Safety Assessment and Licensing Issues of Low Level Radioactive Waste Disposal Facilities in the United Kingdom

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Abstract
More than 90% of radioactive waste generated in the United Kingdom is classified as low level and is disposed of in near surface repositories. BNFL owns and operates the principal facility for the disposal of this material at Drigg in West Cumbria. In order to fully optimise the use of the site and effectively manage this 'national' resource a full understanding and assessment of the risks associated with the performance of the repository to safely contain the disposed waste must be achieved to support the application for the site authorisation for disposal. This paper describes the approaches adopted by BNFL to reviewing these risks by the use of systematic Safety and Engineering Assessments supported in turn by experimental programmes and computational models.

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1. INTRODUCTION

More than 90% of radioactive waste generated in the United Kingdom is classified as low level and is disposed of in near surface repositories. The principal facility for its disposal in the United Kingdom is at Drigg in West Cumbria which has been operating since 1959. Wastes disposed of to Drigg must not exceed 4.0 gigabequerels per tonne alpha and 12.0 gigabequerels per tonne beta/gamma activity. These are upper limits and the bulk of the waste accepted falls well below this activity content. Some of the contaminants disposed of to Drigg, although small in quantity, have extremely long half lives, e.g. uranium, and consequently any assessment of the performance of the site must take into account long time scales. This paper describes the approaches adopted by BNFL to reviewing risks associated with the safety and engineering performance of the repository. These assessments use a variety of systematic risk assessment techniques to help define the boundaries of the system, and to select and evaluate credible scenarios for changes in system performance. The techniques include the use of computational models, relationship diagrams or belief nets, fault trees, event trees and expert judgement and peer review. The paper outlines the structure within which these tools can be used to provide a coherent approach to the safe performance of engineered components of the design. The approach also results in improved documentation and a better understanding of system performance, helping to optimise the design and provide a co-ordinated input into the Safety Case which supports the authorisation of the disposal site.

2. UK REGULATORY FRAMEWORK

2. 1 Legislation: Radioactive Substances Act 1993 (RSA '93*)*

The disposal of liquid, gaseous and solid radioactive waste to the environment is subject to the provisions of the Radioactive Substances Act 1993 (RSA'93). Although a recent Act its purpose was to consolidate an earlier one, the Radioactive Substances Act 1960 with amendments introduced by subsequent legislation including Part V of the Environmental Protection Act 1990. RSA'60 also replaced earlier legislation; the Radioactive Substances Act 1948. There is therefore a long-established legal framework in the UK for exercising control over radioactive wastes.

Limits and conditions on the disposal of radioactive wastes are detailed in site specific Authorisation Certificates. Over 1100 sites in England and Wales are authorised. The majority of these consists of hospitals, universities and industrial research or manufacturing centres. These are generally referred to as 'non-nuclear sites'. The more significant radioactive discharges however are from a relatively small number of sites licensed under the Nuclear Installations Act 1965. These are generally referred to as 'nuclear sites' and are also authorised to dispose of radioactive wastes. These nuclear sites include nuclear fuel fabrication and reprocessing plants, nuclear power plants, atomic research establishments and isotope production centres. (Ref. 1)

2.2 Regulatory Authorities

The Environment Agency (the Agency) is responsible for administration and enforcement of RSA'93 in England and Wales. Separate but similar arrangements exist in Scotland and Northern Ireland where the Scottish Environment Protection Agency (SEPA) and the Environment and Heritage Service are the respective regulatory authorities.

The Agency was established on 1 April 1996 by the Environment Act 1995. It is a non-departmental public body (NDPB) which took over the functions, powers and duties of its predecessor bodies, the National Rivers Authority, Her Majesty's Inspectorate of Pollution, and the Waste Regulation Authorities.

The Agency has widespread responsibilities under environment legislation for management and regulation of the water environment, and for controlling industrial pollution and waste including, those arising from the nuclear industry. Bringing these together in a provides the opportunity for more coherent and integrated environmental protection, and for a more streamlined service to industry and the public.

The Nuclear Installations Inspectorate also has a roll in respect of Nuclear Safety on site and in the issuing of the Site Licence.

3. AUTHORISATION OF DISPOSAL FACILITIES.

For the purpose of implementing Government Policy on radioactive waste management, and after extensive consultation, the environment agencies have prepared Guidance on Requirements for Authorisation of Disposal Facilities on Land for Low and Intermediate Level Radioactive Wastes. Amongst other things this guidance set out principles and requirements for disposal of low and intermediate level wastes. (Ref. 1)

3.1 Principles

The essential principles are

Principle No. 1 - Independence of safety from controls
Following the disposal of radioactive waste, the closure of the disposal facility and the withdrawal of controls, the continued isolation of the waste from accessible environment shall depend on actions by future generations to maintain the integrity of the disposal system.

Principle No 2 - Effects in the future
Radioactive wastes shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.

Principle No 3 - Optimisation (as low as reasonably achievable)
The radiological detriment to members of the public that may result from the disposal of radioactive waste shall be as low as reasonably achievable, economic and social factors being taken into account.

Principle No 4 - Radiological protection standards
The assessed radiological impact of the disposal facility before withdrawal of control over the facility shall be consistent with the source-related and site-related dose constraints and, after withdrawal of control, with the risk target.

3.2 Requirements

The associated requirements are.-.

Requirement R1 - Period before control is withdrawn (dose constraint)
In the period before control is withdrawn, the effective dose to a representative member of the critical group from a facility shall not exceed a source-related dose constraint. Also during this period, the effective dose to a representative member of the critical group resulting from current discharges from the facility aggregated with the effective dose resulting from current discharges from any other sources at the same location with contiguous boundaries shall not exceed an overall site-related dose constraint of 0. 5 mSv/y.

Requirement R2 - Period after control is withdrawn (risk target)
After control is withdrawn, the assessed radiological risk from the facility to a representative member of the potentially exposed group at greatest risk should be consistent with a risk target of 10^{-6} per year (i.e. 1 in a million per year).

Requirement R3 - Use of best practicable means
The best practicable means shall be employed to ensure that any radioactivity coming from a facility will be such that doses to members of the public and risks to future population are as reasonably achievable.

Requirement R4 - Environmental radioactivity
It shall be shown to be unlikely that radionuclides released from the disposal facility would lead at any time to significant increases in the levels of radioactivity in the accessible environment.

Requirement R5 - Multiple-factor safety case
The overall safety case for a specialised land disposal facility shall not depend unduly on any single component of the case.

Requirement R6 - Site investigations
The developer shall carry out a programme of investigations to provide information necessary for the safety case and to demonstrate the suitability of the site.

Requirement R7 - Facility design and construction
The facility shall be designed, constructed, operated and be capable of closure so as to avoid adverse effects on the performance of the containment system.

Requirement R8 - Waste form and characterisation
The developer shall derive waste acceptance criteria consistent with assumptions made in assessments of the performance of the system and with the requirements for handling and transport.

Requirement R9 - Monitoring
In support of the safety case, the developer shall carry out a programme to monitor for changes caused by construction of the facility and emplacement of the waste.

Requirement R10 - System of records
The developer shall set up and maintain a comprehensive system of records for the recordings of detailed information on all aspects of the project affecting the safety case.

Requirement R11 - Quality Assurance
The developer shall establish a comprehensive quality assurance programme for all activities affecting the safety case. This shall include supporting activities such as research and assessment.

The United Kingdom has a well established national framework for radioactive waste and substantial experience in regulating the disposal of solid low level waste by near surface disposal. In order to satisfy and support the application for the licensing and authorisation for disposal at the Drigg Site a programme of technical work has been running for a number of years. This work has centred upon the Safety Assessment and Engineering Risk Assessments for the disposal facility.

4. SAFETY AND ENGINEERING ASSESSMENTS

The purpose of near surface disposal is to isolate radioactive waste so that it does not result in undue radiation exposure to workers, members of the public and the environment. Consideration of safety therefore needs to be included for long term aspects, in particular, after closure at times when there may be assumed to be no management or monitoring associated with the site.

In terms of radiological protection, the principal objective of radioactive waste management is to ensure that exposure of individuals does not exceed acceptable levels and that exposures are as low as reasonably achievable, social and economic factors being taken into consideration (ALARA). This approach has been developed and endorsed internationally for many years. Some of these exposures may be expected to occur, for example, due to gradual leaching of radionuclides into groundwater and subsequent transport to humans. Assessments may therefore need to project site and facility behaviour for time periods of the order of hundreds or even some thousands of years. Difficulties with projecting site and facility behaviour for these times distinguish post-closure assessments from typical operational safety assessments. Some types of exposures may only occur if certain events take place. Examples of such events are earthquakes and unusual weather conditions.

Events induced by human activities may also lead to exposure. Unfortunately there is no technical or logical basis for predicting the future actions of mankind. One of several of the following measures may be envisaged to limit the consequences associated with human activities: establishing concentration limits for specific radionuclides, implementing institutional control or setting design criteria such as a minimum depth for the disposal facility.

Although safety assessments play a role in all stages of a near surface disposal facility, as shown in Figure 1, their use is of greater importance in the stages following early concept development and site selection. Such assessments, inconjunction with the engineering assessments, can then be developed to assist in system optimisation and facility design by carrying out comparative assessments for various combinations of alternative waste packages, disposal modules and site management and closure measures.

The completeness and robustness of the safety assessment will in turn depend on the extent and quality of the data in terms of site characterisation, waste package performance and the role and performance of other engineered barriers. Close co-ordination of the safety assessment and the supporting data acquisition programmes is therefore necessary, with the safety assessment being a very valuable means of identifying and prioritising supporting research and development work.

Safety assessment plays a central role and may be used for multiple purposes during the development of a near surface disposal facility. Because these various uses may require different levels of detail and analysis and imply different data needs, it is imperative that the objective of the safety assessment be clearly defined in accordance with the particular application.

4.1 The Safety Assessment Process

The process of safety assessment for near surface disposal of radioactive waste requires a wide variety of information in order to describe the behaviour of the disposal system and to provide reasonable confidence in the achievement of compliance with safety and regulatory requirements. The process is shown in Figure 2 and involves the following activities: (Ref. 2).

- description of the disposal system, including site, wasteform and engineered structures

- determination of conceptual models of the behaviour of the system and its subcomponents

- identification and description of relevant scenarios
- identification of the pathways potentially leading to the transfer of radionuclides from the repository to humans and the environment
- implementation of appropriate models
- evaluation of the system performance, and
- verification of compliance of the assessment results with the design goal through critical review.

A conceptual model of the near surface disposal system is a description in terms of the general features present and their detailed characteristics. Amongst the most important features are those that identify the relative significance of possible radionuclide transfer routes, known as pathways. Through time, natural phenomena and human activities are expected to alter the characteristics of the system. A picture of that future situation and events is called a scenario. Scenarios deal with natural phenomena and gradual or abrupt changes in conditions that may lead to changes in the repository performance over time. These future situations are usually assessed for near surface disposal by using a deterministic analysis to model the performance of the facility under reasonably expected conditions. The assessment results, including identification of uncertainties, should be compared with the design goals and regulatory criteria. Probabilistic analyses to deal statistically with random events or parameters whose values are uncertain or variable are currently being evaluated as potential safety assessments techniques.

Characterisation of the system and description of the pathways requires appropriate data to be acquired through field or laboratory experiments. Scenario analysis involves the identification and definition of phenomena which could initiate or enhance the release of radionuclides from the repository and subsequent exposure to humans. Description of these phenomena can also initiate data gathering. Throughout the iterative process of safety assessment, additional data collection may be required that is focused on the parameters identified as important for safety of the repository.

To reach the goals assigned to the various uses of safety assessments several iterations of the assessment process should be performed. Activities can be iterated as shown in Figure 2. The first step of the process should consist of performing screening calculations in order to evaluate the ability of the proposed concept to meet safety requirements, and to focus on the relevant radionuclides, pathways, data of release mechanisms on which further knowledge is required. Screening calculations need only limited data on waste package characteristics as well as identification of the major pathways. These data can be obtained through literature search, material specifications, pre-operational monitoring in the surrounding area and through preliminary investigations on the site and characterisation of the waste, The process should continue through the acquisition of additional data, for example, by field and laboratory investigations and appropriate modelling, as the design is developed until a basis for reasonable confidence in the ability of the repository to fulfil the assigned safety requirement is achieved.

At the same time, relevant scenarios should be identified. Determining the relevance of each scenario to the evaluation of the repository and site may need supporting engineering studies and additional data collection, and require further iterations of the safety assessment process. Such studies and analyses may also be useful in reducing uncertainties when attempting to quantify the events and phenomena which lead to radionuclide release and transfer. Even if safety assessments rely on conservative assumptions and are approved as such by the regulatory body, greater uncertainty is inevitably attached to longer term predictions. Consequently, there may be a need to allow a period of comparison of field monitoring results with parameter values used in the analyses. Extending monitoring into the period of active controls (or part of it) is therefore generally considered as a useful practice and is often a regulatory requirement.

4.2 System Definition

Safety assessment of a near surface disposal system is based on a multidisciplinary approach to system definition and on systematic analysis of possible sets of events and processes that may affect the performance of the disposal system. The description of the near surface disposal system requires information on waste characteristics, facility design and site characteristics and is often called the conceptual model of the waste disposal system. The sets of events and processes relevant to reliable assessment of the facility safety are described in scenarios .

4.2.1 Conceptual model development

The ultimate goal of the development of the conceptual model is to provide a complete framework which will permit judgements to be made about the behaviour of the total disposal system. If possible, the model should have enough detail that mathematical models can be developed to describe the behaviour of the system and its components so as to provide an estimate of the performance of the system over time. Varying levels of detail will be required as the iterative safety assessment is conducted and eventually a licensing decision is made. The model should be as simple as possible but include enough detail to adequately reproduce the system behaviour.

Development of the conceptual model usually includes the following steps:

(a) Identification and characterisation of the waste for inventory, wasteform and container. The source term information should be detailed enough to allow adequate modelling of radionuclide release. At a minimum, information should be provided as a basis for the justification of a simple release model such as assuming that release rate is a constant term. This may be refined by iteration as more information on the waste and the disposal system is obtained.

(b) Characterisation of the disposal site by the necessary parameters, including geology, hydrogeology, geochemistry, tectonics and seismicity, surface processes, meteorology, ecology and distribution of local populations and their social and economic practices. This site information is needed to define pathways and receptors and thus to develop a conceptual physical, chemical and biological model of the site.

(c) Specification of facility design. Before the assessment starts, the design should be specified in terms of the material used and the components of the system. Changes in the design, either on the basis of the safety assessment or otherwise, may require the safety assessment to be updated.

(d) Based on the framework defined as indicated above in (a) - (c), identification of events likely to affect the site and the facility and processes that might control transport along pathways.

4.2.2 Scenario analysis

Scenarios depend on the environment and system characteristics, and on events and processes which could either cause initial release of radionuclides from waste or influence their fate and transport to humans and to the environment. The choice of appropriate scenarios and associated conceptual models is very important and strongly influences subsequent analysis of the waste disposal system. In the United Kingdom scenarios are not specified by the regulators and this is described below, although the assessor may also choose to consider others. In other countries the assessor may select the scenarios and be required to justify the selection to the regulator.

The first step in identifying which of the many phenomena are relevant to the safety assessment should be to establish a check list such as that presented in Table 1. It may be helpful in developing a suitable list of scenarios to consider the following headings, namely:

(1) processes and events of natural origin

(2) processes attributable to the waste itself or features of the near surface repository; and

(3) human activities

Some events are almost certain to occur and should therefore be used to define the normal evolution scenario. The assumptions used in developing the normal evolution scenario are based on extrapolation of existing conditions into the future and incorporate changes expected to occur with the passage of time and do not usually consider major perturbations of the system. Events which are less likely to occur may introduce significant perturbations to the system and require the development of alternative scenarios. Some of these scenarios can be handled by using the same models but with revised parameters. Other scenarios may require new models. The intended design will probably be based on the normal evolution scenario but it may be modified to account for the results of the assessment based on other scenarios.

A wide range of scenarios should be considered to develop as complete as possible an understanding of the system. However, where there are options, the assessor should be careful to select for detailed assessment those scenarios which are most likely to occur and have a material effect on the outcome. This selection is to ensure effective use of expensive assessment efforts and that the design of the repository is developed in a way that best protects human health and the environment.

Scenario development should lead to a systematic focusing of the safety assessment on the important conditions and phenomena related to a disposal system performance. The scenario development process should be carried out so as to cover the post-closure safety aspects of the near surface repository adequately. Techniques such as professional judgement, fault and event tree analysis (noted later in the paper), can be used to focus on the important scenarios. Where professional judgement is used, it is important to record the judgements made and the factors considered in making them.

The important pathways for both undisturbed (normal) conditions, and disturbed, (non-normal) conditions should be screened from a comprehensive set of potential pathways. Experience shows that only a few pathways are likely to be important for the undisturbed near surface disposal facility. They include groundwater, soil, land plants, land animals, surface waters and aquatic animals.

4.3 Uncertainty

Uncertainty is inherent in any safety assessment. Sensitivity and uncertainty analyses have the important goal of increasing understanding and reducing, where possible, the uncertainty in some of the results of the safety assessment by directing attention to the better definition of those parameters that may affect uncertainty. The analysis of sensitivity and uncertainty are closely related. Sensitivity analysis helps to identify those parameters, system components or processes that produce significant effects on the predicted disposal system performance. Identification of sensitive conceptual model components and important scenarios is usually done through application of systematic parameter variation. Each scenario may require its own distribution of parameters. Often bounding values for the expected case are used to investigate system behaviour under uncertainty. Statistical techniques may also be employed to explore the whole range of expected parameter variation.

Two main sources of uncertainty are recognised for near surface disposal. One is the uncertainty inherent in the description of the disposal system, the site characteristics and the engineered features of the repository. Associated with this uncertainty is the uncertainty inherent in the behaviour of the systems and their interaction with the environment. The other source of uncertainty results from changes in the environment with time and resulting changes in the site and engineered features of the repository.

Uncertainty may be related, therefore, to either;

(1) system properties or the processes which operate on the system; or

(2) the difficulty of predicting the evolution of the facility and its environment over the long periods of time.

The first source of uncertainty can be reduced by improving data quality, the design of the facility, the conceptual model and the scenario selection. The goal should be to reduce uncertainty to some level deemed acceptable or shown to be unimportant to the performance of the near surface repository. The second source of uncertainty cannot be reduced but should be examined to see its likely effects in the future. There are difficulties in showing compliance with safety criteria over long timescales because of the increase with time of the uncertainty associated with the results of predictive models. This is generally counter balanced, to some extent by the decrease of the radiotoxicity of the wastes with the time due to radioactive decay.

In recognising and then analysing uncertainty it is important to understand which of the types of uncertainty is being dealt with. It is most difficult to deal with uncertainties such as those inherent in formulating the conceptual model of the near surface repository or in the scenarios developed to describe the future events and processes expected to be important to safety of the site. If uncertainty analysis is to be carried out, it should systematically consider the various model and scenario combinations by using various model formulations for differing levels of detail.

A major source of uncertainty in scenario development stems from the potential for missing an important scenario. Peer review of the scenarios chosen can help reduce such uncertainty. Generic studies that have laid out sets of potential pathways can be of assistance.

Similarly, uncertainty in development of the conceptual and numerical models of the site can perhaps be best considered by peer review. The general trend is to use simple models for ease of explanation and for computational efficiency. The uncertainty associated with the simplification existing in building the conceptual and numerical models can often be determined by additional modelling studies and data collection. Again, the modular approach and careful analysis of intermediate computational results can lead to a more detailed understanding of the system. This in turn can increase the chances of error detection and can lead to an overall reduction in model uncertainty. However, an over complex model demands greater quantities of data, which may themselves be uncertain and lead to greater uncertainty in the results.

Inherent uncertainty arises from attempting to predict future events. Some of these uncertainties can be disregarded following careful examination of extreme or bounding scenarios or from the results of probabilistic assessments but only if they have little effect on the performance of the repository system. Other uncertainties, particularly those associated with human activities dictated by future socio-economic conditions or major changes in climatic conditions, may in principle have a significant effect on the exposure of humans in the future yet are not readily amenable to quantified predictions. In such circumstances to impose artificially generated values which disguise this problem could lead to a spurious impression of accuracy and produce misleading results. Safety assessment is based on a conceptual model whose prime purpose is to provide a framework in which to allow analysis to proceed. Where suitable mathematical models can be derived and the data exists then predictions can be quantitative. When this is not the case then only qualitative deductions can be made; perhaps rating risk as high, medium or low according to circumstances. This does not invalidate the assessment process but renders it more dependent on the assessor's judgement, supported where possibly by calculation. Within this framework, however, the basis for the judgement should be carefully documented for examination as part of the safety assessment. The assessor should be careful that the reliability of information available is reflected in the level of calculation detail provided in the assessment, which should therefore change according to the length of time into the future being considered.

4.3.1 Sensitivity Analysis

The system should be analysed to determine how and to what degree the predicted behaviour of the near surface disposal facility depends on the conceptual model used, the scenarios that are applicable to the model and variation in the parameters used to describe the system as input to the model. If the results are sensitive to initial and boundary conditions then the assessor may have to seek more extensive data, including revised measurements from the site. Sensitivity analysis is undertaken by means of a systematic examination over a reasonable range of parameters with the objectives of seeking out the most sensitive areas of variation. The process should look at the model's sensitivity to different scenarios and reasonably expected exposure pathways. If it is determined that the assessment is sensitive to these parameters, consideration should be given to their further evaluation.

Simple parameter variation including variation of combinations of parameters is the most common approach to sensitivity analysis for near surface repository safety assessment. Consideration should be given to extreme but reasonable variation of some parameters because this may change the relative importance of different pathways and cause the model to be no longer applicable.

Various variational methods can be used for this task, but the analysis should be structured with care to ensure that the combinations that are chosen by the computer code are not impossible, or physically unrealistic. In addition, the output from the exercise should be structured to preserve the information needed to determine the sensitive combinations and to identify sensitive parameters.

Sensitivity analysis should guide the iterative process used for improvement of the model formulation, scenario development and gathering of additional data. Sensitivity analysis results can be used to indicate where design features should be effectively improved to yield better performance.

4.3.2 Uncertainty Analysis

Parameter uncertainty is the type of uncertainty most often addressed by uncertainty analysis. This is usually done by concentrating on those parameters shown by sensitivity analysis to be important for defining the result of the safety assessment. Methods commonly used are related to the sensitivity analysis techniques of single variable or multi-variable variation with the goal of developing bounds for the predicted performance of the near surface repository. Bounding analyses should produce fully adequate information on the variability of performance related to expected variation in environmental and engineering parameters. It should be noted that because the systems are so complex using extreme values on a parameter-by-parameter basis may not yield the bounding behaviour of the system. Monte Carlo analysis can also provide distributions of expected results based on statistical analysis of estimates of input parameter variation. When developing the input distributions for the Monte Carlo analysis and correlation between the parameters, the assessor will need to have access to expert judgement, which should be elicited in a formal and recorded manner.

5. ASSESSMENT TECHNIQUES

In order to meet the Regulatory requirements and so allow the continued disposal of low level radioactive waste the operator must demonstrate compliance with the Principles and Requirements noted earlier in the paper.

For the soundness of all decisions based on the results of a safety assessment it is also essential that the results deserve a high level of confidence. Scientists, regulators, decision makers and, if possible, the public should all have confidence in the information, insights and results provided by safety assessments. This section discusses what can be done to ensure that safety assessments deserve a high degree of confidence, as a result of being under pinned by a Technical and Engineering Assessment Programme.

Safety assessors may find it very helpful to use a modular systems approach to model the potential release and transport of radionuclides through selected environmental pathways to humans. This will ensure that individual sub-models can be made available for inspection to assist in understanding how estimated doses were determined. The model will usually consist of the following discrete sub-models: infiltration and leaching, near field transport within and near disposal units, groundwater transport, surface water transport, atmospheric transport, uptake by plants and animals, and dose to humans. A modular approach also allows flexibility and reduces effort when only parts of the system need sophisticated modelling in order to ensure that the results are technically defensible. The benefits of this approach can be significant when sophisticated models are used to provide added assurance that the disposal site and the facility will perform in an acceptable manner.

The source term used in the model should be representative of potential releases of radionuclides from various waste forms under the identified range of environmental conditions and should consider degradation of engineered barriers, for example, such as cover systems and concrete structures. Early models are likely to be simple but as understanding of the system develops it may become necessary to employ more detailed models to ensure that the system is adequately represented. But the models should be simple enough to be compatible and commensurate with available data, or the result could be a greater uncertainty rather than an improved accuracy. The assessor must use judgement here to ensure a proper balance between using simple models and conservative data and more detailed models that may need some data not readily available. This does not preclude the assessor from using more complex models of parts of the system to improve the understanding of the phenomena involved. Examples of such sophisticated models might be the use of finite element groundwater codes to assess hydrologic boundary conditions and temporal variability of water levels if physical characteristics or groundwater monitoring suggest the need to understand changes in the system at an advanced level of sophistication.

Reasonable conservatism should be built into the safety assessment modelling from the beginning. A simple modelling approach is likely to be more efficient, cost effective, and defensible. Assumptions should be formulated based on available data and knowledge of the system or similar systems, to avoid underestimating release and transport of radionuclides or, if required, the exposure of the inadvertent intruder. Worst analyses are not necessarily required to demonstrate that the public and the environment will be adequately protected. Any decrease in the original conservatism used in the analysis should be based on a more detailed understanding of the waste disposal system and will require a more rigorous defence. This should be achieved by additional modelling efforts or refined data. Since a defence of the results can be the most difficult aspect of an assessment, any approach to make the defence easier will be a long term benefit. An approach which balances simplicity, conservatism and realism, is likely to be the starting point for assessments.

The model should be consistent with the assessment objective; easy to use (considering the complexity of the system); and one for which the data can be obtained. The model should be appropriate for the application, the algorithms should be accurate, the assumptions should be reasonable, and the input data representative.

The modelling approach selected should be fully documented along with the matters considered as it is developed.

5.1 Engineering Assessments

At Drigg, although site closure is not imminent, work is being undertaken on the design of a final closure system and on the assessment of the likely performance of the engineered components currently under consideration. These include:

- a final low permeability cap which will be constructed over both the trenches and the vaults, and is intended to help isolate the waste from surface processes and to reduce the ingress of surface water into the repository.

- 'cut off' walls around the perimeter of the facility to limit possible future ingress of water into or egress of leachate.

- a drainage system to collect and control the movement of water and leachate from and around the repository.

Although preliminary designs for these and other components exist, the final design has not been fixed, but forms the focus for a research programme within BNFL aimed at optimising the engineering and design of the final closure system. The objective of this research is to ensure that a safe and cost-effective closure solution is selected.
The approach adopted for the Engineering Risk Assessment (ERA) employs a variety of systematic risk assessment techniques to gain an insight into the likely operation of the closure system or the repository. The conventional definition of risk is used for this work

- Risk = likelihood x consequence

An important criterion in the development of the methodology was that it should be holistic, flexible and easily modified to accommodate design changes and the developments in understanding or knowledge that will inevitably occur during the lifetime of the project. The ERA was therefore conceived as organic and capable of changing in response to the needs of the PCRA and design teams, whilst supporting a well documented audit trail. (Ref. 3)

The conceptualisation of the closure system was undertaken in five stages:

- definition of boundaries and system diseggregation

- development of a conceptual framework

- identification of key events

- event sequence and scenario development

- selection of time slices and performance assessment

The interrelationship of these stages is shown in Figure 3 and described below.

5.1.1 Definition Of Boundaries And System Diseggregation

The boundaries of the closure system were determined and the system was then disaggregated into its key components (Figure 2).These included obvious features such as the cap, cut off walls, drainage arrangements, waste, and local geology. The influences on the closure system were deliberately left constrained, and were taken as anything which could affect the performance of the closure system whether these lay within or outside the proposed physical boundaries of the engineered system.

Within this framework important events (drivers) were identified that could initiate changes in system performance. These included internal drivers such as a *change in waste state and inappropriate design and construction* as well as external drivers such as *tectonic events, climate change and demographic change*. The consequences of a change in system performance were next reviewed and described in terms of changes in the rates of generation and release of contaminants. The approach used was similar to that advocated by several organisations and is essentially aimed at establishing a broad understanding of how system performance may be influenced by internal and external factors.

5.1.2 Development Of A Conceptual Framework

Following establishment of the initial lists, the data was organised and grouped diagrammatically. Possible relationships between components were identified and recorded as linkages. The resulting 'belief net' uses a systems analysis approach to depict the influences on and interactions between the closure system components. In doing so, it provides a conceptual map for guiding the disaggregation of the system into its principal components and its subsequent analysis.

For example, climate change may promote a change in the effective rainfall which could result in surface erosion of the cap leading to a reduction in the efficiency of the cap and an increase in infiltration rates. This increase in infiltration may increase the moisture content of the waste and result in a change of the waste state. The change in waste state may, in turn, result in structural deformation within and around the waste leading to settlement of the cap and the development of cracks in the cap. These will probably reduce cap efficiency and further increase infiltration to the waste.

In the assessment of a closure system the identification of feedback loops is considered important, as a recursive event may lead to accelerated and premature failure, and/or the propagation of complex failure modes through the system which affect previously unrelated areas. It is likely that much of the uncertainty affecting the performance of a closure system over time is due to the effect of feedback loops. It therefore follows that major design improvements may result from including engineered or natural systems to moderate or prevent feedback loops occurring or propogating. In the example given an appropriate response may be to design the cap to resist cracking. This example is obvious, but was chosen to illustrate how the use of a belief net can help identify and explore more subtle interrelationships.

By its very nature a belief net is never complete or comprehensive, but is merely a means of recording at a particular point in time a group's belief and understanding of how a system is likely to behave.

5.1.3 Identification Of Key Events

Key events are defined as those events pivotal to the performance of the system. For example the dominant mechanism by which contamination may be transported into the environment is via water. A change in the rate and relative balance between inflow and outflow from the system can therefore be used as a measure of the performance of the closure system. After much consideration, the key events selected were:

- increased infiltration

- decreased drainage from vault or trench

5.1.4 Event Sequence And Scenario Development

Having established the key events, the next step was to describe in a succinct, logical, and diagrammatic form the event sequences and scenarios leading to and resulting from the key events. The belief net provided an initial framework for this process.

There is no one diagrammatic form ideally suited to this purpose , especially where a system contains interdependencies and feedback lops which give rise to conditional probabilities. However, it was found convenient to use a fault tree structure to characterise the sequences leading to the key events, and to use an event tree structure to explore and document the consequences of the key events in terms of contaminant release.

Both fault and event trees allow the numerical analysis of the likelihood's and consequences of events (and hence risk) to be calculated if the techniques are correctly applied, and provided sufficient data is available.

Although the fault and event tree diagrams can appear complicated, it has been found that maintaining a modular approach has helped to simplify the representation of the closure system as it has avoided the need for very large and complicated diagrams with links that cross and pass through the tree. It also avoids repeating essentially identical branches in different parts of the system but retains the ability to describe feedback loops.

Following the development of the fault and event trees the structure was carefully checked against the belief net for completeness and consistency, and adjustments made to the trees where necessary. Although belief nets and the fault and event trees are related (they are different manifestations of network diagrams) each represents aspects of the same system in a slightly different way. The thought process which is undertaken to develop the different diagrams is also very different. Hence the use of several approaches helps to achieve a relatively comprehensive documented understanding of the interrelationships and response of a system.

5.1.5 Selection Of Time Slices And Performance Assessment

In a conventional risk analysis, the individual probabilities of each event in the fault or event tree are introduced and then used to compute the probability of a given scenario occurring. This data on which probabilities are based are often obtained from some form of reliability data base or other statistically derived performance record. This approach is clearly not possible for assessing the performance of a repository in the long term because, the actuarial data base is to limited. In such a case it is nevertheless often possible to identify processes and events which are analogous to the behaviour of the closure system and which can be used to help predict its performance. This approach uses expert judgement to assess and synthesise available information and then to predict the likely performance of a system for which little or no observed data exists.

Expert judgement can be used to predict both the likelihood of a scenario occurring and its consequences. However, it is less well appreciated that expert judgement can equally be used to predict uncertainty in likelihood's and consequences. The scenarios identified in the fault trees are therefore used as a basis for eliciting expert opinion on the likelihood and consequence of the events as well as their associated uncertainty.

More than 150 scenarios were identified by this means. However, this number is almost doubled when consideration is given to the different settlement characteristics of the vault and trench wasteforms, and is further increased when other considerations such as the response of different parts of the cap are taken into consideration. It will also be appreciated that the response of the individual system components will be time dependant, and in some cases will be affected by their previous performance history. For this reason, an analysis of the system performance is required at each time slice. Currently the time slices being considered are 100, 500, 1000, 5000 and 10000 years. The several hundred individual scenarios already identified are therefore multiplied by the numbers of time slices chosen to characterise the system performance.

Although the technique summarise a few thousand scenarios, it is neither possible nor necessary to assess each of these individually. Many of the scenarios can be grouped and a representative scenario selected for analysis, or may be considered as very unlikely to occur and /or of marginal impact. The approach adopted for Drigg has therefore been to use expert judgement to select the most probable and/or most damaging scenarios for detailed consideration.

Having reduced the scenarios to a more manageable subset, expert judgement is again used to assess both the likelihood and consequence of the event sequence and the associated uncertainties in the assessment. Based on this data, research priorities and design changes can be evaluated to consider how the risk (likelihood x consequence) or its related uncertainty can be reduced, and the performance of the system improved.

5.2 Assessment Codes.

The suite of codes developed for the Drigg assessment target the three major exposure pathways considered in the Drigg Post-Closure Risk Assessment (PCRA), namely:

- groundwater
- gaseous, and
- human intrusion.

The relationship of the PCRA codes are indicated in the flowchart (Figure 4), along with the exposure pathways they are associated with and the processes they simulate. (Ref. 3).

5.2.1 MONDRIAN.

MONDRIAN (**M**igration **O**f **N**uclides at **DRI**gg in an **A**dvective **N**etwork) focuses on the groundwater exposure pathway and is composed of 5 modules. PRE provides an interactive pre-post-processor; VAULT calculates radionuclide release from the waste; GRWOLF calculates groundwater flow velocities for a network representing site hydrogeology; GEO determines rates of radionuclide migration through the geosphere; and BIOS calculates rates of radionuclide movement through the environment and resulting doses and risks to critical groups. Groundwater flows are represented by a 3D network of 1D stream tubes connected at nodes; individual flow paths are characterised by parameters including length, cross-sectional area, hydraulic conductivity, and equilibrium distribution coefficient Kd. The biosphere is represented by a number of compartments both local to the facility and for more distant regions.

5.2.2 DRINK.

The development of a biogeochemical modelling capability DRINK (**DRI**gg **N**ear-field **K**inetic code) has reached the stage where it can be incorporated into performance assessments. The enhanced capability provides insights into near-field phenomena and provides an alternative to a simple VAULT release model. DRINK couples transport with microbiology and geochemistry; separate modules deal with radioactive decay, release, transport, geochemistry, microbiology, corrosion, and sorption. The output from DRINK takes the form of time histories of radionuclide concentrations and of parameters which describe the geochemical evolution of the near field. (Ref 4 & 5).

5.2.3 DEGAS.

The DEGAS (**D**rigg **E**valuation of **GAS**) code determines doses and risks to hypothetical critical groups from the generation of radioactive gases from a facility, their migration through the near-field, and their dispersion in the atmosphere. The codes deal with gases produced by aerobic and anaerobic microbial degradation of cellulosic materials, and by corrosion of metals in anaerobic conditions. (Ref. 6).

Intrusion into a disposal facility may be deliberate or inadvertent. In this context, deliberate intrusion is defined as intrusion in the knowledge that radioactive waste is present. Inadvertent intrusion includes intrusion in the knowledge that an engineered structure and/or waste is present, but not that the waste is radioactive.

In general, deliberate human intrusion is excluded from consideration in assessment studies, as it is argued that the responsibility for assessing the radiological risks and instituting appropriate protective measures rests with the intruder in this case.

In relation to inadvertent human intrusion, concern is primarily with radiation doses and risks to a limited number of individuals. This is because the spatial extent of environmental contamination resulting from intrusion is likely to be limited. However, it should not be assumed that the radiological impact is limited to the intruder and their associates. Excavated wastes may be distributed on or off site and give rise to exposure of other individuals, possibly long after the original intrusive event. In some circumstances, where bulk excavation of wastes occurs, substantial numbers of people may be exposed over a long period and the collective radiological impact of the intrusion may need to be evaluated.

BNFL models of human intrusion, HICODES (**H**uman **I**ntrusion **CODES**), at Drigg involve three components:

a) Estimation of the frequencies of human actions that would result in exposure of individuals to extracted radioactive materials;

b) Estimation of the radiological impacts of such human actions, if they occur, for a facility containing all the radionuclides of interest at unit concentration;

c) Combination of the frequencies and impacts, derived under (a) and (b), with the time-dependent inventory of radionuclides in the facility to estimate radiological risks.

The first component of the BNFL intrusion model calculates the frequency of each human action, as a function of time post-closure. The approach is based on defining event trees for a variety of potential site uses and estimating the likelihood of each event occurring. The second component of the model, calculates the total effective dose (Type A actions, resulting from the examination of small amounts of excavated material) or the effective dose rate immediately after intrusion (Type B actions, resulting after excavated material has been spread of a large area or removed from site) into wastes containing the specified radionuclides at unit concentration (1 TBq m^{-3}). In practice, it is necessary to consider a mixed inventory of radionuclides, which decays during the post closure period and which may be intruded into at any time. Thus the third component of the BNFL intrusion model combines the output of the first two components with a defined initial inventory.

6. SUMMARY

The methods outlined in this paper provides a means of capturing, documenting and predicting the performance of a complex system over time, which ultimately can be used to help improve and optimise the design of the final repository closure system, and highlight any areas where significant uncertainty may exist. Such areas are where further work could most cost effectively be undertaken to improve design, to satisfy any regulatory concerns and give increased confidence in the predictions resulting from the Post Closure Risk and Safety Assessments. Perhaps the greatest benefit of such approaches is as a means of communicating the current understanding of a systems behaviour and the facilitation of documentation of all important decisions in a manner that is open and transparent.

7. REFERENCES

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Figure 1. Uses of Safety Assessment. (Ref. 2)

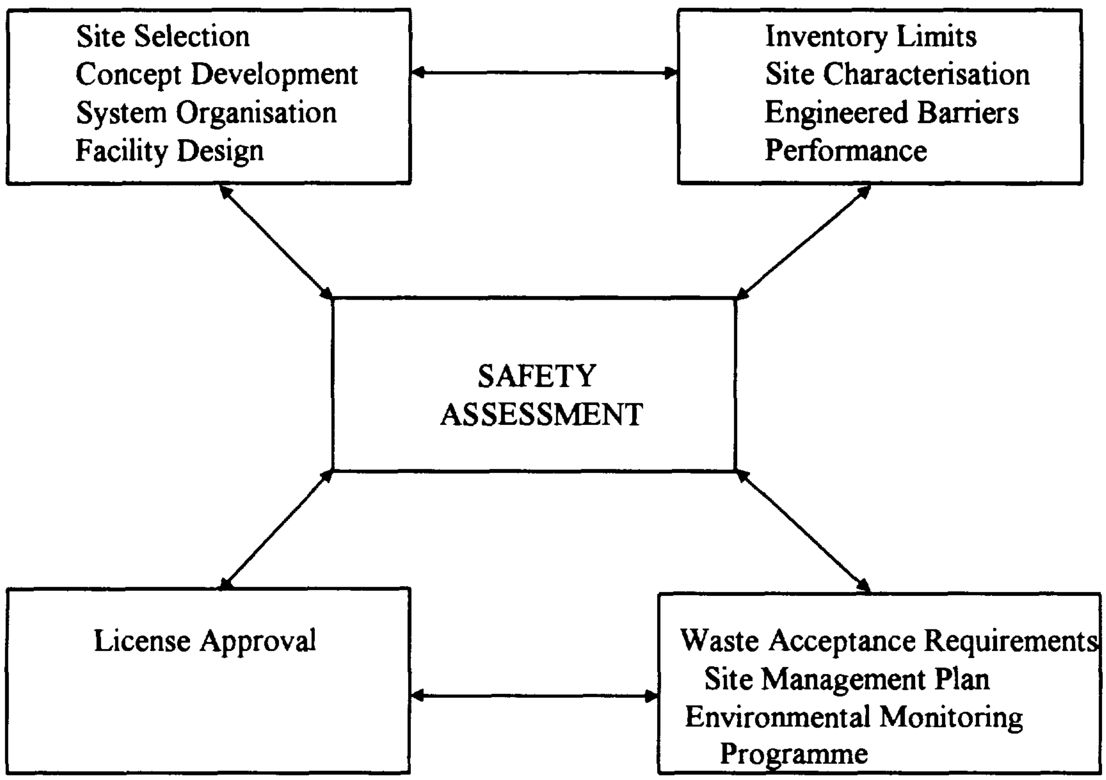

Figure 2. Safety Assessment Iterative Approach.

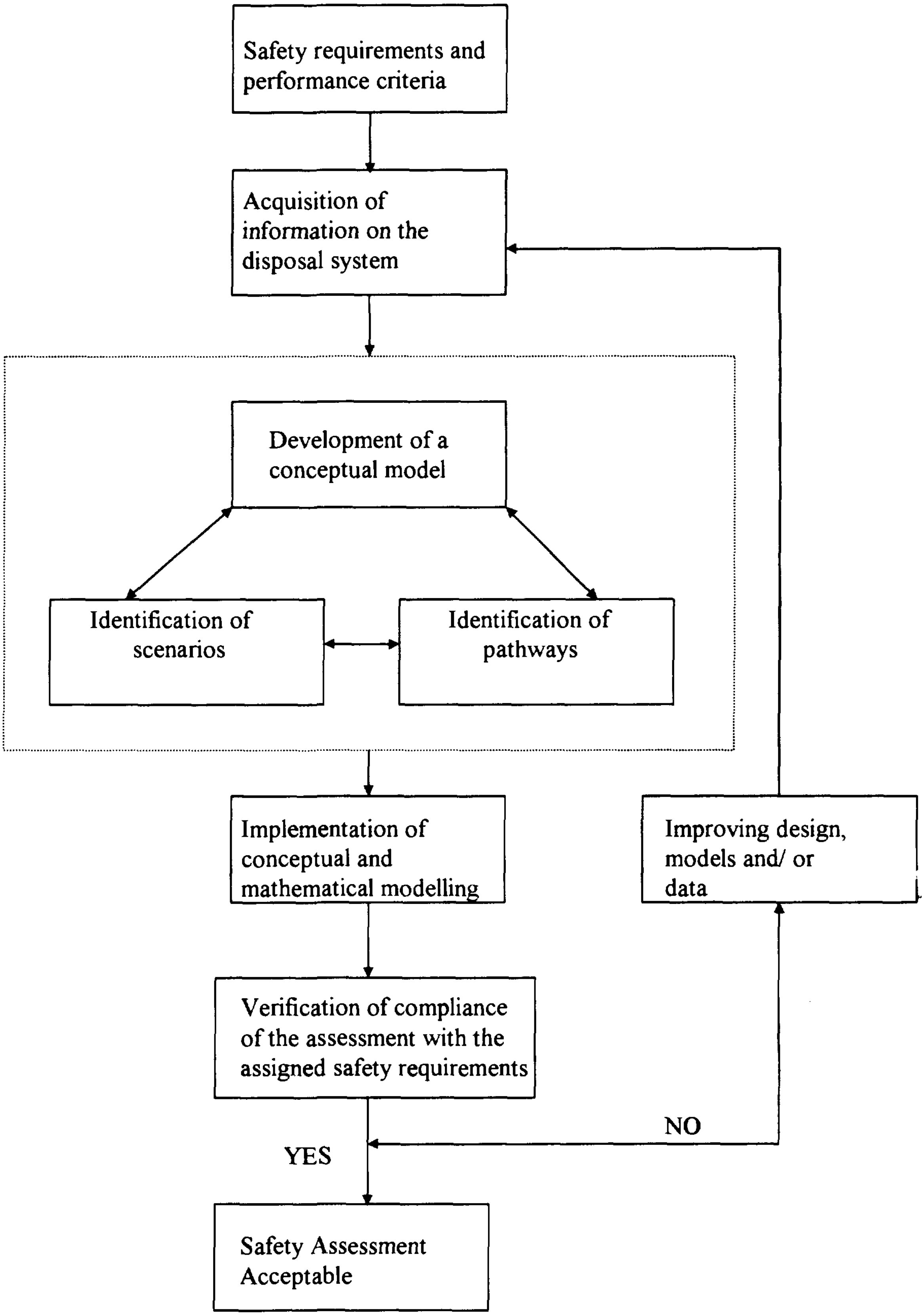

Figure 3. Roll of Engineering Risk Assessment. (Ref 3)

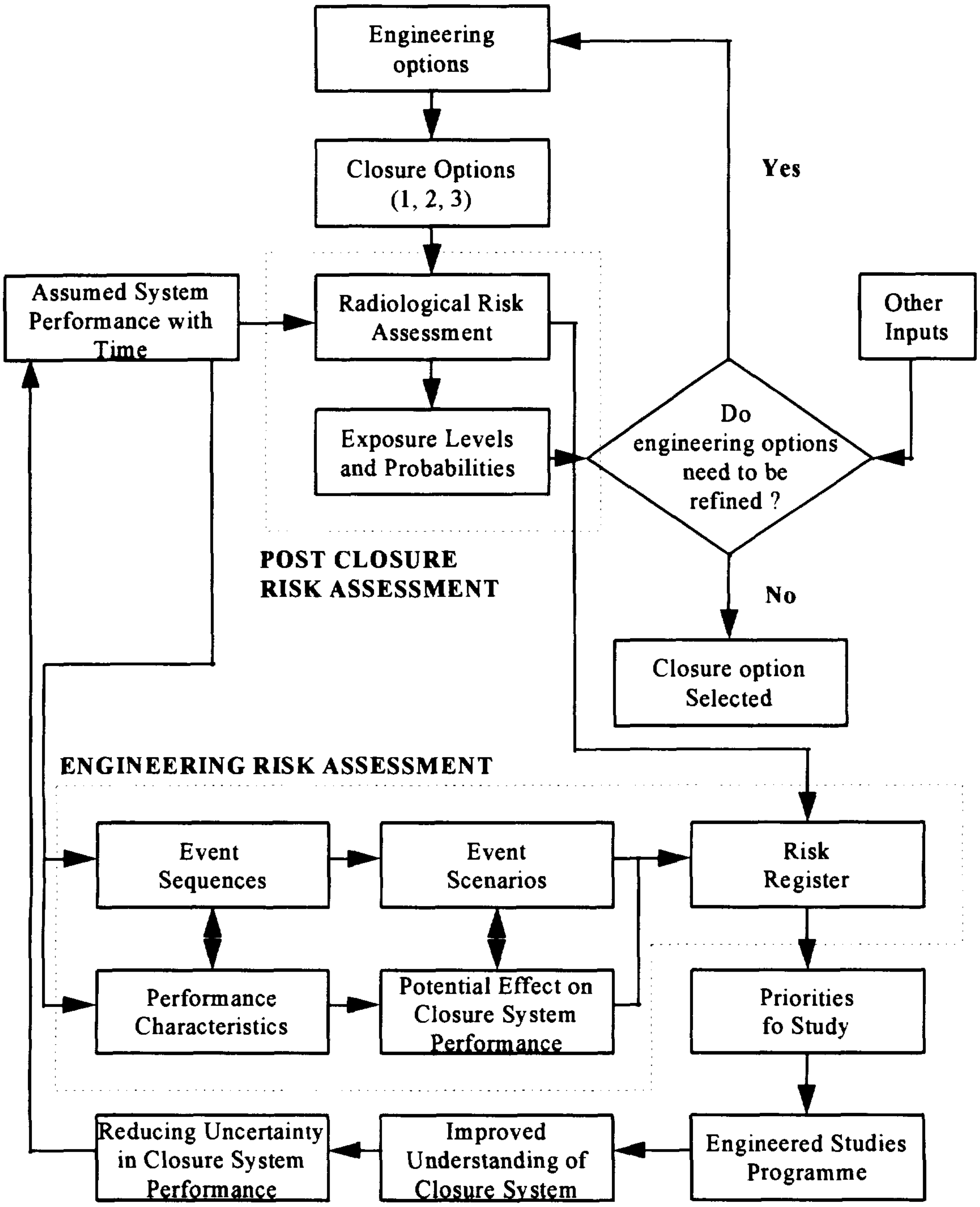

Figure 4. Modular Relationship of Drigg Post Closure Risk Assessment Codes.

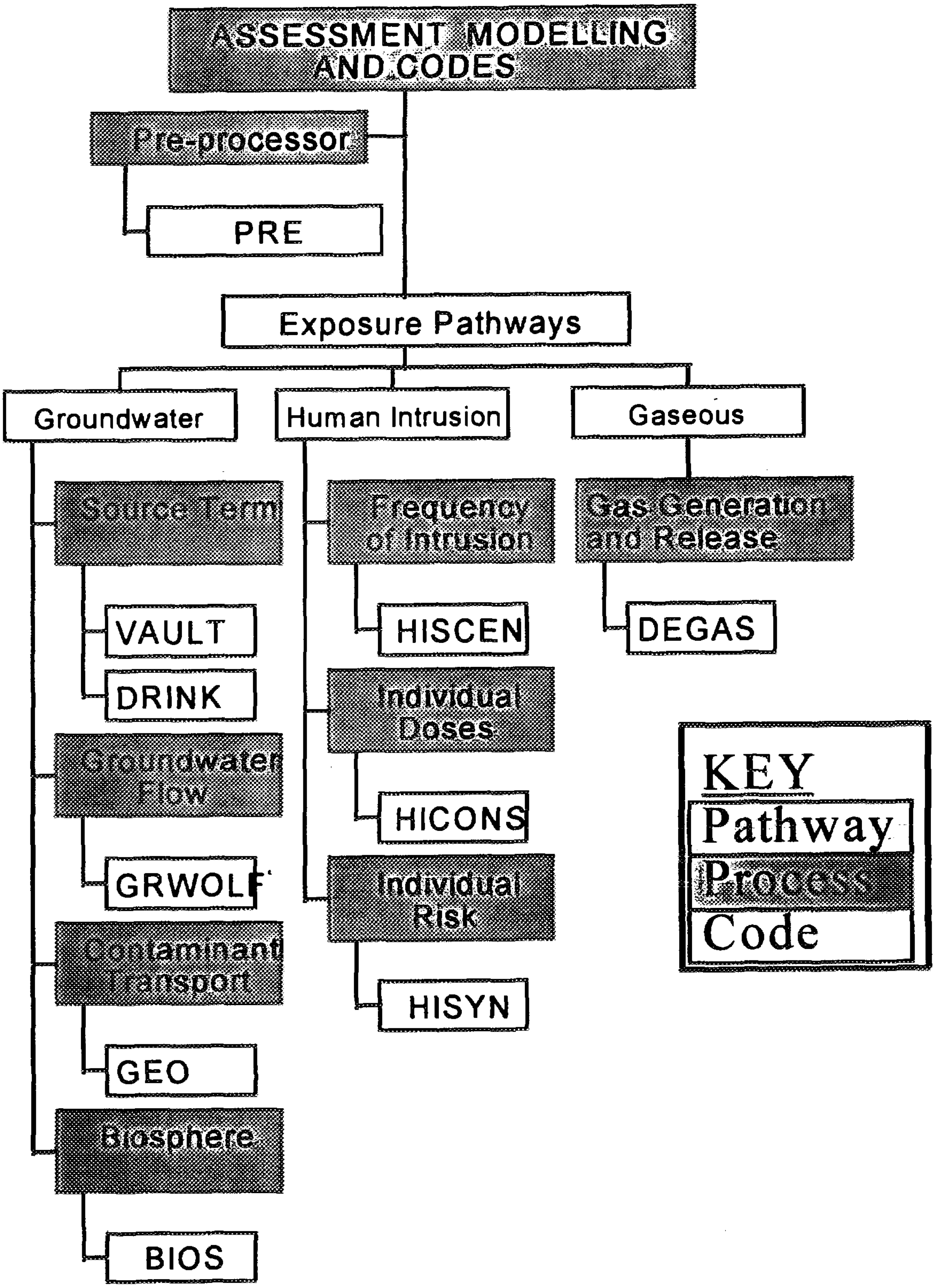

TABLE 1
PHENOMENA POTENTIALLY RELEVANT TO SCENARIO ANALYSIS FOR NEAR SURFACE REPOSITORIES.

HUMAN ACTIVITIES

Improper design and operation
- Chemical liquid waste disposal
- Draining system obstruction
- Improper waste emplacement
- Top cover failure

Future intrusion
- Construction activities
- Farming
- Groundwater exploitation
- Habitation
- Salvage
- Re-use of disposed material
- Archaeology

NATURAL PROCESSES AND EVENTS

Biological intrusion
- Animals
- Plants

Faulting/seismicity

Fluid interactions
- Erosion
- Flooding
- Fluctuations in the water table
- Groundwater flow
- Seepage water

Weathering
- Deterioration with time
- Freezing/thawing
- Wetting/drying

WASTE AND REPOSITORY PROCESSES
- Gas generation
- Waste and soil compaction
- Waste/soil interaction