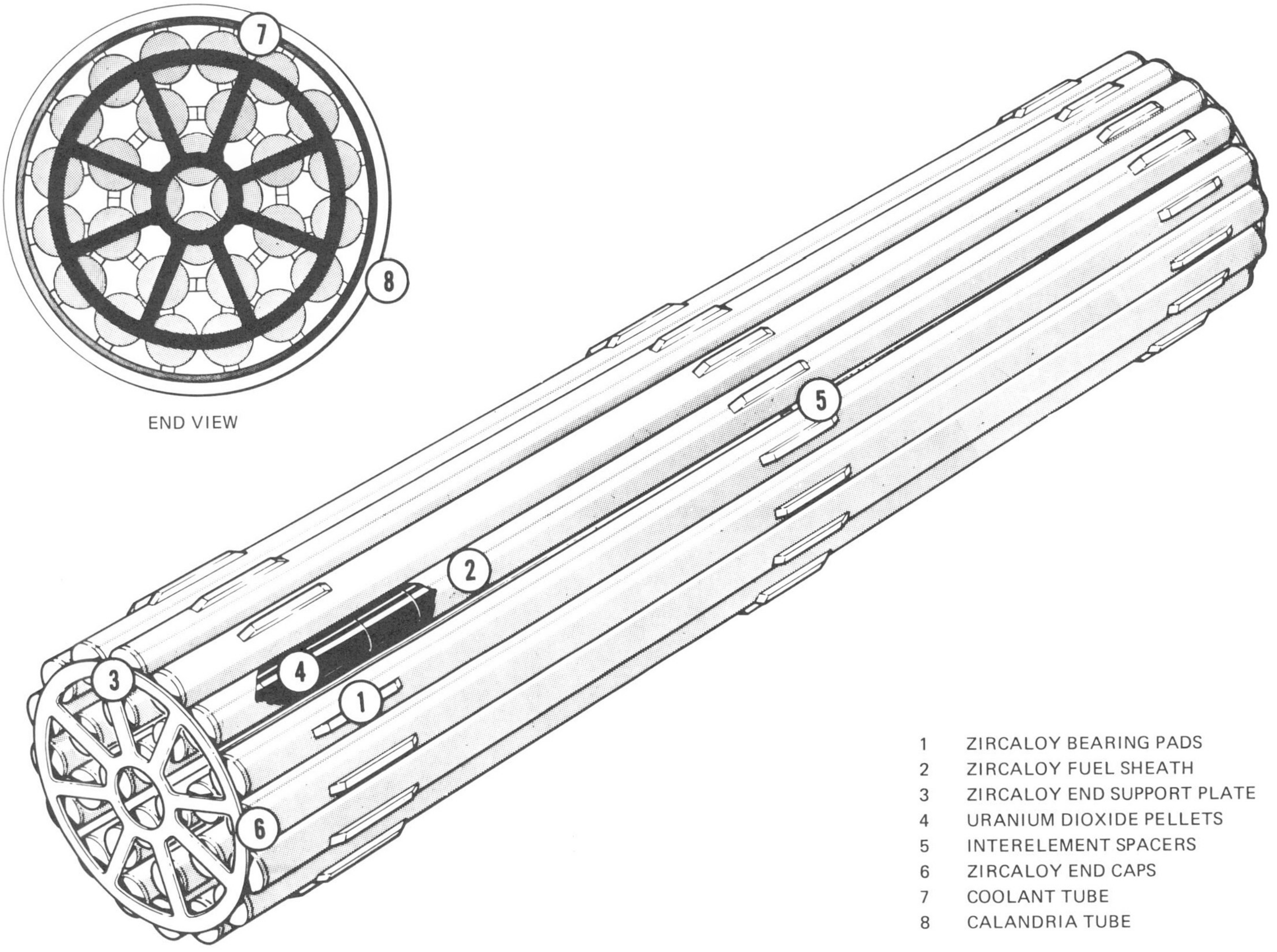

Figure 5.1 28 element CANDU fuel bundle.

The fuel bundles are discharged automatically into fuel storage containers. The containers are stored in stacks up to 4.5 m high with 4-4.5 m of water above the top of the stack. This provides shielding from the radiation emitted.

Cooling circuits are provided to remove decay heat from the fuel and to keep bay water temperature within design limits.

Leakage collection systems are provided to deal with contaminated water should any leak through the primary liner in the bay.

Purification circuits which contain filters and ion exchange columns are provided to remove dissolved and suspended radioactive material from the bay water for personnel protection and to maintain water clarity for good visibility during fuel transfer operations.

Ventilation of space above fuel bays is provided to maintain comfortable air temperature and humidity and to control airborne radioactivity, should this be necessary.

Irradiated fuel storage capacities

The capacity of the station storage bays at Pickering and Bruce is augmented by additional storage bays. The nominal storage capacities of the bays at Pickering and Bruce stations are:

Pickering Station Bay	92 000 bundles
Auxiliary Bay	162 000 bundles
Bruce Station Bay	21 300 bundles
Secondary Bay	262 000 bundles

These capacities do not include the space allowed in the station bay for a reactor core load of fuel.

Future stations are planned to have sufficient irradiated fuel storage space for six station years of operation at 80 per cent capacity factor, in addition to space for one reactor core load of irradiated fuel. Sufficient space will also be reserved to extend the on-site capacity as required.

Storage bay filling dates

A forecast of the filling dates for the storage bays in operation, under construction, or planned has been made but like any forecast, many factors can introduce uncertainty. Some of these are the actual capacity factor achieved in station operation, the actual burn-up levels of the fuel discharged, the operating power level of the reactors, and the packing efficiency achieved in irradiated fuel storage. Consideration of these factors has resulted in a range of filling dates of the various storage bays.

The calculated filling dates for the various bays are:

		Earliest	Most Probable
Pickering GS A	– Main Bay	May 1979	July 1979
	– Auxiliary Bay	Jan. 1990	Apr. 1991
Bruce GS A	– Main Bay	Dec. 1978	Mar. 1979
	– Secondary Bay	Oct. 1988	Mar. 1991
Pickering GS B	– Main Bay	Jan. 1989	Sept. 1989
Bruce GS B	– Main Bay	Nov. 1985	Mar. 1986
	– Secondary Bay	Dec. 1994	Aug. 1996
Darlington GS A	– Main Bays	Feb. 2000	May 2002

Potential energy resource

The irradiated fuel discharged from CANDU reactors contains a potentially valuable future energy resource in the actinide plutonium. Each irradiated fuel bundle contains about 80 g of plutonium of which about 55 g is fissile. This fissile plutonium, if mixed with natural uranium fuel and recycled in the current type of CANDU reactors, would permit a doubling of the energy obtained from each ton of mined uranium. When used in this way, the plutonium contained in a single irradiated fuel bundle is equivalent to 1800 barrels of oil. The fuel discharged from one year's operation of the Pickering Generating Station on the same basis contains the energy equivalent of 25 million barrels of oil (see Table 5.1).

The plutonium in the irradiated fuel could also be used to start a nuclear fuel cycle involving the use of thorium in CANDU reactors. This would provide an opportunity for the extraction of many times the amount of useful energy than would be obtained from our uranium resources using the once-through CANDU fuel cycle. However, the reuse of the plutonium contained in irradiated fuel either with uranium or with thorium would require the development of a reprocessing industry which has not been undertaken in Canada. Whether or not such development should be undertaken, is the subject of debate and discussion and a national decision on the subject could be some time away.

Whether or not recovery and reuse of the plutonium in the irradiated fuel is economic depends in part on the price of uranium and the costs associated with reprocessing irradiated fuel. Current estimates of these factors show that it is not economic at present, but it is anticipated that the real price of uranium will increase as resources are used up. This is most likely to occur in the next century.

These considerations have led Ontario Hydro to propose that the irradiated fuel be stored for a period of 20 to 30 years.

Announced joint program

On June 8, 1978, the Federal Minister of Energy, Mines and Resources and the Minister of Energy for the Province of Ontario announced a joint program on "the first phase of a long-term program to assure safe and permanent disposal of radioactive waste from nuclear power reactors".

Under the announced program, the Federal Government and its agencies have prime responsibility for the program and will undertake research and development of the immobilization and disposal of radioactive wastes whereas the Provincial Government and its agencies will be responsible for studies on interim storage and transportation of irradiated fuel.

Ontario hydro's program activities – status

Irradiated fuel transportation

At some time all Canadian irradiated CANDU fuel will have to be transported from the various nuclear generating stations to a

TABLE 5.1 POTENTIAL ENERGY RESOURCE IN IRRADIATED FUEL

	M. BTU	EQUIVALENT BLS. OIL
1 Barrel of Oil	5.8	1
1 kg of Irradiated Fuel (2.6 g Pu-239)	532	92
Annual Fuel Discharged from Pickering G.S. 'A' (80% C.F.)	145 Million	25 Million
100 Gg of Irradiated Fuel	530 Billion	9 Billion

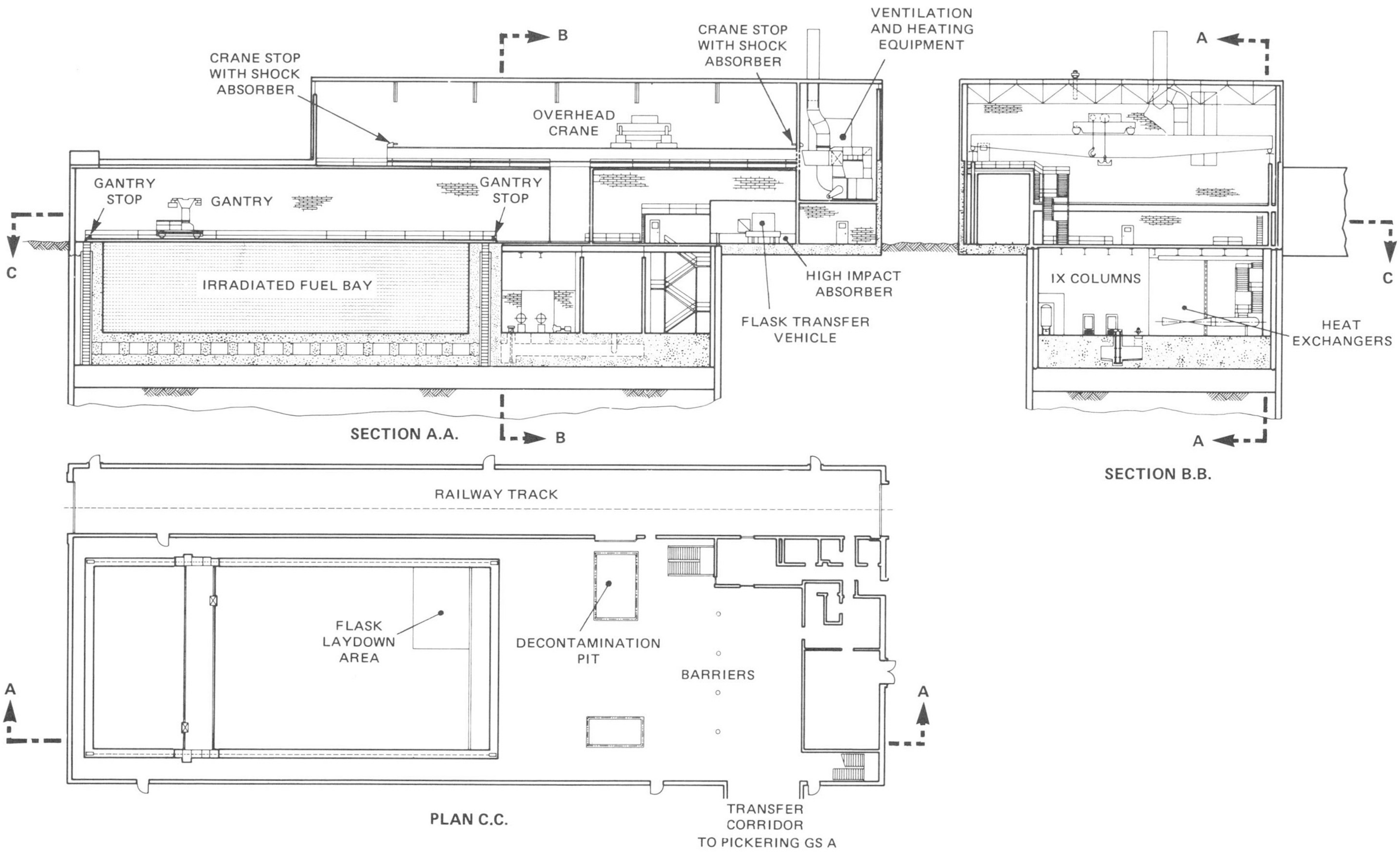

Figure 5.2 Auxiliary irradiated fuel bay facility.

radioactive waste isolation facility or to a centralized interim storage facility. A program has been developed to determine the optimum system. The program is divided into four main areas of effort briefly outlined below.

Shipping flask

A conceptual design of a shielded container or flask is being developed. All credible accidents that could occur during transportation will be considered in the design.

Shipping module

Various concepts of the container or module that will support the fuel in the flask while it is being transported are being developed. The module design must prevent damage to the irradiated fuel bundle by the shock and vibration environment during shipment.

Shipping modes

A program is now underway to determine which of the modes – road, rail or barge should be used to move the irradiated fuel.

Shipping environment

A study has been started to determine the advantages and disadvantages of transporting irradiated fuel with either a dry or a wet environment inside the shipping flask.

Interim storage of irradiated fuel

Aspects of this program are outlined below.

Study of interim storage siting options

Ontario Hydro has underway a study to evaluate the feasibility, safety, economics, and timing of the options open for the safe storage and transportation of irradiated fuel, including:

- storage at individual generating station sites;
- centralized storage alone at an existing site or at a site acquired specifically for that purpose;
- centralized storage in conjunction with facilities to immobilize irradiated fuel or high level radioactive waste at an existing site or at a site acquired specifically for that purpose;
- centralized storage in conjunction with immobilization facilities and a nuclear waste disposal facility.

Design studies

Conceptual design studies of alternative centralized interim storage concepts were undertaken as part of the work of the Ontario Hydro task group during the period 1974 to 1976. Extension of this work has continued in several areas including:

- timing of the need for additional interim storage facilities,
- specifications of engineering requirements for interim storage facilities including those related to safety, environmental protection, reliability, site conditions, fuel handling, construction and commissioning, decommissioning, safeguards, security, and economics,
- identification of aspects of interim storage that require further development, e.g., (1) the behaviour of irradiated fuel during long term storage in water or air, (2) the effect of weathering on the integrity of concrete canisters,
- engineering design of interim storage facilities, e.g., development of analytical methods for calculating temperature distribution in water pools.

Conceptual studies

Ontario Hydro is proceeding with conceptual design studies of interim fuel storage concepts. Additional storage facilities at the nuclear stations will be very similar to the facilities now in existence at the stations. However, centralized interim fuel storage could make use of other storage concepts previously studied such as the concrete canister concept and the convection vault concept.

Summary

1. Irradiated fuel is accumulating at the nuclear electric generating stations.
2. It is at present stored in water pools which have been proven to be a safe, reliable and economic means of storing irradiated fuel.
3. Canada regards its irradiated fuel containing fissile plutonium as a potential resource.
4. It will store its irradiated fuel until,
   (a) it is decided whether or not this potential can be used;
   (b) a repository has been developed to dispose of the irradiated fuel or the reprocessing wastes that would result from the reprocessing of the irradiated fuel.

6. RISK ASSESSMENT FOR RADIOACTIVE WASTE DISPOSAL

R.B. Lyon[1] and E.L.J. Rosinger[1]

All of man's activities carry some degree of risk. Some could be avoided, yet are continued because the activities carry some benefit which is judged, generally implicitly, to balance the risk incurred. A good example is the widespread use of automobiles.

Risk associated with radioactive waste disposal can be accepted in the same way if certain aspects are considered carefully. First, since disposal of these materials is a part of the total nuclear electricity generation system, the effects on the environment and the risks to people, now, and in the distant future must be considered. These effects and risks must then be considered in the light of the benefits gained from the electricity generated. Second, the effects on the local environment and on those who would be employed at the facility or living nearby, must be examined.

The complex to be assessed consists of a vault, 500 to 1000 m deep in a plutonic igneous formation, and its associated surface facilities. There will be access shafts and a grid of rooms for emplacing the waste containers, which will either be placed in drilled holes or in excavated trenches in the floors of the rooms.

To carry out risk assessments, information is gathered from a wide range of disciplines. Often the data are interpreted by detailed analysis using computer models or by the development of empirical correlations. Sometimes only a qualitative interpretation is possible, with identification of the further research necessary to quantify the risk. The research and development, which will provide the data and basic understanding of the relevant phenomena, is underway in a number of organizations such as Atomic Energy of Canada Limited (Whiteshell Nuclear Research Establishment (WNRE) and Chalk River Nuclear Laboratories (CRNL)); Department of Energy, Mines and Resources (Canada Centre for Mineral and Energy Technology (CANMET), Geological Survey of Canada (GSC), and Earth Physics Branch (EPB)); the Inland Waters Directorate (IWD) of Department of Fisheries and Environment (DFE); and many universities. This paper briefly describes the main aspects of the risk assessment studies and, in some cases, illustrates the factors to be taken into account by presenting preliminary assessments and extrapolations. These preliminary studies will be increasingly refined and supported by experimental data as the research and development programs progress.

It is convenient to divide the risk assessment studies into two major parts – the pre-closure assessment and the post-closure assessment. The pre-closure period encompasses the time during which the nuclear waste vault is operational and requires attention by man. It includes the construction, demonstration, commercial operation and backfilling phases, and it is assumed that it will last until at least the year 2025. The post-closure period starts when the vault has been backfilled, the surface facilities have been removed and the surface environment returned to its original state or freed for some other use.

Pre-closure assessment

Risk assessment studies for the pre-closure phase will be similar to other studies carried out for nuclear facilities, and will be subject to well developed licensing procedures and therefore will be outlined here only briefly.

Social and economic studies will be undertaken to assess the effects of increasing the labour force, employment opportunities, the expanded economic base, and the loads on existing services and facilities.

Safety assessments will be undertaken to estimate the probability and consequences of accidents with particular attention to situations where radioactive material might be released. Radioactive and nonradioactive emissions during normal operation will be estimated based on experience with other facilities and handling operations.

Pathway analysis calculations of the movement of radionuclides through the environment and their uptake by man will be performed, using the estimates of the radioactive emissions. Such calculations provide the basis for estimating potential dose to man.

Safeguards procedures will be specified to ensure that unauthorized diversion of nuclear material does not go undetected, and security operations will be designed to prevent theft or sabotage.

The results of the pre-closure assessment studies will be documented in Environmental Impact Statements and facility Safety Reports for review and approval by the appropriate regulatory authorities. Because of their experience with other nuclear facilities, Ontario Hydro will be assisting in the pre-closure studies.

Post-closure assessment

The only significant potential risk to man, identified for the post-closure phase, is the prospect that groundwater may penetrate to the waste, leach out radionuclides and carry them to the surface. Thus the objective of the risk assessment studies for the post-closure phase is to determine the integrity and reliability of the various barriers and protective features which prevent this transfer of radionuclides to man.

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[1] Atomic Energy of Canada Ltd., Pinawa, Manitoba

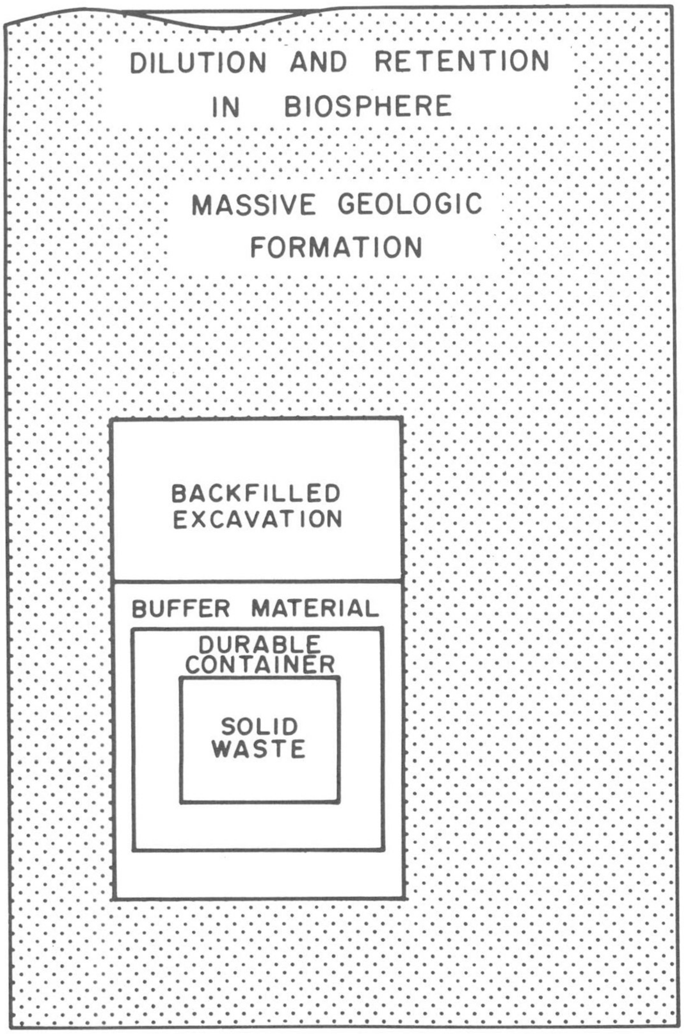

Figure 6.1. Features protecting man from nuclear waste.

These barriers or protective features (Fig. 6.1) are: the integrity of the waste form itself, its container, the buffer material surrounding the container, the backfill and sealing material, the massive geological barrier, and finally dilution and retention in the environment.

Each of these features is considered in turn.

Waste form

First is the waste form itself, which could be irradiated fuel or vitrified waste.

The irradiated fuel consists mainly of irradiated uranium oxide pellets, contained in zirconium alloy sheaths. In this form, the fuel sheath has survived severe temperature and water flow conditions in a reactor for more than a year. In fact, eight bundles have remained in the core of the NPD power reactor at Rolphton, Ontario for sixteen years and they are still intact (Mayman, 1978). The fuel sheath is thus expected to continue to provide containment. Further containment is provided by the very stable uranium oxide matrix. To quantify the integrity of this barrier, the rate of leaching of radionuclides from the uranium oxide pellets and the rate of dissolution of the uranium oxide matrix itself must be determined. The leach rates of various radionuclides from irradiated UO_2 fuel are being measured at WNRE. From results of leaching of ^{144}Ce and ^{154}Eu from fuel pellet segments, it has been inferred that the dissulution rate of the fuel matrix in an unlimited amount of either distilled water or tap water, equilibrated with atmospheric gases, is less than 1×10^{-4} of the original amount present, per year. This would imply that total dissolution of the segments would take more than 10000 years if the rate remained constant. The above extrapolation assumes that the dissolution rate is not limited by the availability of water, of dissolved gases or by the removal rate of the reaction products. In fact, it is expected that the flow rate of water past the UO_2, if water penetrated the container at all, would be very low. Second, UO_2 is virtually insoluble in reducing environments (Hostetler and Garrels, 1962; Langmuir, 1978) (< 0.1 μg/kg water at 25C), but is more soluble in the presence of oxidizing or complexing species (particularly fluorides, carbonates and sulphates). The vault chamber will probably contain an oxidizing environment for only a limited time after being backfilled, and the container should keep the fuel isolated from water for this period. A reducing environment could be assured by the incorporation of suitable reducing agents into the buffer material. The effects of temperature on radionuclide complexing are being investigated at WNRE and the University of Waterloo. There is also the possibility that oxide or hydroxide layers of the UO_2 inhibit dissolution under conditions where UO_2 is soluble and this is also being investigated at WNRE. Thus, there are good reasons to expect that the used fuel will provide a relatively insoluble waste form.

A great deal of research work has been, and is being, carried out on the second possible waste form — vitrified waste. In Sweden, predictions have been made (KBS,1977a) of the time taken to dissolve glass blocks containing waste, placed in a disposal vault. For the case where leaching of the glass is limited by the supply of water, and based on the solubility of silicic acid in water, the estimated leach fraction was 3×10^{-7} per year of the original weight of the glass, or complete dissolution in approximately 3 million years.

In 1960, twenty-five glass blocks containing small quantities of high-level fission product waste were placed in flowing groundwater at a depth of 4 m at the CRNL site (Merritt and Parsons, 1964; Merritt, 1976). Measurements indicated that the leach rates of ^{90}Sr from these glass blocks corresponded to 4×10^{-8} of the original mass leaching per year after three years and 8×10^{-9} after 15 years. This would indicate times to total dissolution of 25 million years for the rate at three years and 125 million years for the rate at 15 years.

The CRNL glass blocks were made from nepheline syenite. The high melting temperature required for the production of this glass makes it less attractive as a practical contender for our purposes. However, studies at Battelle North West Laboratories (Mendel *et al.*, 1977) with borosilicate glasses, which are more suitable, indicate that glass which remains intact and noncrystalline would be dissolved to a depth of less than 1 mm in 100000 years in slowly moving water at 25°C. The same glass, even after crystallization by heat treatment would be dissolved to a depth of only 1 cm in the same time. The higher temperature for vitrified waste over the first hundred years or so would result in a higher initial leach rate. However, the container is expected to isolate the glass from the groundwater through this period.

Extrapolations such as these obviously neglect many complexities of long-term behaviour. However, the low solubility of the glass does give confidence that it will provide a highly effective barrier to the escape of radionuclides.

Waste container

The waste container is the subject of detailed study in which parallel approaches are being taken. The first approach is design and demonstration of a simple container which would be expected to last for at least a hundred years. Candidate materials for the simple container include stainless steel, Inconel, Hastelloy, titanium and copper.

The second approach is the development of a long-term container which would last for thousands of years. One option being explored for long-term containment is the use of lead in a composite container. Research at WNRE in this area is at an early stage but studies have been carried out in Sweden on composite steel containers with an outer lead layer and a titanium shell.

A group in the Swedish Corrosion Research Institute has estimated (KBS,1977b) that the steel/lead/titanium container would remain completely intact for at least 500 to 1000 years. This failure time is based on localized corrosion. They suggest also that the lead could act as a cathodic protector for the inner steel cylinder. In this case, a large fraction of the lead might have to be corroded before the steel container would fail. The Swedish group postulates that the corrosion of lead in the vault will be limited by the availability of oxygen. Based on this, it would take 1.8 million years to oxidize all the lead in the container. It is also suggested that the corrosion products might slow down the corrosion rate if they are not carried away. Gelin (1977) has calculated the lead levels and the time required for complete dissolution on the basis of levels of sulphate and carbonate in the groundwater under the Swedish vault conditions. He estimated that it would require 700 billion years before the lead in the container would be carried away by groundwater.

Buffer and backfill

Buffer material may be placed around the container. Factors influencing the choice of buffer material include its physical properties (thermal stability, compressibility, permeability) and its chemical properties. It will be chosen to impede the movement of water, to condition incoming water to reduce its capability for corroding the containers and dissolving the waste, and to have suitable chemical properties to attenuate radionuclides which might be leached out. The simplest concept is to use crushed rock excavated from the vault, mixed with filler material such as bentonite clay. Backfill material, used to fill the rest of the rooms and shafts, could differ from buffer material since it has only to provide physical support and to impede water movement. Studies on buffer and backfill material are being undertaken by the University of Western Ontario and the Université de Québec.

For the risk assessment it is necessary to draw on all of the vault studies – leaching of the waste, corrosion of the container, and transfer through the buffer and backfill material to develop models which can be put together to estimate the behaviour of the system as a whole. Such models can then be used to estimate the rate at which radionuclides might be expected to leave the vault and enter the geological formation.

Geological formation

A wide range of studies is in progress which will provide design information and safety assessment data relating to the barrier provided by the geological formation. Involved in these studies are EMR, DFE, consultants, universities, and manufacturers.

Investigations are being carried out on specific formations to develop tools and techniques, and to acquire generic information on the internal structure and hydrogeology of plutonic igneous rock masses. No steps have yet been taken to select the actual site for the vault. Field investigations, with drilling at the CRNL and WNRE sites, are now in their second year.

Geochemistry

Geochemical studies have been initiated at WNRE and in several Canadian universities. Generally, the studies indicate that radionuclides which are cations in solution tend to be sorbed on rock surfaces quite effectively. For anionic species, such as iodine and technetium, a suitable buffer is being designed to act as a specific scavenger. Work presently in progress at WNRE suggests, for example, that oxides and sulphides of lead or copper may be suitable.

Computer programs

The hydrogeological and geochemical information will be incorporated into computer programs for the risk assessment studies. One of these is the GARD program (Geochemical Assessment for Radionuclide Disposal), developed at WNRE (Rossinger and Tremaine, in press). Input data to GARD consist of the effective water velocity, volume flow rate, effective path length and parameters for a simplified geochemical model. The output is the rate at which radionuclides would traverse the pluton barrier. Radioactive decay during transport is taken into account. The chemistry model assumes that the description of all radionuclide/rock/solution interactions can be combined into one parameter K which is assumed to be constant for a given radionuclide. The resulting model is specified by a set of partial differential equations which are solved analytically by the Laplace Transform technique, similarly to the method used by Burkholder and Defigh-Price (1977).

With the information available so far, a "first cut" analysis has been completed for the pluton pathway for all the radionuclides of interest. The results indicate that most of the radionuclides will decay to minute quantities before traversing the barrier. Calculational methods are being improved in two major areas. First, hydrogeological models are being developed at IWD and WNRE, and second, chemistry research is providing a basis for the development of a more sophisticated chemical model. There is still a wide range of uncertainty on many of the parameters used in pluton pathway analysis. Nevertheless, it is believed that realistic estimates have been developed of the effectiveness of the features which protect man and the environment from the radioactive material. The results of this first cut analysis are encouraging.

Potentially disruptive events

Various potentially disruptive events or phenomena have been and are being considered, such as earthquakes, erosion, intrusion by man, meteorite impact and glaciation.

While earthquakes are always possible, they tend to occur near previously faulted zones. Siting of the facility in a stable region of the Precambrian Shield away from fault zones makes the possibility of a major earthquake remote.

It is unlikely that erosion or future periods of glaciation will have an effect down to the depths under consideration.

Man-made intrusions into such a facility have been analyzed. Nuclear war and sabotage are not likely to breach the facility. It has been calculated (Clairborne and Gera, 1974), for example, that a facility 600 m deep would not be breached by a 50 megaton nuclear weapon exploded at the surface directly over the facility. The possibility of sabotage leading to containment failure is also considered remote (Kenny, 1977), once the waste has been buried and the facility sealed.

Estimates have been made of the size and frequency of meteorites which can cause damage at significant depth. One estimate (Gera and Jacobs, 1972) suggests that the frequency of a meteorite impact causing a release from a facility 600 m deep is one in 5 x 10^{13} years. Such events or phenomena have been considered in several studies in Sweden and the United States. So far none appears to be of significant importance to the safety of the vault.

Vault perturbations

Of interest, however, are the various perturbations to the properties of the existing system caused by the excavation of the vault and emplacement of the material, i.e. heat-generating radioactive material, structural material, unintended material (nitrates from explosives etc.), and backfill. There will be a chemical transient as the mixture slowly reverts to some equilibrium state, and a temperature transient. The extent of the temperature transient will be significantly different for fuel than for glassified waste. The peak in the transient for vitrified waste is expected to occur about thirty years after the vault is backfilled, with subsequent cooling, whereas, for fuel, the transient is expected to last much longer due to the presence of long-lived actinides, such as plutonium and americium. The temperature rise could have significant effects on the rates of chemical reactions, and the effects of thermohydraulic gradients and thermal stress must be estimated. Temperature effects on the chemical reactions are being studied at universities and at WNRE. Also, a continuum groundwater flow and solute transport model is being developed at IWD. This model will study the transient temperature distribution. Peak temperatures can, of course, be limited by choice of waste-packing density, but the system must be optimized since the wider the spacing between waste packages, the more costly the mine.

CANMET is carrying out an underground heater experiment in a mine at Sudbury to verify thermal and stress analysis computer codes and to assess rock properties and responses on a large scale and under appropriate boundary conditions. (See Paper 3). DFE is studying the possibility of initiating hydrogeological tests coupled to the heater tests. WNRE is applying the methods of linear elastic fracture mechanics (LEFM) to predict long-term crack growth under the influence of the stresses in the rock caused by excavation and by heating.

The end product of the geological formation studies will be an estimate of the rate at which radionuclides could enter the surface environment.

Surface environment

Retention and dilution in the surface environment provide further major barriers which reduce transfer to man. Research into the movement of radionuclides in the environment is underway in the Environmental Research Branches at CRNL and WNRE as well as at various nuclear sites and research institutions around the world. Some of the results of these studies are assimilated in the use of computer programs. Typical of these is the RAMM system (Radioactive Materials Management) developed at WNRE (Lyon, 1976). As input, this program requires a model of the system under consideration in the form of compartments with pathways between. Transfer coefficients define the fractional rate of transfer between compartments. The program solves for the time-dependent contents of the compartments, taking into account radioactive decay. Most effort is required to estimate the transfer coefficients. Detailed finite difference or finite element codes may be used to estimate their values for some pathways. For others, their values may be inferred from measured transfer rates (for example of fallout plutonium) between various compartments in the biosphere.These surface pathway analysis studies give the estimation of the radiation dose to man. This provides a basis for judging the acceptability of the disposal concept from the radiological point of view.

Conclusions

The risk assessment considerations and procedures, which are underway for the pre-closure and post-closure phases of the disposal facility for radioactive wastes, have been described. The efficiency and reliability of the multiple barriers in sequence between the radioactive material and man are being assessed using information from a wide range of scientific disciplines and studies.

Preliminary results have been presented which estimate the probable efficiency of the barriers. Until a deeper understanding of the relevant processes has been developed, conservative estimates erring on the safe side must be used when the complete study is assembled. However, the preliminary results indicate that the multiple barriers should provide sufficient redundancy of protection and that the disposal facility can be accepted as safe by the scientific community, the regulatory and environmental bodies, and by the general public.

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7. THE CANADIAN PROGRAM FOR A HIGH-LEVEL RADIOACTIVE WASTE REPOSITORY: A HYDROGEOLOGICAL PERSPECTIVE

J.A. Cherry[1] and J.E. Gale[1]

Introduction

It is generally agreed by geoscientists that there must exist zones, at various locations in the earth's crust, in which repositories could be created for isolation of spent fuel or fuel reprocessing wastes from the biosphere for hundreds of thousands or even millions of years. As a result of this viewpoint and the lack of practical alternatives for "permanent" waste isolation, all industrialized countries with major commitments to nuclear power are planning research programs or are actively looking for rock masses suitable for repository development. Canada is no exception. Like other countries, Canada developed a considerable capacity for production of nuclear power prior to seriously addressing the problem of high-level waste disposal. Almost complete emphasis in the management of spent fuel was directed toward the development and operation of surface facilities (spent fuel bays) for safe wet storage of spent fuel. With this technology now well established, the thrust moved to the problem of developing a national facility for waste disposal. With this shift, geoscientists and geotechnical engineers moved to centre stage in the waste management field and now find themselves facing demands for predictions of the behaviour of hydrogeological, geochemical, and geotechnical systems over time periods extending much farther into the future than has previously been the case. The involvement of geoscientists in the nuclear power industry is now occurring on an unprecedented scale and seems to have led to some misunderstanding of the nature and scale of the "problem".

Our purpose in this paper is to provide a hydrogeological perspective within which the Canadian program for research and development of a repository can be considered. A significant, but nevertheless quite modest scale of repository-related hydrogeological research was not initiated until about 1977. Results of consequence will not be produced for several years and, therefore, it is inappropriate to attempt to reflect on detailed aspects of this program at present. Hydrogeological research related to repository development began somewhat earlier in the United States and Sweden, but relative to the scale of the problem can also be considered to be in its early stages. As an alternative to focusing on specific aspects of on-going hydrogeological research, this paper attempts to outline, within a hydrogeological framework, the nature of the problems and to identify some general areas of concern with regard to the hydrogeological component of the Canadian program.

The Premise and the Corollary

The basic premise normally associated with the concept of deep rock repositories for high-level radioactive waste is:

For a repository to be capable of providing for long-term isolation of radionuclides from the biosphere, the rock mass that separates the repository from shallow zones of active groundwater flow (in the upper part of the rock mass or in the overburden) must have long-term containment capability.

A corollary from this premise is that:
For a proposed repository to be acceptable for waste disposal, it is necessary to achieve (i) detailed understanding of the site's hydrogeological conditions and (ii) a reliable predictive capability for detailed analyses of radionuclide migration in groundwater through the hydrogeological system to the biosphere.

The hydrogeological perspective presented in this paper is developed within this framework. If it can be established that other "barriers" in the repository system (i.e. the waste form, the cladding or waste capsule, repository backfill) are sufficient to provide the desired confidence in long-term containment, the above stated premise and corollary would become unnecessary. Research is of course proceeding on these other potential barriers, but at present reliable predictions with regard to their long-term containment capabilities are not possible.

The concept of deep rock repositories for radioactive waste has its roots in the belief that there is good potential for finding rock masses in which groundwater flow is very slow or nonexistent, thereby enabling the rock mass to act as a barrier between the waste and the biosphere. There is no basis at present to shift reliance towards other barriers, although development of other barriers must be a continuing objective and may eventually lead to sufficient redundancy of barriers inside the repository to warrant some measure of relaxation of the requirements for containment capability of the rock mass.

Basic Concept and Potential Problems

In the Canadian context, various rock types are worthy of serious consideration at this stage. They can be grouped into two categories:

1. Plutonic igneous and metamorphic rock
2. Marine sedimentary rock

The plutonic igneous rocks of primary consideration for repository development are granite, diorite, and syenite. Of the marine sedimentary rocks, bedded salt and shale (argillaceous

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rocks) are most promising. From a hydrogeological viewpoint bedded salt and shale have some common ingredients because analysis of groundwater conditions associated with salt will necessitate detailed consideration of shale, which in most stratigraphic settings forms the cap rock on the salt and other laterally extensive zones in the stratigraphic sequence. Pathway analyses designed to evaluate the consequence of groundwater migration into a repository in salt would depend heavily on the hydrogeological containment capabilities attributed to shale in the stratigraphic sequence.

Figure 7.1 shows the mined cavern concept. It consists of a room and pillar excavation some 1000m or so below ground surface. The waste, enclosed in canisters, will be placed in holes drilled in the floor or placed within the room itself. As indicated in Figure 7.1, there are at least two potential problems. First, there is the possibility of groundwater flow providing a pathway for the migration of radionuclides from the repository area to the biosphere. Second, there is the possibility of significant perturbations of the rock mass and the groundwater flow system by the thermal-mechanical loads induced by the heat from the decaying waste and by the development of the excavation.

In the first case the rock mass will be saturated and, although the porosity and permeability may be low, after backfilling the groundwater flow system will be re-established and groundwater will flow through the repository area. It can be assumed that in a carefully selected site the porosity and permeability of the rock matrix would be so low that no significant flows will occur through the matrix itself. Thus, the only potential pathway for migration of radionuclides is through fractures in the rock mass. A major problem confronting hydrogeologists is to determine the groundwater flow conditions in fractured crystalline or argillaceous rocks prior to mining and to predict what the flow conditions will be long after the repository is closed.

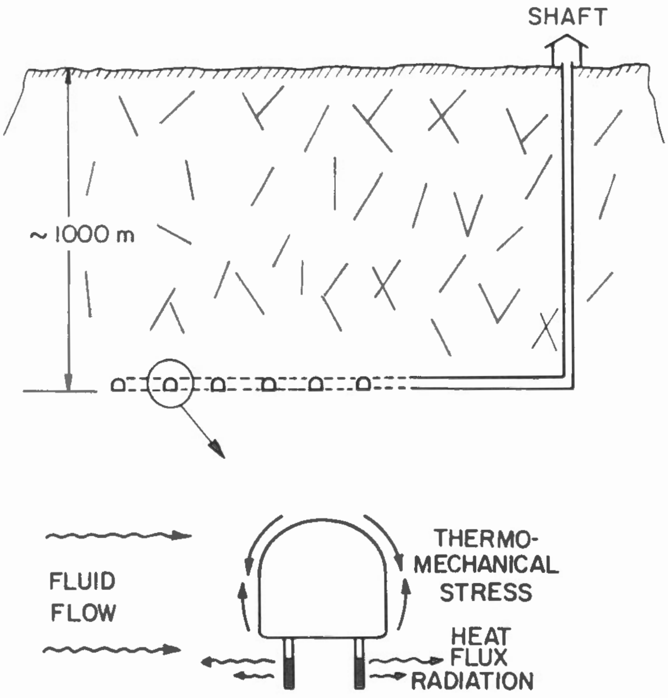

Figure 7.1. Mined cavern concept for radioactive waste storage.

When long time periods are considered, there are two possible mechanisms for radionuclide migration in groundwater. They are advection (transport by bulk groundwater flow) caused by hydraulic gradients, and molecular diffusion due to concentration gradients. Both processes require interconnected, water-filled, pore space in the rock mass.

Thermal-mechanical disturbances of the rock mass are of direct concern to hydrogeologists. Excavation of the storage rooms, access shafts, and drifts and the thermally induced stresses may produce significant displacements in the rock mass. These displacements, which generally will be localized by existing fracture planes or discontinuities, may alter significantly the porosity and permeability of the rock mass. In addition, the groundwater flow system may be altered in the short or intermediate term by thermal gradients and in the long term by thermal-induced solution and/or deposition of mineral phases in the fracture planes. Changes in the nature of the fracture surfaces may cause alteration of capacity of the surfaces for radionuclide uptake. Little is known about the response of rock to moderate increases in temperature (<100C) over time periods of 50 years or greater. Hence, a major question is whether new cracks or fractures will form in the immediate vicinity of the repository. If fractures do form, their potential impact on the flow system is not known.

Hydrogeology of Fractured Rock Masses

Basic considerations

Presently, the Canadian repository research program focuses almost entirely on plutonic rock. Figure 7.2 illustrates the nature of such rock masses. The main flowpaths anticipated are joints, fracture zones, and shear zones. Joints, as shown, are discontinuous in their own planes. In rock masses dominated by joints the hydraulic characteristics are in part a result of the interconnection of the different joint sets. Fracture zones are defined as zones of closely spaced, and highly interconnected, discrete fractures. Fracture zones measure from less than a metre to tens of metres in width but need not be continuous throughout the rock mass. Shear zones also measure from metres to tens of metres in width and are generally filled with broken and crushed rock; depending on the rock type this material may be embedded in a clay matrix. Shear zones tend to be hydraulically continuous throughout large parts of the rock mass. Large-scale features can extend for tens of kilometres but their hydraulic properties can vary considerably over such distances.

Figure 7.3, adapted from one produced by Swedish researchers (Stokes, 1977), shows a hypothetical regional groundwater flow system in crystalline rock. The flow system is short circuited in numerous places by near-vertical shear zones or fracture zones. Between the shear and fracture zones, flow occurs in joints. Presently, this type of flow system concept seems to provide a reasonable framework for a hydrogeological perspective. It must be emphasized, however, that the hydraulic characteristics of fractured crystalline and metamorphic rocks have not been studied in any detail. Almost no studies have been undertaken of deep flow systems in fractured crystalline rock masses. Most field estimates of the porosity (porosity is computed, not measured

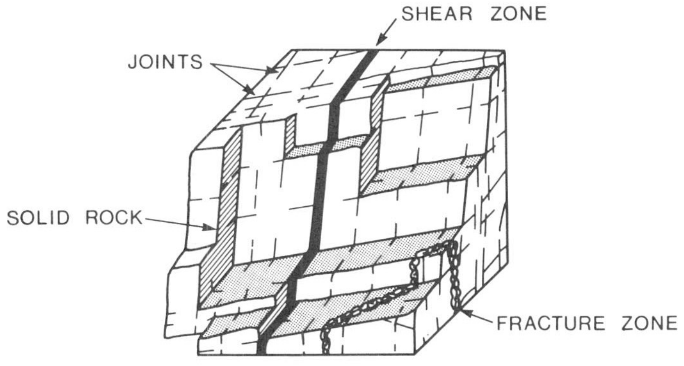

Figure 7.2. Main flowpaths in fractured crystalline rocks.

directly) and permeability of fractured rocks have been made during dam site investigations (such sites are generally located near major structural features) and during the development of domestic and industrial groundwater supplies (generally restricted to depths of less than 150 m). In both cases, the near surface zone in which these measurements have been made forms the most permeable zone within fractured crystalline and metamorphic rocks.

Field values that have been reported for the porosity and permeability of fractured crystalline rocks have been obtained using different testing procedures and the results have been interpreted using widely different theoretical models. Table 7.1 is a compilation of hydraulic conductivity values (LT^{-1}) for different igneous and metamorphic rocks. The values in Table 7.1 were computed on the basis of the "equivalent porous medium concept". For example, if water was injected into a borehole that intersected a number of fractures, no attempt was made to determine what contribution each fracture made to the total permeability. The permeability was computed by assuming that the entire section of the borehole being tested was permeable. This method of computation ignores the distribution of fracture apertures and can result in parameter values that are unsuitable when one attempts to predict the transport of a contaminant in fractured media.

Figure 7.4 is a compilation of porosity data that was summarized by Brace (1975) from field test results computed by Snow (1968) and others. This figure also shows the range of crack and pore porosities of about 30 crystalline rocks determined by laboratory measurements. These data suggest that porosity decreases with depth. It should be noted that the field porosity values were computed using models for which verification has not yet been established. Few data are available on the porosity of crack and pore spaces under confining pressures found at 1000 m or more below ground surface. The relative values of fracture porosity versus crack and pore porosity achieve some degree of importance if diffusion of radionuclides into the rock blocks, as discussed later, is assumed to be a significant mechanism of radionuclide attenuation.

The available permeability versus depth data have been tabulated by Davis and Turk (1964) and Snow (1968). In both cases the data show a rapid decrease of permeability with depth. The factors that control the movement of fluids through fractured rocks and hence contribute to this observed decrease in permeability with depth will be discussed later in this paper.

Conceptual problems in the hydrology of fractured rock

Nearly all hydrogeological analyses of groundwater flow in fractured rock have proceeded on the assumption that fractured rock masses can be represented as an equivalent porous medium. Figure 7.5 portrays the concept commonly used in representing a fractured medium as a porous medium. A parallel plate analogy is used for the fractures. In this example, fractures with apertures of 0.002 cm and space 1 m apart are equivalent to a porous media hydraulic conductivity of 10^{-6} cm/s. The hydraulic conductivity of the single fracture would be approximately 10^{-2} cm/s. In this development the fractures are assumed to be continuous in their own plane. This, of course, is unrealistic. Fractures in most cases are continuous over distances that are probably on the order of three to four times the average fracture spacing. As shown schematically in Figure 7.6, the real situation is one in which the hydraulic continuity depends on the degree of fracture interconnection. Thus, there is need for additional conceptual studies in fracture hydrology, some of which are currently underway (Gale and Witherspoon, 1978). Extensive work will be necessary to test the adequacy of the concepts and to determine the conditions under which they apply.

For hydrogeological evaluation of the concept of a waste repository in crystalline rock, a detailed data base must be acquired from a variety of intensive laboratory and field studies. Realistic numerical models for fracture flow and for radionuclide transport in fracture networks must be developed to yield the needed confidence in analysis of these systems. To put it simply, the problem of detailed analysis of flow in fractured crystalline rock is an exceptionally difficult one. In the repository research program, analyses based on normal porous media concepts seem in most situations to be irrelevant or, even worse, misleading. Until

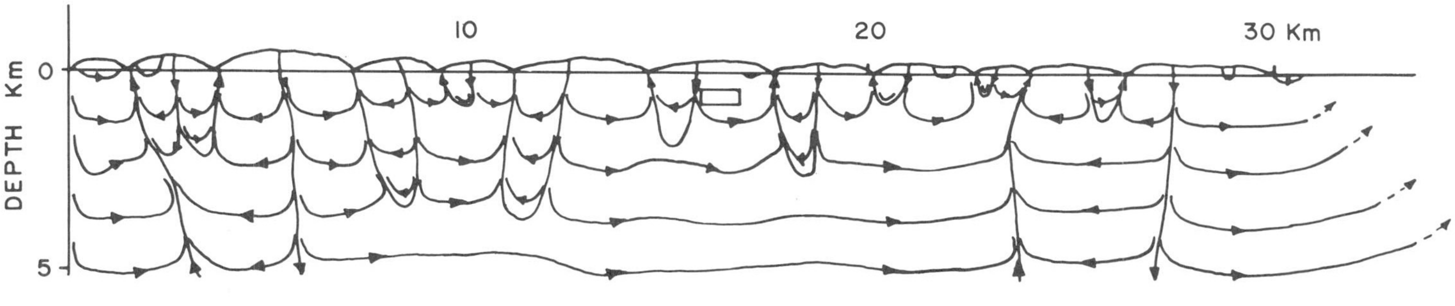

Figure 7.3. Hypothetical flow system in fractured crystalline rocks (after Stokes, 1977)

TABLE 7.1 HYDRAULIC CONDUCTIVITY VALUES FOR DIFFERENT ROCK TYPES (AFTER GALE, 1976)

Rock Type	Location	Hydraulic Conductivity cm/sec	Remarks	Source
Basalt	–	$2.0 \times 10^{-9} - 5.0 \times 10^{-5}$		Richter pers. comm. (1968)
	Oakflat Dam, Calif.	4.0×10^{-5}		Snow (1968)
	Hrazdan River, Yeravan, Aremenean SSR	$3.0 \times 10^{-5} - 5.0 \times 10^{-3}$	Varies with degree of folding & crushing	Ter Stepanian & Arakelian (1960)
	Sulky Site, Nevada N.T.S.	3.0×10^{-3}	Vesicular to dense basalt, computed from packer tests in holes penetrating full strata depth	Sherman and Banks (1970)
	Sulky Site, Nevada N.T.S.	5.6×10^{-3}	Vesicular basalt, computed from packer test results	Lutton and Girucky (1966)
	Snake River, Idaho	1.0×10^{-1}		DeWeist (1969)
	Oahu, Hawaii	$1.0 \times 10^{-1} - 3.0 \times 10^{1}$		DeWeist (1969)
	–	1.35×10^{-10}		DeWeist (1969)
Chert	Marquette Iron Mining District, Michigan	1.84×10^{-10}		Stuart *et al* (1954)
Dolomite		9.66×10^{-7}		Murray (1960)
		$1.18 \times 10^{-3} - 1.91 \times 10^{-3}$	Field measurements	Stimpson (1976)
Gneiss		$1.4 \times 10^{-1} - 2.26 \times 10^{-1}$	Field measurements	Stimpson (1976)
Gabbro	Okanagan Highland, B.C.	4.28×10^{-7}	depth 79.5'	Lawson (1968)
	Okanagan Highland, B.C.	5.25×10^{-8}	depth 45.3'	Lawson (1968)
Granite	–	$4.91 \times 10^{-11} - 9.99 \times 10^{-11}$	lab data (matrix) field measurements	Stimpson (1976)
Granodiorite		5.15×10^{-6}	22.5' depth	Stimpson (1976)
		2.30×10^{-7}	38.0' depth	Stimpson (1976)
		6.17×10^{-7}	46.5' depth	Stimpson (1976)
		9.31×10^{-7}	66.0' depth	Stimpson (1976)
		2.4×10^{-7}	96.0' depth	Stimpson (1976)
Greywacke		4.35×10^{-5}	11 field tests	Lewis (1966)
Greywacke	Marquette Mining District Michigan	$2.6 \times 10^{-11} - 1.4 \times 10^{-8}$ mean 3.1×10^{-9}	Matrix permeability 5 tests	DeWeist (1966)
Iron Formation	Marquette Mining District Michigan	$5.31 \times 10^{-7} - 5.3 \times 10^{-5}$	field measurements fractured	Stuart (1954)
Iron Formation	Marquette Mining District Michigan	$1.06 \times 10^{-10} - 3.7 \times 10^{-5}$ mean 1.59×10^{-6}	Matrix permeability 36 tests	DeWeist (1966)
Marble	Caroll & Frederick counties	1.74×10^{-2}	field measurements	Meyer and Beall (1958)
Metabasalt	Caroll & Frederick counties	1.8×10^{-3}	field measurements	Meyer and Beall (1958)
Migmatites	?	3.30×10^{-3}	field measurements	Stimpson (1976)
Quartzite	Marquette Iron Mining District Michigan	1.84×10^{-9}		Stuart *et al.(1969)*
Quartz Mica Schist	?	3.19×10^{-5}	lab., 21 tests	Stewart (1964)
		9.37×10^{-4}	field	Stewart (1964)
Rock Salt	?	7.05×10^{-9}		Gloyna & Reynolds (1961)
Schist	?	1.35×10^{-3}	field tests	Meyer and Beall (1958)
Slate	?	$1.62 \times 10^{-10} - 7.45 \times 10^{-11}$	lab test; jointed	Stimpson (1976)
Slate	?	1.3×10^{-9}	9 samples	Stuart *et al.* (1954)
Slate	Marquette Mining District, Michigan	$4.83 \times 10^{-10} - 4.3 \times 10^{-8}$ mean 5.8×10^{-9}	unfractured	DeWeist (1966)
Tuff	?	8.39×10^{-6}		DeWeist (1966)
Tuff zeolitized	Oak Spring Fm. Nevada	4.3×10^{-8}		Keller (1960)
pumiceous	Oak Spring Fm. Nevada	1.11×10^{-5}		Keller (1960)
friable	Oak Spring Fm. Nevada	1.3×10^{-6}		Keller (1960)
welded	Oak Spring Fm. Nevada	3.2×10^{-7}		Keller (1960)

sophisticated concepts and models for flow in fractured rock are developed, there will be little basis for determining the conditions or scale under which the equivalent porous medium approach is applicable. At present the equivalent porous medium approach is used almost without exception in investigations of flow in fractured rock. This is not done because this approach has been established as being valid under a wide range of scales or conditions, but rather because of the lack of rigorous and verified theories founded on other concepts. In nearly all investigations of flow in fractured rock reported in the literature, the focus is on flow in a water resources development or engineering excavation or construction framework. Prediction of bulk flow over large areas at shallow depth is usually all that is desired and, therefore, the objectives are significantly different than those inherent in hydrogeological evaluation of potential repository sites. In the repository case a major interest in acquiring a detailed understanding of the groundwater flow conditions is to provide a framework for prediction of radionuclide migration through the fractured rock mass in response to scenarios with various probabilities.

In regard to dispersion of contaminants migrating in groundwater in fractured rock the statement by Castillo et al. (1972, p. 778) is still a reasonable indication of the current status of the topic:

> "Although the basic theoretical aspects of ... (dispersion)... have been treated at length for the case where permeable stratum is composed of granular materials, the classical concept of flow through a porous medium is generally inadequate to describe the flow behaviour in jointed rock, and it becomes increasingly unsuitable for the analysis of dispersion. Despite these limitations, little work has been directed toward extending these ideas to handle flow through jointed rock formations ..."

Research Needs in Fracture Hydrology

It is reasonable to state that in order to proceed with evaluation of crystalline or argillaceous rock masses, many types of hydrogeological information will be necessary. Two specific areas of needed research are (1) determination of the factors controlling the volume and rate of groundwater movement through fractured rock masses and (2) development of methods for describing the permeability characteristics of fractured rock masses.

1. Factors controlling the movement of fluids through fractured rocks

For discussion purposes, the factors controlling the movement of fluids through fractured rock masses are grouped into two interelated categories: (a) geological variables and (b) hydraulic-mechanical properties. In the geological properties category, there is a need to determine the degree of fracture interconnection and its impact on flow in fracture systems and how fracture interconnection is affected by rock type, fracture type, and tectonic setting. Fracture porosity and fracture surface area are also important in the analysis of radionuclide migration. In the hydraulic-mechanical properties category, there is a need to determine fracture permeability as a function of rock type, fracture type, sample size, normal and shear displacement, thermal loading and fracture geometry. Also included are such questions as will the thermal-mechanical effects produce new fractures, will the thermal-mechanical loads produce changes in the stress-permeability relationship for old fractures, and will there be changes in water chemistry and fracture surface properties?

2. Measurement of directional permeabilities

Flow in fractured argillaceous rocks may in some cases be dominated by high permeability layers. In such cases current testing and analysis techniques permit determination of lateral permeabilities in the high permeability zones and vertical permeabilities in the low permeability zones (Witherspoon et al., 1967). Waste disposal considerations require that the nature and distribution of the fractures in the more impermeable layers and their hydraulic characteristics be described. The principal permeability components in the more permeable zones tend to be parallel and perpendicular to the lithologic boundaries. More impermeable, fracture-flow dominated layers tend to be highly anisotropic and the principal components of the permeability tensor need not be geometrically related to the lithologic boundaries.

In fractured crystalline rocks, through-going structural features such as shears and fractures are major hydraulic features and as such can usually be characterized in detail. In other parts of the rock mass, flow is controlled by the fracture system (i.e. fracture permeability) and is highly anisotropic. For nuclear waste storage, it may be necessary to determine the directional permeabilities of the fracture system. Three possible approaches to determining directional permeabilities have been identified (Gale and Witherspoon, 1978). The first method consists of the use of discrete fracture data to describe the rock mass in the form of a permeability tensor (i.e. an anisotropic continuum). This approach requires careful mapping of the fracture system, the drilling of boreholes approximately perpendicular to the principal fracture sets, oriented core drilling, detailed logging of the drill core in order to describe the geometry and characteristics of the fracture plane, detailed injection testing to determine effective fracture apertures, and the mathematical integration of these data into the form of a permeability tensor.

The second approach, described by Louis and Pernot (1972), requires careful mapping of fracture orientations to calculate the directional permeability axes for the rock mass. A central borehole, with peripheral boreholes, is drilled parallel to each of the three principal permeability axes. Interpretation of multiple packer injection test results are based on fluid pressures measured in the peripheral holes.

A third approach consists of drilling orthogonal boreholes oriented with respect to the fracture system and testing the boreholes with increasing packer spacing. It is anticipated that with increasing packer spacing the permeability should approach an average value.

It must be recognized that carefully designed tests will have to be carried out in a number of different rock masses representing different fracture systems and boundary conditions in order to properly evaluate the various approaches and build confidence in the more useful techniques. It is important to be able to identify which of the approaches is most applicable to each of the different fractured rock masses, fracture systems and permeability régimes that will have to be explored in the near future. It should be stressed that no one method will be applicable to all the physical situations that will be encountered.

Diffusion in Fractured Porous Rocks

There is little doubt that sites can be found where rock has sufficiently low permeability to provide conditions such that groundwater inflow will not prevent or endanger mining or engineering activities during repository excavation and waste emplacement phases. If the natural rock conditions are not adequate, grouting could be used to achieve levels of groundwater inflow low enough for these activities to proceed. The concern with regard to groundwater flow focuses on the postoperational phase of the repository and revolves around the question of whether or not there will be a significant potential for radionuclides to migrate to the biosphere via the groundwater system in the rock in a manner that will result in an unacceptable radionuclide flux to the biosphere. To provide a basis for analysis of radionuclide transport in the fractured rock mass, it is necessary to be able to predict the influence of molecular diffusion of radionuclides in groundwater as well as that of flow of groundwater and associated radionuclide advection.

Molecular diffusion occurs as a result of concentration gradients and, therefore, would be capable, in the presence or absence of advection and in the presence of interconnected porosity in the rock mass, of causing radionuclide migration. In the event that radionuclides are leached from the waste mass and that they eventually reach the exterior of the repository, molecular diffusion has potential to be a process that in some situations enhances the eventual flux of radionuclide migration to the biosphere or that in other situations decreases or prevents a flux to the biosphere.

In this discussion, it is assumed that in some manner radionuclides have migrated to the exterior of the repository and, consequently, are available for transport in groundwater in the rock mass. If the rock mass has fractures with a significant degree of interconnection, and if the matrix porosity of the rock is very small, molecular diffusion, in the absence of appreciable hydraulic flow directed inward to the repository, will cause radionuclides to move outward. For radionuclides that do not undergo significant chemical retardation by reaction with the fracture surface, diffusion coefficients in the fracture network may be significant and in some situations be capable of causing the radionuclide front to advance appreciable distances in fractures. This may produce a gradually expanding radionuclide diffusion halo around the repository. Hydrogeologists normally regard molecular diffusion as a process of no practical significance. In the perspective of a high-level waste repository, however, where it has been deemed necessary to consider containment capabilities for tens of thousands of years and more, the consequences of molecular diffusion must be evaluated. A pessimistic approach is to consider the diffusion coefficients for nonreactive radionuclides in fractures to approach their magnitude in free water. This can lead to computed diffusion distances that are considerable. The magnitude of diffusion coefficients of radionuclides or other solutes in crystalline or argillaceous rock (or any other rock type) has, to our knowledge, never been investigated in detail.

The above discussion pertains to situations in which radionuclides migrate in fractures in rock masses with very small effective

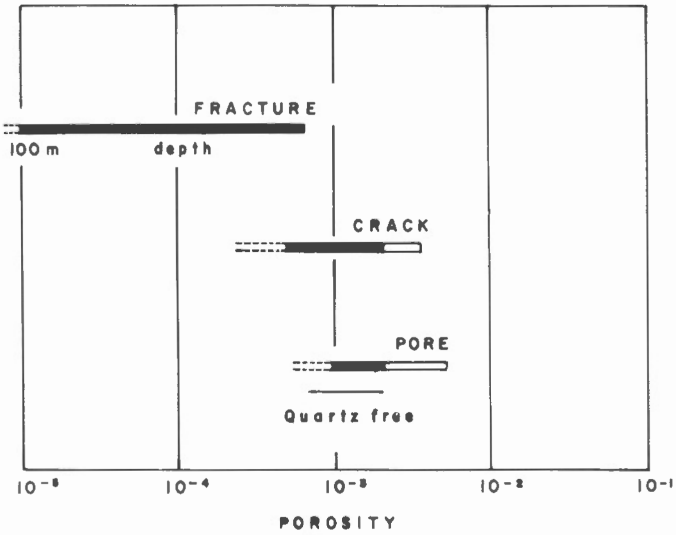

Figure 7.4. Variation in three types of porosity from data compiled by Brace, 1975.

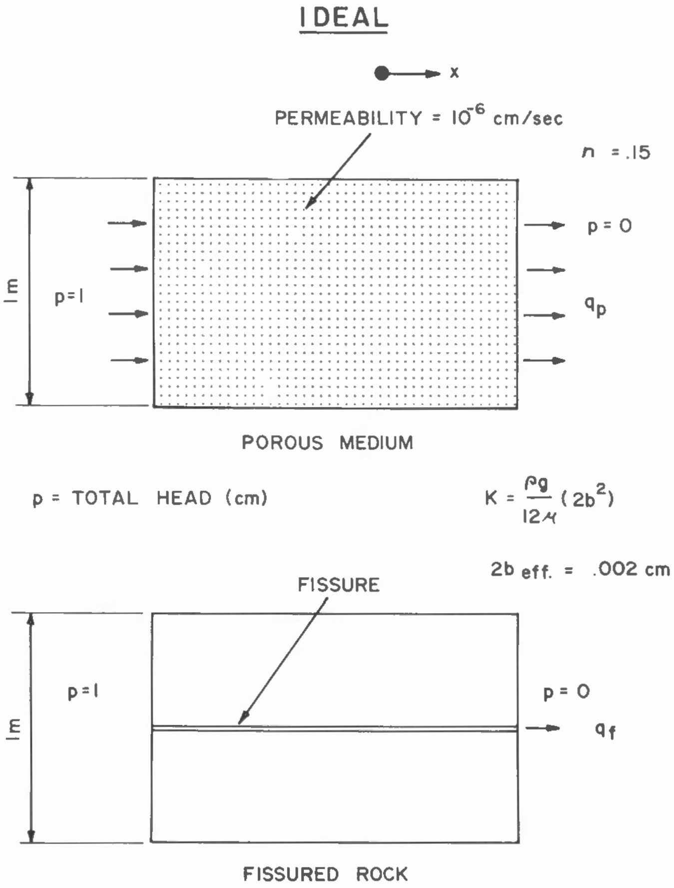

Figure 7.5. Illustration of porous and fractured media idealisation (after Maini, 1977).

matrix porosity. In situations where the rock mass has a much larger matrix porosity, the influence of molecular diffusion can be much different. If radionuclides move by advection or diffusion along fractures in fractured porous rock, part of the radionuclide mass in the fracture is continually removed from the fluid in the fracture. This occurs as a result of migration into the porous matrix due to molecular diffusion. As the radionuclide front in the fracture moves forward a concentration gradient directed from the fracture to the matrix progressively develops along the fracture. If the fracture aperture is small and if the diffusion coefficients for the porous matrix are appreciable, the diffusive loss of radionuclides from the system of groundwater flow in fracture networks can cause the advance of the front of contaminated groundwater to be greatly retarded (Fig. 7.7). The porous rock matrix in effect acts as a contaminant sink which buffers the system of contaminant transport in the fracture network. Given this conceptual framework for diffusion in fractured porous rock, the question arises as to whether or not this diffusive buffer to contaminant transport in fractured rock can be assessed in a quantitative manner at potential repository sites and whether or not particular rock types, such as shale, offer advantages in this regard. These questions have yet to be addressed in any significant research effort. Determination of the role of matrix diffusion in solute migration through fractured rock also will be a necessary prerequisite for quantitative interpretation of naturally occurring isotopes, such as carbon-14, for groundwater dating.

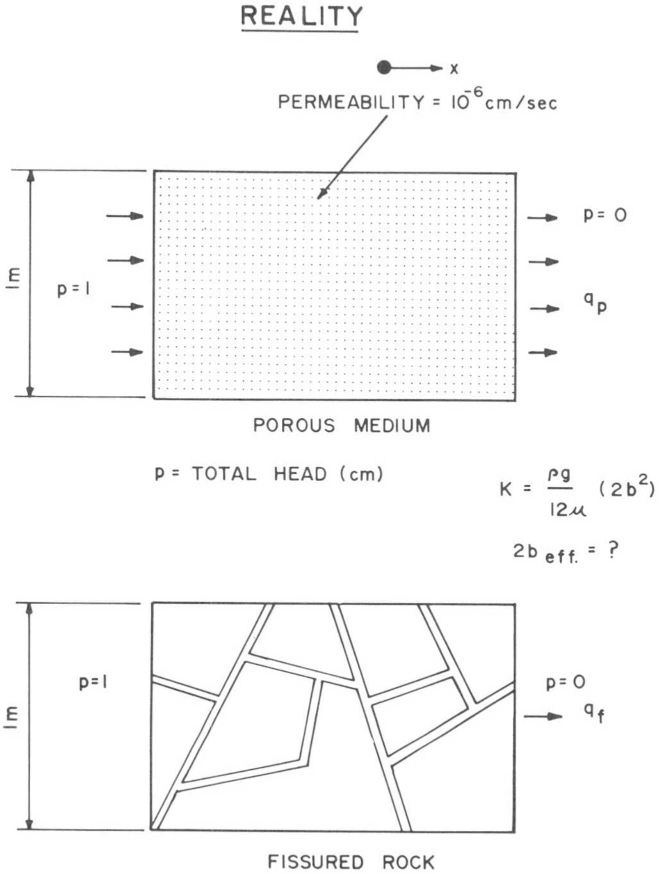

Figure 7.6. Illustration of porous and fractured media.

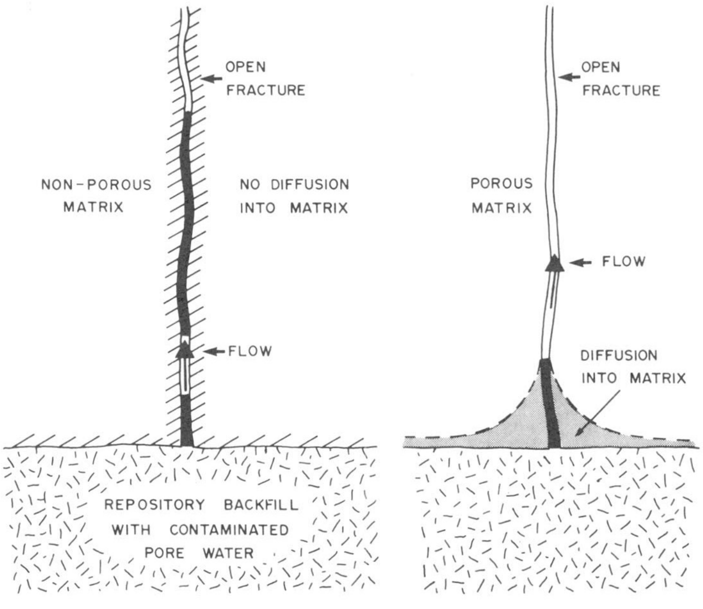

Figure 7.7. Diffusion in fractured nonporous and porous media.

Hydrogeology in A Historical Perspective

Although the basic empirical relation between groundwater flux and hydraulic gradient, now known as Darcy's law, was developed by Henri Darcy in 1856, it was not until the work of C.V. Theis in 1935 and M. King Hubbert in 1940 that the theory of groundwater flow and aquifer behaviour was formulated in a rigorous manner. This provided the foundation for modern developments in hydrogeology. From the 1930s to the late 1950s both the practical and research activities in hydrogeology focused on the behaviour and evaluation of aquifer systems, with fractured rock aquifers being treated as equivalent porous media. The first research-oriented Canadian groundwater group was formed in the mid-1950s. In the 1960s, hydrogeology began to blossom as a subdiscipline in the earth sciences and engineering. Progress was made in many areas, including the behaviour of low permeability (unfractured) deposits, regional flow systems in sedimentary terrain, hydrogeochemistry, isotopic groundwater age determination, and particularly the development of numerical (computer) models for groundwater flow. Some of the earliest significant theoretical work on groundwater flow in fractured rocks was done during this decade. The 1970s marked the beginning of a gradual shift in research emphasis towards topics related to contaminant behaviour in groundwater systems, with emphasis almost entirely on nonfractured systems. Modelling of contaminant and energy transport in groundwater began in the early 1970s, with the advection-dispersion equation for contaminant transport in isotropic granular media serving as the theoretical foundation. In the mid-1970s, the first significant attempts at treating groundwater environments as stochastic systems began to appear in the literature. In all of the above-mentioned endeavours, however, the geological domains were treated with porous media concepts.

It is appropriate to appraise the hydrogeological nature of the task of developing a high-level radioactive waste repository in deep rock environments within this historical perspective. There is little within the knowledge base of modern hydrogeology that equips us for the analysis of regional flow and contaminant transport in fractured rocks, and particularly fractured rocks of low permeability. The thrust of hydrogeological research has been generally on topics remote from this particular problem. Research areas that are most relevant, such as flow and dispersion in fractured media and the incorporation of probabilistic concepts to assess uncertainties, are in their infancy. For pathway analyses of rock masses for repository systems, reliable contaminant transport models will be necessary and in this regard it should be noted that the hydrogeological community is in the very early stages of trying to model contaminant transport in flow systems in unconsolidated granular deposits that possess a significant degree of heterogeneity. In general, these systems are viewed as having much greater simplicity than regional flow systems in fractured rock. Contaminant dispersion in groundwater in unconsolidated deposits is a subject of considerable debate by various research groups. Dispersion in fractured rock is not yet a subject of significant discussion because little or no detailed field data on this topic are being generated, nor have useful conceptual models been developed.

Hydrogeology and the Canadian Program

It has yet to be shown, with an appropriate level of confidence, that multiple barriers within a repository are capable over long periods of time of preventing excessive release of radionuclides to the rock mass containing the repository. Therefore, in the development of Canada's high-level radioactive waste repository it is necessary at present to require that the rock mass provide, within a high degree of probability, long-term radionuclide containment capability. This will necessitate that the hydrogeological nature of the rock mass be understood in considerable detail, and that hydrogeological factors play a major role in the process or rock-type evaluation and actual site selection and evaluation.

Given the present hydrogeological uncertainties noted above, the present schedule for repository site selection and development is unjustifiable on scientific grounds. The recent joint agreement between the Minister of Energy, Mines and Resources and the Ontario Minister of Energy suggests a tentative schedule for planning of 6 to 10 boreholes about 1000 m deep to be drilled in 1979-80, that site selection for a demonstration repository occur in 1981-1983, that repository site acquisition proceed in 1983 and that a disposal demonstration program begin in 1985. This tentative schedule fails to recognize the nature and magnitude of the hydrogeological segment of the problem, and as well fails to recognize the current paucity of knowledge and available expertise with regard to the hydrogeology of deep rock masses. Making a repository is an endeavour that is well within the present capability of the mining industry, whereas hydrogeologically-based site selection methodologies and radionuclide pathway analyses in deep rock systems are not presently within the near-term capability of the hydrogeological community in Canada or elsewhere. There is little indication that government agencies responsible for repository search and development have developed a realistic view of the hydrogeological segment of the problem. Without this view, it will probably not be possible to proceed in a manner that will have credibility within the Canadian hydrogeological community, and without this view repository search and development eventually may lack credibility within the geoscience community at large.

To some readers, the hydrogeological perspective that we have outlined may seem unreasonable. The question can be raised as to the means by which the various government agencies with responsibilities in the Canadian repository program arrived at a state whereby tentative schedules and research emphasis seem to be divorced from the major limiting factors, namely the current inadequacies of the hydrogeological methodologies and models. This situation is viewed as having arisen because none of the agencies involved have had what generally would be regarded as a critical mass of hydrogeological research expertise. Thus, it is not surprising that when a task (the radioactive waste repository) with major hydrogeological components arose, the components were not brought into focus. This lack of recognition of the hydrogeological nature of the problem culminated in 1977 with a publication by the Department of Energy, Mines and Resources (Aikin et al., 1977). This report was "Commissioned by the Department of Energy, Mines and Resources to provide the government and the public of Canada with the views of an independent expert group on the subject of nuclear waste disposal" *ibid.*, p. iii. The three man "independent expert group" that authored this report did not include a member with any experience in the field of hydrogeology or geotechnical engineering. It appears that none of the authors of this report had discussions with a significant spectrum of the Canadian hydrogeological community. Furthermore, views were not acquired from any of the well recognized, experienced, research-oriented hydrogeology groups in the United States. These shortcomings in the report by Aikin et al. (1977) appear to be partly due to the inadequate time, only four months, allocated to its preparation. It is not surprising, therefore, that this report has inappropriate or misleading statements on hydrogeological matters and significant omissions. In general, it does not identify the nature and scope of the problem.

Recommendations

We have attempted to develop a realistic hydrogeological perspective and within this perspective we have identified some concerns with regard to the Canadian program for research and development of a high-level radioactive waste repository. In proposing some positive suggestions, we first should point out that the criticisms indicated above do not reflect a pessimistic view with regard to probabilities for eventual success in the search for and development of a deep repository. Success is anticipated, if this endeavour proceeds at a reasonable pace in light of the scientific nature of the problem. The paucity of hydrogeological knowledge, data acquisition methodologies, and conceptual models for deep rock systems must be fully recognized and accounted for in the research and development process.

1. Our first recommendation is that a "go-slow" progression towards selection of an actual site be adopted. site selection should be delayed until the knowledge base can be developed to an adequate level. This will probably require 5 to 10 years of intensive research. There is no point in entering into a serious site-search phase until more is known about the

thermal-mechanical and hydrogeological properties of the various rock types under consideration. It is unrealistic to expect to obtain definitive data from boreholes until borehole testing methodologies are much more advanced. Drilling and testing of boreholes are, of course, necessary endeavours, but it is too soon to decide on the overall value that they may have in the progression towards identification of suitable rock masses for repository development.

It seems essential to mount a long-term hydrogeological research effort with a commitment to a reasonable progression and continuity, and involving government, industry, and university research groups in a co-ordinated effort. This should not be a crash program with an intensive effort for a few years followed by a rapid withdrawal of resources. It should be recognized that an exceptionally intensive program of hydrogeological research cannot be mounted in the next year or two because of limitations of scientific manpower within the hydrogeological community. The current Canadian effort can and should be expanded considerably (relative to the 1978 effort), but it cannot be expanded quickly by orders of magnitude. In other words, we recommend that a program of Canadian hydrogeological research should be mounted over a 10 year period within a schedule based on scientific realities rather than on short-term political expediency. In the long-run, verification of the deep rock repository concept will have to survive debate in the scientific community at large as well as in the public and political domain.

2. To have a reasonable chance of arriving at an appropriate conceptual framework and hydrogeological methodology, we recommend that large-scale, virgin site studies (test shafts and rooms) be undertaken. These studies should be conducted at experimental sites rather than sites of priority for repository development (i.e. not a pilot repository for transformation into a full scale repository). This will decrease public relations difficulties and will enable the rock mass to be drilled and instrumented in a manner that would not be appropriate for an actual repository. In our opinion, one virgin site study should be brought into operation in Canada in the near future. Although considerable appropriate hydrogeological research is now underway in many countries, including an active research program begun in Canada in 1977, the nature and magnitude of the problem of radionuclide transport in slightly fractured rock is such that hydrogeological experience factors related to deep rock environments can be accelerated only marginally without virgin site studies. Laboratory studies, borehole studies, and modelling efforts will provide for improvement of the hydrogeological knowledge base, but can be expected to be inadequate for verification of key hydrogeological concepts or predictions.

3. The Canadian research and development program for the high-level waste repository is focused almost entirely on plutonic crystalline rock (i.e. the Precambrian Shield) in Ontario. In hydrogeological terms, so little is known about plutonic crystalline rock in Canada or elsewhere that it seems to us that it would be prudent to gradually mount a significant Canadian hydrogeological research effort directed at other rock types, primarily shale and salt (a salt option would necessitate research on shale and associated stratigraphic zones). The level of funding necessary to begin this effort is not so large that it would appreciably detract from the crystalline rock program.

   Plutonic crystalline rock is recognized as being reasonably convenient from a mining point of view and offers many areas in which repository searches could be undertaken far from the population centres of southern Ontario and even from cities farther north. With regard to remoteness from population centres, it is our understanding (and on this point we are certainly open for correction from risk assessment researchers) that the construction and operation (possibly excluding transportation of waste) of a high-level waste repository does not represent, to the population in the repository region, a risk of significance relative to the many other risks with which people coexist within our industrial society. For repository sitings, remoteness from southern Ontario increases the transportation distance for the waste, which may in itself be a significant disadvantage. In other words, with public relations factors aside, we are aware of no scientific reasoning (other than mining convenience) that would lead at this time to the conclusion that plutonic crystalline rock is the only rock type worthy of a significant level of research in the Canadian program. A thick sequence of Paleozoic sedimentary rocks, with appreciable thicknesses of salt and shale exist in southern Ontario very close to existing nuclear power centres. On the basis of current hydrogeological knowledge, or lack thereof, it is reasonable to state that the probabilities of achieving a repository, with long-term rock mass containment capability, in plutonic crystalline rock or in the Paleozoic stratigraphic sequence are very similar. Thus, for example, there is no reason to believe that there is a better chance of finding a suitable rock mass at a remote site in north-central Ontario than there is in some part of the Paleozoic stratigraphic sequence in southern Ontario. There is also the possibility that a repository could be located in crystalline Precambrian rock beneath many hundreds of metres of Paleozoic sedimentary rock in southern Ontario, perhaps combining the advantages of both rock groups.

4. As a concluding recommendation we would like to stress that what is actually needed are national and provincial plans for disposal of nonradioactive industrial wastes as well as for radioactive wastes. With regard to hydrogeological matters, there is an urgent need for a comprehensive long-term research effort, of which hydrogeological matters related to the high-level repository would be an important segment but only one segment within a carefully designed overall framework. Problems that face hydrogeologists in Canada with regard to development of a high-level repository are just one group within a large number of important hydrogeological problems of an environmental nature in Canada at the present time. When considering the nuclear fuel cycle and the role of groundwater in the transmission of radionuclides to the biosphere, the problem of uranium mine/mill tailings could be viewed as having an urgency far beyond that of the high-level repository.

In Ontario, there is a critical problem with regard to the treatment and disposal of a multitude of types of hazardous nonradioactive industrial wastes. It is generally accepted that a considerable portion of this waste mass, even with advanced treatment and processing methods, will have to be disposed of by subsurface burial. These and many other urgent problems require a considerable component of hydrogeological research and development. The Canadian hydrogeological community is small at present. It is growing at a steady but slow rate and it will be many years before the number of hydrogeologists with appropriate training and experience begins to come close to the number needed to address the many existing problems associated with subsurface storage or disposal of wastes. It would be unfortunate if hydrogeological research in Canada were to become excessively focused on the "high-level radioactive waste repository problem". This would ensure a continuation of neglect in these other important and in some cases more environmentally urgent areas. Calling on the Canadian hydrogeological community to focus its major research and development efforts over the next few years on the high-level radioactive waste repository may be analogous to calling the fire department to water the lawn while the house burns down.

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8. GEOLOGICAL ENGINEERING FACTORS IN THE DESIGN OF A RADIOACTIVE WASTE REPOSITORY IN HARD CRYSTALLINE ROCK

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Introduction

A program to develop techniques for the ultimate disposal of high-level radioactive wastes into geological formations was announced by Atomic Energy of Canada Limited (AECL) in 1975 (Tammemagi, 1976). The present paper summarizes the studies carried out by the authors and associates on the development of design concepts for a vault situated in crystalline rocks of the type present in the Canadian Shield as part of the AECL program.

The design studies have been carried out in three phases, the elements of which are described below (Fig. 8.1). The design concepts under consideration provide for emplacement of either immobilized fuel or solidified reprocessing wastes in a room and pillar facility located at a depth of 1000 m.

The principal design considerations are reviewed from the construction, operation and thermal/mechanical response aspects. The project has been studied in both the temporal and spatial domains, and the requirements and responses assessed in each as appropriate.

The availability of relevant experience from previous major underground construction projects is also discussed.

Finally, brief comments are given regarding the interfaces with other programs, design-oriented research and development requirements, and preliminary findings of the current studies.

An overview of the vault design program

Program

The principal elements of the three phases of the studies to date are shown in Figures 8.2, 8.3 and 8.4.

The major objectives of the Phase I studies were:

to develop preliminary facility design concepts for the disposal of reprocessing wastes arising from an upper limit estimate of nuclear power generation to the year 2025;

to assess the feasibility of crystalline rocks as a vault-host medium;

to estimate development and construction costs; and

to identify research and development requirements to validate feasibility.

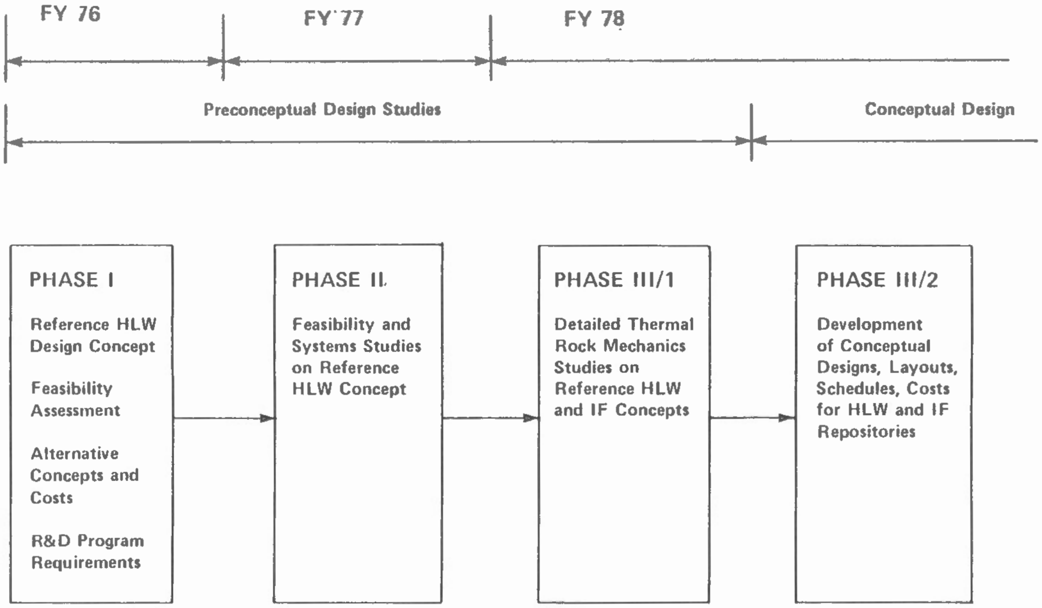

Figure 8.1.
Repository design studies.

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[1] Acres Consulting Services Ltd., Niagara Falls, Ontario.
[2] RE/SPEC Inc., Rapid City, South Dakota.

From: Geological Survey of Canada Paper 79-10.

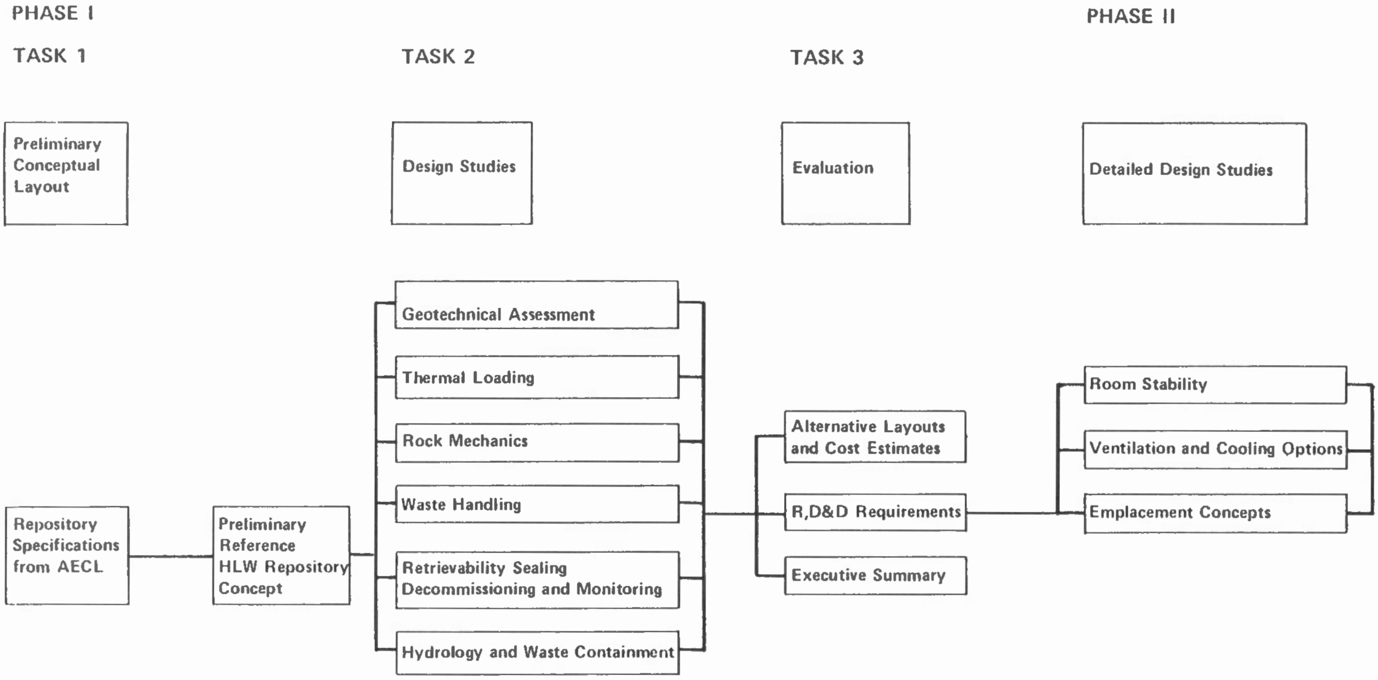

Figure 8.2. Phases 1 and 11 studies, repository design FY 76 and FY 77.

The results of these studies were submitted in a report to AECL by Acres Consulting Services Limited (1977). A summary of the studies was presented at Rockstore 77 (Charlwood and Gnirk, 1977). Thermal/rock mechanics aspects were described by Mahtab et al. (1977), and layout considerations discussed by Grams et al. (1977). The principal conclusions of the Phase I studies were as follows:

- a reference concept was developed which could be constructed using state-of-the-art techniques.
- it was recommended that the crystalline rock design program should proceed into the detailed site study stage and that conceptual studies should continue.

Consequently, AECL initiated the Phase II detailed studies of key aspects of the reference concept in fiscal year 1977.

In early 1978, AECL significantly modified the vault design objectives to include the disposal of either immobilized irradiated fuel (IF) or solidified reprocessing wastes (RW), and initiated the Phase III studies which are currently in progress by the authors and associates. Two design concepts are being considered as the bases for analysis and design studies (one for each fuel cycle option) and are presented below. These waste emplacement and backfilling concepts were developed to illustrate the alternatives available for design. They are for the purposes of current studies and will be subject to complete review, and possibly modification, on completion of Phase III.

Preliminary Design Concepts

The deep geological vaults are expected to accommodate all IF containers fabricated to 2025 or all RW containers fabricated to 2045 from the operation of all Canadian CANDU-PHW reactors until 2015. This requires emplacement of 246000 IF or 186300 RW containers using the preliminary packaging concepts. The heat generation rate per container for both IF and RW at the time of disposal will be 269 W. Other dates for emplacement are being considered, which may afford the advantage of additional decay prior to emplacement.

The vault(s) will be located on a single level at a depth of 1000 m in granite or gabbro. Access to the vault will be provided via main waste handling and service shafts and haulage and ventilation drifts, as shown in Figure 8.5. Room and pillar (actually lane and pillar) type of excavation, using conventional mining procedures, will be employed.

The preliminary layouts were developed prior to undertaking the detailed analyses. The arrangement of the vault will be based primarily on construction and operational considerations. It will consist of several panels 400 m in width, with lengths varying between 800 and 1400 m. Each panel will contain between 50 to 80 rooms depending on the type of waste and the results of the thermal/mechanical analyses. A generalized layout is shown in Figure 8.5. The required storage capacity for IF packages to the year 2025 and RW packages to the year 2045 will be provided by 10 and 7 such panels, respectively.

In particular the following factors were considered in determining the layout of the vault:

- the method of excavation chosen was conventional drilling and blasting for hard igneous rock. Trackless, diesel-powered excavation equipment was used for optimum performance and flexibility.
- it was estimated that effectively ambient rock temperatures would prevail beyond a distance of about 200 m from the storage rooms during the operational life of the vault. Therefore, the recommended layout includes placing the shafts at least 200 m from the active zone of the repository.

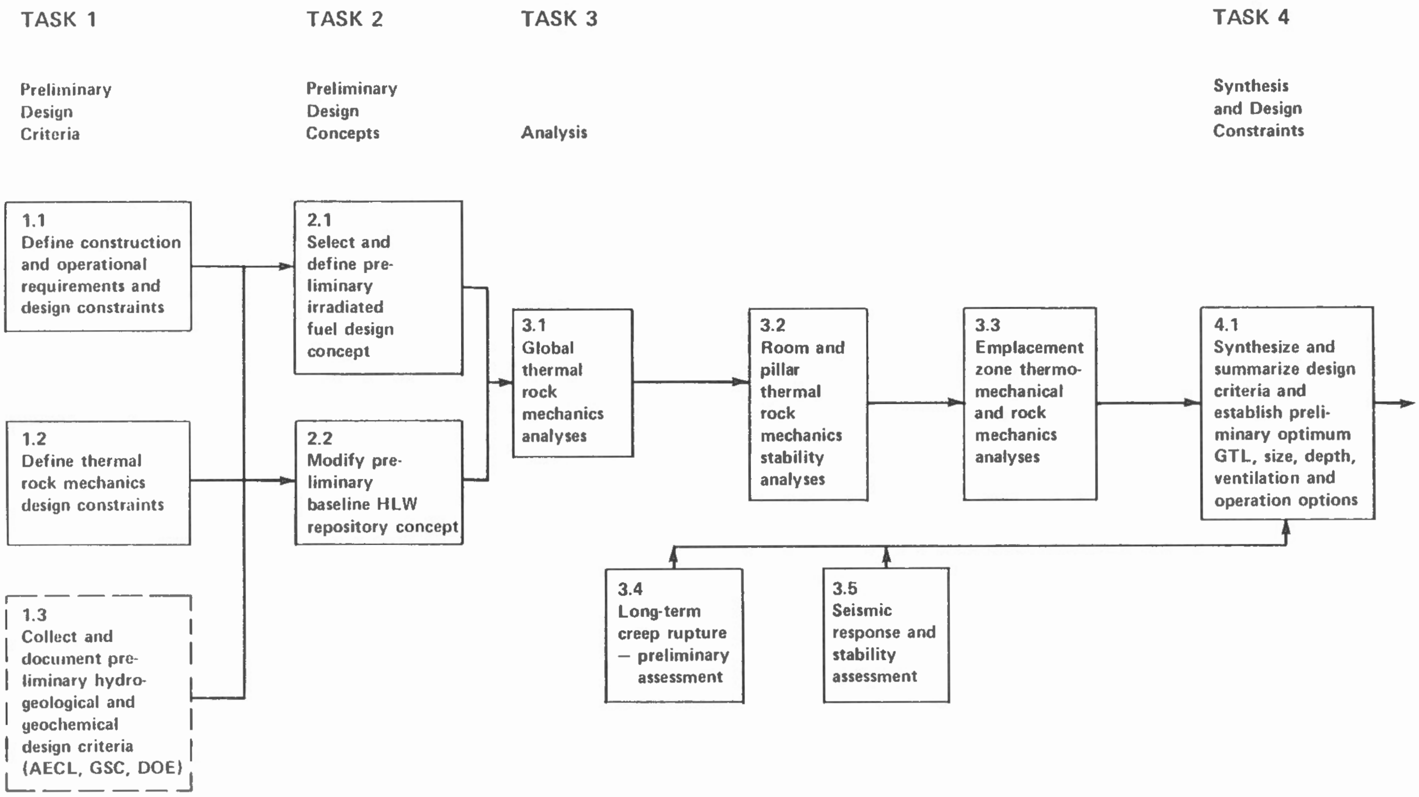

Figure 8.3. Conceptual design phase 111/1 study flow chart, repository design studies FY 78.

- the size, shape and spacing of the storage rooms are functions of the rock properties, gross thermal loading, characteristics of the excavation and backfilling equipment, and ventilation requirements. The thermal/rock mechanics analyses are to determine the thermal loadings that are compatible with the specified temperature and mechanical constraints (both aspects are discussed below).
- the size of the panel was determined by the optimum tramming distance for the rock loading and the ventilation system requirements.
- the layout employed the retreat system of mining and emplacement away from the heated areas. Also incorporated into the layout was a unidirectional flow of ventilation air from the access shafts, through excavations and storage rooms, to the exhaust shafts at the far end of the vault.
- initial development of all the main drifts would allow access for on-site investigations of the entire repository area at the vault level. The pilot panel(s) would be at the exhaust end of the vault.

Various other construction, operational and long-term isolation considerations are being incorporated into the conceptual designs which are expected to be completed by early 1979.

The IF containers will be placed within the backfill, as shown in Figure 8.6. One metre of a geochemically designed backfill will be provided above and below the containers to possibly provide an additional barrier for long-term isolation. The upper part of the room will be backfilled 20 years after emplacement unless continued access is required for some time for retrieval or other purposes.

As shown in Figure 8.7, the RW containers will be emplaced in holes drilled in the floor of the room. This concept simplifies the handling operations since the waste will be effectively shielded once it is in the drillhole. The pillar will be at least 7 m wide. The design concept assumes that the room will be backfilled after waste emplacement with a mixture of 20 per cent clay and 80 per cent crushed rock.

The width of the room (7.5 m for both IF and RW) is dictated by the container spacing (1.5 m) across the room. The heights of the rooms (6.15 m for IF and 5 m for RW) are governed by considerations of access and container handling, backfill depths (IF), and hole drilling (RW). The waste transport and panel drifts, as well as the main haulage drift, are excavated to a height of 4 m by 5 m wide to allow for good tramming conditions for the trucks, and to provide an adequate cross section for the air flow.

Design considerations

Construction and operation phases

The time frames for construction and operation of the vault are shown in Figure 8.8, and consist of the initial construction, short-term and long-term periods. The figure also gives a brief description of the principal processes, occurring in each period, which need to be considered in the design.

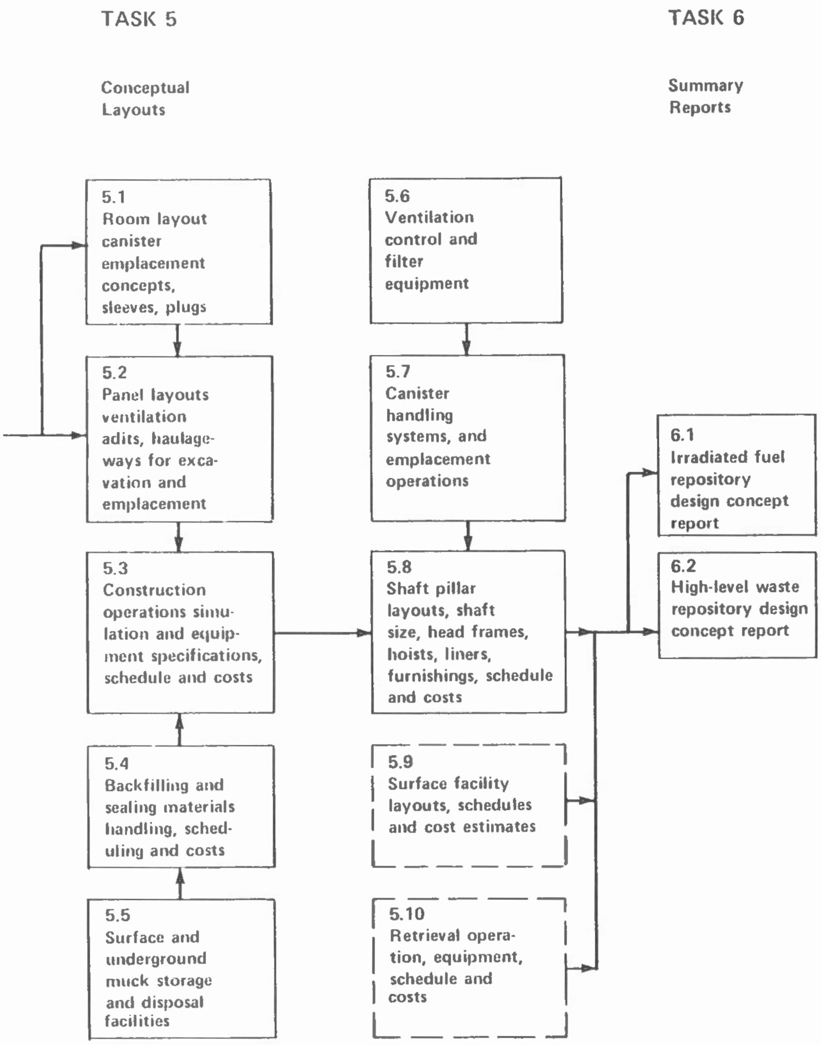

Figure 8.4.
Conceptual design phase 111/2 study flow chart, repository design studies FY 78.

Preliminary design specifications

The IF and RW vaults are considered to be located at a depth of 1000 m in granite or gabbro. The thermomechanical design specifications (that have evolved during Phases I to III of the studies) are given in Figure 8.9. The specifications refer to three distinct geometric regions of the vault. The container near-field region contains the container cavity, and the rock mass along the room and pillar, extending from the floor of the room to a few metres below the container. The room and pillar region contains the rock mass around a room and pillar unit, extending to several room diameters above and below the room. The far-field region envelops the rock mass around the vault, extending from the ground surface to two or more times the vault depth below the vault, and to at least a vault length beyond the edges of the vault.

Thermal/rock mechanics analysis framework

The framework for thermal/rock mechanics analysis stems from the specific objective of the studies, which is to establish the areal emplacement density of the IF or RW in terms of the thermal loadings that are acceptable in view of the design specifications. The matrix of principal parameters to be used in the analysis contains these elements.

Gross thermal loading (GTL)

GTL is the thermal loading per unit (plan) area of the vault, including haulageways, at the time of emplacement. GTL is a function of initial container power (269 W), container spacing, and extraction ratio (width of room/width of room plus width of pillar).

Rock type

The two rock types which are being studied, granite and gabbro, are assumed to have similar mechanical properties, including the geometries and strength of joints. The significant thermal properties, which are different for the two rock types, are the conductivity and the coefficient of expansion.

Ventilation and retrieval option

The possibility of access for retrieval or other purposes is an option that is considered for the IF vault only. An access period of 20 years from emplacement of the waste has been assigned for design study purposes; longer periods are possible if required. An

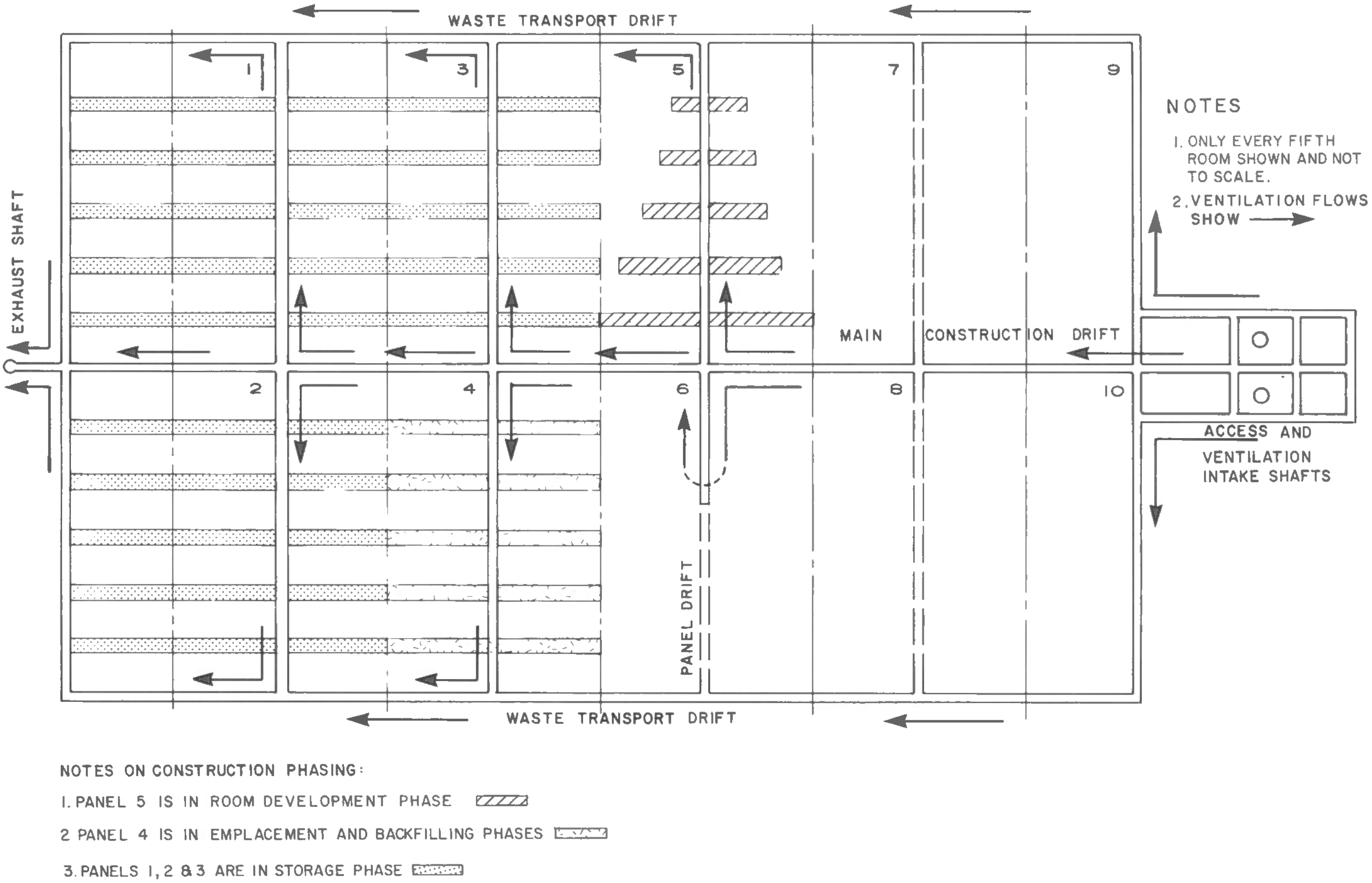

Figure 8.5. General layout of RW and IF vaults.

assessment of the cooling caused by air ventilation required for these operations is also necessary.

Among the principal parameters, gross thermal loading, being a composite of several geometric variables, provides a large number of degrees of freedom. For design we actually use the panel thermal loading, PTL, (which neglects the influence of haulageways and is about 2 per cent larger than the GTL). The relationship of the PTL to the geometric variables, extraction ratio (ER), spacing of containers along room (pitch), and spacing of containers across room, is given by PTL = (269 x S x ER)/(pitch x width of room).

Preliminary results of the investigation show that several combinations of the geometric variables provide a range of acceptable PTL and GTL values.

The thermal/rock mechanics considerations also include the *in situ* stress, the geometry and strength of joints, the failure characteristics and nonlinear behaviour of a rock mass, and the requirements for conventional support in the room and pillar region of the vault.

Other considerations

Additional design considerations include:

identification and assessment of the potential modes or mechanisms (local as well as global) of creep rupture that could affect the vault design;

understanding and prediction of the response of the vault to seismic events in terms of stability of the excavations and operation of the facility; and

an assessment of the requirements for safety in handling the waste, including shielding, hoisting and underground haulage, and ventilation.

Design precedent

In order to set the vault design task in perspective, we have reviewed certain aspects of underground construction experience which are relevant to this task. These are summarized in Figure 8.10.

Experience can be drawn from a range of facilities including mines, civil works for hydroelectric projects, transportation tunnels, underground storage, compressed air energy storage, and various other special projects currently in the development stage (Oberth, 1978; Margison, 1977; Bach, 1977; Livingston and Goodwin, 1951; Milne *et al.*, 1977; Bjurstrom, 1977; Crowley *et al.*, 1977; Morfeldt, 1974; Witherspoon *et al.*, 1974; Willett, 1977).

Many underground projects were constructed hundreds of years ago, and detailed study of their performance should provide valuable data for vault design studies. Current mine design practice is usually to provide an operating life of 10 to 50 years. However, cavities have frequently remained open for hundreds of years and should provide data on long-term performance of pillars, shafts, etc. (Bateman, 1951; Legget, 1962).

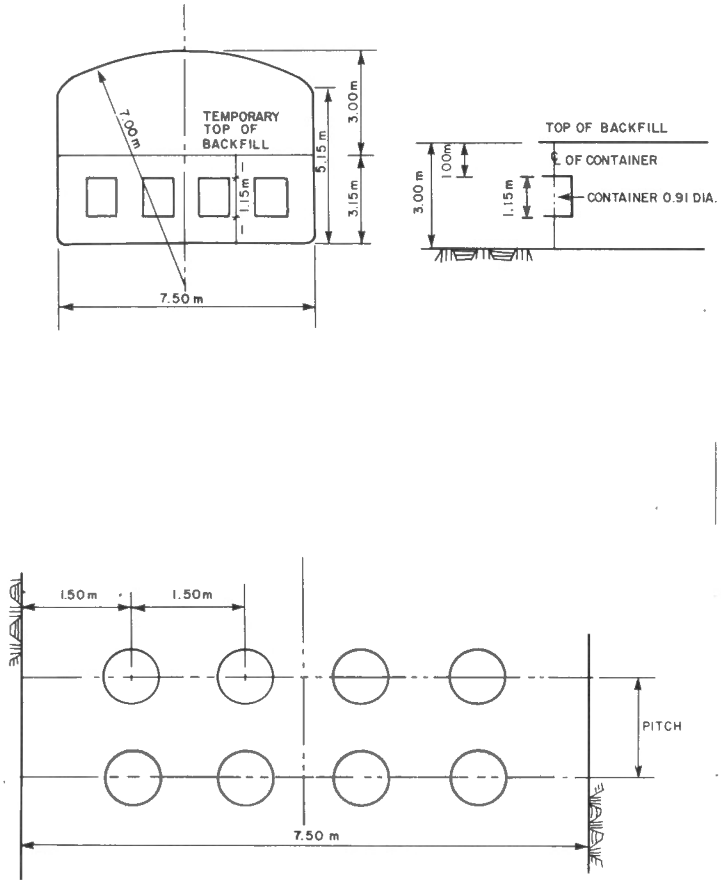

Figure 8.6. IF room and container geometry.

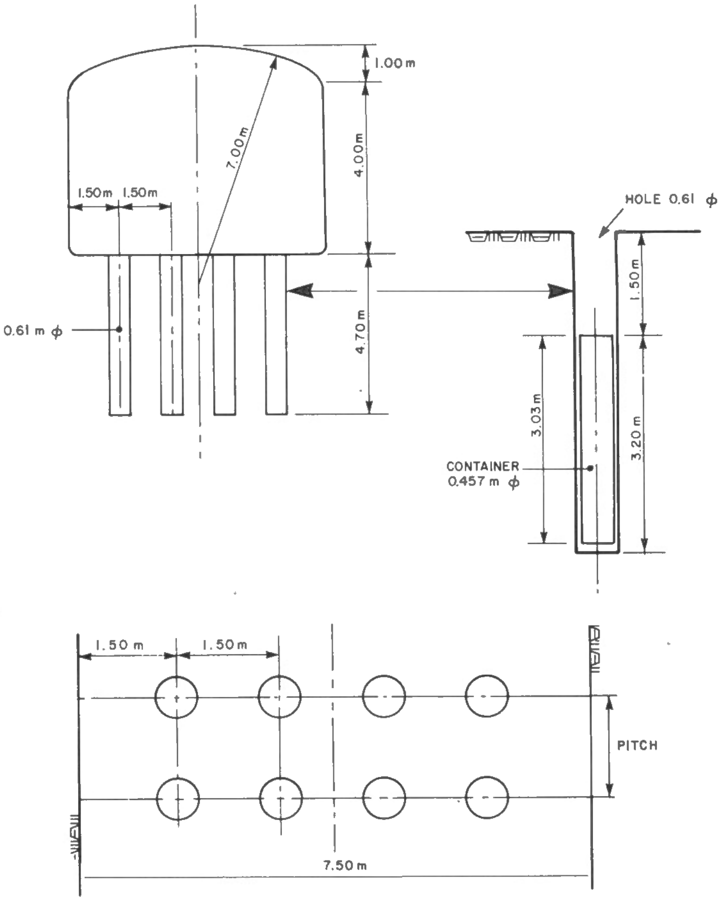

Figure 8.7. RW room and container geometry.

Many facilities have been constructed and operated successfuly in crystalline rocks at depths greater than the 1000-m depth currently under consideration for the Canadian vault. Techniques to handle potential rock spalling and rock bolting for roof support at these depths are available.

The heat generation aspect of the vault design is a major variable. However, options exist to disperse the waste sufficiently to reduce maximum temperatures to required limits. For instance, in Sweden the KBS studies used a design with an initial areal thermal loading density of 5.25 W/m^2, which results in temperature increases of about 60°C (Ratigan, 1977). If temperature effects are limited to these low values, then the analyses show that thermal/mechanical effects are minimal compared to the geostatic and construction effects. Previous experience in facilities in which moderate thermal effects were present includes certain deep mines, the effects of concrete liner hydration in penstocks, oil storage and cold storage facilities. However, in general the thermal rock responses were not considered critical to the operations and, therefore, have not been studied in detail.

The vault design is based on the use of present design, operating and construction technology from the mining and civil underground industry, and consequently considerable precedent exists.

The environmental features arising directly from the vault construction, waste emplacement and backfilling are encountered elsewhere in current activities. Consequently, the practices should be readily adaptable to the vault development. However, the long-term isolation requirements present new problems in the determination of environmental impact.

In summary, there is a substantial body of experience available to form the basis of the design of the vault for the construction, waste emplacement and backfilling operations. If design concepts are adopted which minimize temperature rises, then some data may be obtainable to provide experience for thermal/mechanical aspects. Experience exists on the stability of underground openings for periods of several hundreds of years, and this is the time frame for fission product decay in the vault. Construction experience is limited for the very long time frames required for actinide decay; however, it may be possible to draw data from natural examples.

Commentary

General vault design development

The overall program for the development of the vault is described by Hatcher (this volume, Paper 2). A possible general schedule for the design tasks is shown in Figure 8.11. This shows the expected progression from the current studies on "Mixed Concepts" to the consideration of "Alternatives" and the definition of the "Generic Design Concept" by about 1981. The detailed design of the entire vault and the development of the deep test facility would then follow according to schedule requirements.

TIME FRAME CONSIDERATION	INITIAL	CONSTRUCTION	SHORT TERM	LONG TERM
1. Operations	Premining 1.1	*Construction rock bolting, testing 1.2	*Emplacement, ventilation backfilling, monitoring sealing and decommissioning (possible retrieval of IF) 1.3	Passive monitoring 1.4
2. Groundwater	Regional flow 2.1	*Inflow into excavations 2.2	Probable recharge, thermal pertubations to flow, saturation of backfill, air into solution 2.3	Return to modified regional flow. Possible environmental modification effects 2.4
3. Heat Transfer	Geothermal flow 3.1	Drying of cavities by air ventilation 3.2	*Conduction and convective heat transport from waste, ventilation cooling 3.3	*Near-field cooling, far field subject to thermal cycle 3.4
4. Rock Mechanics	In situ stress field 4.1	*Excavation stresses and local fracture zones 4.2	*Thermal stresses in near field, possible local fracturing 4.3	*Near-field thermal stress relaxation, bulk thermal expansion of far field. Possible creep and seismic effects 4.4
5. Radiation	Background radiation 5.1	Background radiation 5.2	*Radiation from container requiring shielding. Decay of FP activity 5.3	Possible radiogenic effects on backfill rock etc. Decay of actinides 5.4

*Considerations under study by authors and associates.

Figure 8.8. Time frames for design considerations.

GEOMETRIC REGION OF VAULT	THERMOMECHANICAL CONSTRAINT	RW VAULT	IF VAULT
Container near field	Container skin temperature	150°C absolute 135°C rise	150°C absolute 135°C rise
	Container cavity stability	Open and stable hole	Not applicable
	Near-field rock mass stability	Not supported	Not supported
Room and pillar	Backfill volume—average temperature	100°C absolute 85°C rise	100°C absolute 85°C rise
	Roof and rib failure/support	Conventional rock bolting requirements	Conventional rock bolting requirements
	Integrated average of strength-stress ratio in the pillar	⩾2	⩾2
Far field	Rock mass stability	Reversible deformation	Reversible deformation

Figure 8.9. Preliminary design specifications.

Many interfaces already exist with other development activities, e.g., waste packaging, geochemistry, etc., and these have been input into the design tasks in the form of specifications and constraints at the appropriate stages of development. The timing of certain inputs is suggested in Figure 8.11 for hydrogeological, geochemical, rock mechanics, and safety factors to illustrate the ongoing interactive nature of the program.

Research and development requirements

On the basis of the work done so far in this investigation, the following areas for further research and development can be identified.

In Situ stresses

A data base for the *in situ* stresses (magnitude, direction, and variation with depth) needs to be generated for the Canadian Shield generally and for plutons in Ontario particularly.

Facility	Construction and Operational Lifetime	Rock Types and Depths	Experience with Thermal-Mechanical Response	Design and Operating Experience	Construction	Construction and Operational Environmental Features
Mines	Modern mines usually designed for 10 – 50 years operation but many ancient mines (Sweden, Austria, Middle East) still open	All rock types to 2,000 m + in Canada, U.S.A., South Africa	Some construction and operation in geothermal areas up to 70°C	Thousands of years of experience worldwide	Drill and blast and mechanical	Mine drainage, ventilation (dust, radon, fumes), muck disposal
Civil works (water supply and hydroelectric developments)	Modern facilities usually designed for approximately 50 years. Roman and Persian examples still open	All	Heat of hydration of grout and hydraulic transients with penstocks	Widespread	Drill and blast and mechanical	Similar to mines but generally less severe
Underground storage	~50 years nominal	All, but primarily crystalline rock (Scandinavia) and salt (U.S.A.)	LNG, LPG, hot water, refrigerated materials with rock temperatures in range – 160°C to 150°C	Common in Scandinavia, also in Canada, U.S.A., Europe	Primarily drill and blast	Control groundwater to prevent leakage of stored liquids. Environmental impacts generally less than equivalent surface facilities
Transportation tunnels	150 – 200 years	All	Continuous vibrations and minor thermal transients	Widespread	Drill and blast and mechanical	Similar to civil works
Underground compressed air storage	~50 years nominal	Crystalline rock and salt	Pressure and temperature cycling up to 70°C	Some operating plants in Sweden, Finland, Germany and active R&D in U.S.A.	Drill and blast in crystalline rock	Similar to civil works
Underground nuclear test and military facilities		Primarily crystalline rocks (U.S.A., Canada, Europe)	Severe dynamic and thermal transients	Restricted information	Drill and blast and mechanical	Construction as for civil works. Long-term isolation required
Underground nuclear plant siting	~50 years nominal	Primarily crystalline rocks (U.S.A., Canada, Sweden, Japan)	Thermal transients due to LOCA consideration in design studies	Some small operating plants in Europe. Active R&D in U.S.A., Canada	Drill and blast and mechanical	Construction as for civil works. Operational accidents, impacts may be less than for surface plants
Geologic disposal of radioactive waste	20 – 50 years active emplacement operations; very long passive life	All types under consideration particularly salt (U.S.A., Germany), crystalline rock (Canada, Sweden, U.K., Japan, Austria) shales and clay (France, Belgium)	Design concepts and waste density can be selected to limit maximum temperatures	Investigation and conceptual studies only. Depths 500 – 1,000 m. Field pilot tests in U.S.A. and Sweden	Conventional methods for respective rock types	Ventilation, muck disposal and handling during construction and operation: long-term isolation required

Figure 8.10 Design precedence

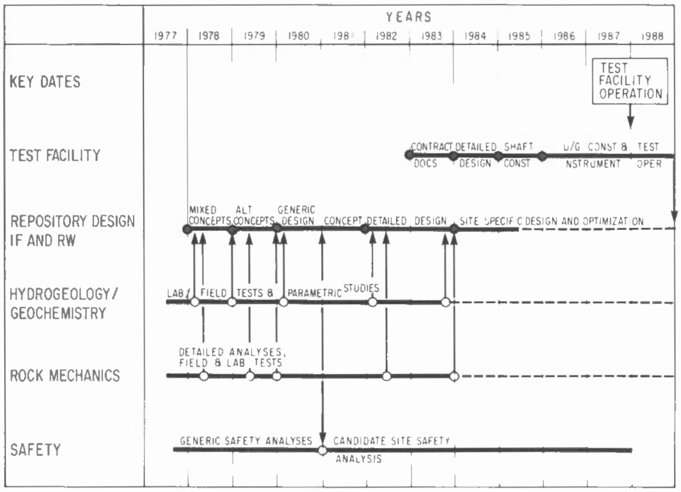

Figure 8.11. General schedule for development of vault design.

Geometry of joints

The attitude, spacing, continuity of joints and the variation in their geometric characteristics with depth need to be measured and quantified.

Strength of joints

The peak and residual strengths of joints in plutonic rocks need to be quantified. In particular, the cohesion and angle of friction values for the joints need to be catalogued for use in failure envelopes relating shear stress to the stress normal to the joint.

Thermal properties of rock

Thermal properties of the rock need to be confirmed both in the laboratory and in the field. Studies of the thermal/mechanical performance of existing underground facilities may provide useful data.

Long-term creep

Long-term creep characteristics of crystalline rocks need to be defined and key mechanisms identified. Again, studies of existing facilities may be useful.

Failure criteria

Rock bursts, thermal spalling, failure of rock under a polyaxial state of stress, and failure of joints need to be expressed in empirical relationships that can be included in numerical analyses for design.

Backfill properties

The thermal/mechanical properties of the backfill materials, such as mixtures of sand and clay, need to be quantified for input to analyses and design.

General comments

The preliminary results of the thermal/mechanical analyses indicate that satisfactory designs can be achieved using normal mine construction practices. The layout and operational design tasks appear to allow the use of state-of-the-art mining practices. Certain aspects will benefit from development, e.g. hole drilling equipment and backfill design and placing systems, but no insurmountable problems have been identified to date. The rock stabilization requirements during construction and emplacement are quite standard, and the thermal perturbations to room stability are minimal.

Considerable flexibility exists in the design concepts to accommodate waste packaging, backfilling and sealing innovations as they are developed. The temperature limits which have been adopted in the Phase III studies can be adjusted up or down by simple layout changes to achieve either a more compact or dispersed design to suit other design factors.

Acknowledgments

The work described in this paper has been carried out by Acres Consulting Services Limited under contract to Atomic Energy of Canada Limited, Whiteshell Nuclear Research Establishment. The technical coordinator at AECL was Dr. H.Y. Tammemagi. RE/SPEC Inc. acted as a subconsultant to Acres on layout concepts and rock mechanics analyses. Dilworth, Secord, Meagher and Associates acted as subconsultants to Acres on preliminary waste handling aspects, and Hagconsult AB provided consultation and review of preliminary layout concepts.

The contributions of all of the above and various Acres specialists including P-O. Sandstrom, D. McKinlay, E.L. Skiba, R.J. Pine, A.B. Cammaert and others are gratefully acknowledged.

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9. NUCLEAR WASTE DISPOSAL: GEOCHEMICAL AND OTHER ASPECTS

W.S. Fyfe[1] and Z. Haq[1]

Introduction

There can be little doubt that recent writings on the geological disposal of nuclear waste (Science, v.200, 1978, p. 1135; Bredehoeft *et al.,* 1978; Aikin *et al.,* 1977; Uffen, 1977; Giletti, *et al.,* 1978; Nature, v.274, 1978, p. 6) would hardly convince the educated layman or politician that scientists and engineers know what they are doing or even what they are going to do! Only one thing is certain: nuclear waste is accumulating at the earth's surface and some of it is in contact with the biosphere. Workers are divided into those who think they can dispose of it now and those who think we can probably do it after much more research. In this report, it is suggested that there are reasonable solutions now but that future work may produce much lower cost solutions.

In defining disposal it is clear that present trends in environmental science show that the desirable level for a toxic element is within the bounds of levels that existed before substantial interference by the human race. Some may say that this is an unrealistic target but it is the only certain target that can lead to acceptable levels.

In this paper terminal storage is discussed. There are many ways of developing adequate schemes of well monitored temporary storage if one is prepared to pay the cost. Further, this paper is concerned only with disposal in the planet earth.

Much of our experience with the nuclear waste problem has arisen from association with the Swedish Nuclear Fuel Safety Project (KBS). In a broad sense, the target has been to develop systems which could be used to dispose of nuclear waste from power reactors in such a way that it could be detected millions of years in the future. At first sight such a time scale may seem unrealistic but such disposal processes are well known in nature where relatively easily transported materials (gas, oil, salt) are preserved in rocks for tens and hundreds of millions of years.

The Approach

Any approach to geological disposal of a material must include a series of decisions, and the exact details of the disposal process will depend on the integration of all the factors. Some of the basic questions that must be answered include; what rock, what location, what depth, what container, what backfill? In such a series of steps there can be a number of barriers with various degrees of predictability of behaviour. For safe deposition, at least two barriers must be highly effective, redundancy is vital.

Repository rock type

A major repository is likely to involve large dimensions. Depth of access and tunnel dimensions may easily be on the kilometre scale. Hence, one is concerned with rock volumes on a scale in the order of 10 km^3. This implies that only major rock units are likely to be involved if we wish to predict the appropriate physical parameters. On the basis of volume considerations there are many candidates from salt to granites.

Given an appropriate volume of rock, a number of additional features must be considered:

- The rock should be as free as possible from fractures and be as nonporous as possible. It should have minimal permeability. However, according to J.A. Cherry, University of Waterloo (pers. comm., 1978), it is very difficult to predict the permeability of 10 km^3 of rock. A single major fracture may completely change the "average" permeability over a large volume of material. Recent analyses of ocean ridge heat flow (Ribando *et al.,* 1976) have shown how small cracks (0.05 mm) at relatively large spacings (10 m) can generate significant permeability, enough for convective cooling on the seafloor.
- In general, the rocks should be salt free, for it is well known that high salt concentrations in the fluid will tend to block or compete with ion exchange on mineral surfaces and to complex many metals.
- The rocks should have low radioactivity and hence a low geothermal gradient. The lower the crustal gradient, the less will be the overall enhancement of temperature by the waste and the lower the chance of initiating strong thermal convection. Recently, Straus and Schubert (1977) have shown that thermal convection is possible for all present crustal gradients, the adiabatic gradient is always exceeded. Thus, whether or not thermal convection occurs will finally depend on permeability and the thermal gradient. On this basis, granulite facies rocks could be ideal.
- The rock should show good ion exchange properties. Most of these processes will involve exchange in the outer few layers of the surfaces of minerals. Thus, rocks with the greatest mineral surface areas, fine grained rocks, should be best. It is not too difficult to estimate which minerals are the most likely to exchange with and dilute a radioactive species. Clay minerals and zeolites are likely to be the best general cation exchangers. One wishes to present the solutions with a maximum array of

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sites, both chemically and structurally. Highly zeolitized volcanics or black pyritic shale could easily be good candidates on this basis. Perhaps granite might be one of our last choices!

- The rock should not be easily perturbed (dehydrated, etc.) by the local thermal aureole of the waste. The significance of this factor will depend on the depth, the thermal proximity to phase changes, and the waste loading. Here, Swedish colleagues indicate that temperatures need not be perturbed by more than 50°C given their proposed loading. In this sense, zeolite facies rocks (with clays and zeolites) may be the most sensitive to thermal disturbance. Salt, with fluid inclusions, will also be strongly influenced depending on the exact nature of the fluid inclusions.
- It is desirable that the rock be as plastic as possible and resist the formation of large new open fractures. If rather shallow depths of burial are contemplated, few rocks with the exception of salt are likely to be plastic but one would expect shale and salt to be better than say granite. At low temperatures creep phenomena in rocks may be related to pressure solution phenomena (see below).
- Given that open fractures may form, it would be desirable to choose a rock with the best self-sealing properties. An open fracture filled with fluid in a water saturated porous rock represents an unstable state unless the fluid pressure and rock pressure are identical and the pressure regime strictly hydrostatic. In most cases of open fractures in the near surface environment where surface waters flow to considerable depths, pressure on solids will be two to three times the fluid pressure. This phenomena leads to pressure solution at highly stressed grain boundaries and deposition in the low fluid pressure regime (the crack or pore). Ideally, one should choose rocks with the greatest response via pressure solution and in general these will have the most soluble mineral phases.
- The pressure solution process (Kerrich, 1978) depends on a pressure differential between mineral grain and fluid and depends on the free energy difference between a crystal in rock matrix and the open space

$$\Delta G_{stress} = V_{solid}(P_{rock} - P_{fluid})$$

As the change in solubility of the mineral is related to this ΔG_{stress} and to the concentration in solution by a relation of the form

$$G_{rock} - G_{fluid} = \Delta G_{stress} + RT \ln \frac{C_1}{C_2}$$

where C_1 is the solubility in the hydrostatic system where $P = P_{rock}$ and C_2 is the solubility where $P = P_{fluid}$, there will then be an exponential response to ΔG_{stress} and $(P_{rock} - P_{fluid})$. All parameters, rate and equilibrium, imply that pressure solution sealing will become more effective with depth and large values of ΔC, the supersaturation, and large values of C, the solubility. The more soluble minerals include salt, carbonates and quartz, in fact the minerals that commonly form veins.

However, there is a second major contribution to crack sealing. When fluid flows through a new crack, it will tend to dissolve the wall (if T is rising), precipitate phases on the wall (if T is falling – the normal route to the biosphere) and hydrate phases if there are appropriate phases in the rock. For example, if plagioclase minerals are present (as in basalt or granodiorite) these may form zeolites; if minerals like olivine or pyroxene are present these may form phases like serpentine or chlorite. In all these cases, the rock will expand because the volume of the hydrated phases exceeds that of the anhydrous present. On this basis, we could arrange rocks in an order of suitability:

peridotite > basalt > granodiorite > granite.

In fact, the only reason we find fresh peridotites at all at the earth's surface is that they preserve themselves by self sealing in an armour of impermeable serpentine. These hydration reactions will increase in rate with T and hence be more effective as depth increases.

Many other properties could be mentioned such as thermal anistotropy, etc., but even with the factors listed above it is clear that there is no simple rule to use in choosing the rock. In the final choice, the first and last variables might be the most critical.

Repository location

The debate about socio-political restrictions cannot be considered herein, but on scientific grounds the first choice of a repositary site must be between continent or seafloor. Recent heat flow studies (Davis and Lister, 1977) have shown how impermeable even almost new marine muds can be. Where thick sections exist in relatively stable regions (away from subduction zones, faults, ridges) they could be attractive rocks for diaposal. However, we have much to learn about seafloor properties before this option is seriously considered.

Repository depth

In the literature concerning appropriate depths for waste disposal one encounters a magic number, one kilometre. Who chose this number and why?

It is well known and documented that porosity and permeability diminish with increasing depth (Fyfe *et al.,* 1978). The great generalization for metamorphism that fluid pressures attain lithostatic pressure at depths in the order of 5 km is a tribute to incredible impermeability of rocks at depth when water of dehydration reactions is released by hydraulic fracture mechanisms. As discussed above, pressure solution crack sealing will become more effective with depth. Flow out from a deep (and hotter) repository is more likely to self-seal by deposition of minerals like quartz.

Modern mines frequently operate below 2 km, some below 4 km depth. In the minds of these writers, the problem is one of cost versus advantage and the ultimate limit of mine safety. There is no obvious reason that depths of 2-3 km should be not envisaged. The advantages of low permeability, long flow paths, etc., may well outweight the additional costs and disadvantage of a slightly warmer repository.

As several members of the nuclear waste population (Tc-99, I-129, Cs-135, N-237, Pu-242) have half lives in the million year range, we must consider what depth is safe with respect to rates of erosion. One cannot doubt, for example, that another ice age could occur long before the products of CANDU become safe.

Perusal of the existing literature reveals uncertainties regarding the amount of surface that can be stripped during an ice age (*cf.* Gilleti *et al.,* 1978; and Laine, 1978 whose conclusions differ by a factor of ten). But in terms of erosion by water there is less uncertainty. In a region where 1 m of rain falls each year, the rate of erosion by solution alone is about 500 m in ten million years. Where there is active water flow the rate appears greater. Gilluly *et al.* (1975) gave an average erosion rate of 500 m/10^7 years for the Mississippi basin. Much higher rates have been measured in the Colorado drainage system (100 m/10^6 years) and in the Columbia River watershed, (380 m/10^6 years). Given these numbers, and the uncertainties of ice erosion, clearly 1 km is minimal, whereas 2 – 3 km would be far more secure. It is interesting that Gilluly *et al.* (1975) note the very slow rate of erosion in the Hudson Bay lowlands.

Waste Containers

At present two approaches are commonly considered with solid wastes: conversion to a glass with dilution in the glass matrix or packing in a long life container shell. Great emphasis has been placed on the container concept in Sweden.

Two major problems are evident with glass. To make homogeneous glass efficiently on a large scale a high temperature process is required. This implies that any volatile elements like iodine, alkali metals, etc., must be contained by some process or preseparated, adding to the technological complexity of the process. To minimize the necessary temperature, low melting borate glasses have been considered.

A problem with any glass is that on account of its high entropy and hence high low temperature free energy, glasses are more soluble than their solid equivalents as witnessed by the use of slags as fertilizers. In this respect borate glasses should be very soluble indeed. Geological evidence suggests that "granitic" glasses have a longer life as glass than most of the common types but their fusion characteristics are bad.

All who have worked in the field of experimental petrology know that glasses, in the presence of water, tend to crystallize or devitrify very easily. They are commonly used as the starting materials to grow crystalline phases. Even at low temperatures (100°C) crystallization can be rapid. At higher temperatures no silicate glass can survive as glass for more than days or weeks (e.g. the conversion of silica tube to a cristobalite tube at 300°C in water). Before any glass matrix is considered, this aspect of the problem must be quantified.

It is also well known that when a glass crystallizes, the fate of each element depends on its ability to form solid solutions in the common host minerals (a function of charge, size, electronegativity, etc.). Many of the exotic elements can be expected to simply concentrate as grain boundary phases and be easily available for leaching.

Finally, glasses have lower densities than their crystalline products, a factor of 5-10 per cent by volume being common. If the glass crystallizes it will shrink in volume and crack. It will become a porous medium which can be rapidly leached.

Much more work is needed in this regard and some is under progress in our laboratory (see also McCarthy *et al.,* 1978). What is the ideal glass composition? For example, zeolite composition glasses could be used that would expand rather than shrink and that would crystallize to good ion-exchangers, perhaps even anion exchangers.

Multi-Million Year Containers

Can a closed container be fabricated which will prevent leaks into the environment and will survive for a million years or more? This is the question that has been seriously addressed in the Swedish research effort. There is good geological evidence that this is not a wild dream. Some metals like Cu, Ag, Au, Ni, survive in rocks in small grains for billions of years.

In working with the Swedish KBS research has been particularly concerned with two possible materials: copper metals and the ASEA corundum ceramics.

If a rock is impermeable, copper will survive for a billion years or more. Copper is attacked by (a) solution via an oxidized species; (b) oxidation; and (c) conversion to sulphides

In rocks, reactions (a) and (b) are controlled by flow and the action of the oxygen buffers in rocks. In general at depth redox equilibria are controlled by the common ferrous-ferric silicates in rocks which keep oxygen at very low levels. Many studies of active thermal areas shown that the copper content of waters is at the ppm level. In reaction (c), reduced sulphur species are again buffered by the ferrous silicate-pyrite system and again reduced sulphur levels in deep hot waters are generally at the level of ppm or less. Our laboratory tests have shown that in a mining operation, magnetite will scrub out residual oxygen faster than copper so trapped oxygen presents no serious problem. All in all, there is good reason to believe that a thick-walled copper container, would survive in a low permeability system for millions of years and this is well confirmed by natural occurrences of copper.

The ASEA Corporation of Sweden has developed superb technology for the high P-T sintering of solid materials. They have fabricated large containers of sintered high purity corundum. Unlike copper, corundum will corrode or decay in natural environments by hydration reactions. The solubility is so low that this is not a significant factor in the life of a container.

Corundum corrodes by reactions such as:

$Al_2O_3 + H_2O \longrightarrow 2AlOOH$ (boehmite)

$Al_2O_3 + 2SiO_2 + 2H_2O \longrightarrow Al_2Si_2O_5(OH)_4$ (kaolinite)

These reactions have been studied in detail in our laboratories in the temperature range 160 - 300°C and in Sweden at 100°C. Earlier studies were made by Fyfe and Hollander (1964). All the available data show that a 10 cm wall of sintered corundum would survive at temperatures below 100°C for times of the order of 10^8 years. Again, this figure is not geological nonsense for residual corundum survives well in the lateritic weathering environment for times in the order of 10^7 years.

In summary, it appears that two types of containers could survive deep burial for times of 10^7 years or more. A ductile metal (Cu) might be excellent for hard rocks where small movements could occur while Al_2O_3 might be more appropriate for salt deposits. Work on these materials continues but the present outlook is good. If such containers are feasible (they are inside the bounds of economic possibility), then the nature of the host rock becomes less critical, as does the geography of site selection.

Backfill

One of the major problems in the engineeringof terminal storage is that of filling the hole. If this is not well filled and hence retains a high porosity and permeability, depending on the thermal loading, the possibility exists of creating a small geothermal convector. Amazingly, Bredehoeft *et al.* (1978, p. 5) state:

> "Moreover, current estimates (Union Carbide Corp., Nuclear Div., Office of Water Isolation, 1977) suggest that the backfilling process will fill the underground working to a density of perhaps 80 per cent of what it was before mining."

The fact is that it is known now how to fill a hole to essentially zero porosity or at least 0.1 per cent.

Much of the work done at the University of Western Ontario in collaboration with Sweden has been concerned with the entire problem of filling a deep hole. Here one wishes to fill the hole so that poposity and permeability are minimal.

It is very difficult indeed to pack any solid material with much less than 20 per cent porosity. This led us to the concept that one could use materials that swell when in contact with water and are replaced by a more voluminous solid. Certain mineralogical examples are well known where thermal stability and rates of reaction (and cost) make them attractive. Typical of such reactions are:

$$\begin{array}{llll} & MgO & \longrightarrow\ Mg(OH)_2 & \\ & \text{periclase} & \text{brucite} & \\ V & 6.44\ cm^3mol^{-1} & 15.09 & \Delta V\ >100\% \\ & Mg_2SiO_4 + MgSiO_3 & \longrightarrow\ Mg_3Si_2O_5(OH)_4 & \\ & \text{peridotite} & \text{serpentine} & \\ & 75.26 & 108.5 & \Delta V \simeq 43\% \end{array}$$

With such reactions, it should be possible to achieve 100 per cent solid *if* water invades the material. The packing must be designed so as not to achieve much greater than 100 per cent solid for the "swelling pressures" of these materials can be of the order of several kilobars.

Another class of materials of great interest is the swelling bentonitic clays. As long as the cavity does not exceed about 100°C, there is good evidence that these will have long term stability. The great advantage of swelling clays is that they have the ability of swelling to fill new cracks. In our work compacts of bentonite have been used which are so dry that they have lost their "excess" interlayer water. To the present, systems based on bentonite-MgO and additives have been studied (Table 9.1). MgO and particularly MgO plus silica gel ought to be seriously considered as container materials for two desirable qualities: (a) Extremely low permeability coupled with negligible void-ratio (0.03), and (b) High absorption capability.

The diffusivity of water in $Mg(OH)_2$ – silica gel compact at 20°C according to our measurements, is of the order of 10^{-11} cm^2s^{-1}. A simple calculation shows that water penetration is less than 20 cm in 1 million years!

Table 9.1

Composition	Coefficients of permeability k at 20C in microdarcies μD (cm sec ^{1} x 10^6)
Bentonite[(a)] + muscovite (150 mesh) (87:13)[(b)]	~0.6
Bentonite + muscovite (65 mesh) (87:13)	~0.58
Bentonite	~0.4
Bentonite + quartz (24 mesh) + Ti0$_2$ (300 mesh) (72:24:4)	~0.34
Bentonite + quartz (24 mesh) (75:25)	~0.28
Bentonite + quartz (24 mesh) + quartz (80 mesh) (75:20:5)	~0.28
Bentonite + quartz (24 mesh) + Mg0[(c)] (68:23:9)	~0.18
Mg0	~0.002
Mg0 + anhydrous silica gel (300 mesh) (87:13)	~0.001

(a) Wyoming bentonite (80 mesh) air-dried for 5 hours at 290℃.
(b) All proportions given are by weight.
(c) Air-dried 300 mesh size Mg0 for 4 hours at 500℃.

The above results are only a beginning but they are so promising that it is clear that the nature of the rock and the container become less important. Many other methods of self sealing are under investigation and encouraging results are expected. An ideal system might be one where a composite packing is used such as:

Rock/Bentonite/MgO/Waste/MgO/Bentonite/Rock

Rock/Bentonite/Mg_2SiO_4/Waste/Mg_2SiO_4/Bentonite/Rock

In both the above cases the MgO and Mg_2SiO_4 (the latter reacts to form $Mg(OH)_2 + Mg_3Si_2O_5(OH)_4$) could be used to compact the bentonite. The advantage of MgO or $Mg(OH)_2$ is that if silica charged waters do enter the cavity they will further tend to seal by processes like:

$$3Mg(OH)_2 + (SiO_2)_{soln} \longrightarrow Mg_3Si_2O_5(OH)_4$$
$$\Delta V = +34\ cm^3\ mol^{1}$$

and because of the low chemical potential of silica in this system, they fix silica even when the temperature is higher in the repository. By such reactions the entire concepts of backfill can be greatly improved. Obviously, various buffer materials (e.g. Fe_3O_4 for protection of copper oxidation) can be added to the backfill and will be chosen in accord with the container and ion exchange processes.

A system of precision tunnel boring with prepacked containers could lead to simple engineering systems with minimal manipulation at depth. Through controlled swelling reactions, there is no need to be concerned about complicated packing operations.

Conclusions

From the above discussion certain main conclusions can be drawn:

(a) there is security with depth of disposal and 2–3 km depths should be considered.

(b) at such depths, copper and alumina (in the case of salt) containers should last for millions of years.

(c) by using self-sealing backfill materials, diffusion into the repository will be so slow that leakage should be essentially zero for 10 million years.

(d) if container and backfill problems can be solved as indicated above, then a repository can essentially be located in any rock at any place given due consideration to topography, erosion rates and tectonic (seismic) environment.

If the waste disposal problem is solved as we believe it can be now if one pays the cost, then nuclear power can be environmentally cleaner than power produced from coal, gas, or oil.

Acknowledgments

We acknowledge support from our work from the Swedish Nuclear Safety Project and presently from Atomic Energy of Canada Ltd. In particular, we have gained enormously from discussions with members of the Swedish KBS, Drs. L. Nilson, K. Hannerz and B. Widell, and from numerous discussions with Professor J.A. Cherry, University of Waterloo. However, we are solely responsible for the contents of this paper.

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10. GEOPHYSICAL METHODS FOR SELECTION AND IN SITU TESTING OF WASTE DISPOSAL SITES

D.W. Strangway[1]

Introduction

The disposal of high-level radioactive wastes is a current problem that must be satisfactorily solved if nuclear power is to be a major element of our national energy program. This disposal is of concern to many of the public, particularly to those who live close to proposed sites. The problem, however, is really only a subset of a much larger class of problems which relate to the disposal of chemical wastes, especially now that landfill sites are being closed. Millions of gallons of nonradioactive industrial waste are already being poured and pumped into subsurface formations. The result is that there is already a considerable body of data available relevant to the motion of fluids beneath the soil cover. In fact, the very operation of oil and gas fields and the storage of fluids in the subsurface requires that a sound knowledge of fluid flow be available.

In understanding and measuring these processes, the use of geophysical logging tools has become standard practice. In fact, the recent announcement of major new gas reserves in the Deep Basin of Alberta is based on drilling information and interpretation of electric log information suggesting the presence of extensive gas in formations with low permeability.

Physical Properties

The physical properties of materials may be discussed under several catagories. The magnetism of rocks is controlled largely by the presence of a few per cent of iron-titanium oxides. These oxides control the magnetic susceptibility and the remnant magnetism of the rock formations. Since this property is not related to either the bulk rock or to the pore spaces, it is of interest only for indirect information about the rock's capacity to contain fluids. However, it is essentially useful as an extension to geological mapping and can be used in looking at the third demension.

Seismic velocities are controlled largely by the bulk properties of the rocks present and are only sensitive to fissures and pore spaces in a secondary way. Nevertheless, there is evidence that seismic velocities can provide information about the presence or absence of faults and fissures. Seismic attenuation, on the other hand, is essentially controlled by the nature of the grain to grain contacts and the pore spaces. In this sense, it is a measurement that is highly sensitive to the pore space fluids contained in bulk rock samples. These two properties form the basis for a number of interesting phenomena. For example, the new, bright spot technology is dependent upon the differing character of water and hydrocarbons in pore spaces. Thus, techniques, which measure the seismic velocities and the seismic attenuation, will probably prove useful in providing some information about subsurface fluid distribution. High frequency seismic reflections in fairly homogenous formations are likely to be useful for detecting and mapping fractures.

It is widely known that the electrical resistivity of rocks is almost entirely an effect of the electric transport through the materials contained in the pore spaces. In vacuum-dried rocks it is not uncommon to measure resistivities of 10^{+15} ohm.m or more, similar to the properties of the best available commercial insulators. The introcution of even one monolayer of water can change this value by several orders of magnitude. Rock which is saturated with saline fluid may have a resistivity value as low as 10^{-1} ohm.m. or less. There is thus, little doubt that the use of electrical geophysical methods, in attempting to find very dry environments, is one of the most sensitive tools available to us.

As fluids are added to rocks, it is found that they acquire the capacity to store a charge. This observation forms the basis of the induced polarization technique and results from the presence of electrical barriers to ions migrating in free space fluids. These barriers are typically either polarizable clays or metallic, electronic barriers. This phenomenon is related directly to the surface area available to fluids in the rock and to the ion exchange capacity of the material.

The measurement of temperature gradients and of thermal properties has not, to date, been extensively used in geophysical mapping methods largely because the variations from place to place are relatively small; many rocks are relatively uniform thermally; and it is necessary to separate out the diurnal and annual temperature cycles to exploit the temperature for mapping purposes. Most rocks have a fairly similar thermal conductivity, although it is known that quartzites have a higher value than most rocks. The major temperature anomalies in drillholes and in the subsurface are undoubtedly related to convective heat transport due to fluid migrations in the subsurface in faults and fissures.

We may apply the above physical properties in three separate problems related to the management of radioactive wastes. The first of these is surface geophysics. The second is drillhole logging by geophysical methods for the purpose of identifying suitable regions for extensive *in situ* mining tests. The third relates to the testing and long term monitoring of *in situ* properties of excavated cavities.

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From: Geological Survey of Canada Paper 79-10

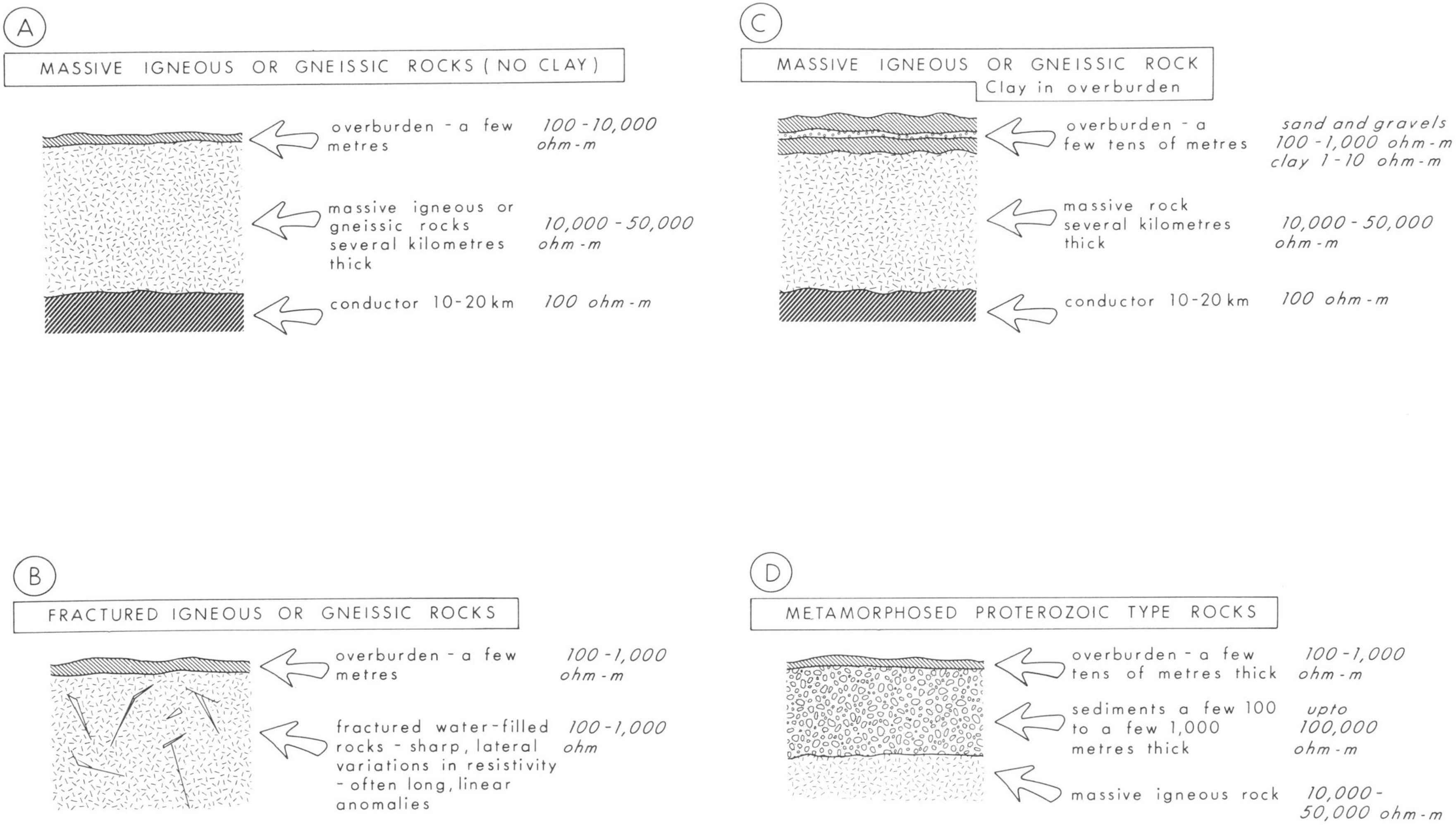


Figure 10.1. Electrical models for typical Precambrian terrains.

Surface Exploration

It is clear that geophysical methods should always be correlated with geological mapping, so that various observations can be put into the most comprehensive context possible.

No clay in the overburden

In using electrical methods for surface exploration we may consider two conditions which are prevalent in Canada. In one case, there is no clay present in the overburden. This means that geo-electrical methods from surface are expecially useful. It is common over much of the Canadian Shield to find a layer, a few tens of metres thick, which has a relatively low resistivity due to the presence of water in the pore spaces, and cracks in the soil and uppermost rock layers. Because of extensive glaciation, however, the weathered rock surfaces have largely been removed and at shallow depths the rocks become extremely resistive electrically. For one possible type of repository, this is an ideal case, the rock has few cracks and fractures and contains little pore space water. The electrically resistive layer extends to depths of several kilometres or more as seen in Figure 10.1A. A schematic magnetotelluric profile over a typical batholith in northwestern Ontario is shown in Figure 10.2. (This paper will not dwell on one electrical method versus another since in general they can be set up to give similar information.) In the magnetotelluric method, the apparent resistivity is measured as a function of frequency. At high frequencies only shallow depths are being observed whereas the depth of observation increases as the frequency decreases. A second case is illustrated schematically in Figure 10.1B. This shows the situation encountered at Chalk River, Ontario, where there is extensive open faulting and water-filled shear zones are abundant. It should be noted that the resistivity values are lower and that there are many lateral variations. There is yet a third case enountered in our Precambrian work. In regions of metamorphosed sedimentary cover the resistivity values are even higher often approaching 100 000 ohm/m. This is illustrated in Figure 10.1C and by a schematic magnetotelluric sounding in Figure 10.3.

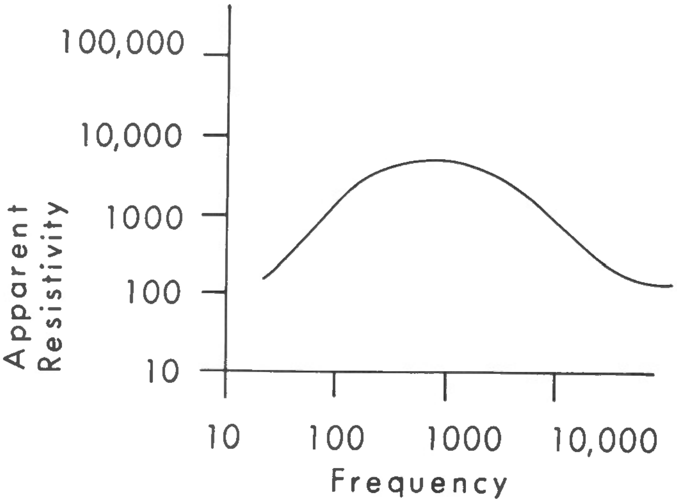


Figure 10.2. Schematic magnetotelluric sounding, sandy or gravelly overburden over massive igneous rock.

If the target is for crustal regions of minimum fluid content and porosity, it would be advisable to launch an extensive electrical study to select those sites with a) the highest resistivities and b) the least amount of lateral variations so that open faults and pore space fluid are at a minimum. This approach should be used as an important criterion for site selection as it is a direct indicator of the fluid régime.

Clay horizons in the overburden

In many parts of the Canadian Shield there are extensive near-surface clay deposits left behind by glacial lakes. These regions have proven to be relatively effective at shielding normal electromagnetic exploration methods and they have consequently made exploration of the bedrock difficult. An example of such a condition is illustrated in Figure 10.1D and in Figure 10.4. These soundings were taken at the Pinawa, Manitoba test site where part of the region is blanketed by about 10 m of clay. We have been able to see through the blanket to the resistive bedrock, but only dimly. It is extremely difficult to do effective testing of the bedrock in the top kilometre in such regions using an electrical method.

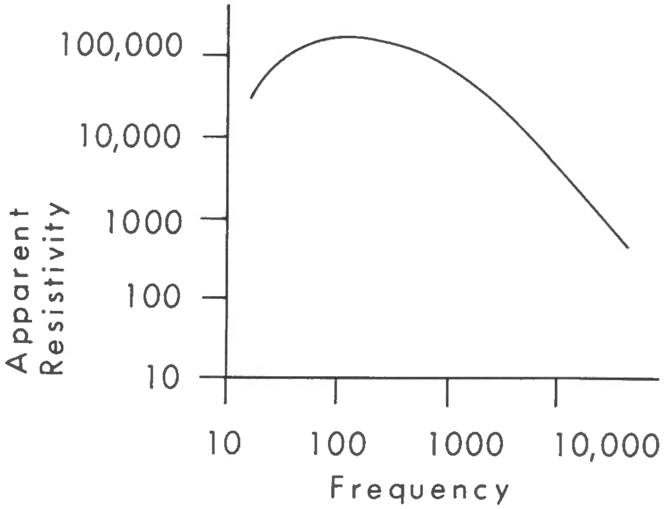


Figure 10.3. Schematic magnetotelluric sounding, overburden over Precambrian sediments.

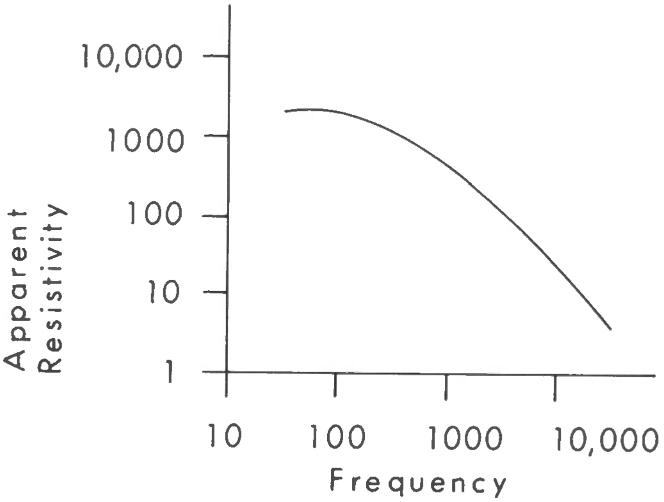


Figure 10.4. Schematic magnetotelluric sounding, clay overburden.

None of the other geophysical methods mentioned above are particularly suited for mapping faults or moisture content, but, they can be used for mapping overburden thickness and for delineating various geological bodies and their contacts, if they have magnetic contrasts. Thus, geophysical mapping using the other methods is a useful direct adjunct to the mapping and selection of sites away from geological contacts.

Drillhole Exploration

The physical properties, discussed earlier, can also be employed in drillhole logging. Open fault structures with flowing fluids can be effectively located by temperature measurement, open faults by seismic or electrical methods. If the hole samples a target represented by a very dry, fissure-free and pore fluid-free zone there is no useful method of logging the holes, since the drilling fluids present in the hole will mask the condition being sought. To measure the moisture content directly in a very dry, massive rock, detailed testing must be done in surface workings.

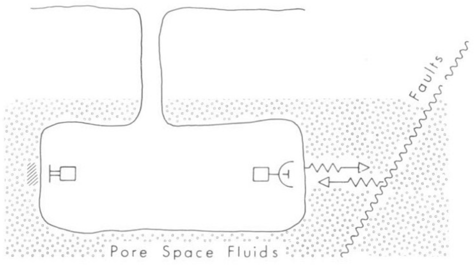
Underground Cavity Testing

In developing and testing an underground cavity there are several philosophies to be considered. The first is to pick a massive, fracture-free rock with minimum pore space fluids and with low permeability. This is the nearest approximation nature can provide to a sealed container. The opposite philosophy is to pick a rock which has a maximum porosity and permeability and/or effective surface area and ion exchange capacity. Such a medium would, in principle, absorb any migrating fluids and thus prevent their entry into the groundwater régime. These two philosophies present different geophysical problems. A variation on the second theme is to pick a rock which expands when exposed to fluids and high temperatures so that it becomes self-sealing no matter what the distribution of fluid pathways. It should be noted that if the first container leaks, the products, while small in volume, might enter the groundwater régime rapidly, given a substantial hydraulic gradient. The present report does not attempt to distinguish which of these approaches is preferable, and given the present stage of the Canadian program, it seems appropriate to consider all three options.

Disposal in salt or granite batholiths represents the first philosophy (Fig. 10.5). This is the Canadian approach although Canadian effort is directed only to the granite batholith case. Shale and clay disposal represent the second philosophy and are not yet being considered seriously as alternate possiblities in Canada (Fig. 10.6). Shale capping or enclosing salt may represent an attempt to combine both cases. No work is underway on the peridotites or carbonatites which represent the third option.

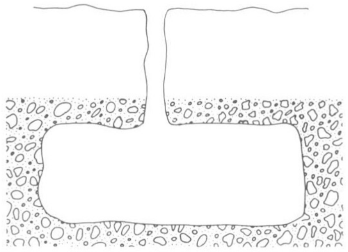
With any option there are a variety of *in situ* geophysical tests that can and should be made to test the nature of the excavated cavern. For the case of the sealed container, there should be extensive mapping of the highly resistive walls using any of the high frequency probing methods. These are illustrated schematically in Figure 10.5. It would be possible to ensure that the amount of water present was less than the equivalent of one monolayer, and to detect brine pockets in the order of 1 – 2 m in size at a distance perhaps 10 – 20 m from the wall. Similarly any nearby faults would be clearly detected. Thus *in situ* testing of the cavity could detect major nearby regions which might release fluids or which would serve as rapid paths to the surface. Experience of this type has been obtained in potash mining where brine pockets are a serious mining hazard. High frequency seismic methods for determining the *in situ* elastic properties of this uniform background material would also be of considerable interest.

In the opposite case, where the object was to have a leaky container with the maximum possible surface area in the rocks to absorb fluids, induced polarization surveys within the cavity, operating at very low frequencies, would give a direct measure of the capacity of the formation to impede fluid flow. Analogous measurements to test which chemical species would be most effectively retarded need to be made. One might also consider establishing artificial electric field gradients using electrodes to develop potentials to retard the migration of various species, just as is done in corrosion protection of pipelines. It would appear that high quality geophysical testing of cavities and of associated backfill material would be very desirable.



GEOPHYSICAL OBJECTIVES	METHODS
i) determine water content in volume adjacent to cavity	i) in situ dielectric constant and loss tangent by radio frequency interferometry ii) D.C. resistivity by expanding electrode iii) infer porosity and permeability
ii) detect open faults with water	i) time domain reflectometry

Figure 10.5. Trap fluids impermeable medium (batholiths or salt).



GEOPHYSICAL OBJECTIVES	METHODS
i) measure water content in volume adjacent to cavity	i) in situ resistivity
ii) determine clay content, surface area and ion exchange capacity	ii) measure dielectric constant and loss tangent by low frequency induced polarization

(if hydrofracing is done to enhance this, repeat measurements)

Figure 10.6. Trap fluids in highly absorbent host (shale, clay, backfill).

Not only does it seem logical to use geophysical methods for "non destructive testing" of any cavity before it is used as a repository, but long term monitoring by these methods could be effective in detecting changes in the subsurface fluid regime resulting from either a disturbed subsurface pressure gradient or a thermal driving effect.

Summary

There are many things which can be done specifically in using and adapting geophysical methods so they are relevant to waste disposal. We must find areas that are free of anomalies, this being opposite to most geophysical endeavours in which the anomaly is the target. There should be extensive testing and subsequent monitoring of sites to observe the seismicity before and after excavation.

In view of the magnitude of the problem it is discouraging to see how little research and development is being applied to this problem in Canada. The approach to date has been to use standard geophysical surveying with almost no effort being made to develop or modify methods so they are optimum. Those who have the responsibility for the radioactive waste disposal program should be developing procedures to tap into the pool of talent that exists in Canada to stimulate this type of development. This should clearly involve major funding, a senior advisory committee, and a process for proposed solicitations to be evaluated by peer group assessment.

PART III
Invited Comments

Dr. O. Brotzen[1]

The Canadian Geoscience Council has kindly invited me to participate in this Forum on the disposal of high-level radioactive waste and to comment on the presentations given. In doing so, I only express my personal views, which do not necessarily reflect those of the Geological Survey of Sweden or of the KBS project. It must also be stated that the following comments represent a strongly revised version of what was actually said at the Forum.

The following comments are based mainly on the work on disposal of high-level waste into the crystalline rocks of the Precambrian Baltic Shield, as carried out in Sweden. During the last two years, this work was organized as a major coordinated effort, called the KBS Project, which was jointly sponsored by all the Swedish utility companies. More than 450 experts from different fields participated in this development of a technology for the safe terminal storage of high-level waste. This provided a description, in considerable technical detail, of the principles, materials, equipment and facilities involved, which has been thoroughly examined by extensive safety analysis.

The results have been presented in a four-volume general report on vitrified high-level waste after reprocessing, and, with much additional data, a two-volume report on spent nuclear fuel. In addition around 120 technical reports on various aspects, including geology, geochemistry, geophysics, hydrogeology and rock mechanics, have been published to date. Many of these are in English and others are presently being translated. Copies of these reports may be obtained through the International Atomic Energy Agency, Vienna.

In the course of this work, it has been shown that different geochemical processes lead to the retardation or retention of the various elements contained in the waste. Examples of transit-times for transport by fluid flow with the groundwater through 1 m of granitic rock, for a number of elements, are given below. They have been calculated for a hydraulic gradient of 0.01, an average distance between fractures of 1 m, and on the conservative assumptions that retardation is due to reversible sorption only, and that, no diffusion of the nuclides into the walls of the fractures takes place. Transit-times (years) for flow through 1 m of rock:

Conductivity (hydraulic)	10^{-9}m/s	2.10^{-12}m/s
Ni	2.7×10^{6}	1.3×10^{9}
Sr	1.4×10^{5}	6.8×10^{7}
Zr	2.7×10^{7}	1.4×10^{10}
Tc	4.3×10^{5}	2.1×10^{8}
Cs	5.5×10^{5}	2.7×10^{8}
Ce	8.6×10^{7}	4.3×10^{10}
Nd	8.6×10^{7}	4.3×10^{10}
Eu	8.6×10^{7}	4.3×10^{10}
Ra	4.3×10^{6}	2.1×10^{9}
Th	2.1×10^{7}	1.0×10^{10}
Pa	5.4×10^{5}	2.7×10^{8}
U	1.0×10^{7}	5.1×10^{9}
Np	1.0×10^{7}	5.1×10^{9}
Pu	2.6×10^{6}	1.3×10^{9}
Am	2.7×10^{8}	1.4×10^{11}

It might be added that these values are theoretically independent of the effective porosity of the rock, and that in one drillhole the conductivity of the rock was shown to be equal to or less than 2.10^{-12}m/s for a length of more than 470m.

Comparison of these figure with the radioactive half-lives of the elements show that many of them will decay to harmless levels during transit through very short lengths of rock. This does not apply to elements with very long half-lives, such as uranium and the other actinides. Again, it has been shown in our studies, that nearly complete retention of these elements will occur due to their insolubility in the reducing environment of the groundwater in granitic rocks at depth. These geochemical processes therefore represent one of the most significant factors in the protection of the biosphere.

These geochemical aspects have not at all been discussed at this symposium, in spite of their obvious importance. For instance, they very effectively refute the claim made by Cherry and Gale that we need to know in detail the hydrogeological conditions of cubic kilometres of rock.

In fact, no adequate description of the principles of the containment concept the Canadian program sets out to verify has been presented at this meeting. The absence of such a basis for constructive discussion leaves room for considerable uncertainty and even for unwarranted concern.

As an example I would like to cite a paper by Maini and Runchal, presented at this meeting only yesterday (Geological Association of Canada, Abstract with Program, v.3, p. 449). There, considerable concern was expressed over the possible effects of thermal convection, which may lead to very short transit-times for the groundwater from a repository situated under an extremely extensive slope. Such conern would appear unwarranted in view of the geochemical barriers. It should also be obvious that upward flow of groundwater would not occur if the

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repository is placed below a local groundwater-divide, where it can be balanced by the downward tendency created by the hydraulic head. Alternatively, no nuclides would reach the biosphere if the waste is isolated from the groundwater by a copper canister, which last throughout the period of thermal convection.

Therefore, it appears that even highly qualified and interested members of the geoscience community are not fully aware of the various factors and options that can be utilized to obtain safe containment of high-level waste. Consequently, it may seem worthwhile to compile such options, within the framework of the Canadian program, and to combine them into geological models, which may then be tested by standard procedures of safety analysis. This would illuminate the relative importance of the different factors involved, and indicate what kind of actual geological settings you should be looking for. This would be more useful than perpetuating a listing of ideal conditions, and might also provide valuable guidance in your work on concept-verification. If publicized, such studies might further serve as a basis for discussion with external parties and thus stimulate suggestions for improvement and modification of the concept.

It must be realized that the presently suggested concepts for safe disposal of high-level waste represent early stages of development. Hence, they are both crude and controversial. Open discussion and effective acquisition of pertinent data are needed to improve this situation. I am confident that the Canadian program, as presented at this Forum will be of very great value in this context. In a few years' time the planning of a repository for HLW will no doubt be regarded as a non-controversial form of advanced engineering geology. Important steps to reach that stage are the development and combined interpretation of the different methods to determine the age of groundwater. Likewise geophysical methods to investigate the rock-conditions in the near field of the individual waste-packages will be increasingly needed.

Dr. K. Kühn[1]

I appreciate the kind invitation of the Canadian Geoscience Council to comment on the oral presentations at the Forum. I would like to cover three items in my short statement:

1. an outline of some differences between Canada and Germany and these differences are, of course, true for most of the Western European countries;
2. to indicate that we are not only doing paperwork and drilling holes into the ground but that since about 1967 there has been a repository operating in Germany; and
3. some general comments on what I have heard at the Forum on what is the situation as compared to Germany.

In Canada, you use the CANDU reactor whereas in Germany, as in the United States, we use the light water reactor (LWR). The largest operating station of this type in the world, the station is named "BIBLIS", is situated on the Rhein River in Germany and has two 1300 MW reactors in operation; they have quite a good record, similar to Canadian ones mentioned earlier. A second difference between Canada and Western Europe is that in Canada you possess a large amount of uranium ore. There are no uranium deposits available in Western Europe, with the exception of Sweden and a small deposit in France. A third difference, covered in the paper by R.W. Barnes, is the question of reprocessing of the spent fuel elements. In Canada, this decision is still pending while it is clearly decided in our country that we must opt for reprocessing and use the rest of the fissile material in the fuel elements. If the uranium and plutonium is only recycled in the LWR cycle, there is a factor of 2 in saving natural uranium compared to the "once through" - LWR-fuel cycle and a factor of 1.5 using the Canadian fuel system. If the recycled uranium and especially plutonium will be used in fast breeder reactors this factor of saving natural uranium is increased to 80. These facts are presently being discussed in an international frame, mainly after President Carter of the United States invited all interested countries in October 1977, to participate in the INFCE (International Fuel Cycle Evaluation) study. In this connection I would like to answer one question which was asked by a member of the audience: The problem of transportation of irradiated fuel elements in Western Europe is considered to be solved. Several thousand tonnes of irradiated fuel elements have been transported to the two reprocessing plants in La Hague, France, and Windscale in Great Britain, also using ship transportation, without any difficulties.

Another difference is, and this was outlined in many papers, that Canada has put the main emphasis on hardrock formations, considering at the same time some others, whereas from the beginning in the early 1960's, Germany has placed emphasis on salt formations because of the favorable geological setting.

The Asse salt mine is used at present (and has been for the past 12 years) as a pilot plant. The repository which I will touch on later, will be located on the Elbe River and the salt dome is named Gorleben. There is a difference in the use of the repositories. In Canada, the pilot plant is scheduled to become the final repository whereas in Germany the Asse salt mine is the pilot repository and the final repository will be developed at another site, namely at Gorleben.

In Germany, all types of wastes have to go into a repository, i.e. also the low-level and intermediate-level wastes from the operating power stations, the reprocessing plants and the nuclear research centres. A great part of these goes presently to the pilot facility in the Asse salt mine. No shallow land burial is used for these types of wastes.

In Germany, underground heat conductivity studies are in progress in the Asse salt mine with electrical heaters which are being inserted into the floor. In one test run five electric elements have been put into a borehole, for the concept in Germany is to use boreholes from 40 to 50 m deep and to stack several cylinders of high-level wastes on top of each other. There were three objectives that we could perform in this test: 1) convergence measurements in the borehole because the salt behaves plastically, 2) the heat dissipation around the borehole, and 3) the rock mechanics behaviour in the surrounding area. These are brief comments on what we are doing in the Asse salt mine. To these, I can add a few comments on what I have heard at the Forum.

It is not necessary to contain the high-level radioactive wastes indefinitely, let us say for several million years. Rather we should look at the relative merits of the disposal systems. Clearly society already exists with a variety of hazards beyond our present technology. For instance, we must look at the potential hazards

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which are originating from uranium ore deposits which have been sitting in the ground for billions of years, with water running through uranium mines, and people living close to these mines.

With regard to risk analysis, risk is defined as the product of probability X consequence and, of course, we therefore need predictive geology, otherwise we are unable to assess the probability of future geologic events. I am a little anxious to find the true values of these probabilities. Therefor, I am not too enthusiastic to use the risk analysis-methodology as an instrument for the hazard assessment of a geological repository. But if you compare the time scale which is necessary for the disposal of radioactive wastes with the geological time scale, that risk for geological failures is negligible.

There was much discussion about different barriers which can be used in the disposal of radioactive wastes: 1) waste itself, 2) containers, 3) buffer material and 4) backfill material. I want to emphasize that we must not forget the geological barrier itself, for otherwise we can solidify and pack the waste and store it on the surface in some artificial building. In this connection an excellent job, under extreme time restraints, was achieved by the present Swedish program. They were able to answer all the questions in the time available. But because of these restraints they put some additional artificial safety barriers into the geological system of the repository in order to achieve better overall safety. But sometimes increasing the safety factor in a technology only reflects a lack of better knowledge.

One further remark which relates to the public debate and acceptance of the repository program. Do not expect to achieve 100 per cent agreement from the public. There will always be some opponents which you will never be able to convince. In this connection the scientific community has to be very careful when discussing its problems before the public. There are always different opinions among scientists on a special topic, which, I think, has to be the case, but the public immediately interpretes these differences that the scientists are not in agreement and that the problem is not solved.

Finally I got the impression that the present program which now operates in Canada should not be looked at as the "milking cow" for the financial support of all programs and subprograms which somehow could be related to radioactive waste disposal in geologic formations.

Despite all the technical and scientific problems discussed at the Forum, I would judge that the majority of the present problems are about 80 per cent of a political nature. So let us, the scientific community, ask of our politicians that the geoscience aspects of radioactive waste disposal are not be treated in political halflives of 4 to 5 years, but that we receive funding and support for several decades to logically plan and solve this fundamental problem of radioactive waste disposal.

P.A. Witherspoon[1]

As the last speaker on the Panel, I would like to add my thanks to those of Dr. Brotzen and Dr. Kühn for the opportunity to participate in this Forum. Rather than describing the U.S.A. program in radioactive waste storage, I would like to offer some criticisms of the Canadian program. In doing so, I wish to make clear, that these are my personal views and should not be construed as representing an official position of the Lawrence Berkeley Laboratory (LBL) nor of any other organization.

In considering the overall question of geologic storage, one is immediately faced with the concept of designing a system of multiple barriers that involves: (a) the waste form, (b) the canister material, (c) the backfill material, and (d) geological containment. The stability of the waste form and its ability to resist dissolution by groundwaters are the prime considerations for the first of these barriers. The corrosion resistance of the canister is the key factor in the second barrier, and the stability and tightness of the backfill material are the key factors in determining the effectiveness of the third barrier.

From what I have heard this afternoon, it would appear that the Canadian program is making good progress toward the resolution of the problems involved with these first three barriers to underground migration of radioactive waste.

What concerns me is the necessity, as I see it, of pursuing the geological containment barrier with a more vigorous program. You are actively involved in gathering the background data that must be collected, and this is good. But, in my opinion, such activities are not enough.

I believe that a successful solution to the geological containment problem will not be possible without having access to a full scale, field test facility. By that, I mean a mined opening that extends to depths of the order of 1 to 2 km and provides access for full-scale experiments to be performed in an appropriate rock type. I do not think it will be necessary to use radioactive waste in such a facility because the key problems can be investigated without such materials ever being needed.

One of the most difficult problems is to understand the hydrogeology of a nearly impermeable rock. With all due respect for the views expressed by Dr. Brotzen, I still feel that we need to understand hydrogeological conditions both near and far from a repository in order to be able to understand the total system. I also believe that until the hydrogeologist can devise a way to characterize the flow properties and sorption characteristics of a given rock mass under real field conditions, we will not be in a position to deal with this problem in an adequate manner nor to proceed with confidence to the larger problem of designing a safe repository.

The crux of this matter is that the hydrogeologist is being asked to characterize the factors that control water movement through nearly impermeable rocks. This is a new régime in which the technologies that have been developed over the years are not applicable. How does one measure flow through nearly impermeable rocks in the field? What are the geochemical factors that affect the migration of aqueous solutions of radioactive substances? How does one collect the data needed to build a mathematical model of such a system? How does one verify the accuracy of such models? These are some of the tough questions that must be addressed, and in my opinion, such questions cannot be answered without access to rock systems under appropriate field conditions.

Another critical problem is that of understanding the role that discontinuities, such as fractures, play in controlling the mechanical response of a rock mass to changes in temperature. This is a problem where much remains to be done. Some of you are aware

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[1] Lawrence Berkeley Laboratory, University of California, Berkeley, California.

that we at LBL have been involved in a Swedish-American cooperative program of investigations on radioactive waste storage in mined caverns. This program was made possible when a formal agreement between the Swedish Nuclear Fuel Supply Company and the U.S. Energy Research and Development Administration (now the U.S. Department of Energy) was signed July 1, 1977. This agreement made available for underground investigation a large granite rock mass at a depth of 335m in an abandoned iron-ore mine at Stripa, Sweden.

We designed a series of thermal studies for emplacement in the Stripa granite, using electric heaters, and initiated the first field experiment on June 1, 1978. Six months of data from these heater tests have produced very interesting results. Despite the pervasive fracture systems that have been found in this body of granite, the thermal field is easily predicted. We measured the thermal diffusivity of intact samples of the Stripa granite in the laboratory and then predicted the temperature history for every point where measurements using thermocouples are being made. The agreement between predicted and measured temperatures is excellent.

This same agreement between theory and practice has not been obtained with regard to the mechanical response. For example, we are making extensive use of extensometers to measure rock displacements in the vicinity of the electric heaters. In every case, we are finding that measured displacements range from one-fourth to one-half what one would expect if the rock mass were a continuum containing no discontinuities. This is an important result because it clearly shows that we must understand the mechanisms by which fractures contribute to the overall mechanical response of a rock mass when subjected to a thermal load. This result also affects the fracture hydrology because thermally induced changes in rock stress will affect the size of the fracture openings (apertures) and thus the transport of waste in solutions that move through the repository. We must understand these phenomena, because without such knowledge, how can we properly design an underground repository?

These results from Stripa also demonstrate that there is no substitute for first-hand experience in a full-scale test facility. It is for these reasons that I urge you to consider developing a test site as soon as possible. From what I understand of the Canadian program, you are already headed in this direction, but a pilot repository will not be available until 1985. In my opinion, that is too far off in the future. I believe that you need the basic technology that I have outlined here in a much shorter time frame.

I again want to thank the Canadian Geoscience Council for inviting me to participate in this Forum. I very much appreciate the opportunity of being able to listen to such an excellent and comprehensive review of the Canadian program in radioactive waste storage.

PART IV

EDITED DISCUSSION

During the Forum, two periods were available for discussion and for questions from the members of the audience to the panelists (authors). These periods were taped and the edited transcripts are included below, with the names of the speakers posing the question (Q) or providing the answer (A) indicated where possible. It was not possible for the speakers to review the transcript. The affiliation of the panelists (authors) is provided earlier in this volume in their own papers.

Q. *C.Kreitler, University of Texas:* What does the Canadian government propose to do when you have gone to the public and they have rejected all your sites? In all seriousness are you going to have to offer high financial returns to the people where the repositories are located?

A. *S. R. Hatcher:* Of course I would not speak for the government; it simply is a political question that you are asking. I am not convinced that we are likely to get to that situation. I think that we are beginning to see some evidence that quite a lot of communities are anxious to find out more information about the whole waste disposal program. There is a good prospect that as we develop the safety analyses and we go into the social-economic impact of the program, that there will be a variety of communities interested in it. We are not in any crash program to have this site in the next year or so, hence we do not even intend to start the site selection process until we are into the 1980's. By that time much research and development will have taken place. In the final analysis, if they do reach that situation there are a lot of areas of Ontario that are pretty remote, and governments may decide that that is where they have to go.

Q. *Anonymous:* May I make a comment, I am from the sister state, to the last questioner and we are both involved in this problem and people are not terribly happy with us at the moment in the Gulf States and Gulf Coast and so we would like to know the secret of the optimism that you have?

A. *S.R. Hatcher:* We don't have any secrets, we are just not getting inquiries from quite a lot of small communities in northern Ontario.

A. *J.L. Wallach:* We also have to distinguish between a local community reaction to a particular project such as a waste disposal site and the reaction of the public in general to the entire concept. In regards to a local communtiy reaction, I do not know whether there is much difference between the kind of reaction, and, say, reacting to any other segment of the Nuclear Fuel Cycle in a particular community. Some communities may object to having a mine open up in their area for perhaps the same reason. They feel that in the risk benefit analysis, they are more on the risk end of things than on the benefit side. In terms of the general public's response to it, that is a situation that I do not think is any different in Canada than in the United States, at least from what I have seen of it.

Q. *Jane Rae, Ottawa Journal:* I have a question for R.W. Barnes. You mentioned at the end of your talk that the Ontario Hydro has methods of transferring irradiated fuel. Are your presently transporting it?

A. *R.W. Barnes:* Not in the quantities we would be when the repository is in service and we are disposing of the waste. For instance, I have just been sent two bundles in their cannisters to the Whiteshell Nuclear Research Establishment, Manitoba, for some tests, dry storage testing, things like that. These are very small quantities, not on the industrial scale that I was speaking of earlier.

Q. *F.Purcell, Miami, Florida:* I would like to ask the question of R.W. Barnes: You mentioned in your talk some time ago that reprocessing was not yet acceptable, can you explain that statement?

A. *R.W. Barnes:* The position is that no decision will be made on reprocessing in Canada on a production scale until the International Fuel Cycle evaluation study is completed, which will be sometime near the end of next year or into 1980.

Q. *John Sodall, Westinghouse Corporation, U.S.A.:* I would address the question to P.A. Witherspoon. It would seem the Swedish program has lowered the concentration in the waste to eliminate some of the uncertainties and to improve the leach resistance of the glass. The Canadian program, as we see now, does not have very highly loaded glass, but if you look at the last 15 years of the U.S. program there has been essentially a drive for higher and higher thermal loading in the glass. I would like to ask P.A. Witherspoon if he has any feelings about the advantages and disadvantages of this and are there any prospects towards, at least initially in the U.S. program, dilute or lower specific activity material?

A. *P.A. Witherspoon:* I believe there is a distinct trend toward lower loadings in the underground systems to avoid the problems that obviously occur as the temperatures rise in the underground repositories. I think the trend is there although it may not yet have expressed itself, but I get the feeling by virtue of the increased interaction among all the countries involved that greater consideration is being given to longer storage, lower loadings and lower temperatures at depth.

Q. *Bruce Sarshell, U.S. Geological Survey:* My question is directed to J.A. Cherry: You mentioned one criterion about the age of old water being, perhaps, a good indicator of a good repository. I take issue with that. Certainly I have seen the same sort of statement recently in the U.S. literature, and I think I know what you mean, but taken on its own, I think it gives the wrong impression. The old water in the groundwater system is generally in the discharge area, and that is certainly not where you want to put the repository. I think I know what you mean but could you elaborate more?

A. *J.A. Cherry:* Yes, I'm glad you brought that point up; because of a time limit I was trying to make the point very direct and concise. What I really meant there was that if you are looking for a repository environment, and if you have detected on a regional scale an extensive zone of very old water, this has a possibility of indicating positive features. It is a criterion that has to be used along with many other hydrogeologic criteria again with the total environment of the old water; it does not mean that it is going to take a long time for the water to move from one site into the biosphere.

Q. *B. Voight, Pennsylvania State University:* E.L.J. Rosinger showed us the multibarrier approach, but you did not address the problem of what will be done with the access shaft, or any exploratory bore holes that will be drilled into the repository environment, after the period of filling with the waste backfilling, and final abandonment. What program do you have to seal off the access shaft and any exploratory holes?

A. *E.L.J. Rossinger:* I showed the various barriers and there was one barrier called backfill and sealing. As I have said the decision has not been made yet what will be used for the backfill and the sealing; whether it will be the same material as the backfill or a different material.

Q. *B. Voight:* No decision at all has been made to cement the shaft yet?

A. *E.J.L. Rossinger:* Well, we have initiated the studies on the backfill material and I believe presently we assume that the simplest model for the backfill and sealing will be to use crushed rock mixed with bentonite clay.

Q. *G. West, University of Toronto:* I think that one thing that impressed me from most of the government presentations is that obviously a very thorough job will be done on evaluation any waste disposal scheme, i.e., in straight-forward scientific evaluations: the numbers, for instance, in measurements being made of how fast the uranium pellets are dissolved in ordinary water. But I think that the public is worried about the many examples in the past where experts like us, have said alright we have engineered it all, its going to work, and probably it did for a while but then something went wrong. Of course, from the scientific point of view we all gather around and take a look at it and we understand why it went wrong. In this case, it is a matter of great public concern and we need to demonstrate that not only have we looked at the straight forward engineering very carefully, but that we have also subjected all proposals to the most careful scrutiny, by people who will look at it from an adversary point of view. I do not see in the present system a great deal of the interaction necessary to do that checking. I see mostly a description of very large engineering projects, of scale decision making, and so on, which is appropriate to the engineering side of the proposal. I would like to know how the interaction at the scientific level, not the organizational level, is actually going to take place so that there is every possible chance that the expertise around the world will be brought to bear on whether something is wrong with the designs.

A. *J.B. Wallach:* From a regulatory point of view, we do not build in, as such, a system of checks in the regard that was referred to by G.F. West. When we receive an application, we will assess that application and if we have people on our staff that are unable to address some of the problems – we don't have expertise in certain areas – we have Radioactive Waste Management Safety Advisory Committees, comprising of people who are from government and nongovernment, who also will assess an application. Therefore, the A.E.C.B. itself makes an assessment, as well as the Radioactive Waste Management Safety Advisory Committee, and hopefully this will help to partially cover the problem. If something has gone wrong, or looks wrong, if not everything has been thought of, then perhaps by having two groups within the realm of A.E.C.B. analyze this, problems or omissions can be discovered. As such, we are not requiring A.E.C.L. or Ontario Hydro, or anyone else to address this problem, asking that they find somebody who can find something wrong with it. In forums like this, in open discussions, there will be questions raised which will indeed direct people to think about things that perhaps were not thought of before.

A. *S.R. Hatcher:* Yes, I agree that is a very important point, and I think the whole business pretext of getting external advice is essential for the program. We had some discussion with the Canadian Geoscience Council, in fact just this last weekend, to establish an Advisory Committee on this program drawing from the technical disciplines that are involved: all the geosciences and from other disciplines such as chemistry, engineering and mining. We will be setting up such an Advisory Committee, and we will have peer review and comments from people outside of the program.

A. *D.W. Strangway:* This, I think, is precisely the issue that this forum is all about. Many of us on the outside have been very concerned. We hear bits and pieces of information, but we have never really been exposed to the complete program and I think the result of the Advisory Committee, which has been mentioned already, has been quite frankly a result of a considerable amount of external pressure by the Canadian Geoscience Council feeling that there was a need for this process. I do not want to begin to second guess what that advisory committee will take on as its tasks. I presume that the C.G.C. and A.E.C.L. will be sitting down very shortly and working out its charter. I would hope that somewhere within the charter of this committee there will be statements to the effect that when the proposals are put together, they will in fact be brought to meetings of this sort; they will be published before final decisions are made; and that there will be chances for responses and rebuttals in the literature. I think too, that there are really two communities that they have to deal with; the primary one to be dealt with is the general public, but I think they also have to deal with what I call the scientific public which is all of us assembled here. The fact that this group is here today and that this room is full means that there are a lot of people out there that really give a damn.

Q. *H.R. Wynne-Edwards, Moderator:* We have in the audience Dr. Jim Harrison who has done a great many things in his career, but among them he is a co-author of the recent Hare Report to the House of Commons, the Federal Report on this whole question and I think we would like to hear him make some comments on the international scene, having spent the last 5 – 6 years in UNESCO.

A. *J.M. Harrison:* Thank You Mr. Chairman. The International Council of Scientific Unions which is the largest body of any international non-governmental scientific agency in the world, had at its last meeting about two or three weeks ago, decided that they would carry out precisely the kind of review that G.F. West refers to, on the international scene and in two or three major areas. I think the three major areas are a) a review of activities being undertaken for terrestrial disposal, b) one on marine disposal and c) one which relates to both, on the pathway analyses. These will be not research examinations, but reviews of research that is currently being undertaken, beginning with the International Intergovernmental Agencies.

Q. *R.A. Freeze, University of British Columbia:* G.F. West has pre-empted some points I wish to make, and that is that an adversary system is very necessary in the Canadian program. This, not only in the scientific fraternity, but also for the ultimate political decision-making that will be made in the public forum. I would argue also that peer review in the scientific field is probably not sufficient. I believe that the government must ensure that there will be parallel sets of earth scientists and engineers working in an adversary role within the federal government or within the consulting and academic communities in Canada. One of these groups should be dedicated to setting up research and development programs, with the energy requirements uppermost in their minds, with an optimistic approach to the interpretation of the data, and feeding their information to the energy development side of the public debate. The other group, which should be equally strong and should be independant, should be setting up research and development programs on the environmental and safety and hazard side, and they should have a pessimistic approach to the interpretation of the data, feeding their results into the environmental side of the public debate. This would hold in the geological, geophysical, geotechnical and hydrogeological spheres. It is my observation in the hydrogeological sphere, with which I am most familiar, that most of the technical confidence is now being co-opted on the energy development repository design side, and I would like to ask the members of the panel from the federal government, whether we are going to follow the lead of the United States in setting up a non conflict-of-interest system with a regulatory commission carrying out research and an energy commission carrying out research in parellel ways to look at this problem in its true conflict. It is a fact that it is a conflict and we all recognize that, but it is one that we have to reach an optimal solution as citizens and scientists.

A. *S.R. Hatcher:* I think it is clear that there is no conflict of interest between the development side, the Atomic Energy of Canada Ltd., and the regulatory side, the Atomic Energy Control Board. We have completely independent bodies that have been so since the start of the nuclear power program.

Q. *A. Freeze, University of British Columbia:* I certainly did not mean to infer that, but the point is that the technical competence in the science field is real, but totally on the one side. Research is being done and I presume you will make your decision on the data they provide and they are honourable men, of course. It is different to look at a program from the point of view of trying to get the waste under the ground as opposed to the point of view of what can go wrong.

A. *H.R. Wynne-Edwards, Moderator:* It may be appropriate to hear some details of the Swedish program from O. Brotzen and W.S. Fyfe.

A. *O. Brotzen:* First I would like to emphasize I am not here as a representative of the (Swedish) government, the KBS or the Geological Survey. I am here in my personal capacity as a geologist. We produced a number of reports on the problem of ultimate storage, of high-level radioactive waste, which were reviewed nationally and internationally and these were later evaluated by the government, with the KBS Project having an opportunity to comment on the reviews. As a result of all this activity, a different party forming the government could not be unified with the verdict and, as a result, the first nonsocialistic government in more than 40 years came to power. It collapsed later and we now have a minority government which must face the same problem and will deal with it in a slightly different way. There will be more emphasis given to the nuclear energy inspectorate which as far as I was informed just before I left for Canada, was forming an independent geological panel with members who had not been involved with the KBS Project in order to review our first results.

A. *W.S. Fyfe:* Some of us who are involved in this project had to present this and review it before a fantastically wide audience, selected from the top of Swedish Science, from the Academy of Science, many of these people having no direct interest at all. But if your were doing a study of the corrosion of material in groundwater, for example, you had to face top organic chemists, top corrosiion experts, even nasty bacteriologists so that you had to defend yourself against an absolute group of people who were all highly respected scientists at the top of the Swedish group. This was most impressive and it is incredible how it creates honesty.

Q. *Ayers, Louisana State University:* I would like to make an observation; my group has just completed this year, two 5000 foot wells into salt domes and in doing this we have not only tested the salt, but we have also tested public opinion. It is a rather interesting thing, and perhaps it may be of some interest generally, that the concern that has been expressed here, and correctly so, has been for the long range, way off into the future. However, the adverse public opinion that has been expressed in Louisana, relative to the studies that our group has been conducting, is directed toward the short term risks, which are practically nonexistent. So it seems to me there is a problem in communicating basically with the people. All of the things we are talking about here, at least as far as the opponents that have risen in my State, are not the problems that are of real concern, the problems are nonexistent ones that might happen tomorrow. The concerns that the people have relative to a particular proposal is not for the long range future in 100000, 4000, 1000 or 100 years. The concern is for what that particular proposal means in terms of safety today and I do not know whether that kind of perception is the same kind of perception that people elsewhere might have, or general public elsewhere might have, but I do not really believe that we are very different down south than elsewhere.

Q. *Anonymous:* I may be under a misimpression as to what the concerns of the public here are, but I do not believe they are quite the same as for the disposal of high-level wastes. I really think they are looking into long term, and the present day concerns are more associated with other segments of the fuel cycle; this is my observation of the major concerns in Canada. In fact, I have not detected public concerns over the short term or the immediate aspects of high-level waste. There have been discussions over the suitability of the storage methods but not the immediate repercussions of disposal in deep rock.

Q. *J.O. Wheeler, Geological Survey of Canada:* I would just like to return to a slightly bureaucratic aspect to read into the record an event that I think has a bearing on how we are here today. The Canadian Geoscience Council and before that, I think individuals, approached the Geological Survey to consider whether the Survey would appreciate having an Advisory Committee to look into its operations. This, the Geological Survey of Canada agreed would be a useful thing, believing that an outside appraisal of our programs, and shortcomings would only make them better. In going that route, which we did, one of the elements that was investigated was the radioactive waste disposal program, to begin with through the Geological Survey's participation in a departmental component of that program. I think it is fair to say that investigation wormed its way into the Department through the Geological Survey and I would just like to have that fact understood. I know that in view of the present climate of constraint there is no way that the Geological Survey, even for its own particular aspects of the program, is going to be able to cover all the base of research. I think it was make clear with the Blais Report some years ago that to tackle the problems in Canada, which are so numerous, and which are particularly of concern to this audience and this topic, is going to take all of the Canadian geoscientific community and even others to solve the problem.

A. *D.W. Strangway:* As one of the members of the Advisory Committee that J.O. Wheeler refers to, I must confirm that when we went into examine the programs we were cordially received and well supported by everybody involved in the process. It was open to us and people did not attempt to hide things from us. That document, by the way, will be published in the 1978 Annual Report of the Canadian Geoscience Council.

Q. *Don Cranston, Mineral Policy Sector, Department of Energy, Mines and Resources:* I have a question I would like to ask of S.R. Hatcher, Atomic Energy of Canada Ltd. I am a little reluctant to ask it, but I think it should be asked. Some years ago I was involved in a compilation of a listing of known mineral deposits in Canada that are not being mined. Because of this, a few months ago, I indirectly received a request from AECL asking if we could provide them with a listing of mineral deposits in Canada that contain poisonous elements such as mercury, arsenic, antimony and so forth. Now I do not know why AECL wanted this, but I have come up with the obvious inference that somebody in AECL is trying to justify disposal of nuclear waste, with the argument that we already have all sorts of deposits around with poisonous elements. This is a very dangerous statement to make, but I wonder if that sort of thinking is going on in AECL; I realize I am only inferring this from the request.

A. *S.R. Hatcher:* I am not familiar with the particular request that you are talking about, but I think that is a fair question and the point has been made by one or two other speakers today, that we should put nuclear power and nuclear waste into perspective. Radioactivity is not a brand new thing that has suddenly been discovered in the nuclear power age. It naturally exists in the world; there's an awful lot of radioactivity locked up in the world's uranium deposits and as one of the other speakers said today there are a lot of poisonous substances that our society deals with and handles. Sometimes well, sometimes not so well.

Q. *K.G. Kennedy, Hydrogeologist, Science Applications, U.S.A.:* I would like to ask two quick questions – one to the governmental side and the other to the scientific side. First, just from an economic standpoint, I would like to know what the dollars are involved in our very clean source of energy that we are developing for Ontario Hydro. We are looking at a "Catch 22 circle game" here where we have a very useful uranium supply providing an economy for a wide variety of the public sector. What are the federal dollars involved in just the waste disposal program? Who has control of those dollars – whether its AECL or whether its EMR ect.?

A. *S.R. Hatcher:* The waste disposal program is funded this year at the level of $9.9 million by the federal government. That does not count what goes in from the Ontario side; I am not familiar with that figure, but possibly it is through the federal government.

R.W. Barnes: Ontario Hydro has contributed about $1.8 million since about 1973.

Q. *K.G. Kennedy:* R.W. Barnes, what are your calculations of an estimated cost for a waste repository and when you say that Ontario Hydro has done an economic analysis; what dollar figure do you include as far as a waste repository being used to dispose of your particular wastes from Ontario Hydro?

A. *R.W. Barnes:* The disposal cost is really an AECL figure.

Q. *K.G. Kennedy:* So Ontario Hydro does not include disposal costs in the generation costs?

A. *R.W. Barnes:* The answer to that is I believe we have not started at this point to charge, but people are looking at it now; but it is very, very small; it is a fraction of a per cent.

Q. *K.G. Kennedy:* What will be the total dollar cost for the repository?

A. *S.R. Hatcher:* It depends on how much fuel you want to store in it. I think the estimates we had from the work that is being done by Acres Consultants Ltd. is that it would be in the order of .02 to .04 cents per kilowatthour. For the construction of a test repository, I can give you the price on that, our estimates are in the order of $50 million. That is for a test repository, that is not for a commerical scale operation.

Q. *C.G. Winder, University of Western Ontario:* Dr. George Wald, Nobel Laureate is very pessimistic about the future of mankind. He pointed out that the United States is making 3 H-bombs per day. I regret that I cannot ask this group my question the same way that I have asked groups of students. I ask them to put a simple answer to the question "How long is Man going to survive on this earth?" In a recent class consisting of 22 students, their average answer was 220 years. Another university group that I spoke to were a little more optimistic, they said 320 years. Dr. George Wald in his particular address at the University of Western Ontario said 5 to 25 years. So ladies and gentlemen, when you are talking about storing material for 10000 years, I think there is a more important question which really is fundamental in this whole Forum — and that is how long is Man going to survive?