PAST PRESENT AND FUTURE TECHNICAL BASIS OF RADIOACTIVE WASTE DISPOSAL IN THE UK

D.E. Billington and R.H. Flowers
United Kingdom Atomic Energy Authority

ABSTRACT

The nuclear industry in the United Kingdom is over forty years old so radioactive waste of all kinds has been safely managed for a long time. Disposal of some solid wastes to the deep Atlantic Ocean was carried out between 1949 and 1982 and near surface repositories for Low-level radioactive wastes were established at Drigg and at Dounreay in the late 1950s. Since 1977 there has been a major effort by the nuclear industry to prepare the means to process and package the wide variety of Intermediate-level radioactive wastes into stable solid products ready for eventual underground disposal. Government criteria have been set for the safety standards to be met by such disposal. A new Company, UK Nirex Ltd, has been formed by the nuclear industry partners to develop the necessary technology for deep underground disposal and to build and operate a repository at an approved site. Current estimates are that this should be achieved by about 2005. The assessment of radiological risk from the repository has been the subject of a large research and mathematical modelling program. There is now a good understanding of the important features of a waste repository which will be constructed deep below the water table.

HISTORICAL PERSPECTIVE

The nuclear industry in the UK goes back to the late 1940s so the question of what to do with radioactive waste is not at all new. For nearly 30 years the volumes of waste were small enough to be satisfactorily managed by:

- disposal of Low-level radioactive waste (LLW) at Drigg from 1959;
- storage of High-level radioactive waste (HLW) and Intermediate-level waste (ILW) on nuclear sites;
- some disposals to the deep ocean bed (1949-1982).

The Drigg site, which is around 130 hectares altogether, has a licence for disposal in trenches 5 to 8m deep and covered with 1m to 1m of rolled earth, over an area of about 45 hectares. The geology is clay, with some sandy sequences, which allow a dilute leachate eventually to reach the sea.

In 1957, a similar type of disposal of LLW was authorized at Dounreay, to service the Fast Reactor Research there. In both cases the LLW was defined as being:

- $< 20 mCi/m^3\ \alpha$ ($\approx$ 4GBq/te);
- $< 60 mCi/m^3\ \beta$($\approx$ 12GBq/te);
- $< 750 mR/hr\ \beta\gamma$ at contact.

Deep ocean disposal in the NE Atlantic was carried out from 1949 to 1982. The IAEA provided guidance on acceptable quantities and the OECD arranged supervision of the operations from 1971 onwards. The operations in the UK were organized from Harwell and by 1982 involved taking about 270te (1,000m^3) of waste per year to a 4,000km site in 4,000m depth of water about 500 miles SW of the UK.

The limits on radioactivity were:

- 1 Ci/te α;
- 100 Ci/te $\beta\gamma$;
- 10^6 Ci/te tritium.

which, in practice, meant that we used this disposal route for wastes which, although rather low in radioactivity, contained too much activity for acceptance at Drigg or Dounreay. The wastes were typically packaged in ten times their weight of concrete. The resultant gross mass and radioactivity disposed between 1949 and 1982 is given in Table I.

Deep ocean disposal stopped in 1983, following objections raised at the London Convention, and the UK Government announced formally in 1988 that no further plans would be made for disposal of drummed radioactive waste at sea.

TABLE I

Sea Disposal 1949-1982

Country	Gross Mass (Tons)	Radioactivity (TBq) Alpha	Beta/ gamma	Tritium
United Kingdom	57,546	612	23,627	10,781
Belgium	28,967	38	1,292	757
France	14,199	8.5	345	-
FR Germany	180	0.02	0.2	-
Italy	50	0.07	0.1	-
Sweden	1,081	1.0	2.0	-
Switzerland	5,330	5.0	647	3,836
Netherlands	19,162	1.1	236	99
Totals	126,515	665.7	26,149	15,473

RECENT DEVELOPMENTS

The whole subject of radioactive waste management took a step forward in public awareness in 1976 when the Royal Commission on Environmental Pollution published the report (1) that criticized the nuclear industry for not

making early plans to package and dispose of HLW and ILW.

Over the following ten years the UK Government and the nuclear industry worked hard to develop a firmer policy and the means of implementing it. The key events over this period included setbacks, as policy responded to public perception of the task.

- September 1976 - the 6th Report of the Royal Commission on Environmental Pollution found a 'lack of clearly formulated policy' for disposal of HLW and ILW. LLW 'should in the longer term be taken to a national facility other than Drigg'.
- May 1977 - Government placed the responsibility for national strategy and research upon the Department of the Environment (2).
- June 1981 - Government statement that HLW will be vitrified and stored for at least 50 years, and that early progress must be made on a repository for ILW.
- December 1981 - the UKAEA planning applications for exploratory drilling in rock types with potential for a HLW repository site were withdrawn on Government advice; drilling was however completed at one site (Altnabraec) in hard rock in Caithness, Scotland.
- July 1982 - the Nuclear Industry Radioactive Waste Executive (Nirex) was formed by UKAEA, BNFL, CEGB and SSEB to implement Government waste disposal policy on behalf of the main waste producers.
- February 1983 - 'London Convention' asked for a review of deep ocean disposal.
- October 1983 - the 1983 deep ocean disposal operation was abandoned.
- October 1983 - Nirex named Billingham and Elstow as sites to be investigated for suitability for a deep (ILW) and a near-surface (LLW) repository.
- November 1984 - the 'Holliday' review of deep ocean disposal was published, recommending no resumption until a 'Best Practicable Environmental Option' assessment had been completed and calling for exclusion of buoyant material from any future operation.
- December 1984 - Department of Environment published 'Disposal Principles' for repository safety. Also the proposal for an investigation at Billingham was withdrawn on Government advice.
- March 1986 - on Government advice, Nirex named further potential sites for the near-surface repository; these were clay sites at Bradwell, Fulbeck and Killingholme.
- May 1986 - on recommendation from the Commons Environmental Committee under Sir Hugh Rossi, the Government decided that no ILW would be placed in the near-surface repository.
- September 1986 - Nirex commenced drilling work at the four clay sites.
- May 1987 - Nirex decided that it will cost no more to put the LLW into the deep repository with the ILW, so all work at the four clay sites was stopped.
- November 1987 - Nirex launched an extensive public consultation campaign to assist in the identification of two or three potential deep repository sites by the end of 1988.
- May 1988 - Government announced that no further plans for deep ocean disposals of drummed radioactive waste will be made.
- November 1988 - Independent analysis of responses to the consultation campaign published.

Key dates for development of the Nirex deep repository are now planned as follows:

Nirex Deep Repository for ILW/LLW

- Evaluate merits of site optionsend 1988
- Select preferred sites for studyearly 1989
- Borehole and geophysics work1989
- Select preferred site and continue ground investigationsearly 1990
- Receive planning approval to developlate 1993
- Start construction1994
- Commission repository2005

THE FUTURE

The task for Nirex is to take into account:

cost;

- responses from the public;
- radiological risk calculations;
- planning issues;
- transport issues.

and then to propose to Government a preferred site or sites worthy of detailed study to accommodate a deep repository for ILW and LLW for the period 2005-2055. Such study would probably not require a Public Inquiry but when, around 1992, a formal application is made to the Local Authority for actual construction of a repository the Secretary of State for the Environment will call a Public Inquiry to advise him in making his decision.

At about the same time Nirex will seek formal authorization from DoE for the operation of such a repository at the chosen site, based upon a detailed safety and environmental impact assessment.

Safety Assessment

There are several aspects of safety to be considered when selecting a repository design and a site. Risks to workers during construction and to the operators of the repository will be important issues in guiding our selection and these will be the concern of the Health and Safety Executive in the UK. The post-closure radiological risks to the public will be very small indeed but

nevertheless must be assessed carefully and taken into account alongside the other factors.

The environment Departments have published principles that will form the basis of any authorization to use an underground repository for disposal of radioactive wastes (3). The principles maintain that:

> 'the appropriate target applicable to a single repository at any time is a risk to an individual in a year equivalent to that associated with a dose of 0.1mSv, about one chance in a million'

(of death from radiation exposure). The UKAEA, on contract to UK Nirex Ltd, are leading a post-closure safety assessment and an associated R&D program to examine the performance of repository designs and sites against that target.

The first task in an assessment is to identify pathways by which the radioactivity in the repository may be transferred to Man's environment. At present, the following four pathways have been considered:

- transport in flowing groundwater;
- human intrusion into the repository or the radioactive plume in the geosphere;
- release of radioactive gases; -natural disruptive events.

A deep repository is well isolated from extreme events on the surface. The only natural event identified that might potentially transfer bulk quantities of radioactive wastes to the accessible environment is impact of a large meteorite. The probability of this occurring is assessed at 10^{-11} per year or less and the associated risk is judged to be negligible. Seismic effects are likely to be of limited significance for a repository in the UK, but could result in the development of preferential groundwater flow paths. This issue will be addressed on a site-specific basis.

The remaining three pathways considered in the assessments are discussed separately below. However, interactions between the major features and processes in the various pathways have to be considered and work is in hand to develop a systematic approach to scenario development.

Groundwater Pathway

The basic approach is to study the behaviour of a number of barriers to water-borne radionuclide migration and then design or select them to minimize, as far as practicable, the return of radionuclides to the environment. Our philosophy is first and foremost one of 'containment to allow radioactive dec', rather than 'dilution in the biosphere'.

In the context of a deep repository, the major barriers are:

- physical containment within the repository;
- chemical containment within the repository;
- a long groundwater return time in the geosphere;
- retardation of many radionuclides in the geosphere relative to the groundwater flow.

Finally, radionuclides must pass through the biosphere before they can reach Man. The reason for using the 'multi-barrier approach' is that it gives some reassurance against unexpected deficiencies in any of the barriers. We can readily show for example that if the other barriers are properly in place, physical containment will not afford much additional reduction in risk. Nevertheless, the near field can be designed to ensure that the toxicity of groundwater in contact with the repository contents is always low (4), so that the overall system is more tolerant of:

- failure of the far field to impose a long delay;
- unexpected extraction of groundwater from, for example, a well.

In addition, the fact that the waste package and its near-field surroundings are designed to contain the radionuclides for some time after repository closure is helpful in emphasizing the containment, as opposed to dispersal, philosophy and gives confidence that retrieval, although not planned, would be perfectly possible for a substantial period after closure of the repository.

We have studied the solubility of waste radionuclides in the repository porewater. In general, a reducing alkaline chemistry gives low solubilities so we are specifying a cement and iron dominated near field. The other important requirements for the Nirex repository are:

- a long time delay for groundwater travelling from the near field to the biosphere (Darcy velocity 10^{-10}m s^{-1} or less)
- a depth of more than 300m to reduce intrusion probability to a low level.

The Nirex deep repository is being designed to accept solid radioactive wastes from the nuclear industry, research establishments, industry and medical sources. It will have a nominal 50-year capacity commencing operation around 2005. There are many uncertainties in estimating the volume and composition of radioactive wastes over such a long period but Table IV shows the waste inventory used in recent assessments, allowing for the intention that LLW arising prior to 2005 will go to Drigg. The expected inventory is being reviewed and the arisings in Table IV are likely to be revised downwards.

An extensive research program has been mounted by Nirex to understand the performance of barriers in the deep underground repository. First, the rate of corrosion of the primary waste container, which may be carbon

steel, stainless steel or concrete, has been assessed under post-disposal conditions. Typically this means that the container is assumed to be taken from its dry surface store and grouted into place in the repository. It sees a few years of wet aerobic conditions followed thereafter by wet reducing conditions as the entrapped oxygen is consumed by iron in the waste containers. The alkalinity from the cement grout is taken into account in assessing the corrosion rates, as are radiolytic and microbial influences.

Secondly, the physical chemistry of the entire repository contents is assessed on the assumption that containers have corroded away and that hundreds of years of exposure to almost static groundwater have established an equilibrium distribution of the various long-lived radionuclides between the groundwater and the near-field solids. This determines the concentration of radionuclides in the groundwater that will be available for migration into the far field.

Table II shows the solubility data used in recent assessments to represent the maximum concentrations in groundwater that could be reached by the elements of interest and Table III shows near-field sorption data used in conjunction with those limits. The data have been derived from empirical observation of the behaviour of realistic laboratory-mounted systems backed up where appropriate by thermodynamic calculations; they apply to our particular conditions of high pH and low Eh..

TABLE II

Solubilitites of Key Elements (pH 11 Eh-500mV)

Element	Solubility (mol/m^3)	Element	Solubility (mol/m^3)
C	3×10^{-2}	Sm	1×10^{-8}
Ca	20	Pb	1
Ni	1×10^{-4}	Ra	1×10^{-3}
Se	5×10^{-2}	Th	3×10^{-6}
Sr	1×10^{-1}	U	1×10^{-4}
Zr	1×10^{-4}	Np	8×10^{-6}
Nb	1×10^{-4}	Pu	3×10^{-7}
Tc	1×10^{-4}	Am	1×10^{-7}
Pd	1×10^{-4}	Cm	1×10^{-7}
Ag	1×10^{-2}	H, C1, I, Cs high	
Sn	5		

The reducing, alkaline conditions in the near field, once established after backfilling of the repository, will persist for many tens of thousands of years in a host rock where the groundwater flow is very low (5), due to the chemical buffering capacities of the iron and ferrous minerals in the repository and of the large amounts of cement used in backfilling and in grouting of waste packages.

With these near-field chemistry data the total waste inventory may be used to calculate the radiochemical composition of the near-field groundwater as a function of time. Figure 1 shows a typical result for ILW. The quantities in solution are expressed as 'toxicities' in order to give some idea of the potential for groundwater-borne radiological risk; a unit 'toxicity' denotes an effective dose equivalent of 1mSv to an average adult ingesting two litres of the water per day for a whole year. This is a purely notional quantity since, even if the porewater in the repository were accessible to Man, it would not be potable. Note that ^{137}Cs and ^{90}Sr dominate the toxicity in the early decades but after that it is determined first by 241Am and then by ^{129}I and the ^{210}Pb daughter of ^{238}U. The line labelled 'no chemistry' shows for reference, the near field groundwater toxicity which would result if all the waste were uniformly dispersed in the water.

Figure 1 applies to the entire estimated content of ILW in a UK national repository to the year 2055, although the additional contribution from LLW would be negligible. It is apparent that, by using waste containers that are likely to exclude groundwater from the waste until $^{13}7Cs$ and ^{90}Sr have largely decayed, the higher part of the curve could be removed. Nirex will probably ask waste producers to take into consideration the ^{137}Cs and ^{90}Sr content of their waste products when specifying the target life of the associated containers. By this means, the toxicity of near-field groundwater would not exceed the very low level of around 1000, even during the early decades after backfilling. In practice a waste container will as a minimum be designed to remain intact during its initial life in a dry surface store and then for a nominal retrieval period of say 20 to 50 years after backfilling underground. The additional target life for particular containers implied by the near-field toxicity limitation would add a further period during which the more concentrated sources of ^{137}Cs and ^{90}Sr would decay.

If we follow this logic, we can predict that at no time will the groundwater in the Nirex repository be more toxic than would deliver a dose of 1Sv/y to someone using it for their sole source of water. Again, it must be emphasized that this is actually impracticable and is postulated only as a convenient measure of toxicity for the purpose of technical discussion.

In Figure 2 we see the effect of adding the behaviour of the far field and biosphere to that of the near field shown in Figure 1. The computation was carried out for a hard rock, low surface relief geology having a hydraulic conductivity of 10^{-10} m s^{-1} at depth and a path length of a few kilometres. The best estimate of the groundwater return time to the biosphere would be between 10,000 and 100,000 years for a repository at 500m depth. The same toxicity unit is used in this Figure to show the effect of the far field barrier on the potential risk. The peak coinciding with the groundwater return marks the

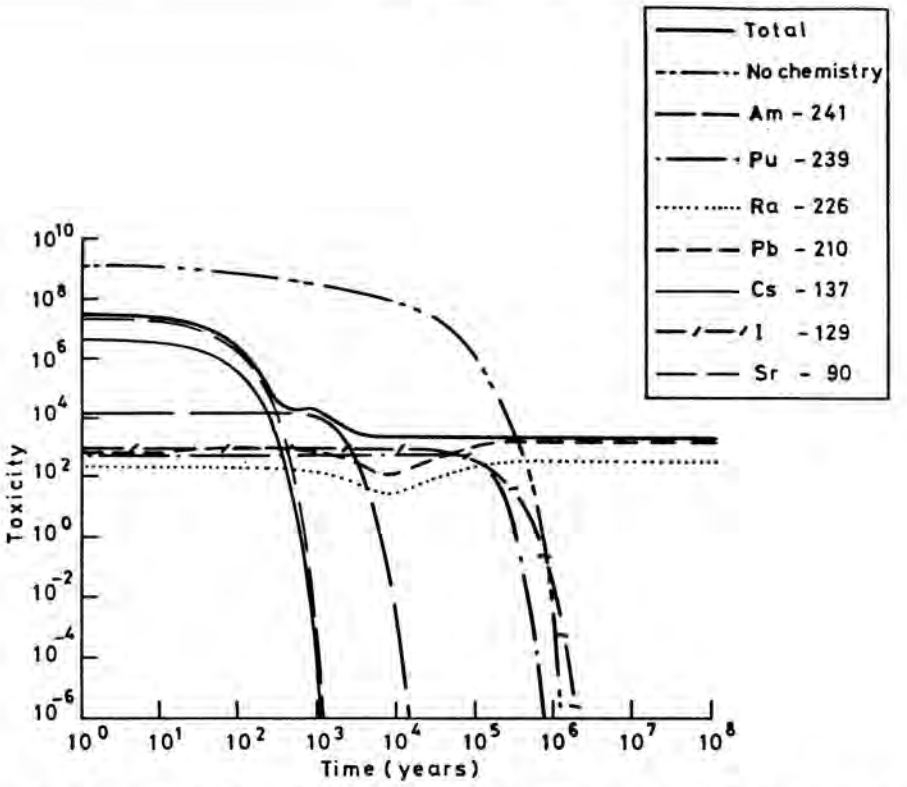

Fig. 1. The Toxicity of the Near-Field Porewater Using Best Estimates of the Chemical Parameters.

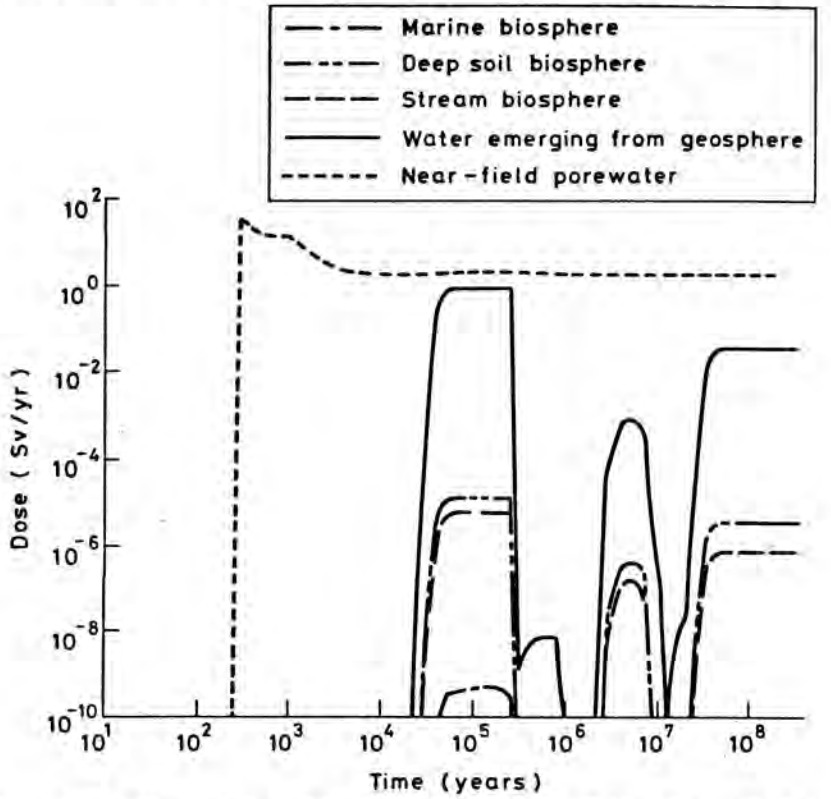

Fig. 2. Example of a Computation of the Annual Dose to the Critical Group for Release to Three Biospheres. The Toxicities of the Near-Field Porewater and the Porewater as it Emerges From the Geosphere are also Shown.

emergence of ^{129}I and ^{36}Cl in solution. There are peaks beyond one million years from ^{135}Cs and the daughter products of ^{238}U.

Nirex is applying this kind of groundwater pathway assessment to potential repository locations in the UK. Deterministic calculations of the type illustrated here are backed up by probabilistic calculations to show the effects of parameter variability and uncertainty.

Intrusion

It is necessary to estimate the frequency and the consequences of potential human intrusion into the repository or contaminated geosphere. A number of scenarios either have been studied or are planned to be studied and these include:

- direct inhalation of dust from excavated material by a geotechnical worker;
- contamination of land on which food is subsequently grown;
- incorporation of excavated materials in buildings.

The individual risk is assessed as the product of frequency of occurrence and consequence. The consequences are computed by considering the various possible routes for inhalation or ingestion of radioactivity by members of the group at risk. Assuming that the 500m deep repository in hard rock considered in discussing the groundwater pathway would be protected from intrusion for the first 100 years after closure, this kind of computation shows that the dose to the geotechnical worker would approach 100mSv. The frequency of such an exploratory borehole being drilled varies with the type of rock. Thus:

hard rock	10^{-5} per year on 30 hectare site
sedimentary rock	10^{-2} per year on 200 hectare site

are typical results based on current knowledge of past drilling for minerals, fossil fuels and for geothermal energy.

The overall result is that individual risk to the geotechnical worker falls from 10^{-8} per year to 10^{-9} per year over the first 10,000 years for a hard rock repository and from
3×10^{-6} per year to 5×10^{-7} per year for a repository in sedimentary rock.

Gas Generation

Gases will be produced in the repository by:

- corrosion of iron and aluminium, producing hydrogen,
- microbiological degradation of organic material to produce CO_2 and CH_4;
- radiolysis of water and of wastes.

In practice, only the first two mechanisms are of significance for LLW and ILW; Nirex is assessing their potential contribution to radiological risk, either by direct inhalation of ^{14}C or ^{3}H, or by physical effects on the groundwater pathway.

Modelling shows that anaerobic conditions will be established within 50 to 100 years of repository closure, after which H_2, CH_4 and CO_2 will be generated. Due to the relatively small amounts of readily degradable organic material in the radioactive waste inventory the normal landfill concerns about methane accumulation are absent.

Current estimates are that:

- $10^9 m^3$ of H_2;
- $10^7 m^3$ of CH_4 and CO_2.

will be generated in the Nirex repository over a period of about 500 years, in the 4×10^6 m^3 of backfilled galleries.

The radiological risk to the group at risk is estimated to be about 5×10^{-9} per year from tritiated species and 10^{-8} per year from ^{14}C species so it appears that physical effects on the groundwater pathway are the main potential concern from the slow release of these gases in the repository.

CONCLUSIONS

Nirex is now at the stage of using mathematical models to predict radiological risk from a deep repository due to groundwater movement, gas release and human intrusion. Compared to any past waste disposal operations, both the performance target and the excellence of the technical design and assessment work are such as to reassure the public on these safety issues. The results will be used, alongside the results from assessments of non-radiological attributes of sites, to select a number of sites for detailed examination. The intent is to submit planning application for repository construction in 1991 and to commission the repository in 2005.

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