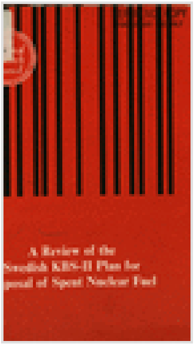

A Review of the Swedish KBS-II Plan for Disposal of Spent Nuclear Fuel (1980)

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Committee on Radioactive
Waste Management
Subcommittee for Review of
the KBS-II Plan

Commission on Natural Resources
National Research Council

NATIONAL ACADEMY OF SCIENCES
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January 16, 1980

Mr. Lars Hjorth
Head of Department (Energy)
Ministry of Industry
Fack
S103 10 Stockholm, Sweden

Dear Mr. Hjorth:

The National Academy of Sciences has completed its review of certain aspects of your KBS-II Plan for the handling and final disposal of unreprocessed spent nuclear fuel. This review, carried out by a Subcommittee of the Committee on Radioactive Waste Management of the Commission on Natural Resources, was confined to "...an evaluation of the adequacy of the technical data base to support conclusions in the KBS-II Plan regarding two key elements of the proposed disposal system: (1) the long-term stability of copper canisters enclosed in a bentonite overpack under a specified range of physical and chemical conditions, and (2) the availability of a deep geological disposal site with the requisite dimensions, stability, and groundwater properties and with the necessary stability to maintain these characteristics." This review is, therefore, not an overall criticism of the entire KBS-II Plan nor is it a systems study of the radioactive waste problem. In fact, it is the intention of the National Academy of Sciences in the near future to carry out a systems study with emphasis on conditions in the United States.

Because of the many different facets of the problem treated in the KBS-II report and considered in our review, it is difficult to summarize the results in a few words. Therefore, we refer you to the report's Summary, which is best considered as a whole. There is also a section entitled Concluding Remarks as well as the main text and two Appendixes.

The National Academy of Sciences wishes to express its appreciation for the responsiveness of Dr. Lars Larsson, Attache for Science and Technology of the Embassy of Sweden in Washington, the Swedish scientists and engineers who met with the Study Committee in Stockholm and the staff of the KBS Project. The assistance and cooperation of these people have made this review beneficial to the United States and, we hope, useful to the Government of Sweden.

I have enclosed five manuscript copies of the report for your immediate use. Printed copies of the report will become available in about five weeks at which time the necessary additional copies can be sent.

Sincerely,

P Handler

Philip Handler
President

Enclosure

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COMMISSION ON NATURAL RESOURCES

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SUMMARY

This review of the Swedish KBS-II Plan was undertaken by a Subcommittee of the Committee on Radioactive Waste Management (CRWM) of the American National Academy of Sciences. The review is confined to an evaluation of the adequacy of the technical data base to support conclusions in the KBS-II Plan regarding two key elements of the proposed disposal system: (1) the long-term stability of copper canisters enclosed in a bentonite overpack under a specified range of physical and chemical conditions, and (2) the availability of a deep geological disposal site with the requisite dimensions, stability, and groundwater properties and with the necessary stability to maintain these characteristics. These two elements, in the opinion of the CRWM and this Subcommittee, are critical to a judgment regarding the long-term functioning of the waste isolation system. Excluded from the study is any consideration of costs, proposed facilities for pre-burial handling of the waste, alternative or "better" methods of disposal, radiation dose calculations, or the wisdom of disposal of economically valuable copper-encased spent fuel rods. The review is in large part a subjective evaluation by members of the Subcommittee of the quality and completeness of the Swedish research and the logic relating the research to the conclusions drawn.

The KBS-II Plan, like some other waste-isolation plans, uses a sequence of engineered barriers and natural geologic barriers to limit the escape of radionuclides. The plan is unique in placing major reliance on an engineered barrier consisting of thick-walled copper canisters surrounded by overpacks of bentonite clay. In the Subcommittee's judgment the effectiveness of this barrier to contain the radionuclides in spent fuel rods for hundreds of thousands of years has been adequately demonstrated, and the required properties for the less easily verifiable geologic barriers are therefore less stringent than in other disposal plans.

The Subcommittee agrees that the available technical data are adequate to support the conclusion in the KBS-II Plan that radionuclides will not escape at unacceptable rates from a repository built as specified in the KBS-II report, provided that construction is well engineered and a proper site is used.

The principal bases for the Subcommittee's judgment, together with the principal remaining uncertainties, are listed below. Numbers following an item indicate sections of the report in which the item is discussed in detail.

1. The canisters: Methods of manufacture have been shown to be currently available, and both experiment and theory have demonstrated that the canisters will have sufficient mechanical strength and corrosion resistance to survive in the designed repository environment for hundreds of thousands and probably more than a million years. (V.1 to V.4)

2. The overpack: Extensive research on bentonite clay has shown fairly convincingly that this material can protect the canisters against mechanical disturbance and corrosive attack by groundwater. Additional research under repository conditions, however, is needed to ensure that compacted bentonite plus loose bentonite filler can be placed tightly around the canisters and that the compacted bentonite will hydrate uniformly without developing cracks or channels of rapid groundwater flow. (IV.6)

3. Existence of repository sites: The existence of at least one site in Swedish bedrock that meets the minimum criteria of dimension and low groundwater movement, though not conclusively demonstrated, is reasonably assured, and it can be inferred from available geologic data that other equally good or better sites, exist in Sweden. Actual location and definition of such sites, however, will require additional exploration and ground testing. (IV-1)

4. Stability of sites: Despite doubts by a very few Swedish geologists, there is substantial evidence that over large parts of Sweden the bedrock is tectonically stable, so that a well chosen repository site is in little danger of damage from either slow rock movement or rapid dislocations accompanying earthquakes. Observations of the effects of past glaciation in Scandinavia indicate that possible renewed glaciation will cause no damage to a well-constructed repository or damage too slight to pose a threat to the post-glacial biosphere. (IV.4 and IV.5)

5. Quantity, movement, and chemical composition of groundwater: Much exploratory work and many analyses have shown that the quantity of groundwater moving through a properly chosen site will be small and that its chemical composition will stay in the range in which the amount of corrosion of the canisters will be small. (IV.2)

6. Temperatures in a repository: Well based calculations indicate that the temperatures of the canister surfaces will be kept below 80°C by the planned pre-disposal aging of the waste and its spacing in the repository.

Temperatures will be low enough so that their effect on corrosion of the canisters and on the properties of the bentonite will be negligible. The rise in temperature in the rock around a repository is expected to be below the level that might cause damage either by setting up convection cells in groundwater or by changing the fracture hydrology of the rock. Additional experimental work on the effects of heat is desirable; such experiments are under way at Stripa. (IV.2, IV.3, V.3)

7. Repository closing: It has been demonstrated fairly convincingly that the planned bentonite seals and backfill for shafts, tunnels, and boreholes after a repository is filled will be adequate to prevent channeling of groundwater. Nevertheless, the Subcommittee thinks that this is the weakest part of the KBS-II Plan. In the United States the sealing of the openings into a repository is regarded as a difficult operation. Additional work on the emplacement and testing of the bentonite seals is needed. (VI.3)

8. Canister failure: If unexpectedly rapid corrosion or a flaw in a canister should permit groundwater to come in contact with spent fuel rods, escape of dissolved nuclides will be greatly retarded by the insolubility of the uranium oxide pellets and by sorption and ion exchange on bentonite and on mineral surfaces in the rock through which the groundwater moves. The retardations, plus effects of dilution and dispersion, is expected to ensure that concentrations in moving groundwater will not reach unacceptable levels. This conclusion is supported by extensive experimental work designed to simulate conditions that would exist near a ruptured canister. Additional research under repository conditions is clearly needed, but members of the Subcommittee, with one exception, think that the work accomlished to date plus the unlikelihood of canister failure is sufficient to ensure adequate containment of radionuclides (VI.1 and VI.2).

9. Criticality: Calculations show clearly that danger from attainment of critical configurations by the fissile isotopes carried by groundwater is virtually negligible. (VI.4)

I. INTRODUCTION

The Swedish parliament in 1977 passed a law (Villkorslagen, or Stipulation Law) requiring demonstration of an "absolutely safe" (helt säker) way to dispose of nuclear waste as a precondition for start-up of new nuclear power plants. In response to this legislation, the Swedish power industry set up an organization (Kärnbränslesäkerhet, or KBS) to develop a plan to show that the requirement could be satisfied. The KBS authorized preparation by Swedish scientists and engineers of 120 technical papers and the KBS Project Engineers prepared two lengthy reports based on these papers. The first report (KBS-I, issued in late 1977) describes a method for the "absolutely safe" disposal of reprocessed high-level wastes, and the second (KBS-II, issued in late 1978) an "absolutely safe" method for the disposal of spent fuel elements. Both reports have been reviewed, at the request of the Swedish government, by a number of organizations and individuals outside of Sweden. The American National Academy of Sciences, responding to a 20 March 1979 request, agreed to review the second report (KBS-II). The review was entrusted to the Committee on Radioactive Waste Management (CRWM), which delegated the work to a Subcommittee.

Because of the shortness of time permitted for the review, CRWM declined to consider the entire KBS-II Plan and limited its review to two items: the long-term integrity of the copper canisters proposed as containers for spent fuel rods, and the geochemical-hydrological conditions of the proposed repositories in granitic rocks. Specifically excluded were technical details of handling and transporting the waste, the design and effectivenss of the interim storage facility, pathways to man in the biosphere, dose estimates, costs, and system risk assessment. Thus the review is focused on the long-term integrity of a granite repository in Sweden, the movement of groundwater to a canister, the long-term effect on a canister of groundwater contact, and the movement of radionuclides in groundwater should a canister be breached. These topics, in the opinion of CRWM, are critical to a judgment regarding the functioning of the waste isolation system.

The review is further limited to an examination of the adequacy of the technical data base to support the conclusions reached in the KBS-II report. Whether the conclusions demonstrate the "absolute safety" of waste isolation in the sense that the Stipulation Law intended is not for the Subcommittee to decide. The Swedish engineers do not agree among themselves as to what "absolute" means in this context, but in general seem to interpret it as meaning "reasonable" or "acceptable" safety instead of using the word in its literal draconian sense. Reasonableness and acceptability are in turn difficult to define. But in the Swedish work (and in most other discussions of waste disposal) they are taken to mean that concentrations of radioactive material escaping from a repository into groundwater and available to the biosphere must remain either below radiological standards for potable water or below concentrations found in natural waters near uranium ore deposits. It is in this sense that such terms will be used in this review. The purpose of the review, then, is a critical study of the science and technology on which the Swedish engineers rest their conclusion that the KBS-II Plan ensures that radionuclides will not be released from a repository at unacceptable rates.

In examining the technical background of the KBS-II report, the Subcommittee had available the 120 technical papers prepared by Swedish scientists and engineers, the KBS-I Plan (on disposal of reprocessed waste), a compilation of comments by outside reviewers of the KBS-I Plan, and a supplemental paper describing work done by the Swedish Geological Survey in response to a governmental request for additional data to fill a gap perceived in the KBS-I Plan. The Subcommittee agreed that its review should also include technical information obtained since completion of the KBS-II report and plans for additional technical studies in the immediate future. Some of the post-KBS-II work involves a cooperative U.S.-Swedish project, supported by the KBS organization and the Lawrence Berkeley Laboratory (LBL) of the University of California for experimental studies in granite near an old iron mine at Stripa, Sweden. Results of these studies are being published in a series of papers from LBL, and these papers were made available to the Subcommittee. In addition to this documentary material, the Subcommittee obtained useful information during a visit by several of its members to Sweden in August 1979. The visit provided an opportunity for interviews with many of the authors of the KBS technical papers, with scientists actually involved in the explorations and experimentation, and for field trips to the Stripa mine and to an area (Finnsjön) where much exploratory drilling has been done.

The Subcommittee had neither the means nor the time for checking the Swedish work directly by duplicating experiments or geologic observations, or for making a quantitative risk analysis. Its study was necessarily limited to perusal of many of the Swedish technical reports and interrogation of some of the investigators who had done the research, its judgment of the Swedish work then depending on the scientific and technical background of the Subcommittee members. Quantitative effort was limited to checking some of the calculations in the technical reports. Most of the review consists, therefore, of subjective evaluation by members of the Subcommittee of the quality and completeness of the Swedish research and the logic relating the research to the conclusions drawn.

In drawing its conclusions the Subcommittee has been aided in its work by many organizations and individuals. In particular, the Subcommittee gratefully acknowledges the assistance of Dr. Lars Larsson of the Swedish Embassy in Washington in obtaining copies of the pertinent technical papers; the cooperation of the KBS Project in Stockholm for providing space and making arrangements for interviews; the helpfulness of the Swedish Geological Survey in making unpublished maps available and in arranging one of the field trips; the kindness of many people at Stripa in arranging a visit to the mine on a weekend, and the patience of the many Swedish research investigators and scientists who appeared before the Subcommittee and carefully described their experiments and calculations and the logic of the conclusions drawn. The Subcommittee is greatly indebted to Dr. Ugo Bertocci and Mr. Gary Walter for their assistance in collecting and organizing much of the technical information on which this review is based.

II. MAIN FEATURES OF THE KBS-II PLAN

The disposal plan described in the KBS-II report has two major steps. Spent fuel elements consisting of uranium dioxide pellets enclosed in tubes of a zirconium alloy (zircaloy), after they leave temporary storage at the reactor, are first to be moved to a central storage facility (centrallager) where they will be kept for 40 years in a water basin a few tens of meters under the ground surface. A central storage capacity for fuel rods equivalent to 9,000 tonnes of uranium is planned, enough to handle the waste from 13 reactors each operating over a period of 30 years. This method of temporary storage is similar to the method now in use at each nuclear plant but would be centralized for economic reasons. The 40-year delay in final disposal is intended to permit sufficient radioactive decay so that temperatures in the ultimate repository can be kept below 80°C. It would also provide time for additional research on possible repository sites and other desirable system options.

The second step is to encapsulate the spent-fuel assemblies in thick-walled copper canisters and place them in the permanent repository (slutsförvar), a cavity mined in granitic rock approximately 500 meters under the ground surface. Copper was chosen for the canisters because the effect of corrosion in the presumed repository environment will be small. The walls of the canisters are to be 20 cm thick to prevent appreciable radiolysis of water in the surroundings; additional shielding and support for the fuel rods will be provided by filling the space around the rods with molten lead. For the repository site (or sites), a mass of granite will be used in which the quantity and rate of movement of groundwater are small. A cavity in the form of a tunnel-grid will be mined at a depth of about 500 m, using methods that cause minimum fracturing of the walls, and the canisters of waste will be placed in holes in the cavity floor. Into the hole around each canister will be inserted shaped blocks of an overpack consisting of compacted bentonite. The bentonite is intended to provide support for the canister, to retard access of water to the canister, to slow the movement of groundwater past the canister surface, to control the acidity of the water, to swell as water is absorbed so as to fill all vacant places and plug cracks in the surrounding rock, and to retard movement of radionuclides if a canister is breached. After delay, for a period to be determined at that time, and after sufficient monitoring to make sure that containment is secure, the cavity above the canisters and all shafts and boreholes into the cavity will be filled with a mixture of bentonite and quartz sand plus a little ferrous phosphate. The bentonite, by swelling, is expected to make a firm seal against the adjacent rock, the quartz will provide mechanical stability and good thermal conductivity, and the ferrous phosphate will ensure that the chemical environment becomes and remains reducing despite entrapment of air during the filling process. Thus the KBS-II Plan interposes both engineered and natural barriers to radionuclide escape: the zircaloy cladding of the fuel rods, the lead and copper of the canisters, the bentonite overpack, the slow movement of groundwater, and the retention of radionuclides by the rock through which the groundwater moves. In addition, the 40-year interim storage period provides for cooling of the wastes as further insurance against possible changes in repository conditions that could be produced if high temperatures were generated within the canisters.

To ascertain whether these barriers will actually be effective in isolating hazardous radionuclides for the necessary great length of time requires answers to many questions regarding the amount, character, and rate of movement of groundwater through granitic rock, the stability of a repository excavated in granite, the resistance of copper to corrosion, the performance of the bentonite overpack and backfill in controlling pH and Eh and retarding movement of ions to and from the canister surface, and the ability of bentonite and granite to minimize the escape of hazardous radionuclides if a canister is eventually breached and groundwater comes in contact with the fuel rods. Questions of this sort are critically examined in subsequent sections of this review report.

All such questions involve time, explicitly or implicitly--for example, the time during which the canisters must remain intact and the time during which the biosphere must be protected from escaping radionuclides. The KBS-II report speaks frequently of "very long times" but mentions specific times only in discussing the canisters, which are confidently expected to last for hundreds of thousands and probably more than a million years. For purposes of the review, times of this order will be assumed as the period for which isolation of the hazardous radionuclides is sought. This does not imply that all the Swedish scientists and engineers, or all members of the Subcommittee, regard such long times as necessary because of radiation hazards for isolation of the wastes.

It is important to remember that the KBS-II Plan is not proposed as the one "best" plan for disposing of nuclear waste. The KBS project engineers interviewed by the Subcommittee think there is actually little likelihood that the plan in all its present detail will ever be put into operation. The objective of the KBS-II engineers was to develop one possible method for waste disposal that would be demonstrably effective in the sense of the Stipulation Law, and this is all that they attempted to do. In reviewing the plan, therefore, no purpose would be served by suggesting other disposal methods that might be superior; the Swedish engineers themselves would be the first to agree that other suitable methods could be devised--and may, in fact, be devised and proved better during the long cooling-off period projected. In line with this philosophy, a continuing research program is being pursued by the Swedish scientists. The question here is not the superiority of the proposed method over all others, but simply, "Has it been demonstrated that this method will work?"

Again, because the focus of this review must be simply on the feasibility of the proposed plan, there is no point in questioning too closely some of the specifications or suggesting improvements in the plan. The figure of 500 m for depth of emplacement, for example, was chosen to make sure that the repository would be below any surface disturbance, but not so deep as to make excavation prohibitively difficult or expensive; the most suitable depth at any particular locality might well be considerably greater to give added security. The 20-cm thickness of the copper canisters seems excessive if the calculated rates of corrosion are accurate, but the pertinent question here is simply whether the 20-cm thickness would perform adequately. Again, the 40 years suggested for pre-disposal storage is not a firm figure, and the need for such long storage might well be questioned, but the point to be examined is whether the 40-year period would accomplish its intended purpose of keeping repository temperatures low. Questions of cost, too, are not at issue, or at issue only in the sense of keeping costs somewhat within reason; the amount of copper required for the thick-walled canisters would be great, but the amount is shown to be a modest percentage of Sweden's annual consumption of copper, and the cost is not excessive as a percentage of the value of the electric power produced by nuclear reactors. If a cheaper material would serve equally well, there is no need here to suggest it. The purpose of the review is not to weigh the merits of possible improvements, or to pass judgment on the degree of "overkill" in the plan; it is merely to take the proposed kind of canister and the specifications of the repository environment as described in the KBS-II report and ask whether an adequate demonstration has been made that these two elements of this particular waste isolation system would function as asserted in the report.

The KBS enterprise represents collaboration on a large scale among experts from many disciplines and many backgrounds--academic, industrial, and governmental. It was carried out under severe time constraints: less than 8 months for the KBS-I Plan, and barely an additional year for KBS-II. Background research continued during preparation of the second report and is continuing today. Results of the research are evident in differences between the two plans: a different canister material, changes in fabrication of the overpack, additional data on physicochemical conditions in a granite repository, and refinement of methods for dating deep groundwater. With this research the Swedish investigators have greatly expanded the store of available knowledge about waste disposal in crystalline rocks, knowledge that will be useful in the future not only to Sweden but to all countries that face the problem of permanent disposal of radioactive waste. Whether or not the details of the KBS-II Plan are ultimately judged to satisfy the requirements of the Stipulation Law, the KBS program is a stimulating example of the kind of effort needed for solving the waste-disposal problem.

III. ORGANIZATION OF THE REVIEW

The KBS-II Plan, in contrast to most schemes for disposal of nuclear waste in an underground repository, places major dependence for the containment of hazardous radionuclides on engineered barriers rather than on the geologic environment. The emphasis of the plan is on the long-term integrity of the copper canisters, aided by the bentonite overpack. The geology is important, of course, in providing an isolated and remote environment in which the canisters can be expected to survive, and in furnishing an additional barrier of last resort if any canisters are breached and groundwater comes in contact with waste. The central question for this review, then, may be phrased thus:

> Does the KBS-II Plan have an adequate technical base to justify the conclusion that spent fuel rods placed in thick-walled copper canisters surrounded with bentonite, under conditions to be expected in a carefully selected site or sites in bedrock, will not supply radionuclides to groundwater where they can be transported to the biosphere in hazardous amounts before radioactive decay has rendered them harmless?

An affirmative answer to this question would go far toward showing that the KBS-II Plan satisfies the Stipulation Law. Uncertainty might remain about the adequacy of the proposed waste-handling facilities and about calculations of radiation doses, subjects that are deliberately excluded from this review. But if a case has been made for long-term survival of the canisters and for a hydrogeochemical environment that will adequately impede the movement of dissolved materials to and from the canisters, a reasonable degree of safety of waste disposal will be practically assured. If serious doubts can be raised about the technical or scientific aspects of either item, its performance cannot be assured.

The answer to the above question requires a review of the following: the adequacy of technical and scientific data on the hydrogeochemistry and geology of the sites in which the canisters will be placed; the adequacy of metallurgical data on the mechanical properties and corrosion resistance of the canisters in the expected geological environment; and finally, the adequacy of the data describing the possible movement of radionuclides in groundwater if canisters should be breached. These three topics are examined in Sections IV, V, and VI of this report.

Section IV, concerning the geology and hydrogeochemistry of repository sites, is subdivided into questions regarding (1) availability of geologic sites of sufficient size where the rock has low permeability, (2) groundwater amounts, movement, and chemistry under natural conditions, (3) effect on groundwater movement of repository construction, (4) possible effects on a repository of tectonic movement, (5) possible effects of renewed glaciation, and (6) ability of bentonite in overpack and backfill to control the movement and chemistry of groundwater.

Section V, concerning the durability of the canisters, involves questions about (1) feasibility of manufacturing and sealing thick-walled copper canisters, (2) mechanical resistance of canisters to accidents in handling and to geologic disturbance, (3) corrosion resistance of canisters in contact with groundwater, and (4) possibility of stress-corrosion cracking.

Section VI, regarding movement of radionuclides if a canister should be breached, includes questions about (1) retarding effect of the bentonite overpack, (2) retardation during movement of groundwater through fissures in granitic rock, (3) control of groundwater movement by backfilling and sealing with bentonite, and (4) possibility of critical configurations as a result of radionuclide movement.

The text is followed by two appendixes, written by consultants to the Subcommittee who recorded details of the interviews in Sweden and combined these details with reviews of the KBS technical reports to give the Subcommittee a synopsis of the technical data base of the KBS Plan. Appendix A, by Gary Walter, describes the hydrogeochemical and geological data base. Appendix B, by Dr. Ugo Bertocci, describes the metallurgical data base.

The Swedish KBS-II Plan to which this review is addressed is described in a report entitled "Handling and Final Storage of Unreprocessed Spent Nuclear Fuel," hereafter referred to as KBS-II. This report consists of two parts, of which only the second (Vol. 2, Technical) is reviewed here. The 120 studies or technical reports on which the report is based are referenced as (KBS TR) followed by their specific number. Studies prepared by the Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock are referenced as (SAC TR) followed by their specific number. References to standard literature are given in the name-date form--e.g., (Smith 1968)--and complete references are listed at the end of the review.

IV. ADEQUACY OF DATA ON GEOLOGY AND HYDROGEOCHEMISTRY

A key element in the disposal system proposed in the KBS-II Plan is the postulate that repository sites can be located and developed in geologically stable areas of Sweden in which physical, hydrological, and chemical conditions are such that copper canisters enclosed in a bentonite overpack will remain unbreached for periods of time measurable in hundreds of thousands or more than a million years. To support this postulate, data are needed to show that repository sites of adequate size can be found where the bedrock is tectonically stable, where it will be little affected by possible renewed glaciation, where movement of groundwater is slow, and where the rate of attack by groundwater on copper is within permissible limits. The adequacy of the data in the KBS-II report and the technical documents pertinent to those questions are considered in this section.

1. Can bodies of granitic rock be found in Sweden of sufficient size and sufficiently low permeability to serve as repository sites?

The total area of the tunnel system necessary to accommodate the 7,000 canisters of the conceptualized waste repository is slightly more than 1 km^2. The Swedish Geological Survey, in preparation for the KBS-I report, was assigned the task of locating such an area (or areas) where the bedrock at a depth of about 500 m would have the necessary strength to maintain openings and the necessary low permeability to ensure that groundwater movement would be slow.

Site investigation was hampered by the reluctance of many property owners to permit the necessary geologic mapping and the work of the drilling crews, but eventually five sites were located that seemed worthy of detailed study. One of the five was quickly eliminated because the rock showed much fracturing, another because schist was encountered at shallow depth, and effort thus was concentrated on the remaining three--Karlshamn, Finnsjön, and Kråkemåla. Exploration at each site consisted of detailed mapping and the drilling of holes to depths of 500 to 600 m, with subsequent study of the holes and the drillcores obtained from them. At Karlshamn a single deep hole was deemed sufficient because excellent exposures of bedrock at depths of 30 to 50 m were available in tunnels that had been excavated for oil storage; at Finnsjön and Kråkemåla three holes were drilled. In addition to these three areas, a fourth site at Stripa appeared to be a good candidate for repository construction, as was shown by excavations in granitic rock designed for in situ experimentation.

Each of the four sites initially appeared to have suitable areas of granite with the necessary qualities of strength and low permeability. Major fracture zones were present in each region, but surface mapping seemed to indicate that they were widely spaced and separated by areas of sound rock possibly large enough for a repository.

Critics of the subsequent KBS-I report then pointed out, quite correctly, that extrapolation of data from a very few drill holes in areas of 1 or 2 km² is not necessarily valid, even in rocks as generally homogeneous as gneiss and granite. Because of such criticism the Plan was not acceptable to government agencies, and the Survey was asked to provide more definitive data. Survey geologists then supervised the drilling of additional exploratory holes at the two sites which seemed most favorable, Karlshamn and Finnsjön, and issued a supplementary report claiming that at least the Karlshamn site had fulfilled expectations (Kompletterande geologiska undersökningar, 1979).

Evidence cited for the suitability of the Karlshamn area includes the following:

(1) Five holes have been drilled to depths of 500 m, one of them to 750 m, and both the drill cores and surface mapping show that rock of uniformly good character exists over an area of the necessary size. Some members of the Subcommittee were able to verify statements about the quality of the rock by examining the drillcores during a field trip.

(2) Although different kinds of rock were encountered in some of the drillholes (gneiss, migmatite, and unfoliated granite), all show exceptionally low permeability and contacts between them are gradational.

(3) The region is cut by a few widely spaced fracture zones, one of which apparently bisects the area that appears suitable for repository construction, but drillholes oriented so as to intersect fracture zones show that the zones are sharply delimited and that the rock on either side is sound.

(4) Between the fracture zones the rock shows only infrequent small joints in random directions, largely filled with secondary minerals (calcite, gypsum, chlorite).

(5) Average permeabilities measured below a depth of 300 m in four of the boreholes were near or below the limit of measurement, 2 x 10^{-12} m/s. Permeabilities in some 2 m or 3 m sections ranged up to 10^{-8} m/s, but many of the high readings resulted from leakage around the packers.

(6) Even at shallow depths (30 to 50 m, which is within the 100 m range where rocks in Sweden commonly show increased fracturing and incipient weathering), permeabilities calculated from the rates of water seepage into tunnels excavated for oil storage are 10^{-9} m/s or less.

(The term "permeability" is used in this review as it is used in the KBS Plan, with units of meters per second. In U.S. practice the same quantity is commonly called "hydraulic conductivity." In U.S. usage the hydraulic conductivity is related to a differently defined "permeability" by the equation:

$$K = \kappa \frac{\rho g}{\mu}$$

K is the hydraulic conductivity (Swedish "permeability")

κ is permeability (U.S.),

ρ is fluid density,

g is acceleration of gravity, and

μ is dynamic viscosity.

Because g is a constant, and ρ and μ are practically constant for the fluids considered here, K and κ are approximately proportional.)

Opposed to the optimistic conclusions based on this kind of evidence is a report prepared by a group of eight geologists and engineers requested by the government to make a critical review (Material angående SKI:s beredning, 1979). Seven of the group flatly concluded that the existence of a body of rock at Karlshamn suitable for repository construction had not been demonstrated; the eighth agreed with the KBS engineers that a good case for a repository site had been made, but doubted that the volume of sound rock was large enough for the expected quantity of waste. The principal arguments of the seven-man majority are as follows:

(1) The number of drill holes is still inadequate to characterize the rock at depth, especially when some of the holes (in their opinion) were not located so as to obtain critical data.

(2) The KBS-II Plan ignores evidence both from earlier geologic work in the area and from topographic features for the probable existence of additional fracture zones in the areas of allegedly sound rock.

(3) Dips of some of the fracture zones indicated by the drill cores imply that the area of sound rock at a depth of 500 m is considerably smaller than at the surface.

(4) Fracture zones in granite are commonly not sharply bounded against adjacent rock, so that the widths of relatively permeable rock may be greater than assumed by the KBS authors.

(5) The relatively low permeability of the rocks exposed in the oil-storage tunnels is the result of treatment of the rock surface after excavation, and hence cannot be used as an indication of rock quality.

In answer to this criticism, KBS Project spokesmen maintain that evidence for additional fracture zones is meager, that the lengths of more than 200 m of sound rock encountered by four of the drillholes is ample proof of the existence of abundant low-permeability material at depth, and that the fracture zone which cuts the proposed volume of sound rock is demonstrated to have sharp borders in the two drillholes that intersect it. The spokesmen agree that a fracture zone on one side of the area is probably wider than originally thought, so that the total area of rock suitable for a repository should be reduced from the first estimate of 1.2 km^2 to 1.0 km^2.

These arguments for and against the suitability of Karshamn as a repository site are based largely on interpretation of geologic data which, in the nature of things, will always be less than completely adequate. The Subcommittee recognizes that deficiencies in the geologic data base do exist, enough to warrant concern, but agrees that taken overall the evidence now available is sufficient to support the conclusion that Karshamn is at least marginally suitable as a repository site. The final demonstration of the adequacy of this site, as is true for any deep geologic repository, can be made only by sinking a shaft and driving exploratory tunnels.

It should be noted that complete continuity of impermeable rock throughout a 1-km^2 or 2-km^2 area, while desirable, is not essential for a repository site. If a site otherwise acceptable is cut in two by a fracture zone, as the site at Karlshamn appears to be, each half may well be suitable for waste disposal. Even finer fragmentation might be permissible so long as the total area of sound rock amounts to 1 or 2 km². The construction of smaller repositories at more than one site is a possibility. Another option, also considered by the KBS engineers, would be a repository with more than one level; a different spacing of canisters would be required to keep the repository temperature below 80°C, but this is not a serious difficulty. The important thing is simply that no canister hole be located in or near a major fracture. This can be assured by careful on-site inspection prior to emplacement.

The additional exploratory work at Finnsjön confirmed that limited areas of granitic rock exist there also that might be suitable for a repository, but demonstrably continous areas are smaller than at Karlshamn. The ongoing study at Stripa of the granite for experimental purposes has provided further evidence that this may be another promising area for a repository site. The Subcommittee at first questioned the suitability of the Stripa bedrock on the grounds that the granite explored so far is close to a contact with leptite, from which iron ore was formerly obtained, and that granite near a contact is often less homogeneous and cut by more veins and dikes than granite in the interior of a large mass. Swedish geologists maintain, however, that detailed study of the granite has shown great uniformity of structure and composition; that impression of uniformity was confirmed by on-site examination of the granite during the Subcommittee's visit to the Stripa mine. It may well be, as the Swedish geologists think, that the chemical composition of leptite is so similar to that of granite that the usual contact effects are subdued. From work done up to the present, some of the Survey geologists regard Stripa as second only to Karlshamn in suitability for a repository site, while Finnsjön and Kråkemåla are still in some degree questionable.

Although the Survey's supplementary report was judged to satisfy the Swedith requirement of the Stipulation Law, exploration of possible areas is continuing. At Finnsjön a detailed study is in progress, less for the purpose of confirming this locality as a candidate site than simply to document carefully the properties of a typical area of granite and gneiss as they relate to possible waste disposal sites. At Stripa the experimental program is providing a steady flow of quantitative information (permeability, internal stress, heat conductivity, thermal expansion) on granite. An exploratory program of mapping and drilling in many parts of the country is planned for the next few years.

In the Subcommittee's judgment, supported by on-site visits, the existence of bedrock areas in Sweden suitable for repository sites has been adequately demonstrated. It must be recognized, of course, that geologic exploration from the surface and from drillholes can never provide all the needed information about a site, and that actual underground exploration will almost certainly reveal a number of unanticipated geologic irregularities. Swedish engineers are fully aware of this possibility, and point to measures that can be taken to circumvent such difficulties--for example, changes in the geometry of the repository, or treatment of tunnel walls to control an unexpected inflow of groundwater. If the geologic difficulties prove so serious at any given site that the site must be abandoned, the number of possible likely areas is adequate to ensure that a suitable alternative can be found.

IV.2 Can the quantity, rate and direction of movement, and chemical composition of groundwater in granitic bedrock be predicted from measurements made on or near the surface together with data from a very few boreholes?

After all the canisters have been emplaced and openings in the repository have been backfilled and sealed, groundwater is expected to fill the repository and to saturate the bentonite in the overpack and backfill. Eventually the original pattern of groundwater movement through the repository area will be reestablished, except for local variations in permeability in and around the repository and a virtual absence of movement through the bentonite buffer around each canister. To ensure that this sequence of events will take place in an orderly manner, and in particular to ensure that the rate of movement and chemical composition of the groundwater will pose no threat to canister integrity, predictions about underground conditions must be made before the repository is constructed. Detailed information about the subsurface can only be obtained by sinking a shaft and driving exploratory tunnels, but locating the shaft requires preliminary estimates of conditions to be expected at depth from observations at the ground surface and measurements in a few boreholes. More than a few holes are not permissible because they would jeopardize the integrity of the planned repository. Thus considerable extrapolation from scanty measurements is necessary, and how successfully this extrapolation can be made is a major point of contention regarding the KBS Plans.

The Subcommittee thinks that borehole data, despite rather wide statistical scatter, convey enough information about the hydrogeologic properties of the rocks to permit reasonable preliminary evaluation of repository sites. The general nature of dense crystalline rocks in all parts of the world indicates a systematic change of hydrogeologic properties with depth (Davis 1979) like that observed in Sweden (KBS TR-54). Specifically:

(a) The choice of reasonable hydrogeologic properties of deep crystalline rocks (based on field measurements) together with measured hydraulic gradients places strict upper limits on the amount of groundwater that can circulate at depths of several hundred meters in crystalline rocks. This amount is only an infinitesimal portion of the total water circulating at or near the land surface.

(b) Permeability, in general, decreases rapidly down to about 300 meters and more slowly thereafter to beyond 500 meters.

(c) Groundwater at great depths tends to have more dissolved solids than groundwater near the surface, suggesting very slow migration rates.

(d) Velocities of deep groundwater will generally be only a few centimeters per year or less.

One of the variables in estimating velocities is permeability, and the KBS data on permeabilities have been attacked both with respect to the methods of measurement and to interpretations of water movement derived from the measurements. Most of the KBS permeability measurements have been made by isolating lengths of borehole (generally 2 or 3 meters) with packers and determining the rate at which water is lost through the walls of the hole when it is injected under pressure (KBS TR-61; Appendix A, part A.4.1). In many of the holes additional measurements have been made of overall permeability, using the entire length of a hole or major portions of it. The accuracy of such measurements can be questioned, especially when permeabilities are low, because of leakage of water around the packers or into fractures in the adjacent rock produced when the hole was bored. The KBS investigators are aware of these possible difficulties, but note that resulting inaccuracies would make apparent permeabilities too high, so that their use in calculations of flow rate would be on the conservative side. A different technique has been used in recent experiments at Stripa (SAC TR-2). The flow through granite from holes on the periphery of a circle 3 m in diameter to a central hole was measured, and the results were comparable to those obtained on sound granite elsewhere, averaging 4 x 10^{-11} m/s at 10°C, and 2 x 10^{-11} m/s at 35°C.

Much more difficult is the question of interpretation. The movement of water in granitic rock is almost entirely along cracks and zones in which the rock has been crushed or fractured; permeabilities measured where a borehole cuts such zones are commonly several orders of magnitude greater than permeability in solid rock. Major zones of fracture may be continuous for many kilometers, and of course would be avoided in locating a repository, but second-order zones commonly form an irregular 3-dimensional network through the rock. How accurately can average permeability in the rock around a given borehole be estimated when measurements range from high values for a few fracture zones to values below the limit of sensitivity for most of the borehole's length? How successfully can the flow of water through a large body of fractured granite be modeled using permeability data from a few widely separated boreholes? These are questions on which the diversity of expert opinion is very wide.

The KBS engineers plan to locate repositories at depths where fracture zones are scarce, and they think that meaningful average values for permeability can be obtained at such depths. To model groundwater flow Swedish investigators use Darcy's law for flow through porous media, on the assumption that a large mass of granite with a 3-dimensional fracture network will behave roughly like a porous medium if the scale is large enough (KBS TR-47). This kind of modeling is adopted simply because no adequate model for water flow through fractured crystalline rock is available. Sample calculations using this model for some of the areas that were intensively studied, with average permeability set at a conservative figure of 10^{-7} m/sec, hydraulic gradient at about 0.01, and effective porosity at 0.003, give rates of groundwater movement on the order of 10 m/yr, and a minimum time of 50 years for groundwater to travel 500 m to the surface. If the permeability is as low as 10^{-10} m/s, as it is in much of the bedrock, the rate would fall to 0.01 m/yr, and the minimum time to reach the surface would be 50,000 years (KBS-II, vol II, p. 106).

As corroboratory evidence on rates of groundwater movement, Swedish investigators cite many measurements of groundwater age (KBS TR-62 and 63). Ages of several thousand years for groundwater, typical of those reported in Sweden, mean that velocities must be very slow; velocities can be estimated if the location of the recharge zone is known. Recent age determinations (SAC TR-12) of Swedish groundwater by three different methods (^{14}C, ^{4}He, $^{234}U/^{238}U$) show fairly satisfactory agreement, which gives considerable confidence in their reliability; velocities estimated from them are within an order of magnitude of those based on fluid-flow equations.

Reviewers of the KBS-I Plan have directed much of their adverse criticism to these interpretations and calculations (Redögorelse för granskning, 1978). It is frequently stated that the average permeabilities used in the calculations have no significance because groundwater flow will be concentrated in a few very permeable zones; that use of Darcy's law for such low permeabilities is not justified; that a model developed for uniformly porous material is not applicable to fractured granite; that age determinations have too many uncertainties to be useful; and that groundwater behavior at an underground site cannot be adequately characterized without data that would permit estimates of 3-dimensional flow at every point of the rock volume.

On the basis of study of the KBS technical reports and conversations with several of the investigators, the Subcommittee thinks that much of this criticism is not well founded. The KBS investigators are well aware of the uncertainties in their measurements and interpretations and feel they have used sufficiently conservative assumptions to compensate for the uncertainties. Moreover, groundwater flow into a repository can be controlled by underground exploration to find the least permeable areas of rock and by grouting of minor fractures in repository walls. The movement of water near canister surfaces, even if flow through the repository is much larger than expected, will be greatly inhibited by the bentonite overpack. The Subcommittee thinks that the kinds of measurements contemplated in the KBS program are adequate to ensure that the quantity of water reaching the copper canisters in a well constructed repository will not be damaging.

Because groundwater movement in granitic rock is largely limited to fractures, some indication of the probable amount of movement at depth can be obtained by the mapping of fractures in rock exposed at the ground surface. Such mapping has been carried out in great detail at the sites selected for special study, both by plotting joints and faults on rock outcrops and by mapping topographic lineaments from air photos and satellite photos (KBS TR-25, 60, 63). Geologists at the Swedish Survey who have done this work are properly skeptical of finding exact correspondence between degree of fracturing at the surface and at depths of a few hundred meters, but they think that a general relation exists in many places. In the Karlshamn area, for example, the scarcity of fractures encountered by the boreholes at depth is reflected in the massiveness of the outcrops and the scarcity of well-defined lineaments at the surface.

Additional indications of the extent of fracturing in large volumes of bedrock may be obtainable from geophysical measurements in boreholes. The usefulness of such techniques is currently being tested at Stripa, where many kinds of well-logging--resistivity, calipers, neutron, gamma-gamma, thermal, and sonic--have been carried out both in long holes drilled from the surface and shorter ones drilled from tunnels (SAC TR-16). Sonic wave-form logs seem particularly promising as indicators of fracture density. The general applicability of these methods in crystalline rocks is not established, but there seems a good chance that further development will make possible estimates of many rock properties by multiple logging in a few holes.

Regarding chemical composition, the KBS investigators have made an exhaustive survey of reports on the composition of groundwater in Scandinavia and other areas of granitic rock, and have analyzed many samples from the deep parts of boreholes in the investigated areas (KBS TR-36, 62, 88; KBS TR-90, App. A and B; Appendix A, part A.2.1). In sampling the borehole water, special techniques were developed for minimizing contamination by drilling fluids and by contact with air. Members of the Subcommittee interviewed three of the authors of analytical papers (Gunnar Jacks, Ingmar Grenthe, and Ivars Neretnieks) and see no reason to question the methods used or the conclusions drawn.

Groundwater composition (as described in KBS TR-36 and TR-88, and more recently in SAC TR-12) shows little dissolved material that might cause corrosion of copper metal. Field measurements of pH give values between 7.2 and 9.7, and redox potentials measured in the laboratory range from -26 to -220 mV; in these ranges, thermodynamic data show that copper is inert with respect to water. Concentrations of dissolved oxygen and dissolved sulfide are commonly below the measurement limit, 0.01 mg/l for both; a few samples show higher values, but for at least some of these contamination is suspected. Other materials that might conceivably play a role in attacking copper, such as CO_2 and nitrogen compounds, also have satisfactorily small concentrations. Possible generation of sulfide by bacterial reduction of sulfate is limited by the very small amount of organic matter available as nutrient for bacterial growth. The bentonite overpack around the canisters and the bentonite plus ferrous phosphate in the backfill will keep water movement very slow and will provide long-term insurance against changes in Eh and pH. For a brief time after a repository is closed the groundwater will be oxidizing because of residual air, but the amount of ferrous phosphate to be included in the backfill material is demonstrably more than sufficient to remove the oxygen. Both Na^+ and Cl^- show a general increase with depth, especially so in recent analyses from Stripa (SAC TR-12); this change in composition is one more indication that the movement of groundwater is very slow.

The Subcommittee agrees with the conclusions of the KBS ivestigators that reasonably reliable predictions on a regional scale about quantity, rate of movement, and chemical composition of groundwater at an intended repository site can be made from measurements at the surface and in a few boreholes. Before actual construction is undertaken, such predictions would have to be verified, of course, by in situ measurements in exploratory tunnels. Surface and borehole measurements that have been made at the sites selected for special study indicate that at these sites the amount of groundwater is sufficiently small, its movement sufficiently slow, and its chemical composition sufficiently innocuous to ensure that corrosion of copper canisters would be no more than superficial for a very long time into the future.

IV.3 Can adequate predictions be made of the effect on groundwater movement of disturbances caused by a repository, particularly the fractures due to blasting during excavation of shafts and tunnels and the heating caused by the buried waste?

The rate of groundwater movement calculated from measurements of permeability, porosity, and hydraulic gradient refers, of course, to the rate in natural undisturbed rock. Conditions in a repository can hardly be regarded as undisturbed because (1) some of the rock around tunnels and shafts will presumably be cracked or shattered by blasting and stress release caused by excavation and (2) because the buried waste will be a source of heat unlike anything in the natural environment. A question thus arises as to the possible effects on moving groundwater of the shattered zones and the thermal anomaly. Some of the KBS scientists have considered this question and reach the conclusion that neither effect is likely to be important (KBS TR-47). In other words, groundwater is expected to resume approximately its original motion within decades or a few centuries of repository closure.

One reason for this conclusion is the planned use in tunnel construction of a blasting method ("smooth blasting," SAC TR-8) that produces a minimum of cracking and limits the cracking to a rock thickness of about a meter. Tunnels excavated in this manner were shown to Subcommittee members at Stripa. Whether blasting will be used in shaft sinking is uncertain; shafts will very likely be bored, and in any event the thickness of disturbed rock should again be no more than a meter. The cracked rock around tunnels would seemingly be capable of serving as a channel for water movement faster than normal, but since the tunnel systems will be isolated in large volumes of sound rock, such possible local channels would hardly be significant in regional horizontal flow. Increased vertical flow in the disturbed rock around shafts is a more likely possibility. If this is found to be a problem, Swedish engineers think it can be handled by carefully removing the disturbed rock from the walls along a length of the shaft and filling the local enlargement with bentonite or cement. In the Subcommittee's opinion this procedure seems reasonable, although the provisos regarding repository sealing noted in Section VI.3 would be applicable here also.

In contrast to the anticipated local effects of stress release related to excavations, thermal effects from radioactivity in the waste will eventually reach very large masses of rock (KBS TR-54.05, 120). The thermal effects, although widespread, will remain small because temperatures in a repository will be kept below 80°C by the 40-year aging of the spent fuel rods, by limiting their number in a canister, and by proper spacing of the canisters. Possible thermal effects on fluid flow would be (1) higher hydraulic conductivities due to heating of the water in fractures, which in turn causes lower viscosities; (2) creation of convective forces by temperature-induced density differences in the water; (3) reduction in crack widths by temperature-induced expansion of the rock; and (4) formation of new fractures by temperature-induced stresses. Of these four effects, the first and third are probably the most important but would commonly tend to cancel each other. Convective forces would produce only very small groundwater velocities.

The Subcommittee agrees that present information is sufficient to justify the conclusions of the KBS-II engineers that the effects of both heating and repository construction on groundwater movement will be small following repository closure. Regarding thermal effects, recent experimental testing of heat-flow models at Stripa (SAC TR-10 and TR-11) has provided additional support. The experiments show good agreement of measured temperatures with temperatures predicted from heat-flow models, and measured mechanical strains considerably less than those predicted. Thus, calculations from the heat-flow models, which indicate only minor thermal effects on groundwater movement, are apparently over-conservative.

IV.4 Can areas of bedrock be found in Sweden where the possibility of tectonic movement that might damage a waste repository is negligible--both slow deformation and sudden displacements accompanying earthquakes?

Bedrock in Sweden, except for the extreme southern part of the country, is part of the Baltic (or Fennoscandian) Shield. This is a huge area of Precambrian granitic and metamorphic rocks in which the latest orogenic movement has been dated at about 900 million years ago. The Shield was eroded to a peneplain about 600 million years ago, and on the peneplain Paleozoic sedimentary rocks were deposited. Remnants of these rocks and of the exhumed peneplain surface show that tectonic activity since the Precambrian era has consisted of minor up-and-down movements of the entire area, with displacements along widely spaced faults amounting at most to tens of meters. The Baltic Shield, like similar Precambrian areas elsewhere, is recognized as one of the most geologically stable regions of the earth's surface. This fact, together with the infrequency and small magnitude of recorded earthquakes, gives a strong presumption of adequate tectonic stability for repository construction over most of the country.

This presumption of stability has been well documented by several of the KBS investigators (KBS TR-17, 19, 20, 59; Appendix A, part A.2.2). Faults, fracture zones, and zones of weakness that can be traced on air photos and satellite photos have been mapped in great detail. Amounts of movement on faults, as shown by displacement of bedrock structures and of the peneplain surface, have been measured and dated. Detailed study shows that much of the country is divided into blocks by major fracture zones with spacings of kilometers, and that within many of the blocks there are only minor fractures spaced tens of centimeters or a few meters apart on which past movement, if any, amounts to no more than a few centimeters. Most of the movement recorded by offsets on both major and minor fractures dates from hundreds of millions of years ago, and movement during the Paleozoic and later ages is practically restricted to zones of weakness that already existed in Precambrian time. Calculations of the probability of a new fault occurring in an area of 1 km^2, even using extravagantly conservative assumptions, give values that are negligibly small. The KBS scientists conclude that future strains which may develop in bedrock will be relieved by movement along the existing major fracture zones, and that a repository located in one of the intervening blocks will not be disturbed, just as blocks of ice on a frozen lake may shift position while the interior of each block remains unaffected. Thus, the conclusion seems well supported that a repository site chosen with due regard to existing fracture zones should be safe from appreciable tectonic displacement for many millions of years.

The chance of appreciable damage from vibratory motion during earthquakes also seems exceedingly slight (KBS TR 21). Most recorded earthquakes in Sweden have had estimated Richter magnitudes no greater than 4; the most severe earthquake in this century, with a magnitude of about 6, had its epicenter in the southern part of the country, near the margin of the Baltic Shield, more than 100 kilometers from any of the areas being considered for repository sites. Study of earthquakes during the period when modern instrumentation has been available (1951-76) shows that detectable seismic disturbances have been concentrated along a belt running from the west coast of Sweden northeastward to the head of the Gulf of Bothnia, bypassing the southeast coastal area which is considered most favorable for repository construction (Båth 1978). Extrapolation from such short-term records to hundreds of thousands or millions of years is risky, of course, but the geologic position of Sweden makes the future occurrence of large or frequent earthquakes at least very improbable. Even in the unlikely event of a large earthquake, as the KBS scientists note, much evidence indicates that well engineered underground structures sustain little damage.

Optimism about the negligible risk from either slow tectonic deformation or seismic activity is not shared by all Swedith geologists. Dr. N.A. Mörner in particular has marshaled many opposing arguments, both in his KBS paper (KBS TR-18) and in several subsequent papers and letters. Detailed study of the uplift of Scandinavia following the last glaciation has convinced him that the Baltic Shield is less stable than ordinarily thought. The uplift, which reaches a maximum of more than 800 meters in a region north of Stockholm, is well known to be continuing at a maximum rate of nearly a centimeter per year. Mörner interprets his data to mean that the upward movement has two parts: the simple isostatic recovery from the weight of the glacier, which ended about 2,000 years ago, and a more recent movement with a different and still unknown cause which started some 8000 years ago and continues today. The uplift in a few places has been accompanied by bedrock faulting, notably in an area near Lake Vättern in southwest Sweden and along the Parvie fault in the far northwest, and Mörner maintains that he can see additional evidence of such recent movement in several other parts of the country. Some of the movement he attributes directly to glaciation, especially to the rapidly changing load on bedrock as the ice front receded. In support of this view, he notes areas of cracking of glacially polished surfaces, which he regards as evidence of slight displacements, and the presence of exceptionally large bedrock blocks with polished surfaces in some moraines, which he interprets as resulting from major earthquakes near the ice margin. Not only did rapid glacial retreat cause earthquakes and near-surface movements in bedrock, but also, in Mörner's view, was responsible for fracturing at depths of several hundred meters. As evidence he notes that drilling for the KBS program has encountered fractured rock not only within the first hundred meters of bedrock, but also occasionally in zones at deeper levels that have no obvious alternative explanation. The finding that extensive local bedrock movement accompanied and was in part prompted by glaciation, plus his conviction that renewed glaciation is inevitable within a few thousand years, leads Mörner to doubt the safety of bedrock disposal of nuclear waste. His further belief that Scandinavia is undergoing uplift from unknown causes, at a rate which if continued into the future might lead to deep erosion of the elevated land surface, adds to his misgivings.

As nearly as the Subcommittee could determine, Mörner stands almost alone among Swedish geologists in this interpretation. Certainly his basic data demand attention, because his decade-long study of the Quaternary history of Scandinavia is among the most detailed and comprehensive of any recent work. His emphasis on postglacial faulting is supported by other recent studies, notably that by Lagerbäck and Henkel (KBS TR-19); the discovery of such faulting in Scandinavia is fairly recent, and it does indeed call in question past opinions about the extreme stability of the Baltic Shield. Other geologists, however, think that Quaternary faulting is limited to a few areas and would not compromise the integrity of a well-chosen repository site. Some who have looked at Mörner's field evidence think that fractured bedrock surfaces and large blocks in moraines are best explained by more ordinary processes accompanying glaciation rather than by tectonic movement. Many who have studied the details of postglacial uplift find support for the classical view that present-day movement is simply a continuation of isostatic recovery from the glacial load, and not a new and mysterious phenomenon. Deep fracturing of bedrock as a result of glacial loading is discounted in a theoretical study by Pusch (KBS TR-89, and personal interview). Without actual field study the Subcommittee is handicapped in judging between these radically opposed views, but perusal of the technical papers and interviews with both Mörner and those who disagree with him suggest that the conventional opinion about bedrock stability has the better support.

Two other questions related to bedrock stability were discussed at length with the Swedish scientists. One concerns the possibility that construction of a repository might so weaken the bedrock locally that future fault movements would be concentrated in or near the repository rather than along pre-existing lines of fracture. In answer to this possible objection, the KBS engineers noted that (1) the major fracture zones that would bound an area selected for repository construction are sufficiently extensive so that local weakening in sound rock nearby would not affect movement along them; (2) the repository would be oriented in accordance with measurements of maximum stress in the bedrock, and laboratory measurements on bedrock specimens show adequate strength to compensate for weakening caused by an opening; and (3) experience with mining in bedrock, which in Sweden goes back for many centuries, has given no indication that mined cavities have caused localized rock movement.

The second question relates to the behavior of a waste canister in the extremely unlikely event that fault movement occurs along a sharply defined plane that directly intersects the canister (KBS TR-66). The exact conditions of such an event are hard to specify. If the movement was confined to a single plane, and if it took place rapidly enough, shearing of the canister would indeed be possible. Rough calculations suggest that as much as 3 cm of movement could be tolerated without damage to the integrity of the canister (R. Pusch, personal interview). More than likely, however, the movement would be distributed through a width of at least a few centimeters; it would not be instantaneous, and the bentonite overpack around the canister would be somewhat plastic, so that the canister would respond by turning or by deforming slightly rather than by fracturing. The chance of serious damage from such an occurrence seems negligible, except insofar as the fault might change the pattern of groundwater movement.

In the Subcommittee's opinion, the KBS conclusions about bedrock stability are well founded. A repository located in one of the large blocks of slightly fractured granitic rock bounded by major fracture zones should be immune to damage from most imaginable sorts of rock deformation. The major fracture zones would serve as conduits for most groundwater movement and would accommodate any expectable tectonic deformation in this very stable part of the earth's crust. The evidence for possible adverse effects of renewed glaciation, or for future tectonic disturbance orders of magnitude greater than any observed in historic time, seems so tenuous that it should not influence the basic conclusions.

IV.5 Can the effect on a repository of possible renewed glaciation be shown to be negligible?

Glaciers covered large areas of the northern hemisphere during the Pleistocene epoch at several periods ranging in length from 50,000 to 100,000 years, separated by interglacial periods lasting 10,000 to 30,000 years. Since the end of the last glaciation occurred about 10,000 years ago, there seems to be a good possibility that Sweden will again be covered by ice within the next few thousand years. No certainty can be attached to such a prediction: since glacial epochs like the Pleistocene are rare in geologic history, and since the causes of glaciation remain unknown, it is also possible that the Quaternary episode of recurrent glaciation has come to an end and Scandinavia will remain free of ice. Future climate may also be influenced by human activity, probably in the direction of increased average temperature, so that renewed glaciation would be postponed or stopped altogether. Despite the uncertainty, one or more periods of glacial advance during the next million years are sufficiently probable that their effect on a subsurface waste repository should be considered. Some of the KBS scientists have given much thought to this question (KBS TR-18, 19, 89).

It should be kept in mind that a sequence of events involving glacial advance, retreat, and reoccupation of the land by human beings may require a time span of at least ten thousand and, more probably, a hundred thousand years. By that time the active fission products ^{90}Sr and ^{137}Cs would have long since decayed to harmless levels, and the only radionuclides that might still pose a hazard to the environment would be the actinide elements, some of their daughter elements, and the fission products ^{99}Tc and ^{129}I.

These substances are present in small amounts or have only feeble radioactivity; collectively, the energy of their emitted radiation would be little greater than that from the radioactive materials of a medium-grade uranium ore deposit. Precise comparison of the radiation hazards from natural ores with those from a repository with aging fuel rods is difficult. The important point is simply that any discussion of the post-glaciation radiation involves waste with far less radioactivity than was present when the repository was sealed. To many geologists the amount of residual radioactivity seems so small and predictions for such long times so uncertain that a discussion of glacial effects seems to have little point. Nevertheless there is enough regularity in the pattern of glacial advance and retreat during the Pleistocene, and enough long-time residual hazard from a spent-fuel repository, so that consideration of a future postglacial world is not entirely without significance.

Glaciation as extensive as that in the past would make all of Scandinavia uninhabitable for long periods. Escape of radionuclides from a repository during such periods would be dangerous only insofar as they might reach the sea and thus create a hazard to marine life or to inhabitants of regions farther south, but the probability of escape in significant quantities seems remote. More important would be the possible hazard to human beings who settled in the area after the ice retreated from repositories damaged in such a way as to allow radionuclides to escape. The essential question is how much a deep repository might be influenced by a changing load on the surface as ice advanced, built up to a thickness of 1,000 m or more, and then retreated. During such a general ice advance minor fluctuations of climate could cause temporary advances and retreats of the ice front, so that a given area might experience successive loading and unloading by ice at intervals of 1,000 to 5,000 years.

The possibility that erosion by such repeated ice advances might be deep enough to expose a repository, or to remove a substantial amount of its bedrock cover, seems negligible. The KBS scientists point out that past glaciation has left no evidence of such deep erosion in bedrock; on the contrary, reconstruction of preglacial topography and estimates of the amounts of glacially eroded sediments indicate that cutting into bedrock during the entire Pleistocene epoch amounted at most to tens of meters (KBS TR-89). This conclusion is not beyond question, since some glaciologists claim to have evidence for much deeper incision at least locally, but the prevailing opinion among Quaternary specialists is that the glacial erosion of hard bedrock in terrain of subdued relief like that in Sweden would be fairly limited. Certainly the large-scale ice-thrust and fold structures that have been noted in glacially overridden sedimentary rocks in North America have no counterpart in the igneous and metamorphic bedrock of Sweden.

The minor erosion produced by glaciation, together with local deposition of sediment by ice or meltwater, could have the effect of making the topography more hummocky, hence interrupting the regional flow of near-surface groundwater and forming cells of local flow in small basins. The effect on a repository, if any, would presumably be beneficial. The greatly increased surface flow of water from melting ice during glacial retreat would augment erosion, but neither the amount nor the duration of such increase would be enough to damage a structure 500 m under the surface.

It also seems unlikely that the mere weight of ice would have much mechanical effect on sound bedrock at a depth of 500 m. Pusch has calculated from analysis of stresses that fracturing of bedrock near the front of a glacier, where differences in loading would be greatest, would not extend more than a few meters below the surface (KBS TR-89). Mörner disputes this conclusion (KBS TR-18), suggesting that fractures and crush zones intercepted by some of the boreholes at depths of a few hundred meters could have been caused by glaciation, and further, that earthquakes might have resulted from load differences at glacial fronts. The evidence presented for these claims does not seem convincing. Glacial loading might well have some influence on permeability at depth by closing microfractures within or between mineral grains, but gross mechanical effects seem highly improbable.

Major effects of renewed glaciation on an underground repository, if any, are likely to be more indirect, resulting from the changes in sea level that accompany glaciation and from possible changes in the groundwater regime.

Sea-level changes result both from the simple change in total volume of the oceans as water is abstracted to form ice and then released when the ice melts, and from changes in land elevation due to the bowing down of the earth's crust under the weight of the glacier. The slow recovery of the Scandinavian land mass from the load of the last Pleistocene glacier is clearly recorded in elevated beach deposits representing former stands of the sea, some of them hundreds of meters above present sea level. If glaciation is renewed, a probable sequence of events would be an initial lowering of sea level as water is removed from the oceans, then a gradual apparent rise as bedrock is depressed under an increasing accumulation of ice. A possible result would be eventual replacement of the fresh water in a near-shore repository by seawater. The effect is not likely to be deleterious, because (1) the seawater would have a low salt content, since the Baltic Sea is already brackish and would become practically a fresh-water lake during the initial drop in sea level; (2) the movement of ions from the invading seawater to canister surfaces would be only by slow diffusion through the bentonite buffer; and (3) corrosion of the copper, even if exposed to normal seawater, would not be greatly increased (see Section V.3). The Subcommittee agrees with the KBS engineers that sea-level changes associated with renewed glaciation would have no harmful influence on a repository.

The possible effects of glaciation on groundwater movement in a repository are difficult to predict with any assurance. The principal long-term effect might well be a decrease in the amount and rate of movement, in part because the ice load would tend to close microfractures in the bedrock and in part because a layer of permafrost beneath the ice would inhibit movement of water from the surface to underground aquifers. One possible set of circumstances during deglaciation, however, might for a time greatly increase deep groundwater flow. These circumstances have not been considered by the KBS scientists, and hence need a more detailed discussion.

Consider the glacial front during a period of active melting: a mass of ice up to a thousand meters thick stands immediately adjacent to open flat terrain from which ice has recently melted; permafrost, if any remains, exists only in isolated patches; abundant meltwater from far under the glacier emerges in streams at the glacial front. Back from the front the water is under pressure from the overlying ice, and this pressure is transmitted to groundwater moving through fissures in the bedrock below. The groundwater, normally flowing sluggishly under a low hydraulic gradient, now finds itself subject to a difference in head of some hundred atmospheres within a short distance at the glacial front, and also to greatly increased recharge from the abundant meltwater. Underground flow would be expected to increase markedly, not only near the ground surface but very probably also in fissures at depths of tens or hundreds of meters. If a waste repository existed beneath the front of the glacier, it might well experience abnormally high groundwater flow as long as the front remained in its vicinity (Parizek 1979).

To what extent the integrity of the repository might be compromised by the increased flow is problematical. The amount of flow would depend on the height of the glacier, the slope of its front, the rate of melting, and the geometry of the fissure system in the bedrock below. Slightly increased movement of water through a repository for a limited time would presumably do no harm, and even a marked increase would cause little additional exposure of the canisters as long as the bentonite overpack remained intact. Sufficiently rapid flow, if the overpack was cracked or a canister was breached, might conceivably lead to the introduction of dissolved oxygen from the surface, to greatly increased corrosion, and eventually to the dissolution of radionuclides. Intuitively, such a result seems unlikely, but the possibility should certainly be explored. Prediction of groundwater movement in an order-of-magnitude sense should be possible by modeling, and the Subcommittee suggests that such modeling would be desirable.

It should be kept in mind that the possible sequence of events just described would occur only some hundred thousand years into the future, after a new ice cap had reached its maximum extent and begun to wane. By that time the shorter-lived beta and gamma emitters would have decayed, , and the possibly still-hazardous radionuclides would be limited to the long-lived actinide elements, some of their daughter products like ^{226}Ra, and a few remaining very long-lived fission products like ^{129}I and ^{99}Tc. The residual fission products would be present in small amounts. If the worst should happen--that is, if canisters were breached and their radionuclides exposed to the increased groundwater flow--the soluble radionuclides would be enormously diluted and the actinides would remain in large part insoluble. The possibility of such an event needs to be considered, but it is hard to imagine any combination of circumstances that would pose a real threat to the postglacial biosphere.

IV.6 Can the bentonite overpack around each canister and the bentonite plus ferrous phosphate in the backfill of tunnels and shafts be depended on to keep the movement of groundwater along canister surfaces very slow and to maintain conditions of pH and oxidation potential that will prevent or greatly inhibit corrosion?

According to the KBS-II Plan, shaped blocks of compacted bentonite will be inserted in the holes around each canister, and empty spaces between and around the blocks will be filled with powdered bentonite (KBS TR-33, 37, 73, 74, 84, 104). Later, when the repository is to be sealed, tunnels and shafts will be filled with a mixture of 80-90 percent quartz sand and 20-10 percent bentonite, to which a small amount of artificial vivianite (ferrous phosphate) has been added. The pure bentonite around each canister is expected to fulfill several functions: (1) to swell so as to fill all vacant spaces as water seeps into the repository, and thus to provide mechanical support for the canisters; (2) to delay access of groundwater to canister surfaces and to ensure that water in contact with the surfaces will be stationary or very slow-moving; (3) to serve as a chemical buffer to minimize changes in the pH and ion content of the groundwater in contact with canister surfaces. In addition, the bentonite is envisioned as a major barrier to the movement of radionuclides if a canister should ever be breached; this function will be discussed in Section VI.1. The bentonite-quartz mixture of the backfill in tunnels and shafts is expected to play a similar role in controlling the motion of groundwater, and in addition will have the desirable qualities of greater mechanical strength and greater heat conductivity than pure bentonite. The added ferrous phosphate will serve to take up oxygen from the residual air left in the repository after sealing and thereafter to ensure that groundwater moving through the repository will remain reducing. Experiments demonstrating the effectiveness of ferrosphosphate are described in Appendixes A:5 and A:6 and in KBS TR-10.

The precise sequence of events to be expected after the repository has been sealed is difficult to specify. Groundwater will surely enter through minor fractures in the enclosing granite, at a rate that will depend on the geometry of the fractures and on the effectiveness with which the fractures are sealed by the expanding bentonite. In the hole around a canister, water would presumably find its first access through the cracks filled with powdered bentonite between the compacted blocks; very probably some water would reach the canister surface, but it would soon be immobilized by swelling of the bentonite, and thereafter the very low permeability of the compacted blocks and the expanded bentonite between them would drastically slow the motion of additional water. Eventually, of course, the entire repository will be saturated with water, but the actual volume of the fluid will be small and its rate of movement to and from the canister surfaces will be exceedingly slow. In other words, the overpack around the canisters, and to a lesser extent the backfill in the repository as a whole, would constitute islands of near-impermeability, no matter what the regional flow of groundwater through the surrounding rock might be. Details of the sequence of events leading to a steady state are uncertain, and the time required is impossible to estimate, but neither the precise sequence nor the timing seems important, since at all stages the canisters will be well protected.

This conclusion, of course, depends to a critical extent on the properties of the bentonite. To these properties the KBS authors have given a great deal of attention. From a survey of possible sources in many countries, they have selected a commercially available bentonite from Wyoming as the variety that best fits their requirements. The properties of this bentonite and of others have been studied exhaustively, both by a search of the literature and by experimental work at many Swedish institutions, most extensively at the Technical Institute at Luleå (Jacobsson and Pusch, KBS TR-32: Appendix A, part A.3). The laboratory work has documented the amount of expansion to be expected under repository conditions, the pressures thereby produced, and the ability of expanding bentonite to inject itself into cracks. Mechanical strength has been measured over a range of densities and water content, and the plasticity of compacted bentonite has been shown to be adequate to protect canisters from remotely possible tectonic displacement of the bedrock. The permeability of compacted bentonite is comparable to that of unfractured granite. Bentonite has been shown capable of maintaining pH in the range of 8 to 9.5, the same range measured in deep groundwater samples, and the mixture of bentonite plus ferrous phosphate has been shown adequate to consume residual oxygen and thereafter to control oxidation potential. A review of geologic occurrences has shown that masses of montmorillonite clay similar in composition to the chosen variety of bentonite have in many places survived for millions of years in environments not greatly different from that to be expected in a granite repository. From the literature review and the experiments, the conclusion seems well founded that Wyoming bentonite will fulfill its expected role in a sealed repository.

Nevertheless, a few questions about bentonite seem inadequately covered in KBS publications, and these were discussed at length with Dr. Pusch.

(1) It seems possible, for example, that the permeability of bentonite might be greatly increased by ion exchange after long contact with groundwater; in particular, the Na^{+} of the Wyoming bentonite might be slowly replaced by Ca^{2+}. Calcium bentonite is well known to be less plastic and more permeable than the sodium variety. Dr. Pusch replied that the Wyoming material, although known as a sodium bentonite, actually contains a substantial amount of calcium, and that experiments in his laboratory have shown that additional calcium does not change the properties of the material significantly.

(2) Bentonite in prolonged contact with water forms a weak gel, and with enough water would form a mobile sol. Is it possible that over very long times the bentonite exposed to water in the fissures of the granite could be mobilized in this way, so that ultimately a good deal of the buffer material might be flushed out by moving groundwater? According to experiments, this is hardly likely; no appreciable amounts of sol were formed in laboratory tests under simulated repository conditions, and the movement of groundwater is extremely slow (KBS TR-79).

(3) Might the pressure exerted by expanding bentonite be sufficient to widen fractures, or even cause new fractures, in the adjacent rock? Pusch and his colleagues measured the pressures resulting from bentonite uptake of water under a

variety of conditions and found that they are much too low for an appreciable effect on sound granitic rock.

(4) Does bentonite retain its properties during long exposure to the somewhat elevated temperatures of a waste repository? Experimental work recorded in the literature shows a good deal of uncertainty about the precise temperature at which bentonite begins to alter in contact with warm solutions, but no reaction has been reported below 150°C with solutions like those to be expected in a repository. Since repository temperatures will be kept below 80°, the stability of the bentonite seems assured.

(5) Difficulties might arise in emplacement of the bentonite. In particular, the filling of open spaces around the compacted blocks in canister holes with powdered bentonite would be troublesome if the holes were wet, and the proposed pneumatic backfilling of the upper parts of tunnels with a bentonite-plus-sand mixture might be difficult under repository conditions (see also Section VI.3). While these possible sources of trouble were conceded by Dr. Pusch and his colleagues, it was felt that satisfactory engineering techniques could be developed in time by working with experimental test set-ups.

(6) Probably the most serious question about the bentonite buffer relates to its content of metal sulfides and organic matter. Analyses show varying amounts of sulfur in the form of sulfides and of organic matter up to about 0.2 percent of each by weight in dry bentonite (KBS TR-90, 4:1). The sulfur might cause corrosion of the copper, although the amount is so small that the integrity of the canisters would hardly be affected. The organic matter could serve as nutrient for bacteria, which could produce additional sulfide by reducing the sulfate of groundwater; if the bacteria were sufficiently mobile to use the organic substance in a large volume of bentonite, the total amount of sulfide released could be cause for concern (KBS TR-90, App. C). Pusch has shown fairly convincingly, however, that the mobility of bacteria in compacted bentonite with only minor organic matter would be greatly restricted. As an added precaution, experiments have shown that the bentonite could be free from nearly all of its sulfide content and about two-thirds of its organic matter by heating it for a few hours at 425°C. Whether this procedure would be adopted in the disposal program remains uncertain; although experiments show that bentonite's swelling properties and ion-exchange properties are not greatly affected by such brief heating, Pusch is inclined to question the stability of bentonite at temperatures above 150°C. The possible effect on canister surfaces of the sulfur contained in the bentonite or produced by sulfate reduction seems slight, but the question is under continued investigation in Pusch's laboratory in Luleå.

Although a few uncertainties remain about the postulated behavior of bentonite and methods of handling it under repository conditions, the Subcommittee agrees that the general conclusions of KBS-II about its adequacy as material for overpack and backfill are well-supported by basic theory, experimental data, and geological observation. Additional experimental work on properties of the compacted bentonite is desirable, and such experiments are underway at Luleå.

V. ADEQUACY OF DATA ON THE PHYSICAL AND CHEMICAL STABILITY OF THE CANISTERS

Copper canisters emplaced in a bedrock repository are expected to resist deformation by possible rock movement and chemical attack by groundwater for the period during which an escape of radionuclides would be hazardous to the biosphere. The length of this period is variously estimated, but to provide adequate insurance the canisters are designed to remain intact for at least a million years. A demonstration of the ability of the canisters to survive for this enormous length of time requires data on the feasibility of canister construction, the effectiveness of canister sealing, the mechanical behavior of canisters with a bentonite overpack, and the long-term resistance of copper to corrosion. Data bearing on such topics, as presented by the KBS scientists and engineers, are examined in the following paragraphs.

V.1 Can copper canisters of the proposed configuration be fabricated using state-of-the-art technology?

Assessing the feasibility of fabricating the copper canisters requires consideration of (1) the processes required to produce the rough starting material, (2) the subsequent shaping and forming procedures, (3) the procedures for canister sealing, and (4) methods of nondestructively testing the integrity of the canister before and after final sealing. These aspects of manufacture were discussed with Professor E. Mattson of the Swedish Corrosion Institute, Professor I. Grenthe of the Royal Institute of Technology, and Dr. K. Hannerz of ASEA, who were members of the reference group appointed by the Corrosion Institute to evaluate the suitability of the proposed canisters for long-term containment of spent fuel elements.

The pure copper (so-called "oxygen-free high-conductivity copper," or OFHC) chosen for the canister material can be produced in a number of ways, but according to current practice the best method is to cast a large ingot and use controlled chilling to produce the desired grain-size distribution (KBS TR-81). The further refinement of grain-size distribution, which is required to facilitate later use of ultrasonic methods in nondestructive evaluation, is accomplished by forging the as-cast ingots so as to produce about a 50 percent reduction in cross-sectional areas of the grains. A survey made by the reference group of the existing capability for such processing indicates that the casting and forging operations are feasible today in Sweden's copper and steel industries.

The final configuration is produced by machining both the interior and exterior of the canisters. Special equipment is required, particularly for machining the interior of the deep hole with adequate control of eccentricity and surface finish. Equipment capable of boring deep holes within a tolerance of 1 mm is reported to be available at the Motala Works. This is more than adequate, since variations as great as 10 mm would not seriously affect canister vulnerability to corrosion.

Welding of the canister tops is to be accomplished by the electron-beam method. The thickness of the canister walls (200 mm) is greater than the thicknesses to which this method is applied in current commercial practice (65 to 100 mm). Discussions with KBS team members and fabricators, however, indicate that with only minor changes and the use of higher energies the method can be adapted to material of greater thickness. The fabricators are reported ready to consider developmental manufacture now. The Subcommittee thinks that an actual demonstration with copper of the intended thickness is highly desirable.

The welds will be evaluated nondestructively by helium leak detection and ultrasonic testing. These are standard industrial techniques, and the Subcommittee has no doubts as to their applicability to the copper canisters.

In summary, the Subcommittee agrees with the reference group that it is feasible to construct, seal, and nondestructively evaluate a canister of the proposed configuration.

V.2 Is the mechanical capability of the canisters plus overpack sufficient to withstand remotely possible tectonic displacement?

The copper canisters, with a length of 470 cm, a diameter of 77 cm, and walls 20 cm thick, are to be filled with molten lead around the fuel rods and closed with three lids with a total thickness of 32 cm individually sealed by electron-beam welding. Canisters so constructed should be highly resistant to deformation by any imaginable external overpressure.

The canisters will be placed in vertical holes (with a diameter of 1.5 m and a depth of 7.7 m) drilled in the floors of tunnels in solid rock. The holes will be lined with blocks of highly compacted bentonite, the remaining spaces will be filled with bentonite powder, and each hole will be capped with a concrete cover. The bentonite in both the blocks and the powder will swell on exposure to water so as to fill the holes and provide a net compressive loading on the canisters. From a mechanical standpoint the canister and bentonite will become integral parts of the rock.

The most extreme conditions to be considered are those of a sudden shear on a horizontal plane normal to the length of the canister. Calculations by the KBS authors indicate that rupture would not occur unless the displacement exceeded 3 cm, an unlikely amount of movement on a shear so oriented. A more likely, but still remote, possibility is one of slow movement along one or more steeply inclined planes; in this situation the stress would largely be absorbed and deflected by the bentonite overpack and the effect on the canisters would be minimal.

The possibility that long-term exposure to radiation from the enclosed waste might cause embrittlement of copper, and hence greater susceptibility to mechanical damage, was considered by the Subcommittee. An inquiry addressed to an authority on radiation damage, Dr. F.W. Young of the Oak Ridge National Laboratory, brought the response that significant embrittlement of the copper by radiation under repository conditions is highly unlikely.

In the opinion of the Subcommittee, mechanical failure of the canisters under repository conditions may be safely eliminated as a cause for concern.

V.3 Will the canisters have sufficient corrosion resistance to prevent the contact of groundwater with waste for hundreds of thousands of years?

In the KBS plan the major barrier to radionuclide escape is the resistance of pure metallic copper to corrosion in the hydrogeochemical environment of a deep repository in granite. No definite time during which the copper canisters must survive is specified, but the KBS engineers confidently expect canister life to be at least a few hundred thousand and very probably more than a million years. This conclusion is supported by theoretical calculations based on experimental data (KBS TR-90; Appendix B).

The Subcommittee and the Swedish corrosion experts agree that complete thermodynamic immunity cannot be demonstrated for the proposed life of the copper canister. Therefore, some of the problems or deficiences in the thermodynamic analyses in the KBS-II report are not relevant. Instead, the service life of the canister has to depend on another consideration. This consideration undelies the KBS Plan for the use of copper as a canister material and the provision of an engineered benign environment that severely limits the mass transport of oxidants to the canister surface. As long as the transport of oxidants of importance in copper corrosion, oxygen and sulfide ions combined with hydrogen ions, is held to a sufficiently low rate by the geologic and overpack barriers, the rate of corrosion of the canister will be at an acceptably low value. Therefore, the transport of oxidants rather than the thermodynamic stability of copper in the presence of granite, chloride ions, carbonate ions, bicarbonate ions, or any other environmental factor, is the principal consideration that determines the life of the canister. The remainder of this section discusses the details of this strategy.

The groundwater in contact with the canisters, as described in preceding sections, will be the water commonly found at depth in granitic rocks, with a composition only slightly modified by the bentonite buffer. The water will be under a hydrostatic pressure of about 5 MPa, and will be practically motionless in the immediate vicinity of the canisters. Its temperature will climb to about 80° within a few decades after repository closure and then gradually decrease. Values of pH will be in the range of 7.5 to 9.5; values of Eh, after oxygen in the residual air is exhausted, will lie in the range of -20 to -250 mV. Concentrations of other ions will be low. Thus the canisters will not be in an aggressive groundwater environment, but a few possibilities for corrosion will nevertheless exist.

Copper in contact with oxygen-free pure water under repository conditions is immune to attack, according to calculations using standard thermodynamic data. In other words, the hydrogen ion in water in these ranges of Eh and pH is incapable of oxidizing copper. If the water contains traces of dissolved sulfide, some cuprous sulfide could form in the lower part of the Eh range. If both sulfide and dissolved oxygen are present, recent work (Syrett, 1977; MacDonald, Syrett, and Wing, 1979) has shown that the sulfide could serve as a catalyst for corrosion by oxygen. Concentrations of both sulfide and oxygen would be very low, however, as is shown by numerous analyses; oxygen would be kept low by the ferrous phosphate mixed with the bentonite in the backfill of the tunnels. Moreover, corrosion would be further limited by the fact that the corroding agents would have to move through the bentonite to reach the canister, and movement through the bentonite can take place only by diffusion. Neretnieks (KBS TR-79) has calculated that diffusion would be so slow that corrosion after a million years from this source would be negligible, affecting no more than 2 kg of the copper of a canister with a total weight of 16,000 kg. Even if Neretnieks' estimated diffusion rate is too low by a factor of 1,000, the copper loss still would not be serious.

The sulfide ion itself is not a corroding agent because it cannot be reduced, but reaction is possible if another oxidizing agent is present. Even the hydrogen ion can play an oxidizing role in a sulfide-polluted environment in a restricted Eh range. The supply of sulfide would be limited, however, by the very small amount of organic material that would be available to facilitate the bacterial conversion of sulfate to sulfide. Another possible mechanism of oxidation involves polysulfides (S_2^{2-}, S_3^{2-}, S_4^{2-}, S_5^{2-}), which are readily formed from sulfide in a slightly oxidizing environment, and which can serve as oxidizing agents in reactions by which they form copper sulfides. But corrosion of the canisters would still be limited by the flux of oxygen (or polysulfide equivalent), and would consequently be very low.

A much more likely oxidizing agent would seemingly be sulfate ion, which is nearly always present in concentrations up to about 15 parts per million (KBS TR-90, App. 1). One can write plausible equations showing the formation of copper sulfides by reaction of the metal with sulfate alone, or with sulfate plus sulfide, or with sulfate plus a reducing agent like Fe^{2+}, and one can show from energy relations that the reactions ought to take place. This prediction is probably of little consequence, however, because the reactions are exceedingly slow. A number of chemical experiments and geologic observations show conclusively that dissolved sulfates at temperatures under 100°C do not react with reducing agents even in geologic time unless bacteria are present. Some varieties of bacteria are capable of catalyzing these reactions, and such bacteria might be present in deep granitic environments. Thus some corrosion would be possible, but it could not go far because the bacteria would soon exhaust the meager supply of organic matter in the groundwater and bentonite. Calculations show (KBS TR-90, App. C) that the amount of organic matter that could serve as a nutrient for bacterial growth would be far too small to make the resulting corrosion significant.

The KBS authors are convinced that the thick-walled copper canisters would not be greatly damaged by corrosion for periods on the order of a million years, even if the repository environment should undergo considerable change.

One kind of environmental change that seems possible--even probable--would be the incursion of seawater into a repository if sea level rose. For a repository on Sweden's east coast the water would have a lower salinity than "normal" seawater, because the Baltic Sea is brackish, but even with brackish water the increase in chloride concentration, free oxygen, and possibly nitrogen compounds, could markedly accelerate corrosion. The KBS authors do not think the increase in rate would be serious, because the bentonite overpack would retard the access of corrosive agents to the copper surface, and ferrous phosphate in the backfill would keep oxygen concentrations low.

An additional circumstance that would help to retard corrosion, but one not mentioned by the KBS authors, would be the accumulation of solid corrosion products (Cu_2O, CuO, Cu_2S, CuS, $Cu(OH)_2$, $CuCl_2$, carbonates, etc.) at the interface between a canister and the surrounding bentonite. All these compounds occupy larger volumes (by a factor of four for oxides and sulfides) than the original copper, and hence would exert a considerable compressive force on both canister and bentonite. This would decrease the permeability of the overpack, and the compressive force would reduce the susceptibility of the copper to stress-corrosion cracking (Section V.4). Thus corrosion, whether seawater is present or not, would be to a considerable degree self-limiting.

In summary, the Subcommittee agrees that the KBS authors have established a technically sound basis for concluding that the copper canisters would be both mechanically stable and highly resistant to corrosion for times on the order of one million years, even if conditions in the repository should be changed by remotely possible rock movement or by the incursion of seawater.

V.4 Will the canisters be immune to stress-corrosion cracking for hundreds of thousands of years?

Stress-corrosion cracking (SCC) of metal surfaces is a catastrophic mode of failure that can make any estimates of long-term resistance to other corrosion failure mechanisms irrelevant. It can occur in environments where a metal is normally resistant to uniform corrosive attack, and it can be initiated by small amounts of specific substances that can concentrate in crevices or flaws. The KBS authors assume that SCC will not affect the copper canisters for two reasons: (1) the high-purity copper used in the canisters is virtually unsusceptible to SCC, and (2) the tensile stresses required to cause cracking would never develop, or, if present as a result of canister fabrication or handling during emplacement, would relax sufficiently with time to eliminate SCC as a problem. Because SCC can have catastrophic consequences, these assumptions need careful examination.

The immunity of high-purity metals to SCC is a long-held belief, but several recent papers have presented evidence that high-purity copper under some conditions can undergo SCC (Pugh et al., 1966; Escalante and Kruger, 1971; Suzuki and Hisamatsu, 1974; Pednekar et al. 1979). The conditions are rather specific, and tensile stress must be present. Dissolved materials described as capable of causing stress corrosion of copper include cupric ammonia ion, cupric acetate, nitrate, and other solutes, some in concentrations less than 0.1 N but higher than 0.01 N. These agents in such concentrations are extremely unlikely in a repository environment unless an incursion of seawater should introduce nitrogen compounds. Although the KBS assumption about the immunity of pure copper to SCC is not strictly accurate, the Subcommittee agrees that cracking should not occur in a repository environment.

Stress levels at canister surfaces will probably be low enough to prevent the growth of stress-corrosion cracks at an unacceptable velocity even if damaging agents are present in sufficient concentrations to cause an SCC problem. This statement is made with a slight reservation because the usual criterion for nonsusceptibility to SCC is a crack velocity lower than 10^{-7} or 10^{-8} cm/sec, and growth rates considerably lower than these would be needed to prevent penetration of a canister in a time span of a million years. The reasons for assuming that stress levels will be low are the following: (1) the geometry of the canisters and the mode of fabrication will minimize possible stress concentrations; (2) the canisters will be annealed by soaking for 48 hours at 300 to 400°C before being filled with molten lead; (3) a highly ductile metal like copper undergoes stress relief by creep at temperatures at least as low as 100°C; and (4) flaws that might concentrate stress or permit the accumulation of damaging agents will be generally absent on the canister surfaces.

Two other conceivable sources of stress should be mentioned:

(1) Considerable pressure may build up on canister surfaces from expansion of the bentonite buffer and from the formation of corrosion products (see Section V.3), but the stresses resulting from such pressure will be entirely compressive. Only tensile stresses can enhance the possibility of SCC.

(2) Periodic fluctuations of stress are known to increase the possibility of SCC failure, but at the 500-meter depth of canister emplacement stress fluctuations of amplitudes sufficient to be damaging are hardly likely. Neither the confining pressures nor the stress fluctuations in a repository environment seem capable of causing SCC in the absence of tensile stresses.

In summary, because the probability of simultaneous localized high stresses and high concentrations of agents known to cause SCC is very small under the conditions of fabrication, emplacement, and storage described in the KBS-II report, the Subcommittee thinks that there is virtually no possibility of canister failure because of SCC.

VI. ADEQUACY OF DATA ON THE MOVEMENT OF RADIONUCLIDES FROM A BREACHED CANISTER

The possibility always exists, however remote, that one or more canisters may fail during the long time needed for protection of the biosphere. A question then arises about the possible escape of radionuclides when spent fuel rods come into direct contact with groundwater. The question is complicated because the mode of failure and the extent of damage to the canisters are speculative, the condition of the fuel rods at the time of canister failure cannot be known, and the interactions of three metals (copper, lead, and zirconium) with groundwater and bentonite are hard to predict accurately. In their treatment of the question, the KBS engineers make the simplifying and unrealistically conservative assumption that spent fuel is immediately exposed to groundwater by canister failure after 100,000 years, so that the chief considerations are the rate of dissolution and the extent of retardation of the radionuclides as groundwater carries them through the buffer material and through fracture zones in the surrounding rock. Important data concerning these matters are the solubilities of compounds in the spent fuel containing radionuclides, the rate of groundwater movement, the length of the shortest path to the biosphere, and the extent of retardation of individual radionuclides by precipitation, sorption, and ion exchange.

It should be kept in mind that the KBS-II Plan envisions the breaching of canisters as a very unlikely event. Every effort is made to ensure that the canisters will be chemically and mechanically stable and that their environment will remain benign; they are confidently expected to last for at least a million years. If an unforeseen accident occurs, it will probably involve no more than a few canisters. The sort of accident that seems most likely is penetration of water into a flaw in a canister surface or into a faulty weld. Thus, contact with water would be minor, and escape of radionuclides would be slow. This sequence of postulated events if a canister should fail highlights the conservative nature of the KBS assumption of immediate and widespread exposure of waste to groundwater.

Despite its improbability, large-scale breaching of the copper canisters should be considered. The resulting movement of radionuclides has been studied at length in the KBS program, and the data obtained are considered in this section.

VI.1 If one or more canisters should be breached, will the bentonite overpack prevent or adequately retard the movement of radionuclides?

In the KBS plan, the first defense against movement of radionuclides toward the biosphere after the breaching of a canister is provided by the bentonite overpack. The overpack would consist of shaped blocks or rings of compacted bentonite, with powdered bentonite added to fill the cracks. If some very unlikely catastrophic geologic event should occur within a few decades after repository closure, the still-dry blocks might conceivably fracture and permit ready access of groundwater to the canister surface. At any later time the bentonite blocks and powder will have absorbed enough water to become plastic and hence to resist fracturing (Pusch, KBS TR-74; Appendix A, part A.d).

On the assumption that a canister somehow is breached because of corrosion or by brittle fracture during an earthquake while the overpack remains largely intact, a little groundwater will come directly into contact with the fuel rods. On the further assumption that both the lead and zirconium cladding are quickly penetrated, some of the radionuclides will dissolve and move out of the ruptured canister. Their outward movement will be greatly impeded by the impermeability of the compacted bentonite, however; the movement will be chiefly by very slow diffusion rather than actual flow (KBS TR-79, 80). During the diffusion the ions will be in intimate contact with clay-mineral surfaces, and most of those with positive charges will be stopped or retarded by sorption and ion exchange. Negatively charged ions, particularly $^{129}I^-$ and $^{99}TcO_4^-$, will not be removed by such processes. Tc will probably be immobilized by reduction and precipitation as TcO_2; ^{129}I has such low activity and would be present in such small amounts that dispersion and dilution should reduce its hazard to levels less than the radiation present in the natural environment. Another ion that might eventually escape in small quantity is $^{226}Ra^{2+}$, produced by decay of ^{238}U and thus not an important constituent of the waste until well after 10^4 years. Dr. Jan Rydberg (personal interview) regards this ion as the most dangerous of those that might ultimately escape, but the hazard is probably small because Ra^{2+} is adsorbed about as effectively as Sr^{2+}. Experimental data on the sorption of various ions by bentonite under simulated laboratory conditions are tabulated in KBS TR-55 and 98, and further work of this type is continuing in Dr. Rydberg's laboratory in Götebörg.

The solubilities of the UO_2 pellets in the spent fuel are shown to be very small by Eklund and Forsyth (KBS TR-70) on the basis of experiments and calculations from thermochemical data. The rates of dissolution of fission products and actinides contained in the fuel pellets are difficult to predict, but presumably would be controlled in part by the dissolving of uranium and hence would also be small. Rates of diffusion cannot be predicted accurately because they depend on many variables, but Neretnieks (KBS TR-79) presents calculations based on reasonable assumptions showing that diffusion would be very slow.

Slow dissolution and slow diffusion through bentonite can be confidently predicted as long as the break in a canister surface is small and the surrounding overpack is not appreciably damaged. A larger rupture, caused by gross corrosion or tectonic movement, would have consequences less easily predictable. Three different metals--copper, lead, and zirconium--would be in contact with groundwater, and a galvanic cell might result in which the more active lead and zirconium would be taken into solution in large amounts. If cracks had developed in the overpack the solution could move outward rapidly, and sorption sites on the clay surfaces would be flooded with lead ions. The mechanism for retarding radionuclides would then no longer operate, and some of them could move in considerable quantity out into the surrounding rock. This is the worst possible sequence of events. Whether it is at all realistic is a matter of conjecture. The rate of reaction of galvanic couples of copper/lead and copper/zirconium would depend on the pH and the Eh of the groundwater, as well as on the electrical resistivity of the surrounding groundwater. If those variables had values like those in present-day deep groundwater the reactions would be slow and the lead and zirconium ions would largely precipitate as oxides or carbonates (PbO, $PbCO_3$, ZrO_2). Some of the radionuclides might still dissolve, and groundwater could carry them through the overpack by flow rather than diffusion, but the clay-mineral surfaces would now be in large part available to retard their motion. Since the kind of rupture of the canister and the overpack cannot be specified, the number of imaginable variations in possible consequences is practically infinite.

The KBS scientists interviewed by Subcommittee members were confident that the bentonite overpack would remain an effective barrier to radionuclide escape in any expectable kind of canister failure. They had not considered the more extreme conceivable accidents, particularly the possibility of rapid dissolution of large amounts of lead and zirconium by galvanic action, but they regarded this as too unlikely for serious concern. The Subcommittee agrees with their position, and that the experimental data on bentonite properties support their conclusion that in most imaginable situations the overpack will serve to prevent or adequately retard the escape of most radionuclides.

VI.2 If radionuclides escape into groundwater from both canisters and overpack, will retention, dispersion, and dilution of radionuclides in their movement through bedrock be sufficient to keep concentrations acceptably low?

Despite the demonstrated durability of the canisters and the nuclide-retarding capability of the overpack, there remains the possibility that some wholly unexpected accident might bring radioactive material into direct contact with moving groundwater. In that event only one barrier would remain between the radionuclides and the biosphere: the bedrock through which the groundwater must travel. The question of the effectiveness of this barrier has been explored at great length, not only by KBS scientists but by experts in many countries where bedrock disposal has been considered. Despite the enormous effort expended, however, no agreement has been reached as to the probability of radionuclide movement in unacceptable quantities. The quantity and rate of movement of groundwater in fractured rock, the forecasting of geologic and meteorologic events, and the ability of natural rock material to retard radionuclide migration evidently depend on so many variables that neither observations nor experiments can be set up that will satisfy all the experts who have looked into the question. Opinions range from a confidence that restriction of radionuclide movement to very minor amounts can be predicted on the basis of present knowledge, to a conviction that the ability to make any reasonable predictions must await many more decades of research.

The evidence presented by the KBS scientists and investigators for the slow movement and benign composition of groundwater under the normal conditions to be expected in a repository, as noted in Section IV.2, seems conclusive to the Subcommittee. Prediction of the possible geologic or meteorologic changes that might radically affect either motion or composition is inevitably more uncertain, but the Subcommittee thinks that here also a good case has been made for reasonable uniformity of conditions in a repository during the necessary time of waste isolation. The remaining question for consideration is the adequacy of the KBS demonstration that radionuclides would still be effectively controlled if some bizarre accident should completely destroy the integrity of a repository.

The demonstration involves in large part the measurement of distribution coefficients (K_d's) of radionuclides between solutions and the kinds of minerals that groundwater would be expected to encounter on its way from the repository to the surface. Such measurements are notoriously undependable with regard to reproducibility and relevance to natural environments. At a recent workshop in the United States, for example, an observer commented that experiments "designed to test the reproducibility of K_d values in different laboratories, using the same rocks and a standardized procedure, were disasters." Despite this lack of complete credibility, K_d measurements seem to be the only reasonable experimental basis for at least rough predictions about the behavior of radionuclides as they move through sorbent material (KBS TR-30, 52, 55, 77, 98; Appendix A, part A.4).

To avoid the criticism of lack of relevance to natural conditions that is often leveled at K_d experiments, the KBS investigators used solutions with compositions similar to those of deep groundwater, and rocks and minerals with surfaces resembling those with which the groundwater would come in contact. The effects of changing temperatures and pH levels were explored, and some experiments were extended as long as 6 months to measure the increase in sorption with time. Radionuclides in different valence states and in different expectable complexes were used in the experiments. Because all the more obvious variables that might affect K_d's were studied over a considerable range, a greater degree of confidence can be placed in the KBS measurements than in much previous work. In addition to their K_d work, some of the KBS investigators considered the initial solubility of the various radionuclide compounds that might be expected in the spent fuel rods, and also the possible formation of colloids that might permit some nuclides to travel even though their compounds are highly insoluble (KBS TR-70, 97, 103).

In an interview with Dr. Jan Rydberg, one of the principal investigators of K_d's, the care taken in the experiments he described to keep conditions similar to nature seemed impressive. Most of his results are qualitatively like others recorded in the literature--very high K_d's for actinide elements, fairly high for Cs, somewhat lower for Sr and Ra. Especially notable are his conclusions that K_d's are little affected by a temperature increase from 25 to 75°C, that many measured apparent K_d's are time-dependent (presumably because ions penetrate crystal structures slowly, so that true equilibrium values for K_d are only slowly attained), that most radionuclides show especially complete sorption on ferric oxide, and that technetium is retained by granite if it is in a solution with Fe^{2+} (presumably because it precipitates as TcO_2, although Rydberg is not sure of this). Iodine in the form of I^- is not sorbed appreciably by granite but is removed by a ground-up mixture of sulfide-containing material from a granite vein. Despite the quantity of data already accumulated in his laboratory and elsewhere in Sweden, Rydberg thinks that more information is needed. He himself is actively engaged in further experiments on sorption and the formation of complexes.

The uncertainty about K_d's and about availability of exchange sites on mineral surfaces in the fissures suggests that in situ tests are needed to measure migration rates of radionuclides and other ions in granitic rock. The KBS program includes such tests at Studsvik, where ions have been injected into one of three boreholes in granitic rock and looked for in the other two (KBS TR-110). Preliminary results of these field experiments indicate that observed relative migration rates correspond to those predicted from K_d's.

Despite the difficulty of judging conclusions based on experimentally determined apparent distribution coefficients, the Subcommittee agrees that a reasonably good case has been made in the KBS-II Plan for considerable retardation of dissolved radionuclides as they move through granitic rock. Retardation would be aided by the dilution and dispersion of radionuclides in the moving groundwater. Many aspects of the problem can be suggested, however, on which further information would be welcome: the behavior of I^-, for example, which shows so little sorption on most mineral surfaces in granite; the possibility that some of the radionuclides may form organic complexes that would greatly diminish their sorption; and the possibility that release of dissolved lead from a breached canister might flood sorbent surfaces in the granite and leave no sites for radionuclides. Important information about the ability of uranium to migrate in a granite environment could also be obtained by comparing the amount of uranium and radiogenic lead in naturally occurring minerals from granite of a possible repository site. It is easy also to point out that laboratory work should be complemented with further in situ experiments. Certainly the experimental program should continue, along these and other lines, but the Subcommittee, with the exception of Dr. Harold James, thinks that enough work has already been done to demonstrate that the combined effects of the precipitation, sorption, ion exchange, dilution, and dispersion as groundwater moves through the granitic rock would keep concentrations of radionuclides that might escape from the breached canister acceptably low. Dr. James, the dissenting member, feels that he cannot endorse this view on the basis of data now available.

The Subcommittee majority bases its judgment in part on the circumstance peculiar to the KBS-II Plan that retardation of radionuclides as they move through rock is not a primary barrier but only a barrier of last resort, a barrier that would come into play only if and when the carefully designed engineered barriers should fail. If the canisters were expected to fail within a few decades, and if no bentonite was to be added as overpack and backfill, the ability of mineral surfaces in granite to trap radionuclides by sorption and ion exchange would be far more critical and additional research would indeed be warranted. But the chance of both canisters and bentonite failing in a catastrophic manner seems so exceedingly small that the additional improbability of insufficient retardation hardly needs documenting down to the last detail.

VI.3 Can the sealing of tunnels, shafts and boreholes with bentonite after the repository is filled be made so effective that movement of water over the long term will be no faster than through the adjacent undisturbed granite rock?

An essential feature of all plans for geologic disposal of nuclear waste is the plugging or sealing of openings into a repository after all the canisters have been emplaced. The sealing is expected to prevent the movement of fluids between the repository and the ground surface or intervening aquifers, and, at a minimum, to ensure that the movement of groundwater through the repository will be no faster than through the adjacent undisturbed rock. Such assured sealing is needed both to control the movement of potential corrosion agents to canister surfaces and to aid in preventing unacceptable movement of radionuclides to the biosphere if a canister should be breached. In many American discussions of waste disposal, adequate plugging and sealing of a repository is considered one of the most difficult steps in repository construction.

The KBS engineers, on the other hand, evidently regard the final closing of a repository as a fairly routine operation. Complete dependence is placed on the properties of bentonite to provide effective seals. Tunnel spaces above the canister holes are to be backfilled with a mixture of 80 to 90 percent quartz sand and 10 to 20 percent bentonite (plus a little ferrous phosphate as a deoxidant). The mixture will be emplaced in the lower part of a tunnel by standard earth-packing techniques used for road embankments and earth-fill dams, and in the upper part by spraying with an air blast (similar to the "shotcrete" process). Shafts are to be filled with the same quartz-bentonite mixture, presumably by tamping it into place, and boreholes will be plugged with highly compacted bentonite. In all the various openings the bentonite is expected to swell by sorption of water, and so to seal the fill firmly against rock surfaces (KBS TR-37).

In the opinion of the Subcommittee, the treatment of sealing is probably the weakest part of the KBS plan. The projected operations may be possible, and the bentonite may behave as expected, but actual demonstration of the different steps seems inadequate. Filling the lower parts of tunnels with quartz and bentonite should present no difficulties, but the pneumatic method for completing the filling is somewhat questionable. The procedure has been demonstrated by blowing a sand-bentonite mixture into a large smooth-walled pipe in the open air, but conditions in a repository tunnel would be different. American engineers questioned about the method were dubious about its feasibility. They noted that it was formerly used in the United States for tunnel filling but is now largely superseded by sidewise tamping or use of a fluid grout; that it does not produce a compact filling, especially in a mined tunnel with irregular walls; that it may lead to partial separation of sand and bentonite; and that the very dusty atmosphere produced by spraying in a confined space, especially a hot repository tunnel, would make working conditions extremely difficult. A further question can be raised about the adequacy of compacted bentonite to seal bore holes effectively.

Just how serious these objections are is a matter of debate. It could be argued that the kind of repository planned in the KBS program is in many respects different from those hitherto considered in the United States; that granitic rock can be expected to maintain large openings indefinitely, so that attainment of high density in a tunnel backfill is not essential for support; that there will be enough bentonite around and above the canisters to immobilize water locally so that rigid control of groundwater flow through the repository will not be needed; that the Swedish plan puts much more reliance on long-term canister integrity than most American plans, so that water movement is a lesser potential hazard to the biosphere; and that Swedish research on the properties of bentonite, more extensive than any so far reported in America, is sufficent to give confidence in its behavior as backfill and grouting material. One can also note that, according to the projected KBS schedule, actual sealing lies several decades into the future, so that ample time is available for developing possible engineering alternatives along with suitable demonstrations.

Despite such counterarguments, the KBS conclusion that the planned sealing procedures will ensure that groundwater movement through the repository over the long term will be no greater than movement through the surrounding undisturbed bedrock seems, in the Subcommittee's opinion, to rest on inadequate evidence. Because the integrity of the planned repository would not be jeopardized by water flow somewhat greater than normal, this is probably not a matter of first importance. But the Subcommittee thinks that additional attention to sealing procedures is a fitting subject for future research.

VI.4 Can the attainment of critical configurations by fissionable nuclides during movement of groundwater be shown to be impossible, or can the effects of criticality be shown to be negligible?

A concern expressed by some critics of the KBS plan is the possibility that radionuclides escaping from a breached canister and carried in solution by groundwater moving through buffer material and fissure fillings in granite might be sorted out chromatographically in such a way that fissile material (^{235}U, ^{239}Pu, ^{243}Am) would accumulate in sufficient quantity, together with water or other material that could act as a neutron moderator, to constitute a critical concentration and hence to start a chain reaction.

The conditions for such an occurrence have been considered by some of the KBS scientists (e.g., KBS TR-108 and TR-120), and their general conclusion is that the chance of fortuitous accumulations of the necessary materials in the proper geometry within a million years is practically negligible. One of them, Dr. Jan Rydberg, pointed out that the chemistry of the actinide elements would nevertheless make a critical accumulation conceivable, and the possibility, however remote, should be taken seriously. In his opinion the hazard of a chain reaction can be discounted on other grounds, namely that even if such a reaction should occur it would be self-limiting. Increased temperature due to the reaction would cause the water retardant to evaporate, and the reaction would cease until cooling permitted more water to accumulate.

The only results would be fluctuating slightly higher temperatures in the repository, and minor production of new fission products. The maximum temperature that could be anticipated would therefore be approximately that of boiling water at the repository pressure.

One can imagine, as a worst possible case, that the escape of water might be temporarily blocked so that temperatures would rise to several hundred degrees before the reaction was brought to a stop. The high temperatures would be local and temporary, however, and would not adversely affect the ability of the great mass of surrounding rock to trap radionuclides that might escape.

Because the escape of actinide elements in the necessary quantity during the next million years is exceedingly unlikely, because the separation and accumulation of fissile nuclides in the appropriate geometric configuration is still more unlikely, and because little hazard would result from a self-limiting chain reaction anyway, the Subcommittee agrees that the KBS authors are on firm ground in dismissing criticality as a substantive objection to their waste disposal problem.

If nevertheless additional precautions are thought necessary, criticality could be avoided by (1) placing the canisters far enough apart that a critical concentration cannot occur even if all the contents are distriuted uniformly and/or (2) by adding a small amount of borax or boron carbide to the bentonite overpack.

VII. CONCLUDING REMARKS

The KBS-II Plan for disposal of spent fuel rods places major reliance on the long-term resistance to corrosion of the thick-walled copper canisters in which the rods are to be enclosed. To ensure that corrosive attack will be slow, the canisters will be placed in an underground repository where the amount and rate of movement of groundwater are small, and where both the flow and the chemistry of groundwater are additionally controlled by an overpack of compacted bentonite clay. This combination of heavy copper canisters and an engineered benign environment is expected to limit the escape of radionuclides during the long time needed for radioactive decay to reduce their activity to innocuous levels. As a safeguard against accidents that might expose waste to groundwater, due either to flawed canisters or to geologic catastrophes, the environment will be chosen and the overpack will be engineered to prevent or greatly retard any movement of escaping radionuclides to the biosphere. Like most schemes for geologic disposal of radioactive waste, the Swedish KBS-II Plan has redundant barriers to the escape of radionuclides; it differs from most other plans in its primery dependence on the engineered barrier consisting of canisters plus overpack, although quite recently many activities in the high level waste isolation business are shifting primary dependence onto to the integrity of the waste package.

To provide technical support for this plan, the KBS scientists have carried out an extensive program of research involving a thorough review of the literature, geologic exploration, and laboratory work at many Swedish universities, technical institutes, and consulting agencies. The data base thus far accumulated, in the Subcommittee's opinion, adequately supports the overall conclusion of the KBS-II Plan that it provides a high degree of assurance that radionuclides will not move from a repository into the biosphere in unacceptable amounts for the necessarily long time spans. The Subcommittee recognizes that some parts of the data base are weak, and that some of the planned backup barriers to radionuclide movement may not function as well as expected. But the existence of multiple barriers in addition to the primary barrier provided by the copper canister means that movement of radionuclides will still be controlled if one of the secondary barriers should fail.

For example, if the bentonite does not sorb radionuclides as well as expected, there is adequate margin in the barrier system so that unacceptable concentrations will still be prevented by the small amount and slow movement of groundwater, by the insolubility of the uranium oxide pellets, by the sorption on mineral surfaces in granite, and by the effects of dilution and dispersion. While the technical support of a few overly-optimistic conclusions about some parts of the secondary barrier system needs further research, the general conclusion about the overall functioning of the highly redundant barrier system seems well based.

The ability of the copper canisters to remain intact for very long periods under conditions that now exist in a deep granitic environment is adequately supported both by theoretical considerations and by laboratory experiments. Corrosive attack might be speeded up, of course, by radical changes in such an environment, but the tolerable limits of variation in temperature, pH, and ion content of adjacent solutions have been shown to be comfortably wide. For example, even if seawater were to enter a repository as a result of rock movement or sea-level change, the rate of corrosion would not be greatly increased. The mechanical strength and resistance to deformation of the canisters also have been shown adequate to maintain integrity during any reasonably imaginable tectonic dislocation in a repository. Except for their high initial cost and their possible later attractiveness as a source of copper, the canisters seem well suited to long-term containment of waste. It should be emphasized that their durability is not dependent on the maintenance of a narrow range of conditions but would persist through many kinds of unexpected changes in a repository. Thus, the effectiveness of this one barrier makes the perfect functioning of all the other contemplated barriers less essential.

Although the corrosion resistance and mechanical strength of the canisters seem sufficient to ensure their survival through the anticipated range of environmental conditions, it is obviously desirable that those conditions be kept as stable as possible. This objective, according to the KBS-II Plan, will be achieved by a number of steps: (1) the temperature of the canister surfaces will be kept below 80°C by aging the waste before burial and by proper loading and spacing of the canisters; (2) repository sites will be located at depths of about 500 m in tectonically stable parts of the Swedish bedrock where scarcity of fractures will ensure slow movement of groundwater; and (3) a bentonite buffer to further impede groundwater movement and to control the chemical environment will be placed around each canister and used as backfill in tunnels and shafts. The ability of the bentonite to control pH is shown by experiments reported in KBS TR-32, in which measured pH's in bentonite suspensions ranged from 8.5 to 10.2 at ordinary temperatures and from 8.4 to 8.7 at 95°C. Redox potential will be controlled by the addition of ferrosphosphate to the bentonite-sand mixture in the backfill (KBS TR-90).

The attempt of the KBS engineers to demonstrate that all these controls on conditions around the canisters can actually be achieved, while impressive, is not entirely free from uncertainties. Regarding temperature there can be no question, because temperature distributions around waste of various ages and various concentrations can readily be calculated by standard techniques and adjusted accordingly. The tectonic stability of large areas of the Swedish bedrock seems assured; even the few doubters among Swedish geologists do not envision tectonic movements of such magnitude that the integrity of canister-plus-buffer combinations in a repository would be seriously affected. The existence of areas of relatively fracture-free rock at a depth of 500 m of sufficient size for a large repository, however, has not as yet been convincingly demonstrated. Among the areas investigated thus far, the only one that seems to have the necessary qualifications (Karlshamn) is only marginally large enough, and the number of boreholes is not sufficient to rule out the presence of additional fracture zones. It is true, of course, that the low permeability of bedrock sought by the KBS authors is conservative, and that a site like Karlshamn, even if additional fracturing is found, could be made usable by careful placement of the canisters or by treatment of the repository walls. Thus the Karlshamn site is almost certainly suitable, or could be made suitable with engineering adjustments, and better sites are likely to be found by explorations that are now in progress. Still, the KBS-II Plan would be on a firmer basis if a site with more ample dimensions had in fact been located. Demonstration of a satisfactory site may well require actual underground exploration by means of a shaft and exploratory tunnels.

One of the large areas of uncertainty concerns the nature and predictability of the hydrologic regime in and around the proposed repository, and it is not likely that this uncertainty can be eliminated in advance of actual repository development. Nevertheless, available measurements do show that the overall permeability in rock bodies of the type being considered is very low, and that the quantity of moving groundwater is very small. Even if estimates of permeability are incorrect by factors of 10 or 100, the movement of groundwater to a canister or past a canister surface would still be controlled by the essentially impermeable bentonite. Experiments with the overpack material show fairly conclusively that any movement of corrosive agents toward the canister surface would be chiefly by slow diffusion rather than by groundwater flow. The experimental work has also demonstrated, in the

Subcommittee's opinion, that the bentonite (plus ferrous phosphate in the backfill) will adequately control pH, oxidation potential, and concentrations of ions in the vicinity of the canisters. Questions can be raised about mechanical details of filling cracks between segments of the compacted bentonite overpack and about the proposed pneumatic emplacement of the backfill in the top parts of the repository tunnels. The Subcommittee thinks that demonstration of these procedures under field conditions is inadequate, and regards this as a notable weakness of the KBS-II Plan. On the other hand, the problem seems to be amenable to further engineering study and experimentation, and is not of first importance because some unanticipated channeling of slow moving groundwater through the tunnels of a backfilled repository would not damage the canisters in the bentonite-filled holes below.

The barriers of last resort, which would be needed only in the event that a canister should be cracked open or deeply corroded during the time when an escape of radionuclides would be hazardous, are provided by the chemical reactivity of the bentonite overpack and backfill and by the nature and dimensions of the bedrock fissures through which groundwater would have to travel. The effectiveness of the latter barrier, in the Swedish plan as well as other plans for bedrock disposal, remains a matter of debate, but even with continued research it seems doubtful that it can ever be expressed in terms other than low probabilities. The Subcommittee, with the exception of one member, thinks that the elaborate KBS studies, in both field and laboratory, of groundwater movement and the retardation of radionuclides demonstrate satisfactorily that motion of radionuclides from a ruptured canister to the surface or to an aquifer in more than minute amounts is highly improbable. This improbability, coupled with the initial improbability that a canister will be breached, supports the conclusion that a KBS-II repository will provide the necessary isolation and containment of the hazardous radionuclides.

In final summary, the Subcommittee finds that the KBS-II conclusions about the satisfactory long-term integrity of a well-engineered bedrock repository in a carefully chosen site, despite few uncertainties that will require further research, have adequate support in the available technical data.

Appendix A

HYDROGEOCHEMICAL AND GEOLOGICAL DATA BASE TO SUPPORT THE KBS-II PLAN

Gary Walter

A.1 Introduction

The high level waste repository design presented in the KBS-II Plan provides three barriers to the transport of radionuclides from the repository to the biosphere. The first barrier is the copper canister in which waste will be encapsulated. The second barrier is a compacted bentonite buffer of very low permeability which will surround each canister; in addition, repository tunnels will be backfilled with bentonite. The third barrier is construction of the repository at a depth of about 500 m in crystalline rocks of very low permeability and with sufficient sorptive properties that no harmful transport of radionuclides by groundwater movement can occur.

The effectiveness of each barrier requires that the geological, hydrological, and geochemical environment of the repository have certain characteristics. The KBS organization has developed an extensive data base to show that such an environment exists and can be located in Sweden. The purpose of this appendix is to describe the supporting data contained in KBS technical reports and additional data and interpretations obtained by personal discussions with KBS engineers and scientists.

A.2 Integrity of the Copper Canisters

In the KBS-II Plan the primary barrier to radionuclide movement is the copper canister in which waste is to be encapsulated. The report presents several arguments to support the choice of copper as canister material and the canister design. First, thermodynamic calculations are presented to show that elemental copper will undergo very limited corrosion in the hydrochemical environment predicted for the repository site. Second, the mechanical properties of the canister are shown to be adequate both to ensure its integrity under static stresses in the repository and to withstand stresses caused by possible rock movements.

Lastly, evidence is presented that the radiation produced by the waste will not cause deterioration of the canister. Only the data relevant to the predicted hydrochemical environment and to rock movements in the repository site are discussed in this appendix.

A.2.1 Hydrochemical Data

Based on equilibrium thermodynamic calculations, dissolved oxygen, sulfide, sulfate, and nitrate were identified as the chemical species in groundwater which are capable of oxidizing elemental copper and thus causing corrosion of the canisters. To ensure absence of these redox reactions requires a reducing environment, the particular redox potentials depending on the pH.

The predicted range of composition of groundwater at depth in crystalline rock, as presented in KBS-II, is shown in Table A-1. The estimated ranges are based on chemical analyses of water samples from existing water supply wells in Sweden, subsurface excavations, boreholes drilled during the course of the KBS investigations, comparisons with the chemical composition of groundwater reported for igneous and metamorphic rock terrains outside of Sweden, and a conceptual model of hydrochemical variations in regional groundwater flow systems. KBS technical reports dealing specifically with the chemical characteristics of waters at the depth of the proposed repository are those by Gidlund (KBS TR-62), Rennerfelt (KBS TR-36), and Jacks (KBS TR-88).

According to Jacks (KBS TR-88), most chemical analyses of groundwater in crystalline rock terrains in Sweden are from water supply wells less than 100 m deep. The relevance of these analyses to the water composition at 500 m depth is uncertain, and Jacks stated in personal discussions that he could not guarantee their quality. In particular, the procedures used by different investigators for the collection of samples for determining dissolved oxygen, redox potentials, and pH were not known.

The data most relevant to water composition at the depth of the proposed repository come from analyses of samples collected from boreholes drilled under KBS auspices as well as samples from the subsurface research facility at Stripa. For the borehole sampling, special downhole sampling equipment was constructed which allowed closed-system sampling at specific depths by isolating 2- to 3-meter sections of the boreholes (Gidlund, KBS TR-62). Despite the great care which was apparently exercised to obtain representative samples, both Gidlund and Grenthe (KBS TR-90, Appendix B5) think that some of the samples may have been contaminated by drilling water and air.

TABLE A.1 Probable Composition of Groundwater in Crystalline Rock at Great Depth

Analysis	Units	Probable Interval	Maximum Value
Conductivity	μS/cm	400–600	1100
pH		7.2–8.5	9.0
$KMnO_4$ consumption	mg/l	20–40	50
COD_{Mn}	mg/l	5–10	12.5
Ca^{2+}	mg/l	25–50	60
Mg^{2+}	mg/l	5–20	30
Na^+	mg/l	10–100	100
K^+	mg/l	1–5	10
Fe^- total	mg/l	1–20	30
Fe^{2+}	mg/l	0.5–15	30
Mn^{2+}	mg/l	0.1–0.5	3
HCO_3^-	mg/l	60–400	500
CO_2	mg/l	0–25	35
Cl^-	mg/l	5–50	100
SO_4^{2-}	mg/l	1–15	50
NO_3^-	mg/l	0.1–0.5	2
PO_4^{3-}	mg/l	0.01–0.1	0.5
F^-	mg/l	0.5–2	8
SiO_2	mg/l	5–30	40
HS^-	mg/l	<0.1–1	5
NH_4^+	mg/l	0.1–0.4	2
NO_2	mg/l	<0.01–0.1	0.5
O_2	mg/l	<0.01–0.07	0.1

SOURCE: Rennerfelt and Jacks, KBS TR-90, A:1.

Determinations of pH were made in the field, and samples for determining dissolved oxygen and redox potential were collected in sealed containers. Dissolved oxygen was determined by the modified Winkler method. The techniques used for measuring redox potential are described in detail by Grenthe (KBS TR-90, Appendix B5). Measurements of redox potential for 6 samples from Stripa and 2 samples from Finnsjön at depths of about 400 m range from -210 mV to -26 mV.

More recent chemical analyses of samples from boreholes in the Stripa mine have been reported by Fritz et al. (SAC TR-12). Some of the Eh values reported for these samples are higher than those listed in KBS-II, but the investigators question their validity.

These analyses represent the water chemistry as it exists at present. Arguments presented in KBS-II with regard to the long-term persistence of these chemical conditions are based on the observed mineralogy of the rock masses and the secondary minerals in filled fractures, thermodynamic calculations, and a conceptual model of hydrochemical patterns in deep groundwater flow systems.

Observations of unoxidized ferrous iron and sulfide-bearing minerals at the proposed repository depth and also at depths of only a few meters are presented as support for the long-term persistence of reducing conditions. Exceptions to this generalization are noted in local oxidized zones near major fractures.

Oxidation of ferrous iron is proposed as the principal control on redox conditions near a repository. Equilibrium thermodynamic calculations presented in KBS-II show that these reactions should maintain the redox potential at between -60 mv and -380 mV. The reaction of ferrous iron with sulfide to precipitate pyrite is also proposed as a mechanism that will maintain low sulfide concentrations in the water.

In KBS-II a conceptual model to explain the transition from oxidizing to reducing conditions and accompanying decreases in sulfate content and increases in pH in deep groundwater flow systems has been adapted from the work of Germanov and Panteleyev (1968). This model originally was proposed to explain uranium enrichment in deep sandstones, and as described in KBS-II appears to conform to similar models proposed in the United States. The principal modification of this model to make it represent Swedish crystalline rock environments is the assumption that the transition area from oxidizing to reducing conditions is only a few meters below the water table.

Assessment of the changes in water chemistry that could occur during the period when the repository is open is based primarily on studies by Pačes (1969), who shows by analyses of water near very old mines that the effects on composition of long contact with air are only local. Presumably, further data relevant to this question will be obtained as research progresses at Stripa.

Subcommittee members obtained much of the information on the hydrochemical environment summarized above, as well as the following details, from a meeting with Gunner Jacks and Otto Brotzen. In response to questions about the possible influence of the repository on water chemistry, Jacks thought that the canisters themselves would have no effect. The effect of 80-degree temperatures on reactions between water and the canisters or wall rock has not yet been studied, but such experiments will be tried at Stripa. Other experiments, however, have shown that the ferrous phosphate in the bentonite of the backfill will serve as expected to keep the groundwater reducing.

Brotzen and Jacks were also asked about the effect of seawater encroachment on the hydrochemical environment of the repository, particularly with regard to increased levels of sulfate. Jacks agreed that such an event could increase sulfate levels considerably above those in normal groundwater. Brotzen was of the opinion that seawater enroachment was unlikely at the repository sites, even with a rise in sea level, because of the very slow response of groundwater flow systems to changes in boundary conditions. He also felt that the ferrous phosphate and naturally occurring ferrous iron minerals in the repository would prevent large increases in sulfide, which is produced by the bacterial reduction of sulfate in saline water.

A.2.2 Rock Movements and Canister Integrity

Mechanical stresses which could affect the integrity of the canisters are (1) external overpressure due to hydrostatic pressure and swelling of the bentonite buffer, (2) shear stresses due to rock movements, and (3) internal overpressure due to helium formation within the waste. Only stresses due to the swelling of bentonite and rock movements are considered in this appendix.

Data on the swelling pressures of compacted bentonite are based on experimental measurements and theoretical calculations by Pusch (KBS TR-73). As reported in KBS-II and also in an interview with Pusch, these data indicate that the pressures would be much too small to damage the canisters.

The ability of the canisters to survive the stresses caused by rock movements of a few decimeters has also been studied experimentally and theoretically by Pusch (KBS TR-76). In experiments performed on approximately quarter-scale models of the canisters, the predicted and observed strains were shown to be roughly comparable. The results indicate that the canisters could survive sudden movements of a few centimeters and total shear displacements of several decimeters.

To ensure the mechanical integrity of the canisters requires estimates of the magnitude of rock movements and placement of the canisters in rock where strains will be minimal. Rock movements that have been analyzed for KBS-II are those caused by regional tectonic forces, isostatic and shear stresses caused by glaciation, and thermal and mechanical stresses arising from the repository itself.

The KBS-II report presents data and interpretations to support the claim that, except in certain well defined areas, the potential repository sites in Sweden are in tectonically stable areas. These data consist in large part of reviews of existing geodynamic studies of the Fennoscandian shield, plus data on the magnitude and areal distribution of historical seismic activity. The seismic record covers 1897 to the present, with expanded coverage beginning in the early 1960s. Data on present tectonic activity developed under KBS auspices include satellite and terrestrial gravity observations (KBS TR-17), air-photo interpretation and field mapping, and precision geodetic surveys.

Considerable controversy has arisen over whether the postglacial uplift observed for the Fennoscandian shield has a tectonic component. Mörner (KBS TR-18) presents data, based primarily on the mapping of ancient shorelines, to support the claim that the isostatic component of uplift ceased 2,000 to 3,000 years ago, and that the present rate of uplift in Sweden (as much as a few cm/year) may be tectonically controlled. The geophysical and theoretical studies reported by Bjerhammar (KBS TR-17) do not support major neotectonic activity, but Bjerhammar states that the data are insufficient to reveal small-scale tectonic movements.

Isostatic changes in land elevation caused by glacial loading and unloading are the subject of many geological studies performed independently of the KBS program. A postglacial uplift of more than 800 m seems to be well-documented. The principal uncertainty regarding isostatic change is the question mentioned above, whether current changes in elevation are part of the last stage of isostatic rebound or are of tectonic origin.

In addition to isostatic effects, glaciation may create mechanical stresses which induce movement on existing fractures and create new fractures. Inferences about these effects are based on field observations and theoretical studies (e.g., Pusch, KBS TR-84). The general conclusion presented in KBS-II, and reiterated in an interview with Pusch, is that glaciation has negligible effect at depths greater than about 300 m.

Of immediate practical importance to the integrity of the canisters and repository are data on the present and past locations, magnitudes, and frequency of rock movements. Assessment of these factors is based on extrapolation from field observations and numerical modeling. The generalized conceptual model of fracture and fault distributions in areas investigated under KBS auspices is that of major fracture and fault zones, with spacings of kilometers which bound units of moderately fractured rock with fracture spacings of a few meters. The blocks of rock bounded by these mesoscale fractures contain microfractures which in many cases are sealed by secondary mineralization.

Knowledge of the location of major fracture zones is based on surface mapping, aided by observation of lineations on air-photos and satellite photos. Photo interpretation is especially useful in areas of low relief, such as Finnsjön. Determining the subsurface location of fracture zones may be aided by surface magnetic and electromagnetic measurements and logging of boreholes. Surface geophysical methods have proved only moderately successful in locating fracture zones in the subsurface.

Major fracture zones have been identified in the boreholes by changes in fracture density in cores, the presence of weathering products, higher permeabilities, and geophysical measurements. Discussions with personnel of the Swedish Geological Survey involved in borehole tests revealed that detection of major fracture zones from borehole geophysical methods was not always straightforward. Temperature, resistivity, and spontaneous potential logs were sometimes successfully correlated with these zones if they were highly permeable and intersected by the borehole. Where the fractures were filled by secondary minerals, however, induced polarity, natural gamma, and spontaneous potential logging were the more successful techniques. Efforts are under way to use induced polarity and electromagnetic methods to detect fracture zones which do not intersect the boreholes.

Determination of displacement along fracture zones has been possible in places where crosscutting relationships between geologic structures can be observed. In a few places Lagerbäck and Henkel (KBS TR-19) have measured Quaternary fault movements manifested as displacements in the glacial till cover. Measured total movements on major fault zones throughout Sweden range from a few meters to almost 2,000 m in a seismically active area in southern Sweden.

Data on the distribution of mesoscale fractures are based on surface mapping, observations in subsurface excavations, analysis of fracture densities in cores from test borings, and borehole geophysical measurements. In discussions with Survey personnel working in the Finnsjön area, a crude correlation between fractures observed at the surface and fracture frequency in cores was reported. Except in areas such as Stripa, where fractures can be observed in the subsurface, most knowledge about mesoscale fracture distribution is based on unoriented cores. Moderate success was reported in correlating borehole geophysical measurements with fractures observed in cores. Inasmuch as these fractures may be either filled or open, the correlation between measured permeability and fracture density is not straightforward.

The largest displacement observed on these mesoscale fractures was 30 cm, reported at the Finnsjön site. Measurements of displacement do not appear to be possible from the cores. As an extension of his view of postglacial tectonic activity in Sweden, Mörner has interpreted many small discontinuities in bedrock surfaces as being due to postglacial faulting. His interpretation, if correct, would imply much greater movement on these fractures than reported in KBS-II. The more conventional view of at least some of these features is that they are due to glacial plucking.

Data on small-scale, intrablock fractures are based on surface and subsurface mapping, examination of cores, and correlation with permeability and borehole geophysical measurements.

Predictions of the magnitude of displacements and distribution of strain between the fractures and faults of various scales as a result of glacial loading, tunneling, and heating are based on numerical modeling and interpretation of field observations. The modeling results show that future strains will be taken up by movement on the megascale and mesoscale fractures, and will not result in the development of new fractures. The models are of both the discrete block type and continuous finite element type. In discussions with Ove Stephansson, who has performed much of the modeling work, good results were reported in using borehole determinations of fracture density and stress fields to model stress effects in tunnels.

A.3. Properties and Integrity of the Bentonite Buffer

The second barrier to radionuclide migration is the highly compacted bentonite overpack surrounding the individual canisters and the bentonite-sand backfill in the tunnels. Proper functioning of the bentonite requires that it have suitable hydraulic, thermal, mechanical, and chemical properties, and that no deleterious changes in these properties occur in the repository environment. Experimental data on the properties of highly compacted bentonite are discussed by Pusch in KBS TR-74.

Data on the permeability of highly compacted bentonite are taken from preexisting experimentally, determined relationships between the density of bentonite and permeability as described in the literature. In the repository environment, the highly compacted bentonite buffer is expected to have a permeability of between 10^{-14} and 10^{-13} m/s. The bentonite-sand backfill material is reported to have a permeability of about 10^{-10} m/s. No measurements of permeability of the highly compacted bentonite are reported to have been performed under KBS auspices. During discussions with Pusch, several mechanisms which could increase the permeability of the bentonite were considered. (1) With regard to the possibility that heat from the canisters could cause dehydration of the bentonite, leading to shrinkage and fracturing, Pusch felt that this was very unlikely under repository conditions, based on his experience with the material. (2) Possible changes in permeability due to cation exchange were discounted on the basis of experiments in Pusch's laboratory. Although pure Na-bentonite is known to show a marked increase in permeability when Ca^{2+} is substituted for Na^{+}, the experiments demonstrated that the Na-Ca-bentonite from Wyoming which would be used in the repository was not significantly affected by this substitution. (3) Experimental data and theoretical calculations were cited to show that open fractures cannot develop if the bentonite is sheared because the bentonite is sufficiently plastic. (4) The possibility that silica cementation or conversion of the bentonite to zeolites might alter permeability was discounted by the observation that naturally occurring montmorillonite in fissures in crystalline rocks in Sweden showed no sign of silica cementation or zeolite formation. Alteration of bentonite to zeolite was thought by Arvid Jacobsson (personal interview) to require a pH greater than 10 and thus would not be possible given the predicted groundwater composition.

The thermal conductivity of the compacted bentonite and bentonite-sand backfill, both unsaturated and with various amounts of water added, has been experimentally determined under KBS auspices. The predicted range of thermal conductivity in compacted bentonite is 0.78 W/m-C° to 1.3

W/m-C°. Also, the temperature dependence of thermal conductivity has been experimentally determined (KBS TR-72).

The saturated and unsaturated load-bearing strength and swelling pressure of the compacted bentonite have been determined experimentally, and theoretical estimates of the shear strength of the compacted bentonite have been compared with results of the previously mentioned shearing experiments (KBS TR-76).

With regard to the swelling properties of the bentonite, Pusch was asked if sufficient swelling pressure could develop to fracture the rock surrounding the canisters. He replied that the swelling behavior is sufficiently well-known that the properties of the bentonite could be adjusted to reduce swelling pressure, if necessary. In addition, experiments have been conducted on the fracture sealing properties of the bentonite and the possibility of electrokinetic injection of bentonite suspensions into fractures (KBS TR-75).

Based on the very low values of permeability (10^{-13} m/s) and the range of hydraulic gradients anticipated to exist across the buffer, molecular diffusion has been predicted to be the principal mode of chemical transport through the buffer (KBS TR-79). Experimental determinations of the molecular diffusivity of compacted bentonite have been made with methane, hydrogen, strontium, and cesium (KBS TR-86 and TR-87). The measured diffusion coefficients ranged from 2×10^{-11} m^2/s for cations to 4×10^{-11} m^2/s for O_2 and anions. In personal discussions, Pusch expressed his opinion that the measured values may be somewhat high because of errors in the experimental technique used.

The ion exchange and sorption properties of the bentonite buffer are important factors in limiting the movement of radionuclides across the buffer. KBS has supported two studies of the sorption properties of the bentonite (KBS TR-55 and TR-98). In both these studies, batch experiments on powdered bentonite-sand mixtures have been performed to determine distribution coefficients for the following elements: Sr, Zr, Tc, I, Cs, Ce, Nd, Eu, Ra, Th, U, Np, Pu, and Am. The experiments have been performed at 50°C in aqueous solutions matching those predicted for the repository.

With respect to the chemical properties of the bentonite, heating to 425°C is proposed in the KBS-II report as a way to remove sulfides and organics which might be present and which could increase corrosion of the canisters. Experiments have shown that maintenance of this temperature for 15 hours is sufficient to eliminate sulfides and much of the organic matter, and does not adversely affect the properties of the bentonite (KBS TR-32). Pusch, however, stated that he would not recommend heating above 150°C.

Although somewhat outside the scope of the Subcommittee's review, some attention was also given to methods of handling the bentonite. Pusch stated that the handling and emplacement of compacted bentonite around the canisters was a straightforward matter and that the swelling of the buffer would seal any fractures produced by handling. The KBS engineers reported that scaled prototype experiments of backfilling techniques using standard shotcreting equipment to spray the bentonite-sand mixture had been successful. Complete filling of a model tunnel of circular cross-section was accomplished with a final backfill density of 1.5 g/cm^3.

A.4. Transport Properties of the Hydrogeologic Environment

Very slow groundwater velocities, sorption of radionuclides by the crystalline rock matrix, chemical reactions which precipitate radionuclides, and dilution effects have been proposed in KBS-II as factors which will prevent harmful quantities of radionuclides from reaching the biosphere should the first two barriers fail. In this appendix, only the data base related to the subsurface transport of radionuclides is considered.

A.4.1. Groundwater Transport

Assessment of the potential for convective transport of contaminants by groundwater depends on an ability to predict groundwater flow patterns and velocities. Groundwater movement is governed by the permeability of the material through which the water moves and by the hydrologic boundary conditions controlling the flow. Data on the flow porosity of the rock matrix are required to determine actual pore velocities which, combined with the flow pattern, determine the travel times of water particles from the repository to the ground surface.

Observational data on the permeability of crystalline rocks in the areas studied by KBS consist of permeability estimates from pumping tests and production records for existing shallow (less than 100 m) water supply wells, measurements in boreholes drilled for KBS, and a variety of tests performed in the subsurface at Stripa. Permeability data on crystalline rocks throughout Sweden have been developed from previous experience with water supply wells and measurements of water flow to subsurface excavations.

The techniques used and the results of permeability measurements in boreholes are reported in KBS TR-61. Those measurements are based on constant injection rate tests of sections of boreholes isolated by inflatable packers. In most cases the results were analyzed using a steady state analytical solution given by Mage (1967). This solution is equivalent to the Theim solution for steady state flow to a well in a uniform and isotropic porous medium. Discussions with personnel of the Swedish Geological Survey revealed that because of time limitations, no attempt was made to allow recovery of the hydraulic pressure in the packed intervals to its undisturbed level before injection was started. Test durations of 5 to 15 minutes were reported to be required to reach quasi-steady state conditions.

Some injection and recovery tests have also been analyzed using the Jacob approximation to the transient Theim solution. Comparison of the values of permeability determined by the two methods, according to Survey hydrologists, showed that in general the steady state method gives a slightly higher value than the transient method. The plots of transient test results available for inspection showed slope changes possibly related to boundary effects beginning after about 10 minutes of injection. To date, permeability measurements have been made on 42 boreholes at 5 test sites, to a maximum depth of about 575 m. Both vertical and inclined holes have been drilled, with deviations from the vertical of up to 40°. Typical values of permeability reported in the KBS documents for various rock types and structural settings are shown in Table A-2.

Tests designed to determine the permeability of larger volumes of rock than those measured by borehole tests have been performed and are in progress at Stripa. These tests include multiple hole injection tests and numerical model calibrations of the total water inflow to portions of tunnels. Laboratory measurements on very large cores have also been performed. The more recent data in large part were not available for inclusion in the KBS-II document.

Data on the vertical distribution of permeability in crystalline rocks at the KBS study areas are based on analysis of existing water supply wells, borehole tests, analysis of fracture density in cores from the boreholes, and geophysical measurements. The water supply wells for which data are given have depths up to about 100 m, which is the base of the zone generally believed to yield usable quantities of groundwater. The borehole injection tests have been performed on 2- to 3-meter packed intervals throughout the length of the boreholes. Some tests have been made on larger intervals, ranging from 50 m to nearly the whole length of the boreholes.

Since vertical fractures would not be well represented in vertical boreholes, the question of whether or not borehole measurements of permeability adequately measure the

TABLE A.2 Representative Values of Hydraulic Conductivity (Permeability)

Geologic Setting	Site	Tested Internal	K (m/s)
Good quality gneiss, >300 m depth	Karlshamn	2 m	10^{-8} to $<10^{-9}$
Good quality gneiss, >300 m depth	Finnsjön	2 m	10^{-5} to $<10^{-9}$
Uniformly fractured granite, >300 m depth	Kråkemåla	2 m	10^{-7} to $<10^{-9}$
Gneiss, <200 m depth	Finnsjön	2 m	10^{-5} to $<10^{-9}$
Crush zone, 100 m depth	Finnsjön	2 m	10^{-6} to $<10^{-8}$
Average gneiss from 20 to 500 m depth	Karlshamn	450 m	$<2 \times 10^{-12}$

SOURCE: KBS TR-61.

effect of vertical fractures was raised in critiques of the KBS-I report. During our discussions with Swedish researchers involved in this question, it was pointed out that many of the permeability measurements have been made in inclined boreholes and hence should yield representative data on both horizontal and vertical fractures. The large-scale permeability tests at Stripa should yield additional data on this question.

Although permeability in crystalline rocks depends primarily on the presence of open, interconnected fractures, the correlation between the fracture density observed in cores and the measured permeability seemed poor. In personal discussions, a better correlation was reported between the fracture density and permeability of the granitic rocks studied than of the gneissic rocks. The general observation was also made that for a given total fracture density, the permeability of granites was as much as 2 orders of magnitude higher than that for gneisses. Thus the structural history of a crystalline rock body is evidently important in determining its hydraulic properties.

Predictions of groundwater movement for the proposed active lifetime of a repository also require knowledge of the factors that control permeability and changes in permeability around the repository. The factors of importance in crystalline rocks in Sweden are changes in fracture density or "openness" due to tectonic, isostatic, and glacial stresses, changes in groundwater chemistry which may cause dissolution of fracture-filling minerals, and stresses created by the presence of the repository.

With regard to increased permeability due to fracturing caused by tectonic or isostatic rock movements, KBS-II concludes that those effects will not lead to increased fracturing in presently sound rock. The effects of glaciation are also predicted to extend only to depths less than 300 meters. The data on which these conclusions are based are essentially the same as those described in the section on the bentonite buffer.

Opening of fractures due to changes in groundwater chemistry has not been explicitly examined. KBS data relevant to this question are mineralogical analyses of the fracture-filling material and the previously discussed water chemistry data and predictions. The principal fracture-filling minerals are reported to be calcite and chlorite.

The effects of thermal stresses on the permeability of the rocks in the repository are reported to be minor. This conclusion is based on numerical rock mechanics models and experimental studies at Stripa. The rock mechanics models have in part been calibrated against the results of the in situ heating experiments at Stripa. Ove Stephansson reported good agreement between the stresses predicted by the models and the observed stress field at Stripa. Experimental studies are also in progress to determine the effects of tunneling on fracture density and permeability. The effects of swelling of the bentonite buffer have been discussed previously.

The permeability of crystalline rocks depends not only on fracture density but also on fracture geometry and degree of openness of the fractures. No empirical data on the effect of stress on these factors are reported in the KBS documentation. Estimates of the effects of thermal and excavation stresses on permeability are presented in KBS TR-54:05, part 1, based on existing analytical and empirical relationships between normal stress and permeability. The effects of shear stresses are stated to be very poorly known. In an interview, Stephansson expressed the opinion that, based on his rock-mechanics models, the greater the initial fracture density, the less is the strain taken up by each individual fracture and the smaller is the permeability change. New experimental data on the relationship between normal stress and permeability have been presented by Witherspoon et al. (SAC TR-17), based on core samples from Stripa. Additional data may be forthcoming from the in situ heater experiments recently completed at Stripa.

Prediction of actual groundwater velocities and travel times of contaminants requires knowledge of the effective flow porosity of the rock matrix. Empirical data on the porosity of rocks in the areas studied by KBS, as well as for crystalline rocks in general, are limited. Values of 1.2×10^{-3} to 1.6×10^{-3} have been determined by field tracer experiments on rock of shallow depth at Studsvik (KBS TR-110), and values ranging from 1×10^{-3} to 4×10^{-3} are reported from laboratory water saturation tests on drill-core samples. Similar laboratory measurements have been reported for rocks in Norway and in North America. A similar value was determined by a field tracer test in deep fractured crystalline rock in the United States by Webster et al. (1970). Indirect measurements based on empirical relationships between bulk rock electrical resistivity and porosity are reported to yield values of 5×10^{-3} based on borehole resistivity measurements. A value of 1.3×10^{-4} has been reported from in situ tracer tests at Stripa using fluorescent dyes (Lundström and Stille, SAC TR-2, 1978). Bulk density and neutron porosity logging of boreholes is planned but has not yet been performed because borehole diameters limit the kind of equipment that can be used.

Although data are presented in KBS-II to support a value of porosity of 10^{-2} to 10^{-3} for rocks at the proposed repository depth, individual authors of the KBS technical reports were divided on this question. Hydrologists at the Swedish Geological Survey thought the porosity values were somewhat high, and Lindblom used smaller values in his numerical modeling studies (KBS TR-54), basing his values on the relationship between permeability and porosity predicted by the Snow fracture-flow model. This model gives porosities of about 10^{-4} for rocks of low permeability. But Brotzen strongly defended values of the order of 1×10^{-3}, basing his opinion on the experimentally determined values and on probable deviations from the Snow model for rock at the repository depth. Additional tracer tests planned at Stripa will presumably clarify this question.

Data on changes in porosity caused by changes in the stress field around the repository are essentially the same as those described previously with respect to permeability.

Hydrodynamic dispersion of contaminants carried by groundwater not only results in dilution of the contaminants but also may cause irregularities in the migration front, so that some of the contaminants may have shorter travel times than those predicted by hydraulic models. Data on dispersivity in fractured crystalline rock are limited to values determined from tracer tests at Studsvik, where field tests showed dispersivities of 1 to 2 m, and at Stripa. The effects of dispersion have been included in the safety analysis in KBS-II only with regard to possible decreased arrival times; dilution effects have not been considered.

Definition of the groundwater flow pattern at a particular site requires a knowledge of the hydraulic boundary conditions governing flow. For the areas studied by KBS, these boundaries consist of the elevation of the water table (including streams and lakes), boundary fluxes caused by regional hydraulic gradients, and lithologic and structural discontinuities across which very large changes in permeability may occur.

Except where surface water bodies intersect the water table, very few observational data are available on the position of the water table at the sites studied. Almost no data are available on regional gradients. A limited amount of water level data are available from existing shallow wells at Finnsjön, and installation of piezometers for collection of additional data is reported to be in progress. To date, no static water levels (shut-in pressures) have been measured in the deep boreholes which might be used to compute regional gradients. Shut-in pressures are being measured in test borings in the Stripa test facility. In estimating regional fluxes at Finnsjön and Kråkemåla, gradients of .008 and .001, respectively, were used.

Data on lithologic discontinuities are based on surface mapping, air-photo interpretation, test borings, and surface and borehole geophysical measurements. Data on structural boundaries have been described previously with respect to rock movements. Permeability measurements on structural and lithologic discontinuities have been made at Stripa and at places where the major fault zones intersect boreholes. Although an impermeable lower boundary has been assumed in some of the modeling studies, the lower boundary conditions of the flow systems in the areas studied are essentially unknown because permeability measurements have only been made to depths of 500 to 600 m.

The possibility that the boundary conditions of a repository site may change either because of changes in topography or because of the hydrologic effects of glaciation was discussed with several investigators of KBS studies. With the exception of Nils-Axel Mörner, whose viewpoint has been described previously, none anticipated large changes in topography due to glacial scouring. The maximum decline in sea level, the ultimate boundary of most flow systems, is believed to be limited to 20 m because this is the depth of the bedrock ridge separating the Baltic Sea from the North Sea. Isostatic changes in land elevation, although large in magnitude, are spread over large areas and do not change regional gradients significantly.

Also discussed were the possibilities that large hydraulic gradients might be produced by pressurized water at the base of a glacier, by glacial loading and release of pore water from compressed sediments, or by the presence of meltwater lakes. These questions remained unanswered because of uncertainty about the physical processes involved and the magnitude of the hydrologic effects. The need to consider the possible effects of climatic change has been largely circumvented by the conservative assumption that the water table coincides with the present land surface in computing flow rates and travel times.

Existing groundwater flow patterns and flow rates for the areas studied cannot be deduced directly from currently available data. Indirect data on travel times are provided by carbon-14 age determinations for water samples collected in the deep boreholes and at Stripa (KBS TR-62). The computed ages, which include corrections for C-14/C-13 fractionation, variations in atmospheric C-14, and contributions of carbon from inorganic carbonates, range from 2,000 to 11,000 years BP. The carbonate contribution from calcite dissolution was estimated to furnish less than 20 percent of total carbonate content.

Two extensive groundwater modeling studies were sponsored by KBS to describe regional groundwater flow patterns and local groundwater movement near the canisters and repository (KBS TR-47 and TR-54). The results of both studies must be regarded as semiquantitative because of a lack of sufficient data on hydraulic parameters and boundary conditions. The modeling results for regional flow patterns given in KBS-II are based primarily on KBS TR-47, which was initiated after TR-54. Evaluation of the local circulation patterns in the repository are based on KBS TR-54. As stated in KBS-II, both of these modeling studies were prepared before borehole permeability tests had been completed. The models used in both these studies are based on the assumption that fractured rocks can be modeled as continuous porous media.

The modeling studies described in KBS TR-54 are 2-dimensional and are based on existing finite element models, slightly modified to handle problems of heat transport and rock mechanics. These models describe the flow patterns around individual canisters and repository tunnels, and also include generalized models of regional flow patterns.

The modeling studies in KBS TR-54 were performed principally to examine the relative importance of various factors which may influence groundwater flow. Coupled conductive and convective heat transport models were used to study the local and regional effects of waste age, repository ventilation, and emplacement sequence on repository temperatures.

Generalized regional flow models were used to estimate the effects of permeability distribution, anisotropy, regional gradients, and fracture zones on flow through the repository. Both uniform and exponentially decreasing permeability distributions were tested, and porosity was coupled to permeability by using Snow's fracture flow model. This assumption resulted in values of porosity about 1 order of magnitude lower than those used in KBS TR-47 and correspondingly shorter travel times.

A fully coupled model was used to study thermally induced groundwater movement on both a local and regional scale. As with most attempts to model this process, numerical instabilities were encountered. The modeling results indicate that if regional groundwater fluxes are very small, thermal circulation cells can develop which extend from the repository to the water table. For regional gradients as low as 2×10^{-3}, however, the thermal cells spread horizontally and do not extend to the water table. In the absence of regional flow, thermally induced upward fluxes of 10^{-12} to 10^{-11} m/s (less than 10^{-3} cm/year) were computed in KBS TR-54.

None of the models used in KBS TR-54 is calibrated. Lindblom, however, reported that he has used these models successfully to estimate inflow to tunnels in work unrelated to the KBS study.

Conclusions about regional flow patterns and travel times presented in KBS-II are based largely on KBS TR-47. In this report, an analytical solution to the 2-dimensional potential-flow problem was used to study the effects of topography, permeability distributions, and geometry on regional flow patterns. Solutions are also presented for natural flow patterns in the Finnsjön area, but these models cannot be considered calibrated because the data base is limited. A 2-dimensional numerical solution for groundwater flow with a free surface was used to estimate the depressions of the water table due to dewatering of the repository site.

A large 3-dimensional finite-element model of the Finnsjön site was developed for KBS TR-47. The model covers an area of 30 km^2 and extends to a depth of about 1,500 m. The model is divided into 5 horizontal layers. Major fracture zones are represented in this model by 50 m wide bands with permeabilities 2 orders of magnitude greater than the surrounding rock. The value of hydraulic conductivity assigned to these zones was scaled to allow for the fact that 50 m is probably greater than the width of the actual fault zone. Some numerical difficulties were reported to be caused by inclusion of the fault zones in the model. An exponential decrease in permeability and uniform porosity of 10^{-3} were used.

This model was used to study the flow patterns at Finnsjön and to estimate travel times and the age of groundwater at repository depth. As with the other models, the available hydrogeologic data were not adequate to calibrate this model. The ages of groundwater at a depth of 500 m determined from this model range from about 100 years in recharge zones to greater than 10^5 years in discharge areas. A rough calibration of the model might be possible by comparing computed groundwater ages with measured C-14 ages at various points in the aquifer.

As stated previously, all of these modeling studies assume that fractured rocks can be modeled as continuous porous media. When questioned about the appropriateness of this assumption, both Lindblom (KBS TR-54) and Thunvik (KBS TR-47) acknowledged problems with this approach, but both felt the results were acceptable for regional flow, if questionable for local flow. Thunvik said he is currently developing a discrete fracture model against which the results of the porous media models can be compared.

A.4.2. Chemical Transport Retardation Factors

The transport of radionuclides by groundwater can be prevented or retarded if these species are precipitated or react with existing minerals, or are sorbed by the rock matrix. Actinides such as U, Np, and Pu have been predicted to exist as practically insoluble species in the range of groundwater composition predicted for the repository environment. This prediction is based largely on theoretical equilibrium calculations using the water chemistry data described earlier. Analogy is also made with existing studies of uranium and plutonium transport.

The possibility of radionuclide transport by organic complexing agents has been considered to the extent that estimates of total transport by this mechanism were made, based on the fulvic acid content of groundwater reported in KBS TR-88. Radionuclides sorbed by colloidal particles may also travel with the velocity of groundwater. Very low natural colloid contents have been measured in groundwater samples from depth at Finnsjön. Experimental data on the bentonite buffer as a source of colloids reported in KBS TR-103 imply that the bentonite will not form colloids in the range of water chemistry predicted for the repository.

Experimental data on sorption of radionuclides are presented in KBS TR-55, 98, and 110. In these reports, equilibrium distribution coefficients for Sr, Zr, Tc, I, Cs, Ce, Nd, Eu, Ru, Th, U, Np, Pu, and Am have been determined from laboratory experiments with powdered granitic rocks. Sorption of Sr, Cs, and Am on chlorite, silt, and old and fresh granitic rock surfaces has also been studied experimentally. Some experimentally determined values are shown in Table A-3. Field tracer tests performed at shallow depths at Studsvik using Br, Tc, I, Sc, Sr, Sn, Nd, Na, and Cs, as well as column and batch tests for certain of the nuclides, are reported in KBS TR-110.

Although sorption of these radionuclides on the solid rock matrix will not permanently prevent their migration, sorption can greatly retard the movement of sorbed species relative to nonsorbed species. If the specific surface area of the rock matrix is known, then the distribution coefficients can be used to compute a retention factor for each species. Computed retention factors are reported in KBS-II and the retardation effect has been included in the safety analysis. Retention factors shown in KBS-II range from a maximum of 6.1×10^5 for americium under reducing conditions to 1.0 for technetium and iodine under oxidizing conditions.

A.4.3 Other Factors Affecting the Impact of Radionuclide Migration

This summary of the KBS-II technical data base has dealt only with the subsurface geological, hydrological, and geochemical factors which may affect the integrity of the

TABLE A.3 Experimentally Determined Distribution Coefficients (K_d) Reported in KBS Technical Reports 55 and 98

			Experimental Conditions				
Element	Report	Contact Time	Redox Conditions	Temp. (°C)	Final Conc. (m M/l)	Aqueous Sol. Conc. (mg/d)	Kd (m^3/kg)
Ni	98	24 hours	Red.	25	–	1105	0.32
Sr	55	–	Oxid.	25	$<10^{-5}$	293	0.0079
Sr	98	<7 days	Red.	25	$<10^{-5}$	1105	0.0063
Zr	55	–	Oxid.	25	$<10^{-5}$	293	1.3
Zr	98	<7 days	Red.	25	$<10^{-5}$	1105	1.3
Tc	55	–	Oxid.	25	$<10^{-5}$	293	0.0005
I	55	–	Oxid.	25	$<10^{-5}$	293	0.0008
Cs	55	–	Oxid.	25	$<10^{-5}$	293	0.13
Cs	98	<7 days	Red.	25	$<10^{-5}$	1105	0.063
Ce	55	–	Oxid.	25	$<10^{-5}$	293	1.3
Ce	98	<7 days	Red.	25	$<10^{-5}$	1105	6.3
Nd	55	–	Oxid.	25	$<10^{-5}$	293	4.0
Nd	98	<7 days	Red.	25	$<10^{-5}$	1105	2.0
Eu	55	–	Oxid.	25	$<10^{-5}$	293	7.9
Ra	98	<7 days	Red.	25	$<10^{-5}$	1105	0.1
Th	98	<7 days	Red.	25	$<10^{-5}$	1105	0.8
U	98	<7 days	Red.	25	$<10^{-5}$	1105	0.0063
Np	98	<7 days	Red.	25	$<10^{-5}$	1105	0.025
Pu	98	<7 days	Red.	25	$<10^{-5}$	1105	0.063
Am	98	<7 days	Red.	25	$<10^{-5}$	1105	5.0

repository. Although numerous other factors may affect the dispersal of radionuclides in the biosphere and are discussed in KBS-II reports, their consideration was judged to be outside the scope of this review.

Appendix B

METALLURGICAL DATA BASE TO SUPPORT THE KBS-II PLAN

Ugo Bertocci

B.1. Introduction

This appendix describes my understanding of the corrosion issues involved in the Swedish plan for burying spent nuclear fuel rods after conversations with Mattson and Grenthe as well as extensive discussions with one member of the KBS-II Subcommittee, E. Verink. The questions asked and answers given by the Swedish scientists, as well as my comments, are incorporated in this appendix. Unfortunately, G. Wranglén, who filed a dissenting conclusion to the KBS-II report, was not available for an interview.

Although I have read or partially examined other KBS reports, the most important one for understanding corrosion issues is KBS TR-90.

B.2 Context of the corrosion problem

As stated by the Swedish scientists, the problem put to them was to establish that the canister as designed had a service life of at least 10^6 years. The canister thickness of 200 mm was decided upon before the corrosion experts were consulted. According to them, that thickness was chosen in order to reduce radiolysis outside the canister to a negligible amount.

The task of the corrosion experts was therefore to verify that such a container would last for the prescribed time, given the environment specified by the geologists and hydrologists. That environment would consist of groundwater with a composition as given in KBS TR-90 (reproduced as Table A-1 in Appendix A), and having a flow rate of 0.2 l/m^2 year.

Some environmental transients also had to be considered, such as a specified temperature excursion between approximately 100°C and 25°C and higher oxygen availability during the period when the access tunnels, after backfilling, had not reached a steady state. The possibility of seawater seepage into the repository also had to be taken into account.

There is a certain weakness in the logic of the exercise. If the main effect of radiolysis is to accelerate corrosion, it would perhaps have been more reasonable to try to determine the minimum thickness of copper which could withstand failure by corrosion, including that caused by radiolysis, for a million years. No optimization was attempted to reduce the amount of copper needed for the canister. Consequently, the corrosion experts did not attempt to forecast the canister's mode of failure at the end of its service life.

B.3. Methods of approach

Verification of the stability of the canister for the prescribed time was approached first by determining whether copper is thermodynamically immune to attack. To this end, a detailed examination of all, or nearly all, equilibria involving copper and the species present in the groundwater was carried out.

In conversation with Grenthe, the issue was raised as to whether quantities such as the redox potential (expressed in the report as pe) could be calculated. The answer was that, in principle, everything including pH and pe could be deduced once the solution composition was assigned. This, however, would have entailed the solution of a very large and complicated set of equations, and neither an adequate computer program nor the time for developing it was available. Therefore, the solution, as shown in the concentration-pe diagrams in TR-90, was to assign some parameters (such as pH) and to calculate the concentrations of various species in equilibrium as a function of pe. Examination of these plots, constructed for various conditions and at two temperatures, enables one to decide whether metallic Cu is thermodynamically stable and which reactions are the most probable.

The value of the redox potential, or pe, of the groundwater was thought to be mainly determined by the Fe^{2+}/Fe^{3+} equilibrium. This conclusion has been supported by experimental measurements in two locations. However, the Swedish scientists made no attempt to assess the effect of an increase in temperature on the pe of the groundwater.

Additional calculations were made concerning nitrogen compounds and increased chloride concentration caused by possible seawater seepage into the repository. These calculations are somewhat sketchy. Only changes in chloride were taken into account, and no attempt was made to estimate the effect of seawater on pH, pe, or other components. Questions were specifically asked as to why the formation of copper-ammonia complexes was omitted in the calculations. In reply, Grenthe carried out an approximate calculation to estimate the concentration of $Cu(NH_3)$, which turned out to be small but not insignificant--about half that of the most concentrated ion, $CuCl_2^-$.

Many of the minor details of the thermodynamic analysis become rather unimportant because the conclusion reached was that although there was a good probability that Cu was immune to attack most of the time, immunity for the entire service life of the canisters could not be unequivocally proven. Examination of the stability of the canisters then took a different approach.

The second part of the analysis consisted of calculating the total amount of reactants--oxygen or sulfide ions--that could reach the canisters during their service life. Steady state content in the groundwater was considered, as well as initial transients when oxygen contained in the bentonite would be available. The effect of the small amount of radiolysis that would be caused by radiation escaping from the container was also taken into account.

A very important assumption was made regarding the amount of sulfide available. Although thermodynamically the reduction of sulfate to sulfide by reaction with copper metal is possible, the sulfate present was not considered a source of sulfide except to the extent that it could be reduced by bacterial action, which was limited by the amount of organic matter available in the groundwater to serve as nutrient for sustaining bacterial life.

As an additional possible mechanism for corrosion, the transport of copper due to variation of solubility of cuprous compounds with temperature was considered. Another thermal effect, the change with temperature of the equilibrium,

$$2\ Cu^+ \rightleftharpoons Cu + Cu^{2+},$$

might lead to disproportionation of Cu^+ in colder areas and an opposite reaction in warmer areas. In answer to a question as to why this possibility was not considered, it was stated that in the presence of sulfides, calculations show that the concentration of Cu^+ is so low that these corrosion mechanisms have negligible effect.

From calculations on the availability of reactants it was concluded that corrosion of the canisters in 10^6 years, even if Cu was not completely immune to attack, would be minor and would not endanger its service life.

The Swedish scientists also examined data concerning the corrosion of Cu buried in various soils, published as a U.S.

National Bureau of Standards report by Denison and Romanoff. They manipulated the data in various ways to obtain an equation for the corrosion rate of copper, but the only use made of these data was for estimating a pitting factor. It was concluded that the tendency to pitting of Cu was not very pronounced and decreased with time, so that a pitting factor of 25 was a very pessimistic estimate and very unlikely to be exceeded. Nevertheless, such a pitting factor would not cause perforation of the canisters in 10^6 years.

Finally, stress-corrosion cracking was dismissed as a possible mode of failure for the copper containers for two reasons, the first that OFHC copper has little susceptibility to stress-corrosion cracking, and the second that the material would tend to relax and would not maintain the stresses necessary to cause cracking.

B.4. Reliability of the Predictions

In the analysis of the thermodynamic equilibria, all calculations were done with competence and care. Questions were asked about the methods used for treating the data, and all answers showed that the analysis had been carried out very thoroughly. Since the reliability of the calculations is based on the quality of the data in the literature on the species and the reactions involved, it is important to state that the data base for copper is in general excellent, the largest uncertainties being of the order of a few kcal for the free enthalpy of formation of some of the oxides. It can therefore be concluded from this analysis that a number of possible causes of failure, such as corrosion due to carbonates or chlorides, can be safely excluded.

Some possible reactions, such as formation of ammonia complexes, were not examined in detail. However, as long as the composition and the redox potential of the water in the bedrock is in the range assumed for the analysis, it would be very hard to find a major system of possible corrosion reactions that has been neglected.

Fault can be found with the fact that variations of the equilibrium potential for the Fe^{2+}/Fe^{3+} couple with temperature were not considered. However, it must be borne in mind that the conclusion of the thermodynamic analysis was only negative in that total immunity for copper could not be established. The thermodynamic analysis can therefore be considered irrelevant for the purpose of establishing the service life of the canisters except insofar as it builds confidence that important reaction paths were not overlooked.

The calculations concerning the amount of reactant available are very simple, and no errors were found. Their degree of reliability is the same as that of the assumptions based on geological evidence that groundwater composition and flow rate will always be between the limits given and are not therefore subject to argument from the point of view of corrosion science. It might only be observed that the amount of copper that would corrode is so small compared to the total mass of each canister that conditions much worse than those envisaged could be accepted without reducing the canisters' useful life below 10^6 years.

Since the design of the repository might lead to the conclusion that corrosion would be limited to the upper part of the canister, a calculation was made based on the assumption that all copper would be removed at the top. Even in this case the depth of attack, assumed uniform, would only be about 13 mm. With a pitting factor of 25, penetration would be achieved in about 6 x 10^5 years.

An important assumption is that sulfates cannot be reduced to sulfides in the absence of bacteria. If sulfides could be produced in quantity from sulfate ion, corrosion of copper would be rapid, as emphasized by Wranglén. Indeed, a linear extrapolation of the corrosion data of Denison and Romanoff to sulfide-rich soils would lead to the conclusion that complete sulfidation through 200 mm of copper could occur in a time as short as 10^4 years. But scientific evidence, both chemical and geological, seems conclusive that reduction of sulfate in the absence of bacteria would not be appreciable even after several million years. Although sulfate-reducing bacteria might be present in a bedrock repository, their growth would be limited by the scarcity of organic matter, and the amount of sulfide produced would be very small.

The possibility of stress-corrosion cracking was apparently not given much consideration. When questioned, Mattson replied that OFHC copper did not exhibit such cracking. When it was pointed out to him that a number of researchers had found stress corrosion cracking in pure copper and in different environments, he elaborated on the two reasons, as stated in the preceding section, why it had not been considered a threat.

Finally, since Prof. Wranglén, regrettably, was not available for discussion, I have examined his dissenting opinion in TR-90, but it seems to me that corrosion stability was less an issue than his doubts that the geological conditions postulated will prevail for the necessary length of time. That argument, however important, is outside the scope of this appendix.

REFERENCES

KBS Technical Reports

KBS TR 17: The gravity field in Fennoscandia and postglacial crustal movements. Arne Bjerhammar, August 1977

KBS TR 18: Rörelser och instabiliteter i den svenska berggrunden. (Movements and instability in the Swedish bedrock.) Nils-Axel Mörner, August 1977

KBS TR 19: Studier av neotektonisk aktivitet i mellersta och norra Sverige, flygbildsgenomgång och geofysisk tolkning av recenta förkastningar. (Studies of neotectonic activities in central and northern Sweden, review of aerial photographs and geophysical interpretation of recent faults.) Robert Laberbäck, Herbert Henkel, Geological Survey of Sweden, September 1977

KBS TR 20: Tektonisk analys av södra Sverige, Vättern - Norra Skåne. (Tectonic analysis of southern Sweden, Lake Vättern - Northern Skåne.) Kennert Röshoff, Erik Lagerlund. University of Lund and Luleå Institute of Technology, September 1977

KBS TR 21: Earthquakes of Sweden 1891 - 1957, 1963 - 1972. Ota Kulhánek, Rutger Wahlström. University of Uppsala, September 1977

KBS TR 25: Blekinge kustgnejs. Geologi och hydrogeologi. (The Blekinge coastal gneiss, Geology and hydrogeology.) Ingemar Larsson, Royal Institute of Technology; Tom Lundgren, Swedish Geotechnical Institute; Ulf Wiklander, Geological Survey of Sweden. Stockholm, August 1977

KBS TR 32: Egenskaper hos bentonitbaserat buffertmaterial. (Properties of bentonite-based buffer material.) Roland Pusch, Arvid Jacobsson. Luleå Institute of Technology, 1978-06-10

KBS TR 33: Required physical and mechanical properties of buffer masses. Roland Pusch. Luleå Institute of Technology, 1977-10-19

KBS TR 35: Project for the handling and storage of vitrified high-level waste. Saint Gobain Techniques Nouvelles, October 1977

KBS TR 36: Sammansättning av grundvatten på större djup i granitisk berggrund. (Composition of groundwater deep down in granitic bedrock.) Jan Rennerfelt. Orrje & Co., Stockholm, 1977-11-07

KBS TR 37: Hantering av buffertmaterial av bentonit och kvarts. (Handling of buffer material of bentonite and quartz.) Hans Fagerström, VBB; Björn Lundahl, Stabilator. Stockholm, October 1977

KBS TR 41: Säkerhet och strålskydd inom kärnkraftområdet. Lagar, normer och bedömningsgrunder. (Safety and radiation protection in the field of nuclear power. Laws, standards and grounds for evaluation.) Christina Gyllander, Siegfried F. Johnson, Stig Rolandson. AB Atomenergi and ASEA-ATOM, 1977-10-13

KBS TR 47: Investigations of groundwater flow in rock around repositories for nuclear waste. John Stokes, Roger Thunvik. Department of agricultural hydrotechnics, Royal Institute of Technology, 1978-02-28

KBS TR 54: Groundwater movements around a repository.

- 54:01 Geological and geotechnical conditions. Håkan Stille, Anthony Burgess, Ulf E. Lindblom. Hagconsult AB, September 1977
- 54:02 Thermal analyses. Part 1: Conduction heat transfer. Part 2: Advective heat transfer. Joe L. Ratigan. Hagconsult AB, September 1977
- 54:03 Regional groundwater flow analyses. Part 1: Initial conditions. Part 2: Long term residual conditions. Anthony Burgess. Hagconsult AB, October 1977
- 54:04 Rock mechanics analyses. Joe L. Ratigan. Hagconsult AB, September 1977
- 54:05 Repository domain groundwater flow analyses. Part 1: Permeability

perturbations. Part 2: Inflow to repository. Part 3: Thermally induced flow. Joe L. Ratigan, Anthony Burgess, Edward L. Skiba, Robin Charlwood. Hagconsult AB, September 1977

54:06 Final report. Ulf Lindblom et al. Hagconsult AB, October 1977

KBS TR 55: Sorption av långlivade radionuklider i lera och berg. (Sorption of long-lived radionuclides in clay and rock.) Part 1. Bert Allard, Heino Kipatsi, Jan Rydberg. Chalmers University of Technology, 1977-10-10

KBS TR 59: Tectonic Lineaments in the Baltic from Gävle to Simrishamn. Tom Flodén. University of Stockholm, 1977-12-15

KBS TR 60: Förarbeten till platsval, berggrundsundersökningar. (Preliminary studies for site choice, bedrock studies.) Sören Scherman.

Berggrundvattenförhållanden i Finnsjöområdets nordöstra del. (Groundwater conditions in the northeastern sector of the Finnsjö district.) Carl-Erik Klockars, Ove Persson. Geological Survey of Sweden, January 1978.

KBS TR 61: Permeabilitetsbestämningar. (Permeability determinations.) Anders Hult, Gunnar Gidlund, Ulf Thoregren.

Geofysisk borrhålsmätning. (Geophysical borehole survey.) Kurt-Åke Magnusson, Oscar Duran. Geological Survey of Sweden, January 1978.

KBS TR 62: Analyser och åldersbestämningar av grundvatten på stora djup. (Analyses and age determinations of groundwater at great depths.) Gunnar Gidlund. Geological Survey of Sweden, 1978-02-14.

KBS TR 63: Geologisk och hydrogeologisk grunddokumentation av Stripa försöksstation. (Geological and hydrogeological documentation at the Stripa research station.) Andrei Olkiewicz, Kenth Hansson, Karl-Erik Almén, Gunnar Gidlund. Geological Survey of Sweden, February 1978.

KBS TR 66: Några synpunkter på mekanisk säkerhet hos kapsel för kärnbränsleavfall. (Viewpoints on the mechanical reliability of a canister for nuclear waste.) Fred Nilsson. Royal Institute of Technology, Stockholm, February 1978.

KBS TR 72: Värmeledningsförsök på buffertsubstans av kompakterad bentonit. (Thermal conductivity tests on buffer material of compåcted bentonite.) Sven Knutsson. Luleå Institute of Technology, 1977-11-18.

KBS TR 73: Self-injection of highly compacted bentonite into rock joints. Roland Pusch. Luleå Institute of Technology, 1978-02-25.

KBS TR 74: Highly compacted Na bentonite as buffer substance. Roland Pusch. Luleå Institute of Technology, 1978-02-25.

KBS TR 75: Small-scale bentonite injection test on rock. Roland Pusch. Luleå Institute of Technology, 1978-03-02

KBS TR 76: Experimental determination of the stress/strain situation in a sheared tunnel model with canister. Roland Pusch. Luleå Institute of Technology, 1978-03-02

KBS TR 79: Transport of oxidants and radionuclides through a clay barrier. Ivars Neretnieks. Royal Institute of Technology, Stockholm, 1978-02-20

KBS TR 80: Utdiffusion av svårlösliga nuklider ur kapsel efter kapselgenombrott. (Diffusion of poorly soluble nuclides from a canister following canister penetration.) Karin Andersson, Ivars Neretnieks. Royal Institute of Technology, Stockholm, 1978-03-07

KBS TR 81: Tillverkning av kopparkapsel för slutförvaring av använt bränsle. (Fabrication of copper canisters for final storage of spent nuclear fuel.) Jan Bergström, Lennart Gillander, Kåre Hannerz, Liberth Karlsson, Bengt Lönnerberg, Gunnar Nilsson, Sven Olsson, Stefan Sehlstedt. ASEA, ASEA-ATOM, June 1978

KBS TR 87: Diffusivitetsmätningar i våt lera Na-lignosulfonat, Sr^{2+}, Cs^{+}. (Diffusivity measurements in wet clay, Na-lignosulphonate Sr^{2+}, Cs^{+}.) Ivars Neretnieks, Christina Skagius. Royal Institute of Technology, Stockholm, 1978-03-16.

KBS TR 88: Groundwater chemistry at depth in granites and gneisses. Gunnar Jacks. Royal Institute of Technology, Stockholm, April 1978.

KBS TR 89: Inverkan av glaciation på deponeringsanläggning belägen i urberg 500 m under markytan. (Influence of glaciation on a waste repository situation in primary bedrock 500 m below the surface of the ground.) Roland Pusch, Luleå Institute of Technology, 1978-03-16

KBS TR 90: Copper as an encapsulation material for unreprocessed nuclear waste - evaluation from the viewpoint of corrosion. Final report, 1978-03-31. The Swedish Corrosion Research Institute and its reference group

KBS TR 97: Colloid chemical aspects of the "confined bentonite concept." Jean C. Le Bell. Institute of Surface Chemistry, 1978-03-07

KBS TR 98: Sorption av långlivade radionuklider i lera och berg Del 2. (Absorption of long-lived radio nuclides in clay and rock Part 2.) Bert Allard, Heino Kipatsi, Börje Torstenfelt. Chalmers University of Technology, 1978-04-20

KBS TR 103: Some aspects of colloids as a means for transporting nuclides. Ivars Neretnieks. Royal Institute of Technology, Stockholm, 1978-08-08

KBS TR 104: Finit elementanalys av bentonitfyllt bergförvar. (Finite element analysis of bentonite-filled rock repository.) Ove Stephansson, Kenneth Mäki, Tommy Groth, Per Johansson. Luleå Institute of Technology, July 1978

KBS TR 110: In situ experiments on nuclide migration in fractured crystalline rocks. Ove Landström, Carl-Erik Klockars, Karl-Erik Holmberg, Stefan Westerberg. Studsvik Energiteknik and The Geological Survey of Sweden, July 1978

KBS TR 120: Some notes in connection with the KBS studies of final disposal of spent fuel. Ivars Neretnieks. Royal Institute of Technology, September 1978

Other KBS Documents

Redögorelse för granskning genom utländsk expertis av rapporten kärnbränslecykelns slutsteg, förglasat avfall från upparbetning. (Report on review through foreign expertise of the report handling of spent nuclear fuel

and final storage of vitrified high level reprocessing waste). Industridepartementet, December 1978

Kompletterande geologiska undersökningar. Kärnbränslecykelns slutsteg: förglasat avfall från upparbetning. Not dated; probably March 1979

Material angående SKI:s beredning av KBS' geologiska kompletteringsrapport. Kärnbränslecykelns slutsteg: förglasat avfall från upparbetning. Not dated; probably March 1979

<u>Technical Reports of the Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock</u>

SAC TR-2: Large scale permeability test of the granite in the Stripa mine and thermal conductivity test. L. Lundström and H. Stille, July 1978

SAC TR-8: Mining methods used in the underground tunnels and test rooms at Stripa. B. Anderson and P.A. Halén, August 1978

SAC TR-9: Theoretical temperature fields for the Stripa heater project, vol. 1. T. Chan, N.G.W. Cook, C.F. Tsang, September 1978

SAC TR-10: Mechanical and thermal design considerations for radioactive waste repositories in hard rock. N.G.W. Cook and P.A. Witherspoon, October 1978

SAC TR-11: Full-scale and time-scale heating experiments at Stripa: preliminary results. N.G.W. Cook and M. Hood, December 1978

SAC TR-12: Geochemistry and isotope hydrology of the groundwaters in the Stripa granite. Results and preliminary interpretation. P. Fritz, J.F. Barker, J.E. Gale, April 1979

SAC TR-16: Preliminary report on geophysical and mechanical borehole measurements at Stripa. P. Nelson, B. Paulson, R. Rochiele, L. Anderson, T. Schrauf, W. Hustrulid, O. Duran, K.A. Magnuson, May 1979.

SAC TR-17: Observations of a potential size-effect in experimental determination of the hydraulic properties of fractures. P.A. Witherspoon, C.H. Amick, J.E. Gale, K. Iwai, May 1979

Other References

Bath, M. Earthquakes in Sweden in 1951 to 1976; and Energy and tectonics of Fennoscandian earthquakes. Typescripts from Department of Seismology, University of Uppsala, 1978

Davis, S.N. Depth-dependent hydrologic characteristics of dense bedrock: the 0- to 500-meter interval. Unpublished manuscript, presented at Workshop on Hydrologic Characteristics of Deep Crystalline Bedrock, Tucson, Arizona, October 17-19, 1979.

Denison, I. and Romanoff, M. Soil-corrosion studies 1946 and 1948: Copper alloys, lead and zinc. Jour. Research, Natl. Bur. Standards, vol. 44, p. 259 (1950)

Escalente, E. and Kruger, J. Jour. Electrochem. Soc., Vol. 118, p. 1062, 1971

Germanov, A.I. and Panteleyev, V.M. Behavior of organic matter in groundwater during infiltrational diagenesis. Intl. Geol. Review, vol. 10, pp. 826-832, 1968

MacDonald, D.D., Syrett, B.C., Wing, S.S. The corrosion of Cu-Ni alloys 706 and 715 in flowing seawater. II - Effect of dissolved sulfide. Corrosion, vol. 35, No. 8, pp. 367-378, 1979

Mage, A. Diamond drilling for foundation exploration. Civil Engin. Transactions, Inst. of Engineers, Australia, pp. 95-100, April 1967

Pačes, T. Chemical equilibria and zoning of subsurface water from the Jáchymov ore deposit, Czechoslovakia. Geochim. Cosmochim. Acta, vol. 33, pp. 591-609, 1969

Parizek, R.R. Continental glaciation: the integrity of nuclear waste repositories, with emphasis on KBS-II. Unpublished manuscript; copy to be made available with this review.

Pednekar, S.P., Agrawal, A.K., Chaung, H.E., Staehle, R.W. Jour. Electrochem. Soc., vol. 126, p. 701, 1979.

Pugh, E.N., Montague, W.G., Westwood, A.R.C. Corrosion Science, vol. 6, p. 345, 1966

Suzuki, Y. and Hisamatsu, Y. Boshoku Gijutsu, vol. 23, p. 29, 1974

Syrett, B.C. Corrosion, vol. 33, No. 7, pp. 257-262, 1976

Webster, D.S., Proctor, J.F., Marine, I.W. Two-well tracer test in fractured crystalline rock. U.S. Geol. Survey, Water-Supply Paper 1544-I, 22p, 1970