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SYSTEMS ANALYSIS APPROACH TO THE DISPOSAL OF HIGH-LEVEL WASTE IN DEEP OCEAN SEDIMENTS

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ABSTRACT

Among the different options being studied for disposal of high-level solidified waste, increasing attention is being paid to that of emplacement of glasses incorporating the radioactivity in deep oceanic sediments. This option has the advantage that the areas of the oceans under investigation appear to be relatively unproductive biologically, are relatively free from cataclysmic events, and are areas in which the natural processes are slow. Thus the environment is stable and predictable so that a number of barriers to the release and dispersion of radioactivity can be defined.

Task Groups set up in the framework of the International Seabed Working Group have been studying many aspects of this option since 1976. In order that the various parts of the problem can be assessed within an integrated framework, the methods of systems analysis have been applied. In this paper the Systems Analysis Task Group members report the development of an overall system model. This will be used in an iterative process in which a preliminary analysis, together with a sensitivity analysis, identifies the parameters and data of most importance. The work of the other task groups will then be focussed on these parameters and data requirements so that improved results can be fed back into an improved overall systems model.

The major requirements for the development of a preliminary overall systems model are that the problem should be separated into identified elements and that the interfaces between the elements should be clearly defined. The model evolved is deterministic and defines the problem elements needed to estimate doses to man.

1. INTRODUCTION

The generation of large quantities of radioactivity is an inescapable consequence of the exploitation of nuclear energy. While some of these radioactive products, such as plutonium, may be valuable, most of them, including the fission products, are at present regarded as wastes. The long term management and disposal of these wastes has become increasingly recognised world-wide as one of the most important technical and political issues facing the nuclear power industry. The majority of the radioactivity which would be classified as high-level waste is contained in the used fuel elements when these are removed from the reactor. In some countries these fuel elements are stored as a potential resource while in others the fuel elements are reprocessed to extract unburnt uranium for re-use and plutonium for potential re-use. It is therefore necessary in a comprehensive international programme to assess the consequences of disposal both of used fuel elements and of the high level waste after reprocessing.

Several methods for the disposal of high-level wastes have been proposed. One of these which appears to be practical using current technology is emplacement in geological formations under the ocean floor. Since 70% of the earth's surface is covered by the oceans it is reasonable that this vast area should be considered as a potential repository for high-level waste. In many ways seabed disposal can be regarded as disposal into geological formations which are submerged under the oceans. Use of the oceans in this way clearly requires international co-operation and with this in view the NEA set up a Seabed Working Group (SWG) in 1977 following a preliminary meeting in 1976 [1].

The objectives and role of the SWG and its subsidiary task groups as reported to the Nuclear Energy Agency of OECD after the 3rd Annual SWG meeting in Albuquerque, New Mexico in February 1978 [2] were:

(i) to provide a forum for discussion, assessment of progress and planning of future efforts;

(ii) to encourage and co-ordinate co-operative research vessel cruises and experiments among the member nations;

(iii) to share facilities and test equipment;

(iv) to exchange information; and

(v) to maintain cognizance of international policy issues.

These objectives have been pursued at annual meetings of the Seabed Working Group and at interim meetings of certain task groups. The current structure of the task groups which was agreed to at the most recent SWG meeting held in Bristol, UK, March 1980, is shown in Figure 1. The task group members from each country are designated by their respective executive member of the SWG. The task group structure is fluid and changes are made from time to time to meet the needs of the SWG.

The Systems Analysis Task Group (SATG) was formed at the 1977 SWG meeting in Washington. Since that time it has met as part of the annual SWG meetings and also held two interim meetings in Italy (May 1978) and France (October, 1979). A major responsibility of the SATG is to ensure that other task groups have identified all the assessment requirements and are producing the necessary information to feed into the complete system model. This is done by an iterative process in which a complete system model is set up containing the system elements appropriate to each area of the overall problem. This model is then used in a preliminary analysis and sensitivity analysis to identify the parameters and data of most importance. These preliminary studies form the basis on which the SATG can suggest to the other task groups the most important areas of research. The work of the other task groups should then be focussed on these parameters and data so that improved results can be fed back into the overall system model. The process is repeated until the predictions of the model achieve the required precision and confidence.

In this paper we describe the complete system model developed by the SATG and give some indication of our future work.

2. SYSTEMS ANALYSIS OBJECTIVES AND APPROACH

Systems analysis provides an over-view of the entire problem structure associated with disposal of high-level wastes and the interactions between the various problem elements. The objectives of the SATG are for the time being somewhat narrower than this and we have concentrated on those aspects of the overall problem relevant to an assessment of radiological consequences of disposal of solidified high-level wastes in the unlithified sediments underlying the ocean bed. At some point it will also be necessary to develop criteria to judge whether or not the predicted radiological consequences are acceptable and whether the results of a comprehensive radiological assessment of seabed disposal compare favourably with those of assessments of other disposal options.

In principle the radiological assessment of a disposal option involves identifying the ways in which radioactivity can be released from its immediate containment, transported through the environment and eventually reach man. In addition, it is necessary to estimate the probabilities of occurrence of release mechanisms as a function of time. These are then combined in an appropriate manner to give an over-view of the risks arising from the disposal option. In this preliminary work we have concentrated on the chronic release of radioactivity from the waste package. We recognise the need to investigate less probable mechanisms and singular events resulting from accidents, for example during transport or during emplacement; these will be the subject of later studies.

We assume that the wastes are in some solidified form in an appropriate container and that they have by some mechanism been emplaced in the unlithified sediments at a suitable depth.

As part of the assessment we will investigate the sensitivity of the results to the assumptions made in the initial scenario, for example the depth of burial in the sediments. In order to carry out this assessment it is necessary to develop mathematical models to predict the rate of release of radioactivity from its immediate package, its transport through the sediment layer, release into the water column, transfer by physical and biological processes through the water column and the eventual doses to man. To break down such a complex problem into manageable pieces we have divided the system into elements, each of which is modelled separately. This breaking down of the system into elements has a number of advantages. The sub-models in system elements can be substituted as better sub-models become available. The sub-models can be validated and experiments designed to improve them independently of the overall system. By separately identifying system elements particular expertise can be brought to bear and the data needs and research requirements can be more clearly identified. It is, however, essential in such a process that the sub-models within the elements can be eventually integrated into a model of the whole system. One of the prime tasks of the SATG is, therefore, to monitor the input and output requirements between each of the system elements.

We commence by using simple models for each system element to obtain a simple analogue of the whole system. These simple models are used in an initial assessment and a sensitivity analysis to identify those parts of the system which have a major impact on the final results and to identify the important parameters and data requirements on which research efforts should be focussed. This information is then provided to the other task groups to clarify their research objectives. While research is proceeding, model development proceeds in parallel so that on the next iteration both improved research results and better models can be combined to give an improved description of the overall system.

3. SYSTEM DESCRIPTION

The preliminary systems analysis model is shown in Figure 2. As noted above this is a deterministic model based on a scenario in which a solidified form of waste in an appropriate canister is buried at a given depth in unlithified deep ocean sediments. The release mechanism is assumed to be corrosion of the canister and leaching of the solidified waste by water in the sediments. The waste is then transported through the sediment into the benthic boundary layer region and via physical and biological transport processes in the water column to give doses to man and doses to marine fauna. The various system elements are described in turn below.

3.1 Waste Form/Canister

Within this system element it is necessary to define the quantity and composition of the waste assumed to have been disposed of. This description will include a complete inventory of the radionuclide composition and thermal output of the waste as a function of time after disposal. In addition, the characteristics of the waste form and the canister in terms of their resistance to corrosion and leaching by the water in the adjacent medium must be specified. These characteristics may also be functions of time after disposal. The output from the waste form and canister element of the system will be the release rate of radionuclides as a function of time, together with, if possible, a description of the chemical and physical form of the release. Since the thermal and radiation fields induced by the presence of the waste may affect the disposal medium immediately adjacent to the canister, these fields are also required as outputs to be taken into consideration in the next system element.

3.2 Near Waste Environment

This is a region of the disposal medium within which there are changes in physical and chemical conditions resulting from the radiation and temperature fields generated by the waste package. The effect of these alterations and the subsequent interaction with the canister and waste form must be taken into account in assessing the release rates from the waste and the rates of migration of radionuclides through the near waste environment. The output from the near waste environment is again a radionuclide flux as a function of chemical species if available. Depending on the time of release this migration may be thermally driven.

3.3 Disposal medium

This is defined as the geological medium surrounding the waste form. It is assumed to be unlithified sediments and the transport process through the disposal medium is of radionuclides in association with or dissolved in water in the sediment. Adsorption and desorption processes must be taken into account in the transport models. The output from this system element is a radionuclide flux upwards.

3.4 Benthic Boundary Layer

The benthic boundary layer is defined as that region of the ocean bottom in which there is intense biological activity. It includes a layer of sediment down to about one metre depth and that portion of the water column immediately above the ocean bottom, including the mixed layer, up to about 100 metres from the ocean floor. This is a complex region of physical and biological interactions and it is not clear which will be the predominant transport processes through the region. Processes which may eventually need to be considered include direct physical transfer of dissolved radioactivity from the sediment water to the main water column, transport of radioactivity associated with the sediment particles along the sediment water interface and transport of radioactivity into biological organisms existing within the sediment or water column portions of the benthic boundary layer. This region forms the interface between the sediment transport and the physical and biological transport processes in the water column.

3.5 Water Column

This system element includes, in principle, the entire ocean beneath which the disposal occurs and adjacent oceans in so far as they interact within the timescales of interest. It incorporates both physical and biological transport processes together with biological reconcentration or uptake mechanisms following physical transport. Although these processes interact, it is possible to sub-divide the system element as shown in Figure 2 into physical oceanographic transport processes and biological transport procesees. The physical transport processes are assumed to be largely advection and diffusion of radionuclides dissolved in the water. Additional processes considered are transport of radionuclides absorbed onto small sediment particles and removal of radionuclides from the water column by sedimentation. Biological transport processes are those in which there is sufficient flux of material to be consequential when compared with the flux of material resulting from physical transport processes. We distinguish, therefore, between biological transport affecting the mass movement of radionuclides and biological processes which transfer material from the bulk areas of the water column to man. The latter may be of critical importance in determining the doses to man but we believe they will have little effect on the mass distribution of radioactivity as a function of time in the water column. In Figure 2 the interactions between the physical and biological transport processes are shown, together with a representation of the output of both processes which lead to doses to man. Also shown is the possibility of direct exposure of man resulting from "short circuit" transport processes direct from the benthic boundary layer.

3.6 Doses to Man

Within the system element both individual doses via critical pathways and collective doses via more general pathways should be assessed. In our initial study we are concentrating on the assessment of maximum future annual effective dose equivalents to individuals. The assessment of collective doses for use in optimisation studies or comparisons of options should not be made until a reasonably reliable overall system model is available. However the sensitivity of annual collective doses and collective dose commitments to variations in parameters and assumptions will be investigated using the simple system model.

3.7 Dose to fauna

Although in principle it is necessary also to assess the dose to fauna this will not be carried out as part of the initial study.

The outputs from each of the system elements in Figure 2 are summarised in Table 1.

4. PRESENT AND FUTURE WORK

At present we are putting together an assembly of simple models for the various system elements in order to make a start on the objectives identified earlier. These models are summarised in Table II. In some cases, for example physical oceanographic transport, the model is that supplied by the appropriate task group of the SWG.

In addition to specifying models for the various system elements it is also necessary to specify a number of base case assumptions and parameter values in order to carry through the preliminary calculation. These were discussed in detail at the last meeting of the SWG in Bristol, UK, March 1980, and the agreed values are summarised in Table III.

The main task of the SATG at present is to complete the first iteration of the overall system model using simple models for the various system elements and based on the scenario given in Table III. This will be followed during the next year by preliminary sensitivity analysis to identify the key parameters. These results will be transmitted to the other task groups and should serve to focus the efforts of the various research programmes being carried out.

We intend to analyse singular events, including transportation and emplacement accidents, at a later stage using deterministic models to assess the consequences and also taking into account the probability of occurrence of such singular events.

5. CONCLUSIONS

The work of the Seabed Working Group and its various task groups is an excellent example of international co-operation at the scientific level in research necessary to assess the feasibility of disposal options for high-level radioactive wastes. The Systems Analysis Task Group plays a major part within this international programme in co-ordinating the research efforts within the major areas of the overall programme. In order to effectively carry out this co-ordination the SATG has constructed an overall model of the system and broken this down into defined system elements. At present the SATG is carrying out, using simple models, an initial appraisal of the entire system which will then be used to provide guidance to research on other elements of the system. When the necessary research and model development have been completed, an appropriate basis will exist for a decision on whether or not seabed disposal is a technically feasible concept.

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TABLES

FIGURES

TABLE I. Outputs required from system elements.

System Element	Output (as a function of time)
Waste/Form Canister	Radionuclide release[a] Thermal output Radiation field
Near Waste Environment	Radionuclide flux[a] Thermal output (Alterations in physical, chemical and mineralogical properties induced by the waste presence - feedback to Waste form/canister element)
Disposal Medium	Radionuclide flux[a]
Benthic Boundary Layer	Radionuclide concentrations in materials leading directly to doses to man[a] Particulate or dissolved radionuclide flux into water column[a] Biological radionuclide flux into water column[a]
Water Column (Physical and Biological Transport)	Spatial distribution of radionuclide concentration in water (including suspended materials and coastal sediment)(a) Spatial distribution of radionuclide concentration in biological products including foodstuffs(a) Radionuclide concentration in fauna(a)

(a) Output also required as a function of radionuclide and chemical species.

TABLE II. Generic Model Types For Initial Assessment Purposes Only.

System Element	Model
Waste form/canister	Canister delay time (mean or minimum and distribution, Surface area and temperature dependent leach rate (bulk dissolution).
Near Waste Environment	Radionuclide migration under influence of coupled heat and water flow.
Disposal Medium	Radionuclide transport by molecular diffusion, including allowance for sorption and radioactive chain decay.
Benthic Boundary Layer	No detailed model identified, instantaneous and complete transfer assumed.
Water Column	(a) Physical Transport Diffusion/advection model using an interlinked network of six compartments. (b) Biological Transport Mass balance model for bulk transport, successive trophic level model for pathway analysis.
Dose to Fauna	No model identified
Dose to Man	Exposure pathways by as many routes as have been identified [3] Dosimetry using current recommendations of the International Commission on Radiological Protection [4]

TABLE III. Base Case Scenario Parameters and Values

SYSTEM ELEMENT	BASE CASE VALUES	RANGE FOR INITIAL SENSITIVITY ANALYSIS
Waste/form Canister		
Power generation	1000 GW(e)y	
Reactor type	LWR	
Burn-up	33,000 $MWdt^{-1}$	
Reprocessing	Purex process 360 days ex-reactor 0.5% Pu and U lost to HLW stream All Tc assumed to be in waste, I assumed to be in similar waste form.	
Waste form	Borosilicate glass 10% by weight fission product oxides. Density 2.5 gcm^{-3} Volume glass per canister 0.2 m^3	5 - 20%
Interim storage	50 a	10 - 100a
Canister dimensions	(i) 3m long x 0.3m diameter (ii) 2.5m long x 0.5m diameter	
Mean canister life	500 a after emplacement.	100 - 10^4a
Radionuclide release rate	Temperature dependent leach rate model [a]	

TABLE III (continued)

SYSTEM ELEMENT	BASE CASE VALUES	RANGE FOR INITIAL SENSITIVITY ANALYSIS
<u>Disposal medium</u>[b]		
Medium	Uniform isotropic fine-grained sediment	
	Porosity 75% by volume	50 - 90%
	Permeability 10^{-7} cms^{-1}	10^{-5}-10^{-9} cms^{-1}
	Molecular diffusion constant 1×10^{-9} m^2s^{-1}	
	Bulk density 1.4 gcm^{-3}	1.2-1.7 gcm^{-3}
	Thermal conductivity 0.78 wm^{-1} $^oK^{-1}$	
	Solids heat capacity 2.3×10^3 K J m^{-3} $^oK^{-1}$	
	pH 7.2 - 8.2 (undisturbed)	
Burial depth	30m	10 - 100m
Total sediments thickness	60m	20 - 200m
Canister spacing	100m	10 - 100m
<u>Benthic Boundary Layer</u>		
Thickness	Zero	
Transfer function	1	
<u>Water column</u>		
Ocean structure	3 horizontal sections 2 vertical layers (top 1000m and remainder)	
	Overall depth 4000m	4000-6000m
	Volume 1.2×10^{17} m^3	
Water motion	Horizontal advection[a] Vertical upwelling and downwelling[a]	
Water mixing (diffusion)	Vertical eddy diffusion coefficient 10cm^2 s^{-1}	10^{-1} - 10^2 cm^2 s^{-1}
	Horizontal eddy diffusion coefficient 3×10^6 cm^2 s^{-1}	0 - 10^8 cm^2 s^{-1}

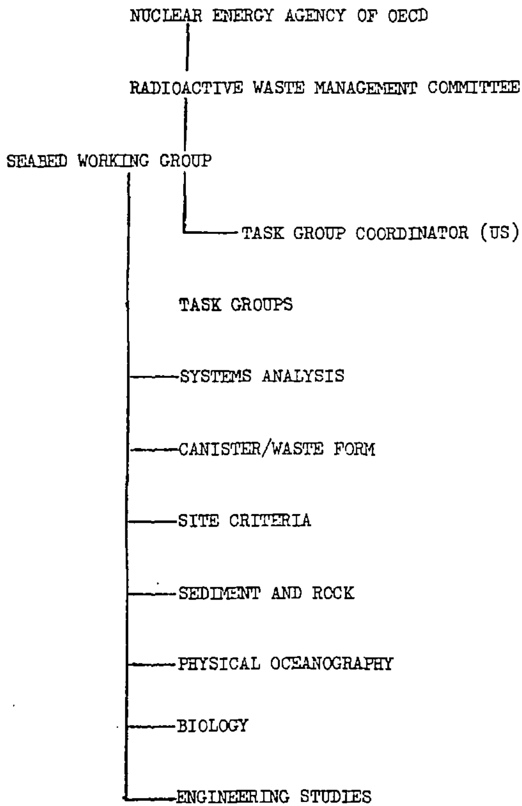
TABLE III (continued)

SYSTEM ELEMENT	BASE CASE VALUES	RANGE OF INITIAL SENSITIVITY ANALYSIS
<u>Biological Transport</u>	see text	
<u>Dose to man</u>		
Dosimetry	Latest ICRP Recommendations [4,5]	
Pathways and intake assumptions	Latest IAEA Recommendations [3]	
Calculation aim	Maximum future annual effective dose equivalent to individuals and annual collective effective dose equivalents (as a function of time)	
<u>Dose to Fauna</u>	No decision on parameters	

(a) Parameter values are given in the report of the 1980 meeting of the Seabed Working Group.

(b) Parameters and their ranges are not independent.

FIGURE 1. Tark Group Structure



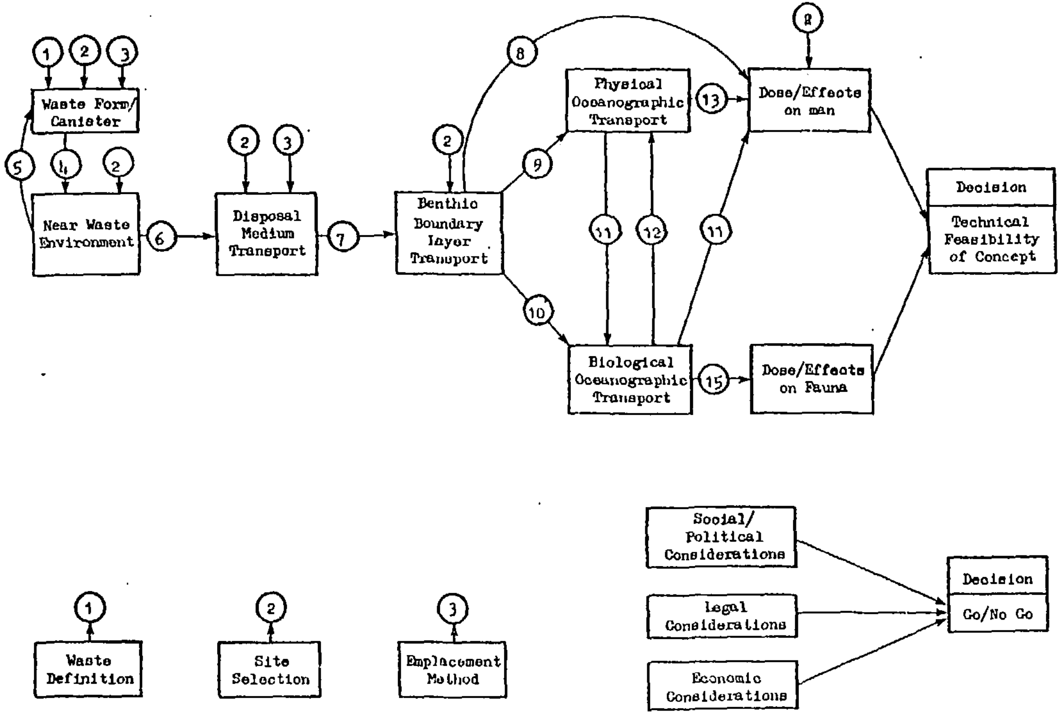


Figure 2. Systems Analysis Model