INFORMATION REQUIREMENTS FOR THE PROBABILISTIC RISK ASSESSMENT OF UNDERGROUND DISPOSAL OF LOW LEVEL WASTES

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ABSTRACT

The UK Department of the Environment (DoE) will perform independent post-closure safety assessment of proposals for the disposal of low-level radioactive wastes in engineered facilities in shallow ground. The assessments will make use of methods and a suite of computer codes developed on behalf of the Department. In particular, a probabilistic risk assessment will be made using the UK DoE SYVAC simulation program and additional models, or a new time dependent probabilistic code. In this paper, the DoE assessment criteria, methodology and modelling capabilities are outlined; the general characteristics of the information required are discussed; and the specific information needs, as presently perceived, are identified. It is concluded that: most of the data that can be obtained by direct means will be provided by site investigations and research now in hand, although there may be uncertainty due to sparse regional data; some parameters can only be obtained by, or with the assistance of subjective judgement; the process of data reduction is not straight forward and adequate time must be allowed for this if a comprehensive and defensible assessment is to be constructed.

INTRODUCTION

In the United Kingdom, the nuclear industry, represented by UK Nirex Ltd., is presently seeking a site suitable for the disposal of low-level radioactive wastes (LLW) by emplacement in a shallow engineered facility. Hydrogeological and geochemical investigations are now proceeding at each of four candidate sites proposed by Nirex.

To obtain authorization to proceed with the development of disposal facilities, Nirex must satisfy the authorizing Departments, principally the UK Department of the Environment (DoE), that certain conditions are met; these are laid out in the authorizing Department's "Principles" (1).

The DoE will carry out independent assessments of post-closure safety of radioactive waste disposal facilities proposed by Nirex and will also audit Nirex's own assessments. The assessments will make use of a suite of methods and computer codes developed on behalf of the Department.

The object of this paper is to outline the DoE approach and capabilities in post-closure radiological assessment, to examine in general terms the information required to support the assessment procedure, and to discuss the difficulties in the generation of data, or reduction of data to the requisite form.

UK Disposal Concept for LLW

Most low level wastes will be compacted and fitted in steel or concrete boxes designed to provide isolation from groundwater for at least 300 y. The boxes will be stacked and grouted into concrete vault structures; the alkaline (high pH) and reducing (negative Eh) chemical environment created is expected to persist for a much longer period and will reduce the movements of longer-lived radionuclides, e.g., actinides. In addition to limiting groundwater movement by its low permeability, the vault structure will limit risks due to intrusion by plants, animals and human activity.

The vault structures are likely to be constructed within the saturated zone in a clay stratum. Clays are favored because of their low permeability, good sorptive properties and plasticity in response to disruption, e.g., earthquakes. The sites chosen for further investigation represent both glacial boulder clay deposits of limited thickness and thick marine clays. Two coastal and two inland sites are being investigated.

It is anticipated that the repository designs will take advantage of the particular geological characteristics at each site and may thus differ considerably. Simple sheet steel lined trenches, concrete lined vaults, shallow tunnelled vaults and tumuli are all being considered (2).

Assessment Criteria and Methodology

In assessing the post-closure radiological safety of proposals for a solid radioactive waste disposal facility in the UK, the DoE will require that the risk to an individual in a year should not exceed 1 in one million (10^{-6} y^{-1}) (1). In this context, risk is defined as the probability that a defined sequence of events may occur leading to a given radiation dose, multiplied by the probability that such a dose will result in a fatal cancer, integrated over all such event sequences.

The aim of probabilistic risk assessment (pra) is to produce an estimate of overall risk from all foreseeable event sequences. The spectrum of events modelled must include the range of event sequences generated by uncertainty in present day behavior of the system and those generated by uncertainty in future conditions.

The DoE assessment methodology and capabilities have been developed through a number of preliminary and "Dry Run" assessments (3,4,5,6). The present DoE approach is to define a number of scenarios that represent the broad range of present and future conditions or evolutions that may affect a repository site. Each scenario is then analyzed, first using deterministic models to investigate parameter sensitivities and to make maximum estimates of consequence, and then, if maximum estimated consequences exceed the risk target, by probabilistic models. This procedure is illustrated in Fig. 1.

Currently, the UK DoE SYVAC (System Variability Assessment Code) is used to undertake pra of groundwater mediated release scenarios (7). It is necessary to use system variability techniques because in the general case of a non-linear dose parameter relationship, the dose $H(\bar{\underline{x}})$ due to the average parameter values $(\bar{\underline{x}})$ is not the same as the average dose $\bar{H}$ from the full dose probability distribution. That is

$$H(\bar{\underline{x}}) \neq \bar{H} = \int_{\underline{x}} p(\underline{x})\, H(\underline{x})\, d\underline{x}$$

Other release modes are treated as separate scenarios and the associated risks are calculated independently (3).

Using the procedure shown in Fig. 1, either it must be shown that the risk estimated for each scenario (given a probability of occurrence of 1) does not exceed the risk target, or probabilities of occurrence must be assigned to each scenario and the risks summed. This latter is difficult to do in a justifiable manner (5). In order to solve this problem, and also to take proper account of the sequential nature of temporal change, a fully time dependent pra code, VANDAL, is currently being developed by the DoE (8). Discussion of this code, and the implications of its use, are outside the scope of this paper.

An overview of the development of the UK DoE disposal assessment methodology is given in Ref. 9.

THE DOE ASSESSMENT TOOL KIT

UK DoE SYVAC

The present version, SYVAC A/C 1.03 has the capability for modelling radionuclide transport by groundwater mediated pathways from both shallow and deep repositories and calculating doses and risk to man. A version with improved features is under development (SYVAC D). The SYVAC A/C model makes use of three sub-models: VERMIN, GEO1, and ECOS; representing the vault and nearfield geosphere, the far-field geosphere and biosphere, respectively.

VERMIN (10) includes representations of the waste matrix, waste canisters, vault backfill, vault liner and the region of geological host medium (clay) damaged during construction. The migration of radionuclides is modelled taking account of:

- delay due to resaturation and canister corrosion;
- solubility and inventory limited leaching from the waste matrix;
- equilibrium sorption onto vault materials;
- radioactive chain decay;
- dispersion and advection.

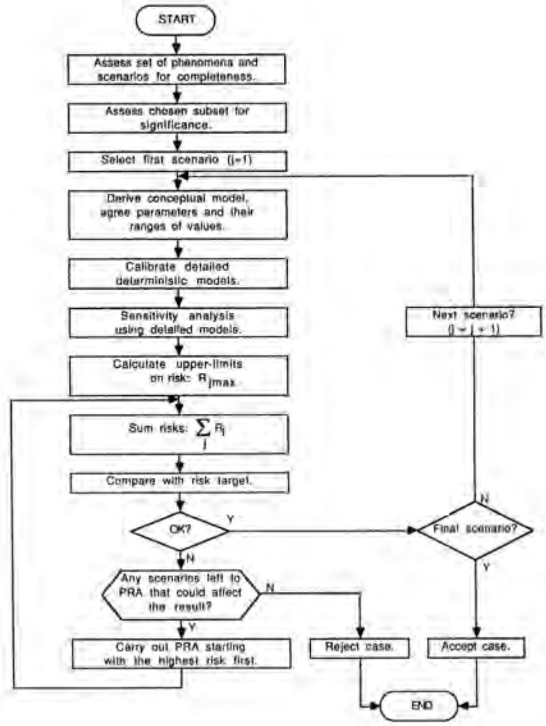

Fig. 1. An outline procedure for post-closure radiological risk analysis.

GEO1 (11) is an analytical model of the one dimensional water flow and radionuclide transport through a multilayer geosphere under saturated conditions taking account of:

- linear equilibrium sorption;
- linear longitudinal dispersion; and
- radioactive chain decay.

Both VERMIN and GEO1 work within the SYVAC program so that vault and geosphere parameers may be sampled. ECOS (12) is run independently of SYVAC to produce equilibrium biosphere dose factors, that is estimates of dose rate to a maximally exposed individual for constant rate of radionuclide input into the biosphere. The dose pathways considered include drinking water, external irradiation, inhalation, terrestrial foodstuffs and aquatic foodstuffs.

Supporting Models

The models used in probabilistic assessment must be as simple as possible so as to reduce computing power or time required. The models in pra should represent implicitly those processes that may have impact on risk by appropriate and well derived parameter probability distribution functions (pdfs). More detailed deterministic models are necessary to investigate the system represented in the probabilistic code and in order to assist in deriving appropriate pdfs for use in pra.

The development of realistic one-dimensional descriptions of groundwater flow relies on an adequate understanding of the hydrogeological conditions in the host and surrounding rock layers. In trail assessments, this has been achieved using two-dimensional porous media groundwater flow and radionuclide transport codes. Both finite element codes, e.g., FEMWATER and FEMWASTE, and a finite difference code, TARGET, have been employed.

TABLE I

UK DoE DISPOSAL ASSESSMENT TOOL KIT

Name	Function
Assessment Codes	
SYVAC A,C,D*	PRA Monte Carlo simulator using VERMIN, GEO1 and ECOS for saturated porous media, deep disposal (A) or shallow disposal (C), with importance sampling (D).
MAIA*	Micro based demonstration/research Monte Carlo pra code including multiple groundwater paths.
VANDAL*	Software engineered pra code with time variations and multiple paths.
PRA Submodels	
VERMIN 1,2,3*	Numerical model for repository resaturation, container failure, leaching and nuclide migration.
GEO 1,2,3*	Analytical solution of 1D migration equation for multiple geosphere layers.
ECOS	Detailed equilibrium biosphere model.
BIO1*	Time dependent compartmental biosphere model for VANDAL.
Supporting and Additional Models	
INVENT	Radionuclide inventory and hazard index code.
INTRUDE	Calculates risks from human intrusions and excavation of contaminated material.
FEMWATER) FEMWASTE)	2D/3D finite element groundwater flow and transport codes.
TARGET) SWENT)	2D/3D finite difference groundwater flow and transport codes.
MINEQL) PHREEQE)	Equilibrium chemical speciation codes
CHEMTRIN*	Coupled chemistry and transport code to include radioactive decay and redox reactions.
TIME2*	Monte Carlo simulation of site evolution including climate driven natural processes and human intervention.

* Codes currently under development by UK DoE.

Such codes are also used to re-examine high risk runs produced by SYVAC in order to verify the assumptions upon which they are based.

Equilibrium chemical speciation codes, MINEQL and PHREEQE have been used to estimate radionuclide solubility limits and speciation in solution. The sensitivity of solubility limits and speciation to the presence of complexing agents, e.g., EDTA has also been investigated. The coupled chemistry and flow code, CHEMTRN, has been used to model movement of dissolved species under equilibrium transport conditions through a sorbing medium and hence to estimate, or verify, simple equilibrium sorption coefficients (13).

A compartmental biosphere model with temporal parameter variation and parameter sampling is presently being developed. It may be used as a standalone code to derive simple biosphere representations for use in SYVAC or as part of the VANDAL time dependent pra code.

Additional Models

Additional models have been developed to represent processes outside the scope of SYVAC.

Preliminary radiological assessments of shallow-land repositories show that overall risk may be dominated by risks from intrusion (3). Risks may arise directly, i.e., to the intruding individual, and indirectly, through exposure of others to excavated materials and disruption of the repository leading to enhanced migration in groundwater. The INTRUDE code (14) has been developed to estimate risks from intrusion. The exposure pathways considered are:

- inhalation of active dust and external irradiation of the intruder; and
- longer term pathways affecting those living nearby, resulting from the excavation, distribution and incorporation into agricultural soils of radioactive materials.

Estimates of the radiological risk from the evolution of radio-labelled gases have been made by simple conservative calculations. The information and scientific understanding necessary to construct more realistic models is lacking at present.

Over the period of interest for radioactive waste disposal, the climatic regime and topography is certain to change and may influence the level of risk. The TIME2 code (15) has been developed to provide a method of predicting future hydrological and meteorological conditions affecting a waste disposal site. This is a stochastic model of essentially climate driven processes, although a facility to model the effects of intrusive activity is also included. For a single run, the model output is a consistent climatic and geomorphic future for the site. These can be used on a one to one basis as input to a time dependent radiological risk assessment code or the results from multiple runs can be analyzed to produce pdfs for output parameters such as temperature, precipitation and repository cover as a function of time.

GENERAL REQUIREMENTS

The assessment procedure outlined in Fig. 1 requires that scenarios are first identified on the basis of available information and professional judgement. The physical and chemical processes and events comprising any scenario will determine the conceptual and mathematical models to be used in the calculations of risk. Some knowledge of the site characteristics and the repository design is required before the detailed scenarios can be identified. Hence, the nature of the models required and their data cannot be predetermined. Initial consideration of the sites selected by Nirex indicates that with minor additions, the models already in use by the

Department will form adequate tools for the assessment of groundwater pathways and intrusion; some additional work may be required on gaseous evolution when data are available.

The main categories of processes and events likely to influence radiological performance have been identified in trail assessments (3,4,5,6) as:

a) Natural phenomena (e.g. release to groundwater and subsequent advection and diffusion; biotic transport; glacial disruption and erosion of the repository and site).

b) Repository-induced effects (e.g. generation and movement of gases; disturbance to local geology).

c) Human-induced effects (e.g. inadvertent intrusion due to construction work; resource exploitation or agricultural activity on the site after the end of a period of institutional control).

The specific information needs relating to each of these areas is given in the "Specific Information" section.

Levels of Detail

Information will be required at several levels of detail:

1) Raw observations (e.g. borehole logs).

2) Processed data for use in detailed calculations (e.g. values of vertical and horizontal hydraulic conductivity at different locations, groundwater chemical composition, Eh and pH).

3) Parameter values, ranges and joint probability distributions for use in simplified models adopted for pra (e.g. probability density functions of spatial averages of hydraulic conductivity and porosity for each segment of the geosphere path; K_d's for each geosphere layer material and for each radioelement.

The acquisition of raw data, level 1, will be the responsibility of UK Nirex Ltd. The DoE will normally require level 2 data but will also wish to assure that adequate and justifiable techniques are used in the collection, assurance and processing of level 1 data; a clear description of assumptions and methods used for interpreting level 1 data will be required. Much of the data is not site specific and will come from general research programs (16).

The DoE assessment team will use level 2 data in detailed deterministic models to define input parameters for probabilistic calculations, level 3 data. A number of judgements are necessary in the process; the most suitable models and boundary conditions must be selected, sensitivity to assumptions and variable conditions must be examined and assessed. Figure 2 shows the interactions of the model and data hierarchies schematically.

Uncertainty, Subjectivity and Bias

Some quantities will be obtained directly from measurement whereas many used for the assessment over the typically long timescales involved, can only be estimated by professional judgement. Techniques for codifying subjective views to obtain statistically justifiable parameter pdfs and the use of Bayesian techniques to incorporate measured data in such pdfs have been investigated and practiced for a few key parameters (17).

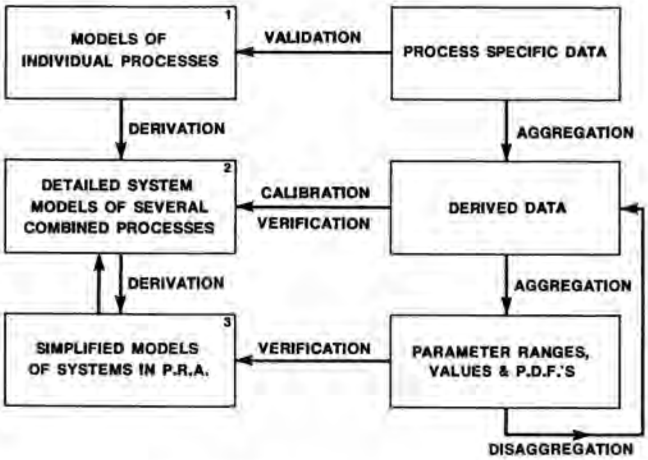

Fig. 2. Levels of Detail.

Even for present day values obtained from direct measurement, uncertainties will exist. These uncertainties must be estimated. Sufficiently large samples of variable parameters are important to permit statistically significant estimates of the probability distributions to be obtained. From field work, observations at a given location may provide satisfactory point values of parameters, however, there will often be considerable spatial variability and estimates of both means and spatial variations will be required. Uncertainties in some parameters are likely to reflect the constraints on a site investigation program.

Considerable uncertainty is associated with any attempt to estimate the long-term evolution of the site environment. For probabilistic risk assessment, many of the level 3 parameters will be gross spatial and temporal averages, over biosphere compartments, over identifiable segments of the repository and over migration paths in a particular geosphere layer. Probability distributions will reflect judgements or degrees of belief about the averages concerned.

At several stages in the assessment systematic error or bias may be introduced due to selection of data, inappropriate model use or other causes. It is important that potential sources of bias are recognized and tracked through the assessment so that the degree of bias and the possible effects of bias combinations (multiplicative, additive or subtractive) can be estimated.

A more detailed consideration of uncertainties in assessing risk and their treatment is given in Ref. 18.

Quality Assurance

Any data provided must, whether from direct measurement or from expert judgement, be supported by information on its source, its method of acquisition and on any subsequent manipulation involved in its transformation into the form required for a particular calculation.

For the Nirex site investigations details of a quality assurance program carried out by contractors independent of those directly involved in data acquisition and site investigation will be requried. This program will be audited by contractors acting for the DoE.

SPECIFIC INFORMATION

Source Term

The types of waste, the inventories of radionuclides in each and the chemical composition of each must be known, as must the dimensions and construction of containers for each type of waste. The materials specifications and the predicted corrosion or degradation behavior in the chemical environment of the repository-groundwater system will be required.

Information on voidage, organic and plastics content and information on organic degradation products due to biological and chemical action are required. The production of any colloidal species by the degradation of the waste and other constituent materials in the repository must be considered. Any potentially deleterious reactions between the waste, the encapsulant, the containers, corrosion products and other materials in the repository should be identified.

The method of construction and backfilling (e.g. whether or not concrete is maintained saturated throughout construction and operation) must be known. The repository and backfill materials should be specified both chemically and physically especially regarding sorption and hydraulic conductivity which should be adequately determined by experiments.

Table II gives the input parameters required for the vault model VERMIN and the anticipated sources of data.

Natural Processes

Before normal radionuclide release scenarios can be examined in detail, some general information will be required. The overall lithology, geometry and hydrology of identified rock layers must be described over the entireregion affecting the behavior of the site. A detailed description of the Quaternary stratigraphy of the region, and an overview of the timing and effects of interglacial, periglacial and glacial periods, is required. The extent of past and present faulting should be ascertained by field investigations as well as by analysis of existing data.

For each scenario requiring analysis for movement of radionuclides in groundwater, the geometry of the flow domain must be specified together with the appropriate boundary conditions for flow and transport. Within the domain, values of hydraulic conductivity dispersion and sorption properties must be known at different locations to provide an adequate description of the spatial variation of these variables for use in deterministic calculations. Boreholes and surface geophysics will provide data on stratigraphy and geometry. Hydraulic conductivity and porosity will be determined by pump tests and laboratory determinations. As time for collection and data analysis will be limited, and because it may be desirable to minimize perforation of the site, the spatial data set may be rather sparse. A geostatistical technique for estimating conditions and uncertainties due to sparse data is currently being investigated.

The calculation of groundwater flow is sensitive to the boundary conditions used in models. A site investigation program entirely within the boundary of a site may leave substantial uncertainties in the hydrogeological parameters and boundary conditions of the flow domain. It is important that these uncertainties are quantified whenever practicable.

The effect of chemical processes in the vault and geosphere have been shown to be a very important factor affecting risk. For the timescales anticipated for the development of LLW facilities, it will be necessary to make use of largely empirical understanding of chemical processes and results from

TABLE II

INPUT PARAMETERS FOR THE VAULT MODEL: VERMIN

Description of Parameter	Source
Inventory of each radionuclide	Nirex/DoE
Time for canister or package failure	Detailed corrosion or degration models
Time for buffer failure and effect on hydraulic conductivity	Detailed degradation model
Solubility limit, C_{sat}, for each nuclide and relation to pH, Eh and temperature	Experiment and chemical thermodynamic calculations
Sorption coefficient, K_d, for each nuclide on repository materials and clay	Spatial average over material of each type derived experimentally
Density of encapsulated waste, and repository materials	From Nirex repository and package specification
Hydraulic conductivities of materials	Experimental results and subjective judgements
Diffusion coefficient of materials	As above
Porosities of materials	As above
Hydraulic gradient across repository	Calculated from 2D/3D hydrogeology
Leachrate for each nuclide from the package	Experimental results and subjective considerations
Number of trenches, dimensions and stacking	From the Nirex design
Thicknesses of concrete liner, clay sheath	From the Nirex design
Properties of damaged zone	Geotechnical considerations

simple laboratory experiments on samples of waste, repository and geological materials. The derivation of appropriate chemical data on a two- and five-year timescale has been discussed in Ref. 16.

When considering the biosphere, it is necessary to consider not only present day water abstraction, surface hydrology, land use, agricultural and fisheries practices, but also possible conditions at long times in the future including conditions in alternative climate states. A degree of conservatism is unavoidable and worst case local land and water use must often be assumed on the grounds that over the long time periods of interest such conditions are likely to occur, if only for a short period. The transport of radionuclides by burrowing animals, soil fauna and deep rooting plant species must be considered.

Repository Induced Effects

The groundwater and radionuclide transport calculations must take account of the chemical conditions within the vault and created in the nearfield geosphere. Possible chemical interactions between the repository and host media will need to be considered. Therefore, the chemical composition of the repository, packaging materials, wastes and their degradation products must be known.

It will be necessary to consider the production of gases, principally hydrogen from metallic corrosion and the possible consequent desaturation of the vault or modification of groundwater flows. In addition, radio-labelled gases generated by biodegradation, radiolytic and chemical action, especially methane and carbon dioxide labelled with C-14, may provide a significant radiological risk. It will be necessary to know the biodegradable content of wastes, the accessibility of the wastes to micro-organism and activity of microbes or bacteria within the vault environment.

The possible effects of different loading patterns on the structural integrity of the repository and hence on the variation over time of the hydraulic conductivity may be significant. The mechanical and hydraulic properties of the host material may be significantly altered by the removal of overburden, excavation, construction and operation of the repository. Hence, in addition to measurements taken in the undisturbed geology, information will be required on how the host material behaves in response to stress relief and as a result of compaction, or other changes, induced by site construction and operation.

Human Induced Effects

Human activity on or near to the site may result in intrusion and hence risks to the intruder and also risks to other members of the public through the distribution of excavated waste or contaminated material at the surface, or through damage to the repository or surrounding geology leading to enhanced water flow.

It is necessary to know the classes of intrusive activity e.g. site investigation, construction, mineral or groundwater extraction, that may affect a site. Risks to the intruder and to local members of the public due to the excavation of wastes can be estimated using the INTRUDE code; the input parameters required and the anticipated sources are given in Table III. It may be noted that the greatest uncertainties are the probability or frequency of intrusion and the fate of excavated material. These must necessarily be estimated subjectively from a knowledge of present day ground investigation and construction techniques.

Risks due to damage to the vaults or surrounding geology and enhanced groundwater movement can be folded into the normal groundwater release calculations or treated as a special case. In either case, information is required on the structural integrity of the vaults, the resistance to degradation of vault materials and radionuclide leaching in these circumstances.

TABLE III

INPUT PARAMETERS FOR THE INTRUSION MODEL: INTRUDE

Description of Parameter	Source
Inventory of each radionuclide	Nirex/DoE
Total mass of cemented waste	Nirex design
Probability of intrusion	) TIME2 and subjective) considerations
Mass of excavated waste	)
Shielding factors for external dose	Calculations
Dust loading during excavation	)))
Duration of intrusion	) Consideration of) modes of intrusion
Mass of waste transferred to ground surface	)))
Contaminated area	)
Dose conversion factors for land contamination	Biosphere model

CONCLUDING REMARKS

The UK DoE approach to post-closure radiological risk assessment has been outlined. It is the intention to undertake probabilistic risk assessments of the sites proposed for low-level radioactive waste disposal.

Comprehensive local hydrogeological information is expected to come from the Nirex site investigations. Regional hydrogeological information will be compiled from existing sources, although, if overall site performance is shown to be very sensitive to regional conditions this may lead to large uncertainties on estimates of risk. Information on the physical and chemical behavior of the wastes, repository materials and geological materials will come from the laboratory investigations and research sponsored by Nirex and DoE. Much of this data cannot be used directly but will be used as input to detailed deterministic models to define scenario conditions or input parameters for simpler probabilistic models.

Some parameters required, e.g. probabilities of intrusion, can only be derived through the use of "expert" opinion; others, e.g. regional hydrogeological properties, must be derived by a combination of measurement data and subjective judgements.

The volume of data and information that will eventually be available is very large; the length of time required to assimilate this, and to construct a comprehensive risk assessment should not be under estimated. It should also be recognized that the assessment process is an iterative one; additional information needs may be identified as the assessment progresses and it will be possible to focus attention on key parameters that have most impact on risk. Adequate time must be allowed so that the results of preliminary assessment can be used to guide data gathering and research.

ACKNOWLEDGEMENTS

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