A Review of the Swedish KBS-3 Plan for Final Storage of Spent Nuclear Fuel (1984)

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A newly formed NAS/NRC Panel reviews the Swedish KBS-3 Plan for the final storage of spent nuclear fuel, considers new supporting information developed by KBS since it published its 1978 KBS-2 Plan, and concludes that there is reasonable assurance that a waste repository built according to the plan will not permit an unacceptable rate of radionuclide escape. Principal review emphasis is placed upon geological repository features of the storage system--particularly on overall canister and repository design and on the calculations and supporting data related to waste form dissolution and to radio nuclide migration from the point of emplacement through the surrounding geosphere.

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Panel for the Review of the Swedish KBS-3 Plan
Board on Radioactive Waste Management
Commission on Physical Sciences,
Mathematics, and Resources
National Research Council

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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OFFICE OF THE CHAIRMAN

March 1, 1984

Ms. Birgitta Dahl, Energy Minister
Ministry of Industry
S-103 33 Stockholm
Sweden

Dear Ms. Dahl:

The National Research Council of the National Academy of Sciences has completed its review of those portions of the KBS-3 plan for final storage of spent nuclear fuel that relate to the geological repository features of the system. This review, as was true of the earlier review of the KBS-2 plan, relies almost exclusively upon information developed by KBS--the panel members performed no original research in the process of review. The panel finds that the conclusions reached in the plan were warranted by the evidence submitted.

The review was conducted by a Panel of the Board on Radioactive Waste Management of the Commission on Physical Sciences, Mathematics, and Resources. Of this six-man Panel, the Chairman and one of the members served on the Subcommittee that previously reviewed the KBS-2 Plan, and two members served on the NRC Panel that has recently completed a study of the isolation system for geologic disposal of radioactive wastes.

Please note that while the bulk of the Panel report is organized around the review and update of the answers to questions identified in the NRC evaluation of KBS-2, the fifth chapter of the report deals specifically with a new topic--suggested additional research activities.

We very much appreciate the responsiveness displayed throughout our review by the managers and scientists associated with KBS, and are especially pleased that they were able to meet with the assembled Panel in Palo Alto, California, and with an individual Panel member in Boston, Massachusetts. These opportunities for significant face-to-face discussions made our task easier and, we believe, the review more valuable.

Three manuscript copies of the report are enclosed for your immediate use; an additional 250 printed copies will be sent to you in about four weeks.

It has been a pleasure for us to work again with your office and with the KBS organization. We wish you every success in the work that lies before you.

Yours sincerely,

Frank Press

Enclosures

PANEL FOR THE REVIEW OF THE SWEDISH KBS-3 PLAN

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BOARD ON RADIOACTIVE WASTE MANAGEMENT

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES

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CHARGE TO THE PANEL

On June 21, 1983, the National Research Council (NRC) of the National Academy of Sciences submitted a proposal in response to the June 7, 1983, invitation by the Swedish Ministry of Industry to review the plan for final storage of spent nuclear fuel--KBS-3. The proposal was accepted on July 4, 1983.

In accord with the proposal, the NRC, through its Board on Radioactive Waste Management (BRWM), gathered a panel of experts to review the KBS-3 plan, with principal emphasis on those portions relating to the geological repository features of the storage system. Particular consideration was to be given to overall canister and repository design and to the calculations and supporting data related to waste form dissolution and radionuclide migration from the point of emplacement through the surrounding geosphere. Within this framework, the review was also to address the following:

- Significant differences between the KBS-3 and KBS-2 systems.
- Any modifications of conclusions reached in the 1980 NRC review of KBS-2.
- Possible weaknesses in the KBS-3 plan.
- Suggested areas for further research.

It was understood that the main task of the panel was to assess the validity of the conclusions of the plan, within the above-mentioned areas of principal emphasis, on the basis of the evidence submitted. The NRC agreed, to the extent feasible, to select panel members who were directly familiar either with the previous NRC review or

SUMMARY

In the judgment of the panel, the KBS-3 plan provides an adequate technical basis for the conclusion it reaches--that there is reasonable assurance that a waste repository built according to the KBS-3 plan will not permit an unacceptable rate of radionuclide escape.

The Swedish plan for disposing of spent nuclear fuel was first reviewed in 1979 by a subcommittee of the Board on Radioactive Waste Management (BRWM; then called the Committee on Radioactive Waste Management) of the National Research Council (NRC). The present review by a newly formed panel of the BRWM is a follow-up to the earlier one, made necessary by the extensive research accomplished during the past five years by the Swedish organization responsible for the disposal plans, the Kärnbränslesäkerhet (KBS). In 1978 the Swedish proposal was described in a document entitled *Handling and Final Storage of Unreprocessed Spent Nuclear Fuel* and commonly referred to as KBS-2; a largely rewritten and considerably expanded version of the KBS-2 document, entitled *Final Storage of Spent Nuclear Fuel*, or KBS-3, is the subject of the present review. Both KBS-2 and KBS-3 are supported by a large number of detailed technical reports, most of which were critically examined in the course of the two NRC reviews, which were undertaken in response to requests from the Swedish Ministry of Industry for external evaluation of the work of their own scientists and engineers.

The current NRC review, as was true in the case of the earlier review, relies almost exclusively upon information developed by KBS. The panel members did not undertake to perform research or to gather evidence.

Essentials of the Swedish plan have not changed between KBS-2 and KBS-3. Both are concerned with the

disposal of spent fuel rods from power reactors (in contrast to KBS-1, which considered the disposal of radioactive waste recovered from the reprocessing of spent fuel and subsequently incorporated into glass cylinders). Like many proposals for managing high-level waste, the Swedish approach involves multiple barriers, some natural and some engineered, to keep the long-term escape of radionuclides within acceptable bounds. The Swedish plan differs from most others in its heavy reliance on engineered barriers, specifically thick-walled copper canisters to enclose the spent fuel rods, surrounded by buffers of compacted bentonite. These are to be placed in holes drilled into the floor of a cavity excavated in bedrock 500 m below the land surface. The bedrock, which is expected primarily to provide stable conditions in which the corrosion of the copper would be very slow, could also serve as a secondary barrier to radionuclide escape should some of the canisters fail. The canisters, however, are expected to last for a million years or more, and the function of bedrock as barrier is envisioned only as insurance against remotely possible accidents early in the life of the canisters. These major aspects of the plan have remained the same between 1978 and 1983, but details have been altered, and much research has been carried out to test predictions about the long-term behavior of canisters and buffer and about the movement of radionuclides through bedrock.

Evaluation of the recent research results is the focus of the present panel's review, and discussion from the earlier KBS-2 review is repeated only when necessary for background and continuity. The panel has devoted its effort primarily to judging how well the new work of the KBS scientists and engineers has supported their conclusions about the long-term safety of the planned disposal system and how convincingly they have answered questions about weaknesses in earlier versions of the plan. Emphasis is on the adequacy of the enhanced technical data base with respect to two elements of the disposal plan: (1) the long-term stability of copper canisters enclosed in a bentonite buffer and (2) the availability of deep geologic disposal sites with the necessary dimensions, stability, and groundwater properties for maintaining a benign canister environment and providing an effective secondary barrier to radionuclide migration. As with the earlier KBS-2 review, shortage of time for this review precluded consideration of some aspects of the Swedish plan--notably costs, facilities for predisposal handling of the fuel rods, comparison with other disposal methods, and the vulnerability of the waste repository to later exploitation for copper or fissile materials. The current review is essentially a subjective evaluation by the panel members of the quality and completeness of the Swedish research and the logic relating research results to conclusions drawn.

Like its predecessor KBS-2 subcommittee, the KBS-3 panel finds that the conclusions reached in the plan were warranted by the evidence submitted and is convinced that an adequate technical basis has been developed to provide reasonable assurance that radionuclides will not escape into the biosphere in unacceptable amounts from a repository located and constructed as specified by the KBS-3 plan. A few gaps and uncertainties in the evidence remain, despite the newer work, but the panel finds little reason to question the overall soundness of the KBS conclusion. The principal reasons for the panel's judgment, together with notes about the remaining uncertainties, are summarized below.

Canisters. Two kinds of canisters are described in KBS-3, both of copper with walls 0.1-m thick, reduced from the 0.2-m thickness proposed in KBS-2. One kind is fabricated as in KBS-2, with molten lead filling around the fuel rods and a cap sealed by electron-beam welding; the new second variety is to be filled with copper powder that is compacted and sealed by hot isostatic pressing. A choice between the two has not yet been made. Fabrication of both kinds has been demonstrated, the former at full scale and the latter at about one-third scale. Recent research has shown that pit corrosion is less rapid than was conservatively assumed in KBS-2; hence the wall thickness can be safely reduced. The research has further amply corroborated the KBS-2 conclusion that stress corrosion cracking is not a significant hazard for the kind of copper that will be used. Experts at the Swedish Corrosion Institute had cautiously estimated a guaranteed canister life of 10^5 years in KBS-2, but they now extend this to more than 10^6 years. The panel concludes that the larger estimate is fully justified.

The Buffer (referred to as "overpack" in KBS-2). The compacted bentonite to be placed around each canister in its deposition hole is expected to (1) provide a cushion for the canister in case of mechanical disturbance; (2) keep groundwater stationary or almost stationary near the canisters, so that access of corrosive agents to the canister walls will be only by slow diffusion through the bentonite; and (3) assist in maintaining slightly alkaline conditions near the canisters. The second and third functions have been amply demonstrated by experiment, but the ability of the bentonite to cushion against sudden shear, as might happen in an earthquake, is not yet adequately proved. This is a gap in available evidence, but not a serious one, because the probability of fault movement of the right magnitude and orientation to cause disruption is exceedingly slight. Questions raised in the earlier KBS-2 review about possible difficulties in emplacing the bentonite without leaving open channels for groundwater have now been answered by full-scale demonstrations in the underground experimental facility at Stripa.

Existence of Repository Sites. Identification of suitable repository sites is made difficult by the need to extrapolate fracture patterns in bedrock from surface exposures to depths of 500 m, aided only by measurements in a few boreholes and by geophysical observations. Such extrapolation is to some degree necessarily speculative, but in KBS-3 the speculative aspect has been diminished by the use of additional deep boreholes and by improvements in geophysical techniques. Three new sites have been found that seem at least as promising as Karlshamn, the site that survived detailed study in KBS-2. Each site has an area of rock between major fracture zones large enough, though only barely so, to accommodate a repository, and each has secondary fractures that would have to be avoided or sealed by grouting. None of the four studied sites is ideal, but any one of them could be made usable by proper choice of locations between fracture zones and by grouting of minor fractures. There is little reason to doubt that better sites will be found by the ongoing Swedish program of geologic exploration in the decade or so that remains before a site will actually be needed.

Stability of Sites. Recent geologic and geophysical studies of faults in the northernmost part of Sweden have shown Quaternary displacements of as much as 30 m. Elsewhere in the country, evidence for even small recent fault displacements is scanty, and the general stability of the crystalline bedrock is shown by the infrequency and small magnitude of Swedish earthquakes in historic time. Much new information has been gained in the past five years about the relative importance of postglacial rebound and tectonic forces in the slow, long-term, country-wide up-and-down motion of bedrock, and doubts once expressed by some Swedish geologists about general tectonic stability have been largely dispelled.

Quantity, Movement, and Chemical Composition of Groundwater. Study of groundwater from boreholes at the newly explored repository sites has shown relations much like those found earlier at the sites described in KBS-2: wide variation in hydraulic conductivity from high values in zones of fracturing to very low values in relatively unfractured rock, and a general decrease in conductivity downward from the land surface. Average values of hydraulic conductivity at different depths, combined with estimates of hydraulic gradient, make possible estimates of rates of groundwater movement. Such estimates are necessarily uncertain, especially since much groundwater flow may be concentrated in narrow channels; but even the higher estimated rates are not large enough to affect a repository adversely, and the water adjacent to a canister is kept practically motionless by the buffer. Many new chemical analyses, aided by improved techniques, confirm earlier results showing that groundwater at depth is uniformly slightly alkaline and slightly reducing, with only minor amounts of possible corrosive agents. In contact with water of this nature, the corrosion of copper canisters would be exceedingly slow.

Temperature in a Repository. Repository temperatures depend on the length of time fuel rods are stored before disposal and on the loading and spacing of the canisters. These variables can be adjusted to achieve any desired temperature, so that no difficulty is expected in holding the temperature of canister surfaces to the intended maximum of 80°C. Recent calculations show that convection currents produced by this temperature are too weak to disturb groundwater flow, and heater experiments at Stripa have demonstrated that the effect on fracture apertures is small. This temperature has also been shown to be too low to affect appreciably the properties of bentonite or the rate of corrosion of the canisters.

Repository Closing. Mixtures of bentonite and sand are to be used as backfill in tunnels and shafts; and the emplacement of such mixtures has now been demonstrated at full scale in the underground facility at Stripa, thus answering a question about feasibility that seemed especially serious to the earlier KBS-2 subcommittee. Recent experiments with compacted bentonite-sand mixtures have shown that densities can be readily attained at which permeabilities are comparable to the permeability of most of the bedrock in which the backfill will be placed. For preventing rapid groundwater flow through the rock adjacent to tunnels and shafts that has been fractured by blasting, seals of compacted bentonite are to be placed in slots sawed into the fractured rock. Demonstration experiments have been planned but not yet carried out. There is reason to doubt that such sealing could be entirely successful, in the sense that natural hydraulic conductivities are completely restored; but movement of groundwater could almost certainly be slowed enough to prevent harm to the canisters in their holes beneath the tunnels. A method of sealing boreholes has been demonstrated recently both in the laboratory and at Stripa: bentonite is packed in perforated copper tubes that are inserted into the holes, and absorption of water by the bentonite causes it to expand through the perforations and so to fill the holes completely.

Canister Failure. Should canisters somehow fail before their radionuclide content has decayed to harmless levels, thus exposing fuel rods directly to groundwater, escape of dissolved nuclides would be retarded by the insolubility of the uranium oxide pellets and by sorption and ion exchange on mineral surfaces in rocks through which the groundwater passes on its way to a point where it may be tapped for human consumption. Details of the movement of released nuclides have been studied intensively during the past five years, especially with respect to oxidizing conditions that may be produced locally by radiolysis, enhancement of radionuclide movement by formation of complexes and colloids, and the modeling of groundwater flow through fractured rock. New models have been devised as alternatives to the commonly used hydrodynamic dispersion models for porous rocks, but the new models have actually been used only to a limited extent in estimating rates of radionuclide migration. Modeling of transport through fractured rock is a complex problem that remains one of the least satisfactory aspects of the effort to predict radionuclide releases. The abundance of experimental data, the partial check of such data by field tests, and the consistent use of pessimistic assumptions all indicate, however, that estimates from the models should not be grossly in error. The further estimates of doses to humans from radionuclide releases are made by generally accepted techniques, and the additional uncertainties inherent in such estimates would not cause excessive risk to health and safety.

Suggested R&D. Research during the past five years has gone far toward answering questions raised in the NRC review of KBS-2. The new work has been especially convincing in that much of it has involved field tests under repository conditions, a notable deficiency in the earlier studies. Some troublesome questions remain, for example those regarding the effectiveness of proposed shaft and tunnel seals, the validity of models for groundwater flow in fractured rock, and the adequacy of treatment of the many variables that influence retardation of radionuclides in their migration through granitic rock. Uncertainties about such questions will doubtless be narrowed in the course of continuing research, although final answers to some will probably remain elusive. Current knowledge is sufficient, however, to ensure that uncertainties will be manageable and that conservative assumptions regarding them have led to reliable estimates of repository performance.

1

INTRODUCTION

Current plans for the development of nuclear energy in Sweden call for a total of 12 reactors to operate for a limited period. All reactors are to be decommissioned by 2010, and at about this time entombment of high-level waste in a repository or repositories constructed in Swedish bedrock is expected to begin. No decision has been reached as to whether the waste will consist largely of spent fuel rods or solidified reprocessing waste, but plans are being developed for handling both kinds.

After the first six reactors were in operation, questions arose about the safety of contemplated waste disposal techniques, and the Swedish Parliament in 1977 passed a law (the "stipulation law") mandating that an "absolutely safe" method of disposal be demonstrated before governmental permission would be granted for the loading of fuel into any additional reactors. To assist in complying with the law, the Swedish nuclear power utilities set up a special organization, Kärnbränslesäkerhet (KBS). The organization has since become a department of the Swedish Nuclear Fuel Supply Company (Svensk Kärnbränsleförsörjning (SKBF)), which is jointly owned by the utilities. The KBS organization, enlisting the aid of scientists and engineers from academia, industry, and government agencies, put together in remarkably short time two reports with accompanying technical documents intended to show that safe disposal could indeed be accomplished. The reports are Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste, known as KBS-1, dealing with vitrified reprocessing waste (late 1977), and Handling and Final Storage of Unreprocessed Spent Nuclear Fuel, known as KBS-2, dealing with spent fuel elements (late 1978). On the basis of KBS-1 and supplementary material the government granted permission for loading fuel into four additional reactors.

Of the planned dozen, therefore, 10 reactors are now in operation, and it is planned that the two remaining reactors (Forsmark 3 and Karlshamn 3) will be ready for fueling in 1984. Because the KBS-2 documents are now five years old, the government requested KBS to prepare a new report to update the demonstration that safe disposal of radioactive waste is possible, before permission for fuel loading is given. This new report is entitled Final Storage of Spent Nuclear Fuel, and is known as KBS-3. According to changed legislation, expected to take effect in early 1984, the requirement for demonstration in the new report is not quite as stringent as for the earlier ones: rather than requiring "absolute safety," the government can now decide to grant a fueling license if the waste-handling plan presented by the plant owner ". . . offers a point of departure which, after carrying out appropriate research and development activities during the next few decades, is certain to provide a safe method for spent-fuel and reactor-waste management and final disposal" (Jan Magnusson, Swedish Ministry of Industry, personal communication to Peter B. Myers, staff director of BRWM, 1983). Actually, the change makes little difference, because in practice the stipulation law has been interpreted along the lines of the new legislation.

To help in evaluating the conclusions reached in KBS-1 and KBS-2, the Swedish government invited reviews from many individuals and institutions both in Sweden and abroad. The National Research Council (NRC) agreed to make such a review of KBS-2, assigning the task to a subcommittee of the Board (then Committee) on Radioactive Waste Management (BRWM) and the review prepared by this subcommittee (NRC, 1980) was published in 1980. With their publication of KBS-3 in May of 1983, the Swedish authorities again sought external evaluations, and the NRC again agreed to undertake a review. The review was entrusted to a new panel of the BRWM, and the current report is a product of this panel's study. To ensure that the review would be consistent with the earlier one and with current thinking about waste management and disposal in the BRWM, the panel was set up to include two members from the KBS-2 subcommittee and two from the BRWM panel that prepared the recently published Study of the Isolation System for Geologic Disposal of Radioactive Wastes (NRC, 1983).

Like the KBS-2 review, the current review was limited in scope by the shortness of time within which it had to be completed. According to the Panel's charge,

> . . . review time and resources (should) be applied principally to a review of those portions of the report which relate to the geological repository features of the disposal system. This would include consideration of overall canister and repository design, as well as the calculations and supporting data related to waste-form dissolution and to radionuclide migration from the point of emplacement through the surrounding geosphere.

Excluded from consideration here are many parts of the KBS-3 plan: technical details of handling and storing the waste, the separate facility for irradiated metal parts of fuel assemblies, the interim storage facility, and costs. The panel's focus was on the long-term integrity of a bedrock repository in Sweden, the long-term integrity of copper canisters enclosed in a bentonite buffer, the movement of groundwater, and the movement of radionuclides in groundwater in the event that a canister is prematurely breached. These topics, in the opinion of the BRWM, are critical to a judgment about the functioning and effectiveness of the waste-isolation system.

Because the KBS-3 report is largely an update of KBS-2 with a substantial amount of new material added, this review of KBS-3 is in effect a supplement to the KBS-2 review. There seems little need to repeat here the background material from the earlier review or those parts of the earlier document where neither the KBS data nor the reviewers' opinion regarding them has changed appreciably. Emphasis in this review is on the considerable expansion of the technical data base by Swedish scientists and engineers since KBS-2 appeared, especially on an evaluation of the extent to which this recent work has filled gaps in data and supplied additional evidence about questionable aspects of the earlier conclusions. The general outline of the present review follows closely that used for the review of KBS-2, and much of the argument here depends on evidence presented more fully in the pages of the earlier document.

It should be emphasized here, as it is in the KBS-2 review, that the task undertaken by the authors of the KBS plans was not to describe how and where an actual repository should be constructed, nor to devise the best possible or most cost-effective repository, but rather to show that development of a safe method for disposing of radioactive waste in Sweden is possible. This means that reviewers need not be concerned with costs of the proposed disposal method, except in a very general way, or with comparisons of the Swedish method with others that might be better, or with suggestions for possible improvements. The problem for reviewers is to judge how effectively the KBS authors have marshaled technical and scientific evidence in support of their conclusion that a repository for the safe disposal of high-level waste can be constructed in Swedish bedrock.

Like the KBS-2 subcommittee, the present KBS-3 panel has had to depend for its information almost entirely on sources provided by SKBF that are favorable to the KBS program. The sources are voluminous: they include the five volumes of the KBS-3 report itself ("Summary," "General," "Geology," "Barriers," and "Safety"), the supporting KBS technical documents published since 1979 (25 in 1980, 16 in 1981, 28 in 1982, and more than 70 in 1983), reports from the research program at the Stripa mine (formerly a Swedish-American cooperative venture, now an international research program), and articles in the standard scientific literature. In addition, the panel benefited from a day-long question-and-answer session with eight of the principal authors of the technical documents and from subsequent telephone conversations. One panel member had follow-up conversations with individuals. The Panel had no first-hand contact with Swedish laboratories or repository sites, although two of its members had visited Sweden earlier as part of the KBS-2 subcommittee. Although one critic provided written material and met with the panel, the panel had no other opportunity to question individuals, Swedish or foreign, who are critical of some of the KBS-3 conclusions. The heavy dependence on data and opinions from enthusiastic advocates could easily lead to unconscious bias, but the panel tried to avoid this by maintaining a hearty skepticism, by perusing critical comments in previous reviews of KBS-1 and KBS-2, and by querying the Swedish experts as to their own opinions of weaknesses in the program. Because the quantitative data could not be directly checked, this review necessarily consists, like its predecessor, primarily of the panel's subjective evaluation of the quality and completeness of the Swedish research and the logic used in relating the research to the conclusions drawn.

In its general outline the KBS-3 plan for disposal is no different from that described in KBS-2: spent fuel rods are to be stored for a 40-year cooling-off period in an intermediate facility a few tens of meters below the ground surface and then moved to a repository site where they will be encapsulated in copper canisters; the canisters will be lowered into a bedrock cavity some 500 m under the surface, placed in holes drilled into the floor of the cavity, and surrounded with blocks of compacted bentonite; and, finally, the cavity, shafts, and boreholes will be filled and sealed with mixtures of bentonite and sand. Principal reliance for isolation of the radionuclides is placed on the durability of the copper canisters for very long periods, in an environment where the temperature remains below 100°C, where groundwater is noncorrosive, and where the flow of water past canister surfaces is negligibly small. The geologic surroundings are also expected to retard effectively the movement of radionuclides to the biosphere, but only as a sort of insurance against early breaching of many canisters. A few specific changes in the KBS-3 plan are noteworthy: walls of the canisters are to be 0.1 m thick rather than 0.2 m, copper is suggested as an alternative to lead for filling the canisters around the fuel rods, and the addition of ferrous phosphate to bentonite backfill as a control on redox potential of the groundwater has been eliminated. A more important new aspect of KBS-3 and its technical support documents is not a specific change, but simply the wealth of additional detail that has been supplied in support of conclusions about the availability of suitable repository sites, the durability of copper canisters under repository conditions, and the slow movement of radionuclides that may escape into groundwater should some of the canisters be breached. An evaluation of these new results of continuing research is the main objective of this review.

This review, like its predecessor, is organized around three major topics: the adequacy of technical and scientific data on the geology and hydrogeochemistry of the sites suggested as suitable for repository construction; the adequacy of metallurgical data on the mechanical properties and corrosion resistance of the copper canisters in the expected geologic environment; and the adequacy of the data describing the possible movement of radionuclides in groundwater when the canisters are ultimately breached. These topics are considered in the following three chapters of the review.

The five-volume KBS-3 report in which the disposal plan is decribed, "Final Storage of Spent Nuclear Fuel," is referred to in this review simply as KBS-3; its 1978 two-volume predecessor, "Handling and Final Storage of Unreprocessed Spent Nuclear Fuel," is referred to as KBS-2. References to the KBS technical documents on which this report is based are given in the form TR 82-11, the first two digits of the number indicating the year in which the document was written. References to standard literature are given in the name-date form (e.g., Anderson, 1979), and complete references are listed at the end of the review. Two differences in nomenclature between KBS-2 and KBS-3 should be noted: "permeability" in KBS-2 (and in the KBS-2 review) is changed to "hydraulic conductivity" in KBS-3, and the "bentonite overpack" is changed to "bentonite buffer." Both of these changes are in accord with current international usage, and the new terms are used in this review.

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ADEQUACY OF TREATMENT OF GEOLOGY AND HYDROGEOCHEMISTRY

The disposal system proposed in the KBS reports depends for its effectiveness primarily on the long-term integrity of copper canisters surrounded by bentonite and placed deep in crystalline bedrock. Canister integrity is a function of both the nature of the canister material and the environment in which it is placed. To demonstrate that a satisfactory environment for the canisters will exist over the long term requires showing that (1) masses of sound bedrock can be found of sufficient size and sufficiently low permeability to serve as repository sites; (2) the characteristics of groundwater under natural conditions (quantity, rate and direction of movement, and chemical composition) can be predicted and will not affect a copper canister adversely; (3) groundwater movement will not be adversely influenced by construction of a repository or by the heat generated from the radioactive waste; (4) tectonic movement in bedrock will not seriously damage the repository; and (5) possible renewed glaciation will not adversely affect the repository. Evidence in support of these five conclusions, as marshaled in the KBS-2 report, was critically examined in the NRC review of that document and found to be generally convincing, although some gaps and weaknesses were noted. The purpose of this chapter is to take a fresh look at the KBS-2 report conclusions in the light of research over the past five years.

REPOSITORY SITES

Can bodies of crystalline bedrock be found in Sweden of sufficient size and sufficiently low permeability to serve as repository sites?

KBS-2 described exploration at four possible sites (Karlshamn, Kråkemåla, Finnsjön, and Stripa), including details of surface geology, study of cores from deep boreholes, geophysical measurements both on the surface and in boreholes, and measurements of hydraulic conductivity at many places in the boreholes. Bedrock at all the sites consists of granite and metamorphic rock cut by many fractures and zones of crushing, with relatively high permeability in some of the fractures and very low permeability in the solid rock between. The problem at each site was to determine whether a body of rock existed at a depth of roughly 500 m sufficiently free of fractures and large enough (covering an area of at least 1 km^2) to permit excavation of a repository. To make such a judgment requires geologic inference from the surface studies and borehole data, and with current technology the data so obtained can never be sufficient to make the judgment with complete confidence. The KBS authors concluded that the number and permeability of fractures at three of the areas made them questionable as repository sites, but the Karlshamn area appeared to have a volume of sound rock large enough, although barely so, to accommodate a repository. The NRC subcommittee concurred in this evaluation of the geologic data.

The authors of KBS-3 retain the Karlshamn site (also referred to as the Stärnö site) as a good possibility (TR 83-56), and they describe exploration in four additional areas (TR 83-40, TR 83-52, TR 83-53, TR 83-54, TR 83-55). One of the new areas was eliminated quickly on the grounds that it had too many water-bearing fractures, but the other three looked promising enough to warrant a more detailed study than had been attempted at Karlshamn. In particular, more long boreholes were drilled, most of them to depths greater than 500 m, and at various angles so that they would intersect differently oriented fracture zones. This provided a partial answer to an objection that had been raised regarding the earlier work, that the boreholes at Karlshamn were too few to justify the attempted geologic extrapolation. Data from the three new sites (Fjällveden, Gideå, and Kamlunge) indicated rocks and structures much like those at Karlshamn; again at these sites the volumes of relatively unfractured rock estimated to be present at appropriate depths are barely large enough for repository construction.

The new studies, like the older ones, start with geologic mapping from surface exposures, aided by tracing of lineaments on air photos; they emphasize appropriately the nature and spacing of fracture zones. Based on the surface maps, boreholes can be located and oriented so as to intersect fracture zones at various depths, making it possible to construct a reasonably complete three-dimensional model of the fracturing. Geophysical techniques are used both at the surface and in boreholes to test the properties of individual fractures and crush zones and to explore for others that may have been missed in the mapping and drilling. Cores from the longer boreholes permit detailed study of rock compositions and textures to depths of 500 m and more. Hydraulic conductivities--both specific values for individual fracture zones and average values for large volumes of rock--are measured by standard techniques on sections of the boreholes isolated by packers. Application of these various techniques by Swedish geologists and geophysicists, as described in KBS-3 and its supporting technical documents, is fully up-to-date and consistent with modern practice in other countries.

Thus the KBS-3 authors have apparently accomplished their purpose, which is simply to show that places can be found in Sweden where the bedrock has the necessary properties for repository construction. None of the places examined so far is ideal, and active investigation is under way to find better ones. The investigation is handicapped by the reluctance of many property owners to permit detailed study and drilling. (Although this is not clear from the written report, in conversation the KBS authors say that often an area that looks especially promising must for this reason be passed over for a second-best site.) But the four sites that have been studied in detail seem sufficiently attractive to ensure that, when the time comes to actually select a repository location (at least a decade hence), a good one will be found in Sweden.

Estimating geologic conditions deep underground from surface observations and a few boreholes, even when aided by geophysical data, is always somewhat speculative. Details of underground conditions can be ascertained only by sinking a shaft and exploring laterally from its bottom, and surprises are to be expected in such exploration. A skeptic can always find grounds for criticizing geologic extrapolation; but where sinking a shaft is not practical, there is no alternative to dependence on surface and borehole data. In the panel's opinion the KBS authors have acquired about as much information from such data as it is practical to obtain and have made a good case for their conclusions.

The weakest point of the KBS argument relates to inferences it draws about amounts and flow of groundwater over long future times from measurements of hydraulic conductivity in intricately fractured rock. The adequacy of the factual basis for these inferences is examined in the next section.

GROUNDWATER IN ITS NATURAL STATE

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

Groundwater is expected to permeate a repository after it has been filled and sealed, and the preconstruction pattern of groundwater flow will reestablish itself within a time that is short in comparison with the very long half-lives of many of the interred radionuclides. If the movement of groundwater is slow, the bentonite around each canister should be stable indefinitely, and the small amount of water that diffuses through the buffer will have little effect on the copper canisters. More rapidly moving water, however, might eventually erode channels in the bentonite and bring corrosive agents into contact with the copper surfaces. To demonstrate that suitable repository sites can be found, therefore, requires that detailed information be acquired about amounts, movement, and chemical composition of groundwater at each candidate site. Efforts to obtain such information have been a major part of the KBS project, assigned by the KBS staff to geologists, hydrologists, and geophysicists of the Swedish Geological Survey.

Groundwater movement in granite and other crystalline rocks is largely confined to fractures, which commonly can be seen to cut the rock in many directions. The rock itself has very low permeability, but parts of some fractures may carry a good deal of water. Studying groundwater movement is thus chiefly a matter of determining the fracture pattern over an area and estimating flow rates in individual fractures or groups of fractures. The problem is difficult because actual observations must be limited to rock exposures on the ground surface and to measurements in boreholes, and the number of boreholes must be kept small to avoid perforating a potential repository site with too many openings. Observations may be supplemented by geophysical measurements, both on the surface and in boreholes; but even with a combination of the most modern techniques, discerning complex fracture patterns at depths of a few hundred meters is subject to much uncertainty. Eventually, when an actual repository site is to be explored in detail, sinking a shaft and driving tunnels will make possible more accurate mapping of fractures and measurements of groundwater flow; but the preliminary studies of the KBS project must be carried out without this advantage.

The authors of KBS-2 were well aware of the difficulties they faced in predicting groundwater conditions at depth from surface and borehole observations, and critics of the KBS-2 plan identified this as one of its most vulnerable parts. The NRC subcommittee, after extensive review of the technical documents and conversations with the KBS investigators, decided that the geological and hydrological work was well done, that enough conservative assumptions had been made to compensate for the uncertainties, and that the measurements were "adequate to ensure that the quantity of water reaching the copper canisters in a well constructed repository will not be damaging." The additional work reported in KBS-3 is not qualitatively different from that done earlier, but the methods of measurement have been refined and abundant new data have been gathered.

Groundwater conditions at the four new sites discussed in KBS-3 (Fjällveden, Gideå, Svartboberget, and Kamlunge) and at the experimental site at Finnsjön have been extensively studied (TR 83-43, TR 83-45, TR 83-52, TR 83-53, TR 83-54, TR 83-55). A critique of the treatment of groundwater flow in KBS-3 involves three questions: (1) Are the reported measurements of hydraulic conductivities accurate? (2) Are the interpretations of these measurements valid? (3) Are the numerical predictions of flow rates likely to be reasonably accurate?

1. <u>Measurement of hydraulic conductivity (K)</u>. The bulk of the measurements used to estimate values of K were made, as in KBS-2, by injecting water into sections of boreholes sealed off with inflatable rubber packers. The test sections ranged in length from 2 to 25 m (TR 83-45). The value of K for each isolated section, expressed in terms of that for an equivalent homogeneous porous medium, is inferred by analysis of recorded values of the amount of water injected and the time variation of pressure in the borehole section. This is a standard procedure for such measurements. There are potential

difficulties with measurements of K made in this fashion, but, unless there is a "borehole skin" effect, errors should not be unreasonably large (TR 82-06).

The packer tests yield values of K that are representative of the rock in the immediate vicinity of the borehole. In relatively unfractured rock (K values of 10^{-9} to 10^{-11} meters/second (m/s)), the effective radius of influence in the tests ranges from 0.15 to 1.5 m (TR 83-43). To estimate the hydraulic conductivity of larger rock masses, an alternative method, referred to as an "interference test," was used. In interference tests, pressure changes in boreholes are recorded as a result of injection or pumping carried out in a nearby borehole. Such tests were conducted at all four sites but were limited to the upper part of the bedrock (0 to 150 m) because the necessary equipment required boreholes of large diameter that could be driven only to this depth, at the time when the testing was being performed (Leif Carlsson, Swedish Geological Survey, personal communication, 1983; TR 83-43, TR 83-45).

The K value measurements reported in KBS-3 are more numerous than those in KBS-2 because more deep boreholes (to depths of 600 m and more, well below the chosen repository level of 500 m) were drilled at each site. In the opinion of the panel, the measurements are consistent with the current state-of-the-art. Within the limits of current understanding of flow in fractured media, the measurements themselves can be considered accurate.

2. Interpretation of measured values of K. The values of K are highly variable, as might be expected in rock cut by fractures of varying width, varying orientations, and varying amounts of secondary filling material (chiefly clay minerals, chlorite, and calcite). For sections of a borehole cutting rock in which fractures are absent or tightly sealed, K values are at or near the limit of measurement, 10^{-11} m/s; for sections with more open fractures, values range up to 10^{-6} m/s or higher. The higher values in all of the studied areas are largely limited to the upper 300 m, below which level values greater than 10^{-8} m/s are very few. This distribution has led the Swedish scientists to fit exponentially decreasing curves to the data on K versus depth. The curves permit estimates of average hydraulic conductivities for different depth ranges in the rock, but many points deviated considerably from the averages indicated by the curves.

One can question the meaning of such averages, on the grounds that all or nearly all of the flow represented by an "average" for a given rock thickness might be concentrated in a few highly conductive fractures. If a repository were intersected by such fractures, it might conceivably be damaged by the concentrated flow even though the predicted "average" flow was suitably small. Damage from such flow seems unlikely, however, because measured hydraulic conductivities in the depth range 400 to 600 m, even for the most conductive fracture zones, are nearly all less than 10^{-8} m/s. On the assumption of a hydraulic gradient of 0.1 percent for these depths (estimated from the leveling-out, with depth, of gradients observed near the surface), the conductivity would give a flow rate of only 0.3 liters/square meter/year ($l/m^2/yr$). A more conductive fracture or fracture zone would presumably either be sealed or avoided in selecting the location for the repository. The exponential curves and the estimated average hydraulic conductivities seem a reasonable interpretation from the measured K values--provided, of course, that the uncertainties are recognized and conservative values are used.

One criticism of the treatment of K values in KBS-3 relates to the interference tests. Although these tests were evidently performed at each site, the data are not presented or discussed. If the "average" values of K indicated by the exponential curves are a valid representation of the large-scale, three-dimensional flow in granite, then the values of K derived from interference tests should be close to those predicted by the regressions. In the only published comparison of values derived from the two methods of testing, at the Studsvik experimental site, hydraulic conductivities given by interference tests were considerably larger than those given by packer tests (TR 82-10). All more recent work, however, indicates excellent agreement between results of the two methods. This includes unpublished analyses of measurements at the four recently studied sites (Hans Carlsson, KBS, personal communication, 1984) and an additional unpublished study at the Stripa experimental facility (Leif Carlsson, Swedish Geological Survey, personal communication, 1983).

Thus in five of six comparisons between the two methods, agreement is reported to be satisfactory. On the basis of these reports, but without the opportunity of checking the actual data, the panel considers that the KBS interpretation of the measured hydraulic conductivities is reasonable.

3. Numerical prediction of flow rates. Groundwater flow rates under natural conditions are predicted in KBS-3 by using a three-dimensional finite-element approximation to solve the governing equation (KBS-3, p. 6:1/21; TR 83-45). This equation (i.e., the theory behind the calculations) assumes that Darcy's law provides a valid description of flow in fractured granite. The assumption is that a large mass of granite with an interconnected network of fractures will, in fact, behave like a porous medium if the spatial scale is large enough. The panel agrees that this assumption is reasonable for a rough calculation of discharge per unit area ("Darcian velocity") through a region. However, the application of such calculations to actual velocities in fractures is problematic because of the difficulty of accurately estimating the "effective porosity" associated with the hydraulically connected, conducting fractures.

The use of finite-element models in groundwater hydrology is by now almost routine. They can be used for accurate calculations of groundwater flow if (1) the underlying theory (Darcian flow) is valid; (2) the hydraulic properties of the medium (most importantly, conductivity) are specified correctly; (3) the boundary conditions (impervious basements, flow divides, and so on), including the geometry of the boundaries, are known; and (4) the elements are of an appropriate size and shape to yield an accurate numerical solution. The first two items have been discussed above. Geological boundaries can almost never be specified with great precision; and so additional uncertainty, over and above that caused by difficulties in measurement and interpretation of K values, is introduced by this incomplete knowledge. Finally, because of computer limitations, the element grid used in KBS-3 was rather coarse. In some cases, this resulted in a physically implausible solution (i.e., one in which conservation of mass of groundwater was violated) and/or in failure of computed groundwater trajectories to be consistent with the specified boundary conditions (TR 83-45).

Similar problems beset all efforts to model groundwater flow. To calibrate and validate numerical models, extensive field data are needed, especially data on groundwater heads over time. Such data were not available prior to preparation of the KBS plan. Thus the calculated results must be regarded as no more than semiquantitative. The lack of precise numbers, however, is not serious for purposes of safety evaluation. This can be illustrated by relating flow rates to hydraulic conductivities and hydraulic gradients in a simple application of Darcy's law. Average hydraulic conductivities (from the packer tests) lie between 10^{-8} and 10^{-10} m/s; hydraulic gradients at repository depths are lower by 1 or 2 orders of magnitude than surface slopes, which in the subdued topography of eastern Sweden are unlikely to be greater than 10 percent. For various combinations of these two variables, Darcy's law gives the flow rates shown in Table 2-1. Now the flow rates calculated by the model for the different areas lie between 0.01 and 0.06 $l/m^2/yr$. As Table 2-1 shows, to get flow rates substantially higher than these values would require unrealistic combinations of gradient and conductivity.

Thus, in the Panel's opinion, the flow rates calculated in KBS-3, although subject to a good deal of uncertainty, are derived by reasonable methods of calculation using the available data.

Studies of groundwater chemistry, like studies of groundwater motion, have added little that is new between KBS-2 and KBS-3, but they have introduced significant refinements of method and have added greatly to the data base (KBS-3, p. 7:1/10; TR 83-34). Especially notable have been efforts to improve and check measurements of Eh (redox potential), a notoriously difficult and often unreliable part of water analysis (TR 83-40). By comparing readings obtained with two kinds of electrodes, platinum and amorphous carbon (gold was also tried, but found to be subject to sulfide poisoning), and by checking the readings against Eh values calculated from overall groundwater composition, the KBS authors have verified that their listed Eh values are meaningful.

TABLE 2-1 Flow Rates or Flux ($l/m^2/yr$) as a Function of Gradient and Hydraulic Conductivity

	Hydraulic Conductivity		
Gradient	10^{-10} m/s	10^{-9} m/s	10^{-8} m/s
1.0%	$3x10^{-2}$	$3x10^{-1}$	3
0.1%	$3x10^{-3}$	$3x10^{-2}$	$3x10^{-1}$
0.01%	$3x10^{-4}$	$3x10^{-3}$	$3x10^{-2}$

Measurements of dissolved sulfide, made rapidly with an Ag/Ag_2S electrode, have likewise been compared to results from titration and found to be valid and replicable. The extent to which samples may have been contaminated by drilling fluid, even after lengthy flushing of the water sources, was checked by analysis for iodide added as a tracer to the water used for drilling. The many new analyses for granitic bedrock in the four recently studied areas (TR 83-17, TR 83-19, TR 83-41, TR 83-59, TR 83-70), carried out with these several improvements, corroborate earlier work. Except for a very few aberrant figures, values of pH lie between 7.5 and 9.5, of Eh between 0.0 and -0.3 volt, of HS^- below 0.1 mg/l, of Fe^{2+} between 0.1 and 7 mg/l, and of total organic carbon between 2 and 7 mg/l. The uniformly slightly alkaline and slightly reducing character of groundwater from depths of a few hundred meters in Swedish bedrock seems abundantly confirmed. The water is in equilibrium with its bedrock environment, in the sense that the concentrations of silica and the major cations (Na^+ , K^+, Ca^{++}, and Mg^{++}) are within the fields of stability representing equilibrium with the common alteration minerals found in the fractures and crush zones (kaolinite, chlorite, smectite, laumontite, and calcite) (TR 83-59).

In summary, work on groundwater during the past five years has added substantially to support for the conclusion that reasonable estimates for the quantity, rate of movement, and chemical character of groundwater at depths of a few hundred meters in crystalline rock can be made from careful geologic mapping at the surface, logging of boreholes, examination of drill cores, a full panoply of geophysical tests, measurements of hydraulic conductivity, and chemical analyses of many samples. Uncertainties still remain about interpretation of the widely variable values for hydraulic conductivity and about the validity of using Darcy's law for calculating flow in fractured rock; but the uncertainties have been narrowed by comparing results of different measurement methods, and they can be partially compensated for by use of conservative values. The panel agrees with the KBS scientists that the accumulated evidence at most of the sites selected for detailed study points strongly to groundwater behavior and groundwater composition favorable to the location of waste repositories of the kind envisioned in the KBS-3 plan.

EFFECTS OF REPOSITORY CONSTRUCTION ON GROUNDWATER

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?

Construction of a repository will necessarily disturb the natural flow of groundwater, and the question arises as to whether the disturbance will persist, after the repository is closed, in a form serious enough to affect the buried canisters. Part of the KBS design for a repository is the use of a bentonite-sand mixture for backfill, which is intended to have a hydraulic conductivity comparable with that of the original rock. If the backfill behaves as expected, the long-term effect of the repository on groundwater flow should be small. (The effectiveness of bentonite as a barrier in backfill and seals is considered more fully in the section in Chapter 4, "Retardation in the Near-Field.")

Questions are still pertinent, however, about possible increased flow of groundwater through the rock material adjacent to shafts and tunnels that was fractured by blasting during construction, and about possible thermal convection cells set up by heat from radioactive material in the canisters. Both questions were treated at length in KBS-2, and little new has been added in the work for KBS-3. Oral statements by KBS personnel (September 1983) indicated that recent experimental work at Stripa has verified earlier predictions that the very localized fracture enhancement near shafts and tunnels would not greatly compromise the low hydraulic conductivities of the rock matrix and thereby disrupt the existing regional flow. A recent study of thermal circulation by means of a mathematical model (TR 80-19) supports KBS-2 estimates that the low planned temperature of a KBS repository (maximum designed temperature of 80°C) would not be sufficient to cause appreciable convection. The calculations indicate, in fact, that movement of groundwater in a repository located beneath a hill would actually be slowed by a slight increase in temperature.

The panel agrees with the earlier NRC subcommittee that a good case has been made for lack of adverse effects on the natural movement of groundwater caused by the presence of a repository.

TECTONIC STABILITY

Can areas of bedrock be found in Sweden where the possibility of tectonic movement that might damage a repository is negligible?

The crystalline bedrock of Sweden is part of the Baltic Shield, a large area of Precambrian rock that is generally recognized as one of the most stable parts of the earth's continental crust. Large faults with spacings of kilometers criss-cross the shield, cutting it into blocks within which fracturing is minor. Displacement on the faults, both major and minor, records movement that was largely completed in Precambrian time, more than 600 million years ago. More recent movement in bedrock has been restricted to small displacements along some of the old faults: in effect, the blocks show some evidence of jostling about over geologic eons, but interiors of the blocks have been largely unaffected. Present-day earthquakes in Sweden are few and small (Richter magnitudes seldom greater than 4); and where resulting fault displacement from individual quakes can be found, it is limited to a few centimeters, again on a few of the ancient fault lines. From such evidence, the KBS-2 authors concluded that repositories placed well within the stable blocks are in little danger of disruption by tectonic movement--either slow deformation or the sudden displacements accompanying earthquakes--and the earlier NRC subcommittee agreed that evidence for the conclusion was convincing.

Research in the last five years has only further confirmed the essential stability of Swedish bedrock. Much attention has been given to movement of some of the blocks over the past few hundred thousand years resulting from the melting of successive Pleistocene ice sheets and the consequent periodic release of bedrock from the load of 3-km-thick masses of ice (KBS-3, p. 8:14/19; TR 83-57, TR 83-58). Interest has also focused on attempts to relate fault movements and measured bedrock stresses in Sweden to large-scale movements of crustal plates, particularly to possible compression of the Scandinavian peninsula against the Baltic Shield by plate movement away from the Mid-Atlantic Ridge (Båth, 1983). Båth also reviewed recent work on seismic risk: he estimated the magnitudes of possible future earthquakes for many areas covering 1° latitude by 2° longitude and found for the most active of such areas maximum expectable magnitudes of 5.1 over a period of 100 years and 6.4 over 500 years.

For most of the areas, the estimated extreme magnitudes are much smaller. Båth recommended that waste repositories should be located away from active fracture zones, and he suggested a depth of 1400 m rather than the 500 m planned by KBS, on the grounds that seismic waves show a marked increase in velocity at about this depth and thus imply a decrease in rock fracturing. Båth noted also that seismic activity is concentrated in a zone running north-northeast through central and eastern Sweden, close to the Baltic shore north of Stockholm. It is doubtful that earthquakes would appreciably damage a repository built within a stable block, even if it were located in this seismic zone (as it would be at Gideå or Kamlunge), but the very slight risk could be avoided by placing the repository near the less seismic southeastern coast (for example, at Karlshamn or Fjällveden).

A principal critic of the KBS-2 report was N.-A. Mörner, who claimed that evidence for the tectonic stability of Sweden was far from convincing (KBS TR 18). He based his skepticism chiefly on many years of study of the levels of old marine terraces. The unloading of Scandinavia by the melting of the last Pleistocene ice cap has resulted in a slow elevation of the land with respect to sea level, an elevation recorded in terraces marking old stands of the seashore. Mörner's study of the terraces enabled him to follow details of the uplift. He concluded that the uplift could not be entirely explained by glacial retreat and that it must also involve a tectonic component of unknown origin that is still active. This led him to look for evidence of recent tectonic activity, and he thought he could see such evidence in small faults cutting glaciated surfaces and huge blocks of bedrock in some glacial moraines. In Mörner's view, Sweden has been active tectonically since the end of glaciation, and such activity will be heightened in the next glacial period, so that locating waste repositories in Swedish bedrock would be foolhardy.

In the intervening five years, Mörner has given no further expression to his skeptical opinions. The panel had no opportunity to interview him, and inquiries of other Swedish scientists elicited only the speculation that he had either changed his views or tired of urging them in the face of steadily mounting contrary evidence. It may also be, however, that Mörner feels partly justified by a change in the climate of opinion in Sweden. Båth (1983) noted, for example, that most Swedish scientists a decade or so ago ascribed all the post-Pleistocene uplift of Scandinavia to glacial unloading, whereas they are now ready to admit a tectonic contribution in some obscure way related to plate movements. Other recent studies (TR 83-57, TR 83-58) have also shown that Mörner is certainly right in his insistence on some late Quaternary differential movement in bedrock. The best evidence for such movement comes from far northern Sweden, where scarps cutting glacial deposits record vertical displacements of up to 30 m in fairly recent geologic time. The movement for the most part is along old fracture zones, although some smaller fractures have cut fresh rock. Interpretation of the precise timing and nature of the movement is uncertain. Båth speculated that this is a region where plate motion eastward from the Mid-Atlantic Rift abuts motion southward from rifts in the Arctic Ocean. In any event, these faults are far from any of the studied repository sites except Kamlunge, and no post-Pleistocene displacements nearly this large are known in other parts of Sweden. Despite these exceptional faults in the far north, there seems no longer to be any expressed dissent among Swedish scientists to the prevailing view that the risk of tectonic disturbance to a properly located repository is negligible. The panel regards this view as well founded.

More details about post-Pleistocene tectonic movements would certainly be desirable. The probability of future disturbance could be better estimated, for example, if it were known whether the dominant kind of fault movement is normal dip-slip, reverse, or strike-slip. Båth noted that such information is hard to obtain, because Swedish earthquakes are so small and seismographs so widely spaced that good first-motion data are very scarce. He hazarded a guess, based on recent work, that strike-slip movement may be the commonest kind, at least for the larger quakes, but cited other evidence from a few faults for reverse movement on steep eastward-dipping planes. Additional studies of this sort would be of much scientific interest, but it seems doubtful that they would add a great deal to the current assurance that future tectonic activity will be too feeble to harm a repository. The panel concludes that the assurance is adequately supported by currently available evidence.

GLACIATION

Can the effect on a repository of renewed glaciation be shown to be negligible?

Development of another ice sheet in Scandinavia is probable during the next few tens of thousands of years, and its possible effect on a waste repository was considered in great detail by the authors of KBS-2. Not only were the expectable surface erosion and deposition by the ice and its accompanying meltwaters a subject of exhaustive study, but also the effects on groundwater, the effects of the weight of ice on bedrock at depth, the bowing down of the land suface beneath a thick ice cap and the consequent probable incursion of seawater, and the generation of earthquakes by the shifts in mass as the ice waxed and waned. The general conclusion was that a repository, properly located and constructed, would not be adversely influenced by any of the phenomena accompanying advance and retreat of an ice sheet, or even by the many advances and retreats that can be anticipated during the next million years. In their review of KBS-2, the NRC subcommittee found that the Swedish scientists had mustered impressive support for this conclusion. Little new has been added in the past five years, and there seems no point in repeating the review of old material here.

One possible question was singled out by the subcommittee as needing further attention. If, during glacial retreat, a thick front of melting ice stands for a time directly over a repository, might the huge volumes of water, under heads possibly as great as the thickness of the ice itself, alter the groundwater regime sufficiently to change the flow at repository depths? Using data from existing glaciers, one can add details to the model. Presumably, there would be a steep ice front 15 to 30 m high, then an ice surface sloping upward at an angle of no more than 10° to the central part of the glacier, where it would probably be 1 to 2 km thick. The hydraulic head in the frontal area of an active glacier may reflect the height to the top of the ice, as demonstrated in some valley glaciers by large quantities of water draining into vertical cylindrical holes through the ice. The glacial front would fluctuate from year to year, but might remain in the general vicinity of the repository for many decades. Now in such circumstances might groundwater flow increase enough to erode bentonite at a depth of 500 m? Could oxygen be introduced from the surface, leading to accelerated corrosion? If some canisters are breached early, could radionuclides be brought to the surface rapidly in large quantity? Such possibilities seem remote, but to prove them completely out of the question is difficult.

The KBS scientists further considered the influence of the ice front, in an effort to derive possible consequences and to set rough limits, but they concluded that loosely constrained variables are so numerous that the effort is futile (Leif Carlsson, Swedish Geological Survey, personal communication, 1983). As the Swedish workers point out, since the necessary combination of circumstances is so very special, since the circumstances would not arise for tens or hundreds of thousands of years (after the more active radionuclides would have decayed), since the likelihood of adverse effects is small, and since escaping radionuclides would be enormously diluted, the possibility of unacceptable exposure to a remote future generation from this cause seems entirely negligible. The panel agrees with this assessment.

3

ADEQUACY OF TREATMENT OF THE PHYSICAL AND CHEMICAL STABILITY OF THE CANISTERS AND BUFFER

Copper canisters enclosed in a buffer of compacted bentonite are the essential feature of the Swedish plan for disposal of spent nuclear fuel. The combination of canisters-plus-buffer is confidently expected to resist mechanical disturbance and chemical attack for at least a million years. If the analysis supporting this expectation is sound, other parts of the disposal plan are of secondary importance: the bedrock in which the canisters will be placed serves only the functions of providing a stable and chemically benign environment and insuring against rapid transport of radionuclides in the very unlikely event of early canister failure. The central role of canisters-plus-buffer has not changed between KBS-2 and KBS-3. A few details have been altered: the thickness of canister walls has been reduced from 0.2 m to 0.1 m; filling the canisters with copper rather than lead is proposed as a possible alternative; and adding ferrous phosphate to the backfill as a reductant is no longer advocated. Performance estimates of the canisters and compacted bentonite have been supported by more elaborate analyses and laboratory testing. But the salient features of this part of the disposal plan remain the same, and the review of these features in the previous NRC report needs only minor supplementing here. The important task in the present review is to judge how well the newer work supports and remedies weaknesses in the technical basis for the original conclusions about durability of canisters and bentonite.

Major considerations are the feasibility of canister construction, the mechanical behavior of canisters enclosed in compacted bentonite, the resistance of the canisters to corrosion and to stress-corrosion cracking, and the ability of the bentonite buffer to control access of corrosive agents in the groundwater to canister surfaces.

FABRICATION OF CANISTERS

Can copper canisters of the proposed sort be fabricated using state-of-the-art technology?

In the KBS-2 plan, canisters with walls 0.2 m thick were to be formed by forging cast ingots of oxygen-free high conductivity (OFHC) copper, establishing a suitable grain size, and machining both inside and outside to close dimensional tolerances. The thick walls were designed to minimize gamma-ray radiolysis of water at the canister surface and to insure against penetration by deep pit-corrosion. More recent studies have shown that radiolysis is adequately controlled by smaller thicknesses and that pit corrosion is slower than originally thought; the planned thickness has accordingly been cut to 0.1 m. The method of forming the canisters remains the same, and its feasibility has now been demonstrated at full scale in Swedish metal-working plants (KBS-3, p. 4:6/14; TR 83-20).

In KBS-2, after fuel rods were placed in a canister, the space around them was to be filled with molten lead, and a copper lid in three layers was to be sealed in place by electron-beam welding. Use of this procedure with canister walls 0.2 m thick was beyond the state-of-the-art at the time of KBS-2, and some question remained about its feasibility; but now that the thickness is smaller, it is well within known industrial capability. All steps in the process have been demonstrated using simulated fuel rods, and procedures for evaluating the welds and for quality assurance in the whole operation have been spelled out and tested in practice (KBS-3, p. 10:5; TR 83-20, TR 83-25, TR 83-32). An attractive alternative process is described in KBS-3. Instead of molten lead, copper powder would be used to fill the remaining space in the canisters, after which they would be sealed and the copper powder compacted by hot-isostatic pressing. This process uses a combination of high temperature and isostatic gas pressure (usually an inert gas), and would produce, in effect, a solid mass of copper around the fuel rods. Hot-isostatic pressing is a widely used industrial process, and existing furnaces in Sweden are large enough to accommodate the 0.8-m diameter proposed for the canisters. So far as the panel is aware, no existing furnaces are tall enough to handle the 4.5-m height of the canisters, but there is no known functional reason why these could not be built. Although not yet demonstrated at full scale, the proposal to fill the canisters with copper powder followed by hot-isostatic pressing seems reasonable. Whether this method or the molten lead method will ultimately be favored remains uncertain, but KBS scientists in conversation (September 1983) expressed a preference for the copper powder method.

MECHANICAL CAPABILITY

Is the mechanical capability of the canisters-plus-buffer sufficient to withstand remotely possible tectonic displacement?

Canisters of either type, filled with lead around the fuel rods or filled with copper powder and isostatically compressed, are solid cylinders of metal 4.5 m long and about 80 cm in diameter. They will be placed in vertical holes, with a diameter of 1.5 m and a depth of nearly 8 m, drilled in the floors of tunnels in solid rock. The holes are to be lined with shaped blocks of compacted bentonite, and each hole will be capped with a cover of concrete or granite. The bentonite will swell as water seeps into the holes, eventually filling all open spaces and exerting an external pressure on the canisters estimated to be 10 to 15 MPa. (One megapascal (MPa) equals 10 bars equals 9.87 atmospheres equals 145 psi). The canisters plus bentonite, from a mechanical standpoint, will be effectively a part of the rock.

A question then arises as to how effectively this combination would resist a displacement of the rock resulting from fault movement. The worst imaginable case would be a horizontal fault cutting many canisters in an array roughly at their mid-points. If the displacement is slow, the copper and bentonite would presumably be malleable enough to adjust to the deformation without serious rupture. But a sudden movement, as in an earthquake, might well fracture both the bentonite and the canisters and provide access for groundwater to the fuel rods of many canisters--just as the opening of a fracture anywhere in the rock would furnish a new channel for groundwater flow. In the opinion of Roland Pusch, the Swedish authority on bentonite, this possibility is the most serious weakness of the KBS plan (Roland Pusch, University of Luleå, personal communication, 1983). For the thick-walled canisters of KBS-2, Pusch estimated that a sudden displacement of not much greater than 0.03 m might be enough to cause serious damage; for the thinner-walled canisters of KBS-3, he would reduce the estimate to 0.01 m (TR 83-47). He hopes to devise a full-scale experiment for testing his estimates of the mechanical response to various kinds of deformation of canisters enclosed in bentonite.

While agreeing with Pusch that uncertainty about the response of tightly held canisters to sudden displacement is a real weakness in the KBS program, the panel notes that the probability of rock movement in precisely the right orientation and of the right magnitude and suddenness to do appreciable damage is exceedingly slight. Earthquakes in Sweden are uncommon, and recorded rock displacements of the last million years that can reasonably be ascribed to earthquake activity are nearly all along planes that are steeply inclined rather than horizontal. Steep or vertical displacement would be less damaging to individual canisters, and would affect only a small number. The possibility that earthquake movement might damage many canisters in a repository sometime in the next million years cannot be entirely discounted. Pusch is right in noting the possibility and seeking to bound its effects experimentally, but the panel regards the possibility as too remote to constitute a serious drawback to the KBS plan.

CORROSION RESISTANCE

Will the canisters have sufficient corrosion resistance to prevent contact of groundwater with waste for a million years?

Copper is thermodynamically stable in pure water under the proposed repository conditions, but groundwater in Swedish bedrock is far from pure. Analyses of water samples from the sites under investigation show enough potentially corrosive solutes to make questionable the ability of the canisters to survive for very long times if they were to be placed simply in contact with moving groundwater. The argument for minimal corrosion over hundreds of thousands of years is thus based, not on the thermodynamics of an unreactive metal in contact with relatively benign groundwater, but on the control of possible corrosive agents by the bentonite buffer and by reactions of the groundwater with bedrock.

The argument in KBS-3 follows the same lines as in KBS-2 (KBS-3, p. 10:8/15). The water that eventually makes contact with canister surfaces is the groundwater commonly found at depth in granitic rocks, its composition only slightly modified by the bentonite buffer. It is kept practically stationary within the buffer, and motion of solutes to and from the canister surfaces is limited to slow diffusion through 0.35 m of bentonite. The principal oxidizing agents of concern are dissolved oxygen and hydrogen ion in the presence of sulfide (the hydrogen ion being capable of oxidizing copper if the reaction is driven by the extreme insolubility of cuprous sulfide). Dissolved oxygen will be significant for a time after repository closure, because of residual air in all unfilled openings and in interstices of the backfill; but after natural groundwater conditions are reestablished, dissolved oxygen content will be kept very low by reaction with minerals containing ferrous ion in the surrounding rock. Sulfide is low in the natural groundwater because of reaction with ferrous ion to form insoluble ferrous sulfide, but dissolved sulfide can form in appreciable amounts by bacterial reduction of sulfate if organic material is present as nutrient for the bacteria. Sulfate is one of the prominent ions in the groundwater (up to 15 mg/l), and enough organic matter is commonly present (2 to 7 mg/l) to be a potential source of 1 or 2 mg/l of sulfide ion; additional sulfate, sulfide, and organic matter may be present as impurities in the bentonite. Dissolved sulfide can be kept low by oxidative preheating of the bentonite to remove most of the sulfides and organic matter, by using bentonite with a low content of sulfate, and by slowing access of groundwater from the backfill in tunnels above the canisters by placing a cap (copper, granite, or concrete) on each canister hole. These methods of control are estimated to be effective enough to limit the amount of copper converted to oxide or sulfide in a million years to no more than 30 kg per canister (out of a total single canister weight of about 20,000 kg) (TR 83-24).

Other possible oxidizing agents (sulfate acting directly, nitrate, nitrite, and hydrogen ion in the presence of chloride) are readily shown to be unimportant, either because of low concentrations or because of extreme slowness of reaction at temperatures below 80°C. Another possibility is oxidation by products of radiolysis of water at canister surfaces (oxygen and peroxides, produced together with hydrogen). Calculations show, however, that the amount of gamma radiation penetrating 0.1 m of copper would be capable of forming only enough radiolytic oxidants to combine with about 10 kg of copper in a million years, even if no recombination of the radiolysis products is assumed.

One significant difference between KBS-2 and KBS-3 is the planned mixing of ferrous phosphate with the backfill material in the former and its absence in the latter. Earlier, the addition was intended to ensure that groundwater in the repository would remain reducing. Omission of the reductant in KBS-3 is in part the result of calculations showing that ferrous ion derived from iron minerals in the bedrock is sufficient to maintain reducing conditions, and in part a response to concern that addition of yet another chemical species to the repository environment would complicate its chemistry unduly (TR-83-36).

In assessing the potential effects of corrosion on the copper canisters, the KBS-3 report consistently takes a conservative stance, generally more conservative than the stance in KBS-2. Examples of the conservatism are as follows:

1. Oxidation of copper by dissolved oxygen can proceed only at high redox potentials (ca. +50 mV), whereas oxidation by hydrogen ion in the presence of sulfide requires much lower potentials (less than -200 mV); yet both reactions are assumed to go to completion in estimating the corrosion rate.

2. No correction is made for the copper powder added to canisters made with the isostatic compression process; the additional copper would consume reactants if the outer part of a canister should be breached by corrosion.

3. In calculating the possible effect of sulfate on canister corrosion, no credit is taken for the ferrous ion in the bentonite in controlling the availability of sulfide as a corrodant.

4. Kinetic studies in KBS-3 were made for the most part with classical, well-founded procedures, but some nontraditional techniques were employed involving the concept of "equivalent flow." At the panel's request the results were recalculated by Hong Lee (University of Florida, personal communication, 1983) using classical diffusion models. The rates obtained by Lee are close to those estimated by Neretnieks (TR 83-24); but where differences exist, the Neretnieks model predicts slightly higher corrosion rates.

By way of contrast, the important effect of pit corrosion is treated less conservatively in KBS-3 than in KBS-2. The latter uses a very conservative value of 25 for the pitting factor; but the KBS-3 authors point out that, in recent metallurgical studies by the Swedish Corrosion Institute (TR 83-24), a factor of 5 has been shown to be more reasonable for the two kinds of copper (oxygen-free high-conductivity copper and phosphorus deoxidized copper) that are contemplated for use in the canisters. A maximum pitting factor of 5 is also indicated by examination of archeological specimens, native copper, and buried lightning-conductor plates (TR 83-24). In KBS-3, corrosion rates are calculated using both of these factors, but the rates obtained with the larger factor are described as unrealistically high.

Overall, the calculations of corrosion rates in KBS-3 are similar to those in KBS-2 but are improved by use of new data and new calculational methods. In the panel's opinion the calculations are soundly based and use assumptions with a safely conservative bias. The ability of canisters surrounded by compacted bentonite in Swedish bedrock to last for a million years and more seems adequately documented--provided, of course, that the canisters are made according to rigid specifications and that the subsurface environment is not subject to radical change.

STRESS CORROSION CRACKING

Will the canisters be immune to stress corrosion cracking for a million years?

One corrosion-failure mechanism that in theory might be capable of causing a catastrophic breach is stress corrosion cracking--the cracking of metal as a result of exposure of a susceptible material in a specific environment to an enduring tensile stress. The possibility of damage by such a mechanism under conditions to be expected in a Swedish repository was investigated by the authors of KBS-2 and shown to be negligible. The reason is that the necessary enduring tensile stress will not exist because of the method of canister fabrication, and in any event could not be maintained for long in a metal as readily stress-recovery-annealed as pure copper. Even if a repository were to be invaded by seawater when the land subsided under the weight of a glacier, the necessary oxidizing conditions and concentrations of nitrogen compounds would not be attained. After careful review, the NRC subcommittee agreed that a good case had been made in KBS-2 for the conclusion that the rather specific conditions needed for initiating stress corrosion cracking would not be found in a KBS repository (NRC, 1980).

The NRC subcommittee raised a possible question on the grounds that newly reported research had suggested some tendency for cracking of high-purity copper in certain nitrogen-containing environments. More recent work by Benjamin et al. (TR 83-06), however, showed that the electrochemical conditions necessary to stimulate cracking of pure copper in dilute sodium nitrite solutions are so remote from conditions expected in a repository that they eliminate stress corrosion cracking of the canisters as a source of concern.

BENTONITE BUFFER

Can the bentonite buffer around each canister and the bentonite-sand backfill in tunnels and shafts be depended on to keep the movement of groundwater along canister surfaces very slow and to maintain conditions in the repository that will prevent or greatly inhibit corrosion?

In both KBS-2 and KBS-3 the canisters are to be surrounded by shaped blocks of compacted bentonite*; and after the canisters are emplaced, a mixture of bentonite and sand is to be used as backfill in the tunnels and shafts. As groundwater penetrates the repository after closure, the bentonite is expected to swell and fill all vacant spaces, thus forming a mechanical cushion for the canisters and serving as a barrier to rapid groundwater flow. At the canister surfaces, the expanded bentonite will, supposedly, keep groundwater motion very slow and prevent movement of possible corrosive agents except by slow diffusion through the clay. To some extent the buffer will also act as a retardant for radionuclide migration should early breaching of a canister occur; this possible function is discussed more completely in the section in Chapter 4, "Retardation in the Near-Field."

*Bentonite is a naturally occurring material with considerable variation in composition and properties. The bentonite mentioned in this section and used as a reference material in the Swedish experimental work is a variety from Wyoming with a high ratio of sodium to calcium smectite.

In KBS-2 an impressive array of experimental and analytical data was presented to support the thesis that the bentonite would indeed perform up to expectations under the chemical, thermal, and radiation conditions anticipated in a repository. The data were in large part obtained by Pusch and his colleagues at the University of Luleå. In more recent years, Pusch has continued his intensive studies of the properties of bentonite and other clays, both at Luleå and in the underground experimental facility at Stripa. The present review is devoted largely to a survey of the recent findings of Pusch and his co-workers.

Some aspects of the emplacement of bentonite were questioned by the NRC subcommittee on KBS-2, particularly the feasibility of placing bentonite blocks in the holes around the canisters without leaving large open spaces, and the feasibility of compacting the backfill in the upper parts of tunnels. Both questions have now been answered by full-scale experiments at Stripa: canisters can be successfully emplaced, either by building the bentonite-block walls around them or by constructing the walls first and then inserting the canisters; and the emplacement of backfill in the upper parts of tunnels, with a final density only slightly less than that of the compacted material below, can be accomplished by a shotcrete process (Stripa 82-06, Stripa 82-07; also, presentation by Pusch to the panel, accompanied by photographs of the operations, September 1983).

The mechanical properties of highly compacted, water-saturated bentonite are of interest in ensuring that canisters do not slowly sink through the bentonite to the bottom of their emplacement holes, and that they will be to some extent protected from shear stresses that may develop in the surrounding rock. A theoretical analysis backed by laboratory experiments has shown that the swelling pressure of the bentonite (10 to 15 MPa under repository conditions) is sufficient to largely restore the original state of stress in the nearby rock. The material is strong enough that the calculated rate of canister subsidence is no more than about 0.01 m in a million years, yet plastic enough to give protection against slight rock displacements (TR 83-04, TR 83-47). As noted in the section in Chapter 3 entitled "Mechanical Capability," the protection against slow moderate displacement is adequate, but a question remains about possible rupture of a canister by rapid horizontal rock movement of more than 0.01 m.

Compacted bentonite under its own swelling pressure has been demonstrated to flow into cracks less than 1 mm wide and to seal them. It has been further shown experimentally that moving groundwater in such cracks will not, at a later time, dislodge appreciable amounts of the bentonite filling (TR 83-04).

The ability of bentonite to control groundwater movement and the movement of dissolved ions is shown by measurements of hydraulic conductivity and diffusivity. For bentonite compressed to a density of 2.0 t/m^3 (tonnes per cubic meter, an SI unit numerically equivalent to grams per cubic centimeter), Pusch gives a conductivity of 5 x 10^{-14} m/s (TR 80-16), a value corroborated, within an order of magnitude, by recent experiments in the United States (Peterson and Kelkar 1983). For bentonite-sand mixtures like those to be used for backfill, Pusch and Börgesson (Stripa 82-06) give experimental values for hydraulic conductivity:

With 10 percent bentonite, at a density of 2.1: 10^{-9} m/s

With 20 percent bentonite, at a density of 2.1: 10^{-10} m/s

In similar experiments, Peterson and Kelkar found

With 10 percent bentonite, at a density of 1.98: 6.1 x 10^{-9} m/s

With 30 percent bentonite, at a density of 2.29: 2.2 x 10^{-12} m/s

The agreement is satisfactory, and the range of values is similar to that for the matrix of granitic rock between major fractures. This finding indicates that the backfill in tunnels and shafts will have a permeability comparable to that of its surroundings. Because of the low hydraulic conductivity, motion of ions through the water-saturated bentonite will be dominated by diffusion; for the diffusivities of different ions, Pusch gives values in the range 8 x 10^{-12} to 5 x 10^{-11} m^2/s.

The chemical properties of bentonite vary considerably from one sample to another. In KBS-2 the favored bentonite was a variety from Wyoming rich in Na-smectite; this material is still used as a reference standard in KBS-3, but a search has been undertaken to find sources that are cheaper and closer to Sweden. Pusch has examined bentonites from many localities, mostly European, and finds much variation in the ratio of Na-smectite to Ca-smectite, the ratio of smectite to other clay minerals, and the content of such impurities as quartz, carbonate, sulfides, sulfates, and organic matter (TR 83-46, and personal communication, 1983). For most repository purposes, a fairly pure Na-smectite is preferable. The composition of bentonite can be somewhat modified, if desirable, by currently available commercial processes: sodium may be substituted for calcium, and much of the sulfide and organic impurity can be removed by several hours of oxidative heating to about 400°C. At the time of the KBS-2 plan, Pusch had reservations about the possible effect of heating bentonite to 400°, on the grounds that its structure might be irreversibly altered and its expansive properties impaired; but results of recent experiments have convinced him that the change in properties is minor if the heating is not continued too long. No final choice among the varieties of bentonite has yet been made, but Pusch is confident that one or more good sources can be found and that the composition can be altered, if necessary, to meet KBS requirements.

Whatever the source of bentonite, the KBS authors think it can be depended on to keep the rate of corrosion low. Presumably, a bentonite with low sulfate content will be selected, and its sulfide and organic content will each be reduced below 200 ppm by oxidative heating. The buffer will limit the supply of water reaching the surface of canisters to a calculated 0.2 to 1.6 l/yr/canister (KBS-3, p. 20.15), and the amount of oxidants in this quantity of water would be trivial. Bentonite is also known to buffer the pH of contained water to values between 8 and 9.5, thus effectively preventing possible corrosion by hydrogen ion in the presence of chloride even up to seawater concentrations of chloride; if the buffer capacity of the bentonite is ever used up (doubtful, because the pH of the groundwater is generally between 7.5 and 9.5, so that little buffering is needed), the bedrock itself would serve to hold the pH in this range. Possible oxidation of copper by the products of radiolysis is largely prevented by the buffer's ability to slow the escape of hydrogen, and hence to promote the recombination of the radiolysis products. Thus, if the buffer behaves even approximately as expected, the rate of corrosion of canister surfaces will be kept to a very small value.

In summary, the panel believes that the experimental data and calculations described in KBS-3 and its technical documents effectively support the KBS claims that, in the system of copper canisters plus bentonite, the canisters are adequately protected from corrosion and stress. The swelling pressure, bearing capacity, and plasticity of the bentonite will provide good mechanical protection; its low hydraulic conductivity will serve as a barrier to active groundwater flow and will maintain a controlled low-corrosion environment immediately adjacent to the canisters.

4

ADEQUACY OF TREATMENT OF RADIONUCLIDE MOVEMENT

The primary barrier against radionuclide release in the KBS plan is the copper canister enclosed in its nest of compacted bentonite. If this barrier functions as planned, safe isolation of waste for a million years and more could be guaranteed in any kind of rock, at any depth where groundwater is not actively flowing or markedly corrosive. But some unexpected, very low probability event is always possible, and the KBS authors devote much effort to showing that the kind of rock they plan to use for a repository, at a depth of 500 m, aided by the bentonite buffer, will constitute an adequate secondary barrier for controlling radionuclide release even if something goes radically wrong.

Suppose that a canister is breached so effectively that all of its contained fuel is at once in contact with groundwater. This is the extreme situation that the KBS authors postulate in calculating rates of radionuclide migration. The extreme nature of the assumption should be kept in mind. Certainly it is plausible to expect that a few canisters will fail prematurely, because of flaws in manufacture or some very unusual natural disturbance; but the failure in all probability would be only a minor crack permitting very limited access of groundwater to the fuel. Dissolution of radionuclides would be slow and localized, and the quantity being added to groundwater at any time would be small. But the extreme assumption of instantaneous exposure of much fuel to groundwater is useful to explore as a means of assessing just how conservative the KBS design is.

Nuclides dissolved from fuel elements exposed in a breached canister will move first by slow diffusion through the buffer (provided the buffer is still reasonably intact), and then into the surrounding rock, where motion will be in large part by diffusion through water contained in narrow cracks and to a lesser extent by diffusion into the rock matrix. For discussing the motion, a distinction is made in KBS-3 between the "near-field" (the buffer and the rock within a few meters of it, where the major questions concern the rate of dissolution and then diffusion in clay and small fissures), and the "far-field" (bedrock between the near-field and the point where groundwater enters a major fracture). An additional consideration is a possible short-circuit path to the biosphere by flow of groundwater through tunnels and shafts, either because the backfill is an inadequate barrier or because rock adjacent to the tunnels and shafts has been rendered more permeable by blasting during repository construction. These three items--migration of radionuclides in the near-field, migration in the far-field, and the effectiveness of planned seals in controlling migration along tunnels and shafts--are discussed in the following paragraphs. A final section presents a brief analysis of the estimates of doses to humans that would result from radionuclide transport. The treatment in KBS-3 is similar to that in KBS-2, but additional experiments, field tests, and mathematical analyses are adduced to support the conclusions.

RETARDATION IN THE NEAR-FIELD

To what extent will slow dissolution and diffusion through bentonite and adjacent small fractures control the migration of radionuclides away from a breached canister in the near-field?

Dissolution. In estimating the rate of dissolution, the KBS-3 authors note that the radionuclides formed from uranium atoms by fission or neutron capture will in large part remain dispersed within the uranium oxide pellets, and hence will dissolve only as fast as the crystal structure of UO_2 is destroyed by the dissolving of uranium. The isotopes of Cs and I are treated as an exception, because they or their precursors are sufficiently volatile to move through the crystal structure to the outer part of the pellets. As long as conditions remain reducing, dissolution is slow because it is controlled by the very low solubility of UO_2 (1 to 2 μg/l). The rate, however, may be affected by radiolytic decomposition of water, and this possibility is examined in detail in

KBS-3. Irradiation of the water in contact with the fuel pellets will produce hydrogen and peroxy free-radicals; the escape of hydrogen gas may make the groundwater in close proximity to the canister highly oxidative. In this oxidizing water, uranium would be much more soluble, as would be Tc, Np, and Pu. The oxidized forms of these elements could diffuse into the buffer, but within a short distance would encounter the prevailing reducing conditions and would tend to precipitate. The calculations indicate that even with the most generous assumptions about the efficiency of radiolysis and escape of hydrogen, the effects of oxidation would be limited to a zone within a few meters of the fuel (TR 83-66, TR 83-68).

Thus, in most of the near-field, the amounts of radioactivity moving through the buffer and adjacent rock would be limited by the low solubility of many of the elements in a reducing environment and, for the more soluble elements, by the rate of dissolution of the uranium oxide.

As a general confirmation of the low solubility of uranium in reducing groundwater (and hence of the low leachability of nuclides dispersed through UO_2 pellets), uranium concentrations were measured in many samples of water obtained from the recently studied field areas. These concentrations, presumably representing equilibrium with uraninite (UO_2) known to be present in traces in much of the Swedish bedrock, are all below 10 μg/l, and mostly below 1 μg/l, in agreement with values calculated from thermochemical solubility data (TR 83-40).

Migration. The dissolved nuclides will diffuse through the buffer away from the fuel rods at widely different rates. Some will be greatly retarded by sorption, others scarcely at all. For nuclides that diffuse slowly and are strongly sorbed (most of the actinides, for example), the delay in moving through 0.38 m of compacted bentonite could amount to thousands of years (TR 82-27). Eventually, however, a steady state will exist in which about as many nuclides are escaping from the buffer's outer surface as are entering its inner surface from the dissolving fuel pellets.

Thus the migration of nuclides in the near-field can be broken down into a transient phase and a steady-state phase. The transient phase is important only for those nuclides that will be retarded for lengths of time many times greater than their half-lives. Calculations show that a few nuclides will decay significantly as they migrate through the bentonite; e.g., ^{241}Am would decay to innocuous levels in the buffer, and the activity of ^{239}Pu would be reduced about tenfold (TR 82-27). For many radionuclides, however, their transit time in the buffer is not long enough to permit significant decay. For this reason the KBS authors, in calculating release times into the far-field and into the biosphere, assign no credit to retardation in the buffer.

The steady-state phase is more important than the transient phase in assessing migration through the near-field. In the steady-state phase, the concentration of a nuclide moving into the far-field depends on the reductive precipitation and the diffusive resistances of the buffer and of the water in small bedrock fractures that makes contact with the buffer. Calculations indicate that the latter is more important than the former, if it is assumed that, on average, one fracture of width 0.1 mm intersects each meter of bentonite and hence that the cross-sectional area for flow is much less in the rock than it is in the clay (TR 82-24, Table 2.2). The diffusive resistance of the buffer is small enough to be neglected, and the quantity of any nuclide transported to the far-field can be calculated from the diffusive resistance in the water-bearing fractures, expressed as "equivalent water flow." This quantity is calculated from an assumed groundwater flow rate at repository depth.

Thus the calculated migration rates through the near-field depend on a series of assumptions, which lead to the conclusion that the buffer plays only a minor role in both transient and steady-state phases. The panel was concerned about the degree of conservatism involved in the basic assumptions, given the uncertainties in estimates of groundwater flow rates. When asked about the conservatism, Ivars Neretnieks (Royal Institute of Technology, personal communication, 1983) pointed out that, even with much different assumptions, the integrity of the bentonite as a retardant for groundwater has little importance in the near-field calculations, and also that the "equivalent water flow" is not very sensitive to the assumed Darcian velocity (a tenfold increase of the latter increases the former only threefold). Even in the absence of any bentonite buffer, radionuclide concentrations in the geosphere and biosphere would increase only twenty-fivefold for the most pessimistic water flow rates and at most threefold for more representative flows (Ivars Neretnieks, Royal Institute of Technology, private communication, 1983). The panel concludes that the assumptions are adequately conservative for estimates of radionuclide concentrations delivered to the far-field.

This does not mean that the important diffusion processes have been completely and rigorously studied. The Swedish scientists recognize this lack ("Diffusion through compacted bentonite is governed by complex mechanisms and cannot be accommodated by a simple pore-diffusion model." TR 83-37, p. 17) and plan additional research on diffusion rates. The Soret effect and surface-migration mechanisms (versus pore diffusion) are examples of topics that are not yet completely documented. But in the panel's opinion, the refinements to be gained by additional research are not likely to change greatly the current estimates of migration rates in the near-field.

RETARDATION IN THE FAR-FIELD

If radionuclides escape from the near-field into the groundwater of the far-field, will retardation, dispersion, and dilution in the bedrock be sufficient to keep concentrations acceptably low?

General. Movement of radionuclides in the far-field of a Swedish repository--that is, movement through granitic or metamorphic rock between the immediate vicinity of breached canisters and the biosphere--is one aspect of the general problem of how effectively natural rock environments can be expected to control nuclide migration. Debate on this subject has gone on for many years, and there is still no prospect of a definitive answer. The difficulty is that radionuclide movement depends on many variables, not all of which are easily measurable. Values for some variables can be obtained in laboratory experiments, but then questions arise as to how closely laboratory conditions simulate those in nature. Experiments in the field are often useful, but they are limited by the long times commonly required and by uncertainties about rock properties in the inaccessible parts of a rock mass. Research in this area is necessarily a multiyear and multicountry enterprise, and the KBS authors have been active participants since their project was started. Recent progress in Sweden has been especially notable along two general lines, dispersion phenomena and sorption, and the panel's review focuses primarily on these subjects.

It should be noted to begin with that one basic premise has changed. In KBS-2 the movement of radionuclides was assumed to take place from a repository at a depth of 500 m through partly filled fractures and crush zones to the land surface; hence the radionuclides would be subject to retardation by sorption both in the fracture fillings and in the rock matrix throughout the entire distance. The more conservative KBS-3 model pictures a repository shielded from major fractures zones on all sides by at least 100 m of relatively impermeable rock, and the only effects of dispersion and sorption considered are those that occur during movement through this 100-m thickness. Once in a fracture zone, radionuclides are assumed to have free access to the biosphere, where radionuclide concentrations are affected only by dilution or by chemical processes at the receptor location.

Dispersion. In a porous medium, dispersion can be adequately described by a convective-diffusion equation, using a dispersion coefficient that is fixed for a given flow field (Bear, 1972; Anderson, 1979). In fractured rock, the dispersion phenomenon is much more complex. Over the past several years, Neretnieks and his co-workers have advanced considerably our quantitative understanding, making it possible to reproduce reasonably well with mathematical models many of the salient features observed in experiments with tracers in fractured rocks.

One modification of the dispersion theory for porous media that must be made for application to fractured material is to allow for diffusion from fractures into the adjacent relatively unfractured rock, referred to in KBS-3 as the "matrix" or "rock mass" (Neretnieks, 1980). A second modification is to introduce "channeling," the variation in size of fractures that leads to faster flow in some than in others. Dissolved material is thereby dispersed because of the differences in velocity among channels as well as through other mechanisms, e.g., hydrodynamic dispersion. Neretnieks (TR 82-03, TR 83-69) has developed a model, called the "stratified-flow model," that takes both channeling and diffusion into rock adjacent to fractures into account. This is a new concept in the modeling of dispersion in fractured rocks; the only additional information required in this model, over and above that in standard dispersion models, is the size-frequency distribution of the fractures. One prediction from the stratified-flow model, i.e., that dispersion increases with distance of travel, has been verified in field tests at both Finnsjön (TR 81-07) and Studsvik (TR 110, TR 82-10).

Other models can be used to calculate dispersion effects in fractured media, for example, a hydrodynamic dispersion model in which the dispersion coefficient is made to increase with spatial scale (thereby mimicking the observed behavior at Finnsjön and Studsvik). This can be done by requiring that the Peclet number, rather than the dispersion coefficient, remain constant. Reasonable agreement with experimental results can be obtained with this model, using a wide range of values for the Peclet number.

Neretnieks is aware, of course, that much additional work is needed to perfect the dispersion models for fractured rocks, but a good start has been made toward understanding the complex phenomena involved.

Sorption. The extent to which sorption can be expected to retard the movement of radionuclides dissolved in groundwater is particularly difficult to estimate. A common procedure is to measure sorption in the laboratory, either by letting a radionuclide solution stand in contact with crushed rock or by arranging a system of constant flow, and then to assume that the laboratory results will apply to rocks in-situ. The method is subject to criticism on several grounds: laboratory conditions may differ markedly from those in nature; the radionuclides in a natural environment may be in a different oxidation state or in the form of complexes with very different sorption properties; and the nuclides may be carried in groundwater as colloids, and for that reason may be more mobile than laboratory results would indicate. Despite these cogent objections, laboratory experiments seem the only feasible way to get rough estimates of the role of sorption in nature, and much effort has been concentrated on improving the experiments so as to counter the objections. In this effort the KBS scientists have played a major part, especially in the last few years.

Basic laboratory data on sorption coefficients (K_d's) have been generated in abundance by Allard, Rydberg, and their colleagues at Chalmers University (e.g., TR 82-21, TR 83-07, TR 83-61). A substantial part of the tabulated data now used worldwide comes from this laboratory, and of course the Swedish workers are continually in touch with similar work in progress elsewhere. The tabulated values for sorption coefficients in KBS-3 (Table 12-7), changed slightly from those in KBS-2, are generally similar to values in recent American publications (Moody, 1982; NRC, 1983) although somewhat larger for the actinide elements.

In the KBS work, laboratory methods for determining sorption coefficients were refined long ago in the more obvious ways of ensuring similarity with natural environments: use of groundwater samples in the experiments; excluding oxygen and carbon dioxide; control of Eh, pH, and temperature; and exposure of both fresh and altered mineral surfaces. Recent results from the continuing laboratory effort have established (1) that sorption of a given nuclide is a maximum in the pH range where neutral hydroxide complexes of the nuclide are dominant in solution, (2) that the sorption of actinides in their lower oxidation states is independent of ionic strength over much of the pH range, and (3) that the amount of sorption on granitic rock can be approximated by a formula using K_d's for individual minerals (TR 82-21). A literature survey of work on organic complexes leads KBS scientists to conclude that increased mobility of radionuclides from this cause is not a serious problem in Sweden, because the content of organic matter in the groundwater is low and because many organic complexes are markedly sorbed on mineral surfaces (TR 83-09). The possible flooding of sorption sites by lead ions dissolved from the canister filling was considered in the review of KBS-2; if KBS-3 adopts the alternative of an all-copper canister, as seems likely from conversations with Swedish scientists, a flood of lead ions (and also possible galvanic reaction with copper) is no longer a concern.

In addition to the continuing work on sorption coefficients and complexes of various sorts, much recent effort has been devoted to the question of the role of colloids, especially for the actinide elements (TR 83-08). Experiments in the presence of air showed, for example, that Am and Pu form colloidal particles as the pH is raised from low values; but Np and U do not, presumably because they are complexed by carbonate. Precipitation of the Am colloid increased, as would be expected, with increasing ionic strength and increasing temperature. Comparison of solutions of colloidal and noncolloidal Am passed through a column of crushed granite showed little increased mobility for the colloid; evidently these colloidal particles were sorbed as readily as the dissolved ions. Certainly not all the nagging questions about colloids and complexes are answered by the new experimental work, but a good start has been made.

In a different kind of experiment, the movement of radionuclides dissolved in artificial groundwater was followed along a single fissure in a cylindrical specimen cut from a drill core (TR 83-01). Three nuclides were used: Eu^{III}, Np^{V}, and Pu^{IV}. As would be expected from batch experiments, Np showed little retardation, Pu a great deal, and Eu intermediate values. K_d's calculated from the flow experiment were somewhat larger than those obtained from static batch experiments, but the agreement was fairly good.

Clearly, it would be desirable to check laboratory results with sorption measurements made in the field, and in this difficult enterprise the KBS scientists have been especially active. At Studsvik, where solutions could be injected in three holes spaced at various distances (up to 30 m) from a central borehole that could be pumped, the movement of Sr permitted a calculation of K_d giving values in the range 4 to 6 m^3/t, which checked well with numbers obtained from laboratory batch experiments using the same kind of rock (6 to 8 m^3/t) (cubic meters per tonne, an SI unit numerically equivalent to milliliters per gram) (TR 83-18). These are unusually low values for Sr, but the check is satisfying. Cs migrated so slowly that K_d could only be estimated as greater than 30--at least an order of magnitude greater than for Sr, in agreement with most laboratory results. A similar experiment with Sr at Finnsjön showed less satisfactory agreement with laboratory values, probably because fractures here are lined with calcite, which has poor sorptive properties (TR 81-07). In the experimental facility at Stripa, a study is under way to follow details of the diffusion of solutes into the rock matrix as solutions move along a small fissure. Preliminary results show satisfactory agreement with diffusivities previously obtained in the laboratory (TR 82-08, TR 83-39).

The above discussion is a brief and incomplete sampling of recent Swedish work on retardation. Despite these efforts, the proof is not complete--and probably never will be--that laboratory data on retardation by sorption are adequate for completely reliable predictions of radionuclide movement from a breached canister to the biosphere. The number of variables in laboratory work, plus the much larger number in natural environments, is simply too great for complete control to be achieved--as is witnessed by the wide disparity in values often reported for experiments conducted under seemingly identical conditions. The KBS scientists, nevertheless, have succeeded in gaining much understanding of the effects of the more important variables, such as pH, Eh, temperature, ionic strength, complexing, and colloidal behavior. In the panel's opinion, recent work has added greatly to this understanding and created increased confidence that the Swedish estimates of rates of radionuclide transport are soundly based. The estimates will be even better when some of the research in progress is completed, but the additional refinements are hardly needed as long as conservative values are used in the calculations. Despite the reasons for skepticism alluded to above, the panel thinks that the KBS authors have developed a sound scientific basis for their conclusion that the barrier to radionuclide movement provided, to some extent, by the bentonite buffer, but mainly by the bedrock will be adequate insurance against unacceptable releases to the biosphere even in the very unlikely event of large-scale canister failure.

Dilution. When contaminated water moving along a fissure zone from the repository comes in contact with the biosphere, for example when it flows into a well or lake, it will be greatly diluted by uncontaminated water from near-surface sources. The radiation dose to users of the water depends on the amount of dilution. In KBS-3 the contaminated water is assumed to be diluted 10,000 times before it is consumed by humans, but the basis for this assumption is questionable. According to Tönis Papp (KBS, personal communication, 1983), 10^4 was chosen as a "reasonably conservative" value after review of available information.

Quantitative estimates of the dilution factor for wells range very widely, from 10^2 to 10^7. The lower part of this range (10^2 to 10^5) is advocated by Thunvik (TR 83-50), who uses a finite-element model to calculate water flux through the repository and into a well for several combinations of boundary conditions and well-repository configurations. The model rests on the assumption that flow in fractured granite can be treated as porous-medium flow. The lowest figures from the model are about 10^2 for a well 200 m deep (much deeper than most domestic wells in Sweden) and 10^3 for a well 60 m deep. Other KBS authors (Tönis Papp, KBS, personal communication, 1983) think that Thunvik's assumptions for deriving the lowest factors (high withdrawal rate and little infiltration from the land surface) are unrealistic. Carlsson (TR 83-45), using a different model, calculates factors ranging from about 10^5 to 10^7, based on assumptions that other KBS authors regard as somewhat optimistic. The chosen figure, 10^4, is a compromise among these widely diverse estimates.

The panel has little basis for judging the suitability of 10^4 as a dilution factor for the well scenario. It is indeed "reasonably conservative," but perhaps not conservative enough for a safety analysis that claims to be based on pessimistic choices throughout. There seems no reason to dismiss out-of-hand the assumptions behind Thunvik's lower estimates. If a factor of 10^3 were used instead of 10^4, calculated radiation doses would still be acceptably low except for the most extreme scenarios of early canister failure. The panel suggests that model-dependent uncertainties in estimating the factor may be reduced by incorporating fracture-flow considerations into the calculation of dilution at various receptor locations.

In the case of a lake, dilution is determined by the lake volume and the turnover rate, with the assumption that all of the contaminated water from the repository enters the lake. Lakes with low inflows and turnover rates represent unfavorable conditions for dose calculations, and so Morpa Lake in the Fjällveden area was chosen for the scenario calculations (TR 83-49); for this lake a dilution factor of about 10^6 was estimated.

TUNNEL SHAFT, AND BOREHOLE SEALING

Can tunnels, shafts, and boreholes be sealed effectively enough to keep movement of water no faster than through adjacent undisturbed rock?

Shafts and tunnels used in constructing a repository, as well as boreholes that may have been drilled during preliminary exploration, must be filled and sealed when the repository is ready for closure, to prevent their becoming channels of easy groundwater flow that could bypass the normal slow movement through relatively impermeable rock to major fissure zones. Methods of filling and sealing described in KBS-3 are similar to those in KBS-2: boreholes will be plugged with bentonite, and tunnels and shafts with a bentonite-sand mixture; to prevent movement of fluids through the disturbed zone adjacent to tunnels and shafts produced by blasting, seals will be constructed at intervals by sawing slots through the disturbed zone into sound rock and filling the slots with compacted bentonite blocks.

The NRC subcommittee reviewing KBS-2 thought that the planned sealing procedures were a weak spot in the KBS proposal, especially since their practicability and effectiveness had not been demonstrated in the field. To some extent this deficiency has been remedied by recent work. Regarding emplacement of backfill, Pusch (TR 82-07 and 1983 personal communication, accompanied by recent photographs) reported that he and his colleagues, using an experimental tunnel in the granite at Stripa, have shown the feasibility of emplacing backfill by mechanically compacting layers of sand-plus-bentonite on the floor and then filling the upper part of the tunnels by use of shotcrete equipment. The shotcreted material remained homogeneous and had a density only slightly less than that of the compacted layers below. An experiment is under way at Stripa to demonstrate the sealing of a tunnel by filling a slot sawed through the disturbed zone with compacted bentonite blocks and concrete (Roland Pusch, University of Luleå, personal communication, 1983). To ensure the complete filling of boreholes with bentonite, Pusch (TR 81-09) has devised an ingenious method of placing cylinders of compacted bentonite in perforated copper tubing that is then inserted into the borehole. As the bentonite absorbs water, it swells through the perforations and ultimately fills the entire hole. The method has proved successful in both laboratory and field experiments. In the field experiment (at Stripa), overcoring of the filled borehole and slicing of the extracted blocks for examination showed that the bentonite had expanded uniformly and formed a tight seal against the rock walls.

The experiments are impressive, but whether they are sufficient to silence all doubts remains unclear. A recent American technical report (Meyer and Howard, 1983) on the use of clays for repository sealing emphasized the need for research into the long-term stability and even solubility of clays, their possible reactions with adjacent rock, and methods of emplacement so as to ensure a tight seal. Pusch and his colleagues at Luleå have made a good start at this kind of research, but additional in-situ experiments would make the demonstration more convincing.

In the panel's opinion, the KBS conclusion that openings into a repository can be adequately sealed has much better support than it did five years ago. Continuing research may take care of remaining uncertainties long before the actual sealing of a filled repository is necessary. It should be kept in mind also that the adequacy of seals in a wet-rock repository is important only in the unlikely event of early failure of a large number of canisters.

CALCULATIONS ON RELEASES TO THE BIOSPHERE

Are the calculated radiation exposures to present and future populations based on adequate data and analyses?

Evaluation of the feasibility of safe disposal of spent nuclear fuel depends ultimately on the calculated radiation doses to this and future generations from the radionuclides that may escape from a repository. The dose calculations for KBS-3 (TR 83-49) are made using a compartment model to simulate the various pathways by which radionuclides can move to human beings from assumed contaminated water sources. The KBS-3 authors make dose assessments primarily for two pessimistic receptor locations in water--a well drawing from a contaminated fracture zone in bedrock and a lake with very slow turnover--as well as for a special scenario where a lake eutrophies to become a peat bog that is used 10,000 years later as a soil conditioner. Concentrations in the water sources are estimated by using some of the models described in preceding sections, starting with dissolution of spent fuel pellets, tracing the movement of leached nuclides through the near-field and far-field, and finally postulating substantial dilution as contaminated groundwater approaches the places where water is obtained for human use. Different concentrations are obtained at the receptor locations depending on various postulated sequences of events ("scenarios") by which canister failure and exposure of fuel to groundwater might take place--different assumed times at which canisters are breached, different numbers of canisters affected, different chemistries of the invading and downstream groundwater. The worst-case scenarios described in TR 83-49 assume transport chemistries that lead to high solubility (oxidizing conditions throughout--Scenario C) or little sorption (colloid transport--Scenario D). Even such unlikely radionuclide transport conditions produce radiation exposures that are at least 100-fold less than International Commission on Radiological Protection (ICRP) limits.

If a single canister somehow fails completely within the first century after repository closure (Scenario B), exposing all of its contained fuel to oxidizing groundwater, the derived doses are surprisingly small, roughly 100,000-fold less than ICRP limits. Even with a far more extreme assumption, involving the highly improbable simultaneous early failure of all the canisters rather than a single one, the resulting calculated dose (4400 times the dose in Scenario B) to a maximally exposed individual would be approximately 4 mrem/yr (0.04 mSv/yr) (millisieverts per year; 1 mSv = 0.01 millirem). This level of exposure is about 4 percent of the ICRP limit for an average individual in a nearby population and 1 percent of the ICRP limit for the maximally exposed individual. Since the postulated sequence of events is hardly credible even as a worst-case scenario, this result shows that requirements of the "stipulation law" are certainly satisfied--provided that the calculations leading to the dose estimate are reliable. How secure is the basis for these calculations?

Reliability of the calculations depends on (1) the validity of the models and (2) the assumptions made as to the values of parameters used in the models. The effort by the KBS-3 group in the development of models (especially the fracture flow work of Neretnieks) is impressive. A complex box (compartment) model has been used to describe the dynamic processes that distribute both radioactive and nonradioactive substances throughout the biosphere, with simplifications tailored to the variables important to a specific site.

The BIOPATH model (Bergström and Röjder, n.d.; TR 83-40, TR 83-28), selected for dose assessment in KBS-3, calculates internal and external radiation doses to individuals living in four ecosystems, each of expanding breadth. Thus, the accumulation of radiation doses by an individual has been evaluated from sources local (e.g., well-water and/or crops), regional (e.g., meats, fish and dairy products), intermediate (e.g., shellfish from the Baltic), and remote (e.g., ocean fish) to his immediate environment. Collective (population) dose is calculated by summing the annual individual doses.

BIOPATH is a system made up of a finite number of reservoirs (at this time, up to 20 compartments), each of which is homogeneous and well-mixed, and the compartments interact by exchanging elements. The dispersion rates and deposition sites are mainly governed by the calculated turnover rates of the elements and the compartment size chosen (either volumetric or gravimetric). The exchange of each element and corresponding radionuclides between reservoirs is described in the model by first-order rate equations that depend on transfer coefficients expressed as turnover rates. All of the interactions between the most important reservoirs that may contribute to radiation exposures in the near and distant future appear to have been adequately accounted for in BIOPATH. Compartment models of this type have been used extensively to evaluate biospheric transport of radionuclides produced in nuclear weapons tests and by natural processes.

The parameters used in the BIOPATH calculations include nuclide-independent and nuclide-dependent transfer coefficients, retention and weathering fractions, terrestrial and aquatic yield values (productivity), and diet and consumption rates. Bergström provided an extensive evaluation (TR 83-28) of these parameters and the values chosen for them. Where a range of values is available for any parameter, the geometric mean is generally selected as input, although pessimistic values were selected in a few instances where the range was extreme. The values for the parameters appear to be well-documented and to have been selected from an abundant source of references of international scope; we judge them to be sufficient for dose assessment.

The BIOPATH code also makes use of dose conversion factors (in sieverts per becquerel (Sv/Bq)) as revised by Johansson (TR 82-14) from values originally developed by the ICRP (ICRP-30). For the most part, the revisions consist of estimating the dose commitment for a 70-year integration period (full lifetime) rather than a 50-year period (occupational lifetime) as used by ICRP. The change in integration period causes only a small increase (less than twofold) in the dose commitment for most radionuclides. For three radionuclides, ^{239}Pu, ^{231}Pa, and ^{237}Np, new uptake data suggest a fivefold increase, an eightfold increase, and a ninefold decrease, respectively, from the ICRP-30 values. These departures from ICRP recommendations appear to be justified adequately by appropriate references.

A sensitivity analysis has been performed (TR 81-03) for an earlier version of the BIOPATH code (TR-100). Thus, the panel believes that the KBS-3 authors have developed in the BIOPATH code a model that adequately represents the complex biospheric and dietary processes that contribute to radiation exposures.

The panel found it difficult, however, to follow just how the KBS authors use each model and how the models and input data are fitted together to arrive at a dose estimate. For example, to calculate dose for the postulated pathway in which water is obtained from a contaminated well, it appears from pages 92 to 93 of TR 83-45 that only a simple analytic solution to the pore-flow model is used to obtain a dilution factor as input to the calculations in TR 83-49. Yet page 10 of the latter document states that the dilution factor comes from a different calculation in TR 83-50. The use of different models may not lead to great differences in calculated dose. However, the uncertainty in the method of calculation is disconcerting, because it cannot be tested readily within the framework of the safety analysis as performed for the KBS-3 report.

In response to the panel's request for clarification, Tönis Papp (KBS, private communication, 1983) provided a calculation scheme specifying the model used at each step of the safety evaluation, as well as the points at which judgmental factors influenced the input data. That diagram is reproduced here (Figure 4-1) as a description of the panel's understanding of the actual sequence of calculations and data input used for the KBS-3 safety analysis for the well recipient. In the diagram, model calculations or analytic solutions are represented by rectangles with the appropriate supporting report referenced, whereas each rhombus represents a judgmental decision for which an explanation can be found in the referenced KBS-3 chapter, and input-output data are represented by arrows.

As shown on Papp's diagram, the "hydromodel" of TR 83-45 is used to obtain an estimate of flux, U_0, through the bedrock surrounding a repository. The single-value output from the hydromodel is used directly as input to the near and far-field calculations (TR 82-24, TR 83-48) to obtain an estimate of the equivalent water flow past each canister, Q_{eq}. Although the Canister Corrosion calculations indicate canister breaching will not occur before 10^6 years and perhaps not until 10^8 years, the KBS authors pessimistically assume as input to the calculation of Fuel Dissolution that canister failure will begin at 10^5 years with the last canister failing at 10^6 years. As noted in the section in Chapter 4 entitled "Retardation in the Far-Field," evaluation of dilution factors for the well recipient ranging from a worst-case value of 10^2 (TR 83-50) to a highly optimistic value of 10^7 (TR 83-45) led to selection (rhombus indicating KBS-3, Chapter 15.2.1) of a dilution factor of 10,000 as input to

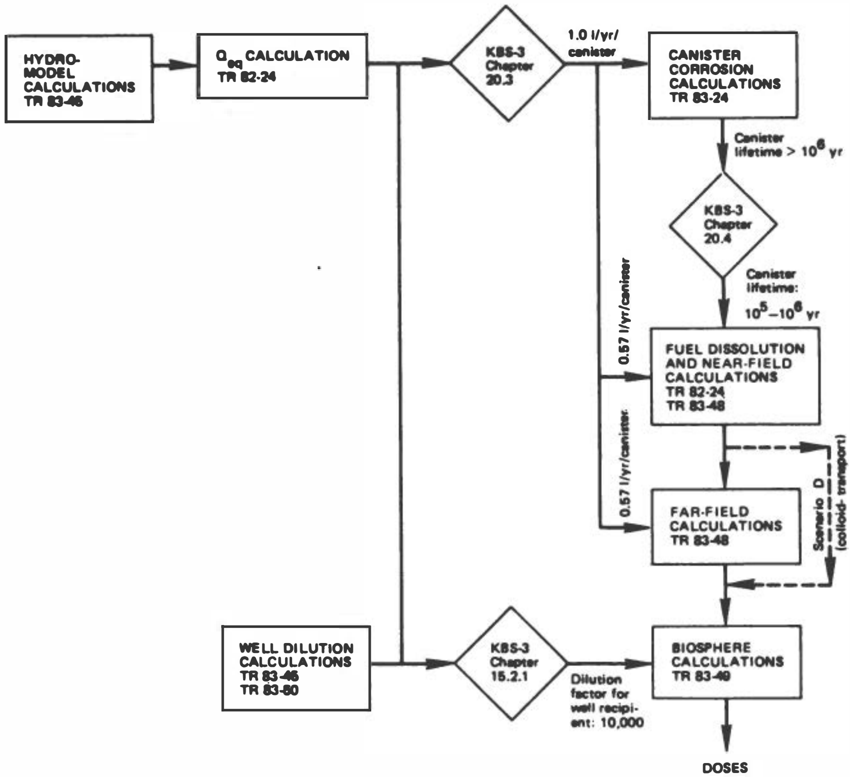

FIGURE 4-1 Calculation sequences in KBS-3.

Biosphere Calculations (TR 83-49) in combination with output from Far-Field Calculations. The safety analysis for a lake recipient is performed in an analogous manner, except for substitution of turnover rates in Morpa Lake (TR 83-52) to estimate a dilution factor for the lake recipient (KBS-3, Chapter 18.2.5).

For parameter values, the KBS authors maintain that "pessimistic" or "conservative" assumptions are consistently used. That is, if a choice or a range of values is available, the number chosen is one that would lead to overestimation rather than underestimation of the resulting dose. In general, the choices do indeed tend to be pessimistic, but in a few instances the pessimism can be questioned. The aforementioned selection of a 10,000-fold dilution from the repository to a well is probably the most important one. As another example, the main scenario assumes failure of the first canister 10^5 years after repository closure and failure of the others at regular intervals of 250 years thereafter, with fuel dissolution occurring over five million years; a higher rate of release may occur should many canisters fail at intervals grouped more closely around the time of average canister life (Chu et al., 1983), or should dissolution of the fuel occur at a greater rate (NRC, 1983). Also, the retardation factors used for KBS-3 (TR 83-48) are somewhat larger (therefore leading to smaller or more "optimistic" doses) than the factors used in some recent U.S. reports (NRC, 1983; Moody, 1982).

Failure to use pessimistic values for every parameter, however, may not seriously affect the estimated doses, especially when the uncertainty in some of the values is very large. For each of the above examples, the KBS-3 authors have provided to the panel persuasive arguments in support of the parameters selected (Tönis Papp, KBS; Ivars Neretnieks, Royal Institute of Technology; Leif Carlsson, Swedish Geological; and B. Allard, Chalmers University of Technology; private communications, 1983). They state, for example, that according to studies by the Swedish Corrosion Institute (TR 83-24), canister failure should be assumed to occur at times 100- to 1000-fold longer than those assumed for the KBS-3 calculations, with a resultant spreading of the failure times (contrary to Chu et al.). Furthermore, based on equivalent water flow and groundwater composition, they believe that chemical solubility limits will restrict the fractional dissolution rate for the fuel to at most 10^{-7} per year, with more likely rates extending to 10^{-8} per year or less. The factors selected for radionuclide retardation are justified by the KBS-3 authors on the basis of extensive laboratory work, especially by Allard and Rydberg (TR 83-61, TR 79-26). Even in the absence of bentonite as a buffer surrounding the canister, KBS estimates that doses would increase, at most, threefold to twenty-five-fold--values that meet ICRP limits. Finally, the conditions assumed by Thunvik to obtain the worst-case dilution factors (TR 83-50), are thought by KBS to be so improbable (especially the assumption that there would be a complete lack of infiltrating precipitation from ground surface to the well recipient) that pessimism beyond the assumption of 10,000-fold dilution is not warranted.

One consequence of the insertion of arbitrary parameters into the modeling procedure and the persistent choice of pessimistic values for parameters is an inability to make systematic sensitivity and uncertainty analyses. Such analyses would be helpful in assessing which parameters and which variants of modeling methods have the greatest effect on calculated radiation exposures, and in calculating the range of uncertainty in the dose estimates.

The panel requested clarification of the criterion that KBS would apply to a decision for sealing off a drift, or section of drift, should a major fracture be encountered after disposal operations begin. Papp (KBS, private communication, 1983) stated that KBS would wish to maintain at least the safety margin provided within Scenario C (approximately 100-fold less than the ICRP dose limit). Since dose to an individual is proportional to the amount (in becquerels per year) of radioactivity delivered to the geosphere (TR 83-49), it is also roughly proportional to Q_{eq} (TR 83-48). Thus, using the dose obtained in Scenario C as a design objective, a large fracture must deliver 20 to 30 l/m^2 yr to all of the 4400 canisters in the repository before it, or the drift it intercepts, would be considered a candidate for avoidance or sealing. However, only at most a few canisters are likely to be affected by such a large fracture, because canisters more than 100 m away from the fracture have no influence on the safety calculations, whereas those at lesser distances have decreasing influence with distance due to design procedures for repository closure. Therefore, it appears unlikely that one or two fractures with excessively large hydraulic conductivity will be inadvertently, or by choice, left in contact with sufficient buried waste to cause any concern as to the safety of the repository. The panel notes that the KBS-3 plan did not address the matter of canister recovery in the event of extremely unlikely catastrophic events.

Despite these questions concerning the calculations, it appears that only under the most unlikely and extreme combination of worst-case conditions (e.g., improbably early canister failure, rapid fuel dissolution, poor radionuclide retardation, and a complete absence of surface water infiltration to a well) would the dose to the maximally exposed individual approach or exceed ICRP limits. The panel concludes that the KBS-3 authors have provided sufficient evidence that radiation doses to a maximally exposed individual, to an individual in a nearby populace, and to a large population (collective dose) will be acceptably small.

5

SUGGESTIONS FOR ADDITIONAL RESEARCH

At several places in this review, topics are noted on which additional research is recommended. The suggested research, in the panel's opinion, will be required to develop a specific system design, but is not critical for establishing system feasibility. The technical basis for the KBS proposal seems already adequate to support the conclusion that a repository for disposal of spent nuclear fuel can indeed be constructed in Sweden with confidence that human health and safety will not be jeopardized for a million years and longer. Such a prediction about very long future times, however, must always be attended with at least minor uncertainties about some aspects, and additional research could be fruitful in narrowing the uncertainties. Suggested research topics are assembled below in these areas: sensitivity analysis, groundwater movement, properties of bentonite, thermochemical data, geologic investigations, and probabilistic risk assessment. The topics are arranged in roughly what the panel considers their order of importance. Several of the listed topics are part of the continuing research program in which the KBS scientists and engineers are already engaged.

Sensitivity Analysis. The KBS has chosen for the most part to use pessimistic assumptions in their safety assessment. However, final repository design will require better evaluation of the effects of various assumptions on dose--especially when these assumptions must be balanced against cost. A formal sensitivity analysis has been performed only for the BIOPATH model. The KBS should develop their calculation plan (see Figure 4-1) into a systematized, formal sequence, using "best-estimate" assumptions as a base calculation much as was done for

BIOPATH. This entire safety analysis could then be subjected to a sensitivity analysis to gauge the relative importance of various sources of uncertainty on the calculated results.

Predictions of Groundwater Flow in Fractured Crystalline Rock. In KBS-3, hydraulic conductivities are inferred from packer tests, on the assumption that the concept of a homogeneous isotropic medium is a valid basis for interpreting the test results. The porous-medium concept is then also used in the finite-element computations of regional groundwater flow. The adequacy of this concept for describing flow in fractured rock is questionable, and the development of more accurate ways of treating flow in such rock is an important subject for research. Examples of questions to be addressed are as follows:

1. To what extent is the porous-medium concept valid? Essential in attacking this question is the use of interference tests for measuring hydraulic conductivity. A possible approach is the experimental design for interference tests described in TR 80-05, using packers rather than the usual pumping tests. Huyakorn et al. (1983) suggest that interference tests may be used to discriminate among four conceptual models for flow in fractured rock. For assessing the applicability of the porous-medium concept, Witherspoon et al. (1983) also suggest the use of fracture geometry statistics.

2. How important is anisotropy? That knowledge of vertical heterogeneity and anisotropy is important for estimating travel times in the fractured conditions examined in KBS-3 has been demonstrated using simulation models (TR 82-01). Interference tests may be useful here also in determining whether anisotropy must be considered in predicting flows through a repository (TR 80-05; Kohut et al. 1983).

3. Are packer tests reliable for determining hydraulic conductivity? How much is their reliability influenced by anisotropy and local heterogeneity? If they are known to be reliable locally, do they give values representative of the region? Calculations in TR 82-06 suggest that heterogeneity and anisotropy should have only a small effect, but that a "borehole skin" effect might be important. Leif Carlsson (Swedish Geological Survey, personal communication, 1983) indicated that preliminary analysis of the transient pressure response observed in the packer

tests showed no evidence of a skin effect, but the potential error is large enough to warrant further investigation. To assess the reliability of packer tests for estimating regional values of hydraulic conductivity, relationships should be explored among values derived from packer tests, from interference tests, and from observations of fracture frequency.

Questions about the adequacy of the porous-flow model are important also when the model is extended to contaminant transport. In the transport calculations for KBS-3, a dual-porosity model was used rather than the standard porous-medium model (TR 83-48), and Neretnieks (TR 82-03) has suggested as an alternative a "stratified-flow" model. These and two other models were tested against available data in TR 83-38, but none of the models could be rejected. This result reinforces Neretnieks' opinion that there is "no experimental evidence at present to assess channeling or dispersion mechanisms over large distances in fissured bedrock" (TR 82-03). Research on the spatial scale over which channeling predominates is needed to resolve the question as to what conceptual model is appropriate for describing contaminant transport.

Properties of Bentonite. Despite the very extensive investigations by Pusch and his colleagues, some questions remain about the suitability of bentonite for its many intended functions in the KBS plan:

1. Will the properties of bentonite be adversely affected by long-continued heating? Laboratory results to date indicate that heating to temperatures that do not exceed 80°C, which is the maximum planned in a KBS repository, will have no appreciable effect. The experiments are necessarily of short duration (months or a few years), however, and slow reactions over very long times still seem possible. Hoffman and Hower (1979), for example, cite geologic evidence for a slow change of smectite to illite over periods up to 50 million years. The change occurred at pressures somewhat greater than those expected in a repository, and whether reduced pressure would accelerate or decelerate the reaction is uncertain. Long-term tests under repository conditions seem desirable to test this reaction and also possible slow reactions of wet bentonite with copper or with minerals of the bedrock. Such tests are in progress at

Stripa, with electric heaters substituted for fuel rods (Roland Pusch, University of Luleå, personal communication, 1983), and their results a few years hence will be of much interest.

2. Are bentonite barriers in tunnels and shafts adequate for sealing against groundwater flow? Tunnels and shafts may possibly become channels for groundwater flow after a repository is closed, either because the backfill is less impermeable than expected or because rock adjacent to the openings has been weakened and cracked by blasting. To block such movement, seals of compacted bentonite at intervals in tunnels and shafts are planned, each seal to be inserted into slots sawed into the weakened rock on all sides. Doubts have been expressed that such seals would function as expected, on the grounds that sawing the slots, no matter how gently it is done, might weaken the adjacent rock by leaving edges and corners under stress, so that permeable fractured rock would still exist around the seals and the bentonite might not expand to fill all the cracks and open spaces. Some in-situ tests of the proposed seals have been carried out at Stripa, and more are planned (Roland Pusch, University of Luleå, personal communication, 1983), and the panel strongly endorses this procedure.

3. Will bentonite protect a canister from rupture by sudden rock displacement? The compacted and water-saturated bentonite around a canister will probably serve as an effective cushion for slow deformation, but sudden displacive rock movement in an earthquake might cause both copper and bentonite to act like brittle solids and fracture. How large a sudden displacement could a canister endure without rupture, and how much protection would the bentonite offer? Tests to answer these questions will be difficult to set up, but the effort should be made.

4. What is the mechanism of transport of water and dissolved materials through bentonite? Much experimental work has already been done on the movement of fluids through bentonite, but details of the diffusion process are still obscure. Rates of migration of different ions should be studied under a variety of conditions, and the possible influence of the Soret effect and surface migration should be considered. The research could be extended to the similar process of diffusion of water and radionuclides from fractures into the matrix of relatively unfractured granite. Such research will probably not

greatly change predictions based on the empirical results already in hand, but a sounder theoretical basis would help to reduce uncertainties.

Solubilities, Retardation Factors, Complexes, and Colloids. Laboratory data already exist in great abundance, but some important numbers are still poorly known. Further refinement is needed in simulating repository conditions as closely as possible, and additional field checks of laboratory data are desirable. The effects of complexes, colloids, and slow reactions in modifying predictions from thermodynamic data are particularly in need of further study.

Geologic Investigations. Further search for repository sites is obviously desirable, and is part of the current KBS plan. Since at least four fairly satisfactory sites are already known, and since a site for actual construction will not be needed for at least another decade, this activity is less urgent than some other kinds of research. Additional study of evidence for postglacial rock displacements in various parts of the country would be of much scientific interest and might aid in the ultimate choice of a repository site, but there is little chance that it would change the general conclusion that Swedish bedrock is sufficiently stable to ensure long-term repository integrity.

Probabilistic Risk Assessment. A probabilistic risk assessment of the repository system should be made.

6

CONCLUDING REMARKS

The KBS plan for waste disposal differs from most plans involving mined geologic repositories in that primary reliance is placed on the long-term integrity of copper canisters. The bedrock and the surrounding buffer of compacted bentonite in which the canisters will be placed are expected only to maintain a stable and benign environment; the bedrock does not, as in most geologic-disposal schemes, play an important role in slowing the migration of radionuclides to the biosphere. It could play that role in the event of widespread early canister failure, but such failure is so unlikely that the retarding effect of the rock is only secondary insurance against a very low-probability accident. (The point deserves stressing, because so much of the technical back-up for KBS-3 is devoted to this secondary insurance--to estimates of migration rates through bedrock and the resulting radiation releases.) Although the bentonite buffer provides some retardation, no credit is taken for it by the KBS authors in their safety analysis. The essential question in judging the technical background of the KBS plan is whether a good case has been made for the durability of copper in a stable repository environment; all else is incidental, necessary for insurance purposes but probably almost irrelevant to the central issue of human safety. The engineered barriers called for in the KBS plan are the important ones, whereas in most geologic-disposal plans the engineered barriers are assumed to fail within short times (i.e., compared with radionuclide half-lives), and the natural geologic barriers are then depended on for slowing long-term radionuclide release.

The technical work on the canisters seems beyond reproach. Methods of fabrication have been demonstrated in the plants that would be called on to produce the ultimate 4400 canisters, at a scale large enough that extension to full scale should be no problem; sealing of the canisters--either by electron-beam welding if lead is used as a filler, or by hot isostatic pressing if copper powder is used--has also been demonstrated; rates of corrosion have been tested at extreme values of the controlling variables; and stress corrosion cracking has been eliminated as a possible threat to canister integrity. Much of the work was completed by the time of KBS-2, and further studies in the past five years have abundantly confirmed earlier results and earlier conjectures about canister performance.

Assurance that bentonite will perform all the functions assigned to it in the KBS plan is somewhat less complete. No entirely satisfactory source of bentonite has yet been identified; and even though properties of bentonite can be in some measure tailored to specifications, there is as yet no guarantee that a uniform product with all the desired properties can be obtained in the necessary large quantities. The compacted bentonite to be placed in the deposition holes around the canisters has been exhaustively tested, and the feasibility of emplacing it has been demonstrated; there seems little doubt that it can perform its expected functions of keeping groundwater stationary or nearly so at canister surfaces, of slowing the motion of corrodents to canister surfaces, and of helping to maintain pH in the range of 8 to 9.5. Some question remains about its ability to protect canisters from sudden mechanical disturbance. Emplacement of bentonite-sand mixtures as backfill in tunnels and shafts has been demonstrated in field tests, and permeabilities have been shown to be comparable to those in adjacent rock. A method of sealing boreholes with bentonite enclosed in perforated metal sleeves has been tested in both laboratory and field. Whether bentonite can be used to make effective seals in more permeable parts of shafts and tunnels is not certain, but field tests are under way. The bentonite used in experiments has lived up to expectations, and there is good reason to think that it will fulfill its various roles at least well enough to preserve canister integrity. Even if its performance is to some extent deficient, estimates of groundwater amounts and flow rates are sufficiently low and sufficiently conservative to ensure that local movement at unanticipated rates will not seriously affect the canisters.

The tectonic stability of large areas of Swedish bedrock seems amply confirmed. Demonstration that sites can be found in the bedrock where groundwater is sufficiently small in quantity, slow in movement, and bland in composition to pose no threat to copper canisters seems convincing to the panel, even though no site completely satisfactory in all details has yet been located. Three sites explored recently look promising, and better ones will probably be found in the planned continuing investigation. The motion of groundwater in fractures at depth in granitic bedrock cannot be accurately deduced from measurements at the surface and in boreholes, especially if there is much channeling along fractures; but conservative estimates for the studied sites are a source of confidence that sizable rock volumes exist where groundwater would not adversely affect a repository.

The most troubling uncertainties remaining in the KBS proposal relate to the part least likely ever to be relevant to actual repository performance, i.e., the migration of radionuclides through buffer and bedrock in the improbable event of early canister rupture. Uncertainties here are great simply because of the number of variables that must be considered in any model used to describe the dissolution of radionuclides from fuel rods and their movement through a variety of materials to the point where they may become hazardous to humans. Solubilities, effects of local oxidation due to radiolysis, retardation by sorption of some radionuclides as they migrate through buffer and rock, effect on retardation of the formation of complexes and colloids, dispersion of nuclides into rock along fractures where flow is concentrated--all these must enter into a system of models for radionuclide behavior. The panel could point to uncertainties in some of the data and assumptions, but since the assumptions are mostly conservative and since the calculated releases are within acceptable limits even for the most radical disruption scenarios--and since, in addition, there is little probability of early canister disruption--the panel concludes that the technical basis for the calculations of low release rates is sound.

The KBS team of scientists and engineers has accomplished a great deal of pertinent research, especially in the accelerated work done for KBS-3. The research program has included geologic field studies, in-situ testing at the experimental facilities at Stripa, Studsvik, and Finnsjön, laboratory work at Swedish universities, technical institutes, and consulting agencies, and work performed at laboratories in England and the United States. The program has covered all aspects of the disposal problem so thoroughly that a critic has difficulty finding weak points that have not already been considered. Where gaps in knowledge still exist, they mostly concern points where the complexities of natural phenomena defeat efforts to arrive at definitive answers. The KBS research has not only achieved its purpose of showing that radioactive waste can be disposed of in Sweden with reasonable assurance of safety for at least one million years, but it has provided the world with a wealth of basic data on the corrosion of copper, on the movement of groundwater in fractured rock, on the properties of bentonite, and on the many factors that influence radionuclide migration. In compiling these data, the KBS authors have performed a valuable service both for their own country and for any country or group considering the disposal of nuclear waste in crystalline bedrock.

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