COMPARISON OF RESULTS FOR GROUNDWATER RELEASE SCENARIOS

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INTRODUCTION

The potential risks to future generations from nuclear waste disposal have been the subject of numerous safety assessment studies both in the United States and in other countries. These studies differ considerably in analytic approach, geologic setting, and model parameter description. Taken together they form the basis for an evaluation of the status of knowledge concerning the long-term safety of nuclear waste disposal.

We have reviewed and analyzed on a comparative basis ten major safety assessment studies[1] as well as the draft EIS on management of commercially generated radioactive waste (DEIS)[2] and the draft WIPP EIS.[3] This paper describes the results of these interstudy comparisons for the most important process for release of waste -- i.e., access, dissolution, and slow transport of waste materials by groundwater.

DESCRIPTION OF SAFETY ASSESSMENT STUDIES

The twelve major safety assessment studies considered are listed in Table I. Detailed parametric descriptions are given of the reference groundwater transport scenarios considered in each study. The first four studies represent early efforts by the United States, France, Italy and England respectively to

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assess geologic disposal of nuclear wastes.[4-7] The next five studies present more sophisticated analyses by the U.S. Department of Energy,[8] Swedish Nuclear Fuel Safety Project,[9,10] U.S. Nuclear Regulatory Agency (two studies),[11,13] and U.S. Environmental Protection Agency.[12] The tenth study is the work of a single scientist and is unique in its approach to the problem of assessing risks.[14] The last two studies are from the two environmental impact statements on nuclear waste disposal recently issued by the U.S. Department of Energy.[2,3]

The study by Campbell, et al., is included here for completeness. No quantitative results are reported; rather this study summarizes the status of the research performed at Sandia Laboratories for the Office of Nuclear Regulatory Research. The objective of this research is to develop analytical methods for risk assessment for possible use by the NRC in licensing waste repositories.

Few of the studies in Table I represent an actual assessment of risk. Most analyses merely explore the potential bounds of possible risk with scenarios that range from perfect containment of the nuclear waste to maximum dispersal. Many of the investigations are of limited scope and care must be taken in judging the results of their analyses. No single effort was intended to be comprehensive.

All of the studies employed, to some degree, conservative assumptions. In evaluating the significance of these studies, it is important to bear in mind that a conservative analysis can only demonstrate that risk or consequences will fall below some upper bound. If a credible but conservative study indicates that risks from HLW disposal are small, then the conclusion that disposal is safe has received very strong support. On the other hand, if risks are predicted to be high, although there is cause for concern, only the necessity for a more realistic study may be indicated. In the following presentation of study results, this notion of conservative modeling should be kept in mind.

SELECTED STUDY RESULTS

The principal results of six HLW studies can be summarized and placed on a single graph as shown in Fig. 2. (The other HLW studies did not present results in this format of dose versus

Table I. Summary of Reference Scenarios for Twelve Safety Assessment Studies

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STUDY	GEO-HYDROLOGIC SCENARIO	RADIONUCLIDE[a] INVENTORY (GWe-yr)	TIME OF INITIAL LEACHING (yr)	LEACH RATE (1/yr)	AQUIFER LENGTH (km)	LONGITUDINAL[b] DISPERSIVITY IN AQUIFER (m)	INTERSTITIAL WATER VELOCITY (m/yr)
Claiborne and Gera[4]	Bedded Salt	5.4×10^{3} HLW	$>1\times10^{3}$	3.4×10^{-4}	32	-	55
de Marsily, et al.[5]	Generic Geology[c]	1.5×10^{3} HLW	0	2×10^{-4} (all nuclides) 5×10^{-6} (iodine) 5×10^{-8} (actinides)	0.5	10	1.2
Girardi, et al.[6]	Direct Transport to a River	9×10^{2} HLW	$>1\times10^{3}$	1.8×10^{-5}	-	-	-
Hill and Grimwood[7]	Crystalline Rock	3.3×10^{2} HLW	1×10^{3}	8.4×10^{-4}	10	30	110
Burkholder, et al.[8]	Non-Salt	4.7×10^{3} HLW	1×10^{2}	3×10^{-5}	16	4×10^{-3}	110
KBS (Swedish Nuclear Fuel Safety Project)[9,10]	Granite	3×10^{2} HLW	1×10^{3}	3×10^{-5}	2.3	0.5	5.75
		3×10^{2} Spent Fuel	1×10^{5}	2×10^{-6}	?	?	?
Berman, et al.[11]	Bedded Salt and Shale	6×10^{3} HLW	1×10^{2}	1×10^{-4}	16	50	1.6
Logan, et al.[12]	Bedded Salt	5.5×10^{3} HLW	(d)	1×10^{-4} to 20×10^{-4}	10 (e) (20)	50 (6)	1.5
Campbell, et al.[13]	Bedded Salt	4×10^{3} HLW	-	1.7×10^{-3}	42	150 (15)	-
B.L. Cohen[14]	Average U.S. down to 600 m	4×10^{2} HLW	$>2\times10^{2}$	-	-	-	-
DEIS[2]	Direct Transport to the Surface	1×10^{4}	$1, 10^{3}, 10^{5}, 10^{6}$	1.7×10^{-3} (f) 6.5×10^{-1} 1.2×10^{-2} (g)	-	-	-
	Generic Geology	1×10^{4}	$1, 10^{3}, 10^{5}$	$1, 10^{-3}, 10^{-4}$	10	4×10^{-3}	100
WIPP EIS[3]	Bedded Salt	1.4×10^{1} Spent Fuel	1×10^{3}	3.9×10^{-6} (h) 1.9×10^{-7} 2.2×10^{-4} (i)	22.5	91	4(j) 0.2

Table I. Summary of Reference Scenarios for Twelve Safety Assessment Studies (Continued)

T-3933

STUDY	GROUNDWATER TRANSIT TIME (yr)	RETARDATION FACTOR ($V_{WATER}/V_{NUCLIDE}$) I,Tc	Np	Ra	Th	U	Pu,Am	BIOSPHERE DILUTION (m^3/yr)
Claiborne and Gera[4]	>6×10^2	-	-	-	-	-	-	1×10^5 (aquifer) 1×10^7 (river)
de Marsily, et al.[5]	4×10^2	1	7×10^2	-	-	-	9×10^4 or 1 (Pu)	3×10^4 (aquifer)
Girardi, et al.[6]	-	-	-	-	-	-	-	1×10^{10} (river)
Hill and Grimwood[7]	1×10^2	1	1×10^2	5×10^2	5×10^4	1.4×10^4	1×10^4	1×10^7 (aquifer, river, or lake)
Burkholder, et al.[8]	1.45×10^2	1	1×10^2	5×10^2	5×10^4	1.4×10^4	1×10^4	1×10^{10} (river)
KBS(k) Swedish Nuclear Fuel Safety Project)[9,10]	4×10^2	1	2.6×10^2	7×10^2	5.2×10^3	4.3×10^1	1.1×10^3 (Pu) 8.4×10^4 (Am)	5×10^5 (aquifer)
	3×10^3	1 (I) 9.5×10^2 (Tc)	2.3×10^4	4.8×10^4	4.6×10^4	2.3×10^4	5.7×10^3 (Pu) 6.1×10^5 (Am)	2.5×10^7 (lake)
Berman, et al.[11]	10^4-10^5	1	10^4	10^4	10^4	10^4	10^4	6×10^4 (aquifer) 1×10^{11} (river)
Logan, et al.[12]	6.8×10^3 (to wells or surface waters) 1.4×10^4 (to river)	1	1.6×10^2	1×10^3	1.6×10^3	-	2.1×10^4	3×10^4 (aquifer) 1×10^3 (surface waters) 3×10^8 (river)
Campbell, et al.[13]	-	-	-	-	-	-	-	-
B.L. Cohen[14]	-	-	-	-	-	-	-	-
DEIS[2]	0	-	-	-	-	-	-	8.8×10^7 (river)
	1×10^2	1	1×10^2	5×10^2	5×10^4	1.4×10^4	1×10^4	3.8×10^9 (river)
WIPP EIS[3]	5×10^3 (lower bound) 1×10^5 (upper bound)	1	1.2×10^4	4.3×10^2	3.7×10^4	1.7×10^2	3.6×10^4(Pu)	1.6×10^7 (river)

a. The inventories for Burkholder, et al., Claiborne and Gera, and the *WIPP EIS* in terms of generated electric power were estimated from the values given for the quantity of uranium in the waste. A metric ton of uranium was assumed to produce 32 MWe-yr of power prior to removal from a reactor.

b. The values given in parentheses are for the transverse dispersivity.

c. Five types of geologic formations were considered by de Marsily. The reference scenario shown here is for geologic formation 3, whose characteristics are intermediate among the five types.

d. Leaching is initiated by the occurrence of a major fault with probability 1.4×10^{-7}/yr.

e. The distance to wells and surface waters is 10 km. The distance to a major river is 20 km.

f. Leach rate for spent fuel. The fraction of the waste affected is 2×10^{-3}.

g. The high value is the leach rate for iodine in HLW. The low value is the leach rate for all other nuclides. The fraction of the waste affected is 1×10^{-3}.

h. Leach rates for scenario 2. The high value is for an upper bound aquifer transmissivity. The low value is for a lower bound aquifer transmissivity.

i. Leach rate for scenario 4.

j. Upper and lower bounds on the average water velocity (calculated from the aquifer length and the travel time).

k. Groundwater transit times and retardation factors are shown for two groundwater scenarios. The upper level values are for the conservative case analyzed in the HLW study. The lower level values are a best estimate and were employed in the realistic case analyzed in the spent fuel study.

time). This graph displays the potential dose to an individual living near a repository as a function of the time after emplacement of the waste. The curve shown for the KBS study represents their results for the most unfavorable groundwater scenario. In the opinion of the KBS researchers, a realistic analysis would lower this curve by over two orders of magnitude. The curve for the study by B.L. Cohen was obtained from his graph of risk versus time by arbitrarily assuming an affected population of one million. The curve for Logan, et al., is a probabilistic calculation which includes meteorite and volcanic events as well as groundwater release due to faulting. The sharp rise at 10^6 years is due to the groundwater release scenario.

The principal nuclides contributing to risk are indicated next to the peak that results from their release into the biosphere. The critical radionuclides are ^{14}C, ^{99}Tc, ^{129}I, ^{237}Np, and ^{226}Ra. The following significant observations can be made:

- For no study does the dose exceed that from natural background radiation
- The peak individual dose ranges over seven orders of magnitude depending upon the study.

A fair comparison of these results on the basis of Fig. 1 is not possible. Among other things each study assumes a different initial quantity of waste in their repository. In the next section, a comparative analysis which adjusts for these differences and also includes other study results is presented.

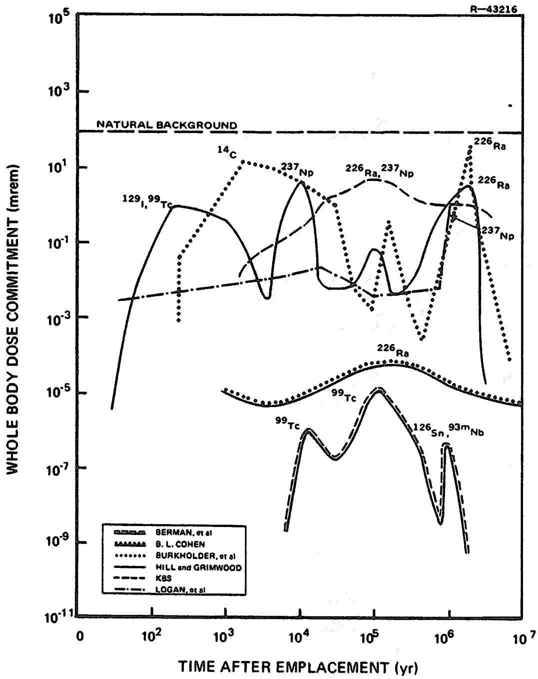


Fig. 1. Potential Dose to an Individual as Predicted by Six Major Safety Assessment Studies

NORMALIZATION OF RISK PREDICTIONS

It is not possible to directly compare the predicted individual doses given in the safety assessment studies. In the first place, each study assumes that the repository contains a different initial inventory of radioactive waste. A second problem is that several studies employ different dosimetry models. Thus, even if predicted intakes of radionuclides by individuals were the same among studies, calculated doses would be different. These problems are addressed by normalizing each study to the waste produced from a fixed amount of generated electric power and by applying a common environmental consequence model. The crucial portions of any risk study are the models for predicting release rates of waste into the environment and these have been preserved. The method used for comparing studies on a common basis is illustrated in Fig. 2.

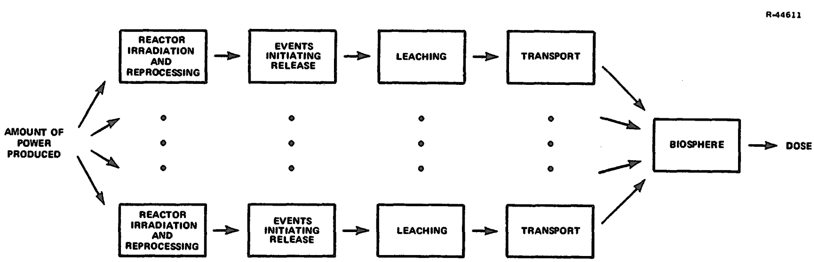


Fig. 2. Illustration of Technique for Interstudy Comparison

The initial quantity of waste is arbitrarily chosen as the waste produced from 10^3 GWe-yr of nuclear power generation. Even after normalization of each study to this quantity of waste, differences in isotopic composition will remain. This is a consequence of the different assumptions made for reactor irradiation and subsequent reprocessing. Not only would it be difficult to normalize to a common isotopic composition, but these variations are considered realistic and reflect basic uncertainties in future nuclear waste production and management.

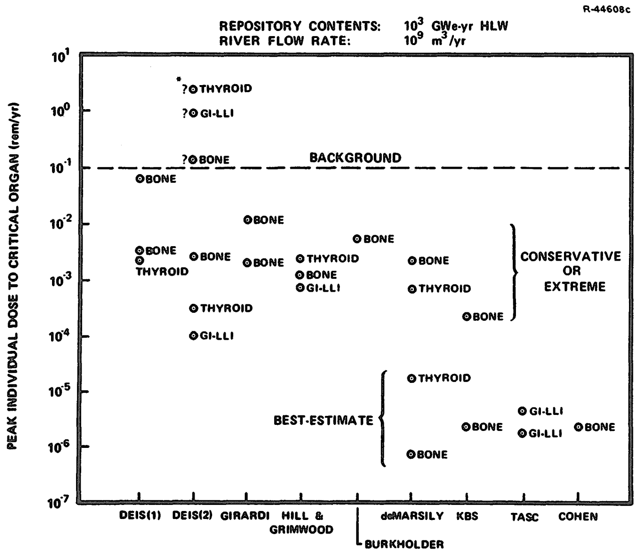
A common biosphere transport, uptake and dose model is applied to every study. The biosphere model adopted is deliberately quite simple. Release is assumed to occur into a river with a modest flow rate of 10^9 m^3/yr. Water concentrations for human consumption are obtained by dividing the rate of release to the river by the flow rate. Doses are computed for the drinking water pathway alone, assuming an average individual intake of 370 liters per year. The individual dose conversion factors are for a 50 year commitment from a single year's exposure and are given in Regulatory Guide 1.109 of the U.S. Nuclear Regulatory Commission.[14]

The first step in the normalization procedure is to convert the peak release rates reported in each study to doses using the common biosphere model described above. The results are then adjusted to reflect a repository contents of 10^3 GWe-yr. For example, in the study by Hill and Grimwood, the peak release rate of the critical radionuclide, ^{237}Np, from a repository containing 3.3×10^2 GWe-yr of waste was 8×10^{-1} Ci/yr. A normalized bone dose of 1.2×10^{-3} rem/yr is obtained from the following calculation:

$$\underset{\text{(dose)}}{1.2\times10^{-3}\ \frac{\text{rem}}{\text{yr}}} = \underset{\text{(release rate)}}{8\times10^{-1}\ \frac{\text{Ci}}{\text{yr}}} \times \underset{\text{(fraction ingested)}}{\frac{0.37\ \frac{m^3}{yr}}{10^9\ \frac{m^3}{yr}}} \times \underset{\text{(dose factor)}}{1.38\ 10^6\ \frac{\text{rem}}{\text{Ci/yr}}} \times \underset{\text{(normalization of quantity of waste)}}{\frac{10^3\ \text{GWe-yr}}{3.3\ 10^2\ \text{GWe-yr}}} \qquad \text{(Eq. 1)}$$

The results of the HLW studies following normalization are displayed in Fig. 3 for the peak individual dose to the critical organ. Errors found in the analysis by Logan, et al.,made it impossible to include this study's results in the figure.[1] The study by Claiborne and Gera is also not included since no explicit calculations were made in that study for release rates into the nearby river. Some studies have two sets of results shown. For Girardi, et al., these represent release at 10^3 or 10^5 years. For de Marsily, et al., results are shown for two leaching models. One model assumes the waste glass structure remains intact. A more conservative model assumes that the glass structure is destroyed at 10,000 years after burial. The Swedish results are a conservative and a best estimate of dose from HLW disposal. The TASC results are for a salt and a shale repository.

Results are shown for the two different scenarios that were analyzed in the DEIS. Both scenarios were considered to be extremely unlikely to occur and were chosen as a "worst case." In Fig. 3 the term DEIS(1) refers to the scenario where faulting is followed by direct transport to the surface. Results are shown for release at 10^3 and 10^5 years. The term DEIS(2) refers to the scenario where faulting is followed by slow groundwater trans-



*Question marks reflect TASC view that assumed leach rates were too high.

Fig. 3. Normalized Peak Individual Doses for HLW Reference Scenarios

port to the biosphere. The results shown reflect upper and lower bounds on the many cases considered. The upper bound values are for a 100% per year leach rate. This leach rate is unrealistically high.

In general, the peak doses fall into two natural classes:

- A class centered at about 1% of average yearly background radiation. The studies in this class represent conservative, scoping analyses of risk where the objective was to determine a reasonable upper bound to the potential hazard.

- A class centered at just above 10^{-5} times natural background. This yearly dose is roughly equivalent to the dose commitment an average individual receives by simply drinking a glass of water. The studies in this class represent either less conservative or more realistic attempts at assessing the hazard from geologic disposal of high-level waste.

In the above, only risks from disposal of high-level wastes have been considered. Inherently higher risk levels are associated with disposal of spent fuel.[1] The next section discusses results from analyses of spent fuel disposal.

SPENT FUEL DISPOSAL

Only a few studies have considered the risks from disposal of spent reactor fuel. Figure 4 shows normalized results from three studies: KBS (Swedish Nuclear Fuel Safety Project), the draft EIS on management of commercially generated radioactive waste (DEIS), and the WIPP EIS. The scenarios for which DEIS results are shown were discussed in the previous section.

The results shown for the KBS study represent a conservative and a best estimate of the expected peak dose. The peak dose occures at 1 million years after disposal in the conservative case and 70 million years after disposal in the "realistic" case.

Four scenarios were analyzed in the WIPP EIS; Fig. 4 shows results from two of these scenarios. For all scenarios, the analysis was restricted to a 100,000 year time frame. In Scenario 2, water from an upper aquifer flows down through two repository shafts, through the repository, and back up to the aquifer through a wellbore. This was considered to be a highly unlikely but credible event. The results shown reflect upper and lower bound estimates of the consequences of this event. In Scenario 4, all the water in the upper aquifer normally moving above the repository passes through the repository and back up to the upper aquifer. This was the worst conceivable groundwater release event.

The normalized results shown in Fig. 4 do not display any special pattern. Except for DEIS(2), doses are generally well below background levels. With the exception of the KBS study, the doses shown are conservative estimates of the consequences of

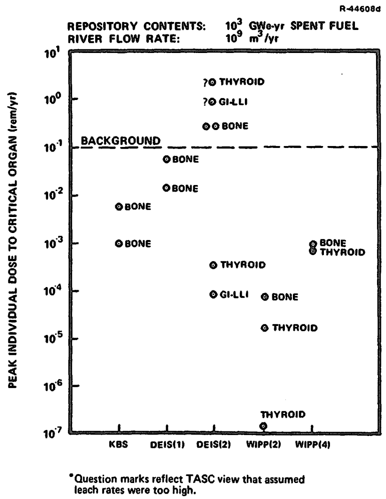


Fig. 4. Normalized Peak Individual Doses for Spent Fuel Reference Scenarios

very unlikely scenarios. In most cases the peak dose is primarily due to members of the ^{238}U decay chain (^{234}U and ^{226}Ra). These nuclides are present in the original ore from which the spent fuel came. It should not be the goal of nuclear waste management to reduce future risks far below that expected from the original uranium ore.

CONCLUSIONS

Results obtained by safety assessment studies can be compared by normalizing the results to a common basis of repository contents at closure and environmental scenario conditions. For the many HLW disposal studies considered this normalization greatly reduces the range of results and produces two classes of risk predictions: conservative (extreme) case studies for which individual doses are about 1% of background, and less conservative, more realistic studies for which doses are about a thousand times lower than those for the conservative studies.

It is frequently argued that these risk assessment analyses are mere "paper studies" and thus do little to "demonstrate" safety. Real data generated at specific sites from deep borings and vault experiments is often called for to provide the necessary confidence that wastes can be disposed of safely. But the studies discussed in this paper do not rely at all on sight-unseen estimates of geologic and hydrologic properties. All the studies are based on a very large pool of data gathered over the years by geologists, hydrologists, geotechnical engineers, mining engineers, etc. A wealth of experience and years of in-situ testing and measurement of real geologic systems have been brought to bear on the problem. Several studies (KBS and WIPP) are supplemented by preliminary site specific investigations including data from deep borings.

Furthermore, every study was conservative to some degree in its approach to modeling groundwater release. Girardi, for example, has assumed that all the HLW is allowed to leach directly into a river at 10^3 or 10^5 years, while de Marsily in one worst-case scenario, has assumed complete dissolution of the waste in 5000 years and virtually immediate transport of plutonium into the biosphere.

Although the results of risk assessment studies all support positive conclusions with respect to long-term safety, there is as yet no broad consensus that geologic disposal can be achieved with adequate safety. This is a consequence of uncertainties associated with predictions of disposal risks. It is very important that there be a balanced viewpoint with regard to risks and uncertainties associated with management of long-lived hazardous nuclear wastes. These risks should be seen in perspective with risks that we commonly live with or take for granted. The long-term nature of the nuclear waste hazard is not unique; dangerous compounds of mercury, lead, arsenic, etc. will remain in our environment forever and their toxicity is not reduced by radioactive decay. Human activities other than waste disposal -- extraction of fossil fuels and minerals, for example -- may affect future generations far more severely than disposal of any kinds of waste.

The purpose of predictive modeling is to establish reasonable bounds on the risks that may be expected and to allow comparison with other hazards that we normally live with and accept. The small risks predicted by the studies considered in this paper are strong evidence of the ultimate safety of the geologic disposal option.

REFERENCES

1. C.M. Koplik, et al., "A Status Report on Risk Assessment for Nuclear Waste Disposal," The Analytic Sciences Corporation, TR-1674-1, for Electric Power Research Institute, NP-1197, October 1979.

2. "Draft Environmental Impact Statement. Management of Commercially Generated Radioactive Waste," U.S. Department of Energy, DOE/EIS-0046-D, April 1979.

3. "Draft Environmental Impact Statement. Waste Isolation Pilot Plant," U.S. Department of Energy, DOE/EIS-0026-D, April 1979.

4. H.C. Claiborne and F. Gera, "Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico," Oak Ridge National Laboratory, ORNL-TM-4639, October 1974.

5. G. de Marsily, et al., "Nuclear Waste Disposal: Can the Geologist Guarantee Isolation?," Science, Vol. 197, No. 4303, 5 August 1977, pp. 519-527.

6. F. Girardi, et al., "Long-Term Risk Assessment of Radioactive Waste Disposal in Geological Formations," Commission of the European Communities, EUR 5902.e, Ispra, Italy, 1977.

7. M.D. Hill and P.D. Grimwood, "Preliminary Assessment of the Radiological Protection Aspects of Disposal of High-Level Waste in Geologic Formations," National Radiological Protection Board, NRPB-R69, Harwell, U.K., January 1978.

8. H.C. Burkholder, et al., "Incentives for Partitioning High-Level Waste," Nuclear Technology, 31, 202, 1976.

9. Nuclear Fuel Safety Project, "Handling of Spent Nuclear Fuel and Final Storage of Vitrified High-Level Reprocessing Waste," Kärn-Bränsle-Säkerhet, Stockholm, Sweden, 1978.

10. Nuclear Fuel Safety Project, "Handling and Final Storage of Unreprocessed Spent Nuclear Fuel," Kärn-Bränsle-Säkerhet, Stockholm, Sweden, 1978.

11. L.E. Berman, et al., "Analysis of Some Nuclear Waste Management Options," The Analytic Sciences Corporation, UCRL-13917, October 1978.

12. S.E. Logan and M.C. Berbano, "Development and Application of a Risk Assessment Method for Radioactive Waste Management," U.S. Environmental Protection Agency, EPA 520/6-78-005, July 1978.

13. J.E. Campbell, et al., "Risk Methodology for Geologic Disposal of Radioactive Waste: Interim Report," Sandia Laboratories, SAND78-0079, prepared for U.S. Nuclear Regulatory Commission, NUREG/CR-0458, October 1978.

14. B.L. Cohen, "High-Level Radioactive Waste from Light Water Reactors," Reviews of Modern Physics, 49, 1, 1977.

15. "Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance With 10 CFR Part 50, Appendix I," U.S. Nuclear Regulatory Commission, Regulatory Guide 1.109, March 1976.