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HIGH-LEVEL RADIOACTIVE WASTE DISPOSAL IN THE DEEP OCEAN

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1. INTRODUCTION

A programme has been initiated in the United Kingdom by the Fisheries Laboratory, Lowestoft (MAFF) to study the dispersion of radioactivity in the deep ocean arising from the possible dumping of high-level waste on the sea bed, in vitrified glass form, which would permit slow leakage over a long time scale. The programme consists of two parts, and is directed by a steering group set up by MAFF which also includes representation from British Nuclear Fuels Ltd and the National Radiological Protection Board. Shortly after its inception, representatives of the Institute of Oceanographic Sciences (IOS) joined the group in an advisory capacity. The first part of the programme consists of the development of a simple model which overcomes many of the criticisms of the earlier model proposed by Webb and Morley (1). The second part of the programme concerns the research cruises planned to measure the advection and diffusion parameters in the deeper layers of the ocean to provide realistic input data to the model and increase our fundamental understanding of the marine environment into which the radioactive materials may be released.

2. THE SHEPHERD MODEL

The Shepherd model (2) is concerned with the continuous release of radioactivity from a point source on the bed of a circulating finite ocean, which for convenience has the dimensions of the North Atlantic Ocean. The model includes horizontal and vertical diffusion and horizontal advection but not vertical advection. Both Fickian (normal, local diffusion where $\nabla^2 = 2Kt$) and Okubo-Pritchard (more applicable to oceanic diffusion, including larger-scale eddies, where $\nabla^2 = v^2t^2$) representations of the diffusion process have been examined since there is reason to believe that non-Fickian diffusion is more appropriate in the oceans. It is found that there are differences in the concentrations arising from the use of the two types of diffusion but these do not seriously affect the main conclusions, and in general Fickian diffusion is used since this gives the higher concentrations and hence is the "safer" formulation. Shepherd's model estimates the equilibrium concentrations and relates these to the average concentration (S_0) which would arise from a continuous release, maintained indefinitely, with complete and thorough mixing over the whole ocean. Results have been calculated for surface concentrations at 10 equally spaced points around the perimeter of the ocean and over depth profiles around the perimeter, which in this study is taken as the edge of the continental shelf. Thus maximum and minimum as well as mean concentrations can be calculated. Because diffusion and advection parameters are not particularly well known for the deep ocean, a range of values of these parameters has been used in the model in order to examine the effects on the results of values outside those generally believed to be the most likely estimates, although a range of vertical diffusion values only is shown in (2), this clearly being the most critical parameter of those examined.

In so far as coastal surface concentrations are concerned, the conclusions are that horizontal variations around the perimeter of the ocean are small, except for very rapid vertical diffusion (16 years vertical mixing time), and even then they are likely to be less than an order of magnitude different from the mean concentrations. Generally the concentrations are less, usually substantially less, than the well-mixed concentration (S_o), only slightly exceeding S_o in the case of very rapid vertical mixing and the shorter half-lives. For the most relevant cases, of mixing times of a few hundred years and half-lives greater than 30 years, horizontal variations may be taken as negligible and concentrations are normally between S_o and $S_o/10$ (Fickian) and between S_o and $S_o/100$ (Okubo-Pritchard). Certainly for half-lives of a few thousand years the surface coastal concentrations do not vary significantly from S_o.

Concentrations below the surface layer would also be generally less than the well-mixed average (S_o) at mid-ocean depths, using reasonably realistic estimates of the diffusion and advection parameters, and indeed it might be expected that above average concentrations would normally be found only within the bottom few hundred metres of a 5000 m deep ocean. Overall it would appear that we might expect fairly uniform concentration horizontally but that significant vertical stratification would occur, especially for those isotopes with half-lives less than 30 years. However, the bottom concentrations are unlikely to exceed S_o by more than a factor of 50 or so, except for a small area very close to the release point; and for the more interesting case of half-lives greater than 30 years and realistic vertical mixing times of a few hundred years, this factor is unlikely to be greater than about 10. Another important point to note is that although vertical advection is specifically excluded from the model, the effects of upwelling from the ocean floor cannot result in the surface layers of concentrations more than those which are expected on the bottom, i.e. even continuous upwelling, lasting for periods of the order of a half-life, should only result in an increase of concentration in the surface layer of about 10, for that particular isotope, at almost all locations.

Thus it would appear that satisfactory estimates of the levels of activity which can be safely deposited (in suitable packaging) on the sea floor can be made simply on the basis of the long-term well-mixed average concentrations which would result, allowing a small safety factor for possible persistent upwelling and the above-average concentration in the bottom few hundred metres, remembering that the shorter-lived isotopes, which have the highest bottom concentrations relative to S_o can be expected to decay considerably before significant leaking occurs from a well-designed package containing vitrified waste.

It is appropriate at this stage to compare the specific surface concentrations estimated by Shepherd's model with those of Grimwood and Webb (3), who now propose a slightly modified version of the Webb and Morley model to estimate the surface concentrations arising locally to the area of release in the short term coupled with a long-term compartment model which becomes increasingly valid for times greater than 100 years or so after release until it approaches (at the order of 1000 years) the S_o levels of Shepherd's model, the levels to which all mixing-type models must inevitably converge in the long term. In effect (in so far as the models are comparable) it can be shown that for half-lives between 30 and 3000 years, the surface concentrations over the disposal site, as predicted by Webb and Morley, do not vary by more than about one order of magnitude from the coastal surface concentrations calculated by Shepherd using, in the Shepherd model, the "most likely" estimate of vertical diffusion (10 cm^2/s). However, the radiological safety assessment associated with the original Webb-Morley model used concentrations 50 times lower than these to allow for dilution between the surface waters above the disposal area and the nearest fishing grounds. It may be concluded that their assessment of the maximum permissible rates of disposal should be reduced by between 10 and 50 times for half-lives less than 1000 years, and by substantially more for longer-lived nuclides, if Shepherd's proposal is accepted, viz that disposal rates be based on the long-term well-mixed average (S_o). Shepherd's proposal is also rather more conservative for the shorter half-lives than the results of Grimwood and Webb's short-term model and is equivalent to the results of their long-term compartment model for half-lives greater than 1000 years.

Some further development of models is planned but, even so, it should not be forgotten that these mixing-type models assume a slow continuous release, and that the steady mixing mechanisms represented mathematically by the diffusion theory are valid. They do not necessarily cater for instantaneous release of large amounts of activity by whatever means, e.g. an accident during dumping, "burping" of radioactivity due to the build-up of heat below the sea bed around an "in the bed" disposal, or subsequent concentration of activity in a specific hot spot by sediment or biota. Thus there is a real need to further our understanding of the small-scale and mesoscale oceanographic processes in the deep ocean, and it is to this end that the second part of the programme is, in part, directed although, clearly, one of the intentions of producing better models it that they should provide guidance on the relative worth of various oceanographic research programmes which might complement the modelling studies, either by indicating which were the critical oceanographic parameters needed for input or where observations might best be made to validate model predictions. Primarily, Shepherd's work suggests that the more important parameters may be vertical advection and diffusion but it is not clear at present how the former could be measured directly, and the latter is obviously difficult - but technically feasible, at least for small-scale diffusion. However, it is clear that there is also an urgent requirement to better understand the horizontal advective and diffusive processes in the deep ocean, and the equipment and expertise for the former, and possibly for the latter, already exist.

3. THE FIELD PROGRAMME

The steering group have concluded that the first priority should be the deployment of about 6 to 8 long-term full depth current meter stations at various locations in the north-east Atlantic selected for oceanographic reasons rather than as possible disposal sites. These stations would be maintained at 6-monthly intervals or so by a suitable vessel which would recover and redeploy the moorings, and it is felt that a minimum length of record of about 2 years is required at each site. In the general locality of these stations it would be sensible to carry out neutrally buoyant float experiments and make salinity-temperature-depth measurements to further our understanding of the formation, and frequency of occurrence, of deep ocean eddies (4) and study the velocity and density fields, particularly in and near the benthic boundary layer. It seems possible that small-scale diffusion experiments might also be possible using a radio tracer at depths below the level to which such data presently exist, viz about 1200 m.

Such a programme which might reasonably extend over 5 years at a cost of about £$1\frac{1}{2} \times 10^6$ would not solve all the problems of the dynamics of the deep ocean, but it is reasonable to think that we would then be in a better position to choose, more confidently, sensible locations for high-level waste dumping. Towards the end of the 5-year period we might also expect to be locating long-term current meters on these sites and studying the spatial variability around them with complementary shorter-term current meter arrays.

Fortunately there is a like interest, in so far as the long-term current meter stations are concerned, in SCOR WG 34 (the Working Group on Internal Dynamics of the Ocean), with which the steering group has established contact, and indeed it seems that profitable cooperation can be established here between MAFF, IOS, Kiel

University, Centre Océanologique de Bretagne and Laboratoire d'Océanographie Physique, Paris, proposals already being well advanced, in the North-East Atlantic Dynamics Study (NEADS), for the establishment of five such sites, which could be supplemented by others when funds are available, and could be recovered and redeployed by various research vessels operating within the group.

Financial support for the 5-year field programme, which it is hoped will involve extensive cooperation between MAFF and IOS, is not yet approved, but a start has been made within existing budgets related in MAFF to a low-level waste dumping project, and in IOS to the NEADS project, and has involved work in November-December 1976 by both RRS DISCOVERY (IOS) and RV CIROLANA (MAFF). During this period a long-term full depth current meter mooring was laid at 46°05'N 17°11'W and three short-term bottom moorings were laid around this position within the NEA dump area. A number of neutrally buoyant floats were tracked through the area for periods up to 17 days. The current meter records have not been processed at the time of writing, but the floats appear to indicate a cyclonic eddy system below 3300 m in the southern part of the area, the floats moving first towards the west, then in a southerly, and later in an easterly direction with mean residual velocities (over 17 days) of 2.8-3.3 cm/s at 3300-3600 m, and 2.2-2.7 cm/s (over 13 days) near the bottom between 4200-4700 m. Towards the north of the experimental area a float was tracked at an estimated depth of 3648 m at a mean velocity of 3.4 cm/s in a north-westerly direction, for just under 7 days and two floats released near the centre of the experimental area at depths of 1000-1200 m, intended to be near the core of the Mediterranean Water, moved relatively rapidly towards the west and north-west at mean speeds of 8.8 and 7.7 cm/s for periods of 3 days 18 hours and 7 days 14 hours respectively. The mean residual current velocities indicated by the floats varied by up to 50% in magnitude during the tracking period. Two short hydrographic sections were made in the float tracking area in approximately north-south and east-west directions. The geostrophic velocities calculated from these hydrographic sections were reasonably consistent with the current field indicated by the floats. A bottom sediment core was also taken during the cruise at 46°07'N 17°13'W. It is intended to use this core, and others to be taken on subsequent cruises, to investigate the adsorption of plutonium on to deep sea sediments.

4. ACKNOWLEDGEMENT

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