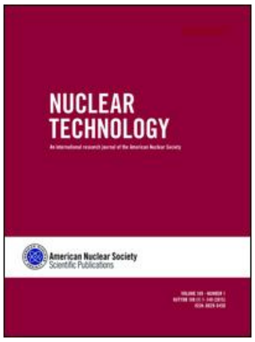

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Evaluation Methodology of Waste Management Concepts

D. E. Deonigi

EVALUATION METHODOLOGY OF WASTE MANAGEMENT CONCEPTS

RADIOACTIVE WASTE

D. E. DEONIGI *Battelle-Pacific Northwest Laboratories*
Richland, Washington 99352

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A methodology has been developed for an overall evaluation of high-level waste disposal concepts. This methodology incorporates the following elements: technical feasibility, safety, research and development requirements, timing, costs, policy, environmental considerations, and public attitudes. Once the technical feasibility of a concept is established, the other elements are studied in parallel. Since system safety is the element of greatest uncertainty, a more detailed description of its methodology is presented. The fault tree analysis technique is used in identification of mechanisms and probabilities of possible releases of radioactive waste constituents to man's environment. A model of the geologic subsystem assists in quantifying the decontamination factors in the waste material transport process. In addition, a comprehensive dose computational model permits ready calculation of radiation doses to individuals and population groups for alternative waste disposal concepts.

INTRODUCTION

The management of high-level waste is a complex problem. Man's decision in this matter can impact not only the environment of his own generation but also that of thousands of generations in the future. A number of concepts have been proposed for disposal and control of this waste. These vary from relatively simple processes such as pouring the waste into a hole in the ground to very advanced techniques such as rocketing the waste out of the solar system.

The detailed analyses of even the simplest sounding of concepts are frequently as complex as those for the more advanced systems, particularly in the conceptual stage. Before an evaluation can be made, a description of the concept is required which includes, in many cases, a description of a generic site. Some of the concepts may present the potential capability to handle a broad range of waste as generated, whereas other concepts require special treatment or handling such as a waste solidification step, special waste partitioning, or extended interim storage.

EVALUATION METHODOLOGY

With the large number of disposal concepts to be considered, each requiring a substantial research and development effort, some order of priority must be established so that those concepts with the greatest potential for solving the problem can be addressed first. To establish the methodology for such an overall evaluation, the following elements were considered:

1. technical feasibility
2. safety
3. research and development requirements
4. timing
5. costs
6. policy
7. environmental considerations
8. public attitudes.

With the outcome of each of these elements being described in completely different units, obviously, simply adding up the performance level by element would not lead to the best concept

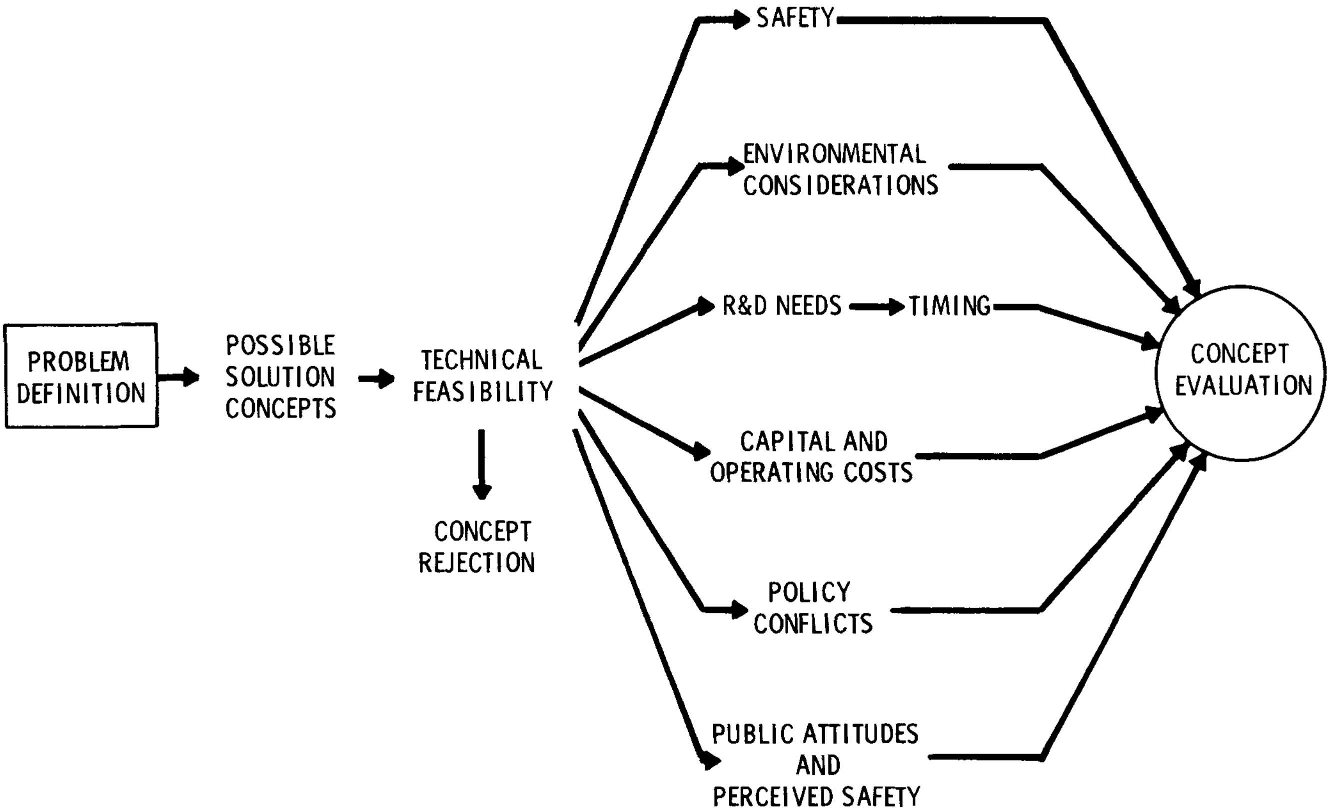

Fig. 1. Relationships among evaluation factors.

selection. Instead, the technique developed was one of overcoming the performance hurdles of those listed. For instance, the technical feasibility hurdle (the hurdle examined first) would be of the "yes-no" type, where "yes" is required before analysis of other requirements would be undertaken. The only hurdle used for rejection of potential concepts was that of technical feasibility. Information on the other factors was developed for the technically feasible concepts and is presented in this discussion. Figure 1 graphically illustrates the relationship between these elements.

The waste management concepts were first developed to the detail needed to describe them for overall investigations and in general were studied on a systematic, generic basis. Concepts were generally developed on the reference basis of having the capability to handle the waste from a plant which reprocesses 5 MT/day (1825 MT/yr) of spent nuclear fuel.[a] This reference capacity was then scaled up as a function of time to accommodate the total need for the U.S. nuclear economy through the year 2000.

After the various disposal concepts were defined, the technical feasibility of each potential concept was determined by answering the questions:

1. Can the disposal concept be implemented using today's technology?
2. Or can the disposal concept be implemented with future technology based upon current theory?
3. Can the disposal concept provide the potential for confining or eliminating the waste over the required time period?
4. Does the concept have a favorable energy balance?

Those few concepts that did not pass this technical feasibility test (i.e., some transmutation and space disposal variations) were rejected from further studies.

Once the technical feasibility of a concept was established, the other elements were studied in parallel. The potential for system *safety* was scanned for each concept. A sample safety analysis was performed for one generic type of

[a] High-level waste produced is about 1900 liter/day as aqueous waste. This quantity amounts to 45 625 MT of fuel reprocessed during the assumed 25-yr life of the plant. Total accumulated solid waste is in 14 700 "typical" canisters 30 cm in diameter and 30 m long.

geologic disposal concept to develop and test the safety analysis methodology. The safety analysis (discussed later) estimated the radiation dose[b] from a hypothetical release of waste from a disposal area.

Environmental considerations, aside from the potential release of radioactive materials covered under safety, were reviewed. These included overall effects on land, air, sea, or water use. The primary nonradiological impact was general land or sea use. None of the concepts required cooling water.

The technology needs were assessed, and *research and development* needs (scope, time, and dollars) were estimated. From research and development time needs, total time for implementation of each concept was estimated. Cost ranged from \$50 to \$500 million and required 10 to 25 years for completion.

Capital and operating costs were estimated, using the basic assumption that the necessary research and development had been successfully completed. These costs were then summed for total waste management system activities such as partitioning, interim liquid and solid storage, shipping, and disposal.

These estimates concluded that the levelized unit cost for the most expensive concept (extraterrestrial solar escape disposal) is less than 5% of current nuclear electric power costs; most concepts are in the range of 0.4 to 1.0%; and two concepts are in the range of 0.2%. Consequently, none of the disposal concepts should increase the cost of nuclear electric power by major amounts.

Major *policy conflicts* that a concept would have with international and national policies were reviewed, such as agreements that prohibit the use of the oceans or the Antarctic continent for waste disposal. The problems involved with changes can then be weighed against the safety and economic potentials of a particular waste management concept.

The potential *public response* to a chosen waste management scheme was examined in a preliminary pilot test. Obviously this is a complex subject and very difficult to evaluate. An initial study of methodology was designed to identify those aspects of the waste management systems that might be deemed most important by the general public. With future analysis in depth, information on public attitudes could be factored into concept design. The public's acceptance of a technically sound waste management system is a most important goal.

Early analysis of evaluation data showed that a number of technically feasible concepts could be developed in a reasonable time period for a cost which is small compared to the benefit of nuclear power. Further, the nonradiological environmental impact appears minimal and operating cost acceptable. The remaining element of greatest uncertainty is system safety and the public perception of safety. Before safety can be discussed with the public, a technical assessment must be completed. The following is a more detailed description of the safety element methodology developed.

SAFETY CRITERIA

Safety is a major consideration in decisions on the use of any potential disposal scheme. An acceptable option must provide adequate protection during operational phases and provide the necessary isolation during the long time periods of the disposal phase.

Long-term immobilization or isolation and containment of disposed waste are the two major protective devices requisite to the implementation of a nuclear waste management system. Substantial interaction can and does exist between these two factors. In this context, isolation is used to mean the factors which influence the time required for migration of waste to man's environment; containment is used to mean immobilization and confinement of the waste constituents within known barriers. Typical isolation factors could include distance, the ion-exchange capacity of interposed earth materials, the lack of a transfer medium such as water, etc. If waste is adequately isolated so that the migration times are greater than the time for radioactive decay, isolation alone can provide adequate protection. Conversely, if adequate containment is provided by man-made barriers that immobilize the waste—again for the length of time for decay—the waste could be placed in many selected locations even within man's environment. Here the word "barrier" is used to include the matrix for the waste, e.g., silicate glasses, wrappings such as metallic sheets, and facilities such as a concrete building, which serve to provide effective barriers to the escape of radioactive materials. The disposal options explored here utilize the maximum benefits from both isolation and containment, although principal emphasis is on isolation.

Safety was equated directly to the potential risk to man (in terms of radiation dose) that could result if a disposal option were implemented. The

[b]Radiation dose is an expression for the energy absorbed by matter as a result of exposure to radiation and has the unit "rad." For these safety studies we have actually used the radiation dose-equivalent, expressed in "rem," which is a measure of the physiological effects of radiation on people.

key elements in a method of assessing potential risk are illustrated in Fig. 2.

Assessment of the risk of a proposed concept starts with the general description of the disposal concept. This implies a generic site description (e.g., ice sheet disposal defines a general location, surrounding geology, and population density), and it implies the characteristics of the waste (e.g., the waste form, containerization, radionuclide content, and age). The most likely sequences of failure events leading to possible release of radioactive materials to man's environment are then defined, and the probability of these sequences taking place is determined. The next step follows the most likely sequences through the physical and chemical mechanisms required to release the waste constituents into man's immediate environment. The generic site defines the media (granite, salt, shale, air, water, etc.) through which radionuclides must move into man's environment. Next, based on the population expected to come in contact with the waste materials, the potential exposure pathways, and the calculated waste release rate, the radiation dose to the population can be estimated.

Finally, the probabilistic risk (dose) to man can be determined by multiplying the probability of the event taking place times the dose if it takes place. By comparing the total integrated risks of proposed concepts with appropriate criteria, it can be determined whether or not the risk to man exceeds acceptable criteria. If the risk level is unacceptably high, the concept could be rejected or changes could be made in the concept to reduce the risk. If the risk for a concept meets all criteria, the concept would be considered to have met the safety requirements, although further improvements may still be made. Of course, concepts in which the risk is substantially lower than the measurement criteria would be rated as most favorable.

Development of suitable safety criteria is most important in a final evaluation of waste management practices. Although development of such criteria was beyond the scope of this study, the following are proposed as representative of major safety criteria:

1. On a probabilistic basis, the risk to the world population from waste management should represent only a minor increase in the total risk presently assumed by the operation of nuclear power plants. The risk contribution from probabilistic releases from the waste production of a power plant should be no more than a fraction of the risk from chronic effluent releases from the plant.

2. Because the risk to man from waste may exist substantially longer than the use of fission reactors as a power source, its risk to future man should compare favorably with other involuntary risks that give little or no benefit. Being struck by lightning, being killed in an earthquake or flood and being hit by a fallen aircraft are examples of involuntary risks with little benefit to those exposed to the risk. Such risks result in about one

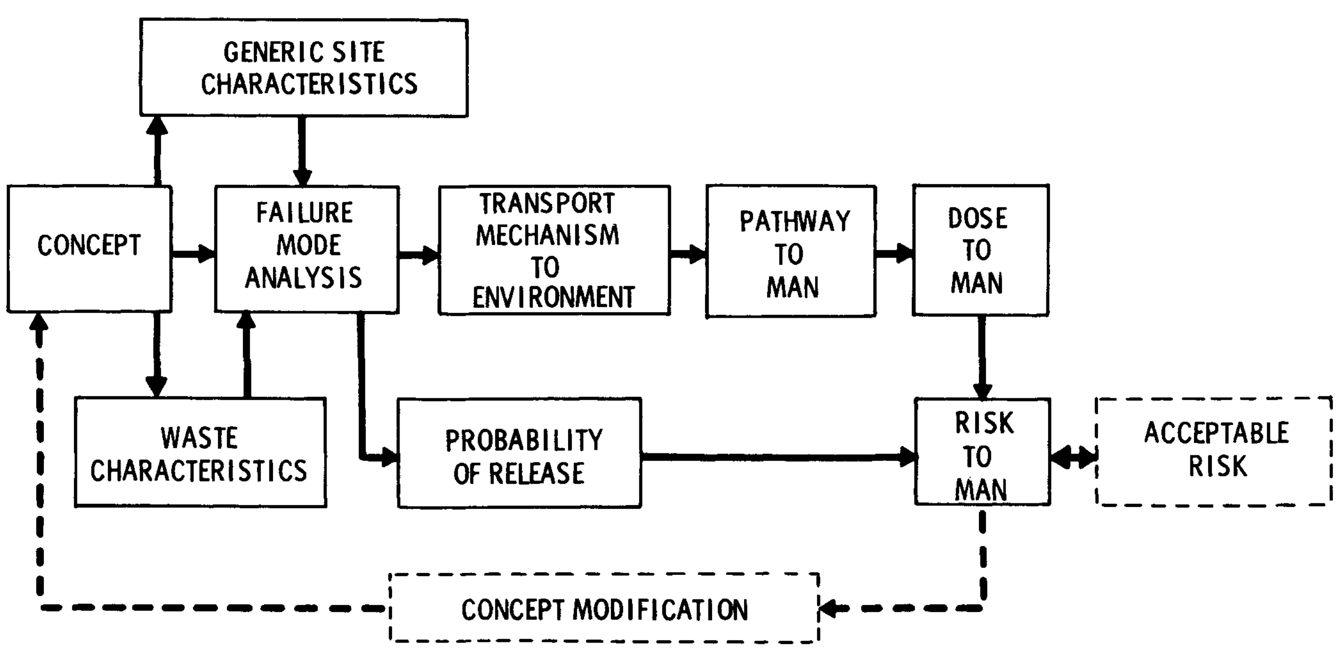

Fig. 2. Interrelationships among pathway, probability, and risk.

death per million population per year.[c] Comparison of the risk from waste management practices would require conversion of radiation dose to deaths to establish a criterion. Several such conversions have been postulated but remain controversial.

3. The dose to the population in the immediate disposal area should not be great enough to put the population at serious immediate risk. This may require that some protective reaction from a release of waste materials be available; for example, the population in the affected area may be evacuated or restricted or the water supplies may be relocated. It is assumed that evacuation may be required if the estimated exposure to a population group were to exceed some maximum standard which could not be decreased through curtailed operation.

The basic problem with this analytical technique is that the values used to describe probabilities of system failures, the actual rates of movement through environmental media to man, and even the population distribution around the release from a plant 1000 years or more in the future are obviously in question. In addition, information on the interrelationships between dose to man, risk to man in units of potential deaths or dollar costs, and acceptable risk were found to be controversial.

Recent studies sponsored by the United Nations Scientific Committee on the Effects of Atomic Radiation and by the U.S. Environmental Protection Agency address what is known and what is assumed for low-level radiation concerning the radiation-dose/radiation-effects problem. Considering the large uncertainties in the derived conversions and the problem of making equivalent conversions for radiation doses to different organs of the body, estimates of harmful effects for these concept comparison studies were not attempted. Others have tried to place a dollar value on increased harmful effects on people to provide a more direct method of comparisons. However, such a procedure involves not only still larger uncertainties, but the basic philosophical problem of equating dollars to human lives.

[c] There is a great deal of concern about natural disasters but essentially no concern about accidents caused by lightning. In natural disasters, the concern is high because many people could be exposed to a single event. These simple comparisons show that perception of risk is very complex and that numerous factors must be considered.

FAILURE MODE ANALYSIS AND RELEASE PROBABILITIES

Evaluation of the safety of any disposal concept requires identification of mechanisms and probabilities of possible releases of radioactive waste constituents to man's environment. The fault tree analysis technique was determined to be the preferred method to provide for achieving these requirements. This method provides for calculating the risk to man (in terms of radiation exposure) on a probabilistic basis.

As an illustration of the method, a generic fault tree was developed for geologic disposal in a mined cavity. In all, 77 basic failure events were identified as possible contributors to a waste release from a geologic disposal site.[1]

For the fault tree to be fully utilized, each failure must be amenable to analysis. Each must have a predictable failure threshold, and it must be possible either to obtain a reasonable data base for predicting the frequency of the event or else to show that the failure event is not an important safety consideration.

Of the 77 failure events in the example studied, over 60 were believed to have predictable failure thresholds; thus, it should be possible to develop a data base for predicting probabilities. They were also fully amenable to analysis.

Of the remaining 17 failure events, the majority were associated with man's future activities. Although man's future activities can never be exactly quantified, the importance of man's presence can be bracketed by first assuming the site is not actively administered and, alternatively, by assuming that man is actively controlling activities in the area. Thus, the degree of reliance placed on man's presence in the region can be roughly quantified. It is believed that disposal concepts that place minimum reliance on man's presence can be found. Thus, for those concepts the final criterion is met; i.e., the failure events associated with man's activity are not an important safety consideration.

The remaining failure events were associated with future tectonic activity. Areas of high tectonic activity may not be readily amenable to analysis, because the forces involved are potentially large, not well known, and particularly difficult to quantify. However, areas of high tectonic stability are available, and disposal in these locations should be amenable to fault tree analysis.

SAMPLE WASTE RELEASE PROBABILITY ESTIMATE

The next step of analysis is to follow each release sequence through its pathway to man's environment and ultimately to man. One release sequence, obtained from the geologic fault tree mentioned above, is followed here. The numbers presented in this analysis are based on limited data and serve primarily to demonstrate the safety evaluation method.

The example waste release sequence considers the release of waste to man's environment by water. This is considered to be one of the more likely release sequences.

The release sequence starts with the premise of "An Aquifer in the Waste Disposal Region" and requires the following three conditions: "Water Finds Path into Disposal Site," "Water Is Flowing," and "Water Flow Cannot Be Controlled by Man." All three conditions must occur together before a release of waste constituents can take place. Based on present tunneling experience, the probability that an undetected flaw in a barrier exists which will allow water entry in a region where there is no detectable aquifer is estimated to occur at a rate of once in 100 000 km of tunnel length. Thus, the failure element "Water Finds Path into Disposal Site" is estimated to occur at a rate of 10^{-5}/km of tunnel constructed for geologic disposal. This and the following numbers are orders of magnitude estimates. Based on the description for the mined cavity concept, 90 km of tunnels will be in existence in the year 2000; thus, the probability of a defect allowing water entry is expected to be once in every 1000 mines (or 10^{-3}) with 90 km of tunnel.

Conditions which could cause an aquifer in the region in the next year were estimated to be once in one billion (10^{-9}). After one million years, the probability of an active aquifer in the region is taken to be much greater, 10^{-1}. At the 1000-year period, an intermediate number was used. It was assumed that man would not be able to control the aquifer and the aquifer would be flowing; thus, the failure elements "Water Is Flowing" and "Water Flow Cannot Be Controlled by Man" have probabilities of 1.

Table I summarizes the sample failure event probabilities and the resultant cumulative probabilities obtained by multiplying the individual probabilities in each vertical column. The ranges of probabilities given reflect uncertainty in the above data.

The table summarizes a release probability estimate from one sample failure sequence. To estimate the overall safety, all significant paths must be analyzed and the probabilities times the respective consequences must be summed.

APPLICATION OF FAULT TREES TO OTHER DISPOSAL CONCEPTS

Preliminary failure modes were identified for seabed, ice sheet, and extraterrestrial disposal concepts. Fault tree analysis can be applied to these disposal concepts in the same manner as to the geologic concepts.

The preliminary analysis pointed out how relatively little data are available to assess the seabed and ice sheet environments. For example, in the seabed environment, very little information is known about the long-term behavior of ocean sediments. In like manner, there is little experience with drilling, placement, and sealing of waste canisters in the seabed. Thus, its apparent safety is uncertain, chiefly because of lack of detailed knowledge about it. The same is true of the ice sheet environment except that more known mechanisms for release of waste can be identified.

For the extraterrestrial disposal concepts, the National Aeronautics and Space Administration has accumulated experience with manned space flights as a basis for estimating the safety

TABLE I

Sample Components of Release Sequence Probabilities for Geologic Disposal

	Probability of Waste Release		
Failure Event	During Operational Period	During 1000 yr	During 1 000 000 yr
Aquifer develops in the region where one did not exist previously	10^{-10} to 10^{-8}	10^{-6} to 10^{-4}	10^{-2} to 10^{-1}
Water finds path into disposal site	10^{-4} to 10^{-2}	10^{-4} to 10^{-2}	10^{-4} to 10^{-2}
Water flow cannot be controlled by man	1	1	1
Water is flowing	1	1	1
Cumulative release probability in the time given	10^{-14} to 10^{-10}	10^{-10} to 10^{-6}	10^{-6} to 10^{-3}

which can be achieved. Failures on the launch pad, by burnup in the atmosphere, or meltdown after loss on the earth's surface are the failure elements of greatest concern and can be estimated with improved confidence as the number of launches accumulates.

TRANSPORT MECHANISMS

All disposal concepts under study provide substantial containment or isolation barriers to initially separate the constituents of nuclear waste from man's environment. A failure or degeneration of these barriers is required before transport to man's environment can be initiated. However, a barrier failure does not necessarily result in release of waste materials into man's immediate environment where exposure takes place; transport mechanisms are required.

The primary transport mechanisms are naturally occurring water and air. In most cases, transport by water will be through soils and/or rock with extensive chemical interaction (ion exchange) taking place. The quantities, rate, and timing of radioisotopes entering man's environment will depend on a host of parameters such as the rate of release of radioisotopes at the source (i.e., solubility of waste in groundwater), the flow rate of the water, the distance traveled to reach man's environment, the efficiency of ion exchange, chemical species, etc.

Transport by air could be achieved as a result of either a single- or a two-step process. In the first, an accident could both directly expose the waste to air and fracture it to such an extent that air currents would resuspend and transport material. In the two-stage process, it is postulated that naturally occurring water would transport the radioisotopes to a water-air (or earth-air) interface. Resuspension and transport could then occur from the residues of evaporation.

Quantification of the decontamination factors (i.e., radioisotope adsorption and holdup time) in the transport process requires an accurate model of the geologic system. Sample transport decontamination factors were calculated for an aquifer 16 km in length flowing at 30 cm/day in typical U.S. Western soil. This calculation assumed that an aquifer penetrated a failed barrier in a geologic disposal site. Dose reduction factors were in the range of 10^5 to 10^6; that is, the calculated doses to man with soil retention were 5 to 6 orders of magnitude lower than those without soil retention. The significance of this calculation is that for properly sited disposal concepts, the earth itself can provide major safety factors.

DOSE TO MAN

A comprehensive dose computational model, developed and used for other U.S. Atomic Energy Commission studies, was adapted to permit ready calculation of radiation doses to individuals and population groups for alternative waste disposal concepts. Typical inputs include source terms (radionuclide release rates to man's immediate environment), population densities, dilution quantities, and consumption rates of food and water. Outputs include individual pathway doses, total doses to individuals and to specified population groups, and fractional dose contributions of specific nuclides.

To demonstrate the capability, calculated doses are shown in Table II for a hypothetical release of

TABLE II

Calculated Whole Body Radiation Doses from Hypothetic Release of Waste Inventory of Year 2000 in Geologic Disposal

	Maximum Annual Dose (mrem)	NCRP Nonoccupational Guide
Maximum Individual	0.4	500
	Annual Dose to Population (man-rem)	
Population	30	[a]

Assumptions

Total waste inventory exposed in the assumed releases is all of the waste resulting from the projected cumulative 167 000 equivalent MT of fuel processed in the U.S. through year 2000. (The latest projection is 185 000 equivalent MT.)

Initial release to soil occurs 100 yr after disposal.

Geologic disposal is in the arid U.S. Western region, with release to aquifer.

Source release rate (or the rate of dissolution of the waste material) is 0.3%/yr of total inventory.

Aquifer is 16 km long; average groundwater velocity is 30 cm/day.

Soil is typical Western desert soil, with its normally good ion-exchange capacity.

Population is 180 000 people within an 80-km radius of the point of release to man's immediate environment.

Aquifer flows into a river which flows through the center of the region and which provides both drinking water and irrigation.

Average river flow rate is 280 m^3/sec.

[a]Guides are not available, but dividing the indicated dose of 30 000 man-rem by the assumed population size of 180 000 gives an average annual dose of 0.16 mrem for comparison with the dose to the hypothetical Maximum Individual.

radioactive waste from geologic disposal (assuming sorption and retention on soil). Also shown in the table is the limiting individual dose from nonoccupational and nonmedical radiation exposure according to the latest recommendations of the National Council on Radiation Protection and Measurements. For comparison, the average annual radiation dose in the United States from natural sources is on the order of 120 to 140 mrem. The dose indicated in the table for the Maximum Individual is less than that received during a cross-country jet airplane flight.

The potential doses (following releases from a geologic disposal site) are highly dependent on the sorption capacity of the soil or other receiving media, the characteristics (especially the leach rate) of the waste, and the measures taken to prevent release.

Calculations can be based on postulated release of the waste materials to man's immediate environment at any period after disposal, but calculated doses at periods of 1000 yr or more would be much less due to decay of shorter lived nuclides. The most significant nuclides in terms of dose would generally be ^{90}Sr and ^{137}Cs at 100 yr, various radionuclides of americium and plutonium at 1000 to 10 000 yr, and uranium daughter nuclides at longer periods.

Doses calculated with the model for various generic cases are primarily valuable for comparative purposes, and such doses would be, at worst, the result of a series of unpredictable or low-probability events leading to the release of radioactivity to man's immediate environment. Detailed analyses will be required to assess the risks to man from specific concepts, sites, and operations.

RISK TO MAN

The sample calculations of probability given in Table I can be multiplied by doses such as those shown in Table II to obtain a hypothetical risk of radiation dose to man from the disposal concept. The maximum measure of risk to an individual from the given failure mechanisms and pathways would then be in the range of 10^{-10} to 10^{-6} mrem/yr at 1000 yr after disposal. Similarly, the risk to the affected large population group would be $<10^{-4}$ man-rem/yr for the same time period.

These previous sections demonstrate the methodology for calculating the probabilistic risk to man from radioactive waste disposal. For actual application of risk calculations, analyses will be required for specific concepts, sites, and operations. In addition, the risks from all major mechanisms and pathways must be summed to obtain the total calculated risk.

CONCLUSIONS

The final product of this study is a compilation of information regarding the evaluation factors for the various disposal concepts. The outcome of each of these elements is described in different units. Therefore, the concepts cannot be evaluated by simply adding up the performance level by elements. Instead, the technique being developed for future studies is one of determining if a disposal concept passes a performance test for each evaluation factor listed. For instance, a passing of the technical feasibility hurdle or test would be required before detailed analysis of other requirements be undertaken. The order in which the pass-reject tests are applied and the criteria for the various performance hurdles (or concept evaluation factor tests) were not developed in this study.

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