MODELLING THE LONG TERM EVOLUTION OF RADIOACTIVE WASTE DISPOSAL ENVIRONMENTS

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ABSTRACT

The design, development and use of a computer model to simulate the long-term evolution of radioactive waste disposal environments is discussed. The model, TIME2, has been developed for use within a probabilistic risk assessment framework in the evaluation of potential shallow land burial sites by the UK Department of the Environment. This paper outlines the processes modelled by TIME2, the operation of the code and some example results. Use of the code in risk assessment is discussed and planned future developments are outlined.

1.0 INTRODUCTION

Post-closure radiological risk assessment of radioactive waste disposal involves attempting to predict the release of radionuclides from a repository, their transport through geological media (the geosphere), through the biosphere and hence their uptake by man. The timescales for which assessments are required - sometimes millions of years - are such that the environmental system within which release, transport and uptake processes operate can undergo radical change. Recognising this, the UK Department of the Environment (DoE) commissioned Dames & Moore to develop a computer model to simulate long term environmental change. This paper describes that model, TIME2, presents some results obtained from its use on a potential disposal site and discusses its place within the wider framework of probabilistic risk assessment developed by the DoE.

Following this introduction, significant events and processes are outlined briefly before moving on to a description of the TIME2 code.

2.0 SIGNIFICANT EVENTS AND PROCESSES

Before design or development of TIME2 was initiated, a review was carried out of natural and human events and processes which could be considered significant for a waste repository [1]. Attention was directed initially at both shallow engineered trench burial and deep mined tunnel disposal. However, developments in the UK research programme subsequently placed a higher priority on shallow disposal. TIME2 has been designed specifically for evaluation of shallow repositories.

Over the timescales of interest, changes in the environment can occur in a variety of ways:

- Changes in the rate of processes;
- Changes in the nature of processes;
- Changes in the environmental system upon which or within which processes operate;
- Occurrence of discrete events, externally or internally generated;
- Changes in the pattern of occurrence of events;

For the purposes of definition, an event may be considered as being characterised by some measure of scale (magnitude, etc.) and a time of occurrence, an example being an earthquake. A process may be considered as being characterised by a rate and duration, for example erosion. In the case of many environmental phenomena, whether they are considered as events or processes depends solely on the timescale of modelling.

In deciding what is and is not significant, the primary criterion must be its influence on radiological risk (risk is the regulatory criterion used in the UK to evaluate the acceptability of radioactive waste disposal). Therefore, any processes or events affecting the release, transport and uptake of radionuclides by a degree sufficient to noticeably alter estimates of risk must be considered significant.

For natural effects, the review examined the following aspects:

- Tectonics (including seismicity and vertical crustal movements);
- Diapirism (salt dome formation);
- Climatic change;
- Geomorphological processes;
- Meteorite impact.

For shallow disposal in the UK, climatic change and geomorphological processes were considered to dominate, with seismicity also having some importance. Diapirism was considered very unlikely due to the lack of suitable geological conditions and meteorite impact was concluded to be of very low probability.

In considering human influences, the potential for intrusion into the repository is of greatest significance for shallow disposal sites. However, human activities have an increasing effect on natural processes and this has proved to be a major area of difficulty. It is very difficult to attempt to predict what mankind may be capable of within the next few years; over tens or hundreds of thousands of years it is impossible. Indeed, to attempt such a simulation would be unjustifiable. Therefore, at an early stage in our work it became clear that present day technology and present day priorities, policies etc., would have to be assumed for any predictive modelling.

From the review studies it was possible to define a dynamic time-dependent system which could be used to form the basis of the TIME2 model. This is illustrated in Figure 1.

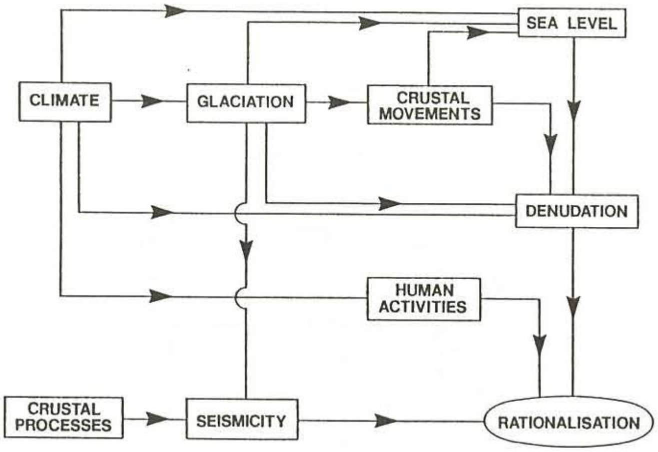

FIGURE 1
TIME-DEPENDENT ENVIRONMENTAL SYSTEM

The system has two primary drivers: climatic change and crustal processes. Climatic change drives surface processes, the most important of which is the expected renewal of ice sheet growth and advance, culminating in the physical destruction of a shallow repository. Glaciation alters the surface environment so greatly that it is not considered possible to model beyond this time for shallow disposal, ie the parameter uncertainty becomes unacceptably large. Other geomorphological processes are active up to this time, such as river and slope erosion. Climate also exerts a fundamental control on the groundwater flow system. Crustal processes in a compressional tectonic regime (such as Southern England) will probably remain quiescent as ice sheets advance. The major implication of this is that seismicity, with its potential to enhance repository release and geosphere transport by induced fracturing, is expected to remain at its current low level. External to the system described above but partly influenced by climate are human activities, major effects being alterations to land use (and hence biosphere state) and intrusion (leading to direct release).

3.0 THE TIME2 CODE

3.1 Purpose And Context

Using the results and conclusions of the review studies an outline design was prepared for TIME2. This was prepared with the specific purposes of the DoE in mind and within the context of the UK research programme. This section discusses these aspects. Previous modelling attempts were also evaluated and helped the project team to formulate concepts for TIME2. The following section outlines this previous work. The structure and characteristics of the code are then discussed, together with an outline of the modelling aproaches used.

Attention is presently focussed on the disposal of low level wastes in the UK, with the chosen route being to shallow engineered trenches. The TIME2 code was therefore required to form part of an integrated approach to the safety assessment of such disposal, for use by the DoE. The assessment methodology is currently centred around the SYVAC A/C code [8,9].

Output from TIME2 was not intended to be transferred directly to SYVAC but to provide detailed information to assist in the overall assessment by:

- o Estimating disposal site "survivability" in the light of potentially disturbing environmental processes or human activities;
- o Enabling a practical limit on the time over which a site can provide adequate waste containment to be set;
- o Setting boundary conditions for other tools in the assessment procedure, for example detailed groundwater modelling codes;
- o Identifying which processes and events are important for individual sites.

Other tools used in the assessment procedure include codes for multi-dimensional deterministic groundwater flow and transport (such as FEMWASTE and TARGET), inventory estimation, intrusion modelling, chemical speciation and biosphere modelling.

3.2 Background

Overviews of previous research and modelling exercises in this area have been given elsewhere [2], but it is pertinent to outline the major developments. To the authors' knowledge, four attempts have been made to model environmental change in the context of radioactive waste disposal:

- o Geologic Simulation Model (GSM) in the USA;
- o Far Field State Model (FFSM) also in the USA;
- o Fault Tree Analysis (FTA) in Belgium;
- o CASTOR model in France.

Both GSM [3] and FFSM [4] were developed for the US Department of Energy and are Monte Carlo simulation models. GSM is designed to be site-specific and geology-specific and is also a large and sophisticated code. FFSM is basically a generic derivative of GSM, intended to provide a "toolbox" for building applications specific to the user's requirements. In testing GSM on a site in the Pasco Basin [5] it was found that a large amount of spurious data was produced and that the results required extensive interpretation. As far as the authors are aware, FFSM has not yet been tested.

FTA has been used by CEN/SCK in Belgium for safety analysis of the Mol research site [6]. This included a consideration of natural events. Within the context of the study, the fault- and event-tree approach was useful, but requires the back-up of predictive models from which occurrence probabilities can be determined.

In contrast to the other models discussed, the CASTOR code is non-probabilistic [7]. It has been developed by the Bureau de Recherches Geologiques et Minieres (BRGM) and has been tested on a hypothetical site in the Fougeres region of Normandy. The modelling approach is highly simplistic compared to GSM and FFSM and in its present form is of limited value as a basis for risk analysis.

Drawing on these previous modelling attempts a Monte Carlo simulation approach was taken for the TIME2 code. The considerable uncertainty in the parameters governing processes and events could thus be taken into account by sampling from probability density functions (pdf's). This uncertainty arises from both spatial and temporal variability. The Monte Carlo approach does have drawbacks, however, especiallty the requirement to perform large numbers of simulations to achieve a prediction that does not change significantly with further sampling, with the consequent computer processing and storage needs.

3.3 Code Structure And Characteristics

In structure TIME2 consists of a small executive program and a number of classes of modules:

- Input;
- Initialisation;
- Sub-models;
- Finalisation;
- Utilities.

A highly modularised and structured approach to code development has been taken, in order to facilitate future modifications and enhancements. The code was developed to standards equivalent to those in the commercial software industry, imposed by the DoE [10,11].

The FFSM code was used as a vehicle for development of TIME2, but most of the modules are entirely new. Existing FFSM code used for TIME2 was translated into Fortran 77 from the original Fortran IV, with some additional alterations also proving necessary. Version 2.0 of the code, planned for 1986/7, will replace the remaining FFSM modules as well as including a number of other enhancements (discussed below).

Input to the code consists of both user-supplied data and master data. The latter is common to all sites and submittals (a submittal is a unique set of input data and may consist of many simulations) and is not intended for alteration by the user, rather it avoids the inclusion of data in the code which may need to be revised at a future date in the light of scientific advances.

Figure 2 illustrates the operation of TIME2. The code loops through time steps and simulations. At present over 100 pdf's are sampled to provide input, along with matrix and other data. Sensitivity studies are planned in the near future, with one of the major aims being to reduce the number of sampled input parameters.

The core of the modelling is carried out in a series of six sub-models, together with the initialisation modules. This is discussed in Section 3.6 below. The next section discusses the data structures used in TIME2 and is followed by an outline of the approach used to climate modelling and how this interacts with the code's time step management.

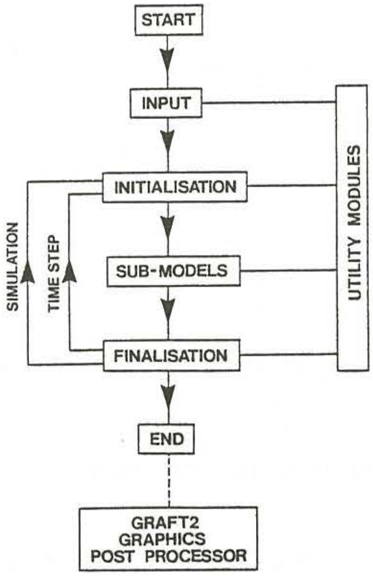

FIGURE 2
TIME2 OPERATION

3.4 Data Structures

Within the code data is stored in three main arrays:

- System state data;
- Point data;
- Summary data.

The data contained in these arrays is briefly discussed below.

System state data consists of nearly 100 parameters. Some of these are input parameters, some internal only and some calculated for output from the code. The parameters are not specific to geographic points. Examples of output parameters are ambient air and river water temperatures, precipitations, runoff, baseflow, sea level, land use proportions and intrusion data.

Up to ten geographic points may be set up by the user for each site area, each of which has twenty attributes. The attributes depend on the type of point (eg repository, river, floodplain), but include coordinates and elevation, repository volume (for a repository point), river characteristics (width, depth, discharge, slope), together with groundwater infiltration and recharge. Attributes are updated by the code at each (merged) time step and in some instances are required as initial inputs to the code.

Summary data consists of parameters selected by the user from the point or system state arrays and is primarily intended for output to the GRAFT2 grahics post-processor program. Up to twenty summary parameters may be selected for each submittal. If full output of all data generated during a typical submittal were requested by the user (this is an option) over 100Mb of data would be produced. It would be impractical to examine this quantity and the time taken to write it to a file would vastly increase run times.

3.5 Time Steps And Climate Sequence

TIME2 updates modelled parameters at the end of each time step used in the code, according to the changes which have occurred in that parameter value over the time step. Three types of time step exist: the climate state sequence, user time steps and merged time steps. These are discussed below.

Modelling is carried out up to the time at which the next ice sheet advance over Britain has reached its maximum extent. This is expected to be between 15,000 and 25,000 years from now and is termed the glacial maximum. Examination of deep ocean cores and other evidence suggests that climatic change in recent geological history can be characterised as a series of recurrent glacial-interglacial cycles. The sequence of climate states to be expected in each cycle is the same, but their durations vary. For the TIME2 code, therefore, one of two fixed climate state sequences is used:

TEMPERATE	TEMPERATE
SAVANNAH	BOREAL
TEMPERATE	TUNDRA
BOREAL	GLACIAL
TUNDRA	
GLACIAL	

This represents one half-cycle of climatic change. Climate state durations are sampled from site-specific pdf's at the start of each simulation.

The user may specify whether the savannah climate is to be included in the climate state sequence. It is intended to model the influence of the greenhouse effect (global warming due to the addition of trace gases to the atmosphere). The glacial climate state is defined as the period during which the site being modelled is covered by the advancing ice sheet, NOT including the retreat phase.

A set of user-defined time steps is also specified for each TIME2 submittal. These may be of varying duration over the modelling period, but are identical for each simulation. This enables the value of output parameters to be examined at the same times for each simulation. For all simulations a pdf of parameter value may thus be constructed for any user time step. This is carried out automatically by the GRAFT2 graphics post-processor program, discussed in a later section of this paper.

The combination of the sequence of climate states and user time steps defines a sequence of merged time steps, which represent the smallest interval at which TIME2 updates parameter values. The exception to this is in the modelling of human intrusion, where time steps are further sub-divided.

3.6 Sub-Models

The dynamic time-dependent system described in Section 2.0 and illustrated in Figure 1 has been implemented in TIME2 within six sub-models and the intialisation modules. Note that in Version 1.0 of the code seismicity and its effects have not been modelled. At the start of each simulation, data is initialised, the climate state durations sampled from pdf's and some ice sheet modelling performed. The six sub-models then perform the remainder of the modelling:

- CLIMATE. Samples precipitation and temperature data for each time step from input pdf's, according to the climate state in existence;
- GLACIER. Calculates the effects of an advancing ice sheet on the study area due to crustal depression and estimates the time at which ice advance will cause the formation of a pro-glacial lake;
- SEA LEVEL. Calculates the net change in sea level for each time step due to global warming (the greenhouse effect) or global cooling (eustatic sea level fall resulting from the retention of water in growing world ice sheets);
- GROUNDWATER. Performs a monthly water balance for each time step based on climatic data (the CLIMATE sub-model) and land use predictions, providing output data on runoff, infiltration and recharge at each geographic point;
- DENUDATION. Based on a calculation of sediment flux in the river system in the study area, which uses predicted runoff and basin areas to calulate discharge, denudation (general surface lowering) is calculated at each point; meander migration and the consequent effects on repository integrity are also modelled;
- HUMAN. This final sub-model simulates the occurrence and effects on the repository of a range of 12 intrusion types: site investigation drilling, groundwater extraction drilling, mineral/groundwater exploration drilling, hydrocarbon exploration/production drilling, foundation excavation for construction (of housing, light industry, high rise blocks or heavy industry) road/rail construction, trenching for services, archaeological excavation, shaft construction and tunnelling.

Details of the modelling techniques have been given elsewhere [12,13] but it is valuable to highlight some of the novel approaches used.

The processes of ice sheet advance/decay and crustal response have been modelled deterministically by G.S. Boulton (University of Edinburgh), by means of a combined set of mass balance, viscous flow and visco-elastic behaviour relationships [14,15]. This model was used to generate a series of simple graphical characterisations which could be input to TIME2 and formed the basis of calculations of eustatic sea level fall, ice sheet advance and crustal depression. A simplified modelling approach, appropriate to a Monte Carlo code, was thus developed which retained the state-of-the-art characteristics of the deterministic model.

Examinations of the problem of human intrusion into a closed shallow repository have concluded that it is the process which could contribute most to total radiological risk [12,16]. In the UK, land use planning controls over site re-use are expected to be of primary significance in determining intrusion occurrence [17]. Failure of these controls due to changes in the planning system, mistakes in the application of planning controls and loss of records is modelled in TIME2. Once control over site re-use has failed, the occurrence of intrusive events is modelled as a Poisson process. Input pdf's of the rates of occurrence of the 12 types of event, exponential in form, are determined variously from present day data and engineering judgement. Our experience has been that the modelling of human activities poses one of the greatest difficulties in radiological risk assessment due to the scale of uncertainties involved.

3.7 Graphics Post-Processor

As shown in Figure 2 a separate graphics program, GRAFT2, is used with TIME2 to process the output produced. The program uses the SIMPLEPLOT library of routines and is able to produce a range of graphs which include:

- Parameter value cdf versus time, expressed as median, upper and lower quartiles and upper and lower deciles;
- Change in form of the pdf describing an output parameter over time, shown as a contour plot of probability distribution;
- Parameter pdf and cdf at a specific time.

Examples of the plots are given later, within the context of the case study results.

3.8 Conclusions

It has only been possible to discuss some of the aspects of interest in the TIME2 code in the brief description above. The documentation set for the code provides further details [18,19]. The next section illustrates the use of the code on a site in the English Midlands.

4.0 CASE STUDY

4.1 Introduction

A detailed case study of a site in the Midlands of England has been carried out using the TIME2 code. The work is part of a larger project designed to evaluate the likely magnitude of the effects of environmental change. Some pertinent aspects of the case study are discussed below and example results shown.

4.2 Site Area Geology

The majority of the site area is underlain by a heavily overconsolidated clay/weak claystone, which in turn is underlain by a relatively low permeability weakly cemented sandstone. Bounding the area on the south are a series of low hills composed of muddy/silty sandstones and on the North a river with strongly developed meanders. Investigation of the geomorphological history of the area indicates that the next glacial advance is likely to be from Northerly and North-easterly directions.

4.3 Case Execution

Experience in the use of TIME2 has suggested that initial submittals (defined as a unique set of input data, containing perhaps many runs, or simulations) should consist of few simulations and be used to tune the input data set. So far, such tuning has been relatively easy. Once a final data set was assembled, a series of submittals was made with gradually increasing numbers of simulations, until it was felt that further increases would not increase the quality of the output data.

Within the context of TIME2, convergence is defined primarily as the point at which further increases in the number of simulations for a submittal do not cause the pdf of an output parameter at a specified time to change beyond acceptable limits. For this case study, repository elevation was chosen as the most representative parameter, since it is significantly influenced by all the modelled processes and events. Figure 3 illustrates the convergence reached by submittals consisting of up to 60,000 runs for repository elevation at 20,000 years from now. Acceptable convergence is defined as a variation in the mean, quartiles or deciles of up to 0.1 metre. This is reached at around 1000 runs. A similar exercise for a time of 30,000 years yielded comparable results.

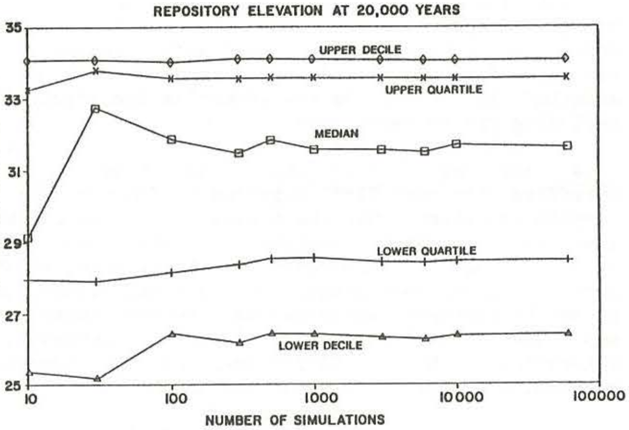

FIGURE 3
EFFECT OF SAMPLE SIZE ON
OUTPUT DISTRIBUTIONS

Another measure of convergence is the confidence which may be placed in the value of a parameter predicted by the modelling. Using the central limit theorem confidence limits on the mean of a parameter, derived from its pdf at a specific time, may be estimated. Increasing convergence is demonstrated by gradually narrowing confidence limits, with acceptability criteria similar to those above. This exercise is currently in progress for the case study described in this paper.

All submittals were performed on a MicroVAX II machine with 5Mb of RAM memory. Run times were as follows:

NO. OF SIMULATIONS	CPU MINUTES	ELAPSED MINUTES
300	16.3	50.6
1000	53.5	97.3
3000	159.0	353.8
10000	542.1	771.3

"Production" submittals have typically consisted of 3000 runs and may be comfortably performed overnight.

4.4 Results

It would be inappropriate in this short paper to describe the results of the case study in great detail. Instead, some of the more significant conclusions will be illustrated.

The modelling has highlighted the importance of human intrusion in the overall evolution of the environment. Since the site is relatively close to a populated area, the future pressure for re-use of the land is likely to be great. Figure 4 shows that as a result of intrusive activities the majority of the repository is simulated to have been removed within 5,000 years of closure. Examination of the number of intrusive events which contribute to this indicates that at 5,000 years the cumulative number peaks at a median of 30 (range of deciles 20 to 75 events), although many of these will be minor events such as borehole drilling. Note that in Figure 4 the sample size indicates the number of runs which contribute to the data; the tail-off after 20,000 years is due to simulations reaching their end point - the glacial maximum - at differing times.

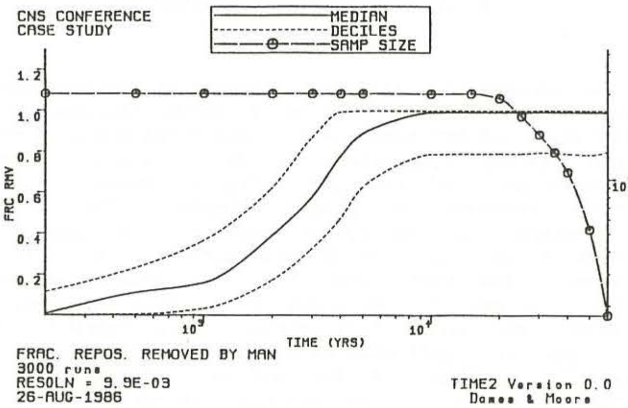

FIGURE 4
FRACTION OF REPOSITORY REMOVED BY INTRUSION
VARIATION OF CDF WITH TIME

Second in importance in the removal of material from a repository is the migration of river meanders over the floodplain of a river. This site is located on the edge of a floodplain and is thus susceptible to meandering. Figure 5 illustrates this process: the volume of material removed is relatively small, since:

- o The site will only be reached by some meander migrations, being on the edge of the floodplain;
- o Although the river may pass over the site, if the top of the repository is at a lower elevation than the bed of the advancing meander no erosion of repository material will take place.

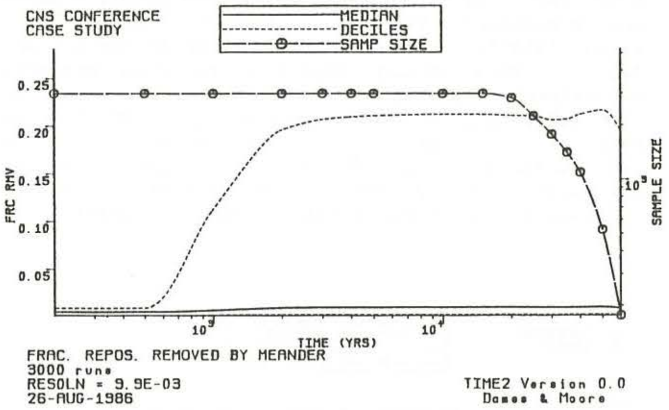

FIGURE 5
FRACTION OF REPOSITORY REMOVED BY MEANDERS
VARIATION OF CDF WITH TIME

The repository has an initial buried depth of approximately 4.0 metres, as shown on Figure 6.

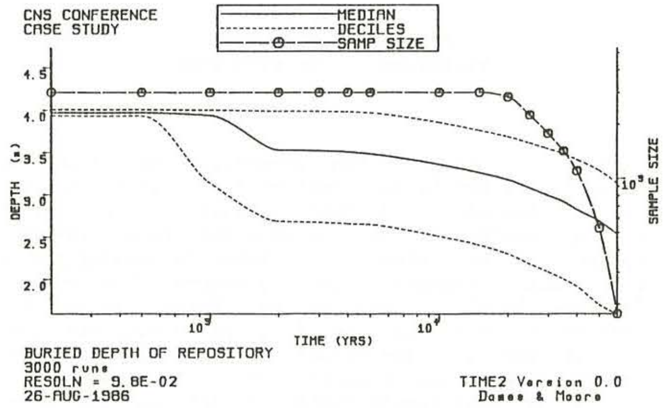

FIGURE 6
BURIED DEPTH OF REPOSITORY
VARIATION OF CDF WITH TIME

This figure also illustrates the influence of denudation, since buried depth is affected only by this. As can be seen, up to 2.5 metres of material is removed by denudation. For other sites, where increased drainage from the site area enables more eroded material to be removed, denudation may be significantly higher. Note that for both meander erosion and intrusion, an equivalent amount of material is assumed to be deposited as has been removed, ie a river deposits channel sands and gravels and excavations are backfilled. In the case of channel erosion, the repository material will become part of the sediment load carried by the river.

The other major influence on topography is crustal depression caused by ice sheet advance. Figure 7 shows the overall change in elevation over time for a point on the land surface directly above the repository (Point 5). Note that elevation is given relative to UK Ordnance Datum at the present day. From around 10,000 years from present, significant depression is predicted, as in more of the 3,000 simulations the advancing ice sheet draws near the site area. Note that the wide spread in the deciles from 20,000 years indicates the uncertainty in ice sheet advance timing. A maximum decrease in elevation of over 8 metres is predicted.

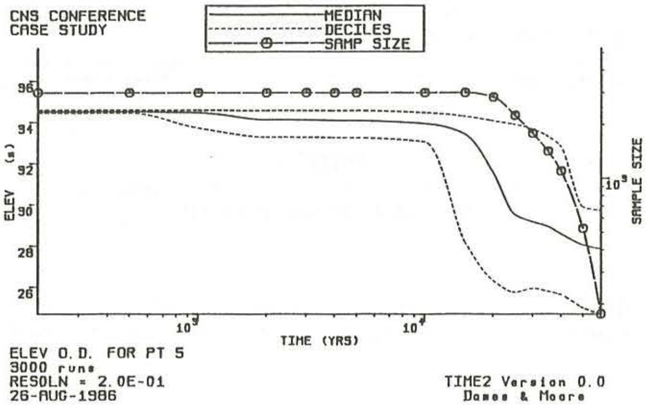

FIGURE 7
REPOSITORY ELEVATION
VARIATION OF CDF WITH TIME

The influence of the greenhouse effect can be seen in Figure 8. Sea level rises by about 5 metres before beginning to fall dramatically as world cooling begins. The eustatic fall in sea levels, caused by the retention of water in growing world ice sheets, reaches over 100 metres below present day sea level. Most of the North Sea and the English Channel will be dry, as during the last glacial period. The cessation of global warming at around 1500 years from the present is conjectural: we assume that fossil fuels will not continue to be burnt and that trace gas levels (notably carbon dioxide) in the atmosphere will consequently not continue to increase. For coastal sites sea level rise may thus bear further more detailed investigation.

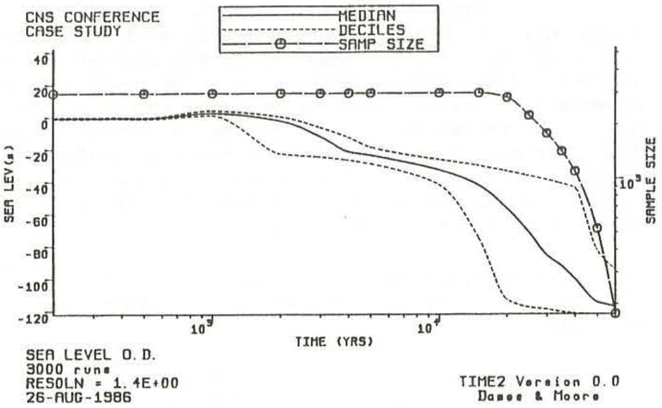

FIGURE 8
SEA LEVEL
VARIATION OF CDF WITH TIME

The final two Figures, 9 and 10, are examples of pdf's and cdf's (cumulative distribution functions) at specific times.

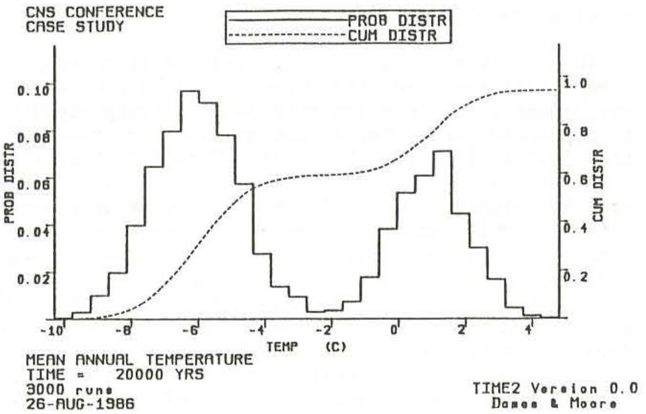

FIGURE 9
PDF OF MEAN ANNUAL TEMPERATURE
AT 20,000 YEARS FROM PRESENT

Some parameters are clearly bimodal in distribution at certain times. Figure 9 shows the combined influence of the tundra and boreal climate states on mean annual temperature at 20,000 years. The coldest peak of the pdf reflects tundra and the other reflects the boreal climate. For other parameters this is not so clear, such as Figure 10 which shows mean annual precipitation at 20,000 years. The main peak of the pdf, with a mode at about 300 mm, represents the influence of the tundra climate and would fall sharply off to around 500mm but for the influence of the boreal climate, which extends the tail of the pdf out to 1300mm. Note that for both figures the cdf does not reach 1.0, this indicates that some of the 3000 simulations have terminated before reaching 20,000 years.

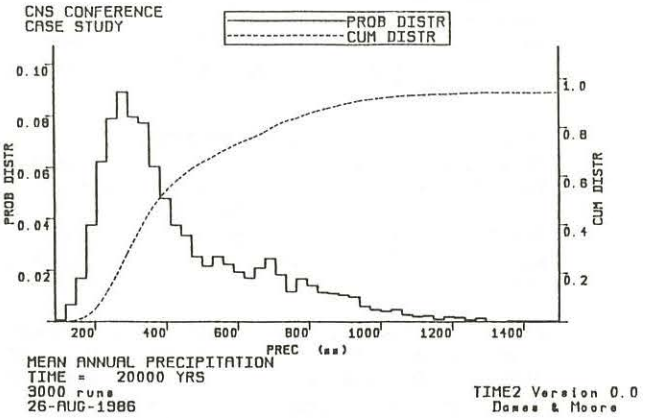

FIGURE 10
PDF OF MEAN ANNUAL PRECIPITATION
AT 20,000 YEARS FROM PRESENT

5.0 DISCUSSION

The TIME2 code has been shown to be practical in use and realistic in its results - although full interpretation of the case study output has not yet been completed. The requirement for extensive and time-consuming review of results by a panel of experts has been avoided by ensuring as far as possible that spurious output is not produced.

Ongoing research is aimed at evaluating the likely magnitude of the effects of environmental change on radiological risk. Output from TIME2 has been assembled for two specific times:

- 1,500 years after present, to represent a typical "savannah scenario";
- 20,000 years after present, to represent a typical "tundra scenario".

Groundwater modelling has been carried out using the Dames & Moore TARGET codes in order to generate input to the SYVAC risk assessment code [8,9]. Biosphere dose conversion files are being generated by Associated Nuclear Services, using TIME2 output as input to the ECOS biosphere code [20]. SYVAC cases are being submitted for alternative radionuclide transport routes for the two "scenarios". Since SYVAC assumes that the environment remains unchanged for the period of modelling (here 25,000 years), the risk arising from the existence of the input scenario over that period is simulated. Initial results indicate a significant difference in risks predicted under the different scenarios.

The inability of currently available risk assessment codes, like SYVAC, to accept time-varying inputs has led the DoE to initiate a feasibility study into the development of a time-dependent probabilistic risk assessment code [21]. This would accept input from a revised version of the TIME2 code, Version 2.0 [22], and realistically incorporate the effects of environmental change on radiological risk. The Dry Run 2 project [23], which has recently been completed, has examined the use of multiple scenarios to represent the effects of environmental change on risk. The scenarios are generated using scientific judgement rather than a formal code and risks arising from the scenarios are summed to give a broad indication of total risk.

As part of the development of Version 2.0 of TIME2, two major enhancements are planned:

- Modelling of periglacial processes, including ground ice development and thermal contraction cracking, and their effects on groundwater flow parameters and repository integrity;
- Modelling of earthquake occurrence and effects, notably induced fracturing of the repository materials and host rocks and the consequent alterations to groundwater flow parameters.

The simulation of pumped well occurrence and improved modelling of the surface water system are also planned.

It is expected that, in the future, proposals will be received from UK industry to consign intermediate and high level wastes to deep underground disposal facilities. Background studies are thus expected to continue examining longer term environmental change - up to several million years post-closure. Multiple ice sheet advance-retreat cycles are expected in the UK, which will require a different approach to be taken in a possible future code to model this - provisionally named TIME4.

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It is noted that the work described in this paper may be used in the formulation of UK Government policy but does not at this stage necessarily represent UK Government policy.

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