Radioactive Waste Management

GEOTRAP: Radionuclide Migration in Geologic, Heterogeneous Media

Summary of Accomplishments

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996); Korea (12th December 1996) and the Slovak Republic (14th December 2000). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 27 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its Member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

FOREWORD

Most countries using nuclear energy are considering, or actively pursuing, the creation of a deep geologic repository for radioactive waste. As part of the assessment of the performance or safety of such a repository, radionuclide transport through the heterogeneous, geologic environment must be modelled. Research in this field began at individual sites around the world as early as the 1970s.

A series of international collaborative projects [INTRACOIN (1981-1984), HYDROCOIN (1984-1987), INTRAVAL (1987-1993)] began under the aegis of the NEA in 1981, as individual countries came to appreciate the benefits of sharing experiences and comparing approaches to modelling radionuclide transport. These projects focused on the development and validation of models of flow and radionuclide transport (Larsson, 1992).

After the conclusion of INTRAVAL, a continuing need was perceived by NEA Member countries for a forum-like project in which those responsible for the implementation of repository programmes ("implementers"), regulators, and the wider scientific community could interact in a structured fashion on issues specifically relevant to understanding and modelling radionuclide migration in heterogeneous, geologic media. Thus, GEOTRAP – the OECD/NEA Project on Radionuclide Migration in Geologic, Heterogeneous Media – was established in 1996.

Five workshops were carried out as part of the project and covered the following subjects: Field Tracer Transport Experiments; Modelling the Effects of Spatial Variability; Characterisation of Water-conducting Features and Their Representation in Models; Confidence in Models of Radionuclide Transport; and Geological Evidence and Theoretical Bases for Radionuclide-retention Processes.

This report provides an overview of the project's main findings and accomplishments over its five-year life. The authors hope that this summary will help make the valuable information collected and generated by the GEOTRAP project accessible to a wide readership both within and outside the radioactive waste community. It is a reflection of the careful attention paid by this community to the question of radionuclide transport.

Acknowledgements

On behalf of all participants, the NEA wishes to express its gratitude to:

- The GEOTRAP Contact Persons from the different countries and organisations for their active contributions to the success of the project.

- The members of Working Group 5 at the GEOTRAP 5 Workshop who made many constructive comments on an earlier draft of this document.

- Peter Flavelle, CNSC, Canada; Gérard Bruno, IPSN, France; Didier Gay, IPSN, France; Klaus Röhlig, GRS, Germany; Javier Rodriguez, CSN, Spain; Jan-Olof Selroos, SKB, Sweden; Paul Smith, SAM Ltd, UK for their helpful and insightful comments during the preparation and review of this report.

- Philippe Lalieux, ONDRAF/NIRAS, Belgium; Piet Zuidema, NAGRA, Switzerland; Alan Hooper, Nirex Ltd, UK and Claudio Pescatore, NEA for their contributions and stewardship of GEOTRAP from its inception through the final workshop and preparation of this synthesis.

- Richard Beauheim, SNL, USA, who prepared this overall synthesis while with the Radiation Protection and Waste Management Division of the OECD Nuclear Energy Agency.

TABLE OF CONTENTS

1. THE GEOTRAP PROJECT

Purpose and participation

In planning the disposal of radioactive waste in a deep geologic repository, consideration must be given to the ways in which radionuclides might leave the repository and migrate through the geosphere. In most cases, an important migration mechanism is transport in groundwater. Potential host geologic formations are chosen, in part, for their ability to prevent or severely attenuate any eventual transport of radionuclides in groundwater. Nevertheless, developing an understanding and modelling capability for how radionuclides might migrate away from the repository through the surrounding geosphere is an integral part of making the safety case for a repository.

Understanding and modelling radionuclide transport through the geosphere is a complex task. It involves identification of potential transport processes and pathways, quantification of the hydraulic properties of those pathways, identification of processes that might retard or retain radionuclides, and quantification of the parameters controlling those retardation/retention processes. This information must be assembled into a coherent conceptual model (or models) that is consistent with all available data, and then a numerical representation of that conceptual model must be constructed. Creation of a numerical model inevitably involves simplification, both in terms of the representation of heterogeneity and of processes. The final model used for performance calculations, in particular, may be a simplified representation of more-detailed process models that are themselves already simplified representations of nature. To have confidence that the final model is adequate for its intended purpose thus requires confidence in all the steps leading to that model.

All of these activities have to be co-ordinated and integrated. Hence, a need exists for a mechanism whereby the different types of engineers, scientists, and decision makers can discuss experiments, data, and models to identify strengths, weaknesses, limitations, assumptions, and other aspects of their work.

The background of GEOTRAP

After the conclusion of INTRAVAL, a continuing need was perceived within the NEA Member countries for a forum like project where those responsible for the implementation of repository programmes ("implementers"), regulators, and the wider scientific community could interact in a structured fashion on issues specifically relevant to understanding and modelling radionuclide migration in heterogeneous geologic media. Consequently, the NEA Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal (SEDE) and the NEA performance Assessment Advisory Group (PAAG) convened a joint workshop in Cologne, Germany, in April 1995 with the objectives:

- to identify relevant issues in the understanding and modelling of radionuclide migration in potentially relevant geologic disposal media;
- to assess availability of practical approaches that address the identified issues; and
- to determine the feasibility of an international co-operative effort.

Forty-two representatives from 13 countries and two international organisations participated in the workshop [NEA/PAAG/DOC(95)2]. Following that workshop, SEDE and PAAG decided to establish GEOTRAP: the OECD/NEA International Project of the Transport of Radionuclides in Heterogeneous Geologic Media in 1996.[1] The mode of operation and programme of work were defined in NEA/GEOTRAP(96)1. The three main topics the project was to address were:

- the rationale; implementation, modelling, and interpretation of field tests;
- the development and testing of transport concepts and codes in light of the information from the field; and
- modes and data abstraction for site-specific synthesis, performance assessment, and confidence building.

Finally, a series of five workshops was defined to provide a logical sequence of work through these three topics.

1. In 1999, SEDE and PAAG were disbanded and their activities, including GEOTRAP, were subsumed within the newly created Integration Group for the Safety case (IGSC).

The producers of data (site investigators and lab. experimentalists) must communicate with the users of the data (performance assessors) to ensure that the needed data are being gathered and that the data are being used properly in modelling. While this communication must occur within each individual repository development programme, added value is found in the communication occurring among a variety of repository programmes, between regulators and implementers, and between the waste-disposal community and the wider scientific community. Thus, the GEOTRAP project was created (see box) to provide a broad international platform for focused interaction and information exchange related to radionuclide migration through the geosphere.

GEOTRAP was open to all NEA Member country organisations represented within PAAG and/or SEDE groups (later combined into the IGSC group) and active in the field of radionuclide transport in geologic formations. It was initially established with the participation of 29 national organisations from 13 countries, as well as the European Commission. By the final workshop, participants had come from 15 countries, representing nine implementing agencies, eight regulatory agencies, 22 research laboratories supporting implementing or regulatory agencies, 18 universities, 17 private engineering companies working in the radioactive-waste field, and one technical oversight body (see Appendix). Thus, GEOTRAP brought together information from a variety of perspectives as well as a variety of geologic sites, repository design concepts, characterisation methodologies, experiments, models, and repository programmes at different stages of development.

Working method

GEOTRAP was structured as a series of workshops on five themes related to the three main topics to be addressed (see box). The workshops were hosted by radioactive waste organisations in five different countries. The first workshop was sponsored jointly by the NEA and the European Commission (EC), while the remaining workshops were sponsored only by the NEA. The project lasted for a period of five years, from 1996 through 2001. Table 1 provides a summary of the sequence of workshops.

Each workshop was planned and organised by a Programme Committee consisting of a representative of the host organisation, experts from other countries, the NEA Secretariat, and a technical consultant. Contact persons nominated by each participating organisation were responsible for disseminating information about GEOTRAP within their organisation and providing for appropriate representation at the workshops. The workshops were

Table 1. **Summary information on GEOTRAP workshops**

Work-shop	Theme	Location	Date	Host
1	Field Tracer Experiments: Role in the Prediction of Radionuclide Migration	Cologne, Germany	28-30 August 1996	German Company for Facility and Reactor Safety (GRS)
2	Basis for Modelling the Effects of Spatial Variability on Radionuclide Migration	Paris, France	9-11 June 1997	French National Agency for Radioactive Waste Management (ANDRA)
3	Characterisation of Water-conducting Features and Their Representation in Models of Radionuclide Migration	Barcelona, Spain	10-12 June 1998	Spanish National Radioactive Waste Company (ENRESA)
4	Confidence in Models of Radionuclide Transport for Site-specific Performance Assessment	Carlsbad, New Mexico, USA	14-17 June 1999	United States Department of Energy (USDOE)
5	Geological Evidence and Theoretical Bases for Radionuclide-retention Processes in Heterogeneous Media	Oskarshamn, Sweden	7-9 May 2001	Swedish Nuclear Fuel and Waste Management Company (SKB)

designed to be highly focused and interactive, requiring active participation by all those present. Two principal methods were used to meet these objectives:

- First, specific presentations were invited on different aspects of each workshop topic from experimentalists, performance-assessment specialists, regulators, and outside experts. Each presenter was given a specific list of 3 to 12 questions to be addressed to make sure their presentation would be as relevant as possible. Each presenter prepared an Executive Summary of their presentation that was reviewed by members of the Programme Committee, who suggested possible modifications to improve the focus of the presentation. The presentation topics, presenters, and questions were all selected to foster a dialogue among the various disciplines represented. Discussion time was allotted either after each presentation or at the conclusion of each topical session.

- Second, following the presentations, the participants at each workshop were divided into a number of working groups to discuss specific topics in greater depth and obtain an international and cross-disciplinary perspective. As with the presenters, the working groups were each given a specific list of questions to consider in their discussions. The working group discussions and conclusions were summarised in a final plenary workshop session, with additional time for discussion by all participants.

In addition, posters dealing with any aspect of the workshop theme were welcomed at each workshop to stimulate informed discussion. Each workshop lasted three days, with approximately 1.5 days devoted to presentations, one day for working group discussions, and half a day for final, plenary discussions.

Shortly after the conclusion of each workshop, a written synthesis of the workshop was prepared and distributed among the workshop participants. This synthesis summarised the major points made in the presentations, working group discussions, and general discussions, and provided integrated lists of conclusions and recommendations from the workshop.

Proceedings were published for each of the workshops (NEA, 1997a; 1998; 1999; 2001a; 2001b). The proceedings included a summary and technical synthesis of the workshop, summaries of the working group discussions, and written papers of the presentations and posters given at the workshop.

Registration fees were charged for some of the workshops to finance the involvement of experts from outside the radioactive-waste field and of a consultant to prepare the workshop syntheses. Many PAAG/SEDE/IGSC Member organisations also provided financial support for various experts and consultants. The expenses of holding the workshops were borne by the host organisations. The NEA provided the scientific Secretariat and overall co-ordination for GEOTRAP.

The five workshop themes

The themes of the five GEOTRAP workshops were selected to cover a range of areas related to the assessment of radionuclide migration.

Field tracer experiments

The first workshop focused on field tracer experiments, which are used to study the distribution of groundwater flow, characterise potential flow paths, and test different conceptualisations of flow and transport at selected sites and at different scales. Topical sessions focused on:

- General overview.
- Rationale behind field tracer experiments.
- Test cases: design, modelling, and interpretation.
- Aims and design of planned field tracer experiments.

Working groups considered:

- Practical challenges of field tracer tests.
- Rationale and promises of future field tracer experiments.
- Alternative methods to tracer experiments.
- Integration of data from field tracer experiments into performance assessment.

Spatial variability

Variability (or heterogeneity) is a common feature of most geologic media over a wide range of spatial scales. It is relevant to the deep geologic disposal of radioactive waste in that it affects siting feasibility, optimum repository layout, and long-term repository safety. A wide variety of techniques exists both to characterise spatial variability in the course of the geologic investigation of a site and to model the consequences of such variability on groundwater flow and radionuclide transport. Developments in these techniques have been rapid in recent years, leading to the decision to focus the second GEOTRAP workshop on the basis for modelling the effects of spatial variability on radionuclide migration. Topical sessions examined:

- Spatial variability: its definition and significance to performance assessment and site characterisation.

- Experience with modelling of radionuclide migration in the presence of spatial variability in various geologic environments.
- New areas for investigation: two personal views.
- What is wanted and what is feasible: views and future plans in selected waste-management organisations.

Topics for working groups were:

- Approaches to confidence building in models of spatial variability.
- Definition and quantification of effective parameters for flow and transport.
- Benefits of further site characterisation for better radionuclide transport calculations.
- Future directions of work in the treatment of spatial variability for radionuclide transport.

Water-conducting features

The characterisation of the structure and properties of preferential flow paths, or water-conducting features, is an important requirement for any performance assessment. These features can, for example, determine the rate at which radionuclides migrate with flowing groundwater and the degree of retention in the geosphere. Emphasis has generally been given to the characterisation of the hydraulic properties of water-conducting features, leading, in several cases, to models of flow that can claim to be "realistic" representations of the natural system. Radionuclide transport through water-conducting features has, however, mostly been treated through rather simplified, conservative approaches. Hence, the theme of the third GEOTRAP workshop was the characterisation of transport-relevant properties of water-conducting features and their representation in transport models. Topical sessions were organised on:

- Identification and characterisation of water-conducting features in various geological environments.
- Reduction of uncertainties in the characterisation of water-conducting features.
- Quantitative representation of water-conducting features in performance assessment.

- Future strategies for characterising and dealing with water-conducting features in performance assessment.

Working groups were asked to consider:

- How can limited data, measured on various scales, be translated to overall assumptions concerning properties relevant to radionuclide transport?
- What is necessary in order to achieve an adequate representation of water-conducting features in performance assessment?
- Future prospects for identification and characterisation of water-conducting features and for their representation in models.
- What are the factors to be considered when assessing the relevance of time-dependent properties of water-conducting features and how can they be dealt with in performance assessment?

Confidence in models

Confidence in the long-term radiological safety of underground repositories for radioactive waste is required to support decision making in the stepwise process of repository planning and development. Confidence is required in the appropriateness of the site and repository design for their intended use, and in the methodologies, models, and databases used to assess their performance. This includes the assessment of the geosphere as a barrier to transport of radionuclides released from the repository. The nature and scope of the confidence-building process is still under discussion by many organisations. The purpose of the fourth GEOTRAP workshop, therefore, was to examine the approaches that have been taken within national waste management programmes to evaluate, enhance, and communicate confidence in models of radionuclide transport for site-specific performance assessment. Topical sessions focused on:

- Confidence in transport models in the overall context of repository development.
- Development of, and confidence in, geosphere-transport models used in performance assessment.
- Approaches to confidence in models that support geosphere-transport models used in performance assessment.

- Impact of new site investigations on confidence in transport models.

Topics for working groups were:

- Role of independent indicators to support transport models.
- Implications of simplifications in geosphere-transport modelling in performance assessment.
- Aspects and sufficiency of confidence in supporting (process) modelling.
- Strategies for increasing confidence in transport models through data acquisition.

Retention processes

Retention of radionuclides for prolonged periods within a multi-barrier system (e.g., waste package, backfill, and geosphere) is an important safety function of deep geologic disposal concepts. In the case of the geosphere, a range of characteristics may favour radionuclide retention, including: (i) the existence of stagnant or very slowly moving groundwater, (ii) groundwater and mineralogical compositions that favour sorption processes, (iii) the accessibility of pore spaces separate from the main flow paths that provide diffusion volumes and sorption surfaces, and (iv) small pore sizes that favour colloid filtration. The extent to which retention processes can be relied upon in performance assessment depends, in part, upon the existence of well-established theoretical bases. It also depends on support for the operation of retention processes under relevant conditions, and models for their quantitative evaluation, from a wide range of laboratory and field experiments and observations from nature. The purpose of the fifth GEOTRAP workshop was to review the theoretical bases and supporting evidence for the operation and modelling of these processes, with emphasis on geological and field evidence, and the treatment of retention processes in performance assessment. Topical sessions examined:

- Fundamental understanding of individual retention processes.
- Geologic and field evidence for retention processes and their representation in models.
- Consideration and representation of retention processes in performance assessment and justification of their treatment.

Working groups considered:

- sorption;
- matrix diffusion;
- colloid-related retention processes;
- immobilisation; and
- conclusions and synthesis of GEOTRAP and proposals for follow-up.

Organisation of document

Chapter 2 of this document summarises the main observations and findings of the individual workshops. Chapter 3 groups the recommendations produced by all of the workshop into three overall categories: those pertaining to field tracer experiments and other data collection; those pertaining to modelling; and those pertaining to confidence building and communication. Five key points that were repeatedly made at the GEOTRAP workshops and can be considered guiding messages for the future are discussed in Chapter 4. The report concludes with an assessment of the value of GEOTRAP in Chapter 5.

2. FINDINGS OF INDIVIDUAL WORKSHOPS

The establishment, in advance, of a series of key questions to be addressed in each session and in each working group at each workshop proved to be a very effective way of focusing the discussions and reaching practical conclusions and recommendations. The workshops achieved lively interaction among the participants and many points of consensus emerged, although differences in views on some topics also emerged, highlighting the need for increased communication between site-characterisation and performance-assessment specialists, between implementers and regulators, and between waste programmes and the wider scientific community. The focus, key lessons drawn, and general observations from each of the GEOTRAP workshops are summarised below.

GEOTRAP 1: Field tracer transport experiments

Field tracer experiments examine the movement of solutes ("tracers") artificially added to groundwater in wells or other test boreholes. Field tracer experiments provide essential information on the processes and properties involved in radionuclide transport through the geosphere. They also allow testing of alternative conceptual models and can demonstrate the adequacy (or inadequacy) of the understanding of the transferability of laboratory data to the field. The first workshop provided a broad perspective on the practice, benefits, and limitations of field tracer experiments. The main findings of the first workshop were as follows:

Observations on tracer tests

- Field tracer experiments have now been taking place for many years. They have a valuable role to play in the identification of the processes relevant to transport, the definition of site models, and the provision of parameter values that are required by transport models.
- The radioactive waste community has become more aware of the complexity of the geological environment within which the tests are performed and of the limitations in the applicability of such tests in performance assessment and site characterisation. Where geological

complexity is not, however, too great, information can be provided by field tracer experiments that is difficult or impossible to obtain by other means.

- The relative importance of different transport-relevant processes, as well as the complexity of structure, varies among different geologic media. This has strong implications for the type of tests to be performed, the type of information that can be obtained, and its uses for performance assessment.
- Field tracer experiments cannot be replaced by alternate sources of data, but neither do they provide all the information necessary to develop a comprehensive picture of solute transport through the geosphere. Tracer tests provide key, but partial, information on transport processes and properties that must be complemented with data from other sources (e.g., natural tracers, natural analogues, paleohydrology).
- There is increased recognition that performance assessment makes use of a combination of quantitative ("hard") and qualitative ("soft") information. Where the system studied is structurally relatively simple (as in the case of plastic clays), field tracer experiments can serve to provide specific hard information. For more complex systems (fractured media), field tracer experiments can play a useful part in building general confidence in the adequacy of system understanding, as well as in the development of the team (modellers and experimentalists) and the tools (analytical and experimental) for performance assessment.
- The greater complexity and more qualitative link to performance assessment in the case of fractured media in particular suggests that field tracer experiments in isolation are unlikely to provide adequate information to quantify the performance of the geosphere. Special efforts are required with respect to (i) integration with other types of studies (e.g., paleohydrology), (ii) the characterisation of the system, (iii) the identification and testing of geological features that are relevant to geosphere performance, and (iv) the testing of alternative hypotheses.
- Although the interpretation of the results of tracer experiments can be non-unique in terms of the operating processes, particularly where the structure of the system is incompletely characterised, no new processes outside the scope of the current models have so far needed to be invoked in order to understand experimental results. This contributes to confidence that the processes relevant to

geosphere transport have been identified. The structural complexity of natural systems remains a significant source of uncertainty, both in the interpretation of tracer experiments and in the modelling of the performance of deep repository systems.

- Efforts are required in the communication (i) of performance-assessment requirements to experimentalists involved in field tracer experiments, (ii) (by modellers) of the need for simplification of geological representations and (by experimentalists) of the extent to which such simplifications are geologically meaningful, and (iii) of key results to programme managers, regulators, and the public.

Limitations of tracer tests

- Field tracer experiments (like any other test) can provide information only on the present (and, to some extent, past) situation; long-term changes and their effects have to be assessed by other means.
- The time and length scales and flow conditions of field tracer experiments can never fully reproduce those relevant to geosphere performance assessment. Only a limited volume of a host formation and its surrounding can be covered by comparatively short-term tracer tests. The length scales that have been explored experimentally may, however, be very relevant for analysis of the transport properties of the near-field host rock.
- Interpretations of field tracer experiments often suffer from problems of non-uniqueness.
- The optimum way in which to integrate field tracer experiments with other studies and with performance assessment may be unclear.
- Transferability of data from one site to another may be limited.

General observations

Despite their usefulness, a number of problems are associated with field tracer experiments, not least that they are complex, expensive, and take long periods of time to plan and perform. Cost-benefit analysis of tracer experiments is not easy because the end-results of such tests (in terms of data and understanding) are not predictable. In fact, the unexpected results of tracer tests (e.g., “anomalous” tracer behaviour or unpredicted pathways) are often their most valuable aspects.

Among causes for concern is the inconsistent use of terminology and assumptions, and the inappropriate use of data. Channelling in fractures, for example, is not treated consistently in different models and different techniques are used for calculating fracture apertures. Consistent assumptions must be used in different models that use the same parameter and, for each parameter, the models/assumptions used to derive its value should be stated.

Greater co-operation between experimentalists and performance-assessment modellers, each representing different scientific cultures, would be especially helpful. To date, the PA input to field tracer experiments has generally been limited, while the direct input of these experiments to performance assessment has been relatively minor except in cases where the proposed host medium is relatively homogeneous. Great benefit could be derived from a more concise and clear presentation of PA-relevant experimental results and by involving PA modellers in the design and analysis of field tracer experiments. Important challenges are to bridge the gap between data users and data producers and to simplify geological descriptions for modelling purposes in such a way that they remain meaningful. While such communication is generally agreed to be desirable, there are few cases where it has been unequivocally successful.

Of particular importance to the future usefulness of field tracer experiments is their integration into overall programmes of investigation (laboratory and field) and PA model development. In this respect, an agreed strategy for integration should be implemented in order to ensure that all of the elements of a programme of investigation are properly co-ordinated.

GEOTRAP 2: Modelling the effects of spatial variability

All geologic environments through which radionuclide migration from a repository may occur are variable (or heterogeneous) on a variety of scales. This variability is manifested in virtually all properties of the geosphere: porosity, permeability, tortuosity, mineralogy, geochemistry, sorptive capacity, fracturing, etc. The second workshop considered the significance and representation of spatial variability in models of radionuclide migration. Techniques were described and discussed both to characterise spatial variability in the course of site characterisation and to model the consequences for groundwater flow and radionuclide transport. The main findings of the workshop were as follows:

Observations on spatial variability

- Understanding of spatial variability is important in assessing:
  - the feasibility of locating a repository at a particular site;
  - the optimum layout of a repository at the selected site; and
  - the long-term safety of the repository.

- Radionuclide migration is affected not only by spatial variability in hydrogeologic (hydraulic) properties, but also by:
  - variation in mineralogy, which may also affect sorption and, through the presence of fracture coatings and infill, affect matrix diffusion; and
  - variation in geochemical properties of the groundwater, which may affect sorption.

- Consideration of the variability of properties over a wide range of spatial scales is necessary to:
  - establish which processes are the most relevant to radionuclide migration in the different parts of the repository system (e.g., in the near field, diffusion from the repository system to a discrete, water-conducting feature; in the far field, advection along fast pathways within water-conducting features);
  - determine the most appropriate models for representing the key processes of radionuclide migration;
  - establish the most appropriate way of deriving effective parameters (if used);
  - evaluate the causes and consequences of uncertainty in the choice of models and in the determination of parameter values; and
  - determine the most appropriate parameters to measure, drawing on the wide range of methods available for site characterisation.

- Unravelling the associations (correlations) between the different (variable) properties influencing radionuclide migration through the geosphere over a range of scales and determining the potential contribution to bias and uncertainty arising from these associations are considered as important areas of development.

Observations on modelling

- The widest range of models consistent with the available observations should be considered in order to evaluate conceptual-model uncertainty (only a limited number of models may be selected from this range for further quantitative evaluations).
- The principle that alternative models should be considered applies not only to models of flow and transport, but also to underlying models such as those of geologic structure.
- The simplified models resulting from the use of conservative arguments are more valuable when supported by a detailed understanding and, possibly, by more complete (and complex) models to evaluate the degree of conservatism.
- Maximum account should be taken in models of all available information from site characterisation, and other relevant sources, as it becomes available.
- Model testing (e.g., where predictions are made in advance of an experiment or characterisation measurements) should be used, where possible, to narrow the range of conceptual-model uncertainty. Calibration and testing of models should be performed, if possible, at a range of different scales.
- The consistency between the model components (structure, flow, chemistry, transport) used to represent a system in an assessment should be demonstrated.
- Transparency in the design, testing, selection, and application of assessment models should be sought.
- Models of groundwater flow are currently available that allow, in principle, a realistic representation of the structural variability of a geologic medium. Availability of data is the most important constraint on the use of these models. An effort still needs to be made, however, to improve our ability to incorporate a wide variety of different types of data (at length scales relevant for the system under consideration) in order to take full advantage of these models.
- Simplified models that employ effective parameters are likely to continue to be important, particularly in the modelling of transport. The use and quantification of effective parameters need careful justification, because these can rarely be measured in the field at the scale they are needed for performance-assessment calculations.

- Calibration and testing over spatial and temporal scales that are relevant to performance assessment would, in principle, be the best method to build the confidence in models of flow and transport. Such calibration and testing is difficult to achieve, especially considering the very long travel times that are expected through the rock formations that are potentially acceptable to host a repository and the possible transient nature of the groundwater flow system. Analogues, both natural and anthropogenic, provide a possible means to address this difficulty.
- Integrated modelling approaches coupling flow, transport, and chemical reactions appear very promising. The computational tools are still, however, under development and only a few examples of realistic applications are currently available.

General observations

A responsive and flexible approach to both performance assessment and site characterisation, with effective inter-disciplinary communication, is essential to the optimal utilisation of resources. This communication helps avoid such things as the development of models for which the necessary data can never be obtained and the gathering of "interesting" but otherwise irrelevant field data. Site-characterisation specialists need to see a clear relationship between the data they collect and the way these data are used in assessment models to maximise their confidence that the assessment models include all relevant features, events, and processes defined during site characterisation and to stimulate the development of alternative conceptual models. Performance-assessment specialists can provide guidance on (i) areas where more or new site characterisation would reduce uncertainty and discriminate between alternative conceptual models, (ii) which data are necessary for particular models, and (iii) the likely effectiveness of specific data-collection strategies, e.g., through the use of scoping calculations.

Vis-à-vis the state of the art at the end of INTRAVAL, progress was demonstrated in the following areas: (i) the development and implementation of alternative models and approaches to represent spatial variability (more so in connection with groundwater flow than with respect to transport); (ii) the consideration of a broad range of site-characterisation information; and (iii) the enhancement of confidence that can be gained by effective communication between site characterisation and performance-assessment specialists. The need for further development in these areas had been identified in the conclusions and recommendations of previous NEA initiatives, namely the workshop on conceptual models (NEA, 1995), and the Integrated Performance Assessment Group (NEA, 1997b).

Overall, the workshop confirmed that a multi-disciplinary approach is necessary in order to address more fully the problems of modelling flow and transport in media characterised by a high degree of spatial variability and in which coupled and, possibly, non-linear processes operate. Effective communication between different groups, including geologists, hydrogeologists, chemists, and performance-assessment specialists will, therefore, continue to be essential.

GEOTRAP 3: Characterisation of water-conducting features and their representation in models

Radionuclides are transported within the geosphere by groundwater, which often flows preferentially through features having higher permeability than the surrounding rock mass. These "water-conducting" features may be fractures or simply interconnected zones of relatively high permeability within a heterogeneous porous medium. Knowledge of the spatial distribution and properties of these water-conducting features is crucial to the modelling of radionuclide migration. Thus, the aim of the third workshop was to trace the treatment of water-conducting features from data acquisition in the field, through the identification and handling of uncertainties, to the direct or implicit representation of the features in assessment models. The key lessons that were drawn at the third workshop can be summarised as follows:

Observations on water-conducting features

- Water-conducting features are likely to provide the dominant pathway for solute transport in all geologic media considered at the workshop. Site characterisation and performance-assessment exercises should, therefore, ensure that these features are adequately represented in the assessment and, in particular, that their impacts on transport are adequately addressed.
- The level of detail required for an adequate representation of water-conducting features in assessment models depends on the stage of repository development, on the approach to safety demonstration (i.e. on the degree to which a realistic or conservative approach is adopted in modelling and on the respective roles of the engineered and natural barriers in the safety case) and, to some extent, on

licensing requirements. Requirements placed on the geosphere as a barrier to radionuclide transport in a given approach to safety demonstration should be consistent with the depth of understanding and the degree of characterisation of water-conducting features that can be achieved.

- An increasing trend towards the conjunctive use of a wide range of methods to identify and characterise the transport-relevant properties of water-conducting features is noted and encouraged, as well as a move towards the more quantitative use of soft information. Increasing emphasis should, if possible, be placed on the development of qualitative correlations between "routine" measurements that can be made in the process of site characterisation and the flow and transport properties of water-conducting features and their surroundings.
- The complete identification of all relevant water-conducting features and their deterministic representation in numerical models on a scale relevant to performance assessment are not practical for most potential host rocks. In order, therefore, to provide a statistical representation of water-conducting features in models, an understanding of the correlation structure of such features is as important as an understanding of data from the analysis of individual features. Special attention has to be given to the scale-dependence of transmissivity and to the problem of upscaling local (e.g., borehole) data to a regional scale.
- The characterisation of water-conducting features needs to provide information not only on the features themselves, but also on the properties of their surroundings. Furthermore, information on water-conducting features may be required over a wide range of scales. Few programmes currently incorporate information on the small-scale structure (including pore structure) of water-conducting features in assessment models, even though the results of transport models can be highly sensitive to the way in which this structure is represented. Small-scale structure can strongly affect, for example, the retardation due to matrix diffusion. Greater emphasis should be placed on small-scale structure and on matrix properties.
- Comparative studies are recommended among disposal programmes to identify properties of water-conducting features that are common to a general geologic environment (e.g., fractured granite) and separate them from site-specific properties or differences that are due to exploration strategies or technical focus. Furthermore, the

classification of water-conducting features into types, according to their characteristics, could be one objective in the planning of future field tests.

Other observations

- Processes that lead to time-dependent conditions in geologic media and in the properties of water-conducting features are recognised as important. The importance of time-dependent conditions and/or rock properties will depend on both the timeframe over which a performance assessment extends and on the structural, hydro-geological, and geochemical stabilities of the rocks involved.
- The testing of transport models is not equivalent to the testing of flow models, and presents particular problems related to time scales and sensitivity to heterogeneity. The geometry of water-conducting features, and the processes that operate within and around them, must be simplified in order to represent them in transport models for performance assessment. These simplifications should, however, be supported by convincing arguments (which may draw on the results of more complex flow models) to ensure, for example, that they do not result in the underestimation of radionuclide transport. Excessive conservatism may lead to the effective disregard of the geosphere as a transport barrier.
- The parameters that are important in safety assessment are highly system dependent and may change during the course of a repository programme as the approach to safety demonstration is refined.
- Soft data provide an increasingly important means of constraining uncertainties in the geosphere characterisation and of building an overall geologic understanding of a site.

General observations

The workshop was structured, and participation invited, with the aim of focusing on the characterisation and representation of transport-relevant properties in general, and not specifically on flow-relevant properties. In spite of these efforts, discussions at the workshop still centred predominantly on the characterisation of hydraulic properties and on their representation in flow models. This confirms that: (i) much emphasis has been given within national programmes to the characterisation of the hydraulic properties of water-conducting features and, in several cases, to their "realistic" representation in flow models; and (ii) the impact of water-conducting features on radionuclide transport has been mostly treated through rather simplified, conservative approaches. This most probably reflects the weighting of current work internationally, and the relative maturity of hydraulic-characterisation techniques and flow models, but may not always adequately reflect the needs of performance assessment.

Defensibility and credibility of a safety case require a depth of understanding greater than that which is actually implemented in assessment models. Overall, the presentations and discussions of the third GEOTRAP workshop indicated significant advances in the achievement of such a depth of understanding in relation to water-conducting features. In particular, advances have been noted in the integration of the methods used to characterise water-conducting features and in the incorporation of a wide range of "soft" data. The workshop also served to clarify issues related to the adequacy of the representation of these features and their surroundings in assessment models.

Experience from the GEOTRAP workshops has demonstrated that communications between specialists can be hindered by problems related to terminology. These problems need to be addressed, both to assist the work of these specialists and to facilitate the transfer of confidence to external scientific audiences. Although international fora, such as GEOTRAP, can help to highlight differences in the way specific terms are employed by different disciplines and/or programmes, a more formal framework should be established to minimise these problems. Apart from encouraging authors to provide clear definitions of potentially ambiguous terminology in their documentation, no specific proposals have been made as yet as to how to resolve the difficulties of understanding associated with such terminology.

GEOTRAP 4: Confidence in models of radionuclide transport

All models rest on a foundation of empirical evidence (data) combined with various assumptions and idealisations. The use to which a model is put plays a large part in determining the level of confidence needed to base decisions on the model output. The fourth workshop focused on "technical" confidence in the methodologies, models, and data used in the site-specific assessment of radionuclide transport. The principal findings of the fourth workshop were as follows:

General aspects of confidence

- A stepwise approach to repository planning and development has been adopted by many programmes as a way to develop and maintain confidence, with models and databases for performance assessment refined iteratively as information and experience are acquired.
- The level of confidence that is required for decision making in each stage of a repository programme, from the initial planning stages to licensing and implementation, depends on the decision at hand. The existence of open issues does not necessarily preclude a positive decision for a specific stage, particularly in the earlier stages of repository planning.
- Confidence in the long-term safety provided by a particular site and design can both increase and decrease in the course of a project as understanding is developed, with the discovery of unexpected and potentially negative features being a common experience in several programmes.
- Confidence in the findings of performance assessment needs to be complemented by wider confidence in the credibility of the organisation(s) that have carried out the work in order to support decision making in repository development. In this regard, publicising both favourable and unfavourable findings and aspects of an assessment enhances the credibility of the organisation carrying out performance assessments.
- Maintaining site characterisation and research and development efforts that are guided by, but not exclusively driven by, specific performance-assessment models is important in creating and maintaining confidence.
- An analysis showing the effects of different conceptual models and ranges of parameter values may not provide sufficient confidence for decision-making purposes. A focus of site characterisation and research and development efforts should be the reduction of uncertainty and the discrimination between alternative conceptual models, even when models have similar consequences in terms of compliance with system performance criteria.
- Traceability of documentation, avoiding undocumented analytical procedures and missing data, is important in the communication of

confidence in that it allows the possibility of independent verification of performance-assessment results.

- The importance of peer review in the evaluation of confidence, and as a major confidence-enhancing measure, is noted for all programmes.

Confidence in performance-assessment models

- The degree of confidence in performance assessment results is a function of the modelled time scale.
- Confidence in the completeness of phenomena analysed in performance assessment does not come from performance-assessment modelling itself. Rather, it comes from the development of a consistent understanding of the disposal system (including the site) taking into account general scientific understanding and a wide range of measurements and observations ("independent indicators") from the field, laboratory, and nature (e.g., natural and anthropogenic analogues).
- Confidence in a numerical performance-assessment model, and in the conceptual models on which it is based, is favoured by its consistency with many diverse and independent observations and sources of evidence (i.e., multiple lines of reasoning).
- Confidence is also favoured by the testability of a model; i.e., its ability to withstand counter-arguments successfully.
- Understanding and being able to explain the past evolution of a natural system is a valuable means of developing confidence in the ability to predict the future behaviour of the system over the long time scales of relevance to performance assessment.
- Some performance-assessment models, or their underlying concepts, are amenable to testing on a field scale. Such testing, especially if model predictions are made in advance of an experiment, contributes to confidence in the model and its underlying concepts. Renewed interest is noted in large-scale field tracer experiments.
- The waste-disposal community needs to be aware of the state of the art in transport modelling, even if such complex models may be either unnecessary for safety demonstration or inapplicable in a performance-assessment context. Complex models play a role in

estimating the degree of conservatism in the results from simpler performance-assessment models.

- Performance-assessment models should incorporate essential features of the system based on a reasonable understanding of the processes being represented and on site understanding and conceptual models that are consistent with wide-ranging observations and evidence, even though all such information cannot be incorporated directly into the models and databases.
- The use of simplifications in performance-assessment models is inevitable. Model simplifications need to be well documented and supported, e.g., by showing they are conservative and/or do not have a strong impact on performance, to avoid undermining confidence. However, a degree of simplification that leads to a clear loss of realism is to be avoided.

General Observations

The wide range of experience and backgrounds of the workshop participants, and the attendance of two scientists from the broader academic community, played a major role in developing, discussing, and challenging the findings that were drawn. Differences in views on the topic of model simplification highlighted the need for waste-management specialists to communicate the reasons for selecting particular models (and for the use of simplified models) to their scientific peers, who may tend to favour more complex, "all inclusive" models.

As an indicator of the confidence that can be attached to current geosphere-transport models, it was noted that, in the last few years, no fundamentally new processes and events have been identified in the course of site characterisation and research and development. The current challenges are: to develop confidence in site-specific understanding of features such as channelling, dominant pathways, and diffusion-accessible porosity; to improve methods of obtaining an adequate representation of those features in models; to derive effective parameters from measured parameters; and to achieve a better understanding of temporal changes.

"Technical confidence" is only one component of the confidence requirements for decision making in repository development. Other components include ethical, economical, and political aspects of the appropriateness of underground disposal and confidence in the organisational structures and legal and regulatory framework for repository development. These aspects were defined as lying outside the scope of the workshop, as were methods for communicating confidence to the general public. The importance of such communication was, however, mentioned several times in the course of the workshop. Indeed, efforts to achieve consensus among technical experts are considered an important step towards gaining public confidence.

GEOTRAP 5: Geological evidence and theoretical bases for radionuclide-retention processes

A variety of processes act in the geosphere to retain or retard radionuclides as they are transported by groundwater. How well these retention processes are understood affects our ability to represent them in models, as well as the confidence we have in that model representation. The purpose of the fifth GEOTRAP workshop was to summarise the geological evidence for the existence of specific retention processes, describe our theoretical understanding of those processes, and discuss the representation of those processes in both detailed and simplified models. Sorption and matrix diffusion were considered, as were "immobilisation" processes and colloid-facilitated radionuclide transport. The main conclusions that were drawn at the workshop are as follows:

Observations on radionuclide-retention processes in general

- An iterative approach is needed to the development of understanding of retention processes and the building of conceptual and quantitative models, with close interaction between performance assessors and technical specialists. The technical specialists must ensure that the full spectrum of possibilities is recognised in performance assessment, while feedback from performance assessment may usefully indicate for which retention processes, if any, improved understanding is required. Performance assessment may also help in establishing the "data quality objectives" that are required in order to assess the safety of a proposed repository adequately.
- The qualitative understanding of sorption, immobilisation processes, and matrix diffusion, as well as, to a lesser extent, colloid-facilitated radionuclide transport, is well supported by laboratory and field experiments, and by observations of natural systems.
- These processes are sufficiently well understood to support realistic modelling of the processes in ideal media under controlled

laboratory conditions. In particular, mechanistic equilibrium models that may be applied to sorption and immobilisation processes are well developed for simple (clean) mineral/water interfaces. Diffusion models for simple solutes in homogeneous porous media have been successfully used in wide-ranging applications and the basic mechanisms for colloid-facilitated radionuclide transport have been studied and, in many cases, successfully modelled in simple systems.

- These processes are, however, often insufficiently well understood to support realistic modelling in the geologic media, and over the scales of space and time that are of interest in performance assessment – uncertainties often lead to the adoption of simplifying assumptions in performance-assessment models, including the omission of immobilisation processes.
- Carefully considering the possible implications of heterogeneity over a wide range of scales, and also of variability in time, is important when modelling retention processes in performance assessments. Averaging may have non-conservative consequences. The structure of relevant features over a range of scales should, therefore, be considered when developing and applying models in performance assessments, as should the possible consequences of variations of structure, mineralogy, and groundwater composition with time.
- The characteristics of the site and repository concept, and the degree to which these are understood, determines how much performance can be attributed to different retention processes, and how much needs to be attributed in order to meet acceptance criteria. The strategy to improve understanding and to develop and refine models for performance assessments thus needs to be determined on a site- and concept-specific basis.

Observations on specific retention processes

- The use of semi-empirical functions to represent the dependence of Kds on geochemical conditions can be useful in representing the effects of spatial heterogeneity and temporal variability of geo-chemical conditions on radionuclide transport. The use of such functions may be seen as a compromise approach between, on the one hand, the use of fixed Kd values (which may be over-simplistic in some circumstances) and, on the other, the incorporation of mechanistic equilibrium sorption models in radionuclide transport codes (which may lead to excessively complicated and non-transparent assessment models). The use of semi-empirical site-binding models could also be considered in performance-assessment calculations, although this would require a greater emphasis to be placed on the site-specific characterisation of the mineral assemblages and variable groundwater composition along radio-nuclide transport paths.

- In order to provide convincing site-specific evidence that matrix diffusion can be relied upon as a retention mechanism, it is advantageous to concentrate efforts on characterising any higher porosity altered zones adjacent to fractures, where the existence of diffusion-accessible porosity may be relatively easy to demonstrate. It is more difficult to demonstrate that matrix diffusion can occur in more distant and less porous, unaltered wallrock. It may, however, be unnecessary to invoke matrix diffusion in unaltered wallrock in order to demonstrate the effectiveness of the geosphere transport barrier. Further development of process-level models of matrix diffusion is likely to require better understanding of the geometry and connectivity of matrix pores, as well as more information on the degree of channelling within fractures (i.e., the flow-wetted surface).

- Colloid-facilitated radionuclide transport is generally of concern in performance assessment only for more radiotoxic nuclides. The mechanisms of colloid generation, deposition, radionuclide uptake, and transport are understood in general terms, but are subject to numerous uncertainties in many natural (chemically and physically heterogeneous) systems of interest. More high-quality data sets from relevant systems are needed to test and further refine colloid-facilitated radionuclide transport models. As a consequence of the low importance of colloid-facilitated radionuclide transport, most performance assessments either treat it in a highly simplified manner or omit it altogether.

- In spite of the evidence for their widespread occurrence, immobilisation processes, by which radionuclides may be taken up in the three-dimensional structure of minerals, have not so far been taken into account in performance assessments in a quantitative manner, with this omission being justified on the grounds of conservatism. Uncertainties are such that the prospects of including immobilisation processes in performance-assessment models in the near future appear low. Nevertheless, prospects are good for improvement in the understanding of these processes.

General Observations

Regulators require "reasonable assurance", or "sufficient confidence", that the representation of retention processes in assessment models can be relied upon, at least not to underestimate radiological consequences. While it is preferable to have as realistic a description of retention processes as possible, a wholly realistic description is not absolutely necessary to support regulatory decisions. Retention processes that are not included in performance-assessment models, such as immobilisation processes, can sometimes be cited as qualitative evidence that safety margins will be higher in reality than those indicated by performance-assessment calculations.

Whether the understanding of retention processes is sufficient for a performance assessment depends on the purpose of the assessment (and, in particular, the decision that the performance assessment supports), and is also site- and concept-specific. The current level of understanding appears sufficient for the decisions at hand in the participating national programmes.

Because of its focus on fundamental retention processes, the fifth workshop involved far wider participation from the academic community than previous workshops, with fully half of the invited presentations being given by academics. These scientists brought an increased awareness of the current state of the art and active research areas with respect to retention processes to the radioactive waste management organisations traditionally participating in GEOTRAP.

3. RECOMMENDATIONS IN RELEVANT AREAS

The GEOTRAP workshops brought together key individuals and organisations active in developing both fundamental understanding and models of radionuclide migration. A variety of repository sites, designs, characterisation methodologies, models, databases, and repository programmes at different stages of development were represented in the workshops. A list of recommendations was produced by each workshop pertaining to the specific workshop topic. The recommendations from GEOTRAP are grouped below in three categories: those pertaining to field tracer experiments and other data collection; those pertaining to modelling; and those pertaining to confidence building and communication. Taken together, these recommendations provide a guide to advancing the state of the art.

In some respects, recommendations arising from the GEOTRAP workshops related to data collection and modelling were outgrowths or further refinements of recommendations made at the conclusion of the INTRAVAL project (SKI and NEA 1996), reflecting the on-going improvements that continue to be made in those areas. The area of confidence building and communication, however, was seen to be much more important by GEOTRAP than had been recognised by predecessor projects such as INTRAVAL. This realisation no doubt stems from the increased public interaction and scrutiny experienced by many waste-disposal programmes as they approach, or have engaged in, licensing hearings. Thus, the need for, and techniques for obtaining, improved confidence and communication are given clear emphasis in many of the recommendations arising from GEOTRAP. These recommendations have general applicability beyond the specific field of radionuclide migration.

Field tracer experiments and other data collection

Regarding field tracer experiments:

1. The continuation of field tracer experiments is generally recommended because they:

   - Provide fundamental, and at times unexpected, information useful in developing and testing conceptual models.

- Are possibly the only way to test assumptions associated with the upscaling of laboratory experiments to field conditions and, more generally, to test models of transport and retention processes under conditions relevant to performance assessment.
- Provide technical input and other supporting information to performance-assessment models.
- Contribute to development of interdisciplinary teams.
- Build confidence in the understanding of transport processes both among the scientists involved and the general public.

2. The specific objectives of a field tracer experiment must be clearly identified before designing the experiment. It is important to be clear whether a test is intended to provide quantitative information about specific transport processes or qualitative information useful in developing and testing conceptual models.

3. The design and performance of field tracer experiments should take account of:

    - The degree to which parameters inferred from experiments are representative of the wider geological medium, which is specific to the scale and conditions of the test and to the specific test domain.
    - The disturbance that the experiment will cause to the natural system, and the resulting danger that the data produced will not be usable in predicting the behaviour of the undisturbed system.
    - Earlier experience on which new experiments should build.
    - The desirability of using sorbing tracers and relevant radionuclides to complement the use of simpler tracers for which results are easier to interpret.
    - The need to collect high-accuracy data from the tails of breakthrough curves, the form of which may reflect matrix heterogeneity.

4. In order to support the modelling of matrix diffusion in both tracer transport experiments and performance assessments, there is a need to develop and refine methods to characterise:

    - The degree of channelling within fractured rocks (the flow-wetted surface).

- The heterogeneity of the matrix and its porosity.
- The distance into the wallrock over which matrix diffusion can be expected to occur.

5. The number of "free" parameters in models used to interpret tracer tests should be minimised by complementary data collection. For example, laboratory measurements of diffusion rates and porosity distributions, as well as geologic characterisation of fracture-infilling material, can provide, or at least constrain, values of particular model parameters.

6. The decades that it will take to site, construct, and operate a disposal facility provide the opportunity for very long term site-specific tracer experiments with both sorbing and non-sorbing tracers, perhaps under natural gradients, to complement the spatially and temporally limited tracer experiments that may be performed during the site-characterisation phase of a project.

7. Tracer tests should be planned by a multidisciplinary team, including experimentalists, hydrogeological modellers, and performance-assessment specialists, to be of maximum value.

8. The results of tracer tests should be integrated with independent sources of information (e.g., paleohydrology, geochemistry, natural analogues) to develop a more complete understanding of flow and transport.

9. The flow system in the region of a tracer test must be well characterised for a meaningful interpretation of the experiment and, in particular, for reducing the degree of non-uniqueness.

A firm scientific basis was found to exist for the decisions at hand in most advanced national programmes, but it was noted that this is a time-dependent statement and that "good science" is assessed always against prevailing standards. Hence, in the interest of providing continual improvement in scientific understanding, additional work was recommended in the areas of:

- Methods of detecting dominant flow pathways and characterising their small-scale structure.
- Coupling among processes.
- Natural analogues and site-specific evidence (e.g., paleohydrological arguments).
- Time-dependent effects and site evolution.

- Definition of correlations among different types of data and increased data integration.
- Methods for deriving effective parameters from measured parameters.
- Characterising the variability of chemical properties, their possible coupling with other properties, and involvement in non-linear processes.
- Development of a database of observations related to retention processes.
- Upscaling of laboratory data on retention processes to field conditions, with model testing.
- Consideration of heterogeneity and variability in the modelling of retention processes such as sorption in performance assessments.
- Improved understanding of the mechanisms of inorganic colloid generation, the kinetics of radionuclide desorption from colloids, and of colloid-facilitated radionuclide transport.
- Improved understanding of immobilisation processes under deep, reducing conditions.

Generally speaking, data-collection efforts should be guided, but not exclusively driven, by performance assessment. Site characterisation and basic research have an ongoing role in defining and developing the conceptual models that will be numerically implemented in performance-assessment models. Performance assessment, in turn, may provide motivation for the development of new experimental techniques.

Modelling

1. Particular attention must be paid to the avoidance of unquantifiable bias in consequence calculations that may arise from the choice of a unique model. A range of alternative models, consistent with the available data, should be identified, and the effects of these alternative models considered. A judgement can then be made as to the way in which this conceptual-model uncertainty can best be addressed in performance assessment.

2. A level of description of heterogeneity should be included within the flow and transport models that enables proper account to be taken of the major

migration pathways as well as of the potential presence of fast pathways that may dominate the performance of the geosphere as a transport barrier.

3. Models should be calibrated and tested using experiments and observations covering different spatial scales, in order to narrow the range of conceptual-model uncertainty.

Confidence-building and communication

1. Confidence-building is a process that needs to be inclusive in order to ensure a wide acceptance of the methods, models, and data used in performance assessment. Confidence is enhanced by clear communication within the project team of an implementing body, between implementers and regulators, and within the wider community of scientists, politicians, and the general public.

2. To instil the confidence necessary for decision making in the early stages of a repository project, when many unresolved issues exist and before the necessary data to resolve the issues have been collected, a step-by-step plan showing how and when the necessary data will be collected should be created.

3. Interaction between technical specialists involved in site characterisation (including laboratory studies) and those involved in performance assessment is essential for efficient progress in repository development. Technical specialists in various scientific disciplines must develop an overall understanding of the repository-geosphere system to identify the features and processes most relevant to performance, while performance assessors can identify where improved understanding is, and is not, required for assessment purposes. Thus, interaction between these two groups is required in order to:

   - ensure that models at all levels of abstraction and simplification are traceable to real data and information;
   - focus field and laboratory work on key safety-relevant issues; and
   - focus on models that are applicable in practice (which may involve a degree of simplification/abstraction), rather than on highly detailed models that, to be applied, require data that are difficult/impractical to acquire.

Given the importance of such interaction, formal procedures may be needed to ensure that it occurs.

4. The regular exchange of views between the regulator and implementer on issues related to the characterisation and model representation of radionuclide transport (and more generally) should be promoted in order to ensure clear communication between the organisations. Regular communication will also contribute to mutual understanding and help establish what data and models are, and are not, acceptable to the regulator.

5. Communications between specialists can be hindered by problems related to terminology. These problems need to be addressed more formally, at the national and international levels, both to assist the work of these specialists and to facilitate the transfer of confidence to external scientific audiences.

6. Significant benefits can be obtained by looking beyond the field of radioactive waste management (e.g., in areas such as mining and management of non-radioactive hazardous wastes), drawing on the knowledge of specialists in other fields of science and engineering for basic understanding, planning, and peer review.

7. International meetings organised around particular radionuclide-migration issues should continue because they are useful both in advancing scientific understanding and in developing confidence in the work that is performed.

8. Documentation should be traceable and transparent, and plans and experimental and modelling results should be open to publicised peer review to enhance and communicate confidence;

9. While simple models that compensate for uncertainty through conservative assumptions may be useful in performance assessment, defensibility and credibility of a repository safety case require that such models be founded on detailed and wide-ranging information and system understanding. Peer review has an important role to play in ensuring that the available understanding is adequately taken into account in transport modelling for performance assessment.

10. The knowledge possessed by key individuals is an important resource for repository programmes. In order to avoid the loss of this knowledge over the decades-long duration of a programme as individuals retire or move

to other projects, a formal process should be established to transfer their working knowledge to new individuals.

11. Both favourable and unfavourable findings and aspects of an assessment should be publicised to enhance the credibility of the implementing organisation. Similarly, when testing alternative hypotheses, confidence can be enhanced by reporting those that are falsified as well as those that provide successful predictions.

These recommendations provide a way forward for all radioactive waste disposal programmes in developing credible, defensible models of radionuclide migration through the geosphere. If successfully implemented, they should contribute to the increased confidence necessary for both technical and public acceptance of deep geologic repositories as the permanent solution to the problem of radioactive waste disposal.

4. FIVE KEY MESSAGES

Among the conclusions and recommendations discussed in previous chapters are five points that were repeatedly made at the GEOTRAP workshops that can be considered guiding messages for the future:

1. The personnel responsible for site characterisation ("experimentalists") and those responsible for performance assessment ("modellers") should be in close communication at all times. Experimentalists must understand, and approve, how the system is being modelled, how their data are being used in the models, and must also understand the limitations of models and what specific data are needed by models and why. Modellers must understand the system conceptualisation(s) that the experimentalists have developed, the limitations of the existing data, what data are and are not possible to collect, and the contexts in which data can be considered to be valid. This communication and mutual understanding allows for improved scientific progress as well as technical confidence by all parties in the correctness of the work. One way of ensuring this communication is by having experimentalists involved in performance assessment, and modellers involved in experimental design.

2. A much deeper understanding of the system is required for confidence in performance assessment and the safety case than can or will be represented in necessarily simplified performance-assessment models. One important implication of this message is that site-characterisation activities cannot be guided solely by the needs of performance assessment. Site characterisation is responsible for developing an overall understanding of the system, including identification of the operative processes and quantification of important parameters. It is only from this comprehensive understanding that informed decisions on model abstraction and simplification for performance assessment can be made and justified. Performance assessment can then provide guidance on important areas where refined knowledge could reduce performance uncertainties, but it should never be relied upon to define the entire scope of experimental investigations.

3. Efforts should continue to be made to improve the integration of different types of data. This integration can take a variety of forms, both quantitative and qualitative. Data collected in the laboratory or field can

be used to reduce the number of free parameters in models of other experiments, such as using measurements of the porosity of fracture-infilling material to constrain tracer test models. Data from experiments or observations at different scales can be combined in models at the large performance-assessment scale. Equally important is the ability to show consistency between interpretations of independent sources of information such as paleohydrology, geochemistry, natural analogues, and natural isotopes. Confidence in the overall understanding of a system is enhanced when multiple lines of evidence converge on a single conceptual model.

4. Significant benefits can be obtained by looking beyond the field of radioactive waste management and drawing on the knowledge of specialists in others fields of science and engineering. This knowledge may take the form of theoretical understanding (e.g., knowledge of diffusion processes from chemical engineering), experimental techniques (e.g., methods of measuring *in situ* stresses from the mining industry), field experience/evidence related to specific processes (e.g., transport of contaminants from hazardous-waste facilities), or techniques for integrating data from diverse sources (e.g., integration of geophysical, geological, laboratory, and well-test data in petroleum industry reservoir models). These other technical communities also provide the opportunity for broader based and more meaningful peer review.

5. Communication between implementors and regulators at all stages of the process of repository development is extremely important. Communication can allow the regulator to gain information and provide feedback on the technical direction being pursued by the implementer, as well as understand the limitations of data and models. At the same time, the implementer can gain an improved understanding of the expectations of the regulator and modify its programme as appropriate. This communication can be both formal and informal. It should not, in any case, be allowed to compromise, or appear to compromise, the independence of the regulator. In this light, the implementation of a stepwise decision-making process, in which technical progress and future plans are routinely reviewed by the regulator, can provide an effective mechanism for obtaining the desired communication.

These messages, in fact, have applicability beyond issues relating solely to radionuclide transport through the geosphere. They pertain equally to virtually all aspects of radioactive waste repository programmes. Thus, they provide guidance to all national repository programmes, as well as to future NEA international collaborative projects.

5. THE VALUE OF GEOTRAP

GEOTRAP provided a unique technical forum where individuals playing different roles in repository programmes and experts from academia and the wider scientific community could have informed interactions on all topics relating to radionuclide migration in the geologic media presently considered for waste-disposal projects worldwide. This interaction allowed sharing of information, the opportunity for feedback from technical peers, a broadening of understanding of the needs and viewpoints of all the various parties involved in repository programmes, and an opportunity to get new ideas.

The organisation of GEOTRAP as a series of workshops spread over five years provided a continuity that allowed relationships to be developed and a means of remaining current on developments in other countries. Holding the workshops in different countries provided the opportunity for highly informative visits to disposal facilities and underground laboratories, allowing examination of a variety of potential disposal concepts and environments.

Some organisations found that their participation in GEOTRAP brought increased credibility to their work, both within their home countries and within the international community. They also found the knowledge gained from participating in GEOTRAP to be helpful in setting the objectives for upcoming phases of their own R&D programmes.

The format of the GEOTRAP workshops was especially appreciated. The mixture of technical presentations with focused discussions, allowing the participation of all present, created an atmosphere for learning and mutual understanding. It allowed for the expression of a diversity of ideas and their ultimate integration. Working groups were found to provide rare, intense, and fruitful opportunities to discuss detailed technical issues among a diverse group of experts.

The technical emphasis of GEOTRAP was seen as one of its primary strengths. By focusing on technical rather than managerial issues, more progress could be made on common problems. The workshop proceedings were found to serve the needs of both technical and managerial personnel, as the individual papers provide a valuable technical resource while the syntheses and working group summaries provide guidance for programme managers.

Other benefits provided by GEOTRAP include:

- Through good exchanges, the previously perceived controversies about transport processes have been reduced significantly; it is now possible to recognise that there is no such thing as "an unimportant process" in a general sense, but that importance can be determined in a specific application.
- A realistic view of modelling capability has been obtained, balanced by an improved understanding of transport processes; this has led to the elimination of the "fitting" of model parameters without a proper scientific basis that was evident in earlier work.
- A better understanding has been reached by site-characterisation specialists of the needs of performance assessment.
- A better understanding has been reached of the use of so-called "soft information" (with examples now of both quantitative and qualitative use), but this area still requires progress.
- Decisions on modelling strategy have been informed by identifying what needs to be taken into account when selecting the type/complexity of model to be applied.
- A firm scientific basis exists for the decisions at hand in most advanced national programmes, noting that this is a time-dependent statement and that "good science" is assessed always against prevailing standards.

In summary, GEOTRAP was seen as a highly valuable and successful project that should serve as a model for future international initiatives in the area of radioactive waste disposal.

REFERENCES

Larsson, A. 1992. "The International Projects INTRACOIN, HYDROCOIN and INTRAVAL," *Advances in Water Resources*, vol. 15, 85-87.

NEA, 1995. *The Role of Conceptual Models in Demonstrating Repository Post-Closure Safety*. Workshop Proceedings, Paris, France, 16-18 November 1993. OECD, Paris.

NEA, 1997a. *Field Tracer Experiments: Role in the Prediction of Radionuclide Migration*. Workshop Proceedings, Cologne, Germany, 28-30 August 1996. OECD, Paris.

NEA, 1997b. *Lessons Learnt from Ten Performance Assessment Studies*. Working Group on Integrated Performance Assessments of Deep Repositories. OECD, Paris.

NEA, 1998. *Modelling the Effects of Spatial Variability on Radionuclide Migration*. Workshop Proceedings, Paris, France, 9-11 June 1997. OECD, Paris.

NEA, 1999. *Water-conducting Features in Radionuclide Migration*. Workshop Proceedings, Barcelona, Spain, 10-12 June 1998. OECD, Paris.

NEA, 2001a. *Confidence in Models of Radionuclide Transport for Site-specific Assessment*. Workshop Proceedings, Carlsbad, New Mexico, USA, 14-17 June 1999. OECD, Paris.

NEA, 2001b. *Radionuclide Retention in Geologic Media*. Workshop Proceedings, Oskarshamn, Sweden, 7-9 May 2001. OECD, Paris.

SKI and NEA, 1996. *The International INTRAVAL Project, Final Results*. OECD, Paris.

Appendix

GEOTRAP PARTICIPANTS

Country	Organisation(s) [Workshops]
Belgium	Nuclear Research Centre (SCK/CEN) [1, 3, 4, 5]
Canada	Canadian Nuclear Safety Commission (CNSC) [1, 2, 4, 5] Ontario Power Generation [3, 4, 5] Atomic Energy of Canada Limited (AECL) [1, 2, 3] University of Waterloo [5]
Czech Republic	Nuclear Research Institute (NRI) [3, 5]
Denmark	University of Copenhagen [5]
Finland	Posiva Oy [1, 2, 3, 4, 5] Radiation and Nuclear Safety Authority (STUK) [1, 2, 3, 4, 5] Technical Research Centre of Finland (VTT) [1, 2, 3, 4] Geological Survey of Finland (GTK) [1, 4] University of Helsinki [5]
France	National Agency for Radioactive Waste Management (ANDRA) [1, 2, 3, 4, 5] Nuclear Protection and Safety Institute (IPSN) [1, 2, 3, 4, 5] Atomic Energy Commission (CEA) [2, 3, 4, 5] National School of Mines of Paris [2] University of Paris VI [2, 4]
Germany	Federal Office for Radiation Protection (BfS) [1, 2, 3, 4, 5] Federal Institute for Geosciences and Natural Resources (BGR) [1, 2, 3, 4, 5] Company for Facility and Reactor Safety (GRS)-Köln [1, 2, 3, 4, 5]

	Company for Facility and Reactor Safety (GRS)-Braunschweig [1, 2, 4, 5] Research Center Karlsruhe [5] Stoller Ingenieurtechnik GmbH [1]
Japan	Japan Nuclear Cycle Development Institute (JNC) [1, 3, 4, 5] Nuclear Waste Management Organisation of Japan (NUMO) [5]
Korea	Korea Atomic Energy Research Institute (KAERI) [1, 2, 4]
Russia	V.G. Khlopin Radium Institute [1]
Spain	National Radioactive Waste Company (Enresa) [1, 2, 3, 4, 5] Nuclear Safety Council (CSN) [3, 4, 5] Research Centre for Energy, Environment and Technology (CIEMAT) [5] Technical University of Catalonia (UPC) [1, 2, 3, 4] Technical University of Valencia (UPV) [2, 3, 4] Technical University of Madrid (UPM) [3] University of Zaragoza [5] QuantiSci SL [5]
Sweden	Swedish Nuclear Fuel and Waste Management Company (SKB) [1, 2, 3, 4, 5] Swedish Nuclear Power Inspectorate (SKI) [2, 3, 4, 5] Royal Institute of Technology (KTH) [2, 5] Chalmers University of Technology [2] Uppsala University [2] Conterra AB [1, 5] GeoPoint [5] Geosigma AB [1, 5] Golder Associates AB [3] INTERA [3] JA Streamflow AB [5] Terralogica AB [5] VBB VIAK [5]

Switzerland	Nagra [1, 2, 3, 5] Swiss Federal Nuclear Safety Inspectorate (HSK) [1, 2, 3, 4, 5] Paul Scherrer Institute (PSI) [1, 2, 3, 4, 5] University of Bern [1, 2, 3, 4, 5] Colenco Power Engineering AG [2, 3]
United Kingdom	Nirex [2, 3, 4, 5] British Nuclear Fuels (BNFL) [4, 5] UK Environment Agency [3] AEA Technology [1, 2] Safety Assessment Management (SAM) Ltd. [1, 2, 3, 4, 5] University of Exeter [1, 5] Birmingham University [2] QuantiSci Ltd. [2, 3] Galson Sciences Ltd. [3]
USA	Department of Energy (DOE) [3, 4] Environmental Protection Agency (EPA) [5] Nuclear Regulatory Commission (NRC) [1, 3, 4] Sandia National Laboratories (SNL) [1, 2, 3, 4, 5] Los Alamos National Laboratory (LANL) [2, 4] U.S. Geological Survey (USGS) [5] Center for Nuclear Waste Regulatory Analyses (CNWRA) [5] Environmental Evaluation Group (EEG) [2, 4] California State University, Chico [5] Colorado School of Mines [5] Oregon State University [5] Golder Associates, Inc. [1, 3, 5] Clearwater Hardrock Consulting [2] COMPA Industries, Inc. [3]
Other	OECD Nuclear Energy Agency (NEA) [1, 2, 3, 4, 5] European Commission (EC) [1, 3]

The NEA wishes to express its gratitude to the Government of Japan
for facilitating the production of this report.

本報告書の作成に関し、日本政府の協力に謝意を表する。

OECD PUBLICATIONS, 2 rue André-Pascal, 75775 PARIS CEDEX 16
Printed in France.