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FIELD TRACER EXPERIMENTS:

ROLE IN THE PREDICTION OF RADIONUCLIDE MIGRATION

Synthesis and Proceedings of an NEA/EC GEOTRAP Workshop
Cologne, Germany, 28-30 August 1996

NEA/AEN **EC/CE**

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Synthesis and Proceedings
of an NEA/EC GEOTRAP Workshop,
hosted by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS),
Cologne, Germany, 28-30 August 1996

A workshop organised in the framework of the NEA Project
on Radionuclide Migration in Geologic, Heterogeneous Media
(GEOTRAP)

FOREWORD

GEOTRAP, the OECD/NEA Project on Radionuclide Migration in Geologic, Heterogeneous Media, is devoted to the exchange of information and in-depth discussions on present approaches to acquiring field data, and testing and modelling flow and transport of radionuclides in actual geologic formations for the purpose of site evaluation, and safety assessment of deep repository systems. The project is articulated in a series of structured, forum-style workshops.

The first GEOTRAP workshop, *"Field Tracer Experiments: Role in the Prediction of Radionuclide Migration",* was held in Cologne (Germany) on 28-30 August 1996. It was co-organised with the Directorate General XII (Science, Research and Development) of the European Commission, and was hosted by the *Gesellschaft Für Anlagen- und Reaktorsicherheit, GRS, mbH* (German Company for Reactor Safety).

The workshop was aimed at providing a structured forum whereby implementors, regulators and scientists could interact, contribute to the advancement of the state of the art in this area, discuss the approaches and rationale of past, current and planned tests, and assess the results and uses of past experiments.

In addition to oral and poster presentations, the workshop consisted of focused discussions within four working groups.

The technical presentations gave an overview of on-going and planned work in the study of radionuclide transport phenomena and the characterisation of relevant properties of the geologic media. Discussions took place on the extent to which it is possible to resolve migration problems using field tracers experiments, and all participants were asked to define the role of tracer tests in the safety assessment of deep radioactive waste repositories.

This publication includes a synthesis of the workshop that reflects the materials that were presented, the discussions that took place and the conclusions drawn, notably during the working group sessions. The publication also reproduces the papers presented at the workshop. The opinions, conclusions and recommendations expressed are those of the authors only, and do not necessarily reflect the view of any OECD Member country or international organisation. This report is published on the responsibility of the Secretary General of the OECD.

ACKNOWLEDGEMENTS

On behalf of all participants, the NEA wishes to express its gratitude to the *Gesellschaft für Anlagen- und Reaktorsicherheit*, *GRS, mbH* (Germany) which hosted the workshop at its Cologne premises, and to the Fuel Cycle and Radioactive Waste Unit (F5) of the Directorate General XII (Science, Research and Development) of the European Commission which co-organised the workshop.

The success of the workshop was due to:

- the members of the workshop Programme Committee: Peter Bogorinski (GRS, Germany), Russell Alexander (NAGRA, Switzerland), Juhani Vira (POSIVA, Finland), Geert Volckaert (SCK/CEN, Belgium), Henning von Maravic (European Commission), Philippe Lalieux (OECD/NEA), and Claudio Pescatore (OECD/NEA);
- the NEA consultants who helped conduct the numerous discussions: Paul Smith (Safety Assessment Management Ltd, United Kingdom), Aimo Hautojärvi (VTT Energy, Finland) and Mike Heath (Earth Resources Centre, Exeter University, United Kingdom), and who also helped the Secretariat in drafting the synthesis; and
- the speakers, the posters' authors and other participants;

all of whom deserve thanks for their active and constructive contribution.

The Chairmen of the sponsoring NEA groups, Alan Hooper (Co-ordinating Group on Site Evaluation and Design of Experiments) and Piet Zuidema (Performance Assessment Advisory Group), made a number of valuable comments and contributions in reviewing the synthesis; their reviews have been addressed in the present publication.

Claudio Pescatore and Philippe Lalieux from the Radiation Protection and Waste Management Division of the OECD/NEA are responsible for the GEOTRAP project's scientific secretariat.

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PART A

SYNTHESIS OF THE WORKSHOP

EXECUTIVE SUMMARY

Several past, current and planned field tracer experiments were described and discussed in the course of the workshop. They cover various potential repository host rocks from soft argillaceous media to hard, fractured crystalline basement; make use of a wide range of both sorbing and non-sorbing (conservative) tracers; and cover various types of geologic features at different spatial and temporal scales.

The workshop provided a broad perspective on the advantages and limitations of field tracer experiments, and a set of conclusions and recommendations that will be useful when designing future tests. The main conclusions of the workshop are as follows:

1. Field tracer experiments have a valuable role to play in building confidence in the identification of the processes relevant to transport, in the provision of parameter values that are required by transport models and in the definition of site-specific models.

2. A good characterisation of the flow system in the region of the test is desirable for a meaningful interpretation of tracer experiments and, in particular, for reducing the degree of non-uniqueness.

3. 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, need to be invoked to rationalise the 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.

4. The relative importance of the operating 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.

5. Tracer tests are most likely to be valuable when planned by a multidisciplinary team, including experimentalists, hydrogeological modellers and performance assessment specialists.

6. In the assessment of the geological barrier of a repository system, integration of tracer tests with other types of studies (e.g. paleohydrogeology) is seen to be crucial, as are the testing of alternative hypotheses and the identification of features of repository host rock relevant to flow and transport. Field tracer experiments in isolation can never provide an adequate proof of the performance of the geosphere.

7. There are inherent limitations in the use of field tracer experiments in support of the assessment of the geosphere as a barrier to radionuclide migration:
    - The experimental time and length scales and flow conditions that can never fully reproduce those relevant to performance assessment. The length scales that have been explored experimentally are, however, very relevant for the analysis of the transport properties of the near-field host rock.
    - The practical difficulties in integrating these experiments with other studies.
    - The limited transferability of data from one site to another.

In summary, field tracer experiments should continue to form part of the research needed for performance-assessment modelling as they provide important technical information, help build confidence in performance-assessment models, and provide much, sometimes unexpected, supporting information and understanding of radionuclide-migration mechanisms. Among the wider benefits to be derived from the continued use of field tracer experiments are also the development of interdisciplinary teams and improvement of public confidence in disposal options, though it should be remembered that the results of field tracer experiments can be difficult to interpret and that such tests cannot provide proof of the performance of the geological barrier of any disposal system, but are rather a technique among others to be used in pursuit of a solution to the safe disposal of radioactive waste.

1. INTRODUCTION

1.1 RATIONALE AND STRUCTURE OF THE FIRST GEOTRAP WORKSHOP

The use of field tracers is a most prominent approach to study flow distribution, characterise potential flow paths, test different conceptualisations (both of flow and transport) and estimate transit times at selected sites and at different scales. The experience to date from field tracer experiments demonstrates the complexity of the techniques used. This led to the decision, within the framework of GEOTRAP, to hold the first workshop on the rationale and planning of tracer experiments, keeping in mind the needs of site characterisation and performance assessment.

The goals of the workshop were:

- To provide a forum whereby implementers, regulators and scientists can interact in a structured fashion.
- To learn about and contribute to the advancement of the state of the art in the area of field tracer experiments in order to build confidence in the modelling of radionuclide transport in geologic, heterogeneous media.
- To comment on the approaches used by different programmes.
- To discuss the rationale, objectives and strategies for past and planned tests.
- To evaluate the uses and results of field tracer tests in the light of alternative testing methodologies.
- To assess the results of past and current tests and their uses/relevance for site characterisation and performance assessment purposes.
- To compare “generic” tests with site-specific tests.

A final aim of the workshop was the preparation of this synthesis, which reviews and summarises the lessons learned at the workshop, putting them into perspective within the scope of the GEOTRAP Project and the state of the art in this field.

The workshop was introduced by three overview papers in order to provide the audience with a common background for the planned discussions. The three sessions addressed the rationale behind tracer tests, presented several test cases and discussed the aims of planned experiments, respectively. In addition, a poster session dealt with more specific, technical details. A key part of the workshop consisted of focused discussions within small working groups, on specific themes. The outcomes of the working groups provided the basis for a plenary, concluding discussion. For each session and for each working group, the Programme Committee had established a series of key questions to be addressed. This proved to be a very effective way of focusing the discussions and reaching practical conclusions.

1.2 STRUCTURE OF THE SYNTHESIS

The workshop is synthesised at three different levels by providing:

1. An overview of the workshop achievements, which includes an assessment as to how each goal specified for the workshop was met, the general conclusions as well as the inherent limitations of the tests and recommendations regarding future work (Chapter 2).
2. Synoptic tables of the key features of the various field tracer experiments that were described in the course of the presentations and discussions (Annex 1). These tables help set the context in which the achievements, general conclusions, limitations and recommendations should be viewed by providing an overview of the main current and planned tests, including their status and principal aims.
3. A detailed record of the workshop that compiles the answers to the key questions specified for the four workshop sessions, and reports the discussions and conclusions of the four working groups and of the final, concluding session (Annex 2).

2. WORKSHOP ACHIEVEMENTS

2.1 ACHIEVEMENTS OF THE WORKSHOP GOALS

The extent to which the principal goals of the first GEOTRAP workshop, described in Chapter 1.1, were achieved can be summarised as follows:

- **To provide a forum whereby implementers, regulators and scientists can interact in a structured fashion.**

  The workshop was attended by 40 delegates from 12 countries, with a range of experience including performance assessment, site characterisation, experimental techniques and modelling. Several implementing organisations and a few regulatory bodies were represented, as well as research laboratories and universities. The workshop comprised 14 technical presentations, each allocated a discussion period, and in-depth discussions by 4 working groups on a range of detailed topics. The technical presentations triggered discussion as to the extent to which it is possible to resolve migration problems using field tracer experiments, and particularly problems relevant to performance assessment; these discussions ultimately led to some constructive ideas for improvements of future experimental programmes. There was no special weighting of issues from the point of view of interest to implementors, regulators or scientists, but regulators were, to some extent, challenged to define the role of tracer tests in performance assessment.

- **To learn about and contribute to the advancement of the state of the art in the area of field tracer experiments in order to build confidence in the modelling of radionuclide transport in geologic, heterogeneous media.**

  The technical presentations gave an overview of on-going work on the study of migration phenomena and the characterisation of properties of geologic media that are relevant to the transport of radionuclides. Planned and performed tracer experiments related to waste-management programmes in various countries were presented and discussed thoroughly in the workshop sessions. The experience gained, and the continuing need for improvement, were summarised in the conclusions drawn by the four working groups. The overall contribution to the field can be judged from the conclusions and recommendations of the workshop. The consensus among the participants was that the workshop was successful and useful, both to themselves and, more generally, to organisations working in the field of radioactive waste disposal.

- **To comment on the approaches used by different programmes.**

  From the presentations and discussions of the workshop, it was apparent that the approaches used by different programmes (i.e. whether the tests are used to provide basic understanding of processes or to test and refine performance-assessment models) are dependent on the “simplicity” or “complexity” of the host rock under consideration (e.g. plastic clays vs. fractured rocks) and on the stage reached by the national waste management programme. There is also a contrast between programmes that emphasise the use of field tracer experiments to develop understanding of the transport of non-reactive tracers in systems of increasing spatial scale (and structural complexity) and those that emphasise the use of increasingly complex tracers in structurally relatively simple systems. The existence of experimental artefacts was identified as a problem area faced by all programmes. This, and other practical challenges, were addressed by Working Group 1 *(Practical Challenges).*

- **To discuss rationale, objectives and strategies for past and planned tests.**

  The changing rationale of field tracer experiments in recent years was noted. Such experiments were previously considered indispensable for "overall validation" of radionuclide transport models. These expectations are now regarded as having been over-ambitious. Field tracer experiments are now better focused and generally adopt a strategy of beginning with simple systems (structural simplicity, non-sorbing tracers), before progressing to more complex systems once the simple systems are fully understood. The desirability of participation by different parties involved in site characterisation and performance assessment was noted, as was regulatory interest (although in no country are field tracer experiments mentioned in regulatory guidelines). Current expectations from field tracer experiments were identified as being: (i) support for hydrogeological and flow models; (ii) support for descriptions of transport pathways; (iii) support for descriptions of interactions between water, solute and rock mass (including the transfer of laboratory data to the field); (iv) testing/calibration of migration models, particularly in relatively simple systems such as the Boom Clay; and (v) development of overall understanding and confidence building, including public acceptance. These topics were addressed by Working Group 2 *(Rationale and Promises of Future Field Tracer Experiments).*

- **To evaluate the use and results of field tracer tests in the light of alternative testing methodologies.**

  The use of tracer-test results for the purpose of performance assessment necessitates transfer, scaling and extrapolation of the results, in both a spatial and temporal sense, even for tests performed within a proposed disposal site. Results of "conventional" field tracer experiments (i.e. relatively short-term tests, using simple tracers, with injection/withdrawal in forced hydrogeological conditions) form an important component of the information required by performance assessment. This information must, however, be complemented by other types of information collected by alternative methods. In this respect, the greater use of natural tracers and natural flow conditions (use of paleohydrogeological and paleohydrogeochemical information) was seen to be crucial. The gap in time scales can partly be filled by long-term experiments which require long-term planning in the programmes. To address the complexity present in many systems, the need for a more sophisticated approach and integration of different approaches was identified. Integration of results obtained using various techniques, including techniques to characterise the site of tracer experiments and identify flowpaths, can give a deeper insight and increased confidence in overall understanding of the migration problem at a given location. This topic was addressed by Working Group 3 *(Alternative Methods to Tracer Experiments).*

- **To assess the results of past and current tests and their uses/relevance for site characterisation/evaluation and performance assessment purposes.**

  The workshop noted an increased integration of field tracer experiments and performance assessment in many national programmes. Field tracer experiments can, in certain cases, provide hard information for performance assessment. There is, however, also an increased appreciation of the qualitative aspects of performance assessment to which field tracer experiments can also contribute, providing confirmation that the methodologies, models, processes and data used in performance assessment are appropriate. It was also noted that the contribution of field tracer experiments to performance assessment depends on the stage reached within the waste-management project. This topic was addressed by Working Group 4 *(Integration of Data from Field Tracer Experiments into Performance Assessment).*

- **To compare "generic" tests with site-specific tests.**

  Generic tests were considered to be necessary in the study and understanding of processes and transferability of data (e.g. laboratory sorption data to *in situ* retardation). Generic tests are well suited to study the completeness of modelled processes and to identify any omitted phenomena, since the ability of models to reproduce the observed results can often be better tested in generic experiments, where extensive pre-test characterisation and "*post-mortem*" investigations can be performed. Generic tests were seen to complement site-specific tests; site-specific experiments can be interpreted with more confidence if supported by understanding gained in generic tests.

2.2 GENERAL CONCLUSIONS

The following general conclusions have been drawn from the first GEOTRAP workshop:

1. **Field tracer experiments have now been taking place for many years. They have a valuable role to play in building confidence 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.**

   Tracer tests have demonstrated the operation of matrix diffusion, that current understanding of transport processes is adequate to provide an interpretation of test results and that methods exist that allow laboratory sorption and diffusion data to be applied in the field. For site characterisation purposes, they can support and refine models of particular geologic features and complement conventional hydraulic tests.

2. **The workshop has provided evidence that 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.**

   Examples of the kind of data that can be obtained by the modelling of field tracer experiments, but are difficult or impossible to obtain by means such as hydrogeological characterisation (which includes traditional hydrological information, as well as geological characterisation), include flow porosity and, of particular relevance to performance assessment in fractured media, the heterogeneity of flow within fractures (e.g. the degree of channelling). The requirement to test methodologies for transferring laboratory sorption data to field systems can also be met by field tracer experiments. In order to ensure that the conditions of a field tracer tests experiment are as well defined as possible, so that interpretation can focus on a small number of unknowns, the geological setting of the tests should be extensively characterised as part of the planning of the experiments. This task is made easier where geological complexity is not too great.

3. **The presentations and discussions of the workshop have highlighted fundamental differences in field tracer experiments, as applied to plastic clays on the one hand and fractured media on the other, in terms of the information that they provide for performance assessment.**

   Field tracer experiments are most successful for simple systems, as exemplified by the Boom Clay tests. The results of field tracer experiments are most easily incorporated into performance assessments, as data for models ("hard" information), when the system is simple in terms of the number of processes operating and in terms of structure (in particular, in the absence of fractures).

   Success in the modelling of field tracer experiments in the Boom Clay may have implications beyond geosphere transport modelling in plastic clays. In particular, the techniques developed could be used to test the performance of emplaced bentonite (intact, unjointed blocks) as an effective barrier to the transport of radionuclides. It also opens prospects for the testing of less plastic clays at depth, where fractures may be closed due to the weight of the overburden and may cease to constitute flow pathways.

   The link between field tracer experiments and performance assessment is less evident in fractured media. Indeed, such experimental data have found only limited direct use in performance assessment analyses to date. Compared to relatively homogeneous media such as Boom Clay, a larger number of features may be relevant to flow and transport in fractured media and characterisation is frequently incomplete (particularly, characterisation of large-scale heterogeneity). This can result in more complex break-through curves and in the existence of alternative models that fit the curves equally well. It also means that experiments tend to focus on individual features within more complex systems. Nevertheless, modelling exercises can be used to provide support for certain aspects of performance assessment models, such as the averaging of small-scale heterogeneities (see the discussion of "soft" information, below). Furthermore, it is not always necessary, for the purposes of performance assessment, to discriminate between alternative models; for example (i) if a conservative treatment is felt to be acceptable and (ii) if the feature/process concerned is, in any case, insignificant on the spatial and temporal scales of performance assessment.

   The usefulness for performance assessment of future tracer tests in fractured media may be increased by carrying out experiments in the structural features that are most relevant to geosphere performance.

4. **There is increased recognition that performance assessment makes use of a combination of quantitative ("hard") and qualitative ("soft") information[1]. Where the system studied is relatively simple (as in the case of plastic clays), field tracer experiments can serve to provide specific hard information. For more complex systems, field tracer experiments can play a useful part in general confidence building, as well as in the development of the team (modellers and experimentalists) and the tools (analytical and experimental) for performance assessment.**

   The acquisition of hard information from field tracer experiments is exemplified by the tests carried out in the Boom Clay. The information obtained from the other tests discussed at

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[1] "Hard" information is, for example, data that can be input, possibly via an interpretative model, into calculational tools. "Soft" information is, for example, wide-ranging evidence that gives confidence that safety assessment methodologies, models, processes, data and system general understanding are appropriate.

GEOTRAP contributes more to general confidence building, particularly in models and the up-scaling of data:

- *Models of processes*: the success of the models used to predict the results of field tracer experiments can build confidence that all processes relevant to solute transport have been identified.

- *Data and up-scaling*: it was pointed out that field tracer experiments are, in general, just one of a number of sources of data, complementing the information from laboratory tests, field hydrogeological tests, natural analogues, natural tracers and geological data. Some of these data sources relate to systems characterised by different scales of space and time to those of interest in performance-assessment calculations (e.g. small-scale laboratory experiments). The application of these data involves assumptions regarding up-scaling. Confidence can be built in these assumptions by demonstrating that they allow the prediction of the results of field tracer experiments, that represent scales intermediate between those of laboratory tests and those of performance assessment, and between those of natural analogues and those of performance assessment.

Field tracer experiments can serve to gather and focus interdisciplinary expert input (for example, through discussion forums such as GEOTRAP). They can also stimulate the development of new experimental techniques (*in situ* and laboratory) and models and establish effective communication between field and laboratory experimentalists and modellers.

5. **The greater complexity and more qualitative link to performance assessment in the case of fractured media suggests that special efforts are required with respect to (i) integration with other types of studies, (ii) the characterisation of the system, (iii) the testing of geological features that are relevant to geosphere performance and (iv) the testing of alternative hypotheses. When testing alternatives, falsified hypotheses should be reported, as well as those that provide successful predictions.**

The approach advocated in the discussions of the GEOTRAP workshop is to reduce uncertainty in the characterisation of the system, as far as is possible, by taking account of, for example, all available geological, hydrogeological and geochemical information and then to test as many alternative models as possible, consistent with the characterisation, against field tracer experiments. Model predictions should be made in advance and tests designed in such a way that they can differentiate between alternative models, thus allowing hypotheses to be falsified. Even if a thorough hydraulic characterisation is a prerequisite for a good experimental design and a proper interpretation of the test, it is advisable, where possible, to analyse the flow system in detail (over-coring or moulding of the fracture system) after the completion of the tracer experiments. This may help fix some of the free parameters that the models may contain.

6. **The similarity, in terms of processes, of the models that are applied in the interpretation of field tracer experiments for a particular medium suggests that a consensus may have been reached in the identification of processes relevant to tracer transport.**

In practice, it is rare in the modelling of field tracer experiments to examine conceptual model uncertainty in the sense of uncertainty in the processes that are operating. Rather, alternative models tend to represent alternative ways of simplifying a geological interpretation of the system in order that transport modelling may be performed. Recent experience in field tracer experiments has suggested that no additional processes, outside the scope of current models, need to be invoked in order to understand experimental results.

7. **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.**

   A number of suggestions were made at the GEOTRAP workshop as to how to achieve such communication. Among these were:

   - Overlap, where possible, of the teams involved in field tracer experiments and the teams involved in performance assessment. This overlap was advocated both on the modelling side and on the experimental side.

   - Information exchange in a form that is as simple and concise as possible, consistent with its intended audience and application.

   In principle, it was agreed that performance-assessment teams should be involved in the identification of experiments to be performed and in the design of these experiments, particularly in the later stages of a repository research programme. The generic experiments performed in the early stages of a repository research programme have provided input to performance assessment, providing support for the basic understanding of transport processes. In the later stages of repository development, where the emphasis shifts to the refinement and testing of models of transport at a specific site, the input of performance-assessment teams to the planning of experiments will become increasingly important. This will ensure that the experiments, in conjunction with detailed hydrogeological characterisation, deliver information (flow porosity, channelling, etc.) that is required in order to assess the performance of the geological barrier.

2.3 LIMITATIONS OF TRACER TESTS

The limitations regarding the use of field tracer experiments in support of the assessment of the geosphere as a barrier to potential radionuclide releases from a deep repository were clearly acknowledged during the discussions. These limitations may be encountered at the licensing process level, or when planning the strategy by which to provide evidence of the fulfilment of safety criteria for waste disposal. They may also be encountered at the level of technical details of experimental procedures. Much progress has been made recently, especially in the use of tracer tests to characterise heterogeneous media and to study transport phenomena therein. Some limitations that are inherently associated with field tracer experiments or that remain regardless of the latest developments will be discussed here.

- **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 geosphere has gone through many evolutionary changes and cycles and will continue to do so in the future. The relevance of present-day determination of structures and properties of transport pathways for a case in the distant future has to be assessed critically. On the other hand, in many cases, conditions deep in geologic formations can be shown to have been stable over long periods of time.

- **The extent to which a repository site can be characterised by means of field tracer experiments depends on the characteristics, location and scale of the planned tests.**

  The thorough study of a site associated with large-scale heterogeneities is, in practice, impossible. The number of boreholes needed for such a characterisation would be so large that, even if hypothetically possible from an economic perspective, the existence of the boreholes would destroy the natural conditions at the site. The characterisation is inherently limited to certain specific areas. Nevertheless, this may prove very valuable.

- **The time and length scales of field tracer experiments compared to those relevant in assessing the performance of the geosphere is problematic. Only a limited volume of a host formation and its surrounding can be covered by rather short-term tracer tests.**

  Tracer tests have mostly to be performed in forced flow conditions over scales such that reasonably high recoveries can be achieved in rather limited times. A combination of long transport paths and slow flows in an unknown flow field is not possible. For sorbing tracers, the test times would exceed any practicable limits. Particular components of the potential migration paths can, however, be examined and provide a basis for the assessment of complete paths. The length scales that have been used experimentally are, however, very relevant for an analysis of the transport properties of the near-field host rock.

- **The extent to which chemical and physical disturbances caused by the tests themselves can be avoided needs to be carefully assessed.**

  The forced flows that are unavoidably used in the experiments, as well as equipment in the test area, cause a disturbance in the test environment that may be difficult to estimate. Development work aimed at minimising disturbances has been, and will continue to be, performed. There is, however, a trade-off between low disturbance and the desire for experiments covering large spatial scales.

- **Non-uniqueness of interpretation.**

  Breakthrough curves from tracer experiments are often difficult to interpret in relation to the different processes operating along the flowpath, and a unique interpretation (say, in terms of matrix diffusion) is rarely possible.

- **The optimum way in which to integrate field tracer experiments with other studies and with performance assessment may be unclear.**

  Tracer experiments are only one source of information relevant to performance assessment. To get the best out of tracer tests, that are often long-lasting and expensive, *they have to be integrated with other characterisation work* and should serve the needs of the performance assessment. It has proved difficult, in some instances, to find a common forum and language for discussions between experimentalists and performance assessors. It is not an easy task to simplify a complex flow and transport path structure, as well as the sometimes complex phenomena taking place within it, as a clear and not excessively conservative conceptualisation. Advances towards such conceptualisations are best achieved in a dialogue between experimenters and performance assessors.

- **The circumstances when, and reasons why, one should perform field tracer experiments must be identified.**

  A tracer test is by no means an overall remedy to every problem, but is an effective tool to study well-defined problems of flow and transport. It can be most useful when supported by as much information as possible, from other techniques, about the system under study. This supporting information may prove to be sufficient in itself, circumventing the need for a tracer test. In some cases, however, there may be specific open questions to which tracer tests are well suited. The rationale will, in such cases, be well formulated and the test design can be based on focused objectives. In other cases, the usefulness of tracer tests should be considered carefully. The role of tracer tests in different programmes and in their different phases varies considerably. It should always be an open question whether a tracer test is a suitable tool in any given circumstances.

2.4 RECOMMENDATIONS

2.4.1 Usefulness of Field Tracer Experiments

Field tracer experiments should continue to form part of the research needed for performance-assessment modelling as they provide important technical information, help build confidence in performance assessment models, and provide much, sometimes unexpected, supporting information and understanding of radionuclide-migration mechanisms. Among the wider benefits to be derived from the continued use of field tracer experiments are also the development of interdisciplinary teams and improvement of public confidence in disposal options. Though it should be remembered that the results of field tracer experiments can be difficult to interpret and that such tests cannot provide proof of the performance of the geological barrier of any disposal system, but are rather a technique among others to be used in pursuit of a solution to the safe disposal of radioactive waste.

- **Technical input to performance assessment models:** Field tracer experiments can serve at several levels in safety-related studies of geologic disposal systems for radioactive waste. Tracer tests sometimes provide the only reference to solute migration under real field conditions and can be used for various purposes at different scales. A good tracer test provides the desired information and data, and confirms (or, perhaps, denies) the anticipated and modelled behaviour of solutes and radionuclides in geologic media.

- **Confidence building:** Field tracer experiments play an important role in building confidence in performance-assessment models and methods and enable realistic models to be developed (or, at least, contribute towards their development). Field tracer experiments are most useful when integrated with other investigations as part of an overall programme; they thus complement other techniques and should not be seen as an alternative to any other type of investigation.

- **Supporting information:** Field tracer experiments can provide a wide range of both hard (i.e. quantitative) and soft (i.e. qualitative) data. The quantitative results of tracer tests can be fed directly into model simulations of tracer behaviour. The importance of qualitative information should not be underestimated, however, as this kind of “understanding” places constraints on, and confidence in, the transport-model development. Unexpected results of tracer tests can be particularly instructive, especially when they reveal unrealistic assumptions.

- **Development of interdisciplinary teams:** Tracer experiments provide a focus for a wide range of studies and act as a spur for the establishment of interdisciplinary teams, including field scientists (geologists and hydrogeologists), experimentalists, modellers and performance-assessment specialists. From this should arise a more complete conceptualisation and understanding that is necessary if modelling of the complexity of radionuclide migration in geologic media is to be tackled successfully.

- **Public confidence:** Field tracer experiments not only build confidence in the models, but can also contribute to public confidence that the level of understanding of radionuclide transport necessary for radioactive waste management is being attained; this, in turn, contributes to the public acceptance of waste management programmes in general.

2.4.2 Design and Performance of Field Tracer Experiments

In designing tracer tests, and in interpreting test results, special attention should be paid to the degree to which the data obtained are representative of the system of interest and to disturbance to the system by the test itself, while full advantage should be taken of the experience from earlier tests:

- **Degree to which data are representative:** Parameter uncertainty should be evaluated considering:

  – that the values of any parameters inferred from the results of the test are specific to the scale of the test and may represent some average over the region of the test (e.g. concentration values will be averages over a sampling interval and some volume around the interval);
  – that the values will be specific to the domain in which the test was performed. This means that, if the geological medium exhibits significant variability on a larger scale, the test could yield very different results for a similar domain at a different location and the test will not enable the larger-scale variability to be characterised. If, however, the results of the tracer test can be related to parameters whose distribution on the larger scale has been characterised, it may be possible to infer the likely results of performing the tracer test at an alternative location.

- **Disturbance to the natural system:** Disturbance to the system caused by the test itself should be considered as this might invalidate the data obtained (the results being related to an artificial rather than natural system) or, at least, make it impossible to reproduce the test using the same flow path.

- **Earlier experience:** Many tracer tests have been performed at many sites during the last two decades, not all of which have been reported at this workshop. There is now some repetition of the work carried out in the past, due to a lack of awareness of previous studies, and the experience gained from these earlier investigations is being lost. In developing new tracer tests, advantage should be taken of the lessons learned from these earlier tests.

- **Relevant radionuclides:** Tracer tests with performance-assessment relevant radionuclides are very rare. As such, any tests using these radionuclides are to be encouraged in order to study their *in situ* behaviour.

ANNEX 1

SYNOPTIC TABLES OF THE TESTS DISCUSSED

Several field tracer experiments were described in the course of the presentations and discussions. In order to set the context in which the achievements, general conclusions, open issues and recommendations should be viewed, Tables 1 and 2 summarise the main characteristics of these experiments, including their current status and principal aims.

Table 1. Geographical locations, geological media and status of field tracer experiments discussed at the GEOTRAP workshop

Test/ organisation	GEOTRAP reference(s)	Geographical location	Geological medium	Status
Tracer tests in **Boom Clay** / SCK-CEN.	Session II: VOLCKAERT & GAUTSCHI	HADES underground research facility, near Mol, NE Belgium.	Plastic, Tertiary clay (Boom Clay).	Diffusion tests with tritiated-water and ^{125}I tracers completed. 3-D tests using ^{14}C-labelled bicarbonate started in 1995. Further tests planned with ^{14}C-labelled organic molecules.
International **Mt. Terri** Project / Andra, BGR, Enresa, Nagra, Obayashi, PNC, SCK-CEN, SNHGS	Session II: VOLCKAERT & GAUTSCHI	Mt. Terri motorway tunnel near St. Ursanne in the Jura mountains, NW Switzerland.	Minor faults and fractures in a well-consolidated Middle Jurassic shale (Opalinus Clay) in the southern limb of Mt. Terri in the Folded Jura tectonic unit.	Feasibility study in progress (laboratory experiments, improvements of over-coring technique).
H-19 and H-11 Tracer Tests at the **WIPP** site / SNL, DOE	Session II: BEAUHEIM et al.; Session III: MEIGS et al.	Waste Isolation Pilot Plant (WIPP) site in the Delaware Basin, SE New Mexico, USA.	Fractured Permian Culebra Dolomite (Rustler Formation).	Field single-well injection-withdrawal and multiwell convergent-flow tests with non-sorbing tracers completed; planning underway for laboratory diffusion tests.
Grimsel Migration Experiment / Nagra, PNC.	Session II: ALEXANDER et al.; Poster Session: ALEXANDER et al.	Grimsel Test Site, east flank of the Juchlistock mountain in the Aar Massif of the Central Swiss Alps.	Reactivated mylonitic shear zone in Carboniferous Grimsel Granodiorite.	Numerous tracer tests with weakly and moderately sorbing tracers completed. Tests underway with more strongly sorbing tracers and with subsequent "*post mortem*" excavation of a portion of the shear zone.
Tracer tests at the **URL** / AECL	Session III: FROST et al.; Session IV: FROST et al.	AECL's Underground Research Laboratory, Lac du Bonnet, Manitoba, Canada.	Fractured crystalline rock, including fracture zones, moderately fractured rock, sparsely fractured rock and excavation damaged zones.	Two-well tracer tests completed within several major low-dipping fracture zones. Tracer tests underway in a region of moderately fractured rock with interconnected networks of discrete fractures. Migration experiment (in co-operation with JAERI) also underway in natural fractures in excavated granite blocks. Tracer experiment has been conducted within excavated damaged zone of a test tunnel.

Table 1. (continued from previous page)

Test/ organisation	GEOTRAP reference(s)	Geographical location	Geological medium	Status
Äspö HRL TRUE Programme/ SKB	Session III: OLSSON & WINBERG	SKB Äspö Hard Rock Laboratory, SE coast of Sweden.	TRUE-1: reactivated mylonitic shear zone in the Äspö diorite. TRUE Block Scale: Fracture network in a rock consisting mainly of Äspö diorite.	TRUE 1: radially converging and dipole expts. using conservative tracers completed. To be followed in 1997 with expts. with sorbing tracers, followed by resin injection and excavation. TRUE Block Scale: suitable site selected, pilot borehole drilled and characterised, preliminary site characterisation in 1997.
Tracer tests at the **El Berrocal** Site/ Enresa, EU.	Session III: GUIMERÀ et al.; Poster Session: GARCIA-GUTIÉRREZ et al.	El Berrocal Site, Central System, Central Spain.	Fractured granite.	7 tests carried out, with tracer recovery from 4 of them. Project complete. No more tests planned.
Tracer experiment at the **Kamaishi Mine** / PNC	Session IV: UCHIDA et al.	Kamaishi Mine in the Kitakami Mountains, Iwate Prefecture, Northern Honshu, Japan.	Cretaceous granodiorite.	Final borehole array completed and site-characterisation on-going to determine candidate fractures. Tracer-test design in progress; tracer tests to be conducted May 1997 to March 1998.
Combined pumping and tracer test at **Palmottu** / GTK, EU	Session IV: GUSTAFSSON et al.	Palmottu study area, SW Finland, within a zone of metamorphosed schists and gneisses that extends from southern to central Finland.	Fracture zones in crystalline rocks (mica gneiss and granite), surrounding uranium mineralisation.	Test is in the planning stage; detailed design is under discussion.
Radionuclide migration following nuclear explosions in **rock salt/**Radium Institute	Poster Session: ANDERSON et al.	Great Azgir salt dome, SW Caspian Sea depression, Kazakhstan.	5 stable cavities filled with radioactive brine. Permian rock salt diapir.	60s - 70s: comprehensive surveys during the conduction of the nuclear explosions. 80s - 90s: radiochemical monitoring. Current: feasibility study: analogue for studying the isolation capacity of rock salt.
Tracer tests at the **Reskajeage Quarry**/AEA, Nirex	Poster Session: HOLTON et al.	Cornwall, UK.	Fractured slate.	Combined colloid and non-sorbing tracer migration tests. Complete.

Table 2. Scales, tracers used and principal aims of field tracer experiments discussed at the GEOTRAP workshop

Test/ organisation	**Scale of tests**		**Tracers**		**Principal aims**
	temporal	**spatial**	**conservative***	**sorbing**	
Tracer tests in **Boom Clay**/ SCK-CEN.	7 years - still on-going.	A few metres.	Tritiated water, $^{125}I^-$, ^{14}C-labelled bicarbonate, ^{14}C-labelled organic molecules.	None used.	(i) demonstration of the predictability of radionuclide migration in the Boom Clay and assessment of the reliability of these predictions; (ii) enhancement of public acceptance.
International **Mt. Terri** Project / Andra, BGR, Enresa, Nagra, Obayashi, PNC, SCK-CEN, SNHGS	Tracer injection in a packed-off section of a single, small-diameter borehole over a long period (2 years or more).	Either over-coring of injection borehole or drilling of a parallel borehole at a distance of one to a few metres.	Not yet fixed (on-going feasibility laboratory experiments at CEN/DAMRI, Grenoble, France and at the University of Berne, Switzerland).		(i) visualisation of flowpaths; (ii) identification of groundwater flow and solute transport mechanisms in a highly-consolidated, fractured claystone; (iii) evaluation of parameters for radionuclide transport models.
H-19 and H-11 Tracer Tests at the **WIPP** site/SNL, DOE	Single-well injection-withdrawal tests: 18-hr pause after injection, 20-40 days pumping; convergent-flow tests: 14-105 days.	Convergent flow fields with travel paths of 11 to 25 m.	Iodide, 4 dichlorobenzoic acids, trichlorobenzoic acid, 6 difluorobenzoic acids, 2 trifluorobenzoic acids, tetrafluorobenzoic acid, pentafluorobenzoic acid, 3 trifluoromethyl-benzoic acids.	None used	(i) test for the occurrence of matrix diffusion in the Culebra; (ii) quantify or bound the amount of matrix diffusion occurring; (iii) evaluate whether or not idealised uniform fracture-matrix geometry is adequate to model test results; (iv) evaluate the effects of layering within the Culebra on flow and transport; (v) investigate the causes of directional differences in transport within the Culebra.
Grimsel Migration Experiment / Nagra, PNC	Min ~ 1 week; max ~ 20 months. Excavation project: injection & dipole pumping ~ 4 weeks.	Dipole flow fields with distances from injection to extraction of 1.7, 4, 5 and 17 m.	Uranine, ^{3}H, $^{3,4}He$, $^{82}Br^-$, $^{123}I^-$.	$^{22,24}Na^+$, $^{85}Sr^{2+}$, $^{86}Rb^+$, $^{137}Cs^+$, $^{99m}TcO_4^{2-}$. Excavation project: ^{99}Tc, ^{79}Se, ^{152}Eu, ^{237}Np, ^{113}Sn, Mo (stable), ^{60}Co (^{63}Ni), $^{234,235}U$.	(i) study of the hydrology and geochemistry of a fractured rock; (ii) testing of models of radionuclide transport; (iii) development of methodologies for site characterisation; (iv) focusing of laboratory, field and modelling studies to the detailed characterisation of a single site.

*It is noted that all tracers, even those classed as “conservative”, display some interaction with the geological medium through which they migrate.

Table 2. (continued from previous page)

Test/ organisation	Scale of tests		Tracers		Principal aims
	temporal	**spatial**	**conservative**	**sorbing**	
Tracer tests at the **URL** / AECL: Fracture zones	~ 1 week to 8 months.	~ 20 m to 700 m	I^- and Br^-; colloid tracers.	None used.	Determination of the physical solute transport properties of volumes of intensely fractured rock and development of methods for extrapolating the test results to larger scales.
Tracer tests at the **URL** / AECL: Moderately fractured rocks	~ 1 week to several months.	~ 10 m to 50 m in a large volume (~ 10^5 m^3) of rock	I^- and possibly others; colloid tracers.	Currently under study.	(i) evaluation of the physical and chemical solute transport properties of a relatively large volume of moderately fractured rock; (ii) determination of the suitability of the porous-media-equivalent method for modelling solute transport in volumes of moderately fractured rock; (iii) evaluation of other modelling approaches such as discrete fracture network models.
Tracer tests at the **URL** / AECL: Sparsely fractured rocks	~ 1 week to ~ 1 year.	~ 1 m	^3H.	^{85}Sr, ^{95m}Tc, ^{237}Np, ^{238}Pu.	Study of the transport of conservative and sorbing radionuclides in natural fractures in 1 m^3 quarried blocks of granite under *in situ* groundwater conditions.
Tracer tests at the **URL** / AECL: Excavation damaged zones	~ 2 days.	1.5 m	I^-.	None used.	Acquisition of information on physical solute transport properties within excavation damaged zones surrounding underground tunnels.
Äspö HRL TRUE Programme / SKB.	Hours - months.	Lab: <1 m; detailed: < 10 m; block scale: 10 - 100 m.	Uranine, Eosine, Rhodamine, Amino-G, metal complexes.	Selection of radioactive cations among: Na, Ca, Sr, Rb, Ba, Cs.	(i) development of understanding of radionuclide migration and retention in fractured rock; (ii) evaluation of the extent to which concepts used in models are based on realistic descriptions of rock and of whether adequate data can be collected in site characterisation; (iii) evaluation of the usefulness and feasibility of different approaches to radionuclide migration and retention; (iv) provision of *in situ* data on radionuclide migration and retention.
Tracer tests at the **El Berrocal** Site / Enresa, EU	Min ~ 1 week; max ~ 3 months.	8 m to 25 m.	Uranine, Eosine, Brillant Sulphaphlavine, Iodide, $^{82}Br^-$, Gadolinium, Rhenium, Phloxine, ^2H.	None used	Hydrodynamic characterisation of main geological structures.
Tracer experiment at the **Kamaishi Mine** / PNC	To be determined on the basis of on-going scoping calculations.	2 m to 60 m.	Uranine + others not yet fixed.		(i) to obtain a conceptual model with realistic geometries and properties of conductive fractures; (ii) to understand the hydraulic properties and geometries relevant to flow; (iii) to test a discrete-fracture model; (iv) to develop a site-characterisation methodology to be used for an eventual Japanese deep repository.
Combined pumping and tracer test at **Palmottu** / GTK, EU	2 - 4 weeks.	Converging flow field, with distance from injection to extraction of 20 - 100 m.	Fluorescent dyes (uranine, amino-G, rhodamine WT) and stable metal complexes (Gd-DTPA, Ho-DTPA, Eu-DTPA).	None will be used.	(i) verification of the updated conceptual hydrostructural model around the central part of the U-mineralisation; (ii) identification of the main potential flow paths within the test domain; (iii) improvement of understanding of flow and transport properties in order to support the forthcoming analogue transport study.

Table 2. (continued from previous page)

Test/ organisa-tion	Scale of tests		Tracers		Principal aims
	temporal	spatial	conservative	sorbing	
Radionuclide migration following nuclear explosions in **rock salt/**Radium Institute	Nuclear explosions detonated between 1966 and 1979. Annual sampling of brine 1980 - 1991.	Sampling of brine at 13 - 200 m (horiz.) from explosion epicentre.	Numerous fission and activation products and residual fissile isotopes of Uranium and Plutonium. Migration in brine of ^{137}Cs and ^{90}Sr studied in detail.		(i) assessment of rock salt as a medium for isolation and disposal of radioactive waste; (ii) evaluation of underground nuclear explosions as large-scale geo-technical analogues of radioactive waste disposal.
Tracer tests at the **Reskageage Quarry/**AEA, Nirex	?	5, 9.4 and 15.4m	Colloids: mono-dispersed silica particles and monodispersed hematite. Dye: rhodamine - wt.	None used.	(i) evaluation of the mobility of different types of colloids in a fractured rock environment; (ii) confidence building in modelling transport processes.

ANNEX 2

DETAILED RECORD OF THE WORKSHOP

1. INTRODUCTION

The first GEOTRAP workshop took the form of a series of oral and poster presentations, followed by discussions by four specific working groups and a final, general discussion session. This chapter compiles the answers, provided in each presentation, to the key questions specified for the four workshop sessions, and synthesises the discussions and conclusions of the four working groups and the final, general discussions.

The oral presentations were organised into four sessions:

- Session I: *General Overview;*
- Session II: *Rationale Behind Field Tracer Experiments;*
- Session III: *Test Cases: Design, Modelling and Interpretation;*
- Session IV: *Aims and Design of Planned Field Tracer Experiments.*

For each overview paper in Session I, in order to maintain focus, specific questions were set, in advance of the workshop, for the authors to address. In Sessions II-IV, questions were set for each session, and all the papers presented within a particular session aimed to address those questions. Section 2, below, indicates how the various papers addressed these questions. The answers provided aim at presenting the authors of the papers points of view and do not especially constitute a consensus statement that was reached at the end of the workshop.

More technical details of field tracer experiments were presented as posters. The presented posters are not included in this record of the workshop.

The four working groups focused on the following key aspects of field tracer experiments:

- Working Group 1: *Practical Challenges;*
- Working Group 2: *Rationale and Promises of Future Field Tracer Experiments;*
- Working Group 3: *Alternative Methods to Tracer Experiments;*
- Working Group 4: *Integration of Data From Field Tracer Experiments into Performance Assessment.*

A series of key questions was also specified for each working group in advance of the workshop. Section 3 presents the conclusions drawn by each of the working groups. These conclusions do not especially represent consensus statements that were reached at the end of the workshop.

Finally, Section 4 provides a summary of issues that were addressed in the final discussion session of the workshop.

2. RECORD OF THE WORKSHOP SESSIONS

2.1 Session I: General Overview

The GEOTRAP Programme Committee set specific questions to be examined in the papers and presentations. It should be remembered, that it is impossible to cover all tracer tests with one general answer. The answers should be seen as representing a trend among the tests that have been performed, rather than being applicable to any individual experiment.

What Has Been Learned from Field Tracer Transport Experiments – A Critical Overview

The paper by HAUTOJÄRVI, ANDERSSON & VOLCKAERT addressed the following questions.

1. Was the rationale of these tests clear enough?

The rationale for field tracer experiments has generally been clear, but the aims are often too optimistic and unrealistically wide, when account is taken of the available resources. For porous media, the typical rationale is the need to know the flow and transport porosity, together with the quantification of dispersion in one, two, or three dimensions. It is a simple and clearly stated rationale. Required test arrangements and procedures may, however, be quite complicated. The rationale for experiments in fractured media have often been expressed in similar terms. This may be a severe problem if the analogy between the media does not hold. A characteristic phenomenon of fracture flow is channelling, and the rationale of many experiments has been based on this point. Experimentally, it is a challenge to address channelling in undisturbed rock and near-natural flow conditions.

2. Which information was really obtained? What have field tracer tests taught us about important transport mechanisms?

Flow velocities and dispersion can usually be obtained quite reliably and accurately. Beyond that, the information obtained depends much on the concepts and modelling used. Usually, there are many different concepts and models that can, at the same time, explain a given set of results. There are thus ambiguities in the interpretation, which cannot be always be resolved due to lack of experimental data. The governing transport mechanisms cannot be distinguished in such cases. The most debated, and perhaps also most important transport mechanism is the matrix diffusion. It is extremely difficult, if not impossible, to show the effect of matrix diffusion on the break-through curves of field tracer experiments. It is certainly not enough to fit an advection-dispersion-matrix diffusion model to a break-through curve and deduce the various transport mechanisms from the model parameters.

3. What use was made of the information obtained?

The information has mostly served to strengthen understanding of the flow in different media: transport calculations in performance assessments are based directly or indirectly on the flow characteristics. Still, there are uncertainties in the basis of transport modelling, as partly discussed under question (2).

4. *Have they helped to build confidence in the predictive modelling of radionuclide transport for performance assessment purposes?*

Tracer tests have partly helped to build confidence in transport modelling. There are, however, important gaps to be filled before a satisfactory level of confidence can be achieved.

5. *Where are the failures? Were these failures clearly reported? What are the lessons learned from them?*

Where tests have failed to fulfil their goals regarding understanding of transport mechanisms, this has mainly been due to practical test limitations and partly also to unfavourable test procedures for the given goals. The reports usually emphasise a good agreement of the experimental and modelled results, and possible ambiguities are not assessed critically. In this sense, the "failures" or insufficiencies of the tests are hidden, rather than clearly reported. The lessons learned from failures of these kinds are that more and better tests and detailed characterisation of the test site is needed before transport mechanisms can be revealed and studied in the field.

6. *What can be expected from future field tracer tests?*

In future tests, ambiguities are likely to be reduced and tests are likely to be more focused on specific transport mechanism studies, compared to the "overall" type of tests made in the past. This may mean the performing of various tests at various scales and the combining of results from different tests (site, generic and laboratory). The aim should be to distinguish different concepts and models by the comparison of predictions with test results. It seems that not all of the tests that might be wished for can be performed in the field at a specific site. The tests at a disposal site will be even more limited in number. Characterisation of hydraulics is the main task at a disposal site and performance assessment has to rely on the relations between the hydraulic and transport properties studied at other places, possibly nearby, and even on generic studies.

The Contribution of Field Tracer Transport Experiments to Repository Performance Assessment

The paper by SMITH & ZUIDEMA addressed the following questions:

1. *What are the PA needs for field tracer tests? What kind of answers can field tracer tests provide?*

PA needs are identified as:

- Confidence building and identification of uncertainties: the success of a model in reproducing the results of field tracer tests, well-designed for specific purposes, builds confidence that relevant features and processes have been identified. Confidence is also built in the methodology for quantifying the rates of processes and the spatial extents over which they operate. The application of alternative models is useful in indicating the degree of conceptual uncertainty and, where some models fail, in narrowing the range of uncertainties.

- Assessment model formulation: assessment models are frequently derived from the more complex models used to interpret field tracer tests. Understanding of tests by means of models that aim at realism can ensure that the simplified assessment models represent key structures and processes, that simplifications do not give non-conservative results and that laboratory and field data are used appropriately.

In addition to the above roles, it is pointed out that, in a few cases, tracer tests have been used directly in the characterisation of flow and transport properties at specific sites.

2. *How can they help to build confidence in the predictive modelling of radionuclide transport for predictive purposes?*

A distinction is drawn between "inverse modelling" of tracer tests, which is used for model calibration, and predictive modelling of tracer tests, which is generally more convincing in terms of confidence building in models that will be used (perhaps in simplified form) to predict radionuclide transport in PA

In order to maximise benefits from predictive modelling of tests, it is recommended:

- that predictions be made *in advance of the tests,* with clear concepts, with a methodology defined for setting parameter values and with "success criteria" that take account of experimental errors; and

- that as wide a range of plausible alternative models as possible are examined.

3. *How are the results of these tests used in performance assessment?*

The primary uses for field tracer experiments in PA, the needs of which are indicated in (1) above, are:

- confidence building and the formulation of models, in which tracer tests have illustrated the importance of an understanding of small-scale geological structure and demonstrated the operation of matrix diffusion. They have also demonstrated that current understanding is adequate to provide an interpretation of many test results and that methods exist that allow laboratory sorption and diffusion data to be applied in the field.

- site characterisation, in which the use of tracer tests is restricted due to large-scale heterogeneity (see 4, below) and possible perturbation of the site by the tests themselves. Tracer tests can, however, be used to support and refine models of particular geological features and the related "tracer-dilution tests" can complement conventional hydraulic tests.

Additional benefits from tracer tests include experience in the practicalities of obtaining field data and relevant laboratory data, the development and refinement of measuring devices and the establishment of successful communications between geologists, laboratory and field experimentalists and modellers.

4. *How can results of field tracer tests be extrapolated and/or transferred to larger volumes of rock and to other sites/geology?*

- It is acknowledged that tracer tests provide no information on features and processes that, though irrelevant on the spatial and temporal scales of the tests, may be important over scales relevant to performance assessment - i.e. slow processes and processes operating on large-scale features.

- It is suggested that the identification of slow processes is the domain, for example, of natural analogue studies, rather than of field tracer tests.

- In the case of large-scale features, attempts that have been made to model tracer tests in networks of fractures have so far met with only limited success due to the lack of detailed characterisation of the networks.

- It is pointed out that the possibility of “fast channels” through the host rock is a key issue in geosphere PA and that, if their existence cannot be excluded, then the results of tracer tests are of rather limited use.

Regulator’s Point of View on the Use and Relevance of Field Tracer Transport Experiments

The paper by BOGORINSKI and BALTES addressed the following questions:

1. *Are the tests expected to be helpful in the perceived safety of a repository?*

Tracer tests are potentially helpful in the assessment of repository safety in that they can:

(i) test the “generic” capabilities of groundwater flow and radionuclide transport models (see 2, below);

(ii) provide certain site-specific data, such as porosities, diffusivities and retardation properties, that are relevant to the modelling of radionuclide migration through the geosphere;

(iii) provide input to the characterisation of the immediate vicinity of a repository and, in particular, the excavation disturbed zone.

2. *How can the tests help to build confidence in the predictive modelling of radionuclide transport?*

Confidence in the predictive modelling of radionuclide transport can be enhanced by performing tracer experiments either at an underground laboratory or within geological formations similar to those at a selected disposal site. The latter provides a test of the generic capabilities of such models. Testing in an underground laboratory at an actual site presents practical difficulties (e.g. disturbance of hydrogeological and geochemical conditions). Nevertheless, the site-specific data that such testing provides can be useful for the modelling of particular, spatially-limited features (e.g. the excavation disturbed zone).

3. *How useful were previous tests? What was missing?*

A problem specific to soft sedimentary rocks, such as those that are relevant to the German waste management programme, is that transport is slow and is not confined to just a few distinctive pathways (as is frequently the case with hard rocks). Field tracer experiments are not viewed by the authors as an appropriate means to characterise the large-scale heterogeneity of such rocks, because recovery of tracers at distant monitoring boreholes would be poor and difficult to interpret.

A more general problem is that, in order to fully understand the migration of a tracer, a network of boreholes is required that inevitably perturbs the system, introducing an artificial heterogeneity. If it were possible to develop novel methods to measure tracer concentrations within a rock without disturbing it with boreholes, this would greatly enhance the usefulness of such tests.

4. What is the relevance of these tests for site characterisation and site evaluation purposes?

It is pointed out that the spatial and temporal scales of relevance to performance assessment may be orders of magnitude greater than those that can be studied in tracer tests and that, in site characterisation, tracer tests can only cover a small part of the region of interest. Tracer tests can, however, be useful in determining hydrogeological and transport parameters at specific locations, in particular where variations due to geological events are suspected and in the excavation disturbed zone.

The authors conclude that they, as regulators, would not request specific tracer tests for the sole purpose of characterising the hydrogeological and geochemical conditions at the site of a proposed nuclear waste repository at a scale relevant to performance assessment.

2.2 Session II: Rationale Behind Field Tracer Experiments

The papers in Session II consider the rationale behind (i) tracer experiments in the Boom and Opalinus Clays (VOLCKAERT & GAUTSCHI), (ii) tracer experiments at the WIPP site (BEAUHEIM et al.) and (iii) the Grimsel Migration Experiment (ALEXANDER et al.). In addition, a paper by VIRA considers the relevance of tracer experiments to site description and understanding and how the benefits of tracer tests can be judged. The following tables indicate how the questions set for Session II are addressed by the papers.

1. What was the general context of the tests and how did this context influence the tests?

Tests	Context	Influence on tests (see also 2, below)
Boom Clay	Safety studies shown that the Boom Clay layer is the most important barrier in the Belgian multi-barrier concept and that diffusion is the dominant transport process.	Emphasis on extrapolation of (diffusion) data from lab to field. Slow transport rates means that use of sorbing tracers is not practical.
Opalinus Clay	Opalinus clay is a potential host rock for a Swiss HLW repository. No formal PA study yet performed.	Emphasis on identification of basic, transport-relevant phenomena (e.g. importance of joints and faults).
WIPP	Review of the 1992 PA for the WIPP site concluded that there was inadequate experimental justification to rule out alternative models and parameters for transport in the Culebra Dolomite Member, which overlies the salt host rock.	Emphasis on provision of a defensible model and parameters for PA modelling of the Culebra Dolomite member.
Grimsel	Fractured crystalline rock is a potential host for Swiss and Japanese HLW repositories. There is a desire to improve confidence in the use of transport codes for such a medium in PA.	Emphasis on testing (in advance of expts.) the predictive capabilities of models.

2. What were the objectives of the tests and how were these objectives incorporated in the test design?

Objective	Boom clay	Opalinus clay	WIPP	Grimsel
Understanding basic phenomena governing mobility of radionuclides.	×	yes	yes	yes
Direct determination of radionuclide migration parameters.	×	yes	yes	×
Studying transferability of lab data to *in situ* conditions (1).	yes	×	×	yes
Development and refinement of radionuclide transport models for PA.	×	×	yes	yes
Demonstration of predictability of radionuclide migration through a potential host rock.	yes	×	yes	(2)
Enhancement of public acceptance.	yes	×	yes	yes

Notes: (1) The lab experiments in question are chiefly, in the case of Boom Clay, diffusion experiments on small-scale samples and, in the case of the Grimsel Migration Experiment, batch sorption experiments.

(2) Grimsel granodiorite is not a potential repository host rock. Rather, it is regarded as a "generic" crystalline rock. A related objective of the Grimsel Migration Experiment is, however, given as - "... indoctrination of staff into the mind-set required for them to make predictions of radionuclide behaviour *in situ* ... ".

The test designs that have been established in order to address these objectives are described in the individual papers.

3. How does the test relate to the overall R&D programme?

Tests	Relation to overall R&D programme
Boom Clay	Direct input to laboratory diffusion programme (relationship between lab. data and *in situ* sorption).
Opalinus Clay (1)	(i) Feasibility of experiments currently under assessment in laboratory studies. (ii) Outcome of tests will provide input in the formulation of an appropriate transport model for PA
WIPP	(i) Linked to field hydraulic-testing programme. (ii) Linked to lab. programme (solubilities, batch-sorption studies with crushed Culebra matrix, matrix porosity, tortuosity and permeability).
Grimsel	(i) Direct input to Nagra's laboratory sorption programme (relationship between lab. data and *in situ* sorption). (ii) "Cross-fertilisation" between experiment and site characterisation/ performance assessment in the field of flowpath description. (iii) Public relations: articles in Nagra Bulletin, production of videos in Switzerland and Japan, public access to Grimsel Test Site.

Note: (1) The Opalinus-clay tests are still at the planning stage.

4. What use was made of the information obtained and how were the results extrapolated?

Tests (1)	Use made of results in *PA*
Boom Clay	(i) General confidence building in diffusion-dominated transport in Boom Clay (as assumed in PA). (ii) Conceptual model and data used for the prediction of tracer tests used directly in performance assessment studies (e.g. EVEREST, EC Study on the Evaluation of Elements Responsible for the Effective Engaged Dose Rates Associated with the Final Storage of Radioactive Waste).
WIPP	(i) General confidence building in the dual-porosity concept for geosphere transport modelling. (ii) Data and revised conceptual models used in PA as part of the formal certification application for WIPP (Oct. 1996).
Grimsel	(i) General confidence building in the dual-porosity concept for geosphere transport modelling (i.e. no significant processes overlooked) and in the transferability of sorption data from lab. to field. (ii) No direct use of data from migration experiment (e.g. diffusion constants and depth of diffusion-accessible wall rock) in PNC and Nagra PA

Note: (1) The Opalinus-clay tests are still at the planning stage.

5. Where was the greatest success and the most significant failure?

Tests (1)	Greatest success	Most significant "failure"
Boom Clay	Close agreement between predictions based in lab. diffusion data and tracer test results on a larger scale has strengthened confidence in the PA migration model.	–
WIPP	Tests designed to test hypotheses and answer questions. Tracer tests have thereby contributed to the evolution of site conceptualisation.	Unsuccessful tests aimed at determining whether the effects of source-term complexity have been inappropriately attributed to matrix diffusion.
Grimsel	Enhanced confidence in dual-porosity model (but see "failure", opposite) and demonstration of consistency between lab. and *in situ* sorption values.	The differences in time scales between the Migration Experiment and PA mean that different phenomena may be relevant in the two cases (e.g. diffusion into low-porosity wallrock insignificant in Migration Experiment, but thought to be important PA retardation mechanism).

Note: (1) The Opalinus-clay tests are still at the planning stage.

6. How do you assess the results of the test in the light of its rationale and objectives?

Objective	Boom clay	WIPP	Grimsel
Understanding basic phenomena governing mobility of radionuclides.	Successful (although not cited as an objective): demonstrated that diffusion is the dominant transport mechanism.	Successful: demonstrated that transport is not limited to fractures. Tracers interact significantly with the matrix.	Successful: no new and safety-relevant phenomena identified - enhances confidence in understanding.
Direct determination of radionuclide migration parameters.	–	Successful: led to estimation of ranges for Culebra physical transport parameters.	–
Studying transferability of lab-data to *in situ* conditions.	Successful: demonstrated, on a scale of metres, the applicability of lab. diffusion data for tritiated water and iodine.	–	Successful: consistency of sorption data demonstrated for some weakly- and moderately-sorbing tracers.
Development and refinement of radionuclide transport models for PA.	–	Successful: led to refinement of processes included in transport model for PA.	–
Demonstration of predictability of radionuclide migration through a potential host rock.	Successful: conceptual model and data used for prediction of tracer tests applied in recent PA studies.	Successful: led to refinement and improved defensibility of conceptual model and parameters used in PA calculations.	Grimsel granodiorite not a potential host rock. However, "culture of rigorous and predictive model testing" has been established.
Enhancement of public acceptance.	Difficult to assess at the current stage.	Successful: based on presentations to date, public acceptance has been enhanced.	35 000 visitors to date at Grimsel Test Site. Effects on public acceptance difficult to assess.

7. Would you plan/design a new test in the same way now and what can be improved?

In Session II, this is only discussed in the context of the Grimsel Migration Experiment. It is acknowledged that several features of this experiment would be changed in hindsight: e.g. a more complete hydrological characterisation of the site and an earlier structural and petrological description of the flow path would be performed. Furthermore, greater involvement in the planning and design by performance assessors, at an early stage in the experiment, would have been desirable to ensure the production of PA-relevant data. In Session III, the question is discussed in the context of WIPP in the paper by MEIGS et al.

In addition to tests with injected, synthetic tracers, the paper by VIRA discusses the benefits of natural tracer studies. The potential advantages of such studies are:

- that they reflect transport in conditions and over time scales that are more relevant to PA than those that prevail in tests with injected tracers; and
- that they give information about rocks that would correspond to the near field of a repository – in several PA studies, the near field is key to the safety concept, rather than high-transmissivity water-conducting features of the far field.

VIRA concludes that "... we may have to live with the possibility of a leaking far field, but we should try to ensure as good as possible a near field." Further, "... Tracer tests are one possible means in site characterisation, but their application should be judged by their costs and benefits in relation to alternative methods and approaches."

2.3 Session III: Test Cases: Design, Modelling and Interpretation

The papers in Session III describe the experience and results of the completed or on-going tests at the URL (FROST et al.), at Äspö (the TRUE project; OLSSON & WINBERG), at WIPP (MEIGS et al.) and at El Berrocal (GUIMERÀ et al.). The tests are at different stages: tests at El Berrocal and WIPP are complete, tests at the URL are at an intermediate stage and tests at Äspö started only recently. The test programmes have many common aspects in the approaches adopted, in the results and in the conclusions. Only a few characteristic features of the test programmes could be pointed out in the summary presented here. Items presented for one programme could, in many cases, apply to other programmes as well. The questions set for Session III and addressed by the papers are summarised in the following tables.

1. *What were the objectives of the test (model building and/or testing, hypothesis testing, methodological development, general understanding, demonstration and confidence building,...)? How were these objectives incorporated in the test design?*

Tests	Objective	Incorporation in the test design
URL	To gain a better understanding of the processes affecting solute transport in fractured rock. Testing of the suitability of the porous-media equivalent method for fracture zones and moderately fractured rock.	Whole rock environment with three fracture domains (fracture zones, moderately and sparsely fractured rock) addressed at various scales (1-700 m)
Äspö TRUE	Development of understanding of radionuclide migration. Evaluation of the link between model concepts and realistic rock description. Assessment of applicability in site characterisation. Evaluation of usefulness and feasibility of modelling approaches. Provision of *in situ* data.	Test series of successively increasing complexity. Integration of experimental and modelling work. Predictive modelling and periodic evaluation of test results and successive improvement of models and test designs.
WIPP	Testing of important model features and recent hypotheses about transport. Quantitative estimation of important transport parameters. Demonstration of matrix diffusion. Determination of adequacy of fracture-matrix geometry, anisotropy and heterogeneity to explain results.	New improved test designs and equipment. More detailed characterisation of Culebra. Use of various tracers having different diffusion coefficients. Use of various pumping rates. Single well injection/ withdrawal tests. New modelling approaches.
El Berrocal	Development of methods for hydraulic characterisation, instrumentation development and data base generation. Integration of flow and transport research in heterogeneous domains: laboratory experiments, field work and modelling.	Pressure, temperature and concentration measurements in isolated borehole sections. Test methodology allowing versatile identification of flow and transport behaviour e.g. by use of dilution measurements both in natural and pumped conditions.

2. *How does the test relate to the overall R&D programme (relationships to theoretical confirmation, to performance assessment, to public relations,...)?*

Tests	Relation to overall R&D programme
URL	Evaluation of a concept for nuclear waste disposal. Documentation and demonstration of the feasibility of the disposal concept in an Environmental Impact Statement submitted for public, regulatory and scientific review.
Äspö TRUE	Generic demonstration of the function of the host rock as one barrier contributing to the multibarrier principle. Addressing the needs of PA by showing that pertinent transport data can be obtained from site characterisation or field experiments and that laboratory and *in situ* data can be related.
WIPP	Direct support for site specific PA. Confirmation of the conceptual model and parameters to be used in assessment.
El Berrocal	Generic hydraulic characterisation studies, building PA know-how and instrumentation development. Submission of test design plans to international scientific discussion and review.

3. *Which information was really obtained from tracer experiments performed till now (and which information was not obtained)?*

Tests	Information obtained	Information not obtained
URL	Adequate fluid flow models developed. Small and large-scale permeability variations within the fracture zones must be taken into account. Non-uniform transport properties needed to explain results fully.	Suitable transport model capable of simultaneously describing all the tracer tests within the same fracture zone.
Äspö TRUE	Hydraulic and other characterisation allowed the development of descriptive models that provide a basis for transport modelling. Predictions reasonably good for boreholes near to injection but uncertainties for more distant holes. Advection-dispersion data obtained but source term not optimal to study dispersion in detail.	Tracers from two of the four holes used for injection did not arrive (at least before test termination). Transport properties other that those related to advection (and to some extent to dispersion) not obtained.
WIPP	Refined conceptual model of Culebra. Heterogeneity of transport properties. Late-time slope (-5/2 instead of -3/2) of "SWIW" tests indicate a multirate diffusion model required.	Uniqueness of diffusion rate distributions, advective and diffusive porosities not demonstrated. Flow rates along the transport paths not known. Initial spatial distribution of the injected tracer slug not known.
El Berrocal	Data according to two alternative conceptual models: advection-dispersion or advection-dispersion-matrix diffusion. Flow rates through injection sections measured both without and with pumping. Most meaningful results obtained by models reflecting the 3D nature of the flow system.	Effects of slug injections not known and thus may be interfering with tailing due to other mechanisms e.g. matrix diffusion. Alternative explanations for the form of the break-through curves: (i) flow in fractures only, with diffusion into the matrix (ii) slow flow also within matrix, could not be distinguished.

4. *What is the reasoning behind the interpretation methodologies? Are alternative interpretation methodologies available? How to screen them?*

Tests	Reasoning	Alternative methodologies available and screening
URL	Success in interpreting previously performed tests (in fracture zones). Further evaluation of suitability of the porous-media-equivalent fluid flow and transport properties in fracture zones and in regions of moderately fractured rock.	Evaluation of other approaches such as discrete fracture network models. Tests at various scales and differently fractured domains. Radiometric analyses of fracture surfaces after completion of single fracture migration experiments.
Äspö TRUE	Parallel use of various interpretation methodologies (e.g. stochastic continuum and discrete fracture network) to interpret a series of tracer experiments with successively increasing complexity. Modelling in all phases of experiments: scoping, planning, pre-test, post-test, final evaluation.	All approaches and concepts used are checked continuously during the test programme. Injection of resin and excavation of tested rock volumes to reveal flow path geometries and tracer concentrations.
WIPP	Experience and results of interpretations of past tests. The need to demonstrate whether or not matrix diffusion is an effective phenomenon during transport in Culebra. The objective to distinguish between the effects of matrix diffusion and heterogeneity in permeability. Use of various conceptual models and checking against experimental results.	It is concluded that one must evaluate whether alternative conceptual models can explain the data. Various types of tests (e.g. RC and SWIW), together, are suited for providing insight into the important processes and for testing conceptual models. It is important to use various test-design features, like different pumping rates and injections into different locations.
El Berrocal	The interpretation is based on the conceptual model of fracture flow and solute transport. Two models were chosen and compared: radial advection-dispersion and radial advection-dispersion with matrix diffusion. The importance of accounting for experimental procedures, e.g. injection, in the modelling was emphasised.	Alternative models tested and the outcome of parameter values estimated. Simplified models led to parameters of doubtful validity for prediction purposes. Heterogeneity may be partly responsible for the observed results. Comparison of results with different tracers exclude the possibility that heterogeneity is the sole cause of the tailing.

5. What can tracer tests teach us about important transport mechanisms?

Tests	What can be learned about transport mechanisms
URL	Transport properties within fractured crystalline rock relevant to various scales are to be used in conceptual and numerical models of groundwater flow and solute transport.
Äspö TRUE	A better understanding of radionuclide transport and retention processes. Ability to obtain pertinent transport data from site characterisation or field experiments. Relation of laboratory data to retention data obtained *in situ*.
WIPP	Significant refinement of the conceptual model for transport at a site (Culebra). Occurrence of flow in various parts of a formation: in Culebra mainly within fractures and, to some extent, interparticle porosity and vugs connected by microfractures. Mechanisms, like multi-rate matrix diffusion, coupled to the flow.
El Berrocal	Models (together with test data) can be used to detect what kind of processes are important for the behaviour of solutes in the flowing groundwater. Diffusion into the crystalline rock was seen to be an important process.

6. How was spatial variability treated when conceptualising, designing, modelling and interpreting these tests (including simplification/abstraction steps when used in PA)?

Tests	Spatial variability treated
URL	Conceptually, the small-scale variability is averaged via the dispersion term. Large-scale variability is modelled numerically by taking into account differing thicknesses, permeabilities, porosities and orientations within flow and transport domains.
Äspö TRUE	The scale of the tests is within an interval of 1 - 100 m. In the tests, all scales of heterogeneity are accounted for in all phases of the tests. In single feature (fracture) tests, the aperture and property variation of the flow and transport paths is examined and, in block-scale tests, the variability of fracture properties and flow paths in the network is studied. Justification of simplifications for PA will be examined.
WIPP	The tests were specifically designed to reveal spatial variability and anisotropy in the Culebra formation. Important properties regarding inhomogeneities could be determined. These properties were accounted for in the modelling of the tests and in the derivation of the conceptual model for solute transport in the formation to be used in PA.
El Berrocal	Spatial variability was used as a concept in designing and interpretating the tests and also checked against simple (homogeneous) models. Experiments were performed so that, in addition to highly conductive fracture zones, the low permeable rock mass was tested. In the interpretation, this was explicitly taken into account.

7. How did performance assessors, modellers and experimentalists interact before and during the test? How did these interactions influence the test? How did the test design evolve?

Tests	Interactions
URL	Prior to any excavations and tracer experiments, a detailed site evaluation programme was carried out in co-operation with experimentalists and modellers from various fields. The tracer experiments are part of PA and, specifically, the prediction of potential radionuclide migration in plutonic rock bodies of the Canadian shield. The tests are, to a great extent, designed on the basis of PA needs and thus performance assessors have influenced the tests.
Äspö TRUE	A group of experts, "The Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes", has been engaged to provide advice on experimental design, predictive modelling and evaluation of experimental data. All experiments are based on thorough investigations performed at the site over about a decade. Interactions are encouraged and supported to a greater extent than is usual by organising the work into stages and iterative cycles.
WIPP	Based on site characterisation and a series of tracer tests performed in the 1980's, the outcome of the preliminary PA for the WIPP site was commented upon by numerous review and regulatory groups. The need to distinguish between alternative conceptual models was indicated. The recent tracer tests were carried out with extensive interaction between modellers and experimentalists prior to and during the tests. Based on the results of preliminary tests at H-19, additional testing was planned and performed at the H-11 hydropad and additional wells were drilled for further tests.
El Berrocal	A close link between theoreticians, modellers, lab and field experimentalists was established to evaluate existing experience on the design, performance and interpretation of tracer tests. Preliminary experimental designs were submitted for discussion and comments to an international group of experts. A multidisciplinary team was integrated into the work.

8. What are the limitations of tracer tests?

Tests	Limitations
URL	Not discussed explicitly from the point of view of individual transport mechanisms. At different scales, different limitations exist, but an averaging of small-scale heterogeneities seems to exist at transport scales over 30 metres (well dispersed break-through peaks). Further work is required in order to develop a model that can simulate all the tracer tests conducted during the different phases of tracer testing.
Äspö TRUE	According to the strategy of a staged approach, where different transport scales are addressed and the degree of complexity is successively increased, knowledge of important transport mechanisms can be obtained progressively. Thus, each tracer test has its limitations, but the next test can be based on experience from the previous one and more information gained (with new limitations). Integration with laboratory experiments is seen as crucial.
WIPP	The stepwise approach used was valuable for designing a good test (and gaining additional insight), but the approach could have been improved by adopting an even more evolutionary strategy over a longer time frame. Design of new tests would be integrated with ongoing laboratory programmes on rock diffusion and sorption properties. Tracer tests will always have the limitation that they cannot test the materials over the spatial and temporal scales of interest for PA calculations. Testing of alternative conceptual models is, therefore, essential.
El Berrocal	Some possibly remaining ambiguities in the modelling and interpretation of experimental results are discussed. More reliable results could be achieved when more realistic and complex models are used in interpretation. These models may, however, encounter difficulties with respect to software and CPU time and memory. It is important to incorporate realistic experimental conditions in the models (e.g. effects of the presence of the boreholes, natural groundwater flow and flushing during injection) which are often neglected.

All programmes appear to address the same problems of the groundwater flow and solute transport, but with somewhat different weightings. Strategies for design, modelling and interpretation of tracer tests are basically similar, even though the geological environments and media may be different. This means that it is possible to learn from the experience of all of these programmes for future experiments at other sites. Study of the experience and results of these programmes will be beneficial for any new tracer test programme.

2.4 Session IV: Aims and Design of Planned Field Tracer Experiments

In Session IV, three papers were presented. These provided descriptions of the planned experiments at the Kamaishi Mine (UCHIDA et al.), Palmottu (GUSTAFSSON et al.) and at the URL. Future tests to be performed at the URL were presented, along with on-going tests, in the paper by FROST et al. in Session III. This paper is therefore not summarised again here, although the questions for the Session IV address issues of aims and design from a slightly different perspective. The questions set for Session IV and addressed by the two remaining papers on future tracer-experiment programmes are summarised in the following tables. The two experiments are very different in scope, scales, environment and many other respects - e.g. Kamaishi experiments dealing with flow and transport in intermediate-scale fracture networks take place in an underground environment, whereas large-scale experiments at Palmottu are performed from the surface.

1. *What are the new approaches to design, implement, model and interpret these tests?*

Tests	Approaches
Kamaishi Mine	The focus on block-scale (10-100 m) flow heterogeneity and transport in a relatively tight rock described by the discrete fracture network concept and model is a relatively new approach, similar to that adopted by the URL and Äspö TRUE experiments (c.f. previous section). The experiments are integrated with laboratory experiments and natural analogue studies. The tests and their modelling have been designed to give more realistic and detailed information to be linked with PA geosphere transport models.
Palmottu	Combining pumping and tracer test, with simultaneous interpretation of drawdown and tracer break-through curves, is also a fairly new approach. The results will reveal properties of the present natural flow system at the natural analogue site, helping the forthcoming analogue studies on mobilisation and retardation of uranium in crystalline bedrock within and around the deposits.

2. *What can be expected of further tracer tests (what is possible - what is not), what are their aims and how are they designed? What are the typical mistakes that need to be avoided?*

Tests	Expectations and aims	Mistakes to be avoided
Kamaishi Mine	Tracer tests are used to derive flow porosity, dispersivity and connectivity information, and to test transport models with emphasis on hydrogeologic structure. By means of a discrete fracture network model, a realistic representation of heterogeneity at block scale will be achieved.	Not to expect, from short duration tests, information on slow, safety relevant processes, such as matrix diffusion. Not to underestimate the inherent limitations of tracer tests, such as non-uniqueness of results, in the sense that several processes may produce similar break-through curves. Not to perform tracer tests in poorly characterised structural and hydraulic environment.
Palmottu	The expected results of the combined hydraulic and tracer test will be hydraulic transmissivity and storativity values, dispersivities, flow porosity, leakage parameters, and possibly boundary parameters. If data so indicates, hydraulic anisotropy values may also be estimated.	To avoid ambiguities caused by uncertainties about hydraulic boundaries to the studied system. Not to interpret man-made artefacts (including equipment failures or effects of other activities nearby) and external disturbances as properties and phenomena of/in the studied transport system. A well kept “Log of Events” will help to avoid this.

3. *What are the rationale and objectives of the planned test (model building and/or testing, hypothesis testing, methodological development, general understanding, demonstration and confidence building, ...)? How are these objectives incorporated in the test design?*

Tests	Rationale and objectives	How incorporated
Kamaishi Mine	The rationale is to confirm the conclusion of the previous PA (H3) about the capability of the block-scale volume of the host rock to effectively retard radionuclide migration. The objectives are: 1) to obtain a conceptual model with realistic geometries and properties 2) to understand the hydraulic properties and geometries of barriers to flow. The results will be used: 1) as a basis for conceptual representation of the block scale in the next PA 2) to build confidence in application of the discrete fracture network model.	By detailed planning of the tests in a programme that advances in a step-wise manner. Preliminary testing preceding the main tests to optimise the chances of achieving the objectives. A well-defined hydraulic characterisation of the test site precedes the tracer tests. Inclusion of various scales and the study of various geometries and phenomena into the supporting test programme.
Palmottu	The rationale is to have more precise and quantitative data from a natural analogue study. There is a need to better constrain the boundary conditions of processes and events relevant to PA. This requires stricter physico-chemical constraints in natural analogue studies. The objectives are 1) validation of an updated conceptual hydrogeological model 2) identification of the main potential flowpaths at the scale of the test 3) increasing understanding about flow and solute transport properties at the site.	By using a combination of robust and well tested equipment and experimental methods/procedures, and making the design as simple as possible, without compromising the possibility of meeting the overall objectives of the experiment. By integrating quantitative and step-wise modelling throughout the sequence of tests, in order to optimise the experimental performance.

4. *How does the test relate to the overall R&D programme (relationships to theoretical work, to laboratory experiments, to site assessment and confirmation, to performance assessment, to public relations, ...)?*

Tests	Relation to R&D programme	Relation to site assessment or PA, PR
Kamaishi Mine	The experiments are part of an integrated programme of experimental activities to understand flow and transport in fractured rocks.	The results are used to develop and apply discrete fracture network models and concepts for PA. By applying a more realistic geosphere transport model, confidence in the result of the previous and future PAs will be enhanced.
Palmottu	The results give generic information on major flow and transport paths and migration behaviour of uranium and the members of its decay chains.	The experiments support PA work by means of quantitative study of the behaviour of uranium in a crystalline granitic bedrock environment (natural analogue).

5. *How are lessons from previous tests integrated in the objectives/design of the planned test?*

Tests	Lessons integrated
Kamaishi Mine	The tests can be seen as an extension of previous tests that have focused more on single features. No new methods are intended to be developed but experience from e.g. Stripa, Grimsel and URL will be drawn upon.
Palmottu	Experience from previous tests at the Hard Rock Laboratory at Äspö and El Berrocal site have been used in objective definition and test design. Equipment development and chosen experimental procedures are also in accordance with this experience and allows the optimal performance of the planned experiments.

6. *What will be its contribution to confidence building in predictive modelling of radionuclide transport, to site characterisation/evaluation, and to performance assessment?*

Tests	Contribution
Kamaishi Mine	It will contribute as part of an integrated programme including laboratory testing in single and multiple fractures, flow and transport tests in Japanese underground facilities, natural analogue studies, geological studies, and co-operative studies in international underground test facilities. It will support the development of numerical simulations of block-scale flow and transport, and will develop a link between discrete fracture network and geosphere PA models, thus supporting performance assessment.
Palmottu	It is an intermediate phase in the Palmottu analogue project and will be used by the project itself for further studies. The tests will make a contribution to confidence building in predictive modelling of radionuclide transport and PA in an indirect and generic way. The tests assess flow and transport in a subhorizontal fracture zone with intersecting vertical zones.

The tests summarised in this section are planned to be conducted in the near future (Kamaishi: starting in spring 1997 and to be completed by March 1998; Palmottu: to be conducted in early summer 1997) and the detailed designs may be changed.

3. RECORD OF WORKING GROUP CONCLUSIONS

3.1 Conclusions of Working Group 1: Practical Challenges

Chairmen: A. Hautojärvi, VTT (Finland) and H. von Maravic, EC

(a) Practical issues

Practical issues that were identified by Working Group 1 as those to be addressed during planning, performance and interpretation of field tracer experiments:

- A clear specification is required of hypotheses to be tested by the experiments. The number of unknowns should be minimised by performing the experiments on a system with:
  - well-defined hydraulic properties (a hydraulic definition of the transport pathways is desirable);
  - well-defined geological/structural properties;
  - well-defined geochemical properties.
- The limitations and uncertainties of field tracer experiments should be recognised; these are related to:
  - the experimental set-up;
  - scale (questions regarding extrapolation);
  - governing processes (the ability to distinguish between processes).
- Transferability of data (to a system of relevance to performance assessment) should be addressed in the analysis of field tracer experiments, bearing in mind:
  - scale (spatial and temporal);
  - geological differences;
  - flow conditions (e.g. forced flow vs. natural, unperturbed flow).
- Frequently, break-through curves are the only output of field tracer experiments from which to meet the goal of a meaningful and unique interpretation.
- Integration of information from many independent sources is most likely to lead to a general understanding of migration, e.g.:
  - tracer tests, combined with natural tracer tests;
  - field tracer test, combined with laboratory tests and natural analogue studies.
- Valuable data and support for performance assessment can be provided by field tracer experiments, irrespective of the performance assessment approach adopted (deterministic or probabilistic).
- Tests are more valuable if targeted at specific objectives, rather that "overall" tests aimed at many objectives: good questions produce good answers *(non specific questions produce hardly anything)*.

- Examples of objectives for good tracer tests are *(it should be recognised that other valid purposes exist)*:
  - pathway definition;
  - porosity-distribution definition;
  - investigation of chemical interaction;
  - model validation for performance assessment.

- The following undesirable characteristics should be avoided (some features of a good tracer test are given in the next section):
  - unknown, undefined transport pathways, geometry and boundary conditions;
  - unknown, undefined equipment behaviour (e.g. equipment failures);
  - unknown, undefined features of the design and artefacts;
  - unknown, undefined source term;
  - lack of pre-test predictions;
  - lack of reproducibility of results[2] (or lack of testing for reproducibility).

(b) Features of good tracer tests

The following were identified as some characteristics of a well-designed tracer test (a fully general definition of a good tracer test was not considered to be possible):

- **Clearly stated rationale for the test, including**
  - identification of processes to be tested and why these processes are likely to be important for performance assessment calculations;
  - formulation of a well-defined conceptual model at the tracer test scale and at a larger scale that includes the effects of the heterogeneous nature of geologic media;
  - description of alternative conceptual models;
  - performance of pre-test calculations, based on alternative models.

- **A multi-disciplinary approach, with**
  - tests planned by a variety of technical expertise, considering (i) practical constraints; (ii) equipment artefacts and (iii) measurement limitations;
  - geochemical interactions (tracer-tracer and tracer-rock) taken into account;
  - hydraulic and geometric limitations taken into account.

- **A review of the design of the test, its results and its use in PA by outside experts.**
  - prior to the test, that the test, as designed, will provide important information on migration;
  - after the test, that the test results have provided important information on migration.

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[2] Testing flow paths sometimes changes them, so reproducibility may not be possible.

(c) Other issues

Other issues that were considered to be important are:

- The need for interaction with performance assessors and regulators:
  - A multi-disciplinary approach is advocated in which (i) a consistency of terminology and (ii) transparency of the relationship between terms and approaches should be striven for.
  - Interaction of experimentalists with performance assessment modellers should allow the *predictive* modelling to be tested.
- The value of an international review of the results of field tracer experiments.

(d) Conclusions

Working Group 1 concluded that:

- the contribution of field tracer experiments to performance assessment depends on the geological medium and on the safety case (scenarios) considered,
- field tracer experiments can be designed and executed such that they provide valuable information to performance assessment.

(e) Recommendations

The following recommendations were made by the Working Group 1:

- The purpose of a field tracer experiment needs to be well defined.
- Field tracer experiments will continue to be required for specific purposes, such as those outlined under "examples of objectives for good tracer tests", above.
- Further work is needed to tackle various practical/ technical issues.
- Continuation of an international review of the results of field tracer experiments is recommended.

3.2 Conclusions of Working Group 2: Rationale and Promises of Future Field Tracer Experiments

Chairmen: J. Vira, Posiva (Finland) and G. Volckaert, SCK/CEN (Belgium)

(a) Rationale: Historical perspective

- Typically in the past, there existed an overall need to demonstrate modelling capability and to "validate" performance assessment models (since relatively little experimental data were available about transport, this need was perceived both by implementors and regulators). This may have led to a degree of frustration, due to expectations being too high.

- Present trends are towards integrated testing strategies (incorporating lab, field and theory), iterative approaches and a perception, at least, of the need for performance analyst/modeller/ experimentalist interaction. The latter is in evidence in the trend towards integration committees, advisory groups, etc.

- A basic issue is the difference in the scales of time and space of relevance to the performance analyst (or "site characteriser") from those accessible to the experimentalist, which implies that abstractions are needed for performance assessment/site characterisation and tests cannot always be done in the way the performance analyst or the modeller would like to see them done.

- From the regulatory perspective, the view of Working Group 2 was that the implementer can hardly do without tracer tests, but, so far, no explicit requirements have been placed on them. Costs should be contrasted to the value of a licence; the regulator also needs support for their (licensing) decisions.

- A final point is that tradition may sometimes overrule rationale judgements. However, even if the scientific advantage of a test is not always clear, tracer tests may bring with them public acceptance benefits.

(b) Expectations: Practical objectives

The following practical objectives were identified by the Working Group 2:

- to support hydrogeological and flow modelling (e.g., to obtain information about connectivity, flow porosity, dispersivity);

- to describe transport pathways;

- to describe/measure interactions between rock, groundwater and moving tracers;

- to "validate" migration models (considered possible over the small spatial scales required for transport in clay);

- to build confidence in models and analyses and to increase scientific understanding;

- to improve testing methodologies;

- to increase public understanding and acceptance.

(c) Question of choice: How unique are tracer tests in providing the expected information?

- Information on flow porosity/groundwater travel time would be hard to obtain by means other than tracer tests with *conservative* tracers.

- Information on interaction rates can be obtained using *weakly sorbing* tracers (but practical experiments are somewhat limited in scope).

(d) Critical challenges

- How to perform the scale transformations needed for PA applications (from smaller to larger scales, for different boundary conditions):

  - Some processes can best be studied in small scale.

  - Could passive tests be designed even for fractured rock?

  - Long-term experiments may be possible during the active life-time of the repository.

- How to transport the information from lab to field, from site to site (critical for design of tracer tests in rock laboratories).

- How to create more sensitive test designs (basically, all the information from a tracer test is in the breakthrough curves - how much can be read from them and how can tests be made to discriminate processes and features?):

  - Better rock descriptions help focus on processes (fracture characterisation and classification).

- How to study slow processes such as matrix diffusion. How applicable is the Kd approach in interpretation of tracer tests?

(e) Broad recommendations

- Build a strategy for transport analysis and modelling together – involve all parties who have related expertise – iterate – re-think.

- Find out relationships – study processes and interactions in the scale where you can get discriminatory information. "Validate" transformations to larger scales. Do not try to answer all the questions with a single test.

- Use independent information (as a consistency check).

- Develop testing with slightly sorbing tracers.

- Make use of international co-operation.

3.3 Conclusions of Working Group 3: Alternative Methods to Tracer Experiments

Chairmen: M. Heath, Earth Resources Centre, Univ. Exeter (United Kingdom) and W. R. Alexander, Univ. of Berne (Switzerland)

(a) Areas of discussion

Several areas were discussed within the Working Group 3:

- "traditional" tracer tests: within this heading came more or less all tracer or hydrological tests carried out to date.

- "realistic" tracer tests: this title was coined to describe those tests which utilise as near as possible the natural conditions of the rock body under investigation and, where possible, use relevant source terms. Although such tracer tests are not unusual in the environmental sciences, they are unknown (at least to the members of Working Group 3) in the radioactive waste disposal field.

- laboratory experiments: taken to mean any measurement of transport or retardation conducted in the laboratory.

- natural analogues: taken to include natural and archaeological analogues.

- natural tracers: in effect palaeogeohydrology and hydrochemistry.

- "anthropogenic" analogues: in other words, either accidental releases of material or man-made disturbances that are not yet old enough to be archaeological analogues.

The main conclusion of Working Group 3 was that the above noted alternatives were not alternatives *per se*, rather they should be viewed as complementary methods to the traditional tracer tests. Indeed, it was strongly felt that not only should traditional tracer tests be retained, but also that none of the alternatives could replace traditional tracer tests and that the best results were obtained when a true mix of techniques was employed.

Unfortunately, such mixes appear to be rare outside the Grimsel MI experiment, the WIPP programme and the on-going work at Kamaishi and it was felt that there is a much greater need for proper integration of such work in any planned projects. Clearly, the greatest advantage can be gained when such integrated planning is carried out from the first stages of any project.

A good example of the need for better integration was provided during the El Berrocal presentation during Session III, where it was pointed out that many complementary methods had indeed been applied, but the data had not been brought together.

A particularly keen discussion point was the suggestion (made during discussions during Session II) that tracer tests be employed during site characterisation. While several regulators at the meeting envisaged greater use of tracer tests throughout the characterisation (from during exploratory drilling to full facility excavation), concern was expressed that it would be difficult to carry out appropriate tests on appropriate features of concern at a particular site.

The most obvious problem relates to accessibility of conductive features (e.g. how can major conductive features be tested when the repository is designed to avoid them?) and experimental timescales (i.e. what point is there in carrying out site specific tests over a couple of years when the data required should be somehow representative of repository relevant timescales?). The conclusions were that, if something is to be done, then it should be done using natural tracers (i.e. more or less the standard palaeogeohydrological studies already carried out in many programmes), natural analogues (although no such relevant natural analogue is currently known and they probably will not be site specific) and realistic tracers (using natural groundwater gradients and doped repository materials such as cements and glasses over very long time periods).

As an alternative, it was noted that generic tracer tests still have much to offer when it comes to understanding specific performance assessment relevant processes and mechanisms. A good example of this is the investigation of the degree of confidence which can be placed in data produced in laboratory experiments. This has been tried in the Grimsel MI experiment with respect to applying laboratory Kd values to predict *in situ* retardation and comparing laboratory matrix diffusion data with natural analogue data - but this approach has been otherwise somewhat neglected.

Finally, it was pointed out that traditional tracer tests which do no more than match tracer output curves with some type of transport model were of little use as it is always possible to explain away a poor model fit by twiddling one or more of the numerous free parameters in the model. Conceptual models of geosphere transport and retardation can only be properly tested when the flow system is described in enough detail to remove as many of the free parameters as possible - otherwise, little confidence can be placed in the models.

(b) Conclusions

1. There are no true alternatives to traditional tracer tests, but there are many complementary techniques which can be applied in conjunction with these tests.

2. Currently, these complementary techniques are not generally well integrated into traditional field tracer experiments.

3. Although greater use of field tracer experiments in site characterisation has been called for, this could be extremely problematic. If relevant features can be tested for relevant timescales, then the tests to be employed should be realistic tracer tests, natural analogues and the palaeogeohydrological studies already employed in many programmes rather than traditional tracer tests.

4. Generic tracer tests can still contribute much to the understanding of specific processes and the testing of how laboratory data may be transferred to the prediction of *in situ* retardation.

5. Describe the flow system - or little confidence can be placed in models supposedly tested by field tracer experiments.

3.4 Conclusions of Working Group 4: Integration of Data from Field Tracer Experiments into Performance Assessment

Chairmen: P. A. Smith, Safety Assessment Management Ltd. (United Kingdom), and P. Bogorinski, GRS (Germany)

The following points were agreed upon within Working Group 4 regarding performance assessment and the integration of data from field tracer experiments:

- **Performance assessment makes use of a combination of quantitative ("hard") and qualitative ("soft") information and analyses.**

  The information and analyses, when taken together, should provide reasonable assurance that safety objectives are met. "Hard" information is, for example, data that can be input directly into calculational tools. "Soft" information is, for example, wide-ranging evidence that give confidence that safety assessment methodologies, models and data are appropriate.

- **The balance between "hard" and "soft" information depends on the approach chosen by the performance assessor, as well as regulatory aspects and cultural aspects.**

  The factors are interrelated. The approach chosen by the assessor is dependent, in part, on the repository system (waste type, host-rock type, etc.), but is also influenced by the stage reached by the national waste management programme, by regulatory guidelines (whether time-frames are specified by regulations) and by the way in which implementors and regulators interact (cultural aspects).

- **Performance assessment is not necessarily about predicting reality; analyses are based on sets of assumptions and simplifications and it is recognised that judgement must be used in determining what simplifications and assumptions to make.**

  For aspects of the repository system where current understanding is adequate, analyses generally aim at realistic prediction. However, for other aspects of the system, due to limitations in available information, the analyses are limited to conservative (over-estimates) of the consequences of the repository. A problem with this approach is that assumptions and simplifications are not always <u>unambiguously</u> conservative.

- **Field tracer experiments can serve to provide both "hard" and "soft" information for performance assessment.**

  With respect to "hard" information (data), field tracer experiments are, in general, just one of a number of sources, complementing the information from laboratory tests, field hydrogeological tests, natural analogues and geological data. Limitations in the use field tracer experiments in acquiring "hard" data for performance assessment are that:

  - They are frequently carried out at "generic" locations (i.e. at sites not considered as candidates to host an actual repository), for example in order not to jeopardise the geological barrier through a very detailed characterisation process.

  - The scales of space and time over which they are performed differ considerably from those relevant to performance assessment.

  - They frequently focus on individual features (e.g. a single fracture or rock unit), rather than on the complete system.

  Field tracer experiments are thus more widely used for identification of processes, testing of hypotheses, testing of the transferability of models and data between sites and confidence building and refinement of models. With respect to other "soft" information, field tracer experiments can test the applicability of laboratory data, build confidence in understanding of features and processes and in migration models and serve to gather and focus interdisciplinary expert input (for example, through discussion forums such as GEOTRAP). They can also stimulate the development of new experimental and analytical techniques and establish effective communication between field and laboratory experimentalists and modellers.

- **The contribution of field tracer experiments to performance assessment and the involvement of performance assessors in the design, modelling and implementation of field tracer experiments depend on the stage reached within the waste management project.**

  It is clearly desirable that maximum information is extracted from field tracer experiments that is relevant to performance assessment and, to achieve this, interaction of experimentalists (in explaining what is feasible) and performance assessors (in explaining what is useful) is to be encouraged. The value of this interaction tends to increase as the project moves from acquisition of basic understanding of processes (e.g. the field tracer experiment programme at Äspö, Sweden), to the testing and refinement of performance assessment models (e.g. at WIPP, USA).

- **Field tracer experiments do not aim to provide analogues of actual repositories, with their associated large-scale heterogeneities and perturbations to geosphere conditions caused by the presence of the repository. They are currently (in most cases) restricted to tests that aim to address characteristics of the undisturbed geosphere.**

  Field tracer experiments do not aim to address, in a single experiment, the full complexity of an actual repository system in terms of either structures or processes. Field tracer experiments do not need to be large scale to be useful (they are generally more successful for smaller-scale, simpler systems) and do not normally address alterations in geosphere conditions (scenarios) that might be caused by the presence of a repository: e.g. the effects on the geosphere of the high-pH plume from a cementitious repository. An exception is the investigation of excavation-disturbed zone properties using field tracer experiments reported by AECL. It is acknowledged that geosphere conditions are inevitably altered to some extent by artefacts associated with any field tracer experiment.

- **Field tracer experiments are most successful (in terms of "hard" information) for simple systems.**

  The results of field tracer experiments are most easily incorporated into performance assessment (as data for models) when the system is simple in terms of the number of processes operating and in terms of structure (in particular, in the absence of fractures), as exemplified by the Boom Clay tests.

- **Tests on more complex systems (fractured media) can be difficult to interpret, but nevertheless modelling exercises frequently give “reasonable” results and may give support to certain performance assessment arguments.**

  Compared to relatively homogeneous media such as Boom Clay, a larger number of processes operate in fractured media and characterisation is frequently incomplete. This can result in more complex break-through curves and alternative models that fit the curves equally well. Nevertheless, modelling exercises can be used to provide support for certain aspects of performance assessment models, such as the averaging of small-scale heterogeneities. Furthermore, it is not always necessary, for the purposes of performance assessment, to discriminate between alternative models, for example (i) if a conservative treatment is felt to be acceptable and (ii) if the feature/process concerned is, in any case, insignificant on the spatial and temporal scales of performance assessment.

- **It is rare in the modelling of field tracer experiments to examine conceptual model uncertainty in the sense of uncertainty in the <u>processes</u> that are operating. This suggests that a consensus may have been reached in the identification of processes relevant to tracer transport.**

  Alternative models are applied to field tracer experiments, but these tend to be alternative ways of simplifying a geological interpretation of the system in order that transport modelling may be performed. Unexpected results are generally explained in terms of uncertainty and incompleteness of characterisation. Additional processes seldom need to be invoked. Sometimes it is not possible, on the basis of field tracer experiments and other information, to discriminate between alternative models. The different models may yield different predictions when applied over performance assessment scales of space and time. If this is the case, then the more conservative model is generally employed.

- **A continuum of experiments (in terms of spatial scale) exists between small-scale laboratory tracer (and other) tests, through larger-scale laboratory tests and smaller-scale field tests, to large-scale field tests.**

  Smaller-scale tests offer better control of boundary conditions and the possibility of more complete characterisation. They are better suited to providing “hard” data for near-field performance assessment. Larger-scale tests offer the possibility of examining the operation of transport processes in larger-scale structures and may allow perturbations (e.g. of geochemical conditions) associated with sampling to be avoided. Such tests build confidence in the understanding of far-field processes. In general, the different types of experiments provide complementary information, that must be considered as a whole in performance assessment.

- **The following are suggested as components of a good tracer experiment programme:**

  (i) A clear connection to performance assessment and site characterisation

  – The aims of the tracer experiment programme should include a statement of the relevance of the test to particular aspects of performance assessment and/or site characterisation – performance assessment specialists should participate in the planning of the tests.

- The function of the tracer experiment programme within the broader national waste management programme should be indicated.

- The conclusions of the tracer experiment programme should indicate the relationship between the results and performance assessment and/or site characterisation.

(ii) Identification of “success criteria” for the tests

- Success criteria should take due consideration of experimental errors.

- Means should be identified by which individual processes can be discriminated – for example, the unambiguous “signature” of a process in a break-through curve.

- In the particular case of matrix diffusion, “post-mortem” tests may provide a useful means by which to confirm the interpretation of experimental results.

An increased integration of field tracer experiments and performance assessment is noted in many national programmes. Field tracer experiments can, in certain cases, provide “hard” information for performance assessment. There is also, however, an increased appreciation of the qualitative aspects of performance assessment to which field tracer experiments can also contribute, providing evidence that the methodologies, model and data used in performance assessment are appropriate.

4. SUMMARY OF FINAL DISCUSSIONS

- During the final discussion it was agreed that field tracer experiments provide useful information for performance assessment modelling. In particular, they allow testing between alternative conceptual models, and can demonstrate the adequacy (or inadequacy) of the understanding of the transferability of laboratory data to the field. Such discrimination between alternative models is essential as it is not always clear which is the more conservative. Moreover, field tracer experiments for sorbing tracers and for determination of the role of matrix diffusion are required by PA, and hydraulic characterisation of sites alone is insufficient for PA modelling.

- Despite their usefulness, there are a number of problems associated with field tracer experiments, not least that they are complex, expensive and take long periods of time to plan and perform. It is not possible, therefore, to carry out very many field tracer experiments. Moreover, the interpretation of the results of these tests is ambiguous, particularly if performed on a large scale.

- Cost-benefit analysis of tracer experiments is not easy because the end-results of such tests (in terms of data and understanding) is not predictable. The unexpected spin-offs of the test (unexpected tracer behaviour or unpredicted pathways, for example) are often the most valuable aspects of field tracer experiments but cannot be anticipated at the planning stage.

- Tracer experiments are normally on a small scale (metres), perhaps testing individual fractures, and the need was identified to develop conceptual models on the scale of the repository (hundreds to thousands of metres). The site-specific nature of tests and difficulty in extrapolating or transferring the results to other sites, particularly in view of rock mass heterogeneity, was also recognised.

- The possible role of field tracer experiments during site characterisation and development was discussed and it was concluded that, although good access to the rock mass might provide many opportunities for tracer experiments, it would be very difficult to identify the individual pathways and, therefore, to prove that the geosphere is not leaky with respect to fast channels. Furthermore, although it would be possible to analyse a few metres around emplacement tunnels and deposition holes, the results would not necessarily be representative of the rock mass as a whole if too few tests were carried out. Neither would the boundary conditions be very stable.

- Test-as-you-go tracer experiments during the excavation and operational period is consistent with the NEA concept of corroborative testing. They would be particularly relevant to fractured rock (in which flow periods would be reasonably short) but not in the Boom Clay (in which tracer movement would be extremely slow). As the operational period of a repository could be up to 100 years, it would be possible to carry out tests with relatively strongly sorbing tracers and to look at areas identified by PA to be of special concern. The identification of flow paths would not be possible and such tests would be confined to the investigation of processes within flow paths. Investigation of short circuits to the geosphere (e.g. through bulkheads or the excavation disturbed zone) would, however, be possible.

- Essential for the effective use of tracer tests is the narrowing down, as far as possible, of the unknowns addressed by a particular experiment. Also recognised is the need to understand the flow system to allow up-scaling.

- The use of gas as a tracer was suggested as a means of identification of fast pathways. The use of gaseous tracers could be particularly useful in clays, as gases generated in a repository in clay could create pathways for radionuclide migration. It was recognised, however, that the results of such tests would be difficult to interpret (due to two-phase flow) and could be ambiguous (fast pathways for gas are not necessarily the same as fast pathways for solutes). The results of a gas injection experiment in fractured slate in Cornwall were described as an example of a gas tracer yielding unexpected (but very useful) information on flow path distribution – see Lineham et al. Radiochimica Acta, 66/67, 757-764 (1994).

- 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 models and different techniques are used for calculating aperture. Consistent assumptions must be used in different models that use the same parameter (i.e. the same assumptions should be made for, say, the transmissivity of channels throughout the analysis) 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 proved to be difficult (as experienced at Äspö), while the input of these experiments to performance assessment is relatively minor in most cases. Great benefit could be derived from a more concise and clear presentation of PA-relevant experimental results and by involving PA modellers in the analysis of field tracer experiments results. It is an important challenge to bridge the gap between data users and data producers and to simplify the geological description for modelling purposes. While it is generally agreed that such communication is 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, it was proposed that an agreed strategy for integration should be implemented in order to ensure that each of the elements of a programme of investigation are properly co-ordinated.

PART B

WORKSHOP PROCEEDINGS

SESSION I

General Overview

Chairmen: C. Pescatore (NEA) and H. von Maravic (EC)

What Has Been Learned from Field Tracer Transport Experiments – A Critical Overview

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Abstract

The general rationale of performing tracer tests has been, and will probably be also in the future, to characterise properties of the medium in question regarding flow and transport of solutes to various degrees of detail. Beyond this common point several concepts and approaches have been and can be introduced. This leads into diversification of the concepts, terminology, modelling and parameters. To some extent the various branches may be equivalent or correspondence may be found between the entities used to describe the medium. On the other hand, two analogous concepts, e.g. a porous media versus fractured media, which can give equivalent results for the description of the hydraulic behaviour, may differ extremely regarding the transport behaviour.

A general concept is used in our paper as a starting point to address the need of a specific and detailed description of the actual flow geometry for obtaining the desired modelling parameters. We focus on experiments made in fractured media and the clay and salt alternatives for repository host formations are touched only cursorily, although some of the principles in general discussions apply also for these media.

In this paper we present an overview of lessons learned and give some examples of tests performed in different scales in fractured media. We discuss the possibilities for ambiguities and failures of tracer tests regarding the certainty to determine various transport mechanisms and properties as well as parameter values for modelling. We discuss also the reasons for possible deficiencies of the tests regarding the given objectives. A short introduction to various important elements of performing tracer tests, such as tracer injection, hydraulic conditions, multiplicity of the pathways and physical as well as chemical interactions, precedes the overview in order to fix the frame of discussion. Inherent uncertainties of field tests are brought into discussion to outline a scope of field tracer tests.

1. INTRODUCTION

Disposal of highly active radioactive waste into deep geologic formations is under planning and preparation in many countries. A principle of a multibarrier system is foreseen to prevent and reduce potential releases and migration of radioactive nuclides into the biosphere. The geosphere itself is the ultimate barrier in this chain. Increased interest and active research in the area of groundwater flow and solute migration has taken place both in the theoretical and model development side as well as in the experimental side in the last decade. Field experiments have been performed in different media at several sites in many countries. The results and conclusions drawn from these experiments have been and will be used in the performance assessment work needed to demonstrate the safety of the planned solutions.

International co-operation has been an essential part in many research programs offering a wealth of data and results to be discussed in order to compare experimental research, modelling and application to performance assessment approaches. This co-operation strengthens the basis on which the safety assessments have to be built. As now three years have passed since the last major international project INTRAVAL ended and new projects have been and will be launched it is a good time to review the outcome of field tracer tests and learn from the experiences to find out potential issues for improvement. Due to practical circumstances there always remain limitations, like financial, temporal, technical and in human resources, which bound the experimental possibilities. It is very important that the experimentalists and especially modellers, who may not follow the experimental phase of the project so closely, are aware of these limitations.

We will make an attempt in this paper to assess critically the outcome of performed field tracer tests in general and to overview the present status of knowledge on transport of solutes. The emphasis will be on fractured media where advection is a dominant process. Diffusion dominated cases are dealt with only cursorily. The examples come mainly from tests that were given for evaluation and modelling exercises in the recent international projects INTRAVAL and STRIPA.

In our paper we present an overview of lessons learned with some examples of performed tracer tests in different scales in fractured media. We discuss the possibilities for ambiguities and failures of tracer tests regarding the certainty to determine various transport mechanisms and properties as well as parameter values for modelling. We discuss also the reasons for possible deficiencies of the tests regarding the given objectives. A short introduction to various important elements of performing tracer tests, such as tracer injection, hydraulic conditions, multiplicity of the pathways and physical as well as chemical interactions, precedes the overview in order to fix the frame of discussion. Inherent uncertainties of field tests are brought into discussion to outline a scope of field tracer tests.

2. RATIONALE – WHY HAVE FTTE’S BEEN PERFORMED?

Many of the Field Tracer Transport Experiments (FTTE’s) in the nuclear waste management programs have been performed to give support directly or indirectly to the performance assessment in its various phases. In demonstrating the safety of a planned or constructed repository large rock volumes and long distances in the surrounding of the repository as well as very long time periods have to dealt with. This can not be based solely on experimental data but concepts and models have to be developed to extrapolate the results in space and time. The general understanding of geologic formations and hydraulic testing at a site can give an overall view on the water movement. Transport of solutes is, however, more dependent on certain details of the water flow paths than the pressure field and averaged flow rates. It is necessary, therefore, to study also these details in addition to the hydraulic testing.

To understand the transport times of non-sorbing solutes one has to know the flow porosity which normally is one of the parameter values that can be determined from tracer tests. To understand transport time distributions in heterogeneous media not only a single value but also a description of the geometrical nature of the porosity and possible spatial variability of the porosity is needed. This description is in practice possible only by means of theoretical concepts which may be based on media descriptions like porous or fractured and homogeneous or heterogeneous. The simplified picture could be e.g. packed beds, bundle of capillaries or set of fractures etc.

Field tracer transport experiments are needed to check the correctness (applicability, validity) of the concepts, theories, models and parameters used to describe the migration at the site in question, or in general in certain kind of media.

Usually there are also some other reasons, especially in early phases of waste management research programs, to perform FTTE’s, like the need of learning and practising to perform and evaluate FTTE’s or to test equipment.

It is clear that there is no single test that can solve all the problems together and at once but FTTE’s are an ongoing activity in interaction with other elements in waste management programs. Actually, only small pieces of the whole puzzle can be put in place based on single tracer tests. Tracer tests are, however, very time and money consuming and it is tempting to foresee more outcome from the planned tests than is realistically possible. Overestimation of the capabilities of tracer tests to solve migration problems in general should be avoided and more emphasis should be given to the specific problems that are planned to be studied in a FTTE.

3. WHAT IS ESSENTIAL IN A TRANSPORT PROBLEM?

The transport of solutes through a distance within a medium is governed by the hydraulic conditions and water flow which may be seen at a very general level as streamlines going through the pore space of the medium. There are two important points to be discussed: 1) the geometry of the flow field and boundaries with medium, and 2) behaviour of solute molecules in this environment.

Let us take as an example one of the perhaps best known and ”simple” situations, the transport of solutes diffusing in laminar steady flow through a straight tube. There we know the parabolic flow field. For impermeable, reflective boundary conditions at the pipe walls we know the behaviour of released solute plumes as a function of position and time. But it is not self-evident that the averaged concentration of the solute over the cross-section of the tube behaves like a moving Gaussian pulse spreading longitudinally in time with a constant dispersion coefficient. In fact, at ”early times” it doesn’t, and the dispersion coefficient approaches a constant value first after a while. This example illustrates the concept of streamlines and boundaries as a basis to solve the transport problem.

Thinking of the rather general result of transport behaviour of solutes in a flow system presented in the example above it is plausible that there may be (but not necessarily are) several concepts that produce the same results within a certain range of flow conditions in different kind of systems. One might ask: So what, does it make any difference what the system is like? For really non-interacting solutes it may not make any difference, but we are mostly interested in solutes that interact with the medium and then the differences in transport resulting from the various concepts of the medium may be huge.

As an example we may state that it is almost sure that it makes a big difference if the concept is based on e.g. packed beds or bricks, bundle of tubes, set of fractures or channels in fractures. Does it follow from this that we need to characterise every single cubic µm of the repository host rock in order to predict the transport?

4. SOLVING THE TRANSPORT PROBLEM

Speaking still in general terms, two things govern the behaviour and transport of the non-conservative (reactive) molecules

1) interaction rate with the boundaries of the medium versus longitudinal transport

2) behaviour in the medium outside the region of longitudinal transport.

The most interesting chemical and physical processes in the medium are usually sorption and molecular diffusion. Other processes may occur as well, like irreversible sorption and precipitation, but these are not usually accounted for because it is difficult to show that these processes take place in all possible conditions.

The problem can in principle be solved if the above mentioned two components of transport can be determined using a reasonably valid concept and parameters. These are needed to ensure the correctness of the extrapolation.

In a heterogeneous medium it would be difficult to determine these entities throughout the whole transport path for all potential transport paths, but fortunately only integrals (not local values) over macroscopic ranges of the two factors are needed, and small scale variations can be averaged out. The transport time consists of two additive factors. The behaviour of the non-interacting tracer is governed by the flow field alone (by definition). This contribution is added to the transport time of reactive tracers spent at the surfaces of the medium or in the medium. Conservative (non-sorbing) tracers can interact with the medium in the sense that it may diffuse through the boundaries and spend some time outside the “flow region”. In this picture we count e.g. stagnant areas of flow, which are directly connected to the flow field, to the “flow region”. The flow field contribution to the transport time is usually not so interesting from the point of view of performance assessment but, it is important when experiments are interpreted.

The interaction rate versus longitudinal transport can be determined either by direct measurements (e.g. by comparing transport of sorbing and non-sorbing tracers) or theoretically with the help of concepts and models. The behaviour in the medium can be revealed by laboratory and in-situ measurements supported by modelling.

5. TRANSPORT EQUATION: VELOCITY, DISPERSION, SORPTION, DIFFUSION INTO THE MATRIX

The widely accepted terminology and formulation of transport in fractured media includes usually the processes: advection, dispersion, sorption (on fracture surfaces and in the matrix) and diffusion into the matrix. The theoretical formulation starts often from the parallel plate concept but it can be generalised e.g. to a heterogeneous, variable aperture case quite easily.

There are some problems applying this stream tube concept for other than point sources. For a point source one stream tube, where no significant variation of properties in the transverse direction of the stream tube exist, is a reasonable approximation. For larger source term extents some questions arise. How large could the extent of one stream tube be? Does dispersion account for different velocities? Is the dispersion really Fickian? How is sorption and diffusion through the boundaries coupled to the stream tube? What is the interaction between stream tubes?

These points should be addressed in the modelling and evaluating process of a FTTE, and when extrapolating the modelling to repository performance assessment (PA). A direct application of the transport model to reproduce experimental results, without a transparent description of the underlying flow geometry, is not satisfactory. This is not, however, an easy task because unfortunately the experimental data does not usually allow one to distinguish between the different flow concepts – in the future something must be done to improve this situation.

Noticing all these difficulties one may end up to ask if the usually presented formulation and the corresponding quantities are the right ones to go with? The answer can be yes, but their role has to be understood correctly and generally enough. There are relations between them and e.g. locally wildly varying quantities like velocity and fracture aperture produce together a very stable quantity: their product is related to the flow rate which is to some extent ”invariant” along the transport path in given flow conditions.

The flow rate as the important quantity gives a very strong connection to the hydraulic characterisation of a site which is “easier” to perform than direct characterisation of transport properties. The hope is that with a valid flow field concept and necessary hydraulic measurements the transport at a site could be under control, and only some FTTE’s would be needed to ensure and demonstrate this.

6. WHAT ARE TRACER TESTS?

Basically tracer tests mean that transport properties in an unknown domain in a medium are studied by sending a signal through the domain. Comparing the source signal and the registered output signal one should deduce which processes have been active during the transport and which kind of transport path geometry was involved. This is, of course, a very demanding task, and any possible support from other measurements and observations is needed for the interpretation.

In the evaluation it should be realised and accounted for that the input has certain spatial and temporal characteristics which are reflected then in the output signal. It is obvious that the input has to be known for a sensible analysis of the system. The significance of the source term is unfortunately underestimated too often.

For a reliable evaluation of the tracer test the flow field should optimally be in steady state, and if disturbed by the experimental procedures themselves the disturbances should at least be well controlled and known. Hardly any system can be studied by just one single measurement, rather a series of measurements is needed with different conditions. The greater number of processes has to be studied the more measurements are needed.

7. WHAT HAVE TRACER TESTS TAUGHT US?

In homogeneous media and especially when transport is diffusion dominated, the control of performing and evaluation of tracer tests is easier in the sense that much less ambiguities regarding e.g. the input or source term exist than in heterogeneous media. The experimental conditions are much closer to the ideal theoretical behaviour. The situation is most difficult with advection dominated, unknown heterogeneous flow systems.

In spite of extensive efforts to characterise experimental sites, most tracer experiments in fractured media have to be performed in the latter conditions. We have learned in international modelling exercises that in the case of fractured media there are often more concepts than experiments, and that it is usually not possible to distinguish between the different concepts and models.

Some of the reasons for this are that it has not been possible to control and measure the source term well enough for purposes of process identification. It is also known that two or more processes can produce the same kind of behaviour of the output signal. Even if the behaviour of two processes is different, it is difficult and uncertain to extract the effects of the two processes from the combined result. The flow fields are not always constant introducing uncertainties and ambiguities. Unknown processes or flow conditions may be responsible for the fact that the tracer recovery is often significantly less than 100 %.

Taking all these uncertainties into account, it can be concluded that it is rather easy to obtain a reliable median or mean transport time and the variance of the transport times, but other characteristics of the break-through curves are then already questionable. In the course of performing and analysing the tracer tests in the past we have learned what are the main weak points in the FTTE's performed so far, and know now better how to tackle the geosphere transport problems in a more efficient and accurate way.

The lessons learned include that we have learned to take conceptual and analytical uncertainties into account, and that we appreciate more and more the role of "predictive" modelling in testing our ability to understand transport processes and bedrock features affecting transport. We have gained an increased knowledge and experience to organise a FTTE together with geologists, hydrologists, modellers, experimentalists, and performance assessors to the interactive and iterative effort of solving the transport problem.

8. SHORT REVIEW OF FTTE'S

This review concentrates in some characteristic details of some FTTE's performed recently. The review is by no means a comprehensive summary of complete results or conclusions, rather it aims at pointing out some important features of the tests that are worth discussing when preparing for future tests. Many valuable results were obtained, and there are many things that have been learned from these tests, but there are also points which may be rethought and improved in the future. These and other performed FTTE's are valuable material to be studied carefully when the overall potential of getting information through tracer tests is assessed. Comprehensive reviews on tracer transport tests have been presented recently, e.g. by Gelhar et al. [1] mainly on the dispersion problem, and by Andersson [2] more related to the nuclear waste disposal.

Finnsjön radially converging and dipole tests

A set of tracer tests in a gently dipping fracture zone in crystalline rock at Finnsjön was performed. The objective was to study and determine transport phenomena and parameters in major fracture zones and to use the results for calibration and verification of radionuclide transport models. An additional objective was to develop and improve experimental equipment and methods [3]. The tests were handled as one test case (Case 5) in the INTRAVAL project in its both phases. Already in the early planning of the INTRAVAL project, the importance of interaction between experimentalists and modellers as well as of the predictive calculations were emphasised. It turned out, however, that in many of the INTRAVAL cases the tests were already performed before modellers could comment the test plans. The Finnsjön case was an exception in this sense, although the schedule was very tight so that comments and predictions could be presented but modellers' further contribution to the tests was limited. In spite of quite comprehensive test program, the experimental results and data were insufficient to distinguish between disparate models. Tracers were injected by circulating and mixing the tracer in the borehole section, but sampling of the concentration was not frequent enough to have an accurately determined source term. The extent to which matrix diffusion occurred in the experiments remained unclear.

Stripa 3-D

Groundwater flow and tracer transport through a three dimensional block of rock above a drift excavated for that purpose was studied in the Sripa mine. These tests formed the INTRAVAL Case 4. The rationale was to understand and quantify transport processes relevant to the safety of a final repository for high level radioactive waste. The measured water flow distribution studied over more than 700 m^2 was observed to be very uneven. Tracers were injected at nine different points and 167 break-through curves of six different tracers were measured [4]. The tracers were injected with overpressure. This may have spread the tracer in the vicinity of the injection point in an unknown way. Due to on-going activities in the mine disturbances occurred during the tests. These facts made it difficult to extract the effects of various transport phenomena, including matrix diffusion, from the results.

WIPP-2

In the second phase of the INTRAVAL project, the simulation of flow by means of stochastic 2-D modelling approaches was studied using the available extensive hydraulic data. In addition to that results of tracer tests (mainly from Hydropad 11) performed at the site were modelled. Anisotropy of the Culebra formation was seen to have an effect on the transport, but some uncertainty remained about the role of heterogeneity. The diffusion from the fractures of the dolomite formation into the highly porous matrix had a significant effect during transport according to the modelled results [5,6]. The parameters could not, however, be determined unambiguously because the effects of uneven flow distribution and source term spreading due to slug injection and borehole flushing were not known.

Stripa SCV

Tracer test in the block scale was performed in the Site Characterization and Validation project in the Sripa mine. The aim was to study water flow and tracer migration in a fracture zone as well as in the rock outside the zone. Compared to the Stripa 3-D experiments the injection technique had been changed to produce a constant injection flow rate instead of constant pressure. Care was taken that no major disturbances due to other activities would occur. The injection took place with slight overpressure. The resulting break-through curves were significantly smoother than in the Stripa 3-D case and agreement between modelled and measured results was better. Dyes and metal complexes were used as tracers, and they showed different break-through curves even though injected simultaneously. This difference could be explained with a small difference in their K_d values meaning that dyes would be slightly sorbing. The sorption was so weak that it could not be seen in laboratory measurements. This sorption could have enhanced the effect of matrix diffusion to the extent that the maximum values of the break-through curves differed roughly by a factor of two. It was concluded that flow in the fracture zone is channelled, and similar to the channelling in the average fractured rock [7].

VLJ-RT

Tracer tests were performed in the VLJ Research Tunnel at Olkiluoto, Finland. The tests were run between two boreholes being 6 metres apart. One of the 56 mm holes was bored at the location of a planned full scale simulation hole. In the first phase the test was run between the 56 mm holes and later from the 56 mm into the 1.5 m diameter hole. Geological and fracture mapping of the cores and later observations from the 1.5 m hole revealed that the rock was tight and sparsely fractured. Single fractures could be identified being responsible of hydraulic connections. The flow through the injection section was measured carefully with high time resolution to know the source term accurately. The experimental set-up in the later tests allowed to change the water of the injection section without disturbing the flow through the section. The relatively short injection pulse allowed a better analysis of the tail of the break-through curve. It was concluded that effects of matrix diffusion can be seen first when the not necessarily Fickian hydrodynamic dispersion behaviour is known accurately [8].

9. FTTE SCALES, PURPOSES, CONTROL OF FLOWS AND SOURCE TERMS

Different aspects of migration can be studied in different tracer tests. There is no single test that would solve all the transport problems. An optimal combination of test scales and types should be found out to gain as much as possible knowledge about transport of solutes and, ultimately radionuclides in various kind of media. The practical constrains for the tests, set by the environmental conditions in the field, should be analysed in test planning. The degree of achievable accuracy usually increases towards smaller scales. More sophisticated tracer tests to study transport phenomena can be performed better in smaller that larger scales. Large scale studies are essential for understanding of water flow in that scale and to determine parameters describing the flow field. The larger the scale is, the longer are usually also the test times and repetitions, and changes of test conditions are not possible to a great extent. A general idea of relations between scales, purposes of studies, governing flow fields and importance and possibilities to control the source term is presented in Table 1.

scale	purpose of study	flow field	source term
regional > 1000 m	conn	natural	not important
site 100 m - 1000 m	conn + por + disp	natural + pump	somewhat contr
block 10 m - 100 m	conn + por + disp + trans	pump + bkg	contr
detailed 0 m - 10 m	por + disp + trans + sorp + md	pump (var) + bkg	adj pulse

conn=connectivity, por=flow porosity including channelling, disp=dispersivity, trans=other transport properties, md=matrix diffusion, natural=natural flow, pump=pumping, bkg=background flow, (var)=various rates, contr=controlled, adj pulse=adjusted short pulse

Table 1. Relations between scales, purposes, flow conditions and source term controlling in tracer tests

The importance of various transport phenomena in migration from repository towards biosphere at different scales should be assessed by means of PA methodology and reflected in FTTE's.

10. ADDRESSED QUESTIONS

The Programme Committee has prepared a list of questions to be answered in this paper. The background for the answers to these questions is presented in the previous chapters and direct answers will be given here more explicitly. It should be remembered, however, that it is certainly impossible to cover all of the performed tracer tests with one general answer. The answers should be seen to represent more a trend among the tests than being applicable as such to any individual experiment.

1) Was the rationale of these tests clear enough?

The rationale for each test has been clear, but often too optimistic and unrealistically wide taking into account the available resources for fulfilling the goals (belonging to the rationale in question). For porous media the typical rationale is the need to know the flow and transport porosity together with the dispersion in one, two, or three dimensions. It is a simple and clearly stated rationale. Required test arrangements and procedures may be quite complicated, though. Experiments in fractured media have been reasoned often in similar terms than those in porous media. This may be a severe problem if the analogy does not hold. A characteristic phenomenon of fracture flow is channelling, and the rationale of many experiments has been based on this. Experimentally it is a challenge to address channelling in undisturbed rock and natural-like flow conditions.

2) Which information were really obtained? What have field tracer tests taught us about important transport mechanisms?

Flow velocities and dispersion can usually be obtained quite reliably and accurately. Beyond that the obtained information depends much on the used concepts and modelling. Usually, there are at the same time many different concepts and models that can explain the results. There are thus ambiguities in the interpretation, which can not be resolved due to lack of experimental data. The governing transport mechanisms can not be distinguished in such cases. The most debated and perhaps also most important transport mechanism is the matrix diffusion. It is extremely difficult, if not impossible, to show the effect of matrix diffusion on the break-through curves in field tracer transport experiments. It is certainly not enough to fit an advection-dispersion-matrix diffusion model to a BT-curve and extract the various transport mechanisms from the model parameters.

3) What use was made of the so obtained information?

The information has strengthened mostly our understanding on the flow in the media, and the transport calculations in performance assessments are based directly or indirectly on the flow characteristics. Still, there are discrepancies in the basis of transport modelling as partly discussed under question 2).

4) Have they helped to build confidence in the predictive modelling of radionuclide transport for performance assessment purposes?

The tracer tests have partly helped to build confidence in the transport modelling. There are important gaps to be filled before a satisfactory level of confidence can be achieved.

5) Where are the failures? Were these failures clearly reported? What are the lessons learned from them?

The failures of fulfilling the goals of the tests regarding understanding of transport mechanisms, were mainly in test limitations and partly also in unfavourable test procedures for the study of transport mechanisms. The reports emphasise usually a good agreement of the experimental and modelled results, and possible ambiguities are not assessed critically. In this sense the ”failures” or insufficiencies of the tests are rather hidden than clearly reported. The lessons learned from the failures of these kind are that more and better tests and detailed characterisation of the test site is needed before the transport mechanisms can be revealed and studied in field.

6) What can be expected from future field tracer tests?

In the future tests, the ambiguities will be reduced and tests will be more specialised in transport mechanism studies compared to the ”overall” type of tests made in the past. This may mean various tests in various scales and combining of the results from different tests on site, generic and laboratory tests. Different concepts and models are distinguishable when compared with the test results. It seems that not all of the tests can be performed in field at a specific site. The tests at a disposal site will be even more limited in number. Characterisation of hydraulics is the main task at a disposal site and the performance assessment has to rely on the relations between the hydraulic and transport properties studied at other places, possibly nearby, and even on generic studies.

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The Contribution of Field Tracer Transport Experiments to Repository Performance Assessment

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Abstract

Models of solute transport in the geosphere are, in general, derived from hypotheses concerning:

- the types of structures present in rock (possibly supported by direct observations in tunnel walls, cores, etc.),
- the transport processes that convey the tracers within the relevant structures (supported by current understanding of geosphere transport),
- the rates and spatial extent over which these processes operate (supported by independent field and laboratory experiments – e.g. batch sorption and laboratory diffusion experiments).

Field tracer-transport tests can be used to provide support for individual hypotheses, for the overall models and for the methodologies to derive parameter values for the models, and thus to build confidence in the applicability of the models and data used in performance assessment. The present paper describes performance assessment needs with respect, for example, to confidence building. The types of confidence building, as well as other information, that can be obtained through the process of modelling the results of tracer tests are outlined. The value of predictive modelling is compared to that of "inverse modelling". The different ways in which the results of tracer tests can be applied in performance assessment are outlined, both where the rock in which the tests are performed is similar to a potential host rock and also where there are significant differences. In spite of the importance of tracer tests, there are limitations in the information that they can provide, particularly in the understanding of slow processes and processes operating over long times and large distances. These limitations are discussed.

1. Introduction: Performance Assessment and the use of Models

1.1 The components of performance assessment

An assessment of the performance of a radioactive-waste repository comprises the following three basic components:

1. An **evaluation** of the evolution of the repository system;

   The evaluation must be quantitative, but, because of the long time scales over which the evaluation is required, cannot be based in direct observations. Rather, the evaluation relies on:

   - A scenario analysis, in which a set of scenarios, representing alternative concepts for the future evolution of the repository system, is derived from a comprehensive list of features, events and processes (FEPs). Some or all of these scenarios are selected for quantitative, consequence analysis.

   - A consequence analysis, in which (i), the structures within the repository and its environment, (ii), the relevant processes operating within these structures and (iii), the rates and spatial extents over which these processes operate, are described quantitatively in a set of models. Due to uncertainty in these descriptions, the model "predictions" do not necessarily aim at realism, but can rather be bounding: for well-understood aspects of the repository system, the model descriptions aim at realism and, for less well-understood aspects, conservative, simplifying assumptions are made that aim to over-estimate adverse consequences of the repository. Ranges/distributions of parameter values and alternative model assumptions typically need to be considered.

2. **Building confidence** that the "predictions" of consequence analysis are sufficiently reliable;

   This involves building confidence:

   - that the list of FEPs identified within the scenario analysis includes all safety-relevant phenomena, that the interactions between FEPs are adequately represented and that an adequate set of scenarios has been identified, covering uncertainty in the evolution of the repository system,

   - that the models, data and computational tools are adequate and that uncertainties are taken into account, either in the set of models and ranges/distributions of parameter values selected for the analyses or in conservative assumptions.

3. **Assessment of available information**

   This typically involves a discussion of the meaning of the results (for example, in terms of compliance with regulations), an evaluation of uncertainties and a statement of confidence in the results, in the light of various confidence-building measures (validation).

1.2 The role of models in performance assessment

Because of the need for quantitative evaluation of the performance of the repository system over long time-scales, the use of models is central to performance assessment. The repository system as a whole is commonly described by a chain of assessment models that each relate to a particular component of the system (e.g., a near-field release and transport model, a geosphere-transport model and a biosphere model), with a series of supporting models and hypotheses that serve to translate field and laboratory data into assessment-model input parameters (e.g., a hydrogeological model to translate the results of borehole tests and observations to geosphere-model input parameters such as flow-wetted surface and Darcy flux). An example of the relationship between supporting models and hypotheses and an assessment model is illustrated, in Figure 1. The figure is based on the geosphere-transport modelling performed in recent Swiss performance assessments [1], [2].

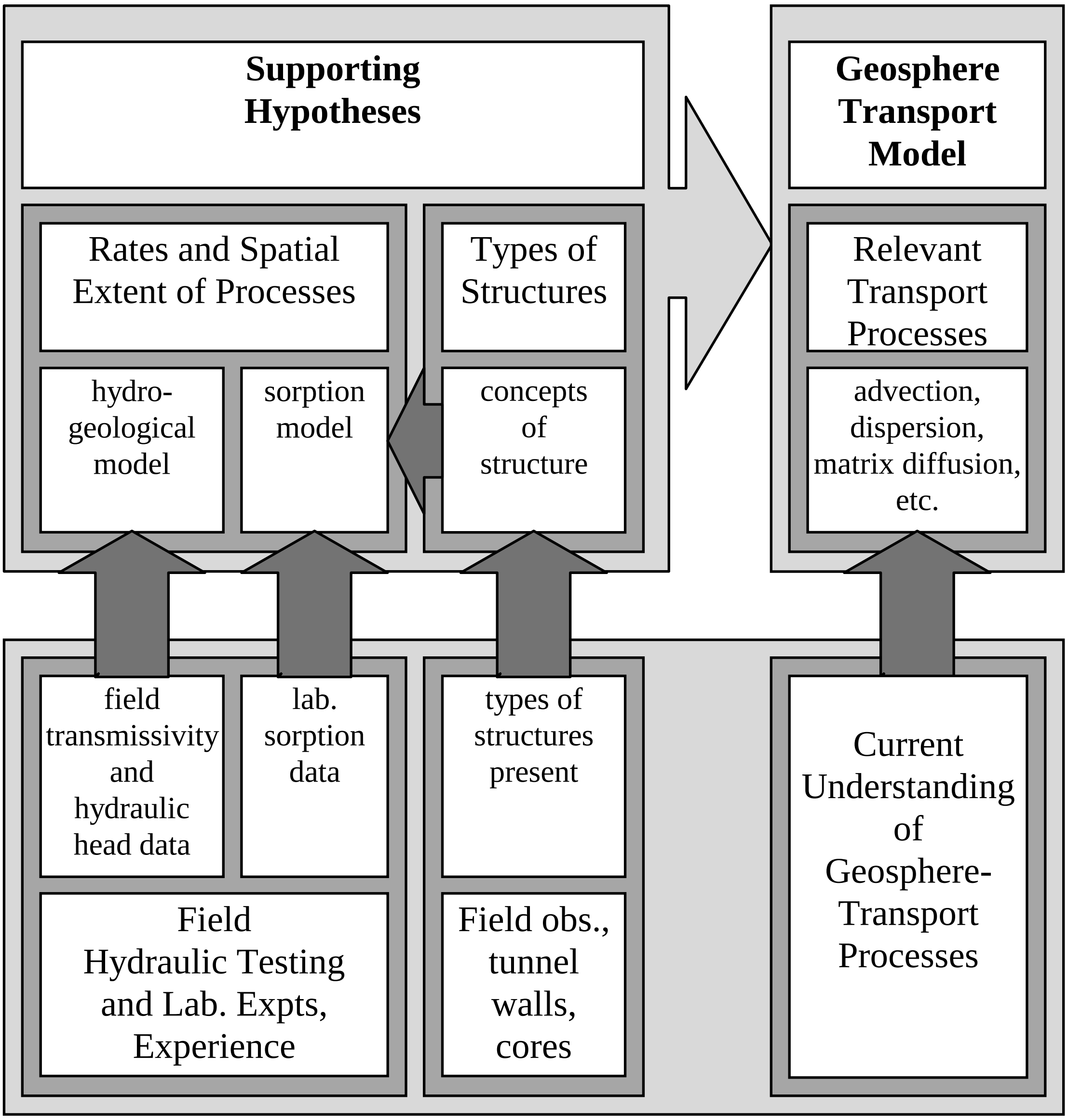

Figure 1. Relationship between supporting models and hypotheses and a geosphere-transport model

An assessment model is often a (conservatively) simplified version of a more detailed research model, with the research model aiming at realism rather that bounding predictions. The same types of relationship illustrated in Figure 1 also apply to research models. The greater level of detail of the research models can arise because:

- Research models are designed for use on systems that are more fully characterised than is achievable in practice at a real site. A research model may be applied to only a (particularly well-characterised) part of the system to which an assessment model is applied. In the case of geosphere transport in a fractured medium, a research model may be applied to a tracer test in an individual, particularly well-characterised fracture. Detailed characterisation is likely to be impracticable for the fracture-networks of relevance to performance assessment (Section 4.2).

- The need to perform large numbers of calculations in performance assessment, in order to explore parameter sensitivity and to estimate the consequences of uncertainty, may require an assessment model that is relatively simple to avoid excessive demands on computer time and memory. The same constraints do not generally apply to research models.

Research models are based on a full representation of performance-relevant features, within the current understanding of the system to which they relate, and provide the theoretical framework on which assessment models are built. In particular,

- Research models provide a tool for validation, testing the hypotheses concerning structures, processes and rates/spatial extents by allowing model predictions to be compared with the results of laboratory and field experiments.

- Research models provide a tool for decisions on simplifications in the formulation of assessment models. Having confirmed understanding of the system, a model developer is in a better position to decide where simplifications can be justified in terms of either conservatism or insignificant effects.

In the context of this discussion of the use of models in performance assessment, a third class of models is mentioned briefly. These models are simplified analysis tools, based on a further simplification of the assessment models. They are fast to run (e.g. analytic solutions), can be of use for sensitivity analysis, allowing a wide region of parameter-space to be covered comprehensively (e.g. [3]), and can assist in the interpretation of assessment model results (e.g. [1]).

1.3 The components of a geosphere transport model

As illustrated in Figure 1, a model of geosphere transport, whether a research model, an assessment model or a simplified analysis tool, is, in general, derived from hypotheses concerning:

- The types of structures present in the rock

  This includes the identification, classification and geometrical description of structures (fault zones, fractures, channels, etc.). Hypotheses concerning structure typically involve extrapolations of direct observations in the field, in tunnel walls, cores, etc., possibly supported by other evidence (e.g. geophysical studies).

- The transport processes that convey the radionuclides (in the case of an assessment model) or tracers (in the case of a research model) within the relevant structures.

  This includes solute transport processes, such as advection, diffusion and sorption, but may also include a range of other processes including precipitation at reaction fronts, colloid-facilitated transport and gaseous-phase transport. These hypotheses are supported by current understanding of geosphere transport.

- The rates and spatial extent over which these processes operate.

  This includes the parameter values that quantify the transport processes, e.g. Darcy velocity and, for fractured media, flow-wetted surface, diffusion coefficients and porosity distribution. These hypotheses are supported either by field experiments by or independent laboratory experiments – e.g. batch sorption and laboratory diffusion experiments.

2. Performance–Assessment Needs

Performance assessment needs, with respect to the prediction of radionuclide transport in the geosphere, where field tracer tests can provide a contribution, are in the following areas:

2.1 Confidence building and identification of uncertainties

The types of confidence building that can be addressed by field tracer transport tests are:

- Confidence that relevant structures and processes have been identified and that a satisfactory methodology exists by means of which rates and spatial extents of structures and processes are determined from laboratory and field data.

  The success of a model, that is consistent with available information about the experimental system, in reproducing the results of an experiment builds confidence that relevant features and processes have been identified and that the methodology (e.g. supporting models) for quantifying rates and spatial extents is satisfactory.

With regard to uncertainties:

- Identification of remaining uncertainties in the understanding of structures and processes and reduction of these uncertainties.

  The success of alternative models, also consistent with available information, in reproducing the results of an experiment indicates the degree of uncertainty in the understanding of these features, processes and rates/ spatial extents. The failure of alternative models serves to falsify hypotheses concerning structures, processes and rates/ spatial extents and thus narrows the degree of uncertainty.

The use of field tracer transport tests for confidence building and identification of uncertainties is further discussed in Section 4.1.

2.2 Assessment model formulation

If the research models need to be simplified for performance-assessment purposes, the understanding of tracer tests by means of these models can ensure that, in the assessment models

- key structures and processes are represented in the assessment models,
- where omissions/ simplifications are made, predictions do not err on the non-conservative side,
- laboratory and field data are used in an appropriate manner.

Field tracer tests can also be used to "calibrate" a model, either for use in further tests or, more rarely, for direct use in performance assessment. The direct use of tracer tests in the characterisation of a site is discussed further in Section 4.2.

3. The Modelling of Field Tracer Tests

As indicated in Section 2, when a field tracer test is performed, it is the process of trying to understand the result, often by means of a (research) model that attempts to reproduce the experimental results that contributes to performance assessment needs. A model can be tested for its ability to reproduce the results of field tracer transport tests in two broad ways:

1. Predictive modelling, where predictions are generated by the model using parameter values derived from independent measurements.

To obtain maximum benefit from predictive modelling, it is desirable to make predictions in a transparent manner before the tracer test is performed, with a clear methodology defined for the setting of parameter values. It is also desirable to establish "success criteria" for the predictions, taking full account of experimental errors.

2. "Inverse modelling" where parameter values are adjusted until a best fit of the experiments are found.

The type of confidence building that is provided by inverse modelling, though valuable, is generally less convincing than that provided by predictive modelling. It is necessary to recourse to inverse modelling where independent measurements are either not available or unsuitable for the determination of all parameter values. It is, however, essential, from the point of view of confidence building, to show that the fitted parameter values are at least physically reasonable and consistent with any available independent information.

Both types of modelling can, by demonstration of "goodness of fit" (within the success criteria), build confidence that the relevant features and processes have been identified and incorporated in a model that is used either directly, or in simplified form, in performance assessment, i.e. that no key processes have been overlooked. It is important to examine as many plausible alternative models as possible in order, by falsifying some of these alternatives by their failure to predict experimental results, to narrow down the range of conceptual model uncertainty and to identify the processes that are most important.

A significant difference between predictive modelling and inverse modelling is that:

- predictive modelling can build confidence in the methodology for deriving rates and spatial extents from field observations and from independent field and laboratory data and to show that parameter values obtained by these means are acceptable.

- inverse modelling can be used to "calibrate" a model, providing parameter values for subsequent application in predictive modelling of further tracer tests (i.e. running the same system in different modes - e.g. with different flow rates and with different tracers) and, in some circumstances, of a repository system in performance assessment.

The use of tracer test results in performance assessment, both for confidence building and model calibration, is discussed in the following section.

4. Use of Tracer-Test Results in Performance Assessment

4.1 Confidence building and identification of uncertainties at "generic" sites

Field tracer transport experiments have, in several cases, been performed at locations that are not intended as sites for future radioactive waste repositories. Tests at such "generic" sites can be useful:

- in providing experience in the practicalities of obtaining field data and relevant laboratory data and in stimulating the development and refinement of measuring devices (e.g. for hydrogeological testing, laboratory sorption tests and diffusion experiments),

- in establishing successful communications between geologists, laboratory and field experimentalists and modellers,

and, of more direct relevance to performance assessment, in various types of confidence building discussed in Section 2.1. Specifically:

- in building confidence, by a "trial application", that the methodology for the construction of a transport model from these and other data is appropriate,

- in building confidence that relevant structures and processes are understood (although structural details are likely to be site-specific) and that no relevant processes have been overlooked,

- in building confidence that laboratory data can be correctly applied.

The success of models in predicting the results of a tracer test (or, preferably, a sequence of many tests with the same system run in different modes) have, in the case of fractured, hard rock (e.g. [4]):

- illustrated the importance of an understanding of small-scale geological structure in constructing a model that, in performance assessment, can be confidently expected either to be realistic or to err on the side of conservatism,

- demonstrated the existence of the matrix-diffusion phenomenon and its key importance as a retardation phenomenon in performance assessment and, more generally, demonstrated that current understanding of geosphere-transport processes is sufficient to understand transport on the scale of these tests,

- demonstrated that, with appropriate consideration of the differences in conditions, laboratory data (e.g. on sorption and diffusion) can be applied to field-scale experiments, giving confidence that they can be applied in performance assessment.

In order to address the topic of conceptual-model uncertainty, in the international INTRAVAL project, seven different teams applying different model concepts attempted to model radially-converging and dipole tracer experiments at the Finnsjön site in Sweden [5]. All conceptual approaches were found to fit the experimental results reasonably well, indicating the range of uncertainty in the understanding of structures, processes and rates/ spatial extents. Conceptual-model uncertainty is of importance to performance assessment if it leads to uncertainties in predictions made for the relevant temporal scales, which are considerably greater than those characterising tracer tests. Predictions made using the different approaches were found to diverge considerably over these larger time-scales and it was concluded that it is not possible to extrapolate a (research) model calibrated on the experimental scale to simulate a much longer time-scale case. As discussed in Section 2, assessment models are thus based on (conservative) simplifications of such research models.

It is more difficult to cite examples where the failure of alternative models has served to falsify hypotheses concerning structures, processes and rates/ spatial extents and thus to narrow the degree of uncertainty. To some extent, this may be because a consensus has been reached as to the broad processes that are relevant to transport (e.g., in the case of fractured media: advection, dispersion, matrix diffusion, sorption). However, there is also an unfortunate tendency to emphasise (in the literature) instances where models are successful in reproducing experimental results, rather than where alternative models have failed.

4.2 Direct use of tracer tests in the characterisation of a site

Where field tracer tests are performed in a geological medium that is a potential host for a radioactive waste repository, "inverse modelling" of the results can, in principle, provide data for direct use in performance assessment. Key data that could be obtained from tracer tests are, for example,

- flow porosity,

- retardation data (e.g. sorption Kd-values),

and, for fractured media,

- flow-wetted surface,

- the distance to which radionuclides can diffuse from fractures into adjacent wallrock.

Problem areas in such direct use of field tracer transport tests in the characterisation of an actual site are the heterogeneity of the site (Section 5), which may mean that many such tests are required for characterisation, and the practicalities of performing large numbers of tests without, in the process, perturbing the favourable hydrogeological properties of the site. It is, therefore, not routine practice to perform field tracer tests to obtain data as part of the characterisation of an actual site. Such tests have, however, been used to support and refine models of important geological features in the region of a site [6], [7]. Furthermore, a related type of experiment, tracer-dilution tests, has been used, for example, in as part of the characterisation of the crystalline basement of Northern Switzerland [8], [9]. Dilution tests involve the flushing of a section of a borehole where there is known to be a water-conducting feature with a tracer and monitoring the tracer concentration as a function of time. These tests are potentially useful, since they minimise the perturbation of the natural hydraulic gradient (conventional hydraulic tests deliberately perturb the gradient) and can be used to infer flowrates. However, practical difficulties and experimental artefacts can limit their usefulness and, in [8], [9], they were used to bound, rather than predict a realistic value for, groundwater flowrates.

5. Treatment of Spatial Heterogeneity – Limitations of Field Tracer Tests

The successful modelling of field tracer tests indicates that heterogeneity on a smaller scale than the tests themselves can either be averaged out (as in the case of heterogeneous sorption) or can be treated in a simple manner (e.g. the modelling of hydrodynamic dispersion as a diffusion-like process); this is also an important assumption underlying most geosphere assessment models. However, a major difficulty with field tracer tests is that they operate in domains of space and time that are significantly different to those of relevance to performance assessment: no information is provided on processes that, though irrelevant on the spatial and temporal scales of field tracer tests, may be important over scales relevant to performance assessment - i.e. slow processes and processes operating on large-scale features, such as:

- matrix diffusion into fracture wall rock (it is the effects of diffusion in loosely consolidated fracture infill material that are apparent in some field tracer tests, e.g. at the Grimsel test site, Switzerland [4]),

- hydrodynamic dispersion in extensive fracture networks.

The identification of slow processes may be regarded the domain, for example, of natural-analogue studies, rather than of field tracer tests. In the case of large-scale spatial heterogeneity, attempts have been made to perform and model tracer tests on extensively fractured rock masses, e.g. in Phase 2 of the international Stripa Project in Sweden ("Migration in a Large Fractured Granitic Rock Mass") [10] and in tracer tests at the Fanay-Augères Uranium Mine in France [11].

In the case of the large-scale experiment at the Stripa Mine, alternative models were applied, each representing a single realisation of the network, and it was concluded that "... the collection of transport models, based on various assumptions ... was not able adequately to reflect features of the tracer breakthrough curves". This inability of any of the alternative models to reproduce experimental results was attributed to:

- uncertainties in the geometries of flow paths through the network,

- uncertainties in the geometrical features of channels.

i.e. a far more detailed characterisation would be required in order to model realistically transport through a fracture network.

In the case of the tracer tests at the Fanay-Augères Uranium Mine, a different approach was adopted. No attempt was made to reproduce the detailed features of the breakthrough curves. Multiple realisations were generated of the network and the ensemble of model predictions compared with broad features such as the overall duration of breakthrough and the recovery rates. Consistency between the ensemble of predictions and observations was found, but the range of predictions within the ensemble was large and thus, perhaps, of limited value to confidence building (e.g. a range of predicted recovery rates of 2-70%, with observations, at 4 measurement points, of 5%, 6%, 14% and 45%). Again, more specific predictions would require a more (possibly unattainably) detailed characterisation.

6. Discussion and Conclusions

This paper has describes performance assessment needs with respect to various types of confidence building and data acquisition. Many of these needs can be addressed by the process of trying to understand the results of field tracer tests in terms of models. These are, typically, detailed research models that are then used as a basis for simplified assessment models. In general, predictive modelling is more valuable than "inverse modelling" in terms of confidence building. Maximum benefit to performance assessment from predictive modelling of field tracer-transport tests can be obtained by:

- making predictions in a transport manner before a test is performed, which involves:
  - a clear methodology or strategy for setting free parameter values (from, for example, independent field and laboratory experiments),
  - establishment of criteria for "successful prediction",
- examining as many plausible alternative models as possible, which involves:
  - covering the full range of conceptual-model uncertainty,
  - aiming to falsify alternatives,
  - publicising "failed" model alternatives and not only those that give successful predictions,
  - taking account of all available information (including independent experiments and general, scientific knowledge and experience about structures and processes),
  - aiming to identify the most important structures and processes,
- extrapolating results to the larger spatial and temporal scales that are relevant to performance assessment, to provide an indication of the consequences of conceptual-model uncertainty.

Apart from practical limitations and perturbations caused to the experimental system by the tests themselves, a fundamental limitation of field tracer-transport tests is in the scales of space and time that they can address. Large-scale structural heterogeneity, in particular, is a highly relevant phenomenon in geosphere performance assessment. The geosphere provides an effective barrier to the transport of a radionuclide if the transport time through the geosphere exceeds the half life. Even where this is true on average, if a few pathways exist where the transport time is less than the half life, then these can dominate the performance of the geosphere barrier as a whole. Large-scale heterogeneity is generally treated simplistically in performance assessments. As discussed in this paper, it is not necessary in performance assessment to predict actual transport behaviour, but rather to make predictions that are confidently expected to over-estimate the consequences of transport. It is thus possible, to some extent, to compensate for lack of information on large-scale heterogeneity through the use of conservative assumptions. The difficulty with this approach, however, is that credit for the performance of the geological transport barrier may be reduced to such a degree that it plays only a minor role in repository safety; this will be the case, for example, if the existence of a "fast channel" through the host rock, that affects releases from a sufficiently large part of the repository inventory, cannot be excluded. In these circumstances, the information from field tracer tests, interesting as it may be, is of rather limited use to performance assessment.

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Regulator's Point of View on the Use and Relevance of Field Tracer Transport Experiments

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1. Introduction

Nuclear waste arising from the operation of nuclear power plants as well as from the use of radionulcides in medical treatment, industrial applications and at research facilities has to be disposed of in a way that future generations will bear no risk to their health and to the environment. Therefore most countries plan to built repositories within deep underground geological formations. In the course of licensing procedures compliance with regulations has to be demonstrated by means of safety analyses for the operational as well as for the post closure phase.

The goal of post closure safety analyses is to demonstrate with a high degree of confidence that in case of a potential release of radionuclides from the repository the consequences to man and to the environment are below regulatory limits. These analyses have to be carried out for long time periods after sealing of the facility. The most important issue is whether numerical safety analyses take into account those migration pathways which may provide the fastest return for the radionuclides to the biosphere and result in the highest calculated exposure.

For the regulator who has to review long-term safety assessments during a licensing procedure for a nuclear waste repository questions arise

- how valid the predictions of the future evolution of the facility and the site are,
- how good the models used to carry out these predictions represent the nature of the site,
- which experimental evidence is needed to support the hydrogeological model of a site on which analyses are based,
- to which extent site investigations have to be carried out to provide the information needed as input into the numerical models, and
- how experiments can be designed to confirm the results of the safety assessment.

In this context we would like to discuss in our paper based on the experience gained during assessments of repositories sites in Germany whether field tracer transport experiments are a sensible tool that may be used to gain confidence in the safety evaluation of the facility.

2. The German Waste Disposal Programme

Before we discuss the relevance of tracer tests for performance assessment we give a brief overview of the situation of waste disposal in Germany. Three waste disposal facilities are currently under consideration.

- The disused Asse salt mine had been operated as an underground research facility which included the experimental disposal of low and medium-level wastes.
- The Gorleben salt dome had been selected to host a final repository for all types of waste. It is currently under site characterisation including the construction of an underground exploratory mine.
- The disused Konrad iron ore mine had been selected to host a final repository for non-heat-generating wastes. The facility is currently in the licensing process.
- The disused Bartelsleben salt mine near the village of Morsleben is in operation as a repository for low-level radioactive waste.

All sites are characterised by a sequence of sedimentary layers above the host rock ranging from jurassic and cretaceous formations as in the case of Konrad to quaternary sandy and clayey deposits as in the case of Gorleben.

3. Performance Assessment Modelling of Sedimentary Systems

In sedimentary systems two types of heterogeneities are to be taken into account, firstly the different geological formations at a scale of a few metres to some hundreds of metres vertically and hundreds of metres to kilometres horizontally. Heterogeneities at this scale may be modelled explicitly for groundwater and nuclide transport simulations. However, these formations themselves are not homogeneous. Mineralogy may vary at very small scales of a few centimetres causing spatial variations of hydrological and transport parameters and these variations may change over the whole region. It is obvious that modelling heterogeneities at this scale explicitly for groundwater and transport simulations with the numerical tools available is not feasible to date since it would require a huge computational effort both in terms of time and memory. As it is state-of-the-art now properties have to be averaged over larger volumes. In doing so potential connectivities existing in low permeable rocks between highly conductive zones of the aquifer system may not be taken into account in the model. However, the question is whether such connectivities are relevant for the results of a long-term safety assessment.

In contrast to hard rock the porosity of sediments is relatively large which means that the storativity for radionuclides is relatively large as well as the dilution capacity. This is emphasised by the results of groundwater flow and transport analyses, where travel times range in thousands to hundred thousands for non-reactive or even millions of years for reactive nuclides. In addition for most sedimentary rocks present at suitable sites the retardation properties are more favourable than in hard rocks.

Therefore, if such connectivities are really small they might well represent a potential fast path for radionuclides to return to the biosphere but only for such a small fraction that no relevant contribution to exposure will result.

For the Gorleben repository project long-term safety assessment calculation have been carried out in the frame of the CEC EVEREST-project /CEC 96/. The geology of the site is characterised by a glacial erosion channel which cuts through the tertiary clay cover of the salt dome as far down as to the cap rock. This channel has been filled afterwards by quaternary deposits consisting of a sequence of sandy/gravely and clayey/silty layers. The Lauenburg clay complex covers most of the area of interest separating a lower aquifer which is in direct contact with the salt formation from an upper near-surface aquifer. This clay layer contributes largely to the isolation capacity of the geosphere at the site. Here the crucial question is whether gaps exists in this clay layer which connect the lower and the upper aquifers thus providing a potential migration pathway for radionuclides escaping from the salt formation into the biosphere.

In the Konrad long-term safety assessment /BfS 94/ travel times of non-sorbing radionuclides from the repository to the biosphere have been calculated to be in the order of 300,000 years, assuming conservative estimates for the parameters governing the radionuclide migration. In this base case simulation the main migration pathway is along the host formation itself for a distance of approximately 30 kilometres from the repository to the biosphere. Additionally several variants of geosphere migration simulations had been carried out to account for uncertainties in the hydrogeologic characterisation of the site. These variants addressed mainly the permeability of clayey layers above the repository. However, travel times range in the same order of magnitude even in cases where relatively high values are estimated for clay permeabilities and radionuclides penetrate the clay barrier directly above the facility with a path length in the range of a few kilometres.

Fault zones within a sedimentary system may be modelled explicitly with their own hydrogeological and transport properties assigned to them. However, such detailed modelling will not be needed for individual fractures which may appear as single features within these faults zones. In contrast to hard rocks the surrounding sedimentary soft rocks will have a sufficient retardation capacity accessible by diffusion that the impact of single fractures on radionuclide migration is negligible.

4. Use of Tracer Tests in Charactering Heterogeneities

One issue to be discussed is how tracer tests represent the real situation of a repository site. At first we have to consider the temporal and spatial scale in long-term safety assessments. In time it ranges from a few thousands to some hundreds of thousands of years and in space from some thousand metres vertically to several tens of kilometres horizontally. It is quite clear that tracer tests cannot cover these scales.

Usually tracer tests will only cover a small area of the region of interest. In order to characterise the geosphere at a repository site one would have to measure the distribution of an injected tracer within the system. This would require a large and dense population of boreholes which would disturb the system by introducing artificially heterogeneities. If novel methods would be available to measure tracer concentrations within the system from the surface without disturbing it by boreholes the results from such investigations will be more useful.

Nevertheless, tracer tests on small scales in space and time are a sensible tool to determine hydrogeological and transport parameters such as permeabilities, porosity, and retardation coefficients at selected locations, in particular where alterations due to geologic events such as e.g. faulting may be suspected.

Next issue is the depth of the repository which is in the range of some hundred metres. Conditions near the surface are not necessarily representative for those deep underground. Two options are available for carrying out experiments at the potential repository level, namely deep drilling or an underground laboratory. Deep drilling require considerable effort which would be only worthwhile if a representative location could be found whereas the construction of an underground laboratory will disturb the hydrogeological and potentially the geochemical conditions and therefore will not represent the real site conditions for the time periods after closure of the facility. Nevertheless results from such experiments might be useful to characterise the immediate vicinity of the facility.

5. Conclusions

Tracer test carried out at an underground laboratory or within geologic formations similar to those at a selected site for waste disposal might be very useful to validate the generic capabilities of models to be used in groundwater flow and nuclide transport simulations for long-term safety assessments and thus might enhance the confidence in performance assessments.

Furthermore, tracer tests might also be very useful to acquire site specific data such as porosities, diffusivities or retardation properties that are relevant for modelling the migration of radionuclides through the rocks of the geological barrier.

In addition tracer tests may be used to characterise the immediate vicinity of the underground facility, in particular the excavation damaged zone.

However, to date we would not request specific tracer tests for the sole purpose of characterising the hydrogeologic and geochemical conditions at the site of a proposed nuclear waste repository at a scale relevant for performance assessment.

The fundamental issue in soft sedimentary rocks is absence of distinctive flow paths such as fractures where water would move much faster than in the rock matrix. Therefore, tracers injected into such a groundwater flow system disperse to a much larger extent and travel much longer than in fractured hard rocks. Recovery of tracers in monitoring boreholes would be poor and breakthrough would be difficult to interpret at a large scale. Therefore, field tracer transport experiments are in our view not the appropriate means to characterise the heterogeneities of a sedimentary system.

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SESSION II

Rationale Behind Field Tracer Experiments

Chairmen: M. Heath (Earth Resources Centre, United Kingdom)
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Field Tracer Experiments in Clays

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1 Introduction

The objectives and rationale behind the design of field tracer tests depend strongly on the type of rock but also on the type of site and on the state of advancement of the waste disposal research programme. Here the objectives and rationale of field tracer tests for two different clays, types of site and different project stages are discussed. We discuss tests performed in the Boom Clay at Mol, Belgium and tests planned to be performed in the Opalinus Clay in north-west Switzerland within the framework of the international Mt. Terri Project.

The Boom Clay is a plastic Tertiary clay. The Mol site is a potential repository site and associated research on it was started at the end of the seventies. The tracer tests are performed in the HADES underground research facility of the Belgian Nuclear Research Centre (SCK·CEN) which has been in operation since 1984.

In the Mt. Terri Project, the Opalinus Clay, a well-consolidated Middle Jurassic shale (claystone) formation is being studied in a service tunnel of the Mt. Terri motorway tunnel that cuts through an anticlinal structure in the Jura mountains. The Opalinus Clay is currently under investigation by the Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra) as a potential host rock for high-level radioactive waste. A potential siting region has been selected in north-east Switzerland, where the Opalinus Clay is in a relatively undisturbed tectonic environment. First scoping studies on the Opalinus Clay were started at the end of the eighties and the international Mt. Terri Project started with the excavation of niches and a first drilling campaign in early 1996. The field tracer test will start in 1997 after a series of laboratory tests (feasibility study).

2 Main characteristics of the considered clays

2.1 The Boom Clay

The Boom Clay formation of north-east Belgium is a marine deposit of Rupelian (Middle Oligocene) age, i.e. 30 to 35 million years. The unit consists predominantly of intimately mixed clay and silt and minor sand. Bedding is mainly defined by rhythmic decimetre-scale variations in mean grain size (Van Echelpoel and Weedon 1990). The carbonate-rich levels contain widely spaced septarian limestone nodules (Vandenberghe and Laga 1986). Some beds also contain pyrite concretions and/or important fractions of organics. Although the Boom Clay is of marine origin, its porewater is dominated by sodium bicarbonate. At Mol, the burial depth of the Boom Clay layer is 180 m and its thickness is about 100 m. From a hydrological viewpoint the Boom Clay is an aquitard with very low hydraulic conductivity and from geomechanical viewpoint it is an overconsolidated plastic clay. The mineral composition and some important hydro-mechanical properties of the Boom Clay are given in Table 1.

2.2 The Opalinus Clay

The Opalinus Clay of Northern Switzerland is a marine shale (claystone) formation of Middle Jurassic age (Lower Dogger, mainly Aalenian, i.e. 180-190 million years). The formation - named after the ammonite *Leioceras opalinum* - consists of well-consolidated, dark grey, micaceous shales, partly with thin sandy lenses, limestone concretions or siderite nodules. Based on its clay, sand and carbonate content, the Opalinus Clay can be subdivided into several litho-stratigraphic units. The average mineral composition and some important hydro-mechanical properties are listed in Table 1. Hydraulic tests in deep boreholes and hydrogeological maps from a total of 6400 m of tunnel sections in the Opalinus Clay of the Jura mountains indicate that the formation has a very low hydraulic conductivity, although joints and faults were present in the sections studied (Gautschi 1996). Porewaters of the Opalinus Clay are of Na-Cl type with a total dissolved solids content of 20 g/l at the Mt. Terri site (Gautschi et al. 1993).

Tectonically, the Mt. Terri site is situated in the southern limb of the Mt.Terri anticline, dipping to the south with 30 to 50°. Here, the Opalinus Clay has a thickness of 150 m and an overburden of roughly 300 m. The overall tectonisation of this part is rather weak, but detailed mapping of the tunnel walls clearly revealed the presence of numerous minor faults, which can be divided into thrust and normal faults (Geotechnical Institute Ltd. 1995).

Table 1 Mineralogy and some important hydro-mechanical properties of the considered clays (NEA/SEDE 1995)

	Boom Clay	Opalinus Clay
mineralogy (weight %)		
clay minerals	60	40-80
illite	20-30	18-36
smectite	10-20	-
chlorite	5-20	6-12
kaolinite	20-30	10-20
mixed illite/smectite	5-10	6-12
mixed chlorite/smectite	5-10	-
quartz	20	18
feldspars	5-10	1
carbonates	1-5	5-20
pyrite	1-5	1
organic carbon	1-5	0.7
hydro-mechanical properties		
total porosity (%)	36-40	3-12
hydraulic conductivity (m/s)	$2\ 10^{-12}$	$< 10^{-11}$
Young's modulus (elasticity) (MPa)	200-400	2000-3000
plasticity index IP (%)	32-51	-

3 Rationale behind field tracer tests

3.1 Tracer tests in Boom Clay

Safety studies and sensitivity analyses (PAGIS, PACOMA, EVEREST) have shown that the Boom Clay layer is the most important barrier preventing radionuclide migration to the biosphere in the multi-barrier concept considered in Belgium for high level radioactive waste. Therefore the objectives of the migration studies performed at SCK·CEN are:

- to understand the basic phenomena governing the mobility of radionuclides;
- to determine their migration parameters;
- to develop the models needed in performance assessment studies to extrapolate the transport of radionuclides over geological time and spacial scales;
- to demonstrate the predictability of radionuclide migration in the Boom Clay and to assess the reliability of these predictions;
- to enhance public acceptance.

During many years of performing experiments, an understanding of basic transport mechanisms in Boom Clay has been developed. Therefore the field tracer tests performed in the HADES underground research facility at Mol concern the two last of the above objectives. The main aim of the field tracer tests is to demonstrate, that on the basis of parameters derived from small-scale (a few cm) laboratory diffusion experiments, we can predict the migration of a tracer injected into the Boom Clay in the HADES facility over a metric scale and a time scale of several years. Thus, the aim of the field tracer tests is not to determine parameters or to derive migration mechanisms, but to validate *in situ* our knowledge gained from laboratory migration experiments and *in situ* hydraulic tests.

Laboratory permeability measurements together with small and large scale *in situ* hydraulic tests have shown the very low hydraulic conductivity of the Boom Clay and the absence of water conducting fractures at the Mol site. Therefore, migration is mainly controlled by molecular diffusion and advection plays only a secondary role. The results of laboratory migration experiments and of sensitivity analyses show that hR (the product of the diffusion accessible porosity and the retardation factor) and the apparent diffusion constant D_a are the key parameters.

3.2 Tracer tests in Opalinus Clay

In contrast to the Boom Clay, which shows no fractures of importance and lithological variations of only minor importance with regard to radionuclide transport, the Opalinus Clay contains joints and faults and shows more important lithological variations. While for the case of radioactive waste disposal in the Boom Clay several performance assessment (PA) studies (PAGIS, PACOMA, EVEREST) have already been performed, for Opalinus Clay no formal complete PA study has yet been performed. This situation results in a different rationale behind the planned first field tracer test in Opalinus clay compared to the running and planned tests in the Boom Clay.

A conceptual model of groundwater flow and solute transport, mainly based on observations in open clay pits, was developed for preliminary safety assessment calculations (Nagra 1988). This model assumes advective-dispersive transport in joints and faults, accompanied by matrix diffusion into the adjacent undisturbed rock. However, hydraulic tests in shallow and deep boreholes indicate a drastic decrease in the hydraulic conductivity of the Opalinus Clay with depth, leading to the question whether joints and faults represent preferential pathways for solute migration also at repository depth (several 100 metres) or if they can be neglected (i.e. diffusion would be the only transport mechanism). Other open questions include the specific role of lithological inhomogeneities (silty, sandy or carbonaceous layers), microfractures and the damage zone around fractures in solute transport.

Given these fundamental open questions regarding Opalinus Clay, initial experiments must concentrate on the earlier objectives in the list given above. Therefore the understanding of groundwater flow and solute transport mechanisms in a highly consolidated fractured claystone formation and the evaluation of parameters for radionuclide transport models are the main objectives of the field tracer experiment planned to be carried out at Mt. Terri.

4 Design of field tracer tests in Boom Clay

The design of the field tracer tests in the Boom Clay is strongly determined by the scale of metres to be studied: tracer tests with retarded species (even moderately retarded) are impossible over this spatial scale as the test would take centuries or even many thousands of years. Therefore, the first field tracer test, the so-called CP1 test, was performed using tritiated water. The test should demonstrate that advection is only of minor importance in the movement of water through the Boom Clay. The experimental set-up consists of a multi-filter piezometer nest containing nine cylindrical filters with a centre-to-centre distance of 1 m (see Fig.1) . The test was installed horizontally through the concrete plug at the end of the gallery. There is a strong hydraulic gradient, and thus flow, towards the gallery caused by its excavation and the permeability of the concrete plug. The tritiated water was injected into the central filter; this should allow the small asymmetry in the diffusion cloud due to the advective flow to be seen. In the undisturbed clay formation the hydraulic gradient is more than a thousand times smaller.

Two field tracer tests of the same type have been installed for the injection of I-125 as I^-. Iodine was chosen as tracer because it is not chemically retarded; as a negative ion is subjected to the effect of anion exclusion (the clay particles are negatively charged) and it thus has a lower diffusion accessible porosity than water. Moreover, performance assessment studies have shown that I-129 is one of the most critical radionuclides. Two piezometers TD41H and TD41V of a similar type to the CP1 piezometer were installed (see Fig. 2) . The laboratory experiments have shown that both the apparent diffusion and the hydraulic conductivity show an anisotropy. This anisotropy is related to the orientation of the clay particles with the bedding plane. In the horizontal plane, i.e. parallel to the bedding, both the hydraulic conductivity and apparent diffusion constant are a factor of two higher than in the vertical direction. Therefore, one piezometer was installed horizontally and one vertically. The vertical piezometer was also used to study another clay horizon. The filters neighbouring the injection filter were placed at a distance of 35 cm because I-125 has a half-life of about 60 days and thus its migration can only be followed for about three years.

A new field tracer test was started at the end of 1995. It is a large-scale 3-dimensional injection experiment with tritiated water and carbon-14-labelled bicarbonate injected as a cocktail. This experiment is called the TRIBICARB-3D test. The test set-up consists of three parallel horizontal piezometers: the injection piezometer, a detection piezometer on the right and one below the injection piezometer (see Fig. 3).The distance between the piezometers at the level of the injection filter is 0.9 and 1.5 metres respectively. The spacing between the fiters on each piezometer is one metre. The reasons for this design are: to follow the contaminant cloud on a scale of metres in the three dimensions and to show that there is no preferential migration pathway along the injection piezometer. Due to the anisotropy in the apparent diffusion constant and the hydraulic conductivity, a contaminant cloud with an ellipsoid shape is expected. The aim of tritiated water injection is the same as for the CP1 experiment. C-14-labelled bicarbonate is injected because performance assessment studies have shown that the potential dose due to C-14 is very sensitive to its retardation factor. The release time for bicarbonate is a few tens of thousands of years. As the half-life of C-14 is only 5730 years, a very small retardation, e.g. a factor of three, is sufficient to cause a large decrease in C-14 release due to radioactive decay.

Further tracer tests are also foreseen in the TD41 piezometers. Within the framework of the EC-NIRAS/ONDRAF project TRANCOM-CLAY it is planned to inject C-14 labelled organic molecules previously extracted from the Boom Clay. The aim of this tracer injection is to follow *in situ* the migration of naturally present organic molecules which potentially play a role in radionuclide transport. This test will also be supported by laboratory experiments.

5 Preliminary design of field tracer tests in Opalinus Clay

To answer the open questions raised in section 3.2 the following concept for a simple the tracer test has been developed (cf. Fig. 4): a cocktail of appropriate tracers will be injected into a packed-off small-diameter borehole over a long period (2 years or more). The resulting tracer distribution will be mapped or visualised in large-diameter overcored drillcores or in cores from parallel boreholes. The *in situ* experiment will be started after a tracer evaluation study including laboratory experiments with Opalinus Clay samples. Laboratory experiments are being performed by the Centre d'Energie Nucléaire in Grenoble, by the University of Bern and by the British Geological Survey. Possible tracer candidates under discussion are non-sorbing tracers (I^-, Br^-, EDTA, fluorescent agents), weakly sorbing tracers (Li^+, Mg^{++}, Sr^{++}), stable isotopes, an oxidising tracer ($KMnO_4$) and KCl brine (for resistivity imaging). There is no permit for the application of radioactive tracers at this test site. It is hoped that this tracer experiment will provide data to enable identification of the dominant physical processes (advection-dispersion, diffusion and related conceptual models) as well as information on a range of input parameters used for transport models.

6 Main results and application of tracer tests performed in the Boom Clay

For the CP1, TD41H and TD41V tests in the HADES facility, the progress of the tracer cloud was calculated prior to the start of the test based on the laboratory data. The concentrations in the filters of the CP1 test were predicted for a hundred years and for TD41V and TD41H for three years. The TD41 tests are finished while CP1has now been in progress for more than eight years. The predictions and the experimental results are shown on Fig. 5. The results of the CP1 test correspond well with the predicted values. The results for the TD41 tests also correspond rather well with the predictions. There is however a small shift between the prediction and experimental results for the injection filters. This shift is due to difficulties in the sampling of those filters.

The field tracer tests performed up till now in the HADES facility in the Boom Clay have been very successful and fulfilled the predetermined objectives. With these tracer tests we have been able to demonstrate that diffusion is the dominant transport mechanism, which is the cornerstone of our performance assessment; we have also been able to show *in situ*, on a scale of metres, the validity of our laboratory data for tritiated water and iodine.

The conceptual model and data used for the prediction of the tracer tests have been used in performance assessment studies e.g. EVEREST (Marivoet et al. 1996). Once the results from the C-14 tests are available they will also be incorporated into ongoing PA studies. The CP1 experiment has been used by five research groups as one of the test cases in the INTRAVAL phase 2 benchmark exercise (NEA, SKI 1996). The good results of the field tracer tests have certainly strenghtened the confidence of both our experimental and PA teams in the migration model and have a positive influence on the acceptability of clay as option for high level waste disposal within the scientific community. The influence of these experiments on public acceptance is however, difficult to assess at this stage.

7 Conclusions

Field tracer tests in clays can provide valuable data at different stages in a geological waste disposal research project:

- in the initial stage when geological media such as clay are being characterised, field tracer tests can help to build an understanding of the dominant transport mechanisms operating on different scales;
- in a later stage when formal performance assessment studies are carried out, field tracer tests can help to build confidence in the applied migration models and data;
- in particular, field tracer tests can increase confidence that predictions based on performance assessment models and data measured in the laboratory can be justifiably used in analyses of long-term performance;
- it must, of course, be recognised that temporal and spatial extrapolations will always be needed since migration tests must be scaled down to produce measurable results;
- nevertheless, when a project is being defended before the scientific community and general public, successful field tracer tests can increase the project's acceptability.

To perform field tracer tests that fulfil the above objectives, a well intergrated combination of laboratory experiments, site characterisation and model development is a necessity. The tests performed in the HADES facility at Mol show that this is possible and the tests in the Mt Terri Project are planned to cover the first step of this methodology, tackling some basis understanding of flow and transport mechanisms using laboratory experiments and a single-hole field tracer test.

Field tracer tests in clays where diffusion is the dominant transport process have the important limitation mentioned above: it is impossible to follow the migration of moderately or strongly retarded species over a scale of metres in a reasonable time period. For such species the only alternatives are the study of natural analogues or the study of the distribution of e.g. rare earth elements at the site itself to derive their migration behaviour.

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Fig 1 , Volck

Fig. 2 Volck.

Fig. 3 Volck.

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The Grimsel Field Tracer Migration Experiment – What Have We Achieved After a Decade of Intensive Work?

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Executive Summary

Introduction

The Nagra/PNC field tracer migration experiment, carried out in association with PSI (Switzerland) and GSF (Germany), began in 1985 with hydrogeological characterisation of a water conducting shear zone in the granodiorite of Nagra`s Grimsel Test Site (GTS, in the central Swiss Alps) and finished in the spring of 1996. The intervening decade has seen a large series of field tracer migration experiments carried out at the site, increasing in complexity from simple, non-sorbing tracers (uranine, ^{82}Br, ^{123}I, ^{3}He and tritium) through various weakly sorbing tracers (^{22}Na, ^{24}Na, ^{85}Sr and ^{86}Rb) to a final, long-term experiment with strongly sorbing ^{137}Cs. Over the last ten years, the experimental methodology has matured as has our understanding of both the site and the processes influencing *in situ* radionuclide retardation in fractured crystalline rocks. However, this knowledge has been won only following significant investement of both effort and funds so it is appropriate to now review the returns on the investment in terms of a repository performance assessment (PA).

1. General context of the Grimsel Migration Experiment (MI)

The general context in which the experiment should now be judged was the desire to improve confidence in the use of predictive models in a repository PA. Few people, even those involved in the disposal of radioactive waste, fully appreciate the difference between blind testing of model *predictions* and testing if a model can *simulate* particular observations - as can be clearly seen in the literature. This is a crucial point, as pointed out by Pate et al, (1994) "This aspect of blind (ie *predictive*) testing is particularly important as, in many cases, the manner in which the simulation is carried out can be very objective and, if the "answer" is known, can be biased either consciously or subconsciously". In a repository PA, simulation of data brings little or no confidence that the models involved can later predict repository evolution: confidence can be much better built by carrying out a series of predictive modelling exercises followed by experimental runs and a final assessment of the accuracy of the predictions. This coming together of transport modellers, field and laboratory experimenters and (to a lesser extent) performance assessors has been the hallmark of the MI experiment.

2. Specific Objectives

These included testing the applicability of current PA transport codes to quantify radionuclide migration in a real flow system (and, later, the development of a new transport code); the identification of the relevant transport processes for consideration in transport models and assessing how successfully laboratory sorption data may be extrapolated to *in situ* conditions. A final (normally unstated) objective was the indoctrination of staff into the mind-set required for them to make predictions of radionuclide behaviour *in situ* (whether the predictions related to hydrology, transport calculations, geochemistry or flow path geometry) when required.

3. Relation to the overall R+D programme

The MI experiment has been the single biggest experiment to date in the Nagra R+D programme and had a web of connections to other areas of the Swiss and Japanese programmes. As already noted above, there was direct input into Nagra`s laboratory sorption programme where an assessment was made of the relevance of laboratory produced sorption data to *in situ* retardation of radionuclides. In addition, there was much cross-fertilisation between the MI experiment and site characterisation/PA in the field of flow path description.

In the PR field, initial use of the MI experiment was limited but this changed with the production of a Nagra Bulletin on the GTS which included an extensive article on the MI experiment (Frick et al, 1988). Some 35,000 people have now visited the GTS and the MI experiment is a routine stop on the tour of the laboratory. Currently, Nagra is producing a video on the GTS which will include footage on the MI experiment and its successor the Radionuclide Retardation Project (or RRP). Finally, the Federation of Electric Power Companies of Japan recently shot footage for inclusion in a PR video about underground rock laboratories worldwide. Arguably, more remains to be done.

4. Uses and extrapolation of the so obtained information

The most important use of the MI experiment has been the development of testing methodologies and the application of those methods to confidence building within PA. Indeed, the recent Kristallin-1 safety assessment (Nagra, 1994) carried out by Nagra specifically mentions the contribution of the MI experiment to model testing in general. Further, it was noted that "...the results provide confidence in the dual-porosity concept as an appropriate foundation for a model of transport in fractured porous media". In addition, it was noted that "...the model provides a satisfactory interpretation of the measured data and no evidence has been found which would indicate that processes relevant to safety assessment and not accounted for in the model are operating ."

Some effort has gone into extrapolating data on retardation mechanisms from MI to repository relevant host rocks, but this has been limited in some instances. For example, it was noted in Kristallin-1 that, "The key mechanism of matrix diffusion has, in many experiments, been identified as important and its existance and effectiveness are much better founded than 10 years ago.". Despite this, the diffusion constants for the rock matrix used in Kristallin-1 were "...selected on the basis of a survey of (*laboratory*) experimentally determined diffusion constants for crystalline rocks." (authors' italics). Further, no reference is made to evidence from the MI experiment when depths of accessible wall rock are considered other than in the case of one parameter variation where data from MI supporting experiments are used to define a minimum depth of diffusion.

While the work on investigating the connection between laboratory measured sorption data and field retardation has shown that, with enough background information on the flow field, it is possible to show reasonable agreement within the MI experiment between field and laboratory data, this has been taken no further as yet and has most certainly not been utilised in recent Nagra or PNC assessments.

5. Greatest sucesses and failures

Apart from the comments noted above, the greatest success has been the rigorous testing of the PSI developed PA transport code RANCHMD (Hadermann and Roesel, 1985). Of particular note have been the attempts to minimise the number of free parameters in the code by including as many hard data on the shear zone structure, flow paths, tracer sorption values etc as possible (see Heer and Hadermann, 1994, for details). In this way, it has been possible to identify the *in situ* retardation mechanisms in a more thorough manner than has previously been the case.

The greatest failure has been in the rigorous testing of the PA transport code RANCHMD. The problem here is not the code, rather the limitations imposed on the code by the experiment. PA transport codes such as RANCHMD are specifically developed to calculate the long-term, slow movement of radionuclides in the groundwaters of a repository site. Unfortunately, outwith experiments such as the RRP (see Alexander et al., 1996a,b), field tracer migration experiments cannot provide analogous conditions against which to test such transport codes. In the case of MI, for example, most experiments lasted days to weeks and even the longest experiment conducted, the last ^{137}Cs migration, no more than 20 months or so. This means that testing matrix diffusion within a code such as RANCHMD is relegated to observations based on highly porous matrix (or fracture fill) which may not be of much relevance to a given repository host rock. Also, kinetic effects may play an important role in the experiment but, obviously, are of no relevance to a repository PA.

6. Assessing the results in the light of the original rationale

As noted in section 1 above, the original rationale was to improve confidence in predictive modelling as applied to a repository PA. To this end, the MI experiment has been a great success for Nagra, PNC and the various contractors involved in MI (and, perhaps to a lesser extent, PA) in that it has built a culture of rigorous model testing and, perhaps more importantly, predictive modelling. Of course, precise measurement of such a change in attitude within a disposal programme is difficult but success can always be judged on the quality of the literature on model testing from before and after an experiment such as MI.

7. Potential changes and improvements in design

To look at something in hindsight is always an easy way to build an experimental programme and in MI several things would almost certainly be changed (for example, more complete hydrological characterisation of the experimental site, an earlier structural and petrological description of the flow path). However, a more realistic question might be “knowing now as little as you knew ten years ago, at the beginning of MI, would you do it differently?”. In this case, it is likely that we would change much less: the entire experiment has been a learning experience for most of the people involved and has certainly contributed to our views on blind predictive testing and the development and testing of conceptual models of groundwater flow. One weakness, which has perhaps only now been acknowledged, is that, while the field experimenters, laboratory experimenters and transport modellers were in it together from the very beginning, the performance assessors were remarkable only by their absence. This would probably be the single greatest improvement possible to ensure the production of PA relevant data from any field tracer experiment - and the eventual inclusion of such data in a repository PA.

Acknowledgements

Thanks to our numerous colleagues in the MI and RRP projects who have contributed to the success of the work over the last decade. Thanks also to Nagra and PNC for funding the projects.

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Tracer Tests for Site Characterisation?

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1. INTRODUCTION

Following a country-wide screening and regional assessment a geologic site characterisation programme for final repository of spent nuclear fuel was launched in 1987 at five sites in various part of Finland. The preliminary programme phase was completed and reported in 1992 with the conclusion that a safe repository could be built at any of the five sites studied and there were no significant differences between the sites with bearing on long-term safety but with respect to the efficiency of future more detailed characterisation three of the sites could be preferred to the others. On this basis, since 1993 the studies have been confined to three areas: Olkiluoto in Eurajoki municipality, Kivetty in Äänekoski and Romuvaara in Kuhmo.

The programme for more detailed characterisation includes extensive hydrogeochemical and hydrogeological investigations at the sites. A site-scale structural modelling combined with borehole measurement programme with local water conductivity measurements and pumping and interference tests were used as a basis for the large-scale flow simulations performed as a part of the preliminary site characterisation phase. In the detailed investigation phase a considerable amount of new data has been collected from new boreholes; in addition new measurement methods have been introduced. For instance, the new Posiva Flow Meter has now been used to measure flow rates and, flow directions and water conductivities of the conductive parts of the deep boreholes with 2-m packer intervals. Interference tests have been continued. In parallel with the measurement programme, new updated structural models are being finalised for all the three sites under study.

So far no tracer tests have been performed at these sites. However, the identified connections between two boreholes, some 130 metres apart from each other, would offer a promising site for testing equipment and methods for field scale tracer experiments. At the same time it gives a practical context of judging the rationale and assessing the benefit of tracer tests for site characterisation purposes.

Before considering the rationale for tracer tests it is reasonable to ask what the rationale for site characterisation is, in particular, is site characterisation itself a goal or an instrument? A safety-oriented, instrumental view might consider it as an input for the performance assessment, and in this opinion, the rationale of the tracer tests should be looked at against the needs for performance analysis. On the other hand, it is fairly obvious that a good site description can be considered as a goal itself, since without a consistent overall picture of the site the credibility of any detailed information may be hard to judge. In this paper, therefore, the focus is how tracer tests can facilitate site description and understanding. Nevertheless, the "goodness" of site description, of course, refers to instrumental value, which should also be borne in mind.

Another thing is how to judge the benefits of tracer tests. We might ask whether tracer tests are *useful* for site characterisation – in which case the question is about optimisation and of managerial nature – but we may also ask whether tracer tests are necessary for obtaining some specific piece of information. The latter question is not only managerial but also a scientific one.

2. EXISTING EXPERIENCE

Till today fairly limited experience exists on using tracer tests for site characterisation for waste repositories. Most of the tracer tests performed during the 1980's and the early 1990's are rather limited in spatial extension and the focus has been on transport processes rather than the transport media characterisation.

One of the earlier tracer tests with possible relevance for site characterisation was made in Savannah River 25 years ago with a scale as long as 540 metres [1]. The test appears to have contributed to conceptualisation of the fracture zone studied as a sufficiently homogenous feature for flow modelling. The tracer tests also indicated some problems in earlier hydraulic measurements.

Finnsjön was not intended for a repository site but it was subject to an extensive fracture zone characterisation including tracer tests in the 1980's. Hydraulic testing and indications played obviously a significant role in revealing the perhaps most interesting feature, the horizontal fracture zone 2. Tracer tests were then used for subsequent characterisation of this feature and produced a lot of information on such things as anisotropy, heterogeneity and connectivity of the feature. The tests were also used as cases for extensive modelling effort in the International Intraval Project during several years and in this context they were also used for derivation of different transport parameters.

The Äspö LPT-2 large-scale pumping and tracer test was a major hydraulic and tracer experiment. It generated a lot of information that was subsequently used for testing different structural model assumptions. It confirmed some connections between fracture zones and indicated needs for modifications in the structural model. Nevertheless, the utility of the tracer test performed was limited. Most of the tracers never appeared in the pumping hole during the observation period and what arrived could be interpreted in a thousand of ways.

At the WIPP site in New Mexico a considerable experience exists. The rationale and results of the latest test have been reported in two papers of this Workshop [2], [3]. The conclusion is that the tracer tests have truly contributed to the evolution of the site conceptualisation and the tests can be described at least as useful.

In Finland tracer tests were in the programme of site investigations both at Olkiluoto and at Loviisa, where the two low-and intermediate-level radioactive waste repositories now are situated. The information produced by these tests was of minor value, but helped to understand the nature of the hydraulically interesting features of the sites.

3. USEFUL INFORMATION AND EXPERIENCE WAS OBTAINED BUT...

Most of the field tracer tests have probably produced some results of interest, although sometimes the most significant product may have been the knowledge of how not to do tracer tests. In most cases they have brought out some features of relevance for site understanding. The more difficult question is whether they were crucial for that understanding, and whether the same information could have been obtained with some other methods, possibly by some cheaper or more conclusive methods.

It is obvious that the information obtained with tracer tests in the Finnish site investigations for low- and intermediate waste repository could also have been obtained by hydraulic testing. The tracer test in Olkiluoto revealed the importance of pegmatite veins as potential transport pathways for further studies, but they were in no way essential for understanding the local flow situation.

At Finnsjön the tracer tests did give structural information about zone 2 that was not readily available from the earlier hydraulic testing but the Finnsjön studies also point out a problem that may be inherent in all attempts to use tracer tests for site characterisation: if the test results cannot distinguish between different conceptual process descriptions, can they distinguish between different rock descriptions?

At the WIPP site the tracer tests have been essential for the development of site understanding. The tests were preceded by considerable planning and iteration and they were specially designed to test hypotheses and answer questions. It seems that the strategy has proved fruitful.

In general, tracer tests with conservative tracers can give unique information on flow porosity and tests with slightly sorbing tracers can, additionally, yield information on rock-water-tracer interactions which can hardly be obtained with any other means. However, to fulfil this promise a number of practical difficulties has to be overcome. For example, the information obtained about flow porosity – and flow pathways – is of little value as long as most of the tracers disappear for good. The tests planned to reveal information on interactions can be reliable only if the flow conditions are sufficiently well-known.

A slightly different perspective is to ask what else one could have done: what kind of methods for hydraulic measurement and geophysical studies are available and how much one can deduce from the measured data by different models of interpretation. In the case of alternatives for pumping tracer tests, what is the promise of natural tracer studies? How much can we learn about transport conditions by looking at the geochemistry and mineralogy of the sites?

The apparent difference between natural tracer studies and field tracer tests is that the process that led to the observed distribution of the natural tracer was caused by nature alone and did not result from massive pumping. This is a possible benefit for studies of natural tracer distributions as they are likely to reflect tracer transport in conditions and time scales much more relevant to the safety of waste repositories than the conditions in the pumping tests. Of course, one can argue for the artificial tracer tests that it is the *possible* future flow pathways that we are interested in, but in building a consistent picture of the site the past conditions are the only thing hat we can learn about.

A related potential benefit of natural tracer studies is that these may give us information about the transport in the kind of rock that we would rather wish to have around our repository and not about the high-transmissivity fractures or fracture zones that one usually has to focus on in the pumping tracer tests. Similarly, the scale over which information is obtained is often much larger than in the pumping tracer tests. In Finland work is being done on both the hydrogeological modelling and geochemical evolution modelling at the investigation sites since the late 1980's and gradually some intercomparisons between the interpretations are becoming possible. Often the outcome seems to be on the falsification side: on the basis of the geochemistry certain hydraulic connections can be excluded. For example, in Romuvaara, the chemistry clearly showed that the rock above a certain fracture zone (R9) forms a flow domain separate from the zone and the underlying rock [4]. At

Olkiluoto the distribution and origin of saline and glacial waters offers many challenges to the hydrogeologists and flow modelers. The measurements indicate high salinities starting from the depth of about 500 metres, but, on the other hand, samples from the same depths show traces of glacial melting waters! It is evident that before we are able to use natural tracers effectively in our evaluation we have to understand the processes that led to the present conditions.

4. YES: DO IT BUT THINK IT OVER!

Tracer tests can certainly give useful and sometimes unique information for conceptual modelling and interpretation of some individual actual site features. The tests planned by Posiva in Romuvaara are intended both to help in confirming conceptual assumptions and to scope the utility of tracer tests for possible future characterisation efforts. The idea is to make it an iterative learning exercise where modelling, experimentation and equipment development are tied together in a stepwise working procedure and where before proceeding from any step, an assessment of the progress and potential benefits from continuation can be assessed.

Nevertheless, one may ask us whether or how much the planned tests between two boreholes in Romuvaara contribute to the characterisation of the whole 10 km^2 investigation site. The answer is probably yes and no. Neither the planned tests between two boreholes or any other similar tests could unravel all secrets of the Romuvaara bedrock. It is unrealistic to expect that, by tracer tests or, in fact by any characterisation methods in hand, we could get a complete picture of the transport properties of a given site. The recent developments on Kivetty, another site candidate, give an example on this.

Based on several years of investigations and information from 10 deep boreholes a fairly consistent picture of the major structural features on Kivetty had already evolved by 1995. Then one of the existing boreholes, KR5, was deepened from 500 metres down to 1000 metres and suddenly something like about 100 metres of altered, densely fractured, well-conductive rock was hit. It was evident that, at least at that borehole, it was a major rock feature and, at least locally, it would be important for flow conditions as well. Later a new deep borehole was drilled in the vicinity of KR5 to learn about the spatial extension of the feature, but, to a surprise, no trace of the feature was found in the new hole. Besides, there is another hole near KR5, where no such anomalous rock conditions had been discovered earlier.

Independent of how the new feature finally looks like, it is clear that it can be important for the local transport conditions and it is clear that by any finite surface investigation effort the odds are high that such feature remains undetected. In that sense the tests like those planned for Romuvaara can never yield the whole picture of the volume of heterogeneous rock that is usually studied in site characterisation projects.

On the other hand, we may try to learn as much as possible about the rock that will become the near-field for performance analysis. Direct measurement by tracer tests of the transport parameters for the whole near-field may still be impossible, but these methods can help in abstraction. Once we go underground we should have effective means to decide where we go with our tunnels and where we drill our deposition holes. Flow and transport conditions are one criterion for the discrimination between good and bad rock. Tracer tests can give us valuable information for the basis of such judgements. In this way the tests in Romuvaara may truly help us in the characterisation of the site. We may have to live with the possibility of leaking far-field, but we should try to ensure as good as possible a near-field.

In the past too great expectations may have been attached to tracer tests and their power of proof. The idea of tracer transport simulation may tempt us to believe that we might prove the site performance by direct measurement. That will never be possible for real-life repositories. Tracer tests are one possible means in site characterisation but their application should be judged by their costs and benefits in relation to alternative methods and approaches.

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SESSION III

Test Cases: Design, Modelling and Interpretation

Chairmen: J. Vira (Posiva, Finland) and P. Lalieux (NEA)

Field Tracer Transport Experiments at the Site of Canada's Underground Research Laboratory

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Abstract

To gain a better understanding of the processes affecting solute transport in fractured crystalline rock, groundwater tracer experiments are being performed within natural fracture domains and excavation damage zones at various scales at the site of AECL's Underground Research Laboratory (URL). The main objective of these experiments is to develop and demonstrate methods for characterizing the solute transport properties within fractured crystalline rock. Estimates of these properties are in turn being used in AECL's conceptual and numerical models of groundwater flow and solute transport through the geosphere surrounding a nuclear fuel waste disposal vault in plutonic rock of the Canadian Shield.

The different fracture domains at the URL include: fracture zones (faults), defined as volumes of intensely fractured rock; moderately fractured rock, defined as volumes of rock containing a small number of sets of relatively widely spaced, interconnected discrete fractures (joints); and sparsely fractured rock, defined as volumes of rock containing microcracks and very sparsely distributed discrete fractures that are not very interconnected. In addition to natural fracturing, the construction of an underground disposal facility in crystalline rock creates a region of altered stress in the near-field, immediately adjacent to excavated openings. Micro-cracks and small fractures develop in this region and could form additional new pathways for groundwater flow or contaminant transport. The portion of the rock damaged by stress changes due to excavation, or by the excavation method, is referred to as the excavation damage zone. Studies conducted during the construction of the URL facility have shown the extent of these excavation damage zones.

A number of groundwater tracer experiments are currently being performed in the natural fracture domains and excavation damage zones at the URL. These experiments have been used and are being conducted to refine the transport models used in the postclosure environmental and safety assessment of AECL's nuclear fuel waste disposal system and to improve methodologies for future site characterization measurements and experiments. The current status of AECL's groundwater tracer testing program at the URL is described below.

- A series of two-well tracer tests has been conducted within several major low-dipping fracture zones at scales ranging from 17 to 440 m to determine the physical solute transport properties of volumes of intensely fractured rock and to develop methods for extrapolating the test results to larger scales. Based on the successful completion of several smaller-scale tracer tests, this experiment has evolved to larger-scale tests to help establish whether the solute transport properties within zones of intensely fractured rock are scale- or direction-dependent. Currently, a tracer test at a scale of 700 m is in preparation. Equivalent-porous-media models have been used

to describe fluid flow and solute advection and dispersion within the fracture zones. Estimates of transport porosity and dispersivity from these models have been used to assign parameter values to the fracture zones in geosphere models for postclosure assessments of AECL's disposal concept.

- In a region of moderately fractured rock containing interconnected networks of discrete fractures, a series of tracer tests is being designed to evaluate the physical and chemical solute transport properties of a relatively large volume (1 x 10^5 m^3) of such rock. As well, because of the suitability of the porous-media-equivalent method for modelling solute transport in volumes of intensely fractured rock, this modelling approach will also be tested for regions of moderately fractured rock during this experiment. Other modelling approaches such as discrete fracture network models, will also be evaluated. The geological, geophysical, geochemical and hydraulic characterization of this region is currently underway.

- A tracer experiment has recently been conducted within a region of the excavation damage zone in the floor of a 3.5 m diameter test tunnel located on the 420 Level of the URL facility to obtain information on the physical solute transport properties within excavation damage zones surrounding underground tunnels. Both mass flux and analytical modelling calculations were performed to determine the permeability, transport porosity and dispersivity characteristics of the excavation damage zone. This initial experiment was performed to support the development of vault and geosphere models for a postclosure assessment of the in-room emplacement of copper containers of used CANDU fuel in a hypothetical permeable geosphere. This assessment complemented an earlier postclosure assessment of borehole emplacement of titanium containers in a region of very low permeability rock. Further tests of this type are planned to be incorporated into the excavation stage of the moderately fractured rock experiment.

- A migration experiment has been designed, in cooperation with the Japan Atomic Energy Research Institute (JAERI), to study the transport of conservative and sorbing radionuclides in natural fractures in excavated blocks of granite (approximately 1 m^3 in size) under in-situ geochemical groundwater conditions. This experiment is being conducted in an IAEA Class B laboratory specifically constructed for this purpose at the 240 Level of the URL using rock blocks containing natural fractures excavated from a nearby vertical fracture.

INTRODUCTION

AECL is conducting hydrogeological research at its Underground Research Laboratory (URL) in southeastern Manitoba, Canada, as part of its evaluation of the concept for disposal of nuclear fuel waste deep in plutonic rock masses of the Canadian Shield. The feasibility of this concept and assessments of its impact on the environment and human health are documented in an Environmental Impact Statement that was submitted for public, regulatory and scientific review [1],[2].

The primary objective of AECL's hydrogeological research is to develop and demonstrate methods for determining the chemical and physical characteristics of groundwater flow systems in plutonic rock bodies of the Canadian Shield at the various size scales relevant to the prediction of potential radionuclide migration through the geosphere surrounding a disposal vault constructed at a depth of 500 to 1 000 m. Investigations conducted as part of this research indicate that the degree of fracturing in crystalline rock of the Canadian Shield is one of the primary distinguishing features between volumes of rock that have significantly different groundwater flow and solute transport characteristics [3]. The different fracture domains identified in crystalline rock of the Shield are:

- fracture zones (faults), which are volumes of intensely fractured rock;
- moderately fractured rock, which are volumes of rock containing a small number of sets of relatively widely spaced, interconnected discrete fractures (joints); and,
- sparsely fractured rock, which are volumes of rock containing microcracks and very sparsely distributed discrete fractures that are not very interconnected.

All three of these fracture domains exist within the upper 500 m of rock mass at the site of AECL's URL (Figure 1).

In addition to natural fracturing, the construction of an underground disposal vault will create a region of altered stress in the near-field, immediately adjacent to the excavated openings where micro-cracks and small fractures will develop. The portion of the rock damaged by stress changes due to excavation, or by the excavation method, is referred to as the excavation damage zone (EDZ). Studies conducted during the construction of the URL have shown the extent of these EDZ's [4]. It is expected that the EDZ will have properties that are considerably different from those of the undisturbed rock mass, such that the EDZ might provide additional new pathways for groundwater flow or contaminant transport from the vault.

This report provides a brief summary of the groundwater tracer experiments that have been, or are being, performed in the natural fracture domains and excavation damage zones at the URL. These experiments have been conducted to refine the transport models used in the postclosure environmental and safety assessment of AECL's nuclear fuel waste disposal system and to improve methodologies for future measurements and experiments.

THE UNDERGROUND RESEARCH LABORATORY

The URL constitutes a well-characterized *in situ* environment in a previously undisturbed volume of rock for experiments to address various geotechnical and engineering issues of importance to AECL's disposal concept and to demonstrate design and engineering elements of the proposed disposal concept. Prior to any excavation at the URL site, a detailed site evaluation program was carried out to characterize the geological, hydrogeological and geochemical conditions of the 3.8 km^2 area of the site to a depth of approximately 500 m. The information from this program was used to select the location for the URL shaft and the underground facility so as to provide access to different fractured rock domains and lithologies in the granitic Lac du Bonnet batholith. The underground workings of the URL comprise a vertical access shaft to a depth of 443 m and major testing levels at depths of 240 and 420 m (each comprising several hundred meters of tunnels) as well as a ventilation shaft connecting the testing levels to the surface (Figure 2).

TEST CASES: DESIGN, MODELLING AND INTERPRETATION

FRACTURE ZONES

An initial series of seven two-well tracer tests (phase 1) has been conducted within a major low-dipping fracture zone (Fracture Zone 2–Figure 1) in the rock mass at the URL site at scales ranging from 17 to 209 m to determine the physical solute transport properties of volumes of intensely fractured rock [5]. The two-well tracer tests have been performed as steady state, recirculating tests: conservative groundwater tracers were injected as a pulse source into a continuous withdrawal/injection flow field, and tracer concentrations of the recirculated water were monitored throughout the duration of each test (Figure 3). To help evaluate the results of this first phase of testing, a series of six additional, smaller-scale tests (phase 2) were planned and conducted within a high permeability region of Fracture Zone 2 to investigate different groundwater tracer testing techniques [6]. These tests were designed to: compare two-well recirculating, non-recirculating and convergent tracer test techniques; examine the effect of direction on the tests; examine the effects of different flow rates or pressure gradients; and to compare the transport behavior of different tracers including different anionic tracers, colloid tracers and redox-controlled chemical tracers. Based on the successful completion of phases 1 and 2, this experiment evolved to larger-scale tests (phase 3) to help establish whether the solute transport properties within zones of intensely fractured rock are scale- or direction-dependent and to develop methods for extrapolating the test results to larger scales by combining two-well tracer tests with crosshole hydraulic response tests. As part of the phase 3 testing, a two-well tracer test has been conducted at a scale of 440 m within Fracture Zone 1.5 and a two-well tracer test at a scale of 700 m within Fracture Zone 1 is in preparation (Figure 1).

The suitability of the porous-media-equivalent method in describing fluid flow and solute transport within fracture zones has also been evaluated during this study. Because of the apparent inhomogeneity of the flow and transport properties of the fracture zones, and the recirculating mode of the two-well tests, the finite-element computer code MOTIF (Model of Transport in Fractured/ Porous Media) developed by AECL [7], has been used to solve the fluid flow and solute transport equations. MOTIF allows the fracture zones to be represented using quadrilateral elements of differing thickness, permeability, porosity and orientation in 3-D space. This modelling approach has been used successfully to simulate flow and radiotracer transport in a similar fracture zone at the nearby Whiteshell Laboratories site [8].

Well-defined tracer breakthroughs curves were obtained for all of the two-well tracer tests that have been performed so far at scales ranging from 17 to 440 m. At a transport scale of less than about 20 m, double, sharp, tracer peaks were observed in the breakthrough curves. The second peaks may be due to tracer recirculation or flow channelling or some combination of both. At a transport scale greater than about 30 m, single, well-dispersed tracer concentration peaks were observed. These results suggest that, at the larger transport scales, there is an averaging of the solute transport properties within these fracture zones.

Modelling of the individual tracer tests indicates that the porous-media-equivalent method is suitable for modelling fluid flow and solute transport in these types of fracture zones. Adequate fluid flow models have been developed for the regions of the fracture zones tested so far. However, both small- and large-scale permeability variations within the fracture zones must be accounted for in the analysis. Development of a suitable transport model capable of simultaneously describing all the tracer tests conducted within the same fracture zone has been more difficult. Simulations of tracer transport using models with uniform transport properties do not describe the test results very well. However, initial simulations with a model having varying “effective thickness” (product of transport porosity and fracture zone thickness) indicate that this type of model may reasonably describe all of the test results. Further work is required in order to develop a model that can simulate all the tracer tests conducted during these different phases of tracer testing.

EXCAVATION DAMAGE ZONE

A tracer experiment has recently been conducted within a region of the excavation damage zone (EDZ) in the floor of a 3.5 m diameter test tunnel to obtain information on the physical solute transport properties within EDZ's surrounding underground tunnels [9]. The tunnel was constructed as part of AECL's Mine-by Experiment to investigate the formation and geomechanical characteristics of the EDZ adjacent to an underground opening. A key goal in the design of the Mine-by Experiment was to conduct the investigation in a geological/geotechnical environment similar to that which might be expected between a depth of 500 and 1000 m in the Canadian Shield. To achieve this, the tunnel was located on the 420 Level of the URL (Figure 2) where the stress conditions are similar to those at a depth of about 1000 m in other parts of the Shield [10].

Following completion of the test tunnel, which was constructed using a mechanical excavation technique to avoid the damage effects of blasting, the connected permeability test phase of the Mine-by Experiment was performed to characterize the groundwater flow properties of the EDZ located in the floor of the tunnel [4]. The results from this phase of testing indicated that the main flow pathway within the EDZ in the floor of the tunnel is within a process zone of intense fracturing (Figure 4); virtually no flow occurred outside the region of the process zone. From the point of view of solute transport, the region of the process zone is a potential pathway for contaminant migration within the tunnel.

The EDZ tracer experiment was performed as a constant head test by continuously injecting a constant concentration of conservative tracer into a region of the process zone, and monitoring tracer breakthrough from the zone at a distance 1.5 m away. The results obtained during the test show good tracer breakthrough. An equivalent-porous-media approach was used in analyzing fluid flow and solute transport within the process zone. Both mass flux and analytical modelling calculations were performed to determine the permeability, transport porosity and dispersivity characteristics of the zone. The results from this initial experiment have been used to support the development of vault and geosphere models for a postclosure assessment of the in-room emplacement of copper containers of used CANDU fuel in a hypothetical permeable geosphere. This assessment complemented an earlier postclosure assessment of borehole emplacement of titanium containers in a vault situated in a geosphere region of very low permeability rock. Further tests of this type are planned to be incorporated into the excavation stage of the moderately fractured rock experiment which is described below.

PLANNED TRACER TRANSPORT EXPERIMENTS

Tracer transport experiments are currently planned for three distinctly different fractured rock domains at the URL. These are described below.

FRACTURE ZONES

Final preparations have been completed for a two-well tracer test at a scale of 700 m within Fracture Zone 1 (Figure 1). This test is being performed as part of the phase 3 series of two-well tracer tests within major low-dipping fracture zones to determine the physical solute transport properties of volumes of intensely fractured rock and to develop methods for extrapolating the test results to larger scales. The results of previous tracer tests, conducted as two-well, steady state, recirculating tests at scales ranging from 17 to 440 m, along with data from hydraulic tests conducted in the same pairs of boreholes, indicate that a relationship may exist between values of transport porosity determined from tracer tests and storativity determined from hydraulic tests. It appears that the results of large-scale hydraulic tests combined with smaller-scale hydraulic tests and two-well tracer tests could be used to estimate the transport porosity of large areas of major fracture zones in a plutonic rock mass. This test is being performed to address this relationship and if successful, it may eliminate the need to perform many expensive, large-scale tracer tests in major fracture zones during the site evaluation phases of a disposal vault siting project.

MODERATELY FRACTURED ROCK

A series of tracer tests are being planned for a region of moderately fractured rock (MFR) on the 240 Level of the URL (Figure 2) to evaluate the physical and chemical solute transport properties of a large volume of MFR and to determine the suitability of the porous-media-equivalent method for modelling solute transport in regions of MFR. For the purposes of this experiment moderately fractured rock is defined as a region of rock mass at least 100,000 m^3 in size having a relatively uniform distribution of intersecting permeable fractures and a fracture frequency (based on a line sample) of 1 to 5 fractures per meter.

The region of MFR has been defined by a series of boreholes drilled from the underground workings of the URL and from surface (Figure 5). This region is transected by a splay of a major low dipping fracture zone (Fracture Zone 2.5–Figure 1). A north-east/north-northwest trending set of near vertical fractures also extends through this region of the rock mass. The volume of interest for the MFR transport experiment measures roughly 50 m x 50 m x 50 m.

Three phases of work are currently planned for the MFR tracer experiment. Phase 1 which is nearing completion has involved excavation of the access tunnel to the region of MFR and the drilling of additional boreholes for the geological, geophysical, geochemical and hydraulic characterization of the test region. The characterization of the test region is near completion. An initial tracer test will be performed during phase 1 at a scale in the range of 10 to 50 m. Many aspects of the design for this test have been based on the successful completion of the series of two-well tracer tests performed within the major low-dipping fracture zones. It is planned to perform the tracer test as a two-well, steady state, non-recirculating test. The testing method, procedures and equipment that will be used during subsequent tracer tests for this experiment will be evaluated following the completion of this initial tracer test. Phase 2 will involve activities related to conducting a series of groundwater tracer tests using both non-reactive and reactive tracers. Phase 3 will involve sampling the fracture network to determine tracer channelling and the distribution of reactive tracers using either a network of boreholes or by excavating a test tunnel through the central portion of the experimental area after completion of phase 2. If a tunnel is excavated through the moderately fractured rock area a series of radial-convergent conservative and non-conservative groundwater tracer tests may be planned for this last phase of work as well as tracer tests to determine the solute transport properties of the EDZ.

NATURAL FRACTURE IN SPARSELY FRACTURED ROCK

An underground radioisotope laboratory has been designed and constructed at the 240 Level of the URL (Figure 2) to study the transport of conservative and sorbing radionuclides in natural fractures under *in situ* geochemical conditions [11]. This experiment has been designed in cooperation with the Japan Atomic Energy Research Institute (JAERI).

The migration experiment is being performed in an IAEA Class B radioisotope laboratory which is located adjacent to a subvertical joint zone, the only permeable fracture intersecting the URL at this depth. Blocks of granite, with dimensions of about 1 m x 1 m x .7 m, each containing a natural fracture, have been excavated from this joint zone using a diamond wire saw cutting technique (Figure 6). Groundwater from the joint zone was used as drilling and cutting fluid to minimize contamination of the fractures.

Two blocks of granite are being used for the migration experiments; each block has been equipped with 12 inlet/outlet ports at the periphery of the fractures. These ports have been used to hydraulically characterize the fractures to select the most appropriate flow path for the migration experiments. The migration experiments will be performed using groundwater from the joint zone as the transport solution to maintain the low Eh, *in situ*, geochemical conditions within the natural fractures. Initial migration experiments have been completed using bromide as a conservative tracer at flow rates ranging from 5 to 400 mL/h. These experiments will be followed by migration experiments using sorbing radioisotope tracers and colloidal material. At the completion of the migration experiments, the blocks will be separated at the fracture and the surfaces analyzed radiometrically to provide further information on the transport pathways within the natural fractures.

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(Frost)Figure 1. Geologic cross section showing the different natural fracture domains at the URL: fracture zones, moderately fractured rock and sparsely fractured rock

(FROST)Figure 2. Sectional view of the URL. Location of the excavation damage zone (EDZ), moderately fractured rock (MFR) and natural fracture transport experiments are shown.

(FROST)Figure 3. Schematic of the two-well tracer testing technique at the URL

(FROST)Figure 4. Photo of the process zone of intense fracturing located in the EDZ of the test tunnel floor

(FROST)Figure 5. MFR experimental layout

(FROST) **Figure 6. Block of excavated granite containing a natural fracture**

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SESSION IV

Aims and Design of Planned Field Tracer Experiments

Chairmen: W. R. Alexander (University of Berne, Switzerland)
and G. Volckaert (SCK-CEN, Belgium)

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POSTER SESSION

The Assessment of Radionuclide Entrapment in Repository Host Rocks

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Executive Summary

The Nagra/PNC field tracer migration experiment (MI) has just been completed following 10 years of intensive study in Nagra`s Grimsel Test Site (GTS) in central Switzerland (see Alexander et al., 1996a, elsewhere in this report). The Radionuclide Retardation Project (RRP) may be thought of taking over where MI left off but, this time, Nagra and PNC are examining specific retardation mechanisms of safety relevant radionuclides as they migrate through fractures in granite. The GTS MI experiment was specifically aimed at transport model testing and understanding how laboratory measured radionuclide retardation could be related to the real environment. In MI, several short-lived, weakly retarded, radionuclides were injected into a borehole in a water-bearing, complex fracture (or shear zone) in the GTS. The behaviour of the tracers was observed from other boreholes in the shear zone and the good fit between the model predictions, laboratory data and the field experimental observations was very encouraging.

The Radionuclide Retardation Project (RRP; see Alexander et al., 1996b) is now taking the MI work further in two main respects: first, strongly retarded radionuclides have been (ie September, 1996) injected, as in MI, into the same water conducting shear zone which has been used for the ten years work in MI and second, the sites of *in situ* radionuclide retardation will be physically defined (and not just assumed as in MI). The second part follows on partly from the first in that the strongly retarding radionuclides to be injected in RRP will travel through the experimental shear zone so slowly (some possibly taking years to decades compared with hours to months in MI) that it will be impossible to sit back and wait for their appearance at the extraction borehole as was the case in MI. Here, it will be necessary to physically excavate the entire experimental zone (approximately two tonnes of rock) and take sub-samples back to the laboratory to assess how far each radionuclide has travelled and compare these results with predictions based on laboratory experiments.

In this part of RRP, as well as producing data on retardation sites in the rock, a full 3D physical description of the shear zone will be carried out, so producing one of the most detailed descriptions of

a water conducting shear zone in a rock to date. This should be of great use to transport modellers when constructing conceptual models of water flow systems in crystalline repository host rocks.

In addition, a second retardation mechanism is under study in RRP, namely matrix diffusion. This is where radionuclides diffuse out from the water conducting fractures and enter the actual matrix of the host rock via connected pores to be further retarded either by uptake on the rock pore surfaces or simply temporarily trapped in the pore waters. Work carried out on natural decay series disequilibrium several years ago showed that matrix diffusion is certainly occurring in the rock matrix close behind the experimental shear zone and so this seems a good area to define in detail the extent and form of *in situ* matrix diffusion. Specifically, the depth to which matrix porosity is connected to water conducting features such as the experimental shear zone will be studied as will the form of pore connectivity. This will provide information on the volumes of rock which could be available to retard radionuclides moving through crystalline repository host rocks and is intended to allow direct comparison with the large volume of laboratory experimental data on pore space availability and connectivity which probably over estimate both values due to experimental artefacts (such as pores opening when the rock samples are destressed on drilling *etc*).

Acknowledgements

Thanks to our numerous colleagues in the RRP and MI projects who have contributed to the success of the work over the last decade. Thanks also to Nagra and PNC for funding the projects.

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Interpretation of Field Tracer Experiments Performed in Fractured Rock and Implications for a Performance Assessment

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This abstract describes the interpretation of combined colloid and non-sorbing tracer migration tests performed in a convergent flow field in fractured rock. It describes the approach used and some of the difficulties encountered in the interpretation procedure. The work highlights the rationale of the interpretation within the broader context of the modelling of radionuclide transport for performance assessment purposes.

The potential for colloids to enhance radionuclide transport has been recognised in many radioactive waste disposal research and development programmes. The experiments described here have been undertaken to evaluate the mobility of different types of colloids in a fractured rock environment. The field experiments, undertaken at Reskageage Quarry Cornwall, are an extension of an earlier laboratory programme. The field site gives access to a longer pathway through a more complex fracture network than experienced in the well-controlled environment of the laboratory. Two types of colloids were investigated:

- monodisperse silica particles (30nm, 65nm, 800nm);

- monodisperse hematite(130nm).

The silica colloids were detected by photon correlation spectroscopy (PCS). Iron colloids, which tended to aggregate, were analysed using ICP-OES. Colloid migration was compared to that of a non-sorbing dye tracer (rhodamine-wt). Eight migration experiments (six silica colloid and two hematite colloid) were performed on length scales of 5m, 9.4m or 15.4m by the use of appropriate pairs of boreholes. Groundwater was abstracted from a borehole to achieve a radially-convergent flow field. Dye and colloid was released passively from neighbouring boreholes.

Break-through curves for two combined silica colloid and dye tracer tests described show a series of high-quality tracer break-through curves. The decay of tracers observed in the injection borehole is also measured. The main observations are:

- the velocities of silica colloids and rhodamine-wt are similar;

- relative to rhodamine-wt, transmission of 3Onm silica colloids ranges from 50% to 119%;

- results are highly reproducible.

The main observations from the hematite experiments are:

- hematite aggregates readily, but flocks are transported in the rapidly flowing water;

- transmission of hematite colloids is low, typically 10%.

The conceptual model for flow in fractured rock is a set of parallel fractures of uniform aperture through which water flows. Diffusion of solute into the rock matrix can occur. In addition there will be fractures, with negligible flow, connected to the flowing fractures, which will also provide paths for solute diffusion.

The interpretation approach involves fitting the observed normalised break-through with a semi-analytical method: inversion of the closed form Laplace transform solution. This method involves taking account of the mixing of solute in both the injection and pumped boreholes.

The long tail can be accounted for by RMD, but involves introducing a dense fracture spacing, which is inconsistent with the expected frequency of fractures allowing significant flow. Similar experiences have been found in the laboratory in which the tail can be accounted for by multiple flow paths.

The field tracer experiments, examples of which are described in this poster, can typically be used to:

- build confidence that the construction of a transport model from the gathered data is appropriate;

- build confidence in understanding transport processes;

- build confidence in a model by demonstrating the interpreted parameters are consistent with independent experiments and expert judgement.

The example tracer tests described in this poster were performed to build confidence in modelling processes in transport in a fractured rock. At a phenomenological level we found good agreement between the experimental observations and a relatively simple description of transport of solute. The break-through curves for the colloid showed little qualitative difference from the corresponding dye tracer experiment indicating significant mobility of the silica colloid.

A number of predictions were made about the likely results of a field experimental programme based on the results from the laboratory. In general, these predictions were confirmed. When, however, the results are examined in detail the added complexity makes the field experiments more difficult to interpret than the simple laboratory-based experiments. In the main, this difficulty no doubt stems from the complexities of the 'real' system. At a phenomenological level we found good agreement between the experimental observations and a relatively simple description of transport of solute.

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