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Performance Assessment Overview for Subseabed Disposal of High-Level Radioactive Waste

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PERFORMANCE ASSESSMENT OVERVIEW FOR SUBSEABED DISPOSAL OF HIGH LEVEL RADIOACTIVE WASTE

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ABSTRACT

The Subseabed Disposal Project (SDP) was part of an international program that investigated the feasibility of high-level radioactive waste disposal in the deep ocean sediments. This report briefly describes the seven-step iterative performance assessment procedures used in this study and presents representative results of the last iteration. The results of the performance are compared to interim standards developed for the SDP, to other conceptual repositories, and to related metrics. The attributes, limitations, uncertainties, and remaining tasks in the SDP feasibility phase are discussed.

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1. INTRODUCTION

The U.S. Subseabed Disposal Project (SDP) was part of the international Seabed Working Group (SWG) of the Organisation for Economic Co-Operation and Development/Nuclear Energy Agency (OECD/NEA), which investigated the technical feasibility of subseabed disposal of high-level waste (HLW) from 1976 to 1987. The SDP also investigated some aspects of subseabed disposal not covered in the SWG program. The major questions in the feasibility assessment were:

1. Can an acceptable site for HLW disposal be found and characterized?
2. Can waste canisters be reliably and economically transported and emplaced in deep ocean geologic formations?
3. Are radiological risks from emplaced waste, accidents, and abnormal events below the limits for similar waste disposal processes?

Feasibility studies for subseabed HLW disposal required development of new evaluation standards, performance assessment procedures, and models. Steps in the SDP risk assessment were iterative. They were improved and updated as the design developed and as the models and database became more complete. First, the reference system (including transportation, emplacement, the operational repository, and possible abnormal events) was defined. Since no official radiological protection criteria exist for subseabed HLW disposal, interim evaluation standards were developed. Analytic and compartmental models were developed for sensitivity and repetitive risk analyses. These fast and convenient computer models were verified with numeric programs. Analyses began with parametric studies to define the sensitivity of each input parameter. These studies were followed by an attenuation factor analysis to define the effectiveness of each component, and the robustness and limitations of the system. Peak individual, peak annual population, time integrated world population, and biota doses were computed using reference parameters. The risks were bounded using least and most favorable input data, and a stochastic uncertainty analysis was conducted when enough data were available to define probability distributions. Probabilistic accident risks were combined with the risks for the undisturbed emplaced base case to obtain total risks for the system. Abnormal events were analyzed deterministically but not included in the probabilistic risk assessment because realistic probabilities were not yet available. Risk assessments were interactive with other SDP activities and were used in functional analyses for equipment and facility designs, as guidance for research, and in feasibility evaluation. Risk sensitivity showed where the largest gains could be made in transportation and repository design and which parts of the database needed to be expanded.

Two of the three iterations planned for the feasibility phase of the SDP have been completed. The performance assessment (PA) used a methodology consisting of the following activities:

1. Upgrade the reference design based on design requirements developed during the first iteration.
2. Develop interim radiological safety standards for subseabed disposal of high-level waste.
3. Modify and expand the nuclide transport and biological models in conjunction with the engineering and scientific task groups, using the latest and most complete processes definitions and data.
4. Sensitivity analyses to define where the most significant design improvements can be made and identifying the processes and data that have the greatest impact on risk.

5. Attenuation factor analyses to define the risk reduction effectiveness of each component and the entire disposal system, the resilience of the system if component effectiveness deviates, and component stability with changing environments.
6. Risk analyses that include transportation, emplacement, an undisturbed repository, and abnormal natural events. Best estimate, bounding, and probabilistic assessments were conducted.
7. Interpretation of the results from activities 4-6 to produce revisions in design, site selection, and research requirements. The practicality of the more inclusive interim standards was evaluated. Risks were evaluated using the interim standards and other metrics.

These seven steps used in the second iteration of the performance assessment and selected examples are the subject of this report. A limited comparison is made with mined geological repositories and other metrics. The limitations, uncertainties, and tasks remaining to evaluate feasibility are discussed. The summary includes the status of the risk assessment and the conclusions that can be drawn at this time.

2. REFERENCE DESIGN

The preliminary assessment completed in 1983 [1,2] pointed out some weaknesses in repository and ship designs, and indicated where model improvements and additional data were needed. The resulting reference system used in the interim assessment completed in 1987 is shown in Figure 1. The free fall penetrator emplacement option was the baseline design for the risk assessment. Each penetrator is 6.7 m long, weighs 8200 kg, and contains 3.76 MTHM of 50-year-old waste. Penetration depth would be 50 ± 20 m in all the study locations.

The conceptual design of the emplacement ship completed by the Glosten Associates [3,4] is shown in Figure 2. The ship is 160 m long, with a beam of 32 m and a draft of 8 m. The ship is designed to withstand collisions, rammings, groundings, fire, and adverse weather conditions. The structural protection system consists of a 7.2-cm-thick, high-yield steel hull over 6.4 m of 128 kg/m^3 urethane foam on the sides and 3.5 m of 32 kg/m^3 urethane foam on the bottom. This is backed up by double longitudinal cargo hold bulkheads. Both are 3.8-cm-thick, high-yield steel. The collision energy absorption capacity is 3.16 x 10^6 kN-m, peak lateral force limit is 673,190 kN, membrane force is 494,330 kN, and peak lateral acceleration is 16.25 m/sec^2. This structure prevents penetration of the cargo hold by vessels with speeds less than 24 knots, regardless of mass or bow construction. Protection from sinking is provided by the urethane foam. Total submerged buoyancy with all compartments flooded is 33,344 MT. The loaded ship weight is 29,595 MT, giving the ship a 12.7% buoyancy margin. The distribution of the foam is such that there is no location where cutting the ship in two would result in the sinking of a portion of the ship containing HLW cargo. The only credible mechanism for losing any penetrators following a collision is through a hole made in one or two of the cargo holds. Insulation from a three-day 982°C fire is provided by 22.9 cm of 1430 °C Fiberfrax ceramic fiber insulation and the urethane foam. The cargo of 450 penetrators is further protected by air-cooled, shielded containers, each holding six penetrators.

Although a disposal site has not been selected, the reference location for this performance assessment was the Southern Nares Abyssal Plain in the Atlantic Ocean. The capacity of the reference repository is 10^5 MTHM. All nuclides in the HLW were included in the analyses, even those that are not in the borosilicate waste form. All

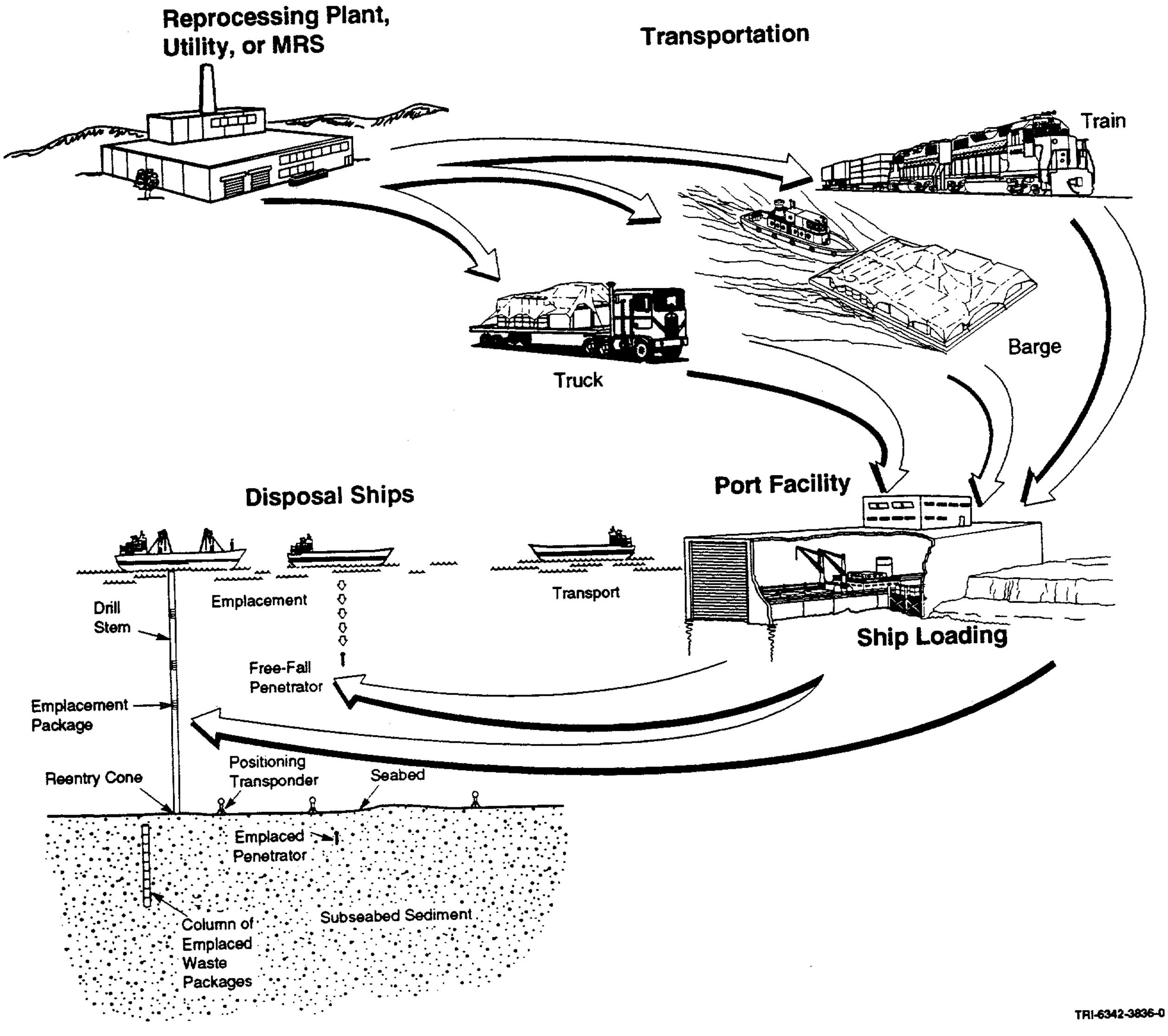

Figure 1. Reference Subseabed HLW Disposal System.

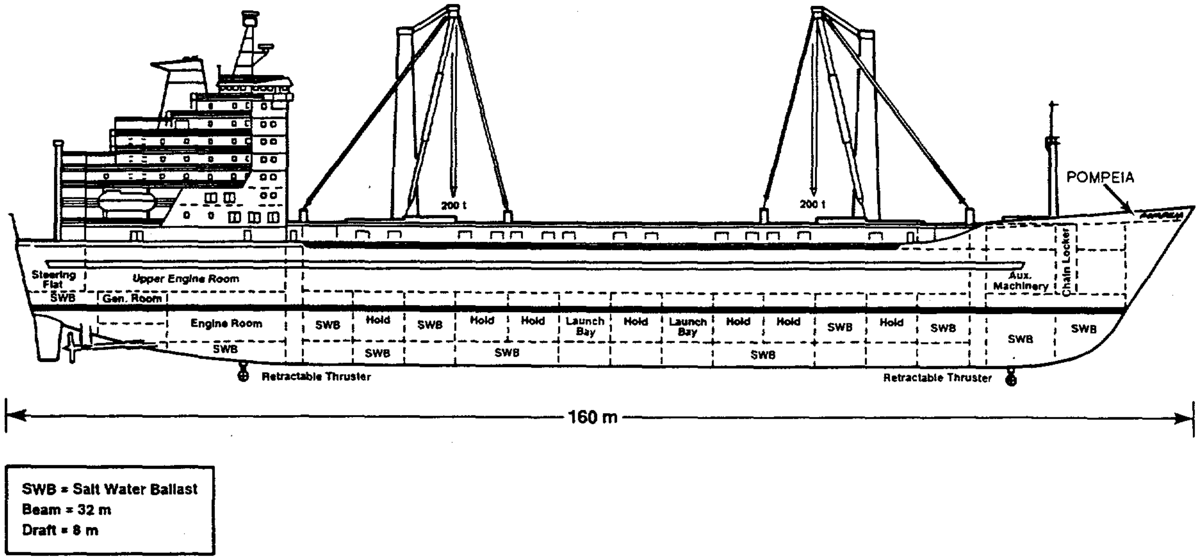

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Figure 2. Conceptual design of a ship to transport penetrators from a port to a subseabed disposal site and launch them in a specific pattern. This ship is designed to withstand accidents and adverse weather conditions.

PA results scale linearly with waste quantity allowing most consequence analyses to be based on 1 MTHM, which facilitates combining probabilistic accident and normal operation risks and scaling the repository size.

3. RADIOLOGICAL STANDARDS

No official radiological protection criteria exist for subseabed HLW disposal. The SDP examined and evaluated the options [5,6] and developed a set of three interim evaluation standards [7]. The interim SDP standards equal or exceed the requirements of national and international guidance and regulations covering similar types of disposal. Risk is defined in this report as the probability of an event happening, times the dose from the event, times the health effect (HE) probability coefficient. At the time of the second performance assessment, the recommended HE probability coefficient was 0.01 HE per sievert. Only the following two standards were used in the second iteration of performance assessments:

1. A standard that limits the dose to the maximally exposed individual. This is an absolute limit, irrespective of the quantity of waste in repositories, making the quantity of waste that can be disposed of dependent on the efficiency (risk attenuation) of the repositories. Individual risk and dose limits for all anthropogenic radioactivity were:

   Annual individual risk limit = 10^{-5} HE/yr
   Peak individual dose rate limit = 10^{-3} Sv/yr

Ten percent of this limit was allocated to HLW disposal in the SDP performance assessment.

2. A standard that limits the dose to collective populations. This is a risk/benefit limit that allows the risk to be proportional to the quantity of power generated, allowing a margin of safety to be computed for each repository design. Collective world population limits were:

   Annual collective risk limit = 10^{-6} HE/yr-MTHM
   World population dose rate limit = 10^{-4} person Sv/yr-MTHM

   The integration time used for the SDP PA was 10^5 years, which included the peak dose rate and was shown by sensitivity studies to be the most conservative. The resulting collective dose limit was 10 person-Sv/MTHM over 10^5 years.

More information on the interim SDP radiological standards can be found in References 5-7. Reference 7 includes the complete set of standards that were planned for the final iteration of the feasibility phase of the SDP. The discussion of development procedures includes evaluation of alternative methods of regulation and the rationale for selecting the standards. The site characteristics and repository design requirements necessary to meet the standards are also discussed. These standards were written to limit peak dose rates to maximally exposed individuals, doses to any single generation, and time integrated collective doses to the world population. This group of standards offers a broader range of protection than those proposed for terrestrial repositories. Although it is expected that subseabed disposal systems would be able to comply with these standards, they may be too stringent for other repositories.

Pathways to humans included food chains and transport through the sediments, oceans, and atmosphere. Exposure mechanisms were inhalation, external exposure, and consumption of desalinated water, sea salt, and aquatic foods. Usage rates for the maximally exposed individual were those of a Japanese fisherman, and the usage rates for the world population were the predicted maximum harvest rates from the oceans without depleting the species.

4. MODELS

The systems models used for the SDP sensitivity and risk analyses were either exact analytical solutions with physical and chemical limitations, or compartmental models with averaged parameters. These models have short run times, are easily modified, and are easy to input and interpret. They have been verified using numeric models for the subseabed scenarios. TMAX and ARRAYF [8] were used for heat transfer analyses. The TRION series [9] modeled canister life, waste leach rate, and nuclide transport through the sediment by diffusion and advection. The compartmental MARINRAD IV program [10], which computes physical and biologic transport of nuclides in the oceans, concentrations in the water, uptake by biota, and exposure and resulting doses to humans, was used for oceanographic transport and dose analyses.

5. SENSITIVITY STUDIES

Parametric studies were conducted to define the response of individual components and the entire system to each input parameter. Sensitivity analyses showed where the largest gains could be made in ship and repository designs, and which parts of the database should be expanded. The results were also an indication of confidence in predictions, with higher confidence in the systems with low sensitivity to variations in input parameters. Subseabed disposal has low sensitivity to most natural and design parameters. The major exceptions are the design parameter - burial depth, and the natural parameter - vertical pore water velocity in the sediments. Vertical pore water movement in the sediments can occur at some locations due to compaction or natural convection cells caused by large local geothermal gradients in the sediments and underlying crust. Convection cells caused by the heat generated by short lived radionuclides in the waste would be small and last less than 100 years. They would no longer exist by the time waste is released from the canister.

Figure 3 shows the fraction of allowable time-integrated, world population dose versus burial depth. With 10^5 year integration, the sensitivity is approximately -1 at 40 m. The sensitivity is much greater for burial depths less than 10 m. This figure shows that increasing burial depth should be a penetrator design goal and that penetration of at least 20 m is required for high confidence in the predictions. Figure 3 also shows that using too short an integration time in standards can be misleading. The steep slope in the 10^4 year integration curve is caused by cutting off the analysis before the nuclides leave the sediment and is not a true indication of total dose attenuation.

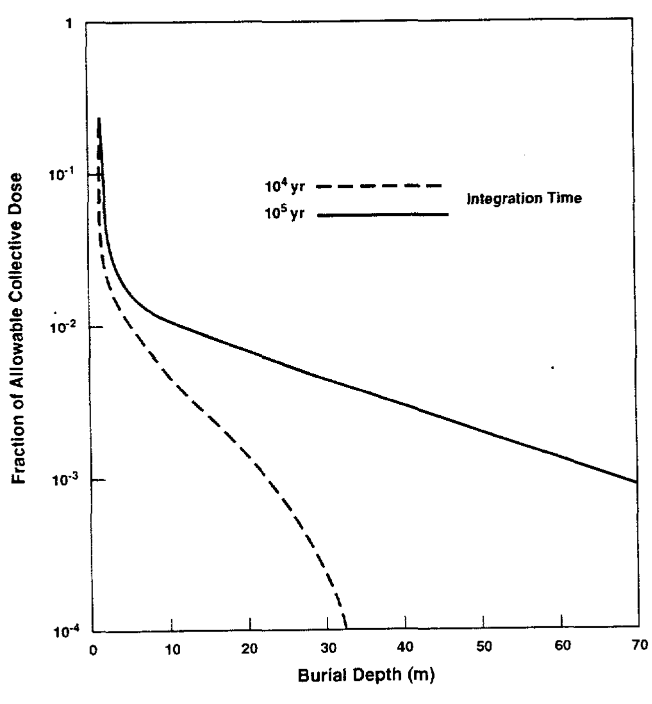

Figure 3. Burial Depth Sensitivity.

Figure 4 is part of the pore water velocity study. It defines the fraction of allowable collective dose versus vertical pore water velocity in one type of sediment. The figure shows that if velocities as low as 0.1 mm/yr can be measured and a site has no measurable velocity, then either there is no pore water movement or it is too slow to affect release from the sediments. The sensitivity is so large in the 10^{-4} to 10^{-2} m/yr range that any change in conditions or errors in measurement could be critical. The plateau above 10^{-2} m/yr has too small a safety factor. Therefore, vertical pore water velocity less than 10^{-4} m/yr should be a goal for site selection. The dominant nuclides are listed in Figure 4 for each velocity range. The remainder of the SDP sensitivity studies can be found in References 11, 12, and 13.

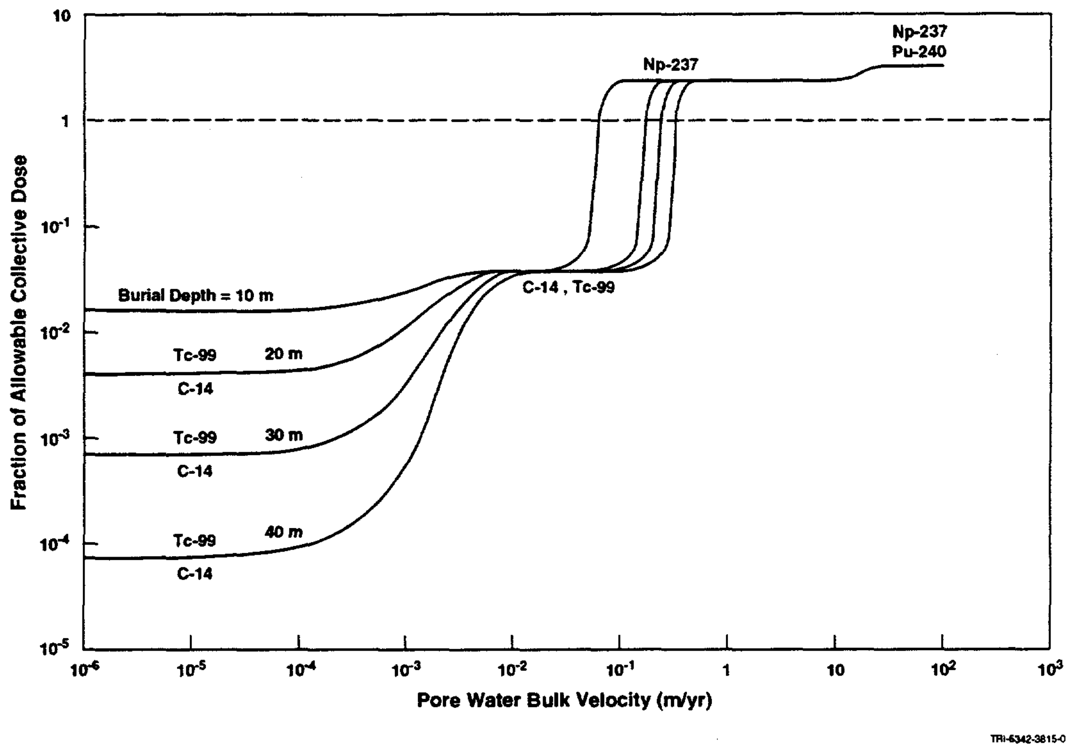

Figure 4. Pore Water Velocity Sensitivity.

6. ATTENUATION FACTOR ANALYSES

The attenuation factor (AF) is a measure of the reduction of flux, dose, or risk by each component or the entire disposal system [14]. All components from the source to the recipient act as pathways and attenuate the risk potential. These analyses include all possible source locations, recipients, and potential component failures. The processes for reducing risk in a waste disposal system are:

1. retardation - Increasing the time for waste to move between two locations, allowing more time for the waste to decay or degrade.

2. temporal dispersion - Causing a potentially high intensity, short duration release of waste from a component to be released at a lower rate over a longer period of time, pulse spreading.

3. dilution - Diminishing the strength or concentration of a contaminant by mixing it with large quantities of another substance.

4. spatial dispersion - The expansion of a moving plume or band of contaminant carried by a moving fluid. Also, scattering of a concentrated source by a multi-directional circulating fluid.

Table I is an example of an AF analysis that included the major components of a subseabed repository. The required system attenuation for 10 repositories is 8.5 x 10^{15} based on a peak individual dose rate limit for HLW repositories of 10^{-4} Sv/yr. The "Complete System" column shows the relative importance of each component and that the system has a large margin of safety. The next column shows the resilience of the system to component malfunctions. Peak dose rates do not increase even if the canister and waste form fail completely. The short-lived nuclides that normally decay in the canister would decay in the sediment, and the temporal dispersion caused by the slow leaching waste form is negligible compared to the temporal dispersion caused by diffusion through the sediment. The "On Sea Floor" column shows the AFs of canisters placed on the sea floor instead of buried in the sediments. In this case, the small safety margin would limit total disposal to less than 10 repositories, making dumping impractical. These AFs are also an input to accident analyses. The last column shows that oceans must be included in SDP risk analyses because the attenuation of the repository alone is not sufficient. The requirement to analyze the entire disposal system is typical of all repositories. Although the AF method of performance assessment was developed for nuclear waste disposal, it can also be applied to toxic waste disposal.

Table I. Attenuation Factors for HLW Subseabed Disposal Based on Maximum Individual Dose Standards. Required System Attenuation for 10 Repositories is 8.5 x 10^{15}. (Nares Abyssal Plain, 5000 yr Canister, 2500 yr Leach, 50m Burial Depth.)

	Scenarios			
Component	Complete System	Failed Canister and Waste Form	On Sea Floor	Repository Alone (without oceans)
Canisters	2.9 x 10^{2}	---	2.9 x 10^{2}	2.9 x 10^{2}
Waste Form	2.6 x 10^{1}	---	2.6 x 10^{1}	2.6 x 10^{1}
Sediment	1.6 x 10^{5}	1.2 x 10^{9}	---	1.6 x 10^{5}
Oceans	1.3 x 10^{11}	1.3 x 10^{11}	5.5 x 10^{12}	---
Total	1.6 x 10^{20}	1.6 x 10^{20}	4.3 x 10^{16}	1.3 x 10^{9}

7. RISK ANALYSIS

Figure 5 illustrates the radionuclide pathways and types of nuclide transport and biological computations that are needed in an SDP risk analysis. Each analysis computes concentrations in the sediment, oceans, and aquatic food; flux from the sediment; and dose rates and doses to biota, the maximally exposed individual, and the world population. The risk analyses include:

1. Properly emplaced waste in the reference repository.
2. Probabilistic transportation and emplacement accidents.
3. Bounding values for 1 and 2 using the most and least favorable input data.
4. Probabilistic analyses of 1 and 2 when there are enough data to define the input variable distributions.
5. Consequence analyses of abnormal scenarios.
6. Total probabilistic risk for the system.

Figure 6 shows the total dose and the dose from each nuclide to the maximally exposed individual from emplaced waste as a function of time, using best estimate input data. Only a few nuclides with low distribution coefficients significantly contribute to peak dose rates. Also shown is that the dose must be integrated at least 10^5 years to obtain meaningful collective doses. Similar curves are generated for each of the above analyses. The results of peak individual dose studies for emplaced waste are summarized in Table II. The principal compartment refers to the location in the model responsible for the peak dose rate.

Risks from sea transportation with the newly designed emplacement ship would be negligible compared to the risk from emplaced waste. Mean values for the probabilistic peak individual dose per MTHM from shipping is 4.4×10^{-20} Sv/yr compared to 5.3×10^{-15} Sv/yr for emplaced waste. A corresponding comparison for collective population dose is 4.4×10^{-12} to 2.2×10^{-2} person-Sv.

Of the abnormal scenarios investigated, damaged emplaced canisters, enhanced leach rate, and changes in ocean currents had almost no effect. Waste isolation consists of keeping humans away from the waste as well as preventing the waste from reaching humans. Human intrusion into a subseabed repository was not considered to be a credible event. If all distribution and partition coefficients were zero, individual doses would increase by a factor of about 300. If sediment vertical pore water velocity was 1 m/yr and the canisters failed, the individual doses would increase by a factor of 5×10^7. Since realistic probabilities could not be assigned to abnormal events, they were not included in the total probabilistic risk.

Total disposal system margins of safety for a single 10^5 MTHM repository using both types of standards and three levels of input data are given in Table III. In this table, an allowable individual dose of 10^{-4} Sv/yr (10% of total allowable manmade) from nuclear waste disposal was used. Collective population margins of safety do not depend on the quantity of waste in repositories. The database and complete 1987 risk assessment are in Reference 13.

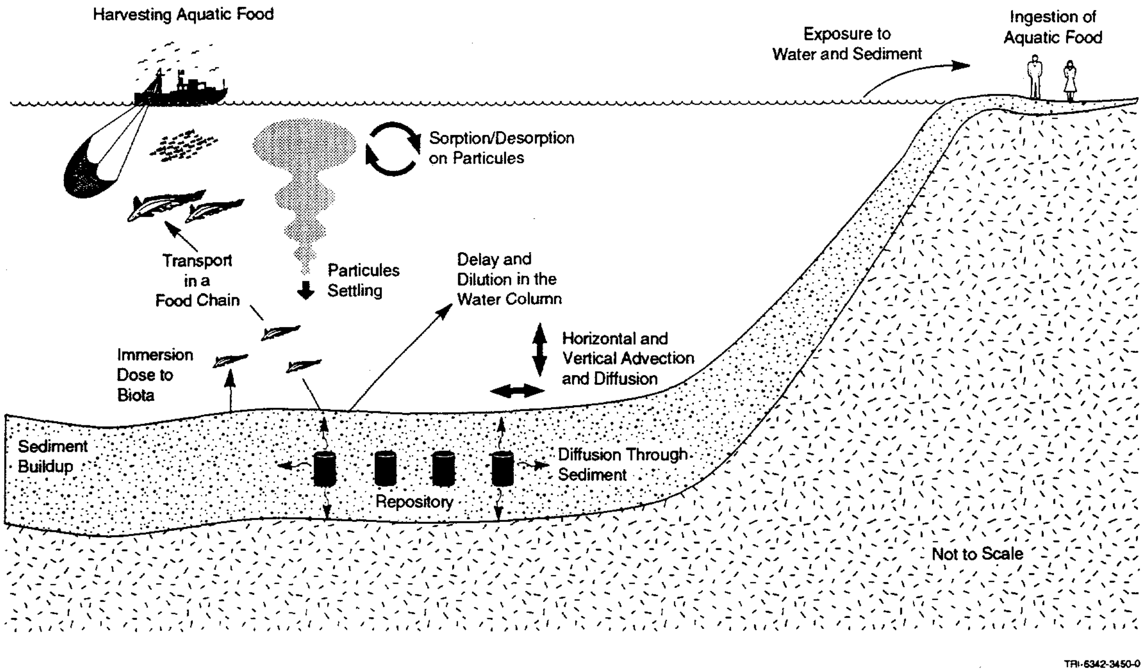

Figure 5. Subseabed Waste Disposal System.

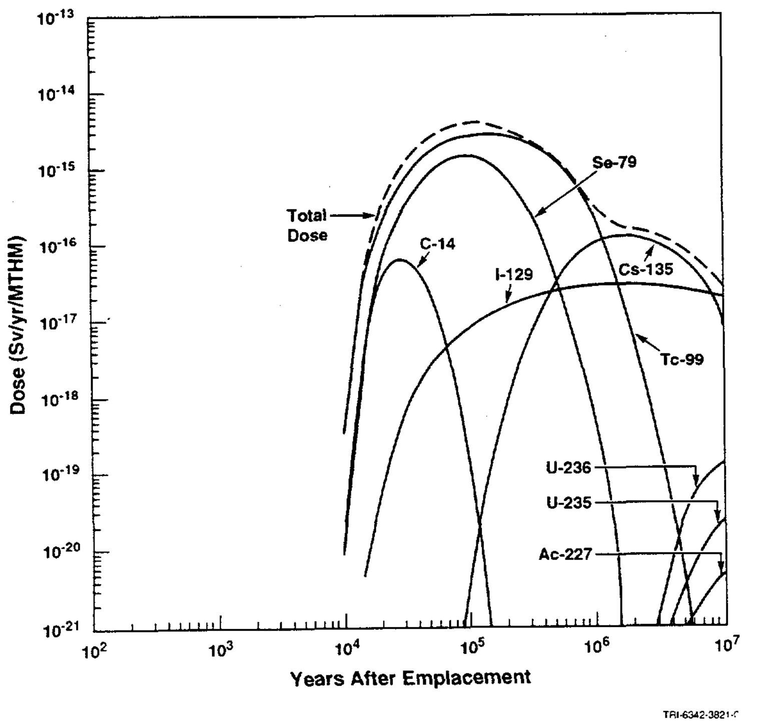

Figure 6. Individual Dose vs. Time in the Top N. American Compartment, by Nuclide -- Emplaced Waste, Mean-Risk Parameter Values.

Table II. Peak Individual Dose -- Post-Emplacement Release (Undamaged Canisters, 50-Year-Old Waste)

Input Data	Peak Individual Dose (Sv/yr·MTHM)	Time of Peak Dose (yr)	Principal Compartment	Principal Nuclides and % Contribution	Principal Pathways and % Contribution
Most Favorable	1.0×10^{-18}	7.0×10^{6}	Top N. American	I-129 (91%) Cs-135 (9%)	Seaweed (94%) Fish (4%)
Best Estimate	5.2×10^{-15}	1.5×10^{5}	Top N. American	Tc-99 (71%) Se-79 (29%)	Mollusc (29%) Crustacean (28%) Seaweed (24%) Fish (19%)
Least Favorable	7.3×10^{-13}	7.0×10^{4}	Top N. American	Sn-126 (55%) Tc-99 (40%)	Fish (31%) Seaweed (30%) Crustacean (23%) Mollusc (16%)

Table III. Margins of Safety for a 10^5 MTHM Repository

Data Level	Peak Individual Dose	Collective Population Dose
Most Favorable	1.0×10^{9}	1.2×10^{8}
Best Estimate	1.9×10^{5}	4.6×10^{2}
Least Favorable	1.4×10^{3}	1.9

8. INTERPRETATION AND APPLICATION

Sometimes it is helpful to compare disposal risks to parameters other than criteria or regulations. Figure 7 shows that individual doses from a subseabed HLW repository would be low compared to average individual dose levels (natural background, food, water, inhalation, and medical), the ICRP limit, and a de minimis level (below

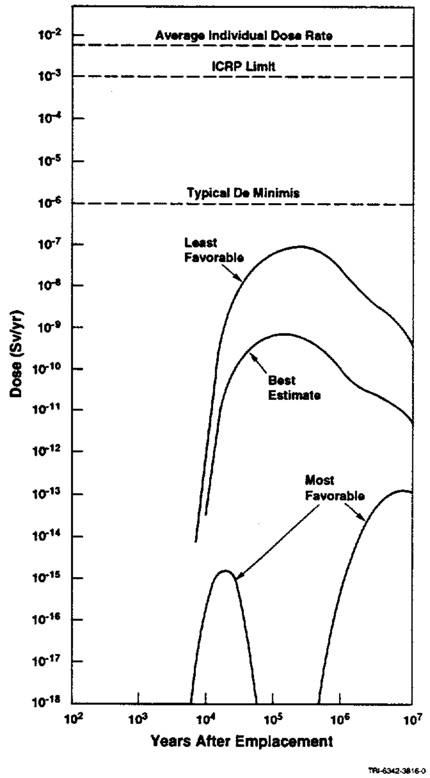

Figure 7. Doses to the Maximally Exposed Individual from a 10^5 MTHM Repository.

regulatory concern). The present radioactivity in the oceans is 1.9×10^{22} Bq. All the release to the ocean from a 10^5 MTHM repository would increase this level by only a factor of 4×10^{-8}. Comparison to other methods of disposal is also useful. A literature search [15] showed that predicted peak individual doses from 10^5 MTHM mined geologic repositories in salt, shale, clay, and granite would range from 1.2×10^{-10} to 1.1×10^{-3} Sv/yr, which averages higher than the 5.2×10^{-10} Sv/yr for subseabed. Predicted 10^5 year collective population doses from a mined geologic repository in tuff [16] ranged from factors of 10^2 to 10^3 higher than those from subseabed disposal, depending on waste leaching assumptions.

The results of the 1983 SDP risk assessment helped in planning the research program, selecting site criteria, and performing the functional analyses for design of the penetrator and emplacement ship for the second iteration of the SDP feasibility phase. As an example, the 1983 risk assessment revealed several weaknesses in the previous reference ship design that caused transportation accidents to be the highest risk in the disposal system. This information was used in the functional analysis and functional requirements studies for the current ship design. Peak individual doses from shipping accidents were reduced by a factor of 1.8×10^6.

The technical feasibility study is not complete, and there are still some uncertainties in the SDP performance assessment. These uncertainties emanate from the following:

- The database is not complete.
- All transport-related processes may not be known.

- Theories for all observed transport and biological processes are not completely developed.
- Biological and ocean models may have to be refined.
- Probabilities of abnormal events are not known.
- Probabilistic risk analyses are based on estimated distributions because of data limitations.
- A method of retrieving emplaced canisters has not been completely developed.
- Site requirements are not finalized.
- Disposal sites are not completely characterized.
- Models are verified but not validated with field tests.

The status of the SDP performance assessment after the second of the three planned iterations in the feasibility phase can be summarized as follows:

- Basic transport models from emplaced waste to humans are complete. Accurate predictions can be made with analytic and relatively simple numeric models.
- Sensitivities of all known input variables are defined.
- Attenuation factor analyses indicated subseabed disposal is resilient to component malfunctions and has low sensitivity to changes in most parameters.
- Interim risk assessments predict large margins of safety even with conservative standards.
- Risk- and sensitivity-based functional analyses have led to penetrator and emplacement ship conceptual designs that meet cost and safety requirements.
- Sites with greater than 0.1 mm/yr vertical pore water movement would be unacceptable and sites with dislocations may be unacceptable.
- Sites have been found in the Atlantic and Pacific that passed initial screening tests.
- Transport properties of all sediments tested indicate that ocean sediment is an effective barrier.
- A waste package can be built that will survive long enough for recovery following an accident and during the thermally active period following disposal.
- Major physical and biological pathways to humans have been identified.

All analyses to date indicate that subseabed disposal would be a safe and economical method of HLW disposal and that predictions could be made with a high degree of confidence.

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