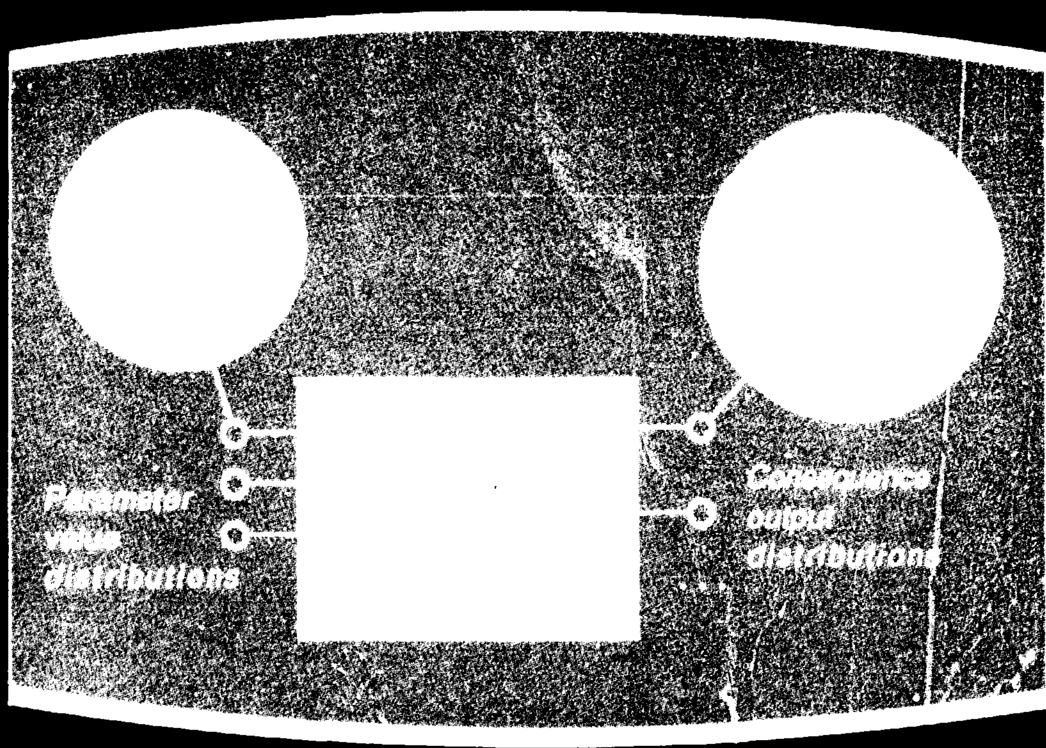
DISPOSAL OF RADIOACTIVE WASTE

THE INTERNATIONAL PROBABILISTIC SYSTEM ASSESSMENT GROUP

BACKGROUND AND RESULTS



NUCLEAR ENERGY AGENCY

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1990

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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

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

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971) and New Zealand (29th May 1973). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention). Yugoslavia takes part in some of the work of the OECD (agreement of 28th October 1961).

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of all European Member countries of OECD as well as Australia, Canada, Japan and the United States. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

- *encouraging harmonisation of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
- *assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;*
- *developing exchanges of scientific and technical information particularly through participation in common services;*
- *setting up international research and development programmes and joint undertakings.*

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

FOREWORD

Radioactive waste management programmes in OECD Member countries currently cover a wide range of activities aiming at the eventual implementation of disposal concepts for various types of waste. These activities address the institutional and regulatory framework as well as research and development. In some countries, site selection and characterization programmes for high-level or intermediate-level waste disposal are at a relatively advanced stage. Several countries already have repositories for low-level waste in operation. In connection with these activities, safety issues are a common concern, and therefore enjoy a high priority in international co-operative programmes.

The **OECD Nuclear Energy Agency (NEA)** devotes considerable effort to the further development of methodologies to assess the performance of radioactive waste disposal systems, and to increase confidence in their application and results. The NEA provides an international forum for the exchange of information and experience among national experts of its twenty-three Member countries, and conducts joint studies of issues important for safety assessment.

In 1985, the NEA Radioactive Waste Management Committee set up the **Probabilistic System Assessment Code User Group (PSAC)**, in order to help coordinate the development of probabilistic system assessment codes. The activities of the Group include exchange of information, code and experience, discussion of relevant technical issues, and the conduct of code comparison (PSACOIN) exercises designed to build confidence in the correct operation of these tools for safety assessment. The Group is now known simply as the **Probabilistic System Assessment Group (PSAG)**.

This report has been prepared to inform interested parties, beyond the group of specialists directly involved, about probabilistic system assessment techniques as used for performance assessment of waste disposal systems, and to give a summary of the objectives and achievements of PSAG. The report is published under the responsibility of the Secretary General of the OECD.

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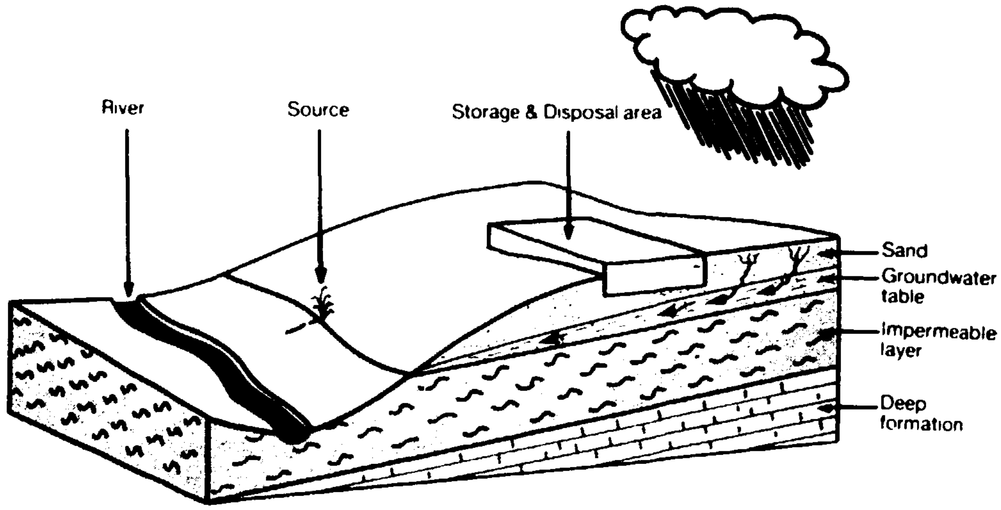
I

THE DISPOSAL OF RADIOACTIVE WASTE

The use of radioactive materials for electricity generation, or for medical, industrial or research purposes, inevitably gives rise to radioactive wastes which must be managed safely for the protection of humans and the environment, both now and in the future. Storage is used in the short term, but every country with a nuclear power programme is now involved in studies to establish permanent safe disposal facilities. The aim of such disposal facilities is to isolate the waste from the human environment until its radioactivity has decayed to acceptable levels. The methods being used, and planned, for this isolation vary according to the nature of the waste (see Figures 1 and 2 for examples). Short-lived, low-level wastes can be safely disposed of by near-surface land burial. Long-lived, high- or intermediate-level wastes require more sophisticated treatment and disposal techniques. For such wastes, deep disposal in stable geological formations is the approach receiving almost universal attention.

Near-surface disposal facilities are in use now in several countries. The first repositories for disposal of high-level wastes may be operational at the beginning of the 21st century. Meanwhile, further research, site selection and evaluation of disposal concepts are being carried out.

Most disposal concepts provide for isolation of the radioactive materials by a combination of both natural and engineered barriers. These may include the solidity and inherent insolubility of the waste form; encapsulation in durable containers; back-filling of excavations with materials selected for their mechanical, chemical and/or hydrological properties; and the overlying rocks and soils, which will inhibit groundwater movement and further retard movement of radionuclides by sorption. A further possible beneficial effect may be dilution and dispersion in surface water bodies.



Credit: ANDRA.

Credit: NAGRA.

Figures 1 and 2 Examples of concepts for the shallow disposal of low-level waste and the deep disposal of high-level waste.

II

SAFETY CRITERIA AND REGULATIONS

Radioactive waste disposal is governed by the principles of radiation protection that are applied throughout the world. These are based on the recommendations of the International Commission on Radiological Protection (ICRP) and are designed to ensure that risks to the public are negligible and that those who work with radiation enjoy a safety standard similar to that in the safest industries. ICRP recommends radiation dose limits for workers and for members of the public that are not to be exceeded, and furthermore that radiation doses should be kept as far below the limits as reasonably achievable. In most countries, these recommendations have become legal requirements.

In the context of radioactive waste disposal, different countries have established a variety of specific regulations or guidelines that are based on the ICRP recommendations, but modify or extend them in various ways. Many of these modifications are associated with various kinds of uncertainty involved in predicting potential doses arising from waste disposal facilities. For example, safety criteria can be framed in terms of limits or targets for *risk*, rather than dose. Risk includes an allowance for the probability that a given dose will be received, and combines the consequences from different possible levels of received dose.

Many of the uncertainties involved in assessing potential doses are associated with the fact that waste disposal facilities are intended to continue their function for a very long period into the future. The radiological consequences of a given release of radioactive materials into the environment depend upon patterns of human behaviour, which cannot be assumed to remain constant far into the future. The regulations in some countries avoid this difficulty by setting limits on the releases into the biosphere, or beyond a certain distance from the repository. The limits set are specific to the radionuclides involved, and have been derived on the basis of simple models for radionuclide transport within the biosphere and uptake by humans. Radioactive waste disposal regulations in some countries specify limits on releases, doses or risk that apply only for a certain period into the future.

In some countries, the regulations go beyond quantitative limits or targets. Limits on doses or risks to individuals may be supplemented by requiring calculations of collective doses to the whole of a population in the affected area. Comparisons with the background level of radioactivity can provide a further basis for judging acceptability.

Whatever regulations may be embodied in national laws, those involved in assessing the safety of waste disposal concepts will have an interest in characterizing the behaviour of a proposed disposal facility in a variety of ways, in order to satisfy themselves and the public that it is, and will continue to be, adequately safe. It is futile to attempt to eliminate all uncertainties in reaching such an assurance. Rather, any safety statement should include an assessment of the uncertainties involved. Probabilistic System Assessment is one means of handling these uncertainties and quantifying them.

III

SAFETY ASSESSMENT AND THE USE OF MODELLING

If it were possible, it would be desirable to demonstrate the safety of a radioactive waste repository experimentally. However, because the activity of the waste will persist for thousands or even millions of years, the natural and man-made barriers associated with a disposal facility must perform their function over very long times, and direct demonstration of this performance is impossible. It is therefore necessary to assess safety on the basis of theoretical evaluations of the behaviour of the system. It is not necessary to predict future behaviour in every detail. What is needed is to understand enough to be assured that any releases will not give rise to an unacceptable level of risk. This requires a sound and defensible understanding of all parts of the system.

It is necessary to build up such an understanding of the important processes at work in the system, and of the present state and possible future evolution of a particular proposed disposal facility, to the point where a safety case can be constructed to the satisfaction of the experts involved and the responsible authorities. This process requires research in many areas, both experimental and theoretical; it requires the acquisition of a large amount of data through laboratory experiments and field tests; and it involves modelling, not only to construct the predictions that will form the basis of a safety assessment, but also to guide the underlying research.

Modelling is the use of a formalized understanding of a system, and of particular processes within it, to evaluate system behaviour quantitatively. The modelling process begins with development of a conceptual model, representing an understanding of the features and processes of interest. Conceptual models are developed by expert judgment on the basis of well-known principles of physics and chemistry and existing understanding of the behaviour of the type of system under consideration. The relationships of a conceptual model are expressed quantitatively through mathematical equations. The resulting mathematical model may then be implemented numerically through a computer code. At every stage simplifications are introduced.

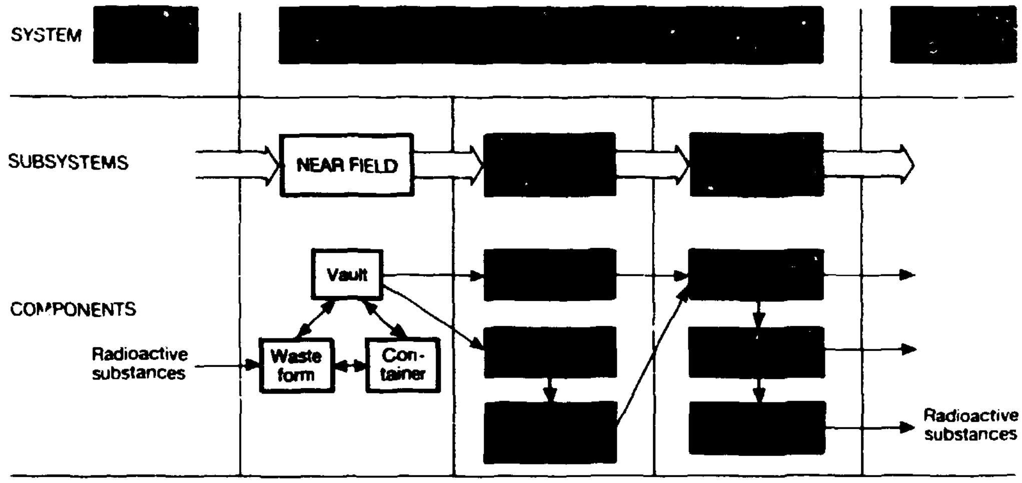


Figure 3 Example breakdown of a waste disposal system into subsystems. Assessing the performance of the whole will involve understanding and modelling each of the components of the system and their interactions.

Modelling is used in safety assessments in at least three complementary ways:

- to build up and demonstrate an understanding of individual processes, such as sorption of radionuclides onto repository materials or rocks;
- to describe and understand subsystem performance, such as the transport of radionuclides through the geosphere;
- to describe the performance of the overall system.

A greater level of detail is usually included in models concerned with a small part of the overall system. The detailed modelling of processes and subsystems can be used to justify the adequacy of the less-detailed overall system models. The results of overall system modelling can give insight into which processes are most important in the context of the task of establishing safety. They can therefore help to identify key areas where further research is needed, guide the allocation of resources for the detailed modelling work and for the acquisition of data, and guide the process of site selection and repository design.

Pathways

A conceptual model of the overall system must involve identification of the major mechanisms or pathways by which radionuclides could pass the natural and engineered barriers to reach the biosphere. There is international consensus that the following pathways should be considered:

- *Groundwater*: Radionuclides escaping from their primary containment will dissolve in groundwater which moves slowly through the surrounding rocks.
- *Gas*: Gas may be generated in a repository (depending on the concept), by corrosion, by radiolysis, or by microbial action. This gas may act to disrupt physical containment barriers. Furthermore, a proportion of the gas will be radioactive, and it may be transported from the repository through the geosphere to the surface.
- *Human Intrusion*: Human activities such as drilling for minerals may lead to penetration of either the repository itself, or the plume of radioactivity being transported by groundwater.
- *Natural Disruption*: Natural processes such as glacial erosion could expose either the repository or the groundwater transport plume.

Must Future Changes be Modelled?

Transport of radionuclides could be influenced by processes on a global scale. For instance, groundwater movement is influenced by surface conditions, which will alter appreciably if the climate changes. Modelling future climate changes and other evolution of the environment is seen by some experts as a necessary part of the overall performance assessment task. Others see such environmental changes as among the scenarios to be considered, but consider it either unnecessary or impossible to predict their occurrence.

Future human behaviour poses an even greater problem. With regard to human intrusion, it is usual to use statistical models, for example assuming a certain annual probability of drilling activity. But the parameters of such models depend on lifestyles, which are impossible to predict. The same applies to the mechanisms whereby doses arise from radioactivity in the biosphere. The only solution appears to be to assume human activity patterns similar to those of today.

Assessed risks far in the future cannot be true predictions. Rather, where future changes are inherently unpredictable, the assessments provide a measure of acceptability based on hypothetical continuance of present-day conditions.

IV

PROBABILISTIC SYSTEM ASSESSMENT

We have seen that mathematical modelling can be used at a variety of levels of detail in performance assessment, to describe behaviour of either part of a system or the whole. Any such modelling is subject to a number of uncertainties. Probabilistic System Assessment (PSA*) is a technique, normally applied in modelling the whole of the system, for dealing systematically with these uncertainties, and discovering how their influence propagates through to the model results. There are several sources of uncertainty, including –

- characterization of the system is limited, so that definitive values of relevant parameters cannot be obtained;
- alternative models of parts of the system may be equally defensible on the basis of existing understanding and data;
- future evolution of the system and future behaviour of human beings are uncertain.

The overall system model can be pictured as a processor, with many inputs – the model parameter values – and a number of outputs, which are measures of performance, such as the individual dose rate via a given exposure pathway at some time (see Figure 4a). The outputs are complicated, yet completely deterministic, functions of the parameters.

Because the parameter values are uncertain, the model outputs are uncertain. It is desirable, and in some cases required by regulations, to describe the uncertainty in consequences quantitatively. This is the principal objective of PSA techniques. To quantify the uncertainty in the consequences, it is necessary to specify quantitatively the uncertainty in the parameters. This is done in terms of *probability density functions* or PDFs (see the box on page 17 for information about how PDFs can be specified). The picture of the modelling process in Figure 4a must now be modified. No longer is the overall model a

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* Some people take PSA to stand for Probabilistic *Safety* Assessment.

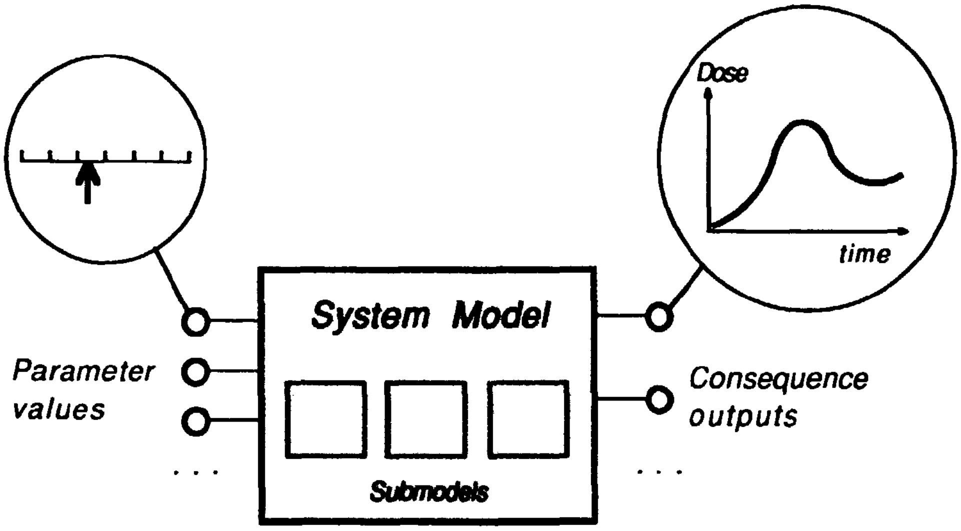


Figure 4a A model of the system (the repository and its environment) can be pictured as a processor with a number of inputs – the parameters of the constituent mathematical model(s) – and a number of outputs – the desired measures of performance, which are usually functions of time, such as predicted dose rate via a particular pathway.

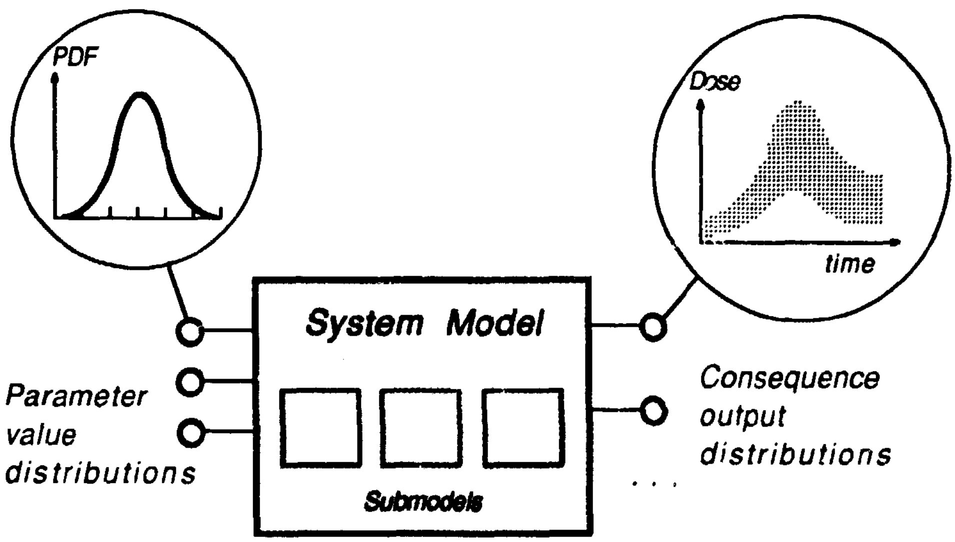


Figure 4b For probabilistic modelling, the parameters are specified in terms of probability density functions (PDFs) rather than fixed values (compare Figure 4a). The outputs, or consequence measures, are correspondingly distributed quantities.

processor fed with precisely defined inputs and delivering precisely defined outputs. Rather, it is fed with distributions of values for the inputs, and delivers a distribution for each output (Figure 4b).

One of the benefits of probabilistic modelling is that it can fulfil several functions at the same time –

- it is possible to calculate probabilistic measures of performance, such as *risk*, defined as the average over all the possible values of some consequence (such as radiation-induced cancer), taking into account the probabilities of the different values arising;
- the full probability distribution of each output value can be obtained (*uncertainty analysis*);
- the relationships between input and output values can be studied and expressed in a variety of ways (*sensitivity analysis*), so as to provide insight into the most important parameters, and to provide guidance for continuing investigations to characterize better the parameter values.

How PSA is Performed

The approach to PSA modelling almost universally adopted is the *Monte Carlo Method*, in which a large number of alternative realizations of the system are generated, each with a different, randomly selected, set of values for the uncertain model parameters. From this sampled collection of system realizations a sampled collection of consequence values is generated by application of the mathematical models. The statistics of the sample results provide an approximation to the statistics of the theoretically infinite number of possibilities embraced by the specified PDFs.

The Monte Carlo PSA technique is illustrated in Figure 5. The first step is generation of the parameter values. This function might be carried out in advance by a separate code, or (as shown in the Figure) can be performed "on demand" as each realization is modelled.

In principle, it would be possible to generate the parameter sets that define the system realizations according to a deterministic pattern. However, the random sampling approach appears to have been universally adopted, no doubt because it is simple to implement, is independent of particular models, and leads naturally to a probability distribution for the results.

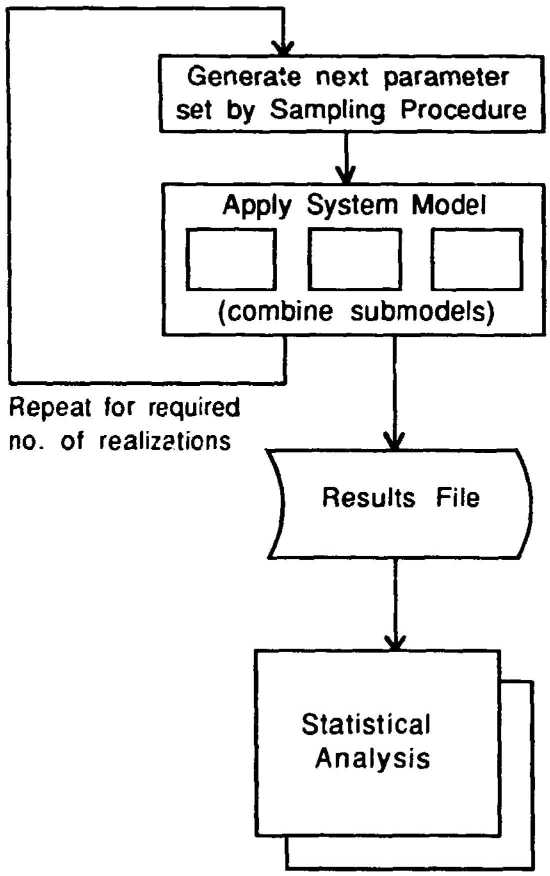


Figure 5 General scheme for PSA modelling by the Monte Carlo method. Multiple sets of model parameter values are generated by a random sampling procedure. This can be done either in advance, or (as shown here) one set at a time. The mathematical models are then applied for each parameter set, constituting a realization of the system. The results from each realization are stored in a file, which may subsequently be analysed in a variety of ways, to extract statistical measures of the system performance.

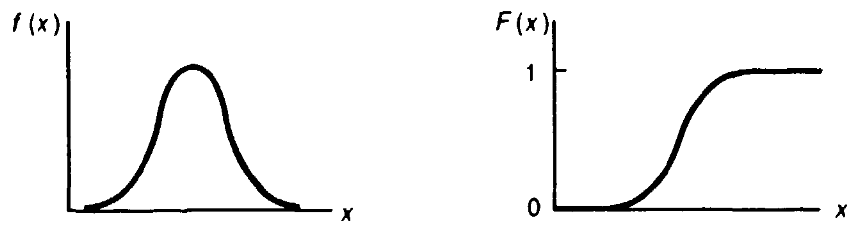
The next stage, that of applying the chosen system model, is repeated for as many times as is necessary to produce the desired number of realizations. This number might typically be hundreds or thousands; it might be chosen in advance, or determined as the sampling proceeds, in order to meet some criterion with respect to accurate determination of statistical properties. The exact nature of the modelling calculations will vary greatly from one application to another, but several common features of PSA codes may be noted –

- There is usually an *executive* part of the program that performs the functions of parameter generation, repeated execution of the model, and storing of results, which are common to many applications.
- The system model is usually constructed from *submodels*, each one representing a particular part of the system, or one physical process. A library of general-purpose submodel code sections is often used, from which the needs of a particular application can be constructed.
- The submodels are usually linked such that timr dependent outputs from one submodel, e.g. radionuclide fluxes, become the inputs to further submodel(s).

Probability Density Functions

A PDF is a mathematical way of describing how likely it is that an uncertain quantity will take any given value. For a model parameter used in PSA, this description of likelihood will be a subjective one – the outcome of expert opinion as to what value would be the appropriate one to use for the given model of the system. This subjective judgment may be made in the light of how often different values are found in experimental measurements, but it is not itself a measure of frequency of occurrence. Rather, it is a quantitative description of our incomplete knowledge.

The probability density function, $f(x)$, gives the probability of the value lying within a small neighbourhood of x, per unit width of the neighbourhood.



The probability density can be considered as the derivative of another function, $F(x)$, called the *cumulative distribution function (CDF).* For any value x, $F(x)$ gives the probability that the quantity has a value less than x.

Many standard distribution functions exist, such as the *Normal distribution* (which the above illustrations resemble), the *Uniform distribution*, *triangular* and ***beta*** distributions, and versions of all these with logarithmic x scale. For specifying model parameters in a PSA, standard forms such as these might be used, or others which better describe the uncertainties.

The output quantities from a PSA are also uncertain, and may be described by PDFs. In this case, standard functions are unlikely to apply, and the results can be plotted graphically in PDF or CDF form. Various properties of the distributions can also be calculated, such as means and standard deviations.

Analysis of PSA Results

The final stage of PSA is statistical analysis of the results. Because a wide variety of tests may be wanted, in combination with expert appraisal, it is usually convenient to implement this analysis with one or more separate codes, which may be run and re-run as required, interrogating a file of stored results from the main modelling code.

The kinds of analysis that are performed on PSA results, and the ways in which they may be presented, include –

Calculations of means and similar statistics The calculation of mean dose is often of interest because of its relationship to risk. Other simple statistics can also be calculated, such as percentiles of the dose distribution. Any of these quantities would typically be presented as plots against time. Because the PSA results represent only a finite sample of the possibilities, all such statistical measures are subject to estimation errors. These can be evaluated in terms of *confidence intervals.*

Uncertainty Analysis includes the foregoing, but extends to more detailed examination of the distribution of consequences. Distributions can be plotted in histogram or CDF form (see the box on page 17).

Sensitivity Analysis covers various investigations aimed at giving understanding of the results, and how they might change if any of the data or modelling assumptions were modified. It includes finding the relative importance of the different radionuclides and different exposure pathways, and especially testing the importance of each of the model parameters. Methods of testing and displaying parameter importance are actively being developed (see Chapter VI); those already in use include the calculation of several measures of correlation between the input parameters and selected output values. It is interesting to note that a parameter that very strongly influences consequences may still not be important in determining uncertainty, if that parameter is very well characterized (has a narrow PDF). An important aim of Sensitivity Analysis is to determine whether the assessed risks could be reduced either by modifying the repository design or by reducing uncertainty about particular parameters through more investigation.

Because the overall system model must be applied many times, the PSA approach involves large calculations. This can make it impracticable to use the most detailed and accurate models available. For PSA calculations models must therefore be developed that incorporate the most important features of the more highly detailed research models, while being more efficient in implementation. Apart from efficiency, simple models have the added advantage that they tend to have fewer parameters, and it is thus easier to understand the physical reasons for trends in the results revealed by sensitivity analysis.

PSA Compared with Alternative Approaches

The use of PSA techniques is not the only valid response to recognizing the presence of uncertainty.

- The result of modelling with each parameter assigned its "best-estimate" value has some interest as a reference point, even though it does not tell the whole story.

- It is possible to take a *conservative* approach, in which each uncertain parameter is assigned its "worst" value, i.e. that leading to the highest consequences. If the result represents an acceptable system performance, then there may be no necessity for more exhaustive analysis. Difficulties with this approach include the fact that "worst" parameter values, and hence worst consequences, may not exist as sharp bounds. Rather, it is a case of increasingly large consequences being associated with diminishing probabilities.

- It is possible to perform a less complete exploration of the range of possible system states, for instance performing a best-estimate model calculation, supplemented by a modest number of alternative realizations, selected by expert judgment to demonstrate the sensitivity of the results to variation of key parameters.

These alternatives may all be classed as *deterministic* modelling approaches, to be contrasted with the probabilistic or *stochastic* modelling approach of PSA. The different techniques may be combined in constructing an overall safety assessment. In particular, it may be impracticable to use the most detailed and realistic models in probabilistic mode. But deterministic application of these may supplement and help to justify the use of simpler models in a PSA.

V

THE PROBABILISTIC SYSTEM ASSESSMENT GROUP

The PSA Code User Group was set up by the NEA in 1985. It is now known simply as the Probabilistic System Assessment Group (PSAG). The terms of reference, approved by the Radioactive Waste Management Committee of the NEA, include exchange of codes, information and experience; conducting mutual peer reviews; contributing to code justification; and identifying and discussing technical issues of concern for further development of the PSA approach.

Since the first meeting of PSAG in May 1985, with seven members from six countries, the Group has grown substantially. Figure 6 illustrates the growth in attendance and in related activity.

The aim of exchanging information and experience is mainly carried forward through presentation of progress reports at PSAG meetings. Examples of the ground covered include –

- Design structures for PSA codes, and how their application fits into national assessment programmes;
- Development of submodels for PSA codes, e.g. for radionuclide transport by groundwater;
- Measures of statistical convergence;
- Studies of the benefits of different parameter sampling strategies;
- Treatment of the effects of climate change.

The NEA Data Bank has assisted PSAG in the exchange of computer codes. The Data Bank has a library of over 60 codes related to radioactive waste management, of which 17 are directly related to PSA; these are distributed on request. As well as several complete PSA codes, the Data Bank holds general-purpose modules such as random number generators and programs for exchanging PSA output data in a standard form.

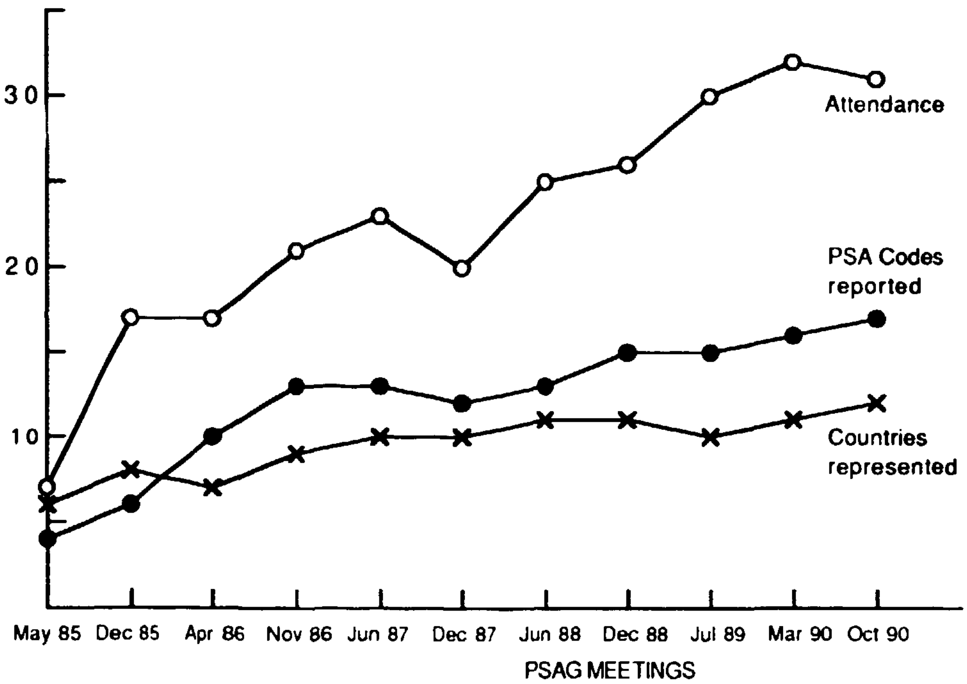


Figure 6 Growth in support for PSAG activities.

A major part of the activity of PSAG has been to conduct a series of code intercomparison exercises (PSACOIN). These exercises, described in Chapter VI, are aimed at contributing to the verification of the participating codes, comparing alternative calculational methodologies, and shedding light on whether the different approaches to model simplification lead to any significant difference in results.

Detailed exploration of important technical issues occurs in the Topical Sessions, which have become a feature of PSAG meetings. These are contributed to by PSAG members and invited speakers from outside the Group. Some of the topics discussed so far are described in Chapter VII.

VI

THE PSACOIN EXERCISES

International code verification, validation and intercomparison exercises are a well-established method for helping to increase confidence in the analytical methods being used for assessment of radioactive waste disposal schemes. There have been many such exercises focussing on models for different constituents of the disposal system, including models for groundwater flow and radionuclide transport through the geosphere (HYDROCOIN, INTRAVAL), biosphere transport models (BIOMOVS), geochemical models (CHEMVAL) and geomechanical models (COSA). In contrast, the PSACOIN exercises aim to contribute to justification of codes that model the entire disposal system using PSA methodology.

Work on the PSACOIN exercises began at the first meeting of PSAG. A series was envisaged in which the basic methodology, independent of the particular models, would first be tested, followed by a progression towards modelling of the kind that will be involved in real national post-closure safety assessments.

After initial conception of each exercise, the usual pattern for carrying it forward has been to appoint a Task Group to draw up a written specification and a questionnaire for eliciting contributions in a standard form. This work may involve pilot running of the case to discover any difficulties inadvertently introduced by the draft specification. With the support of the NEA, the Task Group analyses the responses, and draws up a written report for publication by the OECD. Approval from the whole PSAG is obtained at every stage of this process.

Level 0

This first exercise aimed to test the "executive" functions of PSA codes, and methods of statistical analysis of the results. Consequently, it specified an extremely simplified model of release of radionuclides from a repository vault, one-dimensional transport through the geosphere, and doses arising from consumption of drinking water. Twelve organisations contributed results.

The "simple" model turned out to pose certain problems for statistical convergence unlikely to be typical of real applications, but after four iterations a generally good agreement was obtained for estimates of mean dose versus time, and it was concluded that the executive parts of the PSA codes and their post-processors were operating as expected. Lessons were learnt with regard to specification of exercises, analysis of results for comparison, and presentation of PSA outputs. Unresolved issues over the rating of model parameter importances led to the conception of further exercises.

The Level 0 report was published in 1987.

Level E

Level E shared the same purpose as Level 0, with the important addition of comparison with an exact stochastic solution that enabled mean dose against time to be calculated precisely for a model disposal system. The model, while still relatively simple, was more realistic than that used for Level 0. It involved release from a vault by groundwater leaching, a two-layer geosphere transport path, and a drinking-water dose model. The exercise supplemented the probabilistic case with several deterministic cases (fixed combinations of model parameters), in order to assist with establishing correct code operation and data input. This practice was followed in later exercises.

The different predictions obtained with the 10 participating PSA codes were found to agree generally very well with the exact solution and with each other, despite the use of different sampling methods, different timestep algorithms, and sample sizes ranging from 100 to 10 000. Figure 7 shows an example comparison of mean dose values.

The report for Level E, which was published in 1989, was unable to be conclusive about the relative merits of different parameter sampling schemes, but drew conclusions about the calculation of confidence intervals for estimated mean values, and the testing of statistical convergence.

Level 1a

The Level 0 and Level E exercises had required most participants to write special-purpose code to implement the models specified. Level 1 began the trend to greater realism by encouraging the use of production submodels already developed by participants for use in their national programmes.

The Level 1a test case addressed a deep repository concept; it specified modelling of mobilization of radionuclides within the vault, release into a two-

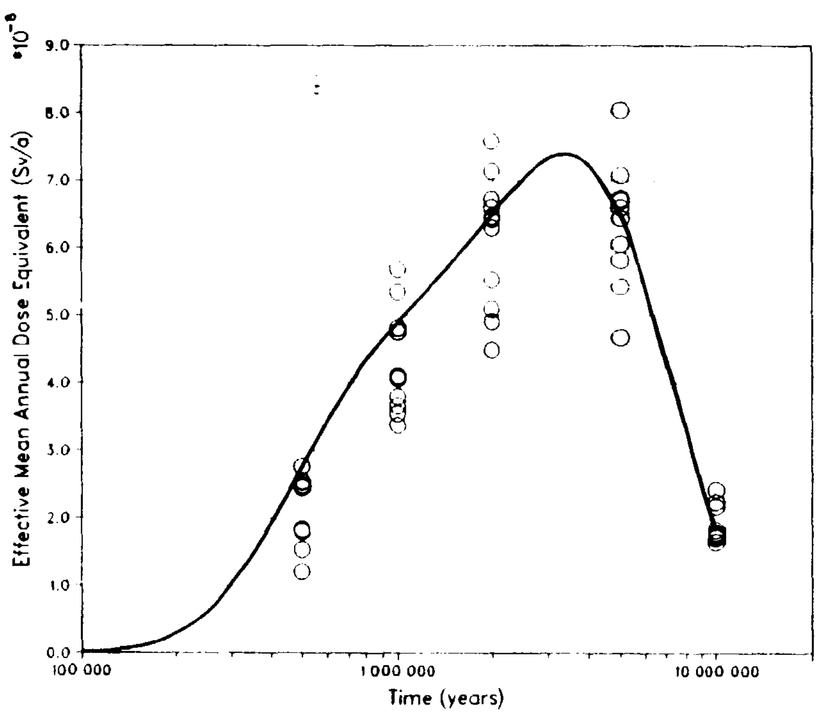


Figure 7 Example comparison of results from the PSACOIN Level E exercise. Participants' estimates of the mean total dose from the chain ^{237}Np - ^{233}U - ^{229}Th at 5 times are plotted together with the exact solution (continuous line).

stage geosphere transport path, and calculation of doses from drinking well-water. The specification was fairly prescriptive with regard to geosphere transport modelling methods, but gave considerable freedom with respect to the vault modelling. This gave opportunity for the exercise to study in a preliminary way the relative importance of the uncertainties associated with data values and uncertainty in model formulation.

The Level 1a report was published in 1990.

Level 1b

This exercise, currently in progress, is a case based around modelling transport within the biosphere. The specification is such that the case could be considered to represent a near-surface disposal facility, but the exercise should be equally relevant to other concepts. It aims to give participants experience of modelling biosphere processes at a level of detail suitable for inclusion in overall system models as used in PSA calculations, and to study the impact of data uncertainty in the biosphere subsystem. Completion of this exercise is foreseen for 1991.

Level S

Level S, for which the final report is currently in preparation, returns to questions of basic methodology, specifically addressing approaches to sensitivity analysis (SA). It uses the Level E case as a basis for investigating SA methods, asking for specific measures of sensitivity to be evaluated, measures that focus on the effect of changing parameter PDFs in some way: shifting the mean or narrowing the range. However, participants were also invited to submit articles exploring the subject of SA and proposing other measures of sensitivity. In this regard, it differs in style from the other PSACOIN exercises.

Further Exercises

Additional PSACOIN exercises are currently being considered. That most likely to be pursued next is *Level 2*, which would be intended to continue progress towards correspondence with real assessment situations. The question of modelling uncertainty would be a primary focus of the exercise. Data would be specified in the form obtained from field or laboratory investigations, not in terms of quantities that are fundamentally unobservable or based on particular conceptualizations of the active processes. The exercise would also address the question of how increasing amounts of site data may affect uncertainties in assessment results.

VII

IMPORTANT ISSUES IN PSA

Many PSAG members not only have the job of developing computer codes that will play a crucial role in their national strategies for performance assessment of radioactive waste disposal facilities, but also have an influence in shaping those strategies. They have therefore always been keen to discuss technical issues ranging from computational techniques to the underlying philosophy of probabilistic assessment. The need has been felt, not only to share the insights and experiences of the Group members, but also to seek outside stimulation by inviting speakers expert in related fields.

An illustrative selection of the topics discussed in this way follows.

Statistical Sampling Strategies

Different sampling methods have been compared, not only in Topical Sessions, but through the PSACOIN exercises. The central issue is how to obtain the most accurate statistical results from a given number of sample modelling calculations. It seems that for different statistics of interest – for example mean dose values, or measures of parameter sensitivity – different sampling strategies are preferable.

Reduction of Research Codes to PSA Submodels

A Topical Session was held in which examples were reported of how submodels, at a suitable level of detail for inclusion in a PSA code, could be derived from and calibrated against more complex models and information. The experience presented covered the repository and waste containment behaviour, groundwater flow and radionuclide transport in both porous and fractured media, the biosphere, and a model for glacial ice-sheet movement and sea-level changes.

Spatial Variability

Several speakers have outlined geostatistical approaches to represent spatial variations and associated uncertainty of hydrogeological quantities when only a sparse set of data is available. This is an important area with many open questions, since the acquisition of such data is extremely expensive, and could in any case be limited by a desire to preserve a site relatively intact. The difficulties of characterizing spatial variations led one speaker to suggest that a highly predictable (spatially uniform) site of medium quality could be far better than a spatially variable site that has a chance of being excellent in performance.

Different Treatments of Uncertainty

Fuzzy Set Theory is thought by some to provide a way of handling vague qualitative descriptions, and of dealing in measures of likelihood that are not subject to traditional self-consistency rules, such as total probability summing to unity. The validity of such descriptions is hotly contested by others.

Different kinds of uncertainty are sometimes distinguished: Type-A, due to stochastic variability in physical processes, and Type-B, arising from lack of knowledge. Some feel that these two types of uncertainty should be segregated in presenting the results of probabilistic modelling. Against this, there is a *Bayesian* view that all uncertainty is subjective: while separating different sources of uncertainty might be useful for presentation purposes, no sharp dividing line exists between one kind and another.

Derivation of Parameter PDFs

Data uncertainties are a fundamental input to PSA calculations. It is thus important that the distribution functions used accurately reflect expert opinion, and that the experts understand how the PDFs are being used in modelling. Experience has been presented of using formal elicitation methods for encoding expert opinion. Studies have also been reported on the impact of using different PDF shapes consistent with limited descriptions of parameter uncertainty.

VIII

PAST AND FUTURE ROLES OF PSA IN PERFORMANCE ASSESSMENT OF RADIOACTIVE WASTE DISPOSAL

In safety assessment of radioactive waste disposal, PSA is a technology which has developed greatly over the past 5 years, and is now maturing. The PSAG has played an important role in this development.

PSA has been successfully implemented and applied. Its use in assessments for licensing purposes has been limited to date, but it has been used in a number of preliminary assessments, either of real facilities or of generic or conceptual systems. For instance –

- The United Kingdom Department of the Environment has conducted three "dry runs" of their assessment methodology, for conceptual deep disposal systems nominally located on the Harwell site. Dry Run 3 incorporated into a probabilistic analysis modelling of climate sequences and their effects on the repository environment, as well as the processes involved in release of radionuclides from the vault and their transport in the geosphere and biosphere.
- The Commission of the European Communities PAGIS study (Performance Assessment of Geological Isolation Systems for Radioactive Waste) included probabilistic assessments of conceptual repository systems for high-level waste disposal at four sites representative of different geological media – clay, crystalline rock, salt and seabed sediments.
- Studies by Atomic Energy of Canada Ltd. of a hypothetical disposal system for spent fuel in a crystalline rock environment have made extensive use of PSA.
- In the United States, a number of probabilistic studies of hypothetical high-level waste repository sites have been undertaken by Sandia National Laboratories (supported by the US Nuclear Regulatory Commission) for the purpose of methodology demonstration.

Looking to the future, many other countries have set out plans for integrated performance assessment of planned disposal facilities. PSA figures largely in these assessment methodologies. An increasing role for probabilistic methods can therefore be foreseen in assessments for licensing of disposal facilities.

In this evolving context, there is reason to believe that the NEA Probabilistic System Assessment Group will remain a vigorous player on the international scene and continue to receive support from the participating countries. Initially, the Group's activities centred around the issues of PSA code development and verification, and consideration of the effect of uncertainties in model parameters on overall assessment results. Yet it is increasingly realized within the Group that the relationship of PSA to the overall process of post-closure radiological assessment requires further consideration. In particular, the Group will most likely give increased consideration to the propagation of uncertainties in conceptual models through a PSA calculation, and how the effects of such uncertainties might be incorporated into the presentation of safety assessment results. As noted earlier, the PSACOIN Level 2 exercise is being designed in part to address these questions.

RECOMMENDED FURTHER READING

Additional information can be found in the following publications:

Uncertainty Analysis for Performance Assessments of Radioactive Waste Disposal Systems. Proceedings of an NEA Workshop held in Seattle, USA, February 1987. Published by OECD/NEA, Paris, 1987.

PSACOIN Level 0 Intercomparison. Published by OECD/NEA, Paris, 1987.

PSACOIN Level E Intercomparison. Published by OECD/NEA, Paris, 1989.

PSACOIN Level 1a Intercomparison. Published by OECD/NEA, Paris, 1990.

PAGIS – Performance Assessment of Geological Isolation Systems for Radioactive Waste. Reports published by CEC as Nuclear Science and Technology Reports EUR11775EN to EUR11779EN, 1988.

Risk Analysis in Nuclear Waste Management. Proceedings of an ISPRA Course held at JRC Ispra, Italy, May-June 1988. Published by Kluwer Academic Publishers, Dordrecht, NL, 1990.

Safety Assessment of Radioactive Waste Repositories. Proceedings of a joint CEC/IAEA/NEA International Symposium held in Paris, October 1989. Published by OECD/NEA, Paris, 1990.

Disposal of Radioactive Wastes: Review of Safety Assessment Methods. Published by OECD/NEA, Paris, 1990.

Organisations Participating in the Probabilistic System Assessment Group

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Canada:	Atomic Energy of Canada Ltd.
Finland:	Technical Research Centre of Finland (VTT).
Germany:	Research Centre for Environment and Health: Institute for Deep Disposal (GSF: IfT).
Japan:	Japan Atomic Energy Research Institute. Power Reactor and Nuclear Fuel Development Corporation (PNC).
Spain:	Technological, Energy & Environmental Research Centre (CIEMAT). National Waste Management Company (ENRESA). Polytechnical University of Madrid.
Sweden:	Swedish Nuclear Fuel and Waste Management Company (SKB). Swedish Nuclear Power Inspectorate (SKI). Swedish National Board for Spent Nuclear Fuel (SKN). University of Stockholm.
Switzerland:	Paul Scherrer Institute.
UK:	Department of the Environment: HM Inspectorate of Pollution. Electrowatt Engineering Services (UK) Ltd. AEA Technology. INTERA Sciences. National Radiological Protection Board.
USA:	Sandia National Laboratories. Nuclear Regulatory Commission. Battelle Pacific Northwest Laboratories. Southwest Research Institute.
CEC:	Joint Research Centre, Ispra (Italy).
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