OBJECTIVES AND LIMITATIONS OF SCIENTIFIC STUDIES WITH REFERENCE TO THE SWEDISH RD&D PROGRAMME 1992 FOR HANDLING AND FINAL DISPOSAL OF NUCLEAR WASTE

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ABSTRACT

The Swedish Nuclear Power Inspectorate (SKI) has recently concluded its evaluation of the Swedish programme for the development of a system for the management of nuclear waste. The programme was compiled and issued by the Swedish Nuclear Fuel and Waste Management Company (SKB). In this process of programme formulation and review, considerable attention has been paid to the question of how scientific studies should be directed and performed in order to provide the support needed in the programme.

When the objectives and limitations of such scientific studies are to be analysed, it is vitally important that the implications of the long timescales and the lack of feedback of post-closure experience are fully understood and adequately dealt with. It must be realised, that simulations will have to be utilized for the systems development work as well as for the assessments of safety. Such *performance simulations* have to be based on a thorough understanding of the pertinent phenomena as well as on a comprehensive base of experimental data. They must also be based on a good overall perspective that can only be obtained through full performance assessments.

Thus, a sound scientific base is needed. The components of this base must be traceable. Moreover, the links must be clearly identified between the knowledge base and the development of the disposal system as well as the performance assessment of such a system. Performance simulations and performance assessments should be utilized, not only as tools to develop a system and to evalute its safety but also to identify areas where further research is required - or unnecessary.

The knowledge base will, however, always be limited, and a lack of understanding must also be recognised and adequately dealt with, e.g. by accounting for uncertainties in the performance simulations, by relying on bounding (conservative) assumptions or by robust repository design.

Thus, the success of a programme for the handling and disposal of nuclear waste is highly dependent on the strategy applied for the utilization of the scientific knowledge base. The requirements on such a strategy increase considerably when substantial commitments are to be made.

INTRODUCTION

Considerable efforts are currently being made in Sweden and other countries in order to develop systems for the disposal of high-level radioactive waste that are safe as well as technically and economically feasible. One important prerequisite for the development of such a system is that a sound scientific basis can be found and that this basis is utilized in the development work in a pertinent manner. The establishment of such a sound scientific basis requires that the objectives of the scientific studies should be made clear and that the implications of any limitations of such studies are fully understood and dealt with.

In September 1992, the Swedish Nuclear Fuel and Waste Management Company (SKB) published a report called RD&D Programme 1992 for handling and disposal of nuclear waste[1-4, see also 5-6]. According to Swedish law, such a programme has to be compiled every third year. The RD&D Programme 1992 was reviewed by the Swedish Nuclear Power Inspectorate

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(SKI) which presented its conclusions in March 1993[7-8]. A general compilation of the conclusions of this review was presented at the SAFEWASTE 93 conference in Avignon [9]. An independent review has also been carried out by the Swedish National Council for Nuclear Waste (KASAM)[10].

According to the plans presented in its RD&D Programme 92, SKB intends to carry out the disposal in stages with the possibility of retrieving the spent fuel deposited in the first stage. Hot operation of this disposal facility as well as of the encapsulation plant is planned to start towards the end of the first decade of the 21st century.

In its programme, SKB finds that - within the next few years - the time will be ripe for the selection of (the main alternative for) the disposal method. This conclusion is based on the PASS-study [5] in which safety, technical feasibility and cost are compared for a number of alternative disposal methods. Also within a few years, SKB intends to select candidate sites for the repository and to start its site investigations. This plan is based largely on some of the conclusions from SKB's latest performance assessment[6] which deals, in particular, with the importance of the bedrock for the safety of the repository. Applications for detailed site investigations and for building the encapsulation plant are planned to be submitted to the authorities by the end of 1996, at the earliest.

The main alternative studied in Sweden for the repository system for spent fuel is the KBS-3 method which originated in the mid-seventies. In this system, the spent fuel is enclosed in thick canisters (containers) with copper on the outside. Two main types of canisters are considered:

- An inner canister of mild steel and an outer one of copper. In addition, there will be a filler material between the inner canister and the spent fuel.
- A canister made of copper with lead in the space between the copper and the spent fuel.

The canisters are deposited in holes drilled through floors of tunnels. Compacted bentonite clay is used as a buffer between the canister and the rock. The tunnels are excavated in good quality crystalline rock at a depth of around 500 meters. The barriers of this system and their anticipated performance are as follows:

- *The spent fuel.* The reaction rate between the spent fuel and the reducing groundwater is low - especially after considerable decay has taken place. In addition, most of the species dissolved from the fuel have a low solubility.
- *The copper canisters.* Copper has a very low rate of corrosion in a reducing hard rock environment.
- *The compacted bentonite.* The bentonite provides for the mechanical protection of the canister and restricts the release of radionuclides to the surrounding rock.
- *The surrounding rock.* The flow of water is low and, in addition, there is a substantial retention of dissolved radionuclides through sorption onto the minerals in the water bearing fractures as well as diffusion into and sorption within the adjacent rock matrix.

THE NEED FOR A SCIENTIFIC BASIS

In many respects, the development of a disposal system for nuclear waste can be carried out in a similar manner as for any other industrial system. Anyone attempting to find a real solution to the waste problem, faces, however, some unprecedented features and requirements on foresight that need careful consideration:

- The repository is likely to be the first of its kind.
- It is intended to function for a very long time.
- There should be no need for maintenance or repair.
- It cannot be expected that the long-term performance of a repository can be based on the feedback of experience from operation.
- There will be considerable uncertainty regarding a number of issues of importance for the future performance of a repository.

- Any control or improvements that future generations may wish to make should not be made unduly difficult.

Access to feed-back from operation together with the possibility of carrying out maintenance or repair are decisive, or at least highly significant factors for the successful operation of most industrial systems. Therefore, the potential for mistakes (of one kind or another) is, in general, much greater in cases where feedback of experience from operation cannot be utilized to identify the corrective actions needed. Moreover, the long time scales make it difficult to make good predictions of the future performance of the repository system.

Therefore, the development of a disposal system for long-lived radioactive waste calls for certain precautions as well as the application of methods not commonly encountered in conventional industrial projects. A careful analysis of the development process is needed in order to establish appropriate methods.

Thus, in technical development work in general, a method frequently employed is to test different alternatives against tentative goals or criteria regarding, for instance, technical feasibility, cost, reliability and safety. The testing is carried out in several ways: at the conceptual stage, on the drawing board, in laboratory and pilot scale experiments and, finally, on prototypes. Scientific knowledge and methods are employed in all these stages, particularly in the planning and in the evaluation of experiments. In many cases, expensive and tedious experiments are nowadays being replaced by computer simulations based on a combination of scientific knowledge and operational experience. In the development process, sooner or later, the results of a simulation will be tested and verified against the actual performance of the real full-scale system.

However, when the long-term performance of a repository for nuclear waste is considered, such confirmation is not possible. A crucial aspect of the development of such a system - as well as of the assessment of its performance - is, therefore, how to simulate the future performance in a credible manner even over very long timescales. Since the long timescales preclude traditional intra- and extrapolation, we have to rely solely on *simulations* of the future performance based on a thorough understanding of the relevant phenomena together with a reliable base of experimental data. Such predictions of the future behaviour of components of a system - or an entire system - will be referred to below as *performance simulations.*

Studies of natural analogues may contribute to the knowledge base by providing indirect evidence about long-term processes that may not even be detected in short-term experiments. On the other hand, large uncertainties can be expected regarding the evolution of the hydrology and geochemistry of a natural analogue which renders interpretations non-unique. Moreover, even if the time scale is relevant, the conditions of such an analogue may not be relevant for a waste repository site.

In any case, a sound scientific basis is needed. The problem is that much of the needed knowledge is not available or is so recent that it is still being debated. Traditionally, good science is characterized by the gradual resolution of issues by a lengthy process of hypothesis testing and peer review that may span over one or several generations of scientists. Therefore, in cases where the scientific understanding is incomplete, we face the possibility of being accused of circumventing the traditional scientific approach, a highly undesirable situation. Limitations in the knowledge base must be recognized and handled properly, e.g. *by focussing on the treatment of uncertainties, by reliance on bounding assumptions or by improving the repository design.* This approach must also have a sound scientific basis.

It appears to be generally agreed that these objectives can be fulfilled through a comprehensive research programme of high quality. The programme should cover all relevant areas and disciplines and needs to be interdisciplinary in character. It also appears to be highly desirable that a lasting consensus be established among the scientists regarding the essentials of the scientific basis.

In addition, the scientific basis should be properly documented and its contents traceable. Moreover, there should be a clear linkage between the items in the knowledge base and the performance simulations. This applies to the data and the models as well as to any computer codes used for the simulations.

PERFORMANCE ASSESSMENTS

Recurrent performance assessments should play an important role in any waste management programme, not only as a means of evaluating the safety of a proposed repository, but also as a tool to direct the research programme. Thus, performance assessments should be utilized to identify needs for further knowledge, as well as areas where the level of knowledge is satisfactory. Moreover, performance assessments should be used as a means to achieve integration in a programme.

In a full performance assessment, it is essential that the knowledge base be documented, i.e. with regard to all items required in a safety report for the repository: site characterization, scenario analysis, description of the model system with motivation for all assumptions, consequence analysis and a comparison of predicted overall consequences with established acceptance criteria.

Thus, performance assessments need to be sufficiently broad in scope. All processes relevant to the future performance of the repository need to be included in the analysis. For example, the scenario developments should be combined with comprehensive and structured compilations of possible features, processes and events[11, 12].

Results from performance assessments should be utilized in systems development work to influence the design of a system and its components early in the process. In fact, performance assessments constitute the only available overall feedback mechanism in the development process. On the other hand, it is not necessary, or even desirable, to carry through comprehensive performance assessments in all cases where feedback is needed. It may be much more efficient to only simulate part of the repository system in performance simulations.

Performance simulations should be used as a tool to obtain a better understanding of the possible behaviour of the different parts of the repository system, including studies of hypothetical scenarios with low probabilities. Such partial analyses could involve studies of processes on a very detailed level as well as full simulations of the total system. *However, partial analyses are meaningful only if they are based on the experience and knowledge gained in a comprehensive performance assessment.*

SYSTEMS DEVELOPMENT AND SYSTEM SELECTION

Performance simulation as well as performance assessment should be utilized in systems development work in order to influence the design of a system and its components early in the process. The impact of such analyses may manifest themselves in the robustness of design (e.g. in view of uncertainties that may be difficult to resolve), or as the establishment of links between the knowledge base and the systems design.

Ideally, the technical work regarding systems development and systems selection should be carried out utilizing the full scientific basis for performance simulation. In the real world, this is not possible, and research activities will have to be carried out in parallel with the technical work. This concerns not only the development of the scientific basis but also the development of performance assessment methods and models.

In the beginning of a technical development process, the research and investigation work may cover very wide areas. When the technical development activities are to be performed, limitations in scope become necessary and choices will have to be made. The main reason for these limitations is that considerable resources may have to be invested in the technical development and it is therefore not feasible to proceed along more than a very limited number of alternative routes, perhaps only one.

Limitation in the number of systems considered should also affect the focussing of the research work since many of the pertinent questions may become apparent only after considerable efforts have been spent on technical development work on a specific system. On the other hand, choices should not be made too early, since it might become apparent later in the process that the system selected was not a good one. In any case, the progress made will be highly dependent on the efficiency of the communication between the research and the systems development work *as well as on the communication between systems development and performance assessment.*

In its evaluation of the SKB RD&D Programme 92, SKI maintains that in order to reject an alternative system in a credible way it is necessary to prove either that the alternative system is less suitable than the selected main alternative, *or that the resources required to investigate the suitability of an alternative are unreasonably high in relation to the expected benefit.* Furthermore, even when the general outline of a method has been established, numerous questions arise regarding the selection of a detailed outline.

It can be mentioned, as an example of this reasoning, that the disposal of spent nuclear fuel into very deep (several kilometers) formations in crystalline rock might turn out to be unfeasible. Even if the concept as such appeared to be very attractive, it might prove very difficult - or even impossible - to find the scientific knowledge basis needed for reasonably accurate assessments of the future performance and the safety.

In its evaluation report, and with the reasoning indicated above, SKI supports the SKB plan to proceed with repositories based on the KBS-3 concept as reference cases for the continued development work. SKI also maintains that a new comprehensive performance assessment is needed before any substantial commitment takes place regarding any particular system.

ENGINEERED BARRIERS

In its evaluation report, SKI request that SKB should, in particular, further develop its ability to simulate the behaviour of the engineered barriers. These barriers appear to have an excellent potential for providing long-term containment of the radionuclides. However, when such a long-term containment is to be proven, simulations over a long time of the performance of man-made constructions have to be carried out. It has been discussed above that such simulations require a combination of experimental data and an understanding of the long-term effects.

In a repository environment, the spent fuel can be expected to react sluggishly to and to dissolve sparingly in the groundwater, and thus in itself provide an efficient barrier towards the release of radionuclides. In order to verify such an assumption, it is necessary to understand the mechanisms for the long-term events as well as to be able to support the assessment of dissolution rates by experimental data. In its evaluation of the RD&D Programme 1992, SKI recommends SKB to improve their integration of the model development and the experimental part of the programme. Such an integration can be expected to lead to a better understanding of the mechanisms and thereby also to an improved basis for the planning and interpretation of the expensive experiments.

In its RD&D Programme, SKB concludes that the copper canister will contain the radionuclides for a very long time, probably longer than one million years. SKB expects that strongly reducing conditions will appear relatively soon after closure (about 100 years) and that the dominant corrosion mechanism will be one of general corrosion through sulphidation of the copper. SKB is also putting forward that the rate of the corrosion will be limited by the low concentration of reduced sulphur species in the groundwater in combination with a low flow of the groundwater near the canister.

In its evaluation, SKI does not put forward any evidence that contradicts the conclusions made by SKB. Nonetheless - and particularly in view of the emphasis put on the long-life canister in the Swedish programme - SKI recommends SKB to improve its understanding of a number of processes which may be important for assessments of the corrosion behaviour:

- The chemical environment and its possible variations in the future.
- Phases formed on the copper surface and their properties.
- Possibilities of localised corrosion and stress corrosion.
- The possibility of reduction of sulphate through the action of microorganisms.

Creep of a copper canister deserves attention for several reasons, one of which is that the effect may manifest itself only after a load has been applied for a long time. The effect is dependent on a number of factors such as choice of material, design, manufacturing method, sealing method and external load situations. In its assessments so far, SKB has been assuming that the mechanisms that dominate during the accelerated testing in the laboratory will do so also in the repository. In its evaluation, SKI points to the need for assessing what the actual mechanism will be in the repository.

The manufacturing and sealing of the canisters require the development of new processes and plants. In its review, SKI emphasizes the need for establishing the scientific and technical basis for these activities, regarding e.g. weld tightness, grain size, residual stresses, (micro)alloying elements, deformation properties, defects from manufacturing, workability, control methods, etc.

A number of requirements can be expected to apply regarding the functioning of the bentonite clay barrier in the repository. The laboratory-scale experiments carried out so far indicate that bentonite as such may well show the desired properties. However, fewer studies - by comparison - have been performed regarding the technical development, that is, pre-treatment of the powder, pressing and application of the bentonite (blocks and/or powder) in the repository. In its evaluation report, SKI suggests that SKB consider the timing of the latter activities. The main reason for this is that the results from the technical activities are needed for a number of other activities, including certain scientific studies.

SITE CHARACTERIZATION AND SITE SELECTION

The objectives of a site investigation are:

- to provide the knowledge base (data, with uncertainties) necessary for the performance assessment,
- to support the site selection process and
- to aid in the adaption of the repository layout and design to the local conditions at the site.

In evaluating a site it is important to be aware of the fact that the information obtained is subject to several limitations:

- The volume of rock represented by quantitative data at a site is very small (on the order of a few percent of the total), partially because of the potential damage to the site that may be caused by too many measurents, (e.g. opening of boreholes).
- The data are inherently associated with many sources of error and uncertainties (for example, due to equipment, measurement technique, disturbances of natural conditions and evaluation techniques)
- It is often difficult to collect data that can be used directly in the form that they are obtained. This applies to most geophysical and hydraulic measurements. Another example is the ability of the rock to retard radionuclides which is very difficult - or even impossible - to measure in a field situation.
- Site characterization data typically represent a "snapshot" in time with regard to the geochemical and hydraulic conditions at the site.

In the evaluation of the SKB RD&D program SKI recommends that SKB reevaluates its development of methods for site investigation with regard to the needs for the performance assessment. Such a coupling is necessary in order for the site characterization database to actually be relevant to the performance assessment. Examples of such development needs identified in the evaluation of the SKB RD&D programme include methods for the detection of horizontal fracture zones, methods for sampling of undisturbed groundwater, and in-situ measurements of rock stresses.

On the other hand, a performance assessment is based on several assumptions and simplifications. In order for performance assessment to be used as a tool to direct scientific studies, it is necessary that these assumptions should be well founded. For example, a first assessment of the properties of a site is typically made using a preliminary geological model based on measurements from the surface and from boreholes. If such a model were to be used in a performance assessment, then the results would suggest that the subsequent detailed investigations underground should focus on characterization of major features, such as fracture zones which were detected in the preliminary investigation. However, there is no guarantee that these easily detectable features are the most important ones to characterize in order to understand, for example, the hydrological and geochemical conditions at the anticipated location of the repository.

In principle, it is necessary to evaluate all uncertainties in the knowledge base that is used in a performance assessment. In its evaluation, SKI therefore emphasizes the importance of evaluating and documenting uncertainties, error sources and limitations both in measurements and in the interpretation methods employed to deduce parameter values. Properties or site conditions that cannot be measured should be documented as a part of the site characterization database. In addition, the properties of a site may become considerably modified during the investigation, e.g. through the opening of boreholes. Such alterations should be evaluated and taken into account when an integrated measurement programme is being developed.

SKI emphasizes the importance of not only recording site data but also of evaluating and interpreting them. The continuous evaluation of measurements and data recorded during the course of a site investigation is vital in order to ensure that measurement methods and data interpretation methods are adequate and provide a sufficient knowledge (data) base. Because of the sparsity and inherent uncertainties often associated with site specific data, interpretations are often not unique. In its evaluation, SKI recommends that data should be evaluated using several, alternative, interpretation models in order to explore the robustness of the site description used for the performance assessment.

An integrated interdisciplinary approach to analyzing site data is crucial in order to obtain an understanding of the historic (and future) evolution of the site. For example, groundwater chemistry data may give indirect evidence of groundwater flow and transport over long time periods and transport distances. A general understanding of site history renders credibility to the interpretations of present-day conditions.

The question of the utilization of a sound scientific knowledge base in connection with site selection is a rather complex one. Preferably, in order for a site selection to be firmly based on technical and scientific factors, data from detailed site investigations (including data from shafts and/or tunnels) need to be available and interpreted. Detailed site investigations are, however, very costly and the number of sites investigated needs to be limited as far as possible. Thus, it is highly important that good prognoses can be made regarding the suitability of a site - based on data from pre-investigations from the surface (including data from boreholes).

In its evaluation report, SKI therefore emphasizes the significance of describing the effectiveness and limitations of different site investigation methods as well as the expected results from an integrated measurement program well in advance of any detailed investigations. In its evaluation report, SKI also requests that a new comprehensive performance assessment be carried out prior to any substantial commitment to a particular site.

CONCLUDING REMARKS

A programme for the development of a repository system for nuclear waste disposal should rest on a solid and sound scientific basis. When the objectives and limitations of such a programme are considered, it is vitally important that the implications of the long timescales and uncertainties as well as the lack of feedback from operation - which are quite specific to the area of waste disposal - are fully understood and adequately dealt with.

This implies that *performance simulations* will have to be utilized for the systems development work as well as for the assessment of safety. In order for the results to be reliable and valid, such simulations must be firmly based on experimental data and on a thorough understanding of the pertinent phenomena. Moreover, in order for the performance simulations to be relevant, they have to be based on a good overall perspective which can be obtained only through full performance assessments.

If the scientific base - or the linkage to it - were not sound, it can be expected that - sooner or later - it will become apparent that the performance assessment is inadequate or that the method or site selected was not a good choice. Moreover, if the objectives were to appear to be obscure or the limitations were to appear to be not respected, it might even be suggested that the research efforts were actually just window-dressing or a facade.

One important aspect of program compilation and evaluation is therefore to identify such critical topics early enough in the process and to give them proper attention in the continued programme. Performance simulation and performance assessment should be utilized not only as tools to develop a system and to evaluate its safety but also to identify areas where further research is required - or unnecessary. The technical development work should also be analysed for areas where the scientific knowledge basis may need to be supplemented.

The desired knowledge cannot always be obtained, however. Lack of scientific understanding must be recognized and adequately dealt with e.g. by accounting for uncertainties in the performance simulations, by relying on bounding (conservative) assumptions or by robust repository design.

In the present paper, a number of examples have been given regarding the significance of scientific studies - including their objectives and limitations - for the Swedish RD&D programme for handling and disposal of nuclear waste. It should be emphasized, that the requirements on a pertinent strategy for the supporting research activities increase substantially when substantial commitments are to be made. In the Swedish programme, such commitments are foreseen within the next few years with regard to the selection of a method for the disposal, construction of a plant for encapsulation of spent fuel and detailed site investigations.

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