CONFINEMENT BY COMPARTMENT: SENSITIVITY ANALYSIS OF A SUB-SEABED REPOSITORY

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ABSTRACT

Feasibility studies of yet undefined sub-seabed repositories require assessment models and codes which are easier to be applied, more versatile and more concise in displaying the results. This contribution on assessment is presented, running on a microcomputer, which can make easy use of sophisticated general circulation ocean models and which shows a novel way of representing results for activity, barrier affectivity and sensitivity.

REQUIREMENTS

Sub-seabed repositories have only begun to attract international interest. At the moment they are still facing severe political opposition which may be due to the early attempts to dispose of LLW on the seabed without burying it. The long-term behaviors of waste disposed of in the seabed shows, however, completely different results in a safety assessment. Therefore, several nations have joined recently in an enforced research work called the Seabed Working Group (SWG) under the auspices of the NEA/OECD which was terminated in 1988 (1).

In such an early stage of a safety assessment, which is aimed solely at proving the general feasibility of a sub-seabed repository, other ways of approach are required than in the assessment of a definitely planned repository where all boundary conditions have been fixed. What is required here are mathematical models and numerical codes which are distinguished by: 1) Ease, 2) versatility, and 3) conciseness.

East, because it must be anticipated that the discussion about sub-seabed repositories will be reopened at some later time after this first intensive period within the SWG. Each such discussion will supposedly require new feasibility studies, preferably on the same footing as the previous ones for the sake of comparison. And the faster these codes are applicable the better they will support these discussions.

The present code has been streamlined to meet this requirement. It runs on a microcomputer and is stored on a 3.5" disk.

Versatility is important, because as long as safety assessments are performed for a generic and imaginary repository the variability of the input data is still large and a high degree of sophistication in modeling would not be appropriate at the beginning. However, the assessment approach should be organized in such a way as to allow a continuous increase in depth of modeling.

In the present assessment model, this requirement is taken into account by a special "scaling" mechanism.

Conciseness is also important, because as long as one is still in search of an appropriate repository and as long as one has to compare different situations with each other, one would like to have the complete information of a feasibility study displayed as concisely as possible. This information not only comprises the final dose curve but also its sensitivity to the individual barriers. The latter constitutes the even more important information for feasibility studies of a repository.

In the present case, this information will be included by way of a new method of evaluation and display, the "confinement by compartment."

However, before going into the details of the model and code developments (2), we shall give a description of the repository which is the subject of the present assessment.

DEFINITION OF THE SUB-SEABED REPOSITORY

Penetrator repositories for high-level waste have been defined and investigated by the Seabed Working Group in particular; an international cooperation under the auspices of the NEA/OECD, over a period of ten years, terminated in 1988 with a series of detailed reports (1).

The model repository which is used in the present assessment is supposed to use penetrators, i.e. pointed cylindrical casks of an 8.5 m length and a .65 m diameter of mild steel which will take five glass molds of the usual COGEMA size with vitrified waste from reprocessing. Their walls will be 7.5 cm thick and the empty excess space inside can be filled with lead. They will have a weight of 10 to 15 Mg.

They are supposed to be transported to suitably chosen sites, e.g. in the Great Meteor East (GME) or South Nares Abyssal Plain (SNAP) off the Canary Islands and Puerto Rico, respectively, with special ships. Over the site, they will be dropped freely to a depth of some 5,000 m. Stabilized by fins in the rear, the penetrators will follow almost ideal vertical trajectories and are planned to penetrate some 50 m into the sediment due to a final velocity of approximately 200 km/h with which they will arrive at the bottom. They will be placed at a distance of 100 m from each other.

For the present feasibility studies, we assumed vitrified high-level waste from 70 Gg original heavy metal which should be sufficient for a 50-year period of operation of all German nuclear reactors. Reprocessed in a German plant, this amount of heavy metal would fill about 60,000 molds of glass or some 12,000 penetrators. From this would result a required repository area of 11 km x 11 km.

Worldwide, one projects an accumulated demand of 1,400 Gg of heavy metal from 1978 up to the year 2000, or of 2,800 Gg of fuel for the lifetime of all reactors installed by 2000. This would mean about 200 to 400 such repositories or a repository area of 150 km x 150 km and 200 km x 200 km, respectively, if all high-level waste would be disposed of in the sub-seabed.

The assumptions about the behaviors of such a repository, which will be made in the present paper, have been partially checked empirically by the Seabed Working Group in the very successful research cruise ESOP (3) where smaller penetrators of half the length were used reaching final velocities of between 150 and 190 km/h.

DEFINITION OF COMPARTMENTS

The radionuclides buried in the sub-seabed sediment are separated from the world by two man-made and four natural barriers. The former are the glass matrix and the steel container of the penetrator which will deteriorate slowly, the latter are the sediment through which the radionuclides have to migrate, the adsorption to its pore walls which retards the migration, the ocean waters which dilute the released nuclides and the adsorption to sinking particulate matter, called scavenging.

Four of these six barriers can be represented as compartments where radionuclides are held confined for a certain time. These are the glass matrix, the sediment around the repository, the water masses of all world oceans and the bottom sediment of all oceans where the scavenged radionuclides are deposited by sedimentation.

Another compartment in the pathway of the radionuclides to mankind is defined by the living organisms (plants and animals) of the oceans which accumulate the elements and are then used in one way or another by man. Other compartments like clouds, aerosols and coastal sand have not been used in the present study.

These compartments constitute a complete set of locations which enclose the entirety of radionuclides over the whole time period, though in different fractions. The history of these fractions will be shown to be an important indicator for the affectivity of a barrier.

MECHANISMS MOBILIZING RADIONUCLIDES

The integrity or the affectivity of a barrier is limited by the processes which destroy it or which mobilize the radionuclides. In the following, the possible processes which are the main object of the modeling efforts in a safety analysis are discussed.

The knowledge about these processes is rather heterogeneous. Some are known well or have been explored in detail whereas little is known about others. But the degree of sophistication which can be achieved in modeling is limited by the least well-known processes in this sequence. The present state of exploration of the release processes is as follows:

Corrosion of the steel penetrators open pathways to water. This has, however, not yet been investigated under the chemical conditions of the sub-seabed sediment. The penetrators are therefore assumed here to yield to corrosion with a linear failure rate.

Leaching of the glass by pore water of the sediment has not yet been investigated empirically either. But there is ample evidence about the behaviors of glass from leaching experiments at an elevated temperature which can be extrapolated to lower temperatures. Additional support is found in the leaching of natural glass samples at the bottom of the ocean which relates to the same order of magnitude. In the examples below, we have used the leach rate of 45 m g/(m^2.a).

Motion of water, in other repositories the most effective process to displace the radionuclides, is inhibited in the sediment due to the lack of pressure gradients. Only geothermic effects, the heating power of the enclosed activity or compaction processes, could in principle lead to slow motion as detailed model calculations show. This motion would be enhanced to a more relevant size, though, if open fissures or discontinuities exist. In the present investigation, we neglected this possibility altogether

In the absence of advection, molecular diffusion remains the only process to spread radionuclides. But this motion is a very slow one in which the sediment confines the radionuclides for a very long time and becomes a most effective barrier. Here the diffusivity coefficient 5.E-10 m^2/s was used.

The effect of this barrier is increase by sorption which retards the migration still more, though not for all radionuclides. The distribution coefficients for the sub-seabed case had been elaborated by the SWG (1, 3).

In the boundary bottom layer between the sediment and the ocean, the transport can be enhanced beyond the diffusive velocity by bioturbation due to the relatively high level of animal life in and on the bottom, like worms in burrows, etc. The overall effect should, however, not be overestimated and is disregarded altogether here.

Dissipation in the ocean occurs via turbulent mixing and ocean currents. The former is, as usual, taken into account numerically by assuming homogeneous distributions in the unit volume cells of the numerical calculus. Large-scale transport by ocean currents is modeled by special box models discussed below.

The scavenging process of small particles sinking to the bottom of the oceans with adsorbed radionuclides is modeled using a constant sedimentation rate of 20 g/(m2.a) for all oceans. The related distribution coefficients for adsorption of radionuclides are taken from the SWG data (1).

MODELING APPROACH

As stated previously, the main requirements in a feasibility study for an imaginary repository whose details are not yet well-defined are versatility and conciseness. The former is ensured by a particular "scaling" mechanism built into the individual submodels. The latter is met by a new way of evaluation and display in terms of "confinement by compartments."

Scaling

An unprecedented feature of sub-seabed repositories is the big discrepancy between available local data and available generic models of considerable sophistication.

In a release analysis of land-based geological repositories, both the near and, in particular, the far-field models are developed on the basis of the existing, more or less detailed data. Hence, all models are in concord with the acquired data. This holds especially for the far-field models of migration through the geological formations which depend heavily on the local stratigraphy and hydrogeology, but also for the models of pathway to man which depend on local agricultural and water use.

In a sub-seabed repository, on the other hand, none of the dissipation processes like the migration in the sediment, the transport in the ocean or the sedimentation, nor the pathways to man like food chain, water use or beach activities, are dependent on the circumstances of the repository. On the contrary, most of these processes are even well known on their own and sophisticated models have been or can be developed for them.

It is novelty, in the assessment of a geological repository, to be able to make use of existing, rather sophisticated calculations. In order to take due advantage of this fortunate situation, a special method was applied in the present analysis to "scale" down the sophistication of these models and yet to use their results. This saves a considerable amount of computer time allowing the whole code to be run on a microcomputer.

Moreover, if this scaling-down is performed in a unique way, any degree of sophistication of the respective model can be attained without much numerical effort. This allows for adjustment of the model to a possibly increasing degree of accuracy in the repository exploration. This adjustment is necessary since the accuracy of a complex code with a series of submodels is always limited by the least accurate or least sophisticated submodel.

This scaling method, therefore, has a high versatility because it not only relieves the numerical calculations but also allows a direct comparison of the various degrees of approximations with each other. All scaling is done consistently from one and the same accurate mode.

The sketched procedure has been applied in a rather trivial way to the migration behaviors of radionuclides in the sediment where more detailed computations by the Sandia Labs (1) could be scaled down to the present requirements.

The more important application, however, was achieved by scaling down a precise general-circulation model (GCM) of the oceans which had been developed by the German Hydrographic Institute (DHI) in Hamburg (4). This model had been computed with a high number of cells of only $1^0 \times 1^0$ horizontal extension and an average depth of 300 m for the Atlantic Ocean with slightly larger cells for the world oceans. The results were in excellent agreement with measured values of the ocean currents.

The model was scaled down to a meter 34 cells for all world oceans. Such a box model had been suggested by the Seabed Working Group for the very purpose of analyzing the sub-seabed repositories in the GME and SNAP area. It features box sizes increasing with the distance from the repositories. The smallest boxes are therefore just over the repositories followed by slightly larger vicinity boxes. Next, the North Atlantic Ocean is dissected horizontally into four areas along the Mid-Atlantic Ridge, i.e. over the four ocean basins with three boxes beneath each area. The adjacent Arctic Ocean in the north and the whole South Atlantic are then only represented by two boxes each, whereas the remaining world oceans are condensed in one single box.

Unlike its application by the SWG, this roughly-sketched grid of boxes had to be adjusted to the real topology of the Atlantic Ocean (supplied on tape by the DHI) in the present investigation. This step enabled us to evaluate the necessary exchange currents between the individual boxes from the accurate German ocean model. This is performed by reading the host of original current data from tape and by adding them up appropriately. Thus, a scaled-down box model emerges from a very accurate model in a unique and self-consistent way and without much demand for computer time.

Hence, it is obvious that any improvement of the box model by adding more boxes or changing their arrangement can easily be handled in the same consistent way and can be compared to the previous one on a common basis. This shows the versatility of the chosen method.

A similar procedure was devised for the sedimentation model which is also known to have a higher degree of accuracy.

Unfortunately, food chain models are themselves not yet very well known, but it can be anticipated that eventually, similar procedures can be applied also in this field.

Summarizing the previous cases of scaling-down, one can state the criterium that the required degree of accuracy of a scaled model should be given by the affectivity with which the modeled compartment contributes to the final dose result. This, therefore, demanded a method to disclose this affectivity with respect to each compartment and led to the devising of the "confinement by compartment" principle.

Confinement by Compartment

A criterium for the affectivity of a barrier is the amount of mobilized radionuclides or their resulting activity which it can hold and the time it can confine it. The affectivity is therefore proportional to the product of the two, or more exactly, to the time integral over the enclosed activity. In a diagram of the buried product, total activity versus the time this product or integral can be represented by part of the surface is under the total activity curve.

Since the radionuclides or their activity must appear, at least, in one of the compartments, the surface under the total activity is thus dissected completely into a final number of partial areas, each of which corresponds to one of the compartments.

This representation by areas has many features as one can easily read, e.g. from Fig. 1:

1) For each time point, a vertical cut through the different areas shows the confinement of activity into the different compartments, and the relative width of the areas reveals the affectivity of each compartment at the respective time.
2) The change of the width of the area of each compart-

ment with time shows the migration of the radionuclides in this compartment.

3) The total size of the area is a direct measure of the affectivity, if the compartment is a barrier.
4) Finally, the full power of this method to evaluate and display the activity by compartments shows up in sensitivity considerations.

Sensitivity is defined as the amount of change in the final quantities (e.g. activity reaching human beings, or dose values) upon the variation of a certain parameter. In our evaluation of individual compartments, however, the sensitivity expresses itself much more directly in a change of the area of the corresponding compartment and can therefore be visualized immediately.

The present method is even more versatile. By this unique correlation of a change of parameter to the respective compartment, more parameter changes can be performed at the same time since they can be traced individually. This reduces, clearly, the number of necessary computations.

And, most of all, this method improves the display of results considerably since both the activity received by mankind and the affectivity of each barrier can be represented by a single, intuitive diagram, and the sensitivity with respect to several simultaneous parameter changes can be visualized by the comparison of only two such diagrams.

RESULTS AND DISCUSSION

According to the three requirements stated at the beginning, the code underlying the present calculations was developed to run on a microcomputer and in BASIC, with I/O procedures adjusted exactly to this kind of computer. The program is contained on a 3.5" disk, including in- and output data, and it is therefore a matter of minutes to restart the program whenever desired.

The essential input data have been laid down in the discussion of the involved processes. As an example, we have computed two different cases, both for the same five long-lived radionuclides Tc-99, Pd-107, Sn-126, I-129 and Cs-135, and both ending with the activity accumulated in the used sea-fish. This is directly proportional to the activity received by a human being who eats a certain amount of fish, since we consider only the fish path here. Both figures show the result under the assumption of a linear failure rate by penetrator corrosion between 100 a and 1,000 a after disposal

For the sake of comparison, we have assumed in Fig. 2 that the glass fails as a barrier at the same rate as the penetrator. This shows up very strikingly since the activity then leaves the sediment compartment almost completely

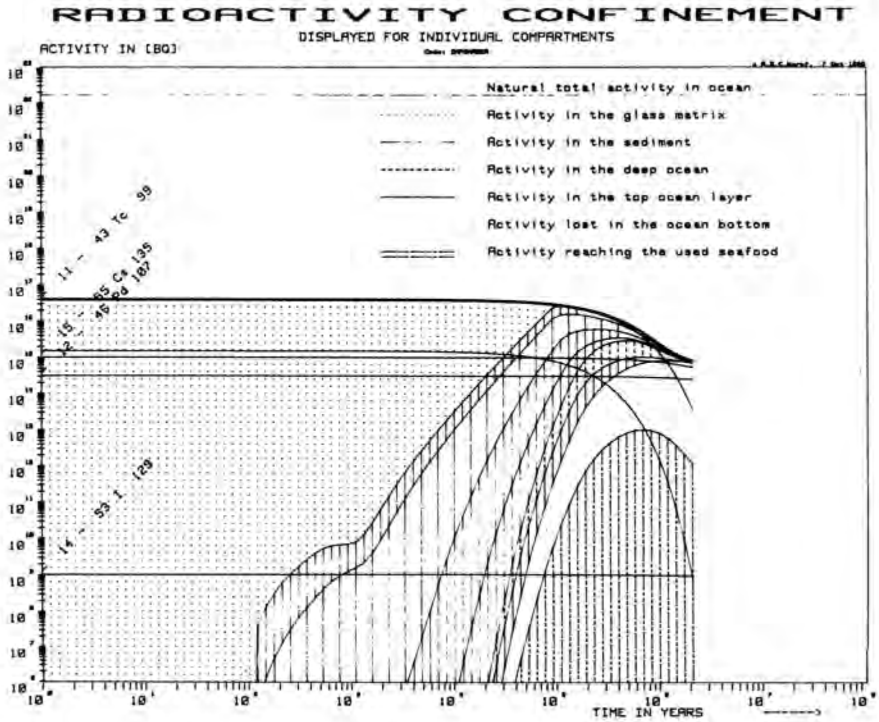

Fig. 1. Total Radioactivity Confined in the Set of Carpartments of a Sub-Seabed Reository.

already within 300,000 a, whereas in Fig. 1, this happens only after 2 Ma when the total activity has already declined by almost two powers of magnitude.

The change in the glass barrier behaviors shows up, thus, immediately in the considerably smaller glass area of Fig. 2, indicating a reduced affectivity as expected. It also yields a larger activity area for the sea-fish, revealing the sensitivity of the latter to the change in the glass behaviors.

For reasons of comparison, the two diagrams show at their tops the total activity in the oceans due to the natural radionuclides like K-40. This is almost six orders of magnitude higher. Hence, even a factor of 200 or 400, as it would result from a disposal of the waste of all nuclear plants in the world, would ont increase the total radioactivity content beyond dangerous limits.

The results for the committed dose equivalent are displayed, respectively, in Figs. 3 and 4. They show little difference in the peak values but considerable difference in the beginning and duration of the maximum exposure. This is due to the assumption of a complete failure of the glass matrix which is, of course, one of the most conservative assumptions.

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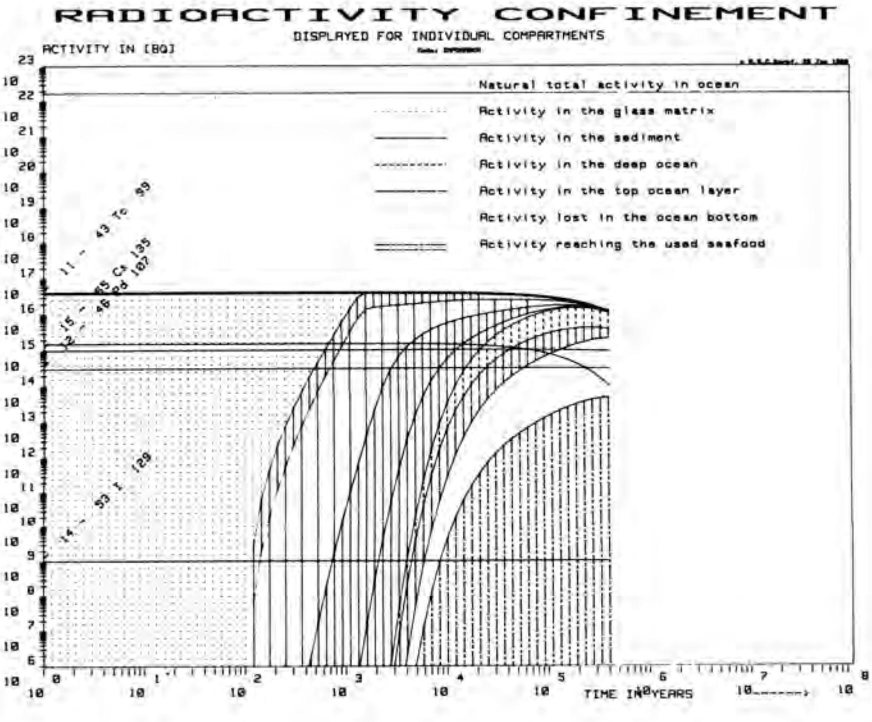

Fig. 2. Total Radioactivity Confined in the Set of Compartments of a Sub-Seabed Repository with Rapid Glass Deterioration..

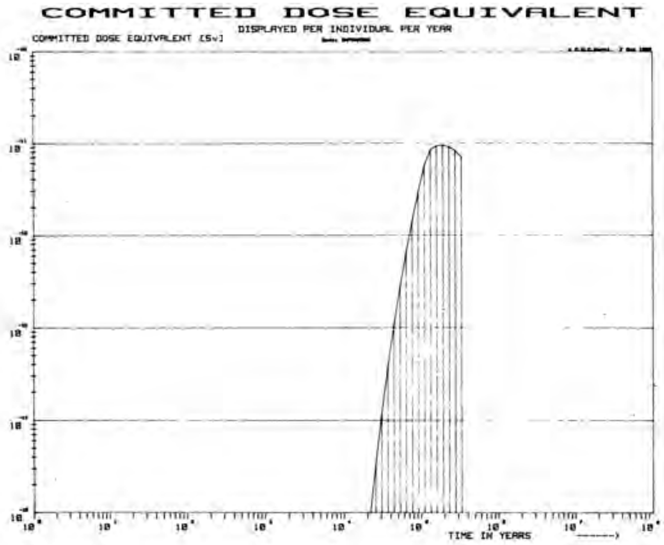

Fig. 3. Committed Dose Equivalent Per Year for an Individual Eating 100 kg of Contaminated Fish Per Year According to Fig. 1.

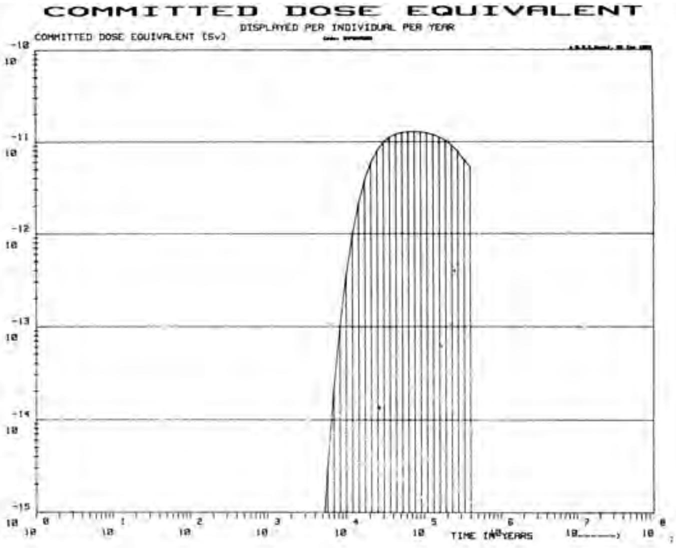

Fig. 4. Committed Dose Equivalent Per Year for an Individual Eating 100 kg of Contaminated Fish Per Year According to Fig. 2.