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LONG-TERM SAFETY OF NUCLEAR WASTE DISPOSAL: A BASIS FOR CONFIDENCE

Prepared for:

UTILITY NUCLEAR WASTE MANAGEMENT GROUP

and

EDISON ELECTRIC INSTITUTE

(DOCUMENT 3 OF 4)

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FOREWORD

This report was prepared by The Analytic Sciences Corporation (TASC) for the Utility Nuclear Waste Management Group (UNWMG) and the Edison Electric Institute (EEI) as part of the analyses of current technical and scientific information developed for the UNWMG-EEI presentation in the Nuclear Regulatory Commission's proposed rulemaking on the storage and disposal of nuclear waste. The report focuses on safety assessments of nuclear waste disposal. Two other reports developed for purposes of such presentation by working groups of UNWMG-EEI are entitled "The Capability for Disposing of High-Level Waste Safely" and "The Capability for the Safe Interim Storage of Spent Fuel". In addition, a "Summary Statement of Position of the Utility Nuclear Waste Management Group - Edison Electric Institute", which presents an overview of the entire UNWMG-EEI submittal, has also been prepared.

The authors would like to acknowledge the contributions of Charles M. Koplik, Benjamin I. Ross and Maureen F. Kaplan to the contents of this report.

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1. INTRODUCTION AND BACKGROUND

1.1 PURPOSE AND SCOPE

This report was prepared by TASC for the Utility Nuclear Waste Management Group (UNWMG) and the Edison Electric Institute (EEI) as part of the analyses of current technical and scientific evidence developed for the UNWMG-EEI presentation of information in the Nuclear Regulatory Commission's proposed rulemaking on the storage and disposal of nuclear waste. The report focuses on safety assessments of nuclear waste disposal. Two other reports developed for purposes of such presentation by working groups of UNWMG-EEI are entitled "The Capability for Disposing of High-Level Waste Safely" and "The Capability for the Safe Interim Storage of Spent Fuel". In addition, a "Summary Statement of Position of the Utility Nuclear Waste Management Group - Edison Electric Institute", which presents an overview of the entire UNWMG-EEI submittal, has been prepared.

This report presents a basis for confidence in the long-term safety of nuclear waste disposal. Sufficient technical and scientific evidence exists to justify a conclusion that disposal safety will be maintained for times and conditions beyond experimental verification. The report focuses on three related areas: the positive results from safety assessments of nuclear waste disposal, the major issues which affect confidence in these results, and the technical basis for justifying acceptance of these results as conservative estimates of safety.

Since the contents of this report are concerned with safe long-term performance of disposal technologies discussed in "The Capability for Disposing of High-Level Waste Safely", the two documents are closely related. Several subjects, such as waste toxicity and barrier performance, are discussed in both documents, in each case with a perspective apropos the focus of the document. Points of interaction are highlighted in this report by references to the "Disposal Capability Document".

Section 1.2 of this chapter gives a comprehensive summary of prior long-term safety assessment studies. Collectively, the studies provide a firm basis for assessing the status of knowledge concerning nuclear waste disposal risks. All of the studies are shown to support positive conclusions with respect to long-term safety.

Issues affecting confidence in analyses of disposal safety are described in Chapter 2. The issues are primarily a consequence of the long time periods over which risk predictions are made. The doubts of many people regarding the safety of disposal stem from concern over predicting phenomena for long times. This issue is first addressed by presenting a number of reasonable comparisons to other known hazards or phenomena. The comparisons provide a useful perspective on the potential hazards of nuclear waste. Next, sources of uncertainty in risk prediction results are considered in detail. Issues surrounding events that could occur and affect waste containment are explored including a discussion of human action scenarios. The role of testing and research as a means for reducing uncertainties is described including the need for perspective on the costs and benefits of data acquisition and analysis. Finally, an overview is presented on how and why the "systems approach" can lead to fully adequate repository siting and design.

Chapter 3 provides a technical basis for confidence in the results of safety assessments. Such confidence is based on conservatism in the analysis, conservatism in repository siting and design, and the existence of multiple barriers to waste release. A review of major past experimental evidence demonstrates that the predictions of current and future analyses are or will be justified.

The information in Chapters 1, 2, and 3 is brought together in Chapter 4 to show why great confidence exists in the ultimate safety of nuclear waste disposal. Certainly disposal safety is not "proved" (this would require observation of the repository over the time period wastes remain hazardous). Nor have all uncertainties about the future been eliminated (this is impossible to accomplish). But there is clearly a firm basis for confidence in the capability to locate and design a repository which will provide a fully acceptable solution to disposal of nuclear wastes.

A bibliography of relevant documents and literature is presented in Appendix A.

1.2 SUMMARY OF PRIOR LONG-TERM SAFETY ASSESSMENT WORK

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.

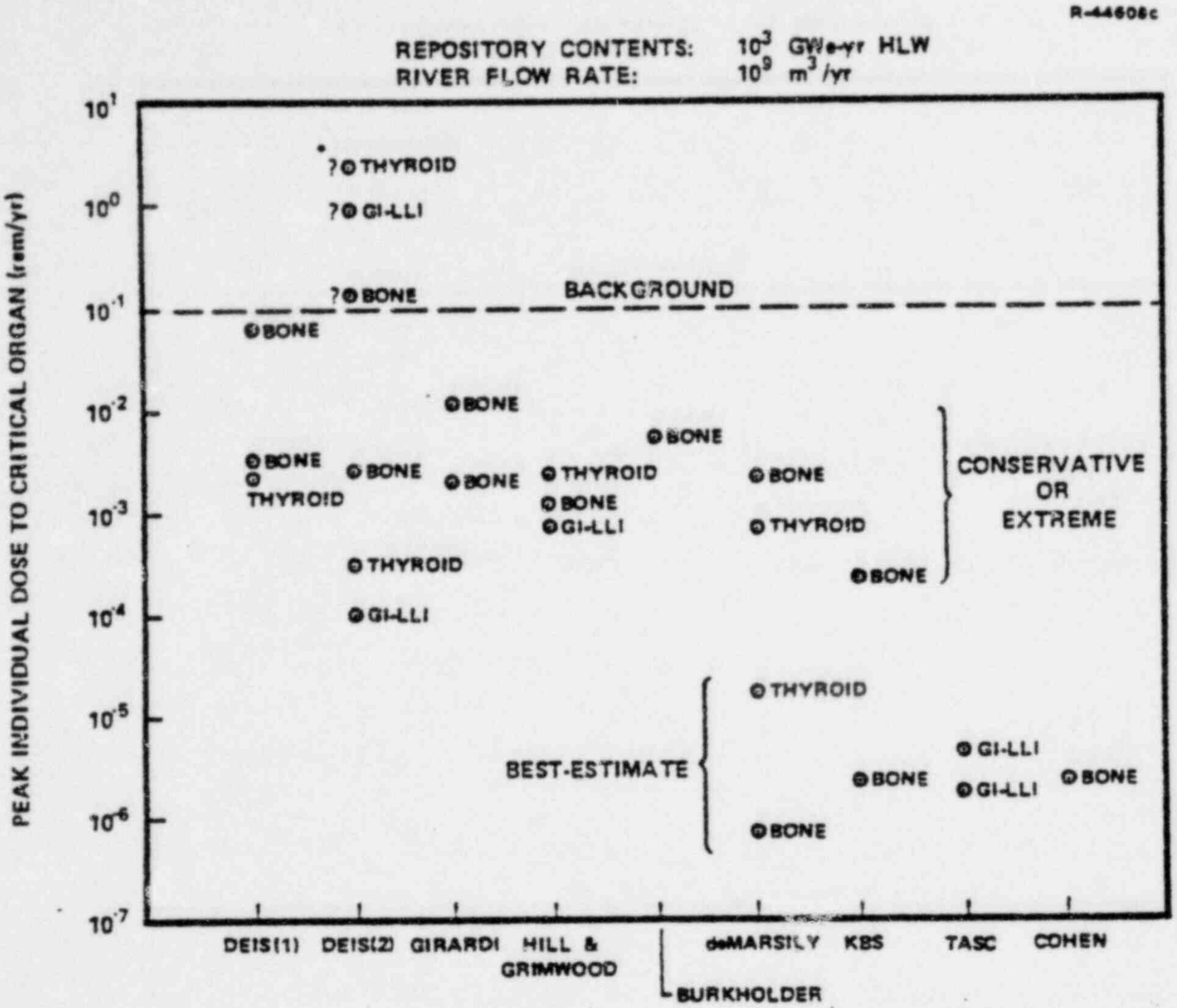
A detailed review and comparative analysis of all major available safety assessment studies has recently been completed and is reported in Refs. 1 and 2. On the basis of this review the following general conclusions are drawn:

- Disruptive events which could result in direct and sudden release of waste into the environment are extremely unlikely and have consequences that are only serious within a small region neighboring the repository site. Appropriate site selection can virtually eliminate the occurrence of such events.
- The most important process for release of waste is access, dissolution, and slow transport by groundwater. For a reasonable site location and repository design there are no plausible mechanisms whereby such release can occur prior to five hundred years after disposal. By this time the fission products that dominate early risk will have decayed to negligible levels.
- Safety assessment studies have quantified the ranges in the potential risks to future generations. The ranges in predicted risks are quite similar to that currently experienced from naturally deposited uranium ore bodies -- i.e., several times natural background in some areas to many orders of magnitude below natural background in others. The pessimistic risk estimates for HLW and spent fuel disposal derive from studies which have assumed large-scale failure or human intrusion of engineered barriers in a poorly selected site. The very low risk estimates derive from studies which assume at least limited performance of some barriers for an average site.

In Refs. 1 and 2 the results from the studies reviewed were reconciled and analyzed by comparison on a common basis. Each study's results were normalized to the waste produced from a fixed amount of generated electric power. A common environmental consequence model was applied to every study. The models for predicting release rates of waste into the environment are crucial, and these were preserved for each risk study examined.

The normalized results of the HLW (high-level reprocessing waste) studies are displayed in Fig. 1.2-1 for the peak individual dose to the critical organ. Some studies have two sets of results shown. For Girardi, et al, (Ref. 3), these represent release at 10^3 or 10^5 years. For de Marsily, et al, (Ref. 4), 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 KBS results (Ref. 5) are a conservative and a best estimate of dose from HLW disposal. The TASC results (Ref. 6) are for a salt and a shale repository.

Results are shown for two different scenarios that were analyzed in DOE's draft EIS on management of commercially generated radioactive waste (Ref. 7). Both scenarios were considered to be extremely unlikely to occur and were chosen as a "worst case". 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 transport 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, i.e., total dissolution of the waste in one year. This assumption is clearly unrealistic.



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

Figure 1.2-1 Normalized Peak Individual Doses for HLW Reference Scenarios

Figure 1.2-1 also presents results from studies by Hill and Grimwood (Ref. 8), Burkholder (Ref. 9) and B.L. Cohen (Ref. 10). In general, the peak doses fall into two natural classes:

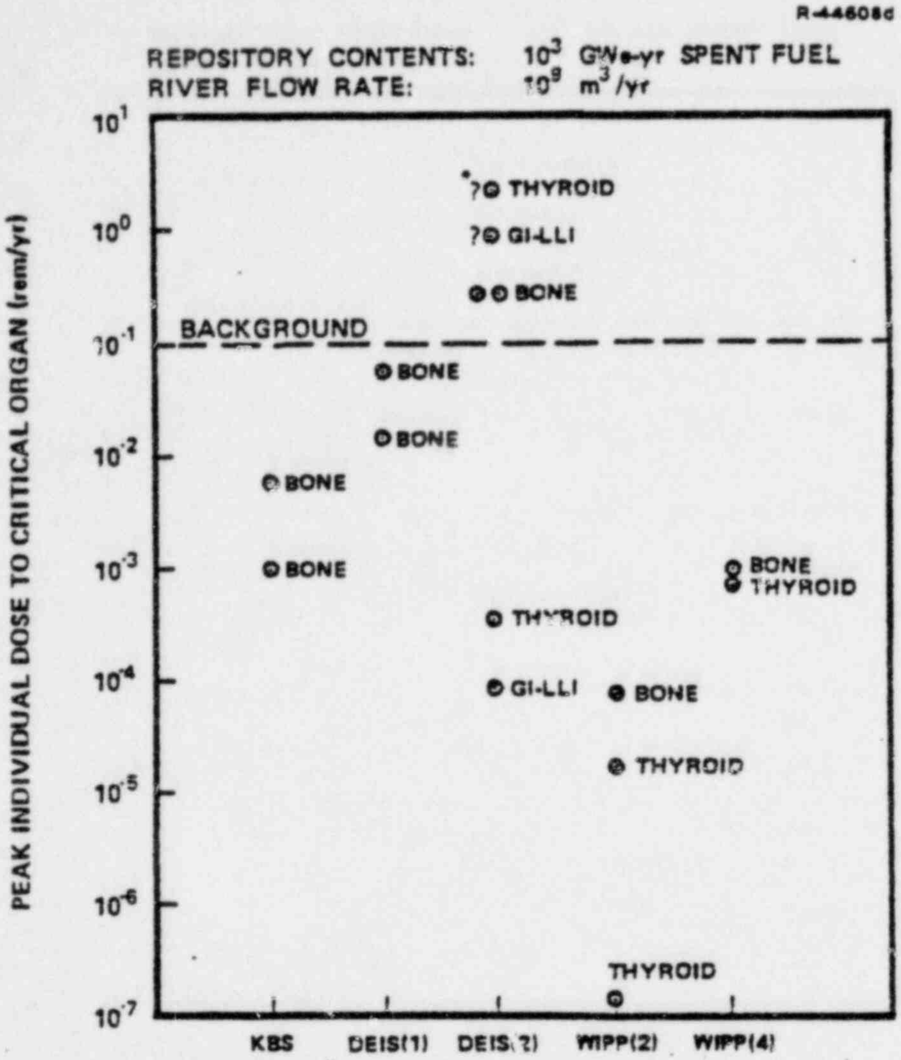
- A class centered at about 1% of average yearly background radiation. The studies in this class represent extremely conservative, scoping analyses of risk where the objective was to determine a reasonable upper bound to the potential hazard.

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

A few studies have specifically considered the risks from disposal of spent reactor fuel. Figure 1.2-2 shows normalized results from three studies: KBS (Swedish Nuclear Fuel Safety Project, Ref. 11), the draft EIS on management of commercially generated radioactive waste and the draft WIPP EIS (Ref. 12). The scenarios for which DEIS results are shown were previously discussed.

The results shown for the KBS study represent a conservative and a best estimate of the expected peak dose. The peak dose occurs 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 draft WIPP EIS; Fig. 1.2-2 shows results for the two most significant scenarios for a repository containing 10^3 GWe-yr of waste. For all scenarios, the analysis was restricted to a 100,000 year time frame. In Scenario 2 (WIPP(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



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

Figure 1.2-2 Normalized Peak Individual Doses for Spent Fuel Reference Scenarios

consequences of this event. In Scenario 4 (WIPP(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.

With the exception of the KBS study the results shown are conservative estimates of the consequences of 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).

All of the studies (HLW and spent fuel) 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 consequence will fall below some upper bound. If the upper bound calculated in any single such study corresponds to an unacceptable risk, although there is cause for concern, only the need for more realistic studies may be indicated.

The major conservative assumption in most safety studies is the presumption of loss of containment followed by transport to the biosphere and subsequent human interaction. This consequences-only approach to assessment of waste disposal safety only determines the magnitude of the maximum potential problems. It does not account for the likelihood of occurrence. A risk assessment, in contrast, would require evaluation of likelihoods and consequences of release.

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 doses predicted by the studies which are considered to be either less extreme or more realistic are therefore strong evidence of the ultimate safety of the geologic disposal option.

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 here do not rely 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.

Based on dose factors taken from NRC Regulatory Guide 1.109, after about five hundred years spent fuel and reprocessing wastes placed in geologic disposal present little more hazard than the uranium ores from which they came. Containment of the wastes is certainly necessary for several hundred years. That this can be done appears to be demonstrated. Beyond this time, the concentrated nature of the wastes and the disturbances caused by their emplacement by man must be shown not to create hazards significantly greater than those resulting from a small fraction of natural variations in background radiation. Risk assessment studies have gone a long way to assure us that this is indeed possible and that safe disposal can be achieved.

1.3 OTHER REVIEWS AND ASSESSMENTS OF WASTE DISPOSAL SAFETY

The conclusions drawn in the preceding section have been echoed by virtually every significant review of the waste disposal problem. The APS study on nuclear fuels and waste management concluded (Ref. 13):

> "The geologic and hydrogeologic conditions that can provide for satisfactory isolation of radioactive waste exist in a sufficient number of

> places that we anticipate no difficulty in locating several suitable sites in different geologic media within the immediate future."
>
> "Current knowledge and technology are adequate to design and locate a suitable waste repository of the conventional mined type, if utilized with appropriate site selection criteria."

More recently a committee of the National Academy of Sciences critically reviewed the literature pertaining to the risks associated with nuclear electric power (Ref. 14). Their conclusions regarding waste disposal are:

> "In none of the cases so far studied in the literature have alarmingly high values been estimated for the time-integrated population dose that people in the future might receive if buried wastes were to be leached by groundwater into the surface environment. Thus, although many authorities have called attention to gaps in our knowledge about some of the factors that bear on the probability and time scale of such eventual leaching, it is not necessary to strive for absolute assurance against escape. One can pursue the much more attainable goal of finding disposal sites for which the product of probability of escape times the consequences if escape occurs can be made reasonably small on the scale of normal operation consequences."
>
> "This last conclusion is supported by a number of studies, and there seem to be no detailed analyses disagreeing with it."

Perhaps the most significant statement with regard to the safety of spent fuel disposal has come from a recent report by the National Academy of Sciences reviewing the Swedish KBS disposal plan (Ref. 15). The NAS review committee came to the following conclusions regarding the principal barriers to waste release in the Swedish plan:

> "Methods of manufacture have been shown to be currently available, and both experiment and theory have demonstrated that the canisters will have sufficient mechanical strength and corrosion resistance to survive in the designed repository environment for hundreds of thousands and probably more than a million years."

> "The existence of at least one site in Swedish bedrock that meets the minimum criteria of dimension and low groundwater movement, though not conclusively demonstrated, is reasonably assured, and it can be inferred from available geologic data that other equally good or better sites exist in Sweden."

> "Much exploratory work and many analyses have shown that the quantity of groundwater moving through a properly chosen site will be small and that its chemical composition will stay in the range in which the amount of corrosion of the canisters will be small."

> "It has been demonstrated fairly convincingly that the planned bentonite seals and backfill for shafts, tunnels, and boreholes after a repository is filled will be adequate to prevent channeling of groundwater."

> "The Subcommittee agrees that the available technical data are adequate to support the conclusion in the KBS-II Plan that radionuclides will not escape at unacceptable rates from a repository built as specified in the KBS-II report, provided that construction is well engineered and a proper site is used."

Finally, we quote from the conclusions of the Interagency Review Group on nuclear waste management (Ref. 16).

> "Successful isolation of radioactive wastes from the biosphere appears technically feasible for periods of thousands of years provided that the systems view is utilized rigorously to evaluate the suitability of sites and designs, to minimize the influence of future human activities and to select a waste form that is compatible with its host rock."

> "Beyond a few thousand years and during the period of time in which actinides and long-lived fission products remain toxic, our capability to predict and therefore our assurance of successful isolation diminishes. Some uncertainties can be bounded or compensated for and therefore need not be resolved completely before selecting a site or constructing a repository. In addition, some will be resolved during repository construction. Although some residual uncertainty will always remain, reliance on conservative engineering practices and multiple barriers can compensate for a lack of total knowledge and predictive capability."

1.4 IMPLICATIONS FOR PERFORMANCE CRITERIA

The conclusions drawn from the conservative safety analyses discussed in Section 1.2 are based on the reasonable presumption that exposures which are a small fraction of variations in natural background radiation are acceptable. A performance criterion for waste disposal based on the concept of "small in comparison with natural variations in background radiation" has received increasing support. The Department of Energy in its statement of position to the NRC in the waste confidence rulemaking adopted the following performance objective (Ref. 17):

> "Wastes will be considered to be <u>isolated</u> if long-term radiological consequences to the public due to the effects of any reasonably foreseeable events or processes are predicted to be within the range of variations experienced with background radiation. Releases with consequences of a few millirem to a few tens of millirem per year would be considered acceptable provided that the ALARA standard for man-made systems is met."

The "range of variations in background radiation" in the United States has been adequately quantified. According to Adler (Ref. 18) the standard deviation (weighted with the exposed population) of natural background is 20 mrem/yr. The approach described above seems quite reasonable. Man has received low-level doses of radiation throughout his history. Attempts to correlate variations in background exposure to health effects have proved inconclusive (Ref. 19). Furthermore, no significant efforts are made to avoid small increases in background exposure. No exodus from the state of Colorado has been reported even though natural background exposures in Colorado are roughly 150 mrem/year per capita greater than in Louisiana (Ref. 7). This subject is discussed in more detail in Section 1-B of the Disposal Capability Document, Ref. 21.

A characteristic of the possible consequences from waste disposal is that releases could occur over exceedingly long time periods. Some analyses have therefore calculated consequences by integrating effects over time. Such analysis can be useful if the results indicate negligible risks either on an absolute basis or on comparison to natural sources of radioactivity. However, the value of such a computed result as a measure of repository performance is exceedingly dubious. A procedure which cumulates very very small effects over periods of millions of years may not be scientifically justified and interpretation of the results is difficult. As Morton Goldman has pointed out (with reference to mill tailings piles, Ref. 20):

> "Concern based on estimates of population dose extrapolated into the murky future derives from a sort of "theoretical tunnel vision" which neglects the rest of the real world in which natural radiation exposure has been present from the beginning, and has been enhanced by human activities."

This leads to consideration of the time frame of importance for evaluations of repository performance. Certainly the critical time period of concern stretches no further than about 500 years, by which time the fission products which dominate early risk have decayed to harmless levels. Beyond this time period, the potential hazard of spent fuel falls off gradually, finally leveling off after several million years and remaining relatively constant for the next billion years (Ref. 21). Within this time frame (from 500 years to a billion years) the potential hazard is not significantly different from small variations in natural background radiation. During this time frame, concern should be less on absolute performance levels and more on whether repository performance can be expected to be better than natural ore bodies. A detailed discussion of these concepts is provided in Ref. 21, the Disposal Capability Document.

1.5 THE NUCLEAR WASTE DISPOSAL CONTROVERSY

The information presented in this chapter (and supported in the rest of this document) suggests that the difficulties in achieving safe waste disposal have been greatly exaggerated. Technical experts and prestigious review committees have repeatedly agreed that disposal of nuclear waste in a mined repository is feasible and that reasonable safety criteria can be met. Positive expectations of the ability to achieve safe disposal have existed from the very beginning of waste disposal research and development work -- work that began almost twenty-five years ago. Nonetheless, some have perceptions of the problem that are in sharp contrast to the views of the individuals who have carefully studied and appraised the risks from nuclear waste disposal. In this section some of the issues in the debate on the safety of nuclear waste disposal are discussed.

1.5.1 Overstatement of the Dimensions of the Problem

Nuclear wastes have been described as representing unparalleled hazards. While the wastes are indeed potentially quite hazardous and do require safe disposal, the dimensions of the problem have been greatly overstated. Seen in perspective, nuclear wastes once buried should represent little more threat than many natural ore bodies and certainly less hazard than the large volumes of hazardous chemicals that are routinely produced in the U.S. (see Section 2.1 for a detailed presentation of perspectives on disposal safety). As bioethicist Dr. Margaret Maxey has cogently pointed out (Ref. 22):

> "The nature of the nuclear waste problem is neither unique nor unprecedented. We have always lived with toxic elements in our environment, and they have not been sequestered with the skill and planning applied to radioactive wastes. As an ethical imperative, criteria for acceptable risk must avoid two potential extremes: capitulation to the requirements dictated by a vocal minority whose values and priorities neglect basic necessities of the living majority; and excessive preoccupation with imaginable risks to future generations whose claim on the intellectual and moral responsibility of existing persons has not yet been clearly defined."

A classic example of the use of hyperbole when describing waste hazards are the claims concerning plutonium, which is described as an unnatural and inordinately toxic substance. Plutonium is certainly not unnatural (it exists in minute quantities in uranium-bearing rocks) and its ingestion hazard (isotope 239) is comparable to that of ordinary caffeine (measured in terms of the quantity required to achieve a lethal dose).* Again this discussion is not meant to suggest that plutonium is innocuous (far from it), but the point is that there exist greatly exaggerated fears and misunderstandings of the whole nuclear waste disposal problem.

1.5.2 Extreme Case Studies

Scientists, when investigating aspects of proposed waste disposal systems or attempting to quantify long-term risks, have attempted to perform their research in a careful and conservative manner. As a research objective, extremes in performance are examined so as to better understand the system under study and to determine if safety can be achieved under the worst conceivable conditions. This work is often misinterpreted (sometimes by the scientists who do the work themselves) and often raises doubts where none are really justified. A full discussion of worst-case analysis and the use of conservative modeling is given in Sections 2.2 and 3.1. Here a few examples will be given to illustrate how results can be misunderstood.

- The integrity of the waste form can be important if all other aspects of the repository system fail (which is highly unlikely). Testing of waste forms has been carried out under extreme conditions to determine its limits of performance (tests have been carried out at temperatures up to 400°C). The tests indicate failure of the waste form at very high temperatures; a useful piece of scientific information. However, such a result by itself means nothing when evaluating the safety of nuclear waste disposal since repository temperatures can easily be held well below these levels.

*The LD_{50} for ingestion of PuO_2 (^{239}Pu) has been estimated to be 13 g (Ref. 23). The LD_{50} for caffeine taken orally is 14 g (Ref. 23).

- Salt, when temperatures exceed roughly 250°C, can decrepitate (the water contained in the rock expands and fractures the rock). This phenomenon (like all others in the universe) is not completely understood. But this "gap" in knowledge means nothing in regard to disposal safety. Decrepitation (which can easily be avoided by keeping temperatures below specified limits) would not reduce the overall safety of disposal even if it occurred.

- Analyses of repository performance are replete with conservative assumptions, some of which are related to the nature of the subject matter under study. For example, de Marsily (Ref. 4) carried out an analysis which postulated groundwater flow through a repository, failure of all engineered barriers, and transport vertically to the surface. His purpose was to examine the <u>geo-hydrologic</u> barriers to release under a simple generic setting. Some have pointed to the high radionuclide concentrations in groundwater that he calculated as evidence of the dangers of buried waste. Such claims, however, find no justification in the work of de Marsily as his analysis is not relevant to actual repository performance.

Many more examples could be given. The real problem is that those who raise the "what if" questions and point to imagined problems are never called upon to prove their case -- i.e., that a real threat to disposal safety exists. The call is always for additional government research.

1.5.3 The Search for the Best

Paradoxically, one of the real obstacles to successful disposal of nuclear waste is the effort to assure the maximum degree of safety to the public. This is seen in the search for the best possible elements for each aspect of the repository system, an approach which contrasts strongly with conventional strategy, i.e., definition of acceptability criteria followed by acceptance of systems that meet those criteria. Taken at face value the search for the best would lead to unending research without achieving a solution to the disposal of nuclear wastes. A thorough discussion of the difficulties created by this overzealous approach is given in Section 2.5 on the systems approach and the search for the best. A discussion of the proliferation of research and the role of experimental evidence is provided in Section 2.4.

It is important to distinguish between two kinds of research efforts:

- Research aimed at providing confidence that deep geologic disposal will be a satisfactory solution to the nuclear waste management problem. There is abundant evidence (some provided in this volume) that such confidence is fully justified without any further such research.
- Research carried out in a carefully organized and step by step fashion to ensure proper selection of a repository site, appropriate engineering design, and safe operation of the repository facility. This research, which includes in situ data gathering and experimental tests, is necessary for implementation of the geologic disposal option. This type of research is not necessary in order to have confidence that safe disposal can be achieved.

Implementation of geologic disposal for nuclear wastes will require a cooperative effort between the various states, the Federal government, and the regulatory agencies. In the past, delays created by the lack of firm direction have exacerbated the waste disposal problem. It is time for the country to move forward and deal effectively with the problem of disposal of its nuclear waste by setting a clear objective to implement disposal, by focusing on research supportive of the implementation objective, and by following proven, reasonable approaches to setting and meeting safety criteria.

2. ISSUES AFFECTING CONFIDENCE IN LONG-TERM SAFETY

2.1 DISPOSAL SAFETY IN PERSPECTIVE

There are at present roughly 4,000 m^3 of commercial high-level waste (including spent fuel) in the United States. By the year 2000 this is expected to increase to an estimated 40,000 m^3 (Ref. 24). Such a quantity of waste could all be contained in a cube roughly 35 meters on a side. The waste, whether it consists of spent reactor fuel or reprocessing wastes, will exist in a highly compact, non-dispersible and readily handled form. The risks entailed by its highly radioactive nature are therefore amenable to control and mitigation by appropriate actions by man.

There are two approaches to judging the degree of hazard associated with disposal of these wastes:

- Comparison of the hazards of nuclear waste with other toxic substances. In this way, the risks are placed in perspective with other risks that we live with and accept.
- Analysis and estimation of the risks following disposal of nuclear wastes in deep geologic repositories.

The latter method is the most appropriate for quantifying the level of risk. It explicitly takes into account the many barriers to the release of waste materials (canister, waste form, geology, etc) and addresses the complex interactions of the waste with its surroundings.

The first approach, which is the subject of this section, can help provide a reasonable basis for confidence that a fully adequate solution to the problem of nuclear waste disposal is possible. To be sure, a comparison of hazards in general does not constitute a demonstration of safety for a particular disposal scheme. But a rational comparison of relative hazards does provide an understanding of the real nature of the disposal problem. Such an understanding helps put to rest many of the myths that have unjustly surrounded the nuclear waste disposal controversy. These include such myths as: "release of nuclear wastes could destroy life on this planet", "nuclear wastes present unprecedented and unknown hazards", and "nuclear wastes remain highly dangerous for hundreds of thousands of years". In this section we will show that:

- Spent fuel wastes have toxicities comparable to other hazardous non-radioactive materials. Disposal of nuclear wastes is far easier and controllable than these other wastes whose hazard is not reduced by radioactive decay.
- After about five hundred years, a nuclear waste repository is less toxic than certain non-radioactive ore bodies.
- The original uranium ore from which nuclear wastes are derived present hazards comparable to or greater than that which might reasonably be expected after deep disposal.
- The hazards from nuclear wastes are not unprecedented. Man has always lived in the presence of natural radioactive materials.

2.1.1 Toxicity of Various Hazardous Wastes

High-level reprocessing wastes and spent reactor fuel can be compared (on a basis of direct hazard) to other non-radioactive wastes that are also produced in the United States. One such comparison is shown in Table 2.1-1 (taken from Ref. 10). The table shows that initially nuclear wastes are quite toxic, but after only 500 years the toxicity has fallen off by a factor of 400 (by a factor of 5000 for reprocessing wastes). This drop-off in toxicity is a consequence of decay of the two principal radionuclides (^{90}Sr and ^{137}Cs) contributing to the radioactivity of the waste. (The differences in toxicity between HLW and spent fuel are explained by the fact that reprocessing both removes actinides and concentrates fission products.)

At 500 years such compounds as cyanide, arsenic and mercury are far more toxic if ingested than commercial nuclear wastes. A comparison at 500 years is certainly not inappropriate, since there is virtually no credible way that waste could be released from a deep geologic repository this soon. Therefore, while nuclear wastes are indeed a potentially hazardous material they are not <u>unusually</u> so. Further, the quantity of non-radioactive hazardous waste in the U.S. dwarfs the radioactive waste problem. There are an estimated 35,000,000 tons of hazardous waste generated each year (Ref. 25) compared to roughly 5,000 tons of commercial spent reactor fuel (Ref. 24). All types of hazardous materials, wastes or not, need to be managed properly. The small quantities of commercial nuclear power wastes and the proven technologies for managing them make associated "problems" much easier.

TABLE 2.1-1

LETHAL QUANTITIES* OF HAZARDOUS MATERIALS IF ORALLY INGESTED

MATERIAL	COMPOUND	LD-50 (av) mg/kg	ANIMAL	MAN (gm) (EXTRAPOLATED)
Selenium	Na_2SeO_3	5	rabbit, mouse, rat, guinea pig	0.35
(Cyanide)	KCN	10	rat	0.7
Mercury	$HgC\ell_2$	23	rat, mouse	1.6
Arsenic	As_2O_3	45	mouse, rat	3
Barium	$BaC\ell_2$, $Ba(NO_3)_2$	250	rat	18
Copper	$CuO, CuC\ell_2$	300	rat	21
Nickel	$Ni(NO_3)_2$	1620	rat	110
Aluminum	$A\ell C\ell_3$ $A\ell_2(SO_4)_3$	4000	rat, mouse	280
High-Level Waste				
10 yr				0.03
500 yr				170
Spent Fuel**				
10 yr				0.15
500 yr				57

*The quantity of material such that half the affected people die; the extrapolation to man from the test animal data is scaled by weight to a 70 kg man.

**Spent fuel was not included in the original table taken from Ref. 10. The values shown here were computed using the same procedures that were used for high-level waste in Ref. 10.

2.1.2 Comparison to Natural Ores

The toxicity of natural ores containing Cd, Pd, Hg, Se, Cr and U has been compared to the toxicity of high-level waste and spent fuel under burial conditions (Refs. 26 and 27). The results (adapted from Refs. 19 and 20) are shown in Fig. 2.1-1. The toxicity is normalized to that of 0.2% uranium ore. After 500 years of decay the buried waste is significantly less toxic than several of the non-radioactive ores (selenium, chromium, and mercury), based on allowable concentrations in drinking water as set by the NRC and EPA.

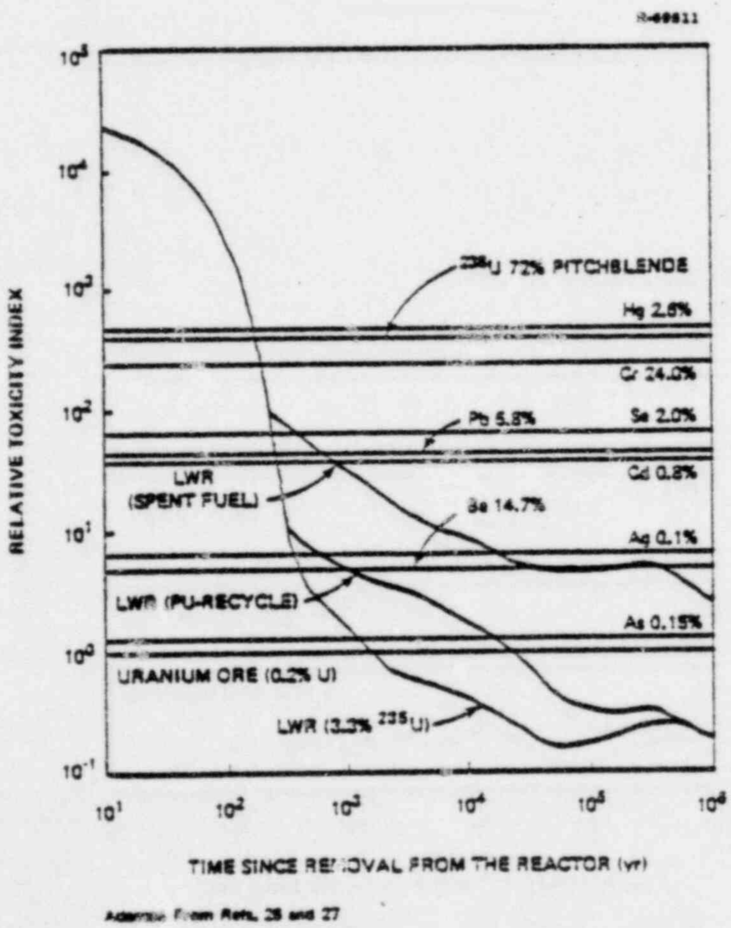


Figure 2.1-1 Relative Toxicity of Nuclear Waste Over Time, Compared With That of Average Mineral Ores of Toxic Elements

The relative toxicity index was computed as follows:

$$T.I.(\text{element}) = (C/DWC)/(C(^{238}U)/DWC(^{238}U)) \qquad (2.1\text{-}1)$$

where

T.I. is the relative toxicity index of a given element or radionuclide

C is the average concentration of the element or radionuclide in its mineral ore (g/m^3) or in the waste (Ci/m^3)

DWC is the maximum permissible concentration of the element or radionuclide in public drinking waters, the former being in terms of mg/liter and the latter in μCi/ml.

The toxicity index for the buried waste is calculated by assuming the waste is uniformly distributed over the areal extent of the repository. This reduces the concentration of the buried waste by roughly a factor of 3000. The fact that the wastes are initially highly concentrated and located in discrete packages can be important, particularly for scenarios in which there is direct intrusion into the waste repository. However, for scenarios in which release occurs due to slowly migrating groundwaters, the comparison appears quite reasonable and increases confidence in the ability to safely dispose of nuclear wastes by burial. This subject is discussed in more detail in the Disposal Capability Document, Ref. 21.

2.1.3 Comparison to the Original Ore From Which the Waste Came

The preceding section compared the hazards of various natural ores and radioactive waste on the basis of volume. An alternative and quite revealing approach is to compare the waste hazard to that of the original uranium ore which was mined to produce the waste. Such a comparison is shown in Fig. 2.1-2 taken from Ref. 28. The ingestion hazard is measured by the quantity of water needed to dilute the substance to RCG levels. The RCG is the maximum concentration of a given radionuclide allowed by federal regulation in public water supplies contaminated by the nuclide.

The toxicity of both spent fuel and HLW is initially several orders of magnitude above that of the ore. However, by 500 years the hazard from HLW crosses that of the ore and continues to diminish past that point. After 1,000 years the hazard from spent fuel exceeds that from the ore by less than an order of magnitude. The crossover for spent fuel occurs after 10,000 years. Certainly it should not be the goal of waste management to reduce hazards far below that which would occur in the absence of nuclear power from the original uranium ore.

The comparison shown in Fig. 2.1-2 is recognized as not being entirely satisfactory since the wastes are concentrated and differ both chemically and physically from the uranium ores from which they came. Furthermore, the waste will be placed underground in a man-made excavation with pathways (shafts, tunnels and boreholes) connecting the repository to the surface. Extensive, detailed discussion of these factors and their role in the "Retention Quotient", a means of parsing the attainment of waste containment and isolation is given in the Disposal Capability Document.

There should be greater confidence in the containment achievable by man than that achieved by accident by nature. Nuclear wastes will be buried with great care in specially chosen locations and with engineered barriers to prevent or reduce release to the environment. Uranium ores are far less

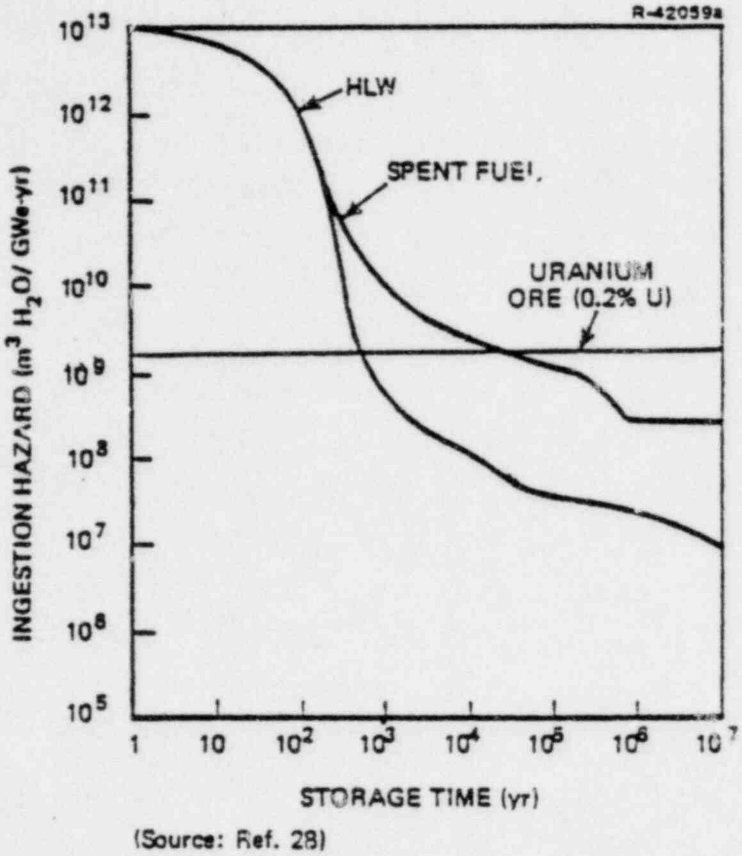


Figure 2.1-2 Ingestion Hazards from Spent Fuel, High-Level Waste and Uranium Ore from 1 GWe-yr Operation

securely contained and isolated. Most uranium ore in the United States occurs in permeable strata with flowing groundwater. Some ores are present at or near the surface. Radium, a uranium daughter, pervades our fresh waters and topsoil.

The comparison can be expanded beyond the hazard index which is, after all, a static and not a dynamic measure of risk. The hazard index does not consider for example:

- Release mechanisms (e.g., leaching of waste)
- Pathways to the biosphere
- Dispersion or buildup of radionuclides in the biosphere

- Pathways to man (food, water, and external exposure).

Biosphere transport and uptake was included in the hazard comparisons developed in the Disposal Capability Document, Ref. 21. The approach is based on defining retention quotients -- the factors of biosphere and geosphere containment required to assure that a selected dose is not exceeded. By exercising a biosphere transport model, retention quotients were obtained for the containment required by the geosphere alone. It was found that the conclusions drawn from hazard index analysis are not affected by inclusion of transport and uptake in the biosphere.

Waste package dissolution and geosphere and biosphere transport were included in the analysis in Ref. 29 which provides a more comprehensive comparison of the potential risks. In this study a reference ore body was compared to HLW or spent fuel assuming they were initially located within an aquifer upstream from a river. Such an assumption implies that the study's results are quite conservative. Repository site location and design make this a highly unlikely scenario. Results of the comparison are shown in Fig. 2.1-3. The analysis was performed for a variety of groundwater conditions and over a range of leaching rates. The results show that, even for worst-case repository conditions, consequences may be expected to be comparable to or less than that from the originally mined uranium ore. A similar conclusion was reached in a study performed for the EPA (Ref. 30) which included a comparison between a waste repository and a uranium ore body occupying the same volume as the repository.

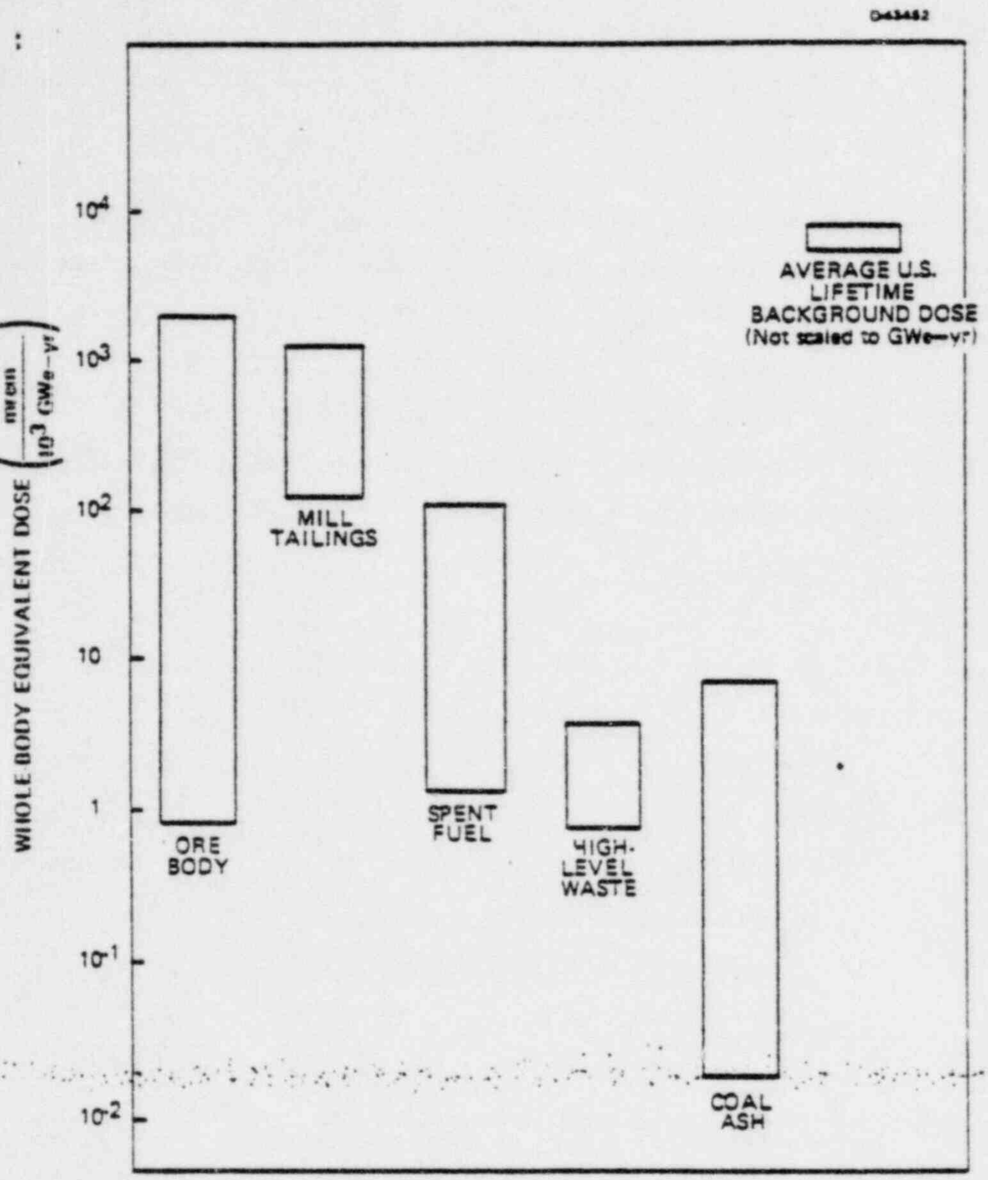


Figure 2.1-3 Maximum Individual Lifetime Dose to the Whole Body from Various Fuel Cycle Sources and from Natural Background

2.1.4 The Natural Waste "Repository" at Oklo

Safe disposal of nuclear wastes cannot be "proved" over the long time periods of potential hazard except by experience. However the adequacy of the geologic disposal concept has been successfully demonstrated. Evidence from the natural uranium reactor discovered in the Oklo uranium mine in the Republic of Gabon clearly indicates that geologic barriers alone, under appropriate conditions, can largely prevent waste release.

The uranium ore body at the Oklo site sustained criticality for almost six hundred thousand years. At the beginning of the chain reaction (approximately 1.8 billion years ago) the ore body was nearly saturated with water. This water which moderated the reaction was necessary to sustain criticality. The reactor [illegible] about 15 GW-yr of fission product "waste" (Ref. 31).

According to scientists who have studied Oklo (Ref. 31):

> "A remarkable aspect of the Oklo phenomenon is that the majority of the ~6 tons of fission products "emplaced" have remained by and large immobile over the period of their half-lives. ... The actinide elements Th, U, Np, and Pu were fairly successfully isolated in the reactor system during and following criticality. ... Thus for periods comparable to the 2.3×10^7 yr half-life of ^{236}U, thorium did not migrate. ... A most important observation of the Oklo system is that the ~2 tons of ^{239}Pu produced via ^{238}U (N,γ) did not disperse."

There is no reason to believe that "Oklo" is in any way unique. In fact repositories for nuclear waste can be expected to offer superior containment as a result of the application of engineered barriers and through judicious choice of a repository site.

2.1.5 Summary

The previous sections have shown that the magnitude of the nuclear waste disposal problem and the difficulties involved in solving it have been greatly overstated. In fact, of all the hazardous wastes routinely produced in the U.S., nuclear wastes are perhaps the most amenable to successful management. The wastes are in a highly concentrated and non-dispersible form; the total volume of waste requiring disposal is relatively small; and a practical technology for handling and emplacing the wastes exists. In addition, the economic costs associated with managing the waste are small, thus allowing an elaborate approach to waste disposal. Confidence that deep geologic disposal will indeed provide adequate safety can be based on comparisons to natural ore bodies. Furthermore, the deep geologic disposal concept has been successfully demonstrated by the containment of waste constituents at Oklo.

It should be stressed that complete containment of nuclear wastes over geologic time is not a requirement for successful waste disposal, and there is nothing special about the nature of the hazard from radioactive wastes to justify such a requirement. The radioactivity emitted from the constituents of nuclear waste does not differ in kind from the sea of natural radioactivity that surrounds all of us. There are large variations in this background radiation, but this fact does not seem to be the cause of any great concern.

The analysis in this section should not be viewed as the complete argument for confidence that nuclear wastes can be disposed of safely. Although the case made is a strong one, it should be taken together with the safety analysis work that is discussed in the remainder of this report. The safety analyses provide the firm quantitative support needed to back up the comparative analyses presented here. The safety analyses show that there are no special characteristics of deep geologic disposal which would invalidate the conclusions drawn from comparative analysis. All safety analyses known to us support the view that nuclear wastes can be safely disposed of in deep geologic repositories.

2.2 UNCERTAINTY IN PREDICTIONS OF LONG-TERM SAFETY

In using any particular risk assessment to judge safety, assurance is required that uncertainties in the results of the study are not so great that the conclusion about safety is called into question. Although more precise uncertainty assessments may be useful for scientific or engineering design purposes, as far as judgments about safety are concerned, uncertainties need only be considered to assure that safety is not in question.

Uncertainties in predictions of the long-term performance of a repository have three principal sources: the scenarios, or possible future sequences of events, which are considered in the analysis; the models used to describe the scenarios; and the parameter values used to calculate results with the models.

In any scientific analysis, the accuracy with which the various relevant factors can be assessed varies widely. Almost always, the dominant contribution to total uncertainty in the results will come from one or a few aspects of the problem. Accuracy improvements in areas other than those which are the dominant contributors to uncertainty will not improve the quality of the final results.

2.2.1 Evaluating Uncertainties

A number of approaches can be used to assure that safety is not in question as a result of uncertainties in predictions of repository performance.

Worst-case analysis - In this approach, extremely unfavorable values are assigned to all uncertain parameters, and unfavorable events are assumed to happen. A convincing worst-case analysis of a nuclear waste repository has been performed by the Swedish Nuclear Fuel Safety Project (KBS) and has shown the repository to be safe (Refs. 5 and 11). A recent review of this study by the U.S. National Academy of Sciences has reaffirmed the validity of its results (Ref. 15).

A common misconception about worst-case analyses is that they can show something to be unsafe. However, worst-case analyses place an upper bound on the consequences of an accident; they do not indicate whether the consequences can approach that upper bound or, if they are possible, how likely such accidents are.

Sensitivity analysis - Some studies (e.g., Refs. 6, 22 and 33) have used sensitivity analysis to assure that results are valid even if parameters are widely varied. Generally, sensitivity analysis is performed by varying parameters singly or in groups and noting how the calculated results change. This permits identification of the variables which most influence risk.

Extreme care, however, is required in the use of this technique to evaluate uncertainty. There are a number of ways in which large changes in output values can be missed, including:

- Failure to sample the entire range of parameters upon which the output depends in a non-linear way.
- Failure to vary all combinations of interacting variables.
- Extension of models to parameter values beyond the range in which the model equations are valid.

Many sensitivity analyses include only a small number of trials and unexpected relationships can be overlooked.

Sensitivity analysis is most useful in cases where only a few parameters are significant sources of uncertainty. This can occur either because these parameters alone determine outputs or because all other parameters have been accurately measured. In such circumstances, sensitivity analysis can be a powerful tool for bounding uncertainty.

Quantitative estimation of uncertainties - A third, more difficult, approach is to estimate quantitatively the uncertainties in results. In this approach, a probability density function is estimated describing the range each uncertain input variable may take. The input uncertainties are used to calculate a probability distribution of repository performance.

For some relatively simple models, analytic formulas can be used to transform input uncertainties into output uncertainties (Ref. 34). Otherwise so-called "monte carlo" methods can be used, as has been done in several cases (Refs. 34 and 35).

In either case, the reliability of the results is limited by the accuracy of the input probability distributions rather than any calculational limitations. Usually, no direct evidence is available to describe the probability density functions and expert opinions must be used. The uncertainty calculation is then an exercise in Bayesian statistics. In one widely held point of view (Ref. 36), Bayesian estimates are simply a description of the state of mind of the experts whose opinions have been consulted. This form of uncertainty analysis might therefore be regarded as a systematic way of using opinions of expert consultants.

2.2.2 Uncertainties in Choosing Scenarios

A critical part of any risk assessment study is its choice of release scenarios. The requirements for justifying scenario choices are indicated in Fig. 2.2-1. The initial step is to present a list of credible scenarios for disruptive events and geosphere transport. These derive from reference to previous studies of disposal risks, from expert opinion, and from predictive analysis of the repository system. The latter would include, for example, heat transfer studies, stress analysis, and prediction of occurrence rates for geologic phenomena. Long lists of possible scenarios are given in Refs. 12, 37 and 38.

It is possible to drastically reduce this list so as to allow detailed analysis of the most important failure modes. Two valid methods are available for eliminating scenarios from consideration:

- The expected risk (probability times consequence) is computed and found to be extremely low.
- The consequence of a given scenario is much less than the expected consequences of other scenarios. Therefore, it is shown that even with a probability for occurrence of unity the scenario will not contribute significantly to the total risk.

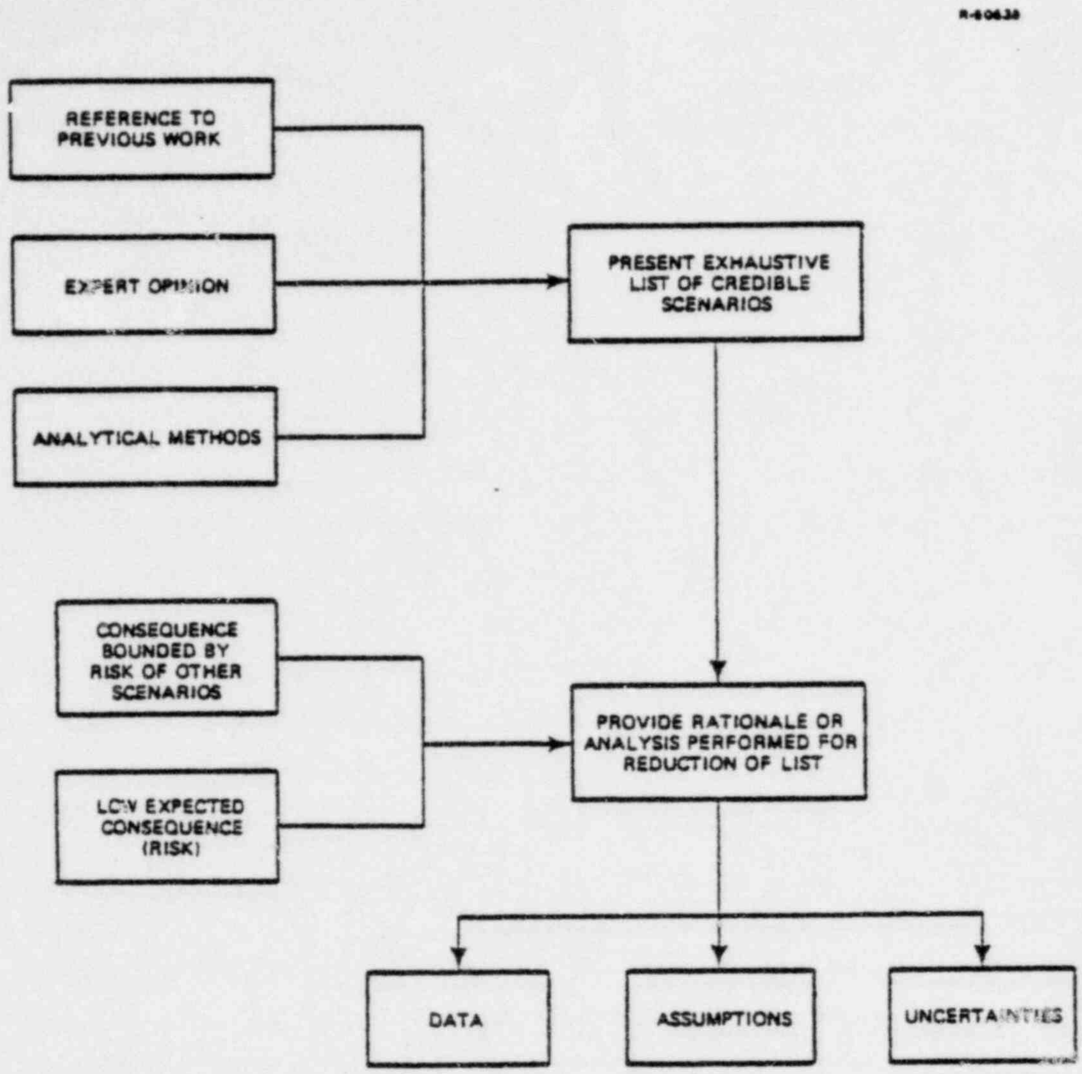


Figure 2.2-1 Requirements for Justifying Scenario Choices

It is possible to further reduce the list of scenarios by aggregation of scenarios which have different causes but similar consequences. The draft WIPP Environmental Impact Statement (Ref. 12) provides an example of this procedure. In many cases, especially when groundwater migration is involved, a large number of scenarios have the same pathways for transport of radioactivity even though the processes which cause those pathways to open may vary widely. The values of parameters describing the pathways do differ in the various scenarios, although often uncertainties in these values are so large that the cases cannot be distinguished. In such circumstances, a single analysis can cover all cases which involve the same set of pathways. The analysis can be either a worst-case analysis of the scenario with most severe consequences or a sensitivity analysis covering the range of credible parameter values.

By using these methods as part of a careful scientific and engineering effort to conceive of all scenarios, it is possible to produce a suitably complete but manageable list of scenarios for analysis. To be sure, one can never be certain that a list of scenarios is complete. The inability to distinguish fundamental forces which control geologic processes makes it more difficult to anticipate scenarios. But in no issue which society faces is absolute certainty about the future possible. The scenarios which could affect a nuclear waste repository have been thoroughly enumerated (see Section 2.3), and analysis of them provides an adequate basis for action.

2.2.3 Modeling Uncertainties

On the basis of the postulated scenarios and available data, mechanisms for waste transport to the biosphere must be described. First one must consider those predictable physical processes to which the waste is subject. These processes are governed by relevant scientific principles. For example, waste-rock interactions are described in terms of geochemistry, diffusion of heat, and radiolytic effects. Transport of dissolved materials in convective-diffusion waste systems must be evaluated. The response of rock formations under conditions of elevated temperature and stress needs to be examined. The input-output response of biological entities to the chemical forms corresponding to radioactive waste components is also a necessary area of investigation. In sum, a wide variety of basic scientific principles have to be brought to bear on this subject.

The primary result of exercising the fundamentals of physics, chemistry, and biology is the development of analytic methods, models that can predict the behavior of the environment in response to the emplacement of waste in a repository. (Models can also be phenomenological and not based on fundamentals). Typical analytic methods provide information on rock temperature-time histories and concentration distributions of waste isotopes in water systems.

Models can be a source of uncertainty in either of two ways. First, questions can exist about the completeness and accuracy of the scientific principles used to describe repository behavior. Second, the analytic methods used to solve equations almost always involve numerical approximations and computer programs. Uncertainties can exist about the accuracy with which the fundamental equations have been solved. The process of assuring that neither of these sources has introduced unacceptable errors is known as model validation.

Uncertainties in scientific principles - In most scientific fields relevant to nuclear waste disposal safety assessment, the fundamental scientific principles are well understood. The principles of radioactive decay, heat conduction, and fluid flow, for example, are very solidly established.

In some other areas, such as the transport of dissolved contaminants in dispersive media and the mechanical properties of rock around mine openings, uncertainty about underlying principles does exist. In most of these areas, however, phenomenological models -- models which assume or infer relationships among system variables and empirically relate the parameters -- can provide adequate predictions. For example, mines have been built safely for many years using empirical equations (Ref. 39) even though the underlying principles of rock mechanics are difficult to model. Similarly, the transport of radionuclides in groundwater has been successfully modeled (Refs. 40 and 41) even through the scientific basis of the equation used is in dispute.

There are three areas in which lack of complete scientific understanding does contribute significantly to uncertainties in risk assessment: sorption, or chemical interactions between radionuclides and geologic media, groundwater flow in fractured media, and leaching of solid waste forms. While the scientific principles governing behavior are well understood, and a large amount of experimental data is available, the experiments have not been fully correlated with the underlying principles, and care is required in extrapolating experimental results. Even here, however, it is possible to limit uncertainties through conservatism in analysis, through testing, and through carefully engineered design of a repository. For example, uncertainties in sorption can be reduced both by conservative application of test results and by using chemical additives in backfill to control groundwater chemistry (Ref. 11). These topics are discussed further in Sections 3.1 and 3.3.

Uncertainties introduced by numerical methods - The equations governing many physical processes relevant to waste disposal are too complex to be solved exactly. Approximate solutions must be obtained, usually with the help of a computer. The approximations which must be made to obtain computer solutions can introduce errors into results. For example, "numerical dispersion" and other problems can affect finite element solutions of the solute transport equation (Refs. 42 and 43). Additional inaccuracy can result from programming errors.

Quality assurance and validation procedures are used to control these types of uncertainty. For example, results of computer analyses of simple cases are compared with more approximate hand calculations or with other computer analyses to detect errors. An example of such work, in which small error in previous work was detected, is given in Ref. 44. In one case, two analyses of a complete repository system and environment were conducted using two almost entirely different computer codes (Ref. 45, pp. 143-147). The results, which were in excellent agreement, indicate that errors due to numerical methods are not a major source of uncertainty in the results of the two studies.

It can be safely concluded that numerical error is not a significant contributor to uncertainty in repository safety analyses compared to other sources of error discussed in this section. To be sure, individual studies could contain large errors (for example, see Ref. 1, Section 3.8). However, the better established models have undergone repeated peer review, as illustrated by Refs. 1, 16 and 46, and it is quite unlikely that significant numerical errors remain in the codes.

Model validation - Model validation procedures have become accepted as standard in many areas of mathematical modeling (see, for example, Ref. 47). However, it is important to remember that model validation is not an end in itself, but a means to be more confident that model predictions are correct. The validation of nuclear waste management models should be viewed from this perspective.

In general, the ideal form of model validation would be to observe the predicted behavior and confirm that observation and prediction agree. However, the objective of predictive modeling is to anticipate results which have not yet been observed.

Predictive modeling is directed at using observations to make inferences from phenomena which have not been observed. Such inferences are, to be sure, more reliable when the phenomena to be predicted closely resemble those which have been observed, i.e., when the same scientific principles apply. Confidence in a model rests on the correctness of the scientific reasoning which justifies that inference and not on the nature of any particular observations which may have been made. As shown elsewhere in this document and its references, it is only the model interpretation of key scientific principles concerning disposal safety that is disputed. For this reason, the opinion of the California Energy Commission (Ref. 48) that demonstration of repository safety is intrinsically impossible without field tests has no logical (i.e., with respect to principle/model relationships) foundation whatsoever.

Because repository models must predict performance far into the future, field observations cannot extend over all time scales in the models. Validation therefore cannot be conceived as a straightforward replication of model predictions. Rather, it must rest on an accumulation of evidence of various kinds in much the same way as the proof of a scientific theory. Among the issues which must be addressed in the course of model validation are:

- Proper interpretation of existing data
- Accurate computational methods
- Adequate knowledge of the system or geometry modeled
- Accounting for all relevant phenomena
- Confining input parameters to regimes in which the models are valid.

IMAGE EVALUATION
TEST TARGET (MT-3)

6"

MICROCOPY RESOLUTION TEST CHART

Although the nature of the validation procedures will vary among different models, the importance of validation cannot be underestimated. A mathematical model by itself is nothing more than an assertion. Only if properly validated can it be used to show a repository is safe, or indeed to make any predictions at all.

How do we accomplish model validation? The answer for long-term disposal safety models is by (1) distinguishing actions that can and cannot be taken to accomplish validation; (2) performing those actions (experiments) that will definitively contribute to validation; (3) bounding, by analysis, the effects, on model-based predictions, of factors that cannot be experimentally verified; and (4) subjecting all of the above to comprehensive peer review. More detailed discussions of these activities are given in succeeding sections and in Ref. 1.

2.2.4 Uncertainties in Data

The data required to analyze the long-term safety of nuclear waste repositories consists of diverse elements that can conveniently be placed into two categories. There are measurable data which can be derived from laboratory or in situ experiments, or from studies of events in recent history. Here, analysts are working with the relatively known elements of the system, such as creep rates of salt at elevated temperatures. This area is a safe one for technologists and the usual questions of detail and precision of observations can be applied, i.e., the amount and reproducibility of the information to be obtained can be evaluated.

Perhaps a more critical portion of the data base is that containing immeasurable data. This category consists primarily of information about the ability of the repository and the surrounding geology to contain wastes at future times and the future behavior of individuals and populations. For instance, estimates must be made of the occurrence of disruptions of the local geology and hydrology due to earthquakes and glaciation based on past data, and of rates of natural processes. Certain assumptions are also necessary to provide scenarios for human intrusion into the repository and for human food and water utilization. A typical assumption is that future human behavior will be like today's.

Although there are uncertainties associated with the measurable elements of the data base, they are small relative to the uncertainties inherent in the immeasurable data. It is important to recognize the category to which each type of information input to analytical models belongs and whether it is measurable or immeasurable data that controls the accuracy of model results. Excessive precision of measurable data often is not warranted because of the rough assumptions contained in other aspects of the model employed.

At present, several approaches to estimating immeasurable data elements are available:

- Obtain a consensus of "experts" by Delphi or other techniques. The results may have a higher information content and less bias than the opinion of a single researcher.
- Rely on engineering judgment provided by highly experienced, qualified individuals.
- Assume current conditions and behavior can be extrapolated to the future. This assumption represents a scenario where nothing occurs save predictable physical and biological processes. It serves as a sensible baseline for risk calculations.

- Develop a model for simulation of future scenarios including both geologic and man-caused phenomena. A model for this purpose is being developed in the Waste Isolation Safety Assessment Program (now AEGIS), Ref. 38. This model produces sets of potential future geologic and hydrologic state descriptions with estimates of occurrence probabilities. Uncertainties and subjective estimates are handled with probability density distributions.

- Provide upper bound (worst case) estimates of parameters. Here the intent is conservatism, and the method is an excellent one if calculated risks are still insignificant.

- Draw analogies to other technological problems, especially those involving public risks and hazards.

2.2.5 Relative Importance of Different Sources of Uncertainty

Uncertainties in the different aspects of waste management safety assessment differ greatly in magnitude and importance. Many widely cited uncertainties are in fact irrelevant to the determination of whether waste disposal systems are safe. In this connection, the following general conclusions concerning the relative importance of different uncertainties can be drawn:

- The specification of the system design and most areas of basic scientific understanding do not make large contributions to overall uncertainties in estimated risks. Therefore, efforts to sharpen our insights in these areas are unlikely to significantly improve the accuracy of risk analysis results.

- In the areas of sorption, groundwater flow in fractured media, and leaching, an improved scientific understanding would be helpful. However, adequate models can be developed on a phenomenological basis.

- The least certain of all the risk assessment elements are the scenarios for loss of containment and isolation and the immeasurable data, both of which depend on the ability of the analyst to account for future events of a disruptive nature in his risk assessments. There always remains doubt whether all important disruptive events are included.

The principal efforts of the risk assessment community ought to be addressed toward the open questions of scenarios and immeasurable data, which are the dominant sources of uncertainty in risk assessment results. No more than reasonable technical competence should be expected from the model development and data measurement phases of risk assessment. Analysts and experimentalists alike are prone to seek improvements in their respective disciplines, but greater accuracy in these relatively well understood areas contributes little or nothing to our understanding of the overall performance of the repository system.

Predictions of the detailed evolution of a repository can not be made with certainty. But uncertainty in what will happen to the repository is not the same as uncertainty about whether the repository is safe. Uncertainties about events and processes occurring in a repository may

- Concern phenomena which have no bearing on repository performance,
- Concern relevant phenomena, but be of negligible magnitude, or
- Contribute significantly to uncertainties in system performance.

Only uncertainties in the third category are of any concern, and several methods (described in Section 2.2.1) are available for ensuring that they do not impair safety. Most of the frequently cited uncertainties fall into the first two categories and are irrelevant to the question of whether a repository is safe. More than enough is known now to provide great confidence in the safe geologic disposal of nuclear wastes (see Chapter 3 for discussion of the technical basis for confidence in long-term safety).

2.3 SCENARIOS AFFECTING MAINTENANCE OF DISPOSAL SAFETY

It is conceded by even the most vociferous critics that high-level waste repositories can be designed in such a way that radioactivity will be contained as long as nothing untoward happens to the repository. Safety analysis of a repository is therefore focused on scenarios involving natural events or processes or human actions which reduce its effectiveness. These are known as release scenarios.

2.3.1 Natural Release Scenarios

A wide variety of means have been hypothesized whereby radioactivity might be released to the surface without the aid of any human action. Exhaustive lists of such scenarios have been compiled in Refs. 12, 37, and 38. Generally, the causes of release fall into three categories: processes induced by the presence of the repository, slow processes proceeding from causes external to the repository, and sudden cataclysmic events.

The only natural cataclysms identified to date as being severe enough to cause a sudden release of radioactivity are an impact by a large meteorite and volcanic action. These scenarios were analyzed in the earliest attempts at repository risk analysis (Ref. 49) and found to have an extraordinarily low probability. The same events have been reanalyzed since (e.g., Ref. 50) and the same conclusion reached. The proper evaluation of these events has been well stated in Ref. 1 (p. 3-52): "The consequences of a catastrophic release have already been well addressed by Claiborne and Gera and their work needs little further refinement. Such events, therefore, should be dismissed out of hand."

Slow processes, whether or not repository-induced, are of concern to the extent they facilitate the release of radioactivity by way of groundwater transport. Two means of release other than groundwater transport have been suggested: exhumation of the repository by erosion and gas-phase transport. However, neither of these is of significance if even a modicum of effort is made to choose a reasonable site. Erosion by water, even at the rate at which the Grand Canyon was excavated, will not uncover a repository within a million years if it is built a half-mile deep. (See accompanying report, Ref. 21.) Areas subject to severe erosion by glaciers can be avoided either by choosing climates not subject to glaciation or else by appropriately choosing the topography of the site (Ref. 38). Gas transport is not of concern for repositories located below the water table (the overwhelming majority of proposed concepts) because the radioactive gases produced in a repository are small enough in quantity to be easily dissolved by groundwater (Ref. 51). Buildup of non-radioactive gases requires further investigation; however appropriate design features should eliminate this problem if it arises at all (Ref. 52). If a repository were to be located above the water table (the "vadose zone" concept), gas transport would require further investigation; however those who have investigated the concept to date have felt that groundwater transport is the principal means of release to be considered (e.g., Ref. 53).

For groundwater transport to be a potential means of release of radioactivity, three elements are required: the presence of water, a pathway for its movement through the repository, and a driving force to cause movement of water. Sites can be found at which one or more of these elements are absent at present. However, groundwater conditions can be affected by a wide variety of processes and events. These include alterations in rock near the repository due to repository construction, degradation of engineered seals, and changes in regional hydrology due to topographical alterations, climate change, and glaciation. The potential for and consequences of migration of radioactivity in groundwater should be the principal subject of safety analyses of particular repository sites. The existing knowledge about groundwater transport, which gives us confidence that a successful repository site can be found, is discussed in Chapter 3 of this document.

2.3.2 The Contribution of Siting and Design to Safety

Discussions of nuclear waste disposal have, with very few exceptions (Refs. 5, 11, and 12), focused on generic safety analyses rather than discussions of specific, well characterized sites and designs. In these generic discussions, a wide variety of hypothetical mechanisms and scenarios for the release of radioactivity have been proposed. Very often, although it may be impossible to rule out the proposed release mechanism at the generic site under discussion, appropriate siting or design features can make the mechanism entirely impossible or of no consequence.

Thermally induced phenomena are a particularly large group of release mechanisms. The decay heat produced by wastes could lead to thermal expansion of rock, brine migration, reduced rock stength, release of water of hydration, accelerated corrosion of canisters and waste forms, and a variety of other physical processes. Some of these processes are well understood, while the fundamental mechanisms of others are yet to be fully explained. All of them must be carefully evaluated in the course of designing a particular repository. However, none of them can in any way cause doubt about the ability to dispose of wastes safely.

These phenomena cannot make safe disposal of waste impossible because they are all functions of the temperature of the repository. A repository designer can choose whatever temperature he wishes by, for example, adjusting the spacing of the canisters. The designer must first conduct studies to determine the temperature at which thermal effects could interfere with repository performance, and then select a canister spacing which holds temperatures safely below this threshold. Such procedures are regularly included in repository development programs (Ref. 54).

Other release mechanisms can be mitigated by adding special design features. For example, the failure of borehole seals will be of little consequence if the boreholes are isolated by leaving large unexcavated pillars around the boreholes on the repository level (Ref. 55).

The Swedish Nuclear Fuel Safety Project (KBS) has devised a number of design concepts which eliminate potentially dangerous scenarios (Refs. 5 and 11). Among the release mechanisms mitigated in this way are:

- Loss of effectiveness of geochemical retardation or increased canister corrosion due to changes in groundwater chemistry. Oxidation potential of the groundwater in the repository is controlled by adding 0.5% ferrous phosphate to the backfill.

- Direct contact of water in rock fractures with waste canisters. The canisters are surrounded with a cylinder of dry bentonite, a low-permeability clay which expands when wetted. The expansion will force clay into any cracks in the surrounding rock.

- Acceleration of canister corrosion by radiation through creation of chemically active species. The canisters are heavily shielded.

- Rapid migration of wastes through the backfilled repository corridors. The backfill is a mixture of sand with bentonite, which has low permeability and a strong tendency to sorb radioactive ions chemically.

The literature of nuclear waste disposal encompasses a wide variety of processes and phenomena, not all of which are well understood. It is often alleged that "gaps" and "uncertainties" in our knowledge of these phenomena must be eliminated before confidence in safe disposal of wastes is possible. As the above examples show, many imperfectly understood processes can be avoided by incorporation of mitigating features into the site selection and repository design process. While further research to close the "gaps" may in some cases be useful for the purpose of allowing less expensive repository designs, safe disposal is possible without reliance on such research. Most of the so-called "gaps" and "uncertainties" are entirely irrelevant to the question of whether wastes can be disposed of safely, as discussed in the Disposal Capability Document, Ref. 21.

2.3.3 Release Scenarios Involving Human Action

As long as active surveillance of a repository site is maintained by DOE or successor organizations, it is extremely unlikely that the repository could do any harm to human life even if some presently unforeseeable mechanism should cause a significant release of radioactivity. Contamination of potable groundwater would be quickly detected and possible human use could be prevented either by administrative controls or by corrective measures such as interceptor wells.

Even if active control of the site were to stop, harm would likely be avoided as long as the repository's existence were known. Sensible people would not use nearby ground and surface waters unless they had been tested for radioactivity. The foolhardy might be able to hurt themselves by drilling wells into potentially contaminated aquifers or even by penetrating directly into the repository itself, but there are far easier ways to injure oneself by use of heavy drilling equipment.

Nearly all analyses of repository safety to date, including all of those discussed in Ref. 1, assume implicitly that all knowledge of the repository's existence is lost. EPA has even proposed that repository designers be required to assume such a loss of knowledge after only 100 years. Such an assumption is extraordinarily pessimistic, as is shown by the brief historical discussion in the next section. More importantly, it shows a lack of perspective on the significance of nuclear wastes to human existence.

The sort of catastrophe which would obliterate knowledge of the repository's location would, of course, obliterate the location of nearly everything else. Hazardous chemical wastes, often dumped near the surface, would be far more accessible to primitive farming implements likely in use after the catastrophe than a deep repository. Abandoned mines would pose a far greater danger of polluting ground and surface waters, not to speak of unexpected cave-ins.

There is, indeed, a wide variety of information that will be of far greater value to the survivors of a global catastrophe than the location of nuclear waste repositories. To begin with, knowledge of how to detect and evaluate radiation sources would make it possible to avoid (if they wished to do so) not only the repository, but also a large number of far more dangerous natural sources of radiation. Even more valuable would be a knowledge of how to use nuclear (and other) fuels to produce useful energy, thus making it possible to recreate a technological civilization and extend their life expectancy by decades. Valuable as well would be knowledge of where reserves of oil and coal have been left behind, if any. In short, when our descendants think about what we have left for them and what we have used up ourselves, nuclear waste repositories will be a very minor item.

2.3.4 Continuity of Human Records

In the course of human history, a remarkable record has been established of continuity of knowledge of languages, facts, and specific locations. It cannot, of course, be guaranteed that the location of a repository will be remembered. But almost all decisions made by society have implications for the future, and the future can never be guaranteed. It is possible to examine the historical record and learn that only an extraordinary world-wide calamity would be likely to cause loss of knowledge of a well-marked repository location. This discussion restricts itself to literate cultures, since the culture which will build the repository belongs to that class.

A century is only a 2% increment in the time period for which mankind has been writing down contemporary information. (The earliest written records date to c. 3000 B.C. from Egypt and Mesopotamia.) A century in our own country's history brings us back to the period of the Civil War. Sherman's march to the sea destroyed everything in its path but Atlanta was rebuilt and not forgotten. The San Francisco earthquake is an example of extensive destruction by natural forces, yet that city is also flourishing today. Two centuries brings us back to the period of the Revolutionary War. Boston and its environs still contain many buildings, including private homes for which the title has been established, which date to this period.

England is an example of a country which has been invaded (in 55 B.C. by the Romans and 1066 A.D. by the Normans), bombarded (in WW II), and torn apart by internal strife by factions contesting for the throne. Yet Cambridge grew out of the Roman town of Cantabrigia, and it is not uncommon to find houses, pubs and castles several centuries old. The Public Records Office in London holds, among other items, the "Domesday Book", a statistical census and survey ordered by William the Conquerer in 1086. The four extant copies of the Magna Carta signed by King John in 1215, are located in the British Museum, Salisbury Cathedral and Lincoln Cathedral.

This brings us back to the "Middle Ages" of Europe, often dated from the deposition of the last emperors of the Western Roman Empire (476 A.D.) to the sack of Constantinople by the Turks (1453 A.D.). During this time, Rome and what it stood for was not forgotten, although the area was avoided for many centuries because it was malarial. The Acropolis of Athens was never forgotten. The first part of this period, the "Dark Ages" of Europe, corresponds to the rise of Islam and the flourishing cultures of the Abbasid and Umayyid dynasties (722-1258 A.D.). Much of Greek philosophy was preserved in Arabic translations and commentaries written during this period. In other words, the "Dark Ages" were a local phenomenon restricted to Europe.

The wealth of knowledge concerning the ancient Greeks and Romans has already filled thousands of volumes of history, archaeology, and literature. These cultures provided foundations for our present day Western societies and the languages never really went out of use. This knowledge has been preserved even though printing - let alone xeroxing - was unknown and all copies had to be made by hand.

Earlier languages, such as those in Egypt and Mesopotamia, were temporarily lost because no records were kept when they were replaced. The Romans supplanted the Etruscans, and while we can't yet read Etruscan, we can read the much older Sumerian language. The latter language hasn't been used as a living language for about 4,000 years, but it can be read because the Akkadians (Semitic-speaking people who conquered Mesopotamia about 2300 B.C.) wrote Akkadian-Sumerian dictionaries. In addition, the language continued to be used in religious ceremonies and texts for a longer period of time, much as Latin continued in use (until very recently) in the Roman Catholic church.

The histories of Egypt and Mesopotamia are well enough known that at points the difference of one year in a king's reign can create scholarly arguments. Even when the name of a king was intentionally obliterated from all the records by his successors for religious reasons, much information has been recovered. Such a situation happened with Akhenaton, king of Egypt from 1375-1353 B.C. His son (and/or grandson; this point is disputed) was Tutankhamun who reigned for nine years and died when he was nineteen. Yet all that was required to find his tomb was a systematic search of the valley where the other kings of that period were buried. The fact that it was almost unlooted was a hoped-for, but unexpected, surprise.

There are things we know are missing. We will never find Solomon's temple in Jerusalem because whatever traces remained were obliterated when Herod cleared the area down to bedrock for his temple, but the site has never been forgotten. Herod's temple, which was sacked and burnt by the Romans in 70 A.D., still has the retaining wall surviving today. It is known as the Western or Wailing Wall of Jerusalem.

The thread running through the examples cited above is that records can and do survive. Much information has been lost, however, because contemporary records were never kept at all. The conscious making of records at and about the repository and the wide dispersal of that information increases the probability of survival of that information. There is no evidence in past history of a world-wide "blackout" of knowledge, only local disruptions. A scenario which describes such a wide-spread destruction of knowledge is one of such cataclysmic proportions that the additional loss of the repository's location would be negligible.

It follows that an assumed loss of administrative control at 100 years is conservative in the extreme. If control or knowledge is maintained for 300-500 years, which history indicates is reasonable to expect, the waste will then not differ significantly from a natural ore body.

2.4 TESTING AND RESEARCH AS A MEANS FOR IMPROVING CONFIDENCE

Although it is widely held in the technical community that deep geologic disposal is safe and feasible, how the nation should best resolve the technical uncertainties that do exist is a matter of political dispute. One of the central subjects of this argument is whether further testing and research are needed to attain sufficient confidence in our predictions of long-term public safety from deeply buried nuclear waste materials.

Three different currents of opinion seem to exist on this subject. They may be summarized as follows:

- Current knowledge is adequate for confidence in the safe disposal of nuclear wastes. Site characterization and selection can now begin, in parallel with a program of research and testing aimed at optimizing waste forms, site selection, and repository design.
- As far as we can tell at present, safe disposal of nuclear wastes is possible, but an extensive program of fundamental research in materials and earth sciences is needed before we can be sure.
- No one can tell whether wastes can be safely disposed of until <u>in situ</u> vault tests have been performed.

The purpose of this section is to discuss each of these approaches and thereby attempt to delineate the important issues involved with defining an adequate waste management research and testing program in the U.S.

The third opinion has been espoused most notably by the California Energy Resources Conservation and Development

Commission (Refs. 48 and 56). The contention of that commission is: demonstration of geologic disposal is a necessity and demonstration cannot be achieved by mathematical modeling techniques unless there is direct experimental verification. Their logic is summarized in the following quotes (from Ref. 56):

> "A proposed California approach recognizes that safety of geologic disposal has not been demonstrated largely because of major knowledge gaps, identified earlier, in the earth science and the materials science disciplines which are sufficiently large and important that they have prevented the development of a high enough level of understanding to establish the feasibility of the geologic disposal concept. These knowledge gaps can be removed, and the related elements of a social consensus achieved, only by a rigorous experimental program."
>
> "Scientists working in waste management have stressed the importance of in situ rather than laboratory experiments to remove these knowledge gaps."
>
> "Vault tests are the most sophisticated of the in situ experiments."

To the Commission, the value of vault testing is contained in these items:

- Vault testing will provide rock mechanics data useful for repository construction and operation; and
- Vault testing is one of the necessary elements of establishing technical and public credibility in the geologic disposal concept.

The Commission recommends that vault tests be conducted in at least two different media with a minimum of two sites for each medium selected. Further, the tests are to last several years.

This point of view is based on a misunderstanding of the scientific method which has led to an obsession with the form which tests take and a disregard for their substance. Repositories must perform for hundreds of years or longer; assertions about their performance can only be based on scientific models and not on direct observation. As discussed in Section 2.2.3, scientific predictions always rest on inferences from the known to the unknown. Confidence in nuclear waste disposal rests on the large body of scientific and engineering knowlege discussed in Chapter 3. It no more requires vault testing than confidence in Copernican celestial mechanics needed to await the launching of artificial earth satellites.

Vault tests are not only unnecessary, but in fact largely irrelevant to the demonstration of long-term safety. As the California Commission recognizes, the tests' only value is to describe near-field phenomena. This data is primarily of use for design of the repository and preventing mining accidents while it is in operation. Long-term safety analysis depends on knowledge of waste form performance and geohydrology. These area are well enough understood to allow confidence in predictions. Certainly, data must be collected in situ before a specific repository site can be approved. But the existing scientific knowledge of geology is already based largely on direct in situ observations of the earth. This knowledge clearly indicates that acceptable sites can be found.

A further argument against the California approach is that it is a costly one, both in terms of dollars and technical resources, and is one that would delay ultimate disposal. The commandeering of these resources, in fact, might result in less confidence in the long run if important research areas are neglected.

This rebuttal leads naturally to the second opinion. Proponents of this view may be said to wish to see the multi-barrier concept (see Section 3.2) carried to an extreme. A waste management program oriented in this direction allows various researchers to bear heavily on a particular aspect of containment that is within their interest. The goal for the individual researchers is to better understand their areas of expertise and to optimize their application to waste management. Collectively, the entire program creates a defense in depth, a collection of individually optimized and fully understood barriers to prevent radionuclide transport to the biosphere. The desired full understanding involves not only the individual barriers, but the interactions between them as well.

The attitude described is most prevalent in two areas of technical expertise: the earth sciences area and the waste form development area. In the earth sciences, laundry lists of areas for further research have ranged from the fundamental mechanisms of sorption in clays to development of new remote exploration techniques. Materials science topics on which further research has been demanded include such items as the precise structural location of radionuclides in waste after reaction with cement and materials design for greater densification of spent fuel storage. In reports by scientists working in these areas there are constant recommendations for intensive research in the authors' areas of expertise. Such commentaries decry the present state of knowledge as being incomplete and fraught with uncertainty as at least a partial justification for their research recommendations.

The issue, as we see it, is not strictly whether these groups are correct about the desirability of more research in these areas; certainly the scientists involved are competent and able to assess what they know and what more they would like to know. The question to be answered is more nearly that of whether the unknowns are important to waste disposal. Scientists have a natural tendency to work on topics of interest. Judgments must be made whether recommended work reflects waste management needs or researchers' curiosity and personal priorities.

It is necessary to distinguish among types of research which

- Might be necessary to determine whether safe disposal is possible
- Are needed to determine details of waste forms, site selection, or repository design
- Would be useful to improve repository performance or reduce costs
- Are chiefly of academic or scientific interest.

As the rest of this document demonstrates, enough is already known to conclude that safe disposal is possible. The research projects proposed by the adherents of this current of opinion fall into one of the three other groups. Policymakers should distinguish carefully among them, in order to develop an effective R&D program without unnecessarily delaying repository development.

The key issue here is understanding what purpose any given research project will serve. It is particularly important to understand that development of an acceptable repository need not -- indeed, cannot -- await the development of the "ideal" repository, as proposals for new research projects will continually promise. This issue is treated in greater detail in the next section.

Finally, we come to the first opinion, which embodies the most confidence in safe disposal with current knowledge of any of the options. This is the approach recommended by the IRG report:

> "Current knowledge is adequate to proceed with site selection and characterization, and it appears that this can ultimately be followed with underground disposal of radionuclides with a high probability of successfully isolating them from the biosphere for many thousands of years."

With regard to resolution of uncertainties, the IRG makes the following observations:

- "Current emphasis is on the system comprising the entire hydrogeologic and geochemical environment and on the multiple barriers that it provides"
- "Not everything has to be known about all parts of the system at each potential repository site in order to have confidence that the system will provide adequate isolation"
- "The pertinence of some gaps in our knowledge will likely be resolved during construction and operation of a repository"
- "The detailed effects of thermal loading of a repository are currently uncertain but can be dealt with. Thus the most likely perturbation of the natural environment surrounding the repository can be successfully dealt with."

The IRG report in its attempt to resolve waste management uncertainties does not slight the work advocated under the second two options. Quite to the contrary, it states:

> "Active research and development programs are underway or planned. Consequently, understanding of the relevant hydrogeology, geochemistry, rock mechanics, and risk assessment should increase rapidly in the next few years. In situ testing and the construction and operation of even a small facility for several years would likely resolve certain questions, and would permit the testing of new methodologies that are being developed for site characterization. The validation of rock mechanics models and evaluation of important hydrogeologic factors must, of course, be undertaken at a potential repository site, not through generic studies."

The first opinion constitutes the best consensus of the technical and political community who feel that the job of deep burial can be done and that we should proceed in that direction. Their opinions encourage much of the work recommended by others, namely intensive research projects and in situ vault testing, not to demonstrate the safety of waste disposal or as ends in themselves, but rather to serve as useful input information for repository siting and design. Further justification for advocacy of this approach will be found in Section 2.5 and Chapter 3 of this document, which, as will be seen, emphasize the high confidence level that can be associated with current waste management technical understanding and overall systems strategies.

2.5 SAFETY PERFORMANCE OF ALTERNATIVE DISPOSAL SYSTEMS

2.5.1 Introduction

The goal of nuclear waste disposal management is to design, construct, and operate repositories which do not put the public health and welfare at unacceptable risk. This seemingly straightforward statement of purpose suffers from the ambiguity inherent in the notion of acceptable risk. The problem of exactly defining what risk is acceptable (c.f., Chapter 1 and the Disposal Capability Document) may never be satisfied explicitly but will evolve from actions of various regulatory agencies and political institutions. The one certainty about the definition of acceptable risk is that if repositories are to meet it then some level of risk must be accepted for them. The operation of a nuclear waste repository, like almost any other modern technology, cannot be totally risk free.

There are two ways to approach the problem of defining acceptable risk. One approach contends that for the good of the public, both now and into the far future, the disposal system must reduce the risk to as low as possible. This contention is very attractive to regulators and technologist since it offers the temptation to design the "perfect" repository system by eliminating every source of technical uncertainty prior to construction and operation of the repository. It also promises to provide the ultimate in safety for the public: only the best components imaginable can be accepted for the disposal system so the risk is minimized.

The other approach to the definition of acceptable risk is to choose a well defined standard of safety for repository performance and to demand that repositories meet or exceed this standard. This method of defining acceptability is commonly used by, among others, the Environmental Protection Agency in the regulation of industries which produce harmful by-products. It is an attractive option because regulatory agencies have a great deal of experience in setting safety standards and can enforce compliance based on the standard which is assumed adequate to protect the public from significant harm.

The two approaches are sometimes used in tandem. If several possible repository systems were shown to meet the standard then it might be argued that the least harmful system should be constructed since it minimizes risk among the possibilities. Further, it can be argued that the "best" repository can only be achieved by choosing from the available systems the best site, the best repository design, the best waste form, and the best waste form packaging. In sum, the "best" achievable repository is the one containing exclusively the best components.

The principal contentions of this section are that:

- The concepts of "perfect" or "best" disposal system are unattainable and may be counterproductive to the waste management goal
- The systems approach with a well-defined standard of safety is the best means for achieving the waste management goal.
- Using the systems approach, various alternative systems can be engineered to levels of predicted safety performance which are acceptable.

2.5.2 Perfect Is Not Good Enough

Perfect repositories, like perfect marriages, are made in heaven. On earth the goal of perfection has been sought by many with few, if any, successes. This failure to succeed is almost certainly due to the ability of humans to imagine improvements in almost anything. Thus, if a very good disposal system is proposed, one has only to imagine an improvement and the goal of perfection has been thwarted. Consequently, the one certain cost of a search for the perfect repository is time, a very great deal of time.

The goal of nuclear waste management -- to design, construct, and operate an acceptable repository -- should not require an excessive amount of time. Sufficient time does exist for a careful and systematic design process, but unlimited delay cannot be accepted before the construction and operation phases begin. It is doubtful that the search for perfection is compatible with the primary goal of the exercise: the timely, safe disposal of high-level radioactive wastes.

As was pointed out by Commissioner Kennedy of the NRC (Ref. 22), the "perfect" repository is, at best, an illusory goal. Waste disposal technology is a new and burgeoning field of knowlege. It will require about 10 years to construct and begin to operate a repository. In that period of time "one cannot attempt to freeze a rapidly developing technology without the risk of some obsolescence". Consequently, today's "perfect" repository is almost certain to be superseded by the natural growth of knowledge before it begins operation.

Thus, the notion of a "perfect" repository is both unattainable, and at variance with the goal of waste disposal.

2.5.3 "Why Not the Best"

If the perfect repository is not a viable objective, it is natural to consider next the concept of the "best" achievable repository -- that waste disposal system whose components are each individually the best. This concept of "best" has great appeal to the public because it sounds like a waste disposal system with minimal risk and avoids the unrealistic goal of perfection.

However, the best repository concept suffers from a defect similar to the perfect repository: the passage of time will undoubtedly result in improvements which will supersede the designation of best. It is generally accepted that several repositories will be necessary and the times of the initiation of their construction will stretch over a period of many years. Because of improvements from the increasing store of knowlege, it is natural to expect that the newer repositories will be better than the older repositories. Hence, it must be assumed that some repository will have been built which either puts the public at greater risk than the others or does not take full advantage of new discoveries. In the first case, provided that the higher risk repositories are acceptably safe, no reasonable person would contend that they be replaced; in the second case, the concept of maximum care for the public well-being would be ignored. The conclusion to be drawn is that the "best" repository concept inevitably leads to the construction of repositories which are not the "best", but which are environmentally acceptable. Thus, the "bottom line" for repositories is not whether they are the best, although it is comforting to think that the best available repository will be chosen at the time, but whether they meet acceptable standards of safety.

None of the above obviates the value of choosing a repository which is the best among a set of alternatives. What we do argue against is the unending examination of alternatives in order to find the "best".

2.5.4 The Systems Approach to Repository Design

The Interagency Review Group (IRG) has used the term "systems approach" to describe the appropriate method for selection of the geologic environment, repository site, and waste form (Ref. 16). They state,

> "A systems approach recognizes that, over thousands of years, the fate of radionuclides in a repository will be determined by the natural

> geologic environment, by the physical and chemical properties of the medium chosen for waste emplacement, by the waste form itself and other engineered barriers. If carefully selected, these factors can and should provide multiple, and to some extent independent, natural and engineered barriers to the release of radionuclides to the biosphere."

The IRG notes that in the public comments on their draft report,

> "In general the systems approach, addressed in the first technical finding, was endorsed. Some commenters, however, questioned the meaning of the concept and criticized it for being contentless, full of jargon, and vague. Other individuals felt that more emphasis should have been placed on the need for multiple barriers to hedge against uncertainty while still others observed that the barriers might not be truly independent and therefore not provide sufficient protection. Another group of individuals said that more credit should be given to engineered barriers than the Draft Report does."

The IRG's reply to these criticisms was,

> "The IRG recognizes that the term "system approach" can be misunderstood. However, it believes that the use of this term in reference to mined repository, is now widely understood within the technical community and is quite useful. The IRG supports its continued use. The IRG also continues to endorse its statements contained in the first technical finding on the important subjects of multiple barriers and engineered barriers."

The principal objection to the systems approach seems to be that the words used are not meaningful. Often it is true that "systems" studies make the reader feel like a scavenger hunter in a junk yard -- sure that with all the available material something useful is probably around, but equally certain that, whatever it is, it has been carefully disguised.

However, with respect to the nuclear waste disposal problem, the systems approach provides a simple and direct guide to appropriate procedures for attaining repositories with acceptable levels of risk.

The American Heritage Dictionary defines a system as "a group of interacting, interrelated, interdependent elements forming or regarded as forming a collective entity." Throughout this report the word "system" has been used to describe the repository because there is no intuitive doubt that waste disposal is achieved through use of a system.

The concept of a system is slightly refined when systems analysis is considered. A standard textbook on systems analysis (Ref. 57) provides the following useful definition of a system, "a collection of interdependent and interactive elements which act together in a collective effort to attain some goal". The same text defines systems analysis as "that discipline devoted to the study of systems in order to isolate their salient components and to delineate their interactions, relationships, and dynamic behavior mechanisms."

Clearly a waste disposal system is a collection of interdependent, interactive elements (waste form, geologic environment, repository site, etc) which act collectively to attain the goal of protecting the public health and welfare. Moreover, demonstration that the system does not expose the public to unacceptable risk requires identification of the salient components of the waste disposal system and delineation of their interactions, relationships, and dynamic behavior mechanisms. In sum, the goal of nuclear waste management can be attained through the systems approach, and it is difficult to understand how to attain it without a systems approach. Quibbles over words aside, the systems approach is generally recognized as an appropriate and effective means for attaining the goal of design, construction and operation of acceptably safe nuclear waste repositories.

A final word should be said concerning the criticism of the IRG that the emphasis on the effectiveness of the various elements of the system was misplaced. The multibarrier concept will be fully discussed in Section 3.2, but one of the thrusts of that section is that there should be optimism about the attainment of the waste management goal because several of the barriers to waste migration seem to be sufficient by themselves to guarantee accomplishment of the goal. When all these barriers are considered together it is very reasonable to assume that public risk will be effectively limited. The criticisms are thus likely to represent some technologists' claims that their solution to the problem is better than the others. The important thing to recall is that under the systems approach many of these approaches can be incorporated into one waste disposal system which can meet the goal of safe nuclear waste disposal.

2.5.5 Systems Approach to Alternative Repository Designs

In the previous sections we defined the goal of waste management and described three approaches to the achievement of this goal. The concepts of the "perfect" and "best" repositories have been shown to be unachievable and counterproductive to the goal of the enterprise. The systems approach has been shown to fit the goal and to offer a firm direction for waste disposal efforts.

An important question remains: once a definition of acceptable risk has been promulgated by appropriate authorities, can the system approach be expected to help produce several acceptable repositories. The answer to this question given by the IRG is "yes". Moreover, use of the systems approach can provide designers with an extra measure of flexibility in their approach to the selection of repository locations and designs.

Once the systems approach is adopted, the need for every component of the system to perform to some very exacting standard disappears. What becomes important is that the total system -- the integrated functioning of the components -- achieves the goal of operation without exposing society to unacceptable risk. Thus, the capability to engineer some specific components of a waste disposal system to high performance and high certainty of performance assumes a special importance because these portions of a system can compensate for less certainty in the performance of other components.

A vivid example of the safety available from the use of engineered barriers to insure long-term safety is provided by the Swedish KBS report (Ref. 5). This report sought to demonstrate that nuclear wastes could, in principle, be disposed of with "absolute safety". They thus took advantage of a costly and over-designed engineered system which might or might not be adopted for eventual use. Operation of the repository was not expected to begin until the year 2020. The Swedish study proposed several engineered barriers, for example,

- A vitrified waste form for reprocessing wastes designed to resist leaching
- The high-level waste canister: the reprocessing wastes will be packed in a chrome-nickel steel cyclinder which is surrounded by about 4½ tons of lead all enclosed in a 6 mm thick titanium shell (Ref. 58)

- The buffer material, consisting of 10% bentonite and 90% quartz sand, surrounding the canister and filling the tunnel and shaft.

The Swedish study was based on a repository sited in bedrock. Potential repository locations within Sweden have been identified with very small groundwater flow rates. The KBS report assumes that it requires only about 400 years for groundwater to flow from the repository to the biosphere. Even under this fairly conservative assumption, calculated doses to the public were found to be extremely low because of the protection provided by the engineered barriers. In its conclusion, the report claims to have demonstrated the "absolute safety" of nuclear waste disposal in Swedish bedrock. In no small part, this claim is based on the protection which was engineered into their system: protection which does not depend on future geologic events, but on the ability of present-day engineers to devise methods to isolate and contain the nuclear wastes.

In the United States, many people believe that basement rock is not the best repository medium. Bedded salt has several properties, especially its relative impermeability, which suggest it may be superior. However, the Swedish study shows that if sufficient engineering effort is expended then granite can be shown to be an acceptably safe medium for repository siting.

The Swedish experience provides an important basis for confidence in the ultimate solution of the waste disposal problem. Each disposal medium has some generic properties that are attractive for a potential repository site and others which are less desirable. The systems approach allows for engineering concepts to mitigate the effect of the detrimental properties, while still taking full advantage of the desirable properties.

For example, bedded salt has intrinsically desirable properties such as uniformly low permeability, high thermal conductivity, abundant availability in thick masses, and plasticity that enables fractures to self-heal at proposed repository depths. It also has some undesirable properties: for example, the possiblity exists that saturated brine solutions may form around the canister and cause deterioration of the canister and waste form. Thus, on the plus side, bedded salt is a material that does not permit large groundwater flows, dissipates heat produced by the waste, is self-healing, and is readily found in masses appropriate for use as a disposal medium. On the other hand, bedded salt may provide a potentially hostile environment for the waste form and canister.

It is possible to reduce the potential for corrosive brines to contact the canister and waste. Materials which readily react with brines to form solid corrosion products can be placed around the canisters and thereby reduce the brine concentration. Moreover, the waste form and canister can be engineered to better withstand a brine environment. If the rate at which waste enters into solution in the groundwater is appropriately reduced, then the natural low permeability of the salt will be sufficient to provide a viable repository concept.

Similar examples can be provided for the other candidate media. The IRG Subgroup Report on Alternative Technology Strategies (Ref. 53) has provided a list of the various candidate media together with the desirable and detrimental properties of each, and specific suggestions for mitigating many of the problems.

Use of the systems approach allows designers to compensate for deficiencies in the performance of certain portions of the waste disposal system if careful engineering can improve other portions. Hence, under the systems approach the search for the best geology, best waste form, etc. can be replaced by the search for a system which can be shown to adequately protect the public in spite of the fact that it may not have the <u>best</u> geology or the perfect waste form.

3. TECHNICAL BASIS FOR CONFIDENCE IN LONG-TERM SAFETY

The preceding chapter has described the spectrum of attitudes, philosophies, and points of dispute that constitute the issues now faced by scientific and public groups in evaluating the long-term safety of nuclear waste disposal. This chapter will examine the technical aspects of this problem. In the following sections, we discuss these areas that contribute to risk and safety evaluation:

- Conservatism in modeling and risk analysis
- Isolation of wastes as seen from a multi-barrier, defense-in-depth point of view
- Engineered safety features compatible with the natural geology
- Site selection and site characterization procedures
- Field and *in situ* test results.

3.1 CONSERVATISM IN ANALYSIS

A prime requisite for public confidence in the safety of nuclear waste disposal is that the models used for the prediction of public risk be exercised in a conservative fashion, i.e., no assumptions are made which would underestimate risk. In this section, the notion of conservatism is explored, and it is shown that past risk and safety analyses have been conservative. Some have been excessively conservative, as was discussed in Chapter 1. We conclude that the conservative approach is likely to be continued in future risk analysis studies.

3.1.1 The Case for Conservatism

No nuclear waste repository will be licensed without firm assurance that its operation is unlikely to harm the health and safety of the public. This assurance will be based in large part on the results of site specific studies performed using models of waste transport.

Models must be used because they constitute an important aid for quantitatively assessing the consequences associated with nuclear waste disposal. Protecting the safety of future generations requires estimation of radionuclide distributions and concentrations for millions of years. It is obviously impractical to conduct experiments on these time scales. Hence, mathematical models that simulate radionuclide transport from the repository to the biosphere help provide assurance that present-day nuclear activities will not adversely affect our descendents or ourselves.

The IRG Subgroup on Alternate Technologies (Ref. 53) states that current models adequately represent the more important processes involved in waste transport and are appropriate for use in preparing site selection guidelines. The IRG also points out that, "the results (of these models) will be meaningful to the degree that valid data are utilized and the ranges of uncertainties in the data are specified."

Using a model requires specification of input data. When some of the data are known only within a range, the question of choosing appropriate values from the range becomes important. Obviously, the results depend on the data chosen, and consequently, on the investigator who makes the choice. How this choice is made is an important issue when deciding on the validity and acceptability of the results of a study.

In order for a repository to be licensed it is not necessary to know exactly the safety consequences to the public of the operation and existence of that repository. It is only required to know that it is highly unlikely for that repository to cause an unacceptable consequence. Analyses, therefore, can be conducted to estimate bounds on the safety consequences or risks from a repository. A key requirement for showing that safety criteria are met is that nothing has been included in the model which will produce smaller consequences than are likely to happen. That is, the model and model parameters must be chosen conservatively. For example, suppose a value must be assigned for a physical parameter which is known to have a range of possible values. An appropriate choice is a value which produces consequences at least as severe as those produced by any other reasonable value of the parameter.

When all parameters have been chosen according to this conservative criterion, and the consequence has been calculated, the actual consequence of the repository is unlikely to exceed that calculated. Thus, given that the choices have indeed been made in a prudent, responsible manner, it is reasonable to credit the analysis as being an upper bound on the consequence that might be caused by the repository.

In the next section there is a discussion of conservative assumptions found in previous repository safety studies.

3.1.2 Examples of Conservatism in Long Term Safety Analyses

"Conservative" has many synonyms: moderate, prudent, or cautious, for example. Thus, a conservative approach should avoid unreasoned extremes and practice common sense. Attaining public confidence requires responsible, prudent choices by those who will perform the analyses leading to repository licensing. Is it reasonable to have faith that these future studies will be instilled with the proper spirit of conservatism?

The litmus test most often used by society to determine whether to trust people in the future is their behavior in the past. The granting of credit and of security clearances both rest on examination of people's past behavior. To a large extent, elections are an expression of public faith that the candidate's past determines his future leadership qualities. Thus, an important basis for confidence that an appropriately conservative approach will be taken to future modeling is that past modeling efforts have been extremely careful not to underestimate risks.

In order to support the contention that past repository consequence studies have been conservative, a review of several studies will be presented in this section (these are some of the studies whose results were summarized in Fig. 1.2-1). Twelve studies of the long-term safety of geologic disposal of nuclear wastes were reviewed and compared in Refs. 1 and 2. It was concluded that the twelve studies share the common characteristic of conservatism despite the fact they have different objectives, utilize diverse methodologies, and consider dissimilar situations. Some were also extreme, i.e., excessively or unreasonably conservative, as noted below, in Chapter 1, and in Refs. 1 and 2.

Four of these studies are discussed below. In each case a brief description of the study's purpose and method are given followed by a listing of the main conservative assumptions used, and where appropriate, a discussion of these assumptions.

<u>De Marsily, et al., Nuclear Waste Disposal: Can the Geologist Guarantee Isolation?</u> - This study (Ref. 4) used a simple model for describing the geologic system: water flows through the buried waste and carries it upwards to the surface. The model was not developed, however, to predict future releases of radioactive material from actual repository sites. <u>The objective was to simulate repository failure in order to assess the capability of the geologic media to confine the waste</u>. The following conservative assumptions were made:

- The canisters containing the waste were assumed to possess no significant containment value. The Swedish KBS study (Ref. 5) shows that it is possible to design canisters with very long expected lifetimes (10,000 yrs or more).
- Groundwater flow through the repository was assumed to take place. For repositories located in highly impermeable formations such as salt, no significant groundwater flows are expected.
- The release rate of radioactive material from the waste form was taken to be independent of the quantity of water available.
- The flow was assumed to carry dissolved waste directly to the surface 500 m above the disposal area.

The first two assumptions negate any salutory effect of the engineered waste package and repository. By the third assumption, solubility does not limit the quantity of waste entering the groundwater. By the final assumption, waste reaches the surface after a very short time. In more realistic models of local hydrology, the waste has flow paths of tens of kilometers to reach the biosphere.

Hill and Grimwood, Preliminary Assessment of the Radiological Protection Aspects of Disposal of High-Level Waste in Geologic Formations - This report by two British researchers was prepared for the Commission of the European Communities (Ref. 8). It is divided into two sections. In the first, potential mechanisms that could lead to release of waste are described. Release of waste due to circulating groundwater is identified as by far the most likely failure mode. In the second section, the consequences of groundwater circulation through the buried waste are analyzed. In the consequence analysis, all the waste is contacted by groundwater at 1000 years and leaching begins. Groundwater is assumed to transport the dissolved waste through a heterogeneous rock column to a point 10 km downstream where it is then accessible to man.

Hill and Grimwood have developed a preliminary assessment of disposal risks, but the objective of their study was really to provide input for the development of more sophisticated models. The assumptions that are made therefore reflect this overall purpose, i.e., the models are tested for scenarios in which significant releases occur. The high degree of conservatism in the calculations is indicated by the following:

- Migration of radionuclides to the biosphere begins about 1000 years after disposal. As Hill and Grimwood point out, the probability of a natural geologic event leading to groundwater circulation through the waste as early as 1000 years is quite small.
- No credit is taken for the possible confining value of certain engineered barriers -- e.g., the waste container and clay backfill.
- A very high value is chosen for the groundwater velocity (110 m/yr). A typical value for deep groundwaters is 1 to 2 orders of magnitude below this.

- Hill and Grimwood suggest that a more realistic path length would be 100 km or greater for very deep groundwaters.
- The flow rate chosen for the surface water body into which waste is ultimately released is very small, comparable to the quantity of water flowing past the repository. There is, therefore, very little dilution of the waste. (However, the flow rate chosen would not be inappropriate for a shallow aquifer from which water might be withdrawn by man.)
- Population doses are computed by assuming that 100% of the surface water body is utilized for public water supply. Removal of radionuclides by water treatment or sorption onto sediments is not considered.

One can calculate how the results of this study would be changed if more realistic assumptions had been made. Assuming a path length of 100 km, a groundwater velocity of 1.1 m/yr, and a 10% utilization of the contaminated water supply by the population, collective doses for ^{129}I and ^{99}Tc would, as a consequence, drop by a factor of 500. None of the other nuclides would reach the biosphere until after 10 million years.

Burkholder, et al., Incentives for Partitioning High-Level Waste - A sequence of reports by Battelle Northwest Laboratory (Refs. 9, 37 and 59) describes the development of a risk assessment method for analyzing geologic disposal of radioactive wastes. Fault trees are developed for the identification of release events and a groundwater and biosphere transport model is used to assess consequences. So far, only the transport models have actually been applied to repository risk assessment. In these studies, the consequences of direct release of radioactive material into an aquifer are determined.

The geologic model is in essence identical to that of Hill and Grimwood as is the one-dimensional geosphere transport model. The biosphere transport and dose models were taken directly from an earlier set of generic models used for assessing impacts from nuclear power plant effluents.

The principal conservative assumptions in the geosphere transport model are:

- No credit is taken for the waste canister and package in reducing waste outflow
- No credit is taken for geologic barriers preventing circulation of groundwater through the disposal zone or impeding the transport of radioactive material to an aquifer
- A very high groundwater velocity, more than 10 times higher than is typical of the region modeled, is assumed
- An extremely small axial dispersion coefficient, roughly 10,000 times smaller than used in comparable studies, is assumed.

The large groundwater velocity and small axial dispersion severely limit the attenuation of the waste concentration to less than that which would naturally be experienced.

In predicting the consequences of release into a river, the model uses several conservative assumptions to ensure that the maximum dose to an individual cannot be underestimated. These assumptions include:

- The individual is assumed to obtain all his drinking water and foods directly from the contaminated water supply

- The individual has a dietary intake of water and food products several times the average U.S. intake
- The individual is assumed to spend, on the average, 1½ hours per day in recreation activities on the river shoreline.

Berman, et al, Analysis of Some Nuclear Waste Management Options - The models developed and applied in this study (Ref. 6; some additional results are presented in Ref. 60) represent one of the most advanced methodologies for the long-term generic assessment of mined disposal of nuclear wastes. The objective of this study was to construct a flexible and efficient model for the analysis of both generic and potential repository sites. The models were used to study the effects of different parameter values on the waste isolation effectiveness of repositories in bedded salt and shale.

Assumptions which were highly conservative include:

- The canisters containing the waste prevent release only during the first 100 years
- A vertical head is present that is sufficient to cause flow of water through the depository towards an overlying aquifer and from there to a nearby river. Repositories, in practice, can be sited where water flows do not exist or are downward to deep aquifers
- No engineered barriers were modeled to prevent flow around the waste and through fracture zones surrounding shafts and tunnels even though these effects can be mitigated by appropriate drilling, sealing, and backfill techniques
- Constraints placed upon the release of waste due to solubility limits in the groundwater are ignored

- Salt is assumed to have a relatively high permeability (10^{-9} cm/sec). There is much evidence that salt is almost totally impermeable to the transport of water
- Doses are computed for an individual who maximizes his exposure to radionuclides in the water systems. This dose is much more than ten times what might be expected for an <u>average</u> individual.

These four studies, as well as the others discussed in Ref. 1, constitute a significant body of evidence that the investigations of long-term repository safety have used, if not in fact over-used, conservatism in modeling. Despite the extreme conditions often assumed, potential radiation doses to individuals are projected to be small fractions of the variations in natural background, as shown in Fig. 1.2-1.

3.1.3 Summary

Conservatism is the appropriate approach to the modeling of consequences of long-term nuclear waste isolation. With the conservative approach, it is possible to analytically bound the consequence of the repository. If the conservatively calculated bound is less than the acceptable consequence, then the repository has been shown to be unlikely to produce unacceptable harm to the public.

A study of past modeling efforts indicates that investigations of long-term safety have incorporated conservatism in an appropriate manner. This past behavior is a strong indication that future studies can be expected to be done in a moderate, prudent, cautious manner that will safeguard the public health and safety.

3.2 THE MULTIPLE BARRIER CONCEPT

Nuclear waste buried in a repository cannot harm humans unless there is interaction between the radionuclides or their radiation emission and humans. Nuclear waste management aims at limiting possiblities of interaction to very small levels which will not produce harm. One of the principal problems in achieving this aim is our uncertainty about the effectiveness of the physical methods which are relied on to limit interaction. However, it can be plausibly argued that the uncertainties are relatively unimportant because there is a multiplicity of substantial barriers that individually inhibit the entry of waste into man's environment. Although these barriers may not be entirely independent, no single event could reasonably be expected to breach all of them. The existence of these barriers provides substantial confidence that nuclear waste can be contained without exposing the public health and safety to unacceptable risk. The following discussion is a generic description of the barriers most likely to be present in a repository.

3.2.1 The Barriers to Waste Flow

In order for wastes buried in a geologic repository to reach man by groundwater transport, several events must occur. Groundwater must reach the emplaced waste, the waste canister must corrode, and the waste form must begin to deteriorate. The contaminated groundwater must then flow through the repository and the surrounding rock. For salt, the water must be diluted to become potable. Under most circumstances flow of water will not begin until the repository resaturates -- i.e., the mined excavations refill with water. Ultimately, the contaminated water must reach either an aquifer from which water is removed by man, or flow into a surface water body. Once in the surface water, the radionuclides can enter the human food chain either directly, by drinking water, or indirectly by irrigated crops.

Throughout the course of its travel from the repository the movement of the waste toward man is delayed by several effects. Some of these delays are potentially quite long:

- The amount of time necessary for contamination of the groundwater in the repository may be lengthy if groundwater intrusion is substantially delayed, if the canister resists corrosion, or if the waste form resists deterioration and solution.
- Flow times through the repository and geologic media may be large if the waste is retarded by geochemical barriers, if the flow paths are extremely long, or if the flow rates are quite small.
- Wastes in the biosphere may take a long time to reach man and are often diluted or dispersed by natural processes.

The fact that many barriers exist, each with a potential for limiting waste flow, provides strong confidence that acceptable nuclear waste repositories can be developed.

3.2.2 The Relationship Between the Multi-Barrier Concept and the Systems Approach

In Section 2.5 of this report support was provided for the contention that the systems approach was appropriate for repository design. Systems analysts do not consider the components of the systems individually, but only how these components, acting in concert, affect the overall performance. A repository with an associated level of low public risk is an acceptable repository, even if it is located in a less than optimal geology, or has a relatively high waste dissolution rate. In colloquial terms, the systems approach considers the waste disposal system as a "black box" with an input -- the amount of waste buried -- and an output -- the radioactive dose to the public.

The multi-barrier concept is the basis for belief that the methodology of systems analysis is adequate to protect the public. It encompasses the idea of defense in depth: if several barriers exist, and no credible event can cause severe deterioration of them all, then it is most unlikely that operation of the repository will produce unacceptable consequences.

3.2.3 The Multiple Barrier Concept in Practice

When a specific waste disposal site has been chosen and field tests have been performed, the effectiveness of the various natural barriers can be assessed. Engineering concepts can be employed to enhance naturally occurring barriers or to provide new barriers to waste flow. This section contains a description of some of the natural and man-made barriers that might be included in a typical repository. This catalogue of barriers is by no means inclusive, but is intended as an indication of the variety of barriers which may be found in a repository. Additional discussion of man-made or engineered barriers may be found in Section 3.3.

To focus the discussion, four generic barriers will be considered: the waste package, the repository, the geology, and the biosphere.

The waste package consists of the waste form, canister, overpack, sleeves, and other materials placed in the repository by the transporter. The purpose of these materials is to prevent deterioration of the waste form for as long a time as possible beyond the several hundred years necessary for decay of the most dangerous fission products, and to limit the rate of egress of the radionuclides from the waste package if deterioration occurs.

Ideally, the waste form should be durable: it should resist deterioration if groundwater reaches it and have a small leach rate if deterioration is initiated. The canister and sleeves provide physical protection for the waste form by blocking groundwater from reaching the waste. The overpack can provide chemical protection for the waste form. For example, in a bedded salt repository, overpack materials that readily react with brine to form corrosion products can be used to reduce the amount of brine reaching the waste form. Finally, various other materials can be placed near the canister to reduce the solubility of the waste in the groundwater and to retard the progress of various radionuclides away from the waste form.

The repository is a barrier with design features intended to reduce flow through man-made structures. Low permeability backfill in these structures can restrict groundwater flow, and backfills can be chosen which expand when they absorb water so that any open pathways for water flow will be sealed. Ion exchange material can be used in the backfill to retard the motion of nuclides. Engineering plugs can increase the time needed for the repository to fill with water. Multi-component shaft and borehole seals can be used to reduce groundwater flow into or out of the repository. Finally, linings could be used to have the repository function as a civil structure to divert groundwater around excavated areas. Reference 61 contains a description of many repository design possibilities.

The geologic barrier consists of the rock surrounding the repository that retards or restricts groundwater flow. In some geologies, as bedded salt, no groundwater flow is expected. According to the draft WIPP EIS (Ref. 12) no radioactive material is expected to be released from the repository, based on the expected integrity of the massive and impermeable salt beds that contain the waste. These salt beds have remained stable and free from circulating groundwater for hundreds of millions of years. Groundwater is also unlikely to reach wastes emplaced in repositories located above the water table (Ref. 62). Hence, waste disposal in the vadose zone at NTS is an attractive possibility.

If groundwater pathways do exist, they will generally require long flow times, either because the pathways are very long or because the waste moves slowly through them. Candidate repository sites located tens of kilometers from surface water bodies have been identified. The retardation of nuclides can produce extremely long flow times, especially for the actinides. Long flow times can result in significant radioactive decay of the waste, and along with dispersion can greatly reduce the peak outflow of waste to the biosphere.

Thus, if the repository is appropriately sited, the geologic barrier can prevent waste flow to the biosphere, or, in any case, reduce the outflow to acceptable levels without the help of other barriers.

The biosphere barrier consists of the various pathways for entrance of waste into the food chain or into water used for recreational purposes where the waste can be substantially diluted and dispersed. The waste will be significantly diluted if it enters a surface water body such as a lake, river, or ocean. See Section 1-C of the Disposal Capability Document.

3.2.4 Defense in Depth

The multi-barrier concept owes much of its appeal to the idea of defense in depth. So many barriers are placed between the waste and man that even if one or two should deteriorate there are still sufficient barriers remaining to allow the repository to function adequately.

It is human nature to single out a particular barrier as being the most substantial. For example, the IRG Subgroup on Alternative Disposal Technology (Ref. 53) claims that the principal barrier is a sufficiently long nuclide travel time to the biosphere. Others (Ref. 63) claim that the waste form is the only reasonable barrier to rely on because it is the only common element of all geologic disposal systems. The key point is that there is a multiplicity of barriers, any of which can limit the waste outflow, but none of which needs to do the job by itself.

To illustrate the reasons for such confidence in the overall system, we consider four barriers that may each limit waste release to acceptable limits without regard to other barriers: waste form, waste package, repository liner, and geologic transport. Other barriers may also be devised or conceptualized that reduce flow of waste to man.

Waste form durability is potentially a key element in the barrier concept. If the waste form is absolutely durable, no waste can escape. If the waste release rate is very small, then the release rate to the biosphere will also be small because all other facets of the systems tend to decrease waste flow or disperse the waste. Experimental data have shown that leach rates from spent fuel are comparable to those of high-level reprocessed waste glasses (Ref. 7).

The waste package performs a dual function. The canister and sleeves initially protect the waste form from groundwater. The overpack and surrounding materials then delay the waste by producing chemical conditions which reduce the solubility of waste and retard the more mobile nuclides. Thus, even if the waste form were not very durable, an appropriately designed waste package could restrict access of groundwater to the waste, or limit the release from the waste package to acceptable levels.

An effective repository liner could severely restrict groundwater from entering the repository, or limit groundwater flow so that the only available waste transport mechanism would be molecular diffusion. Models of transport of waste by molecular diffusion in a bedded salt repository indicate almost no dose to the public by this process (Ref. 64).

Geologic transport can limit waste release to the biosphere to extemely low levels. Favorable geologies with small hydraulic driving forces, long flow paths, and large retardation factors can produce extremely long flow times during which decay and dispersion can reduce outflow from even rapidly leaching waste forms to acceptable levels. Moreover, favorable geologies can produce long repository resaturation times.

Thus, it should be possible to design repositories with two or three barriers each of which can contribute significantly to limiting waste release to acceptable levels and to augment these with many other barriers to waste flow. It is difficult to conceive of any event at an appropriately selected site which could breach these barriers if they were appropriately incorporated into the repository design.

3.2.5 Summary

Between the buried nuclear waste in a geologic disposal scheme and man, there exist many natural and man-made barriers that retard or even prevent the passage of radionuclides. The barriers involve the waste form and its packaging, the design of repository, the hold-up capacity of the geology, and the dilution potential of the biosphere. The existence of these barriers provides substantial evidence that the containment of nuclear waste can be performed without exposing the public health and safety to unacceptable risk.

3.3 CONSERVATISM IN ENGINEERED FEATURES OF REPOSITORY SYSTEMS

> "The waste form and other engineered features of the repository system can also provide significant barriers to radionuclde migration, but only to the extent that they are tailored to be compatible with the geologic features of a repository." (Reference 53.)

3.3.1 Concepts for Engineered Features

As discussed in the previous section, a repository for deep geologic burial of nuclear waste can be viewed in terms of multiple barriers; these barriers provide resistance to the transport of radionuclides from the repository to the biosphere. Here, we will be concerned with a portion of the multiple barrier system, engineered barriers -- those aspects of the overall disposal scheme that are directly controlled by man. The intent of engineered features or barriers is that by proper design of the physical space, process variable selection, and choice of construction materials, a repository can be rendered safe. Further reassurance of safety is obtained because there is no need for each of the engineered features to perform perfectly, as pointed out in Section 3.2. As described in Section 2.1, engineered barriers which function for about five hundred years will prevent escape during the period of greatest danger.

Engineered features, because they can be closely controlled and demonstrated through testing to perform reliably, offer the best chance for achieving demonstrated safety within the five hundred year time frame. Natural barriers will also contribute substantially to repository safety, for example, the ability of the surrounding host rock to absorb and retard migrating radionuclides. While natural barriers give additional assurance of safety, they nevertheless cannot be characterized as completely as can engineered barriers. Two reasons are apparent. First, natural barriers are much greater in length and volume than engineered barriers -- they can be described generically, but local variations in properties can never be completely known in detail and thoroughly tested. Second, natural barriers will behave in a less predictable manner in response to random or unknown future alterations in the geology or hydrology surrounding the repository. Thus, the engineered features, as a design objective, should be viewed as a principal means of waste containment during the first five hundred years.

Engineered features of geologic burial can be divided into the following categories:

- Waste form. The waste form includes spent fuel, cladding, and possible filler materials.
- Waste containment package. The package includes a canister and sleeve, usually of metal construction.

- Sorption barriers. These are solid materials in the neighborhood of canisters or additionally as backfill material. Sorption barriers are intended to slow the migration of radionuclides or to limit contact by water.

- Repository design. The layout of the repository can be designed to minimize the possibility of radionuclide release. Design features include room, pillar, and corridor arrangements and dimensions. The location and characteristics of shafts and their seals are also important design considerations.

While cost and safety during the operational phase are important, one of the primary goals for the engineered design of a repository and its contents is the long-term safety to the public. The remainder of this section explains in more detail the means by which engineered repository features can ensure waste containment for long periods of time.

3.3.2 Waste Form

If spent fuel undergoes disposal as discharged from a reactor there is little that can be done, save the process of aging, to reduce the potential for release of radioactivity; previous temperature, pressure, and irradiation history will for the most part determine its physical properties. Even in this condition, however, uranium oxide has manifested itself as a low leaching material, especially with the presence of cladding. Various schemes to further prepare spent fuel for disposal are under consideration. These include fuel bundle disassembly, chopping the fuel into a uniform waste form, and the addition of gaseous or solid stabilizers.

3.3.3 Waste Containment Package

An appropriate and well designed waste canister could "provide a significant barrier between the radioactive waste form on the inside and the geologic environment on the outside" (Ref. 1). Admittedly, the requirements for an effective canister are stringent. In addition to its being a safe and reliable vehicle for containing the wastes prior to burial, the canister may be exposed to a severe environment subsequent to burial. Depending on the burial medium, the canister may be subject to high temperatures, high stresses, and a chemical environment conducive to corrosion.

Many types of canister materials can withstand the adverse burial environment (Ref. 65). These include alloys of nickel, titanium, copper, or zirconium (Ref. 7). Employing tubes or coatings with a glass ceramic or aluminum composition (Ref. 53) are also under consideration. These materials can be used either alone or in combinations, with thicknesses determined by the exact application.

One example of the extremes to which canister design can be taken is the design proposed for the Swedish KBS project (Ref. 11). For burial of spent fuel in granite, the KBS group has recommended a solid copper canister (15½ tons) with fuel rods embedded in 2½ tons of lead. The canister was expected to completely protect the waste for times on the order of hundreds of thousands of years, and probably for millions of years. A group of specialists appointed by the Swedish Corrosion Institute concluded that "it is realistic to expect a service life of hundreds of thousands of years" (Ref. 58). The National Academy of Science's Subcommittee for Review of the KBS-II Plan also came to the same conclusion (Ref. 15, see Section 1.3 of this report for additional details). Such work indicates that it is possible to design an encapsulation system capable of withstanding attack by the action of groundwater for extended periods of time.

3.3.4 Sorption Barriers

Engineered sorption barriers are materials that absorb or retard the radionuclides that migrate away from the waste package after canister dissolution and waste form leaching take place. Sorption barriers work by various processes: adsorption on the surface of barrier particles, ion exchange, and oxidation-reduction (redox) effects. They may be placed around the waste canister as an overpack, act as a backfill for the repository and its various shafts, or, in fact, be an integral part of the waste package itself, forming a barrier between the canister and waste matrix. Requirements for sorption barriers, in general, include mechanical, thermal, and chemical stability, plus good thermal conductivity and a low permeability to water.

Inorganic sorption materials such as zeolites and bentonite clay have been the subject of recent study (Ref. 7). The Swedish KBS work indicates that a quartz sand-bentonite mixture has many of the desired properties for a backfill or sealing material, including a high ion exchange capability, plasticity, and swelling upon absorption of water (Ref. 66). Redox materials that bring radioactive species into less soluble or less mobile oxidation states might also be developed (Ref. 7).

Mixtures of various sorption materials, each specifically tailored to inhibit the migration of particular groups of radionuclides, have potential for isolating wastes from surface waters. Tailoring must be accomplished according to the local geochemistry and supply of available water. However, within these restrictions sufficient thicknesses of sorption materials can retain nuclides for many half-lives. Current additional research into artificial crystalline minerals (Ref. 63) also shows promise for containment.

3.3.5 Repository Design

The details of a repository design must satisfy many constraints. Some constraints are related to technical feasibility within the state-of-the-art of mining technology. Other constraints are determined by safety considerations during the operational phase. Here, we are concerned with the long-term safety aspects of the repository design.

Criticism of deep burial concepts has been centered in three areas:

- Repositories are vulnerable to major disruptive events, such as meteor impacts and severe earthquakes
- The very presence of the repository excavation disturbs the local geology to produce pathways to the biosphere
- The nature of the waste in producing heat for long periods of time also disturbs the local geology.

The long-term hazards implied by these criticisms can, to some extent, be mitigated or even eliminated by an appropriate and conservative repository design.

Depth of Burial - Various geological factors mandate that the waste be placed at considerable depth for isolation. These factors include slow processes such as erosion by weathering, water, and glaciation as discussed, for instance, in Ref. 7. However, according to Ref. 67:

> "Even if the full effect of deformation is added to the estimated erosion rate along a significant river, potential for eroding to typical repository depths requires hundreds of thousands of years."

Events of a more catastrophic nature, for instance meteor impact and earthquakes, will have a correspondingly smaller effect on a repository as the depth of burial is increased. Similarly, events caused by the action of man -- nuclear detonation, aircraft crash, and intrusion -- are less likely to provide pathways to the surface for buried waste at large burial depths. Depths of 500 m to 1000 m are now cited as reasonable. Local conditions must be judged in selecting burial depth, but it does remain a flexible design solution to isolate wastes.

Thermal Effects - Heat may have a potentially harmful effect on host rock media through loss of strength and possible increased permeability due to fracturing. In salt, thermal gradients can induce brine migration in the direction of waste containers, a process that could result in accelerated corrosion. In all media, elevated temperatures promote corrosion of canisters. Expansion of rock followed by subsequent contraction, which is due to the heat of radioactive decay of the waste over hundreds of years, may tend to promote uplift and subsequent subsidence of the ground surface above the repository, which might induce additional fracturing of the rock.

It may be necessary to avoid these deleterious effects of waste heat, but this is easily accomplished by reducing the heat output per area of the repository. Repository rock temperatures can be lowered by a number of design options:

- Increase canister spacing. This option will result in a larger area of the repository for a given amount of buried waste. Temperature criteria that ought not be exceeded are currently being developed for all potential host rocks, especially for bedded salt (Ref. 68). These criteria apply to near-field regions (in the vicinity of canisters), to far-field regions (the rock supporting the repository) and to the surface above the repository.

- Provide ventilation for long enough periods of time to remove a significant fraction of the decay heat in and very close to the canisters (Ref. 39).

- Provide a longer interim storage period prior to final emplacement, allowing radioactive decay to lower the heat output of the waste. From Ref. 53, "increasing the decay time from 10 years to 100 years is roughly equivalent to halving the number of spent fuel elements per unit of area of the repository."

In summary, conservative criteria are being defined for maximum allowable thermal effects of various locations in and around a repository. By careful distribution of wastes in a repository these criteria can be met. As aptly concluded by the IRG, "the detailed effects of thermal loading are currently uncertain but can be dealt with."

Mechanical Effects - Stresses may be introduced into the geologic medium either from the thermal loading imposed by the waste heat, from the excavation of the repository site itself, or from seismic activities of natural origin. Stresses are important only to the extent that the host rock cannot sustain them and fractures develop. Rock fractures have relevance to public safety insofar as they may permit flow of groundwater to and from the region in which the waste material is buried.

These considerations are of more concern with brittle rocks and less with salt, which flows under mechanical loadings.

Obviously much information is needed in order to characterize completely the thermomechanical response of rocks to the various loadings, in particular from in situ experiments and tests. There is, however, well developed technology and understanding of the important issues in a number of areas that indicate our ability to deal with repository problems involving mechanical effects.

- There exists considerable information and experience in the excavation and maintenance of deep mined cavities, including various techniques for extraction and lining of tunnels and shafts. Such experience can be utilized to minimize the formation of residual stresses from the construction phase (Ref. 69). Ref. 53 also states: "Inasmuch as considerable experience already exists in the development of large underground cavities in a variety of rock types, the existing rock mechanics technology would appear to be fully capable of developing a stable cavity suitable for a waste repository in rock types other than salt."

- Temperature distributions are well understood and predictable analytically. Hence, thermal stress problems can be handled acceptably by reducing the thermal pulse from radioactive wastes.

- Appropriate siting procedures (see Section 3.4) that are conservative in the sense of avoiding untenable local hydrologies can reduce the impact of any fracturing of host rock. Intelligent siting can also reduce the probability and effects of seismic disturbances that could affect rock integrity.

- Flexibility exists in the design of the shafts, burial rooms, and corridors to

> reduce mechanical loadings. Certainly, excavation ratios (fraction of rock removed), shaft diameters, and numbers of shafts and boreholes drilled will be kept at a minimum for future repositories (Ref. 39).

<u>Shaft Sealing</u> - Although the capability of <u>present</u> technology for the sealing of shafts and boreholes to maintain the integrity of seals beyond 50 to 100 years has not been confirmed by modern standards, it should be noted that the cement in Roman aqueducts still holds water after 2000 years. The best available standard technology utilizes cement as a sealant. Organic chemical grouts are also within the current state-of-the-art and may offer greater durability under repository conditions. However, it is known what properties are desired for a suitable seal material: strength, bonding, low permeability, elastic properties matching those of the formation, and resistance to chemical or thermal degradation. The Swedish KBS study has concluded that the sand-bentonite mixture does fulfill many of these requirements, at least for a granite bedrock formation. Their conclusion has been supported by a review of the KBS plan carried out by the National Academy of Sciences (Ref. 15, see Section 1.3 of this report for additional details). There is, therefore, evidence that sufficient research in this area can produce sealants with adequate properties. From Ref. 70, further solutions to the shaft sealing problem are discussed:

> "For example, Olsen and Martin have described seals of compacted clays or shale that can have a permeability to water as low as 10^{-10} cm/sec and because of their chemical and mineralogic composition would be effective for long periods of time. One might also point out that to the extent it is deemed necessary or desirable, consideration can be given to locating shafts away from the central repository area to minimize

possible potential complications of thermal effects on shaft seals."

The potential consequences of radionuclide release through deteriorated shaft or borehole seals have been studied. In the WIPP EIS (Ref. 12) discussed in Section 1.2, salt repository shaft failure was analyzed and the resultant peak individual doses found to be orders of magnitude below background. Work presented by Berman et al (Ref. 6) has demonstrated, similarly, that very low doses result from borehole failure in both salt and shale repositories even though additional pathways are opened between the repository and an overlying aquifer. It can be concluded, then, that even if shaft or borehole failure were to occur, other barriers would greatly mitigate the consequent health effects. Furthermore, considerable research is underway to reduce the likelihood of such failures.

3.3.6 Summary

The emphasis on engineered barriers in promoting safety is an appealing one because these barriers are within the control of the repository designer. The principal engineered features of geologic burial are the waste form, the waste containment package, sorption barriers, and the design layout of the repository itself. Many points of uncertainty regarding the potential perturbations on the local geology by the very existence of the repository have been raised. Our conclusions regarding these perturbations -- thermal effects, mechanical (stress in rock) effects, and leakage through shafts -- is that any implied hazards can be mitigated or even eliminated by appropriate, conservative design procedures.

3.4 CONSERVATISM IN SITING

Proper location of a repository site is a very large factor in assuring public safety from the buried radioactive materials. It is not clear how many sites bearing the prerequisite characteristics exist in the country. Nevertheless, there is considerable evidence based upon geologic data and experience that indeed many safe sites can be found. Furthermore, we do know what information is needed and what procedures must be followed in order to lend confidence to the site selection process. Optimism can be based on the wide variety of test techniques available (many non-intrusive) and a systematic organization of such data.

3.4.1 General Geologic Requirements

The objective of deep geologic disposal is containment and isolation of the wastes. To meet this objective, there are a number of criteria, which are very general in nature, that must be met by any site regardless of the rock type or geographical area under consideration. These criteria are:

- Tectonic and seismic stability
- Favorable hydrology
- Rock properties compatible with repository integrity
- A low potential for local resource exploration.

In addition to this list, the repository must be located at a suitable depth below ground level.

There appear in the literature many fears about the unpredictability and complexity beyond understanding of future geologic events (Ref. 56). Comments to the effect that geology is a retrodictive, not a predictive science are commonly heard (Ref. 71). There has also been a somewhat <u>defensive</u> attitude in seeking out suitable repository sites. Some scientists have primarily concerned themselves with the search for geological defects; if such defects are not found then there is inference of suitability.

A recent study (Ref. 67) has placed the geologic processes that may affect repository performance in a more <u>positive</u> light; it states:

> "The emphasis in these studies is on identifying positive evidence for site stability, rather than on absence of evidence for instability."

This point of view serves as basis for enunciating obvious, but often ignored truths:

- Major geologic process occur slowly and with great inertia.
- Geologic processes are interrelated. Favorable (stable) aspects of the geology often imply stability in other aspects as well.

3.4.2 Geologic Stability

There is unanimity about requirements for the tectonic environment of a repository site. According to Ref. 53, "a repository site should be located outside regions of high seismicity, volcanism, or other expressions of tectonism." In Ref. 72 it is stated that, "a long history of tectonic stability is a prerequisite for a potential repository site. The rate and amount of predictable long-term regional uplift and/or subsidence of bedrock should not pose a threat to the physical integrity of the repository." Similar comments are to be found in Ref. 72 regarding the presence of faults, igneous or volcanic activity, and seismic activity, such as:

> "It should be clearly demonstrated that any structural features found onsite are not associated with potentially active features in adjacent regions."

Tectonic activity is important because it is a primary mechanism for causing other types of geologic processes. Tectonic activity manifests itself in the appearance of faults, seismicity, alteration of hydrologic conditions, and the causation of stress fields. However, tectonic activity is sufficiently understood to locate areas with little likelihood of a major event occurring over long time periods. This fact gives confidence to repository siting. As summarized in Ref. 67:

- There is a unifying concept for distribution of tectonic activity in space and time, allowing general forecasting of tectonic events.
- Tectonic crustal movements result from motions of very large masses of the earth. The mechanical and thermal inertia of these masses is such that significant change in direction or rate of movement require millions of years.

The implications of these concepts are clear. While tectonic movements exist on earth, the areas in which they occur -- e.g., near plate boundaries -- can be avoided. Other areas of the earth can be shown to have been stable for periods of many millions of years and are thus excellent locations for a repository. Stability is not a vague concept; it can be defined, for example, in terms of identifiable slip rates, erosion rates, volcanic recurrence, etc.

Seismicity, a companion to tectonic activity, has been often quoted as a source of danger to a geologic repository. Although shaking of the ground is detrimental to surface structures, experience shows (Ref. 55) that ground motion is not of great consequence to deeply buried structures.

To locate a repository in a tectonically inactive region, such regions must be found and tested. There is a variety of methods to establish regional stability. Available techniques include aerial photography, geophysical exploration, drilling, and establishment of the local geologic history. These factors can reduce, to a considerable extent, the uncertainties in geologic stability.

In a similar way, igneous activity (that includes volcanism) is associated with tectonic deformations and can be avoided. Again quoting Ref. 67:

> "Areas which have not experienced tectonism or volcanism for several million years and are not adjacent to zones of active crustal spreading would be very unlikely to have igneous activity in the next million years or less."

3.4.3 Hydrology

A general requirement on site selection with regard to hydrogeology may be found in Ref. 72:

> "The repository should be located in a region where the groundwater hydraulic gradients are low. This would aid in reducing the rate at which groundwater would leave the repository site. In addition, the repository should be

> situated far away from any point where the site groundwater flow system discharges to the biosphere or is used by man."

These thoughts are echoed in Ref. 53:

> "Geomorphologically stable regions should be favored where groundwater flow is slow and groundwater flow paths are long."

Those factors that determine the flow of groundwater are the permeability of the rock, its hydraulic gradient, and the flow path length. It is well established that a very wide variety of hydrogeologic conditions can exist. The important issue is whether suitable conditions are likely to be found that minimize the transport of radionuclides via groundwater. More precisely, conservative site selection demands <u>evidence</u> that the region has a favorable hydrogeology <u>and</u> an indication that it will remain favorable for at least a thousand years.

To a large extent, demonstration of an acceptable hydrology can be accomplished by measurements <u>in situ</u> of the rock permeabilities and hydraulic gradients, that is, head differences between wells of a known depth. For most potential host rocks such as basalt and especially bedded salt, the movement of fluid is very slow.

There is additional inference of groundwater stability based upon absolute dating methods on fluids contained for very long periods of time in rocks. Times for the isolation of water in brine pockets and in crystalline rocks have been determined to be in the range of tens to hundreds of thousands of years. Because fluids are able to be contained for extensive periods of time, repositories can, therefore, be located where water circulation is low enough to preclude waste from entering an aquifer for well over one thousand years.

As to future changes in hydrology, Ref. 67 adds an interesting, but vital, perspective:

> "As discussed previously, groundwater flow is controlled by hydraulic conductivity, gradient, and flow path. Therefore, it is a relatively "passive" process in that it can only change in response to changes in these controlling factors. In an area that is not expected to experience tectonism, volcanism, or shallow deformation there is no reason to anticipate changes in hydraulic conductivity of flow paths below the expected depth of erosion or weathering. Similarly hydraulic gradients should remain within the range of climate-induced variation if there are no changes caused by uplift, tilting, or downwarping. In summary, if a location can be shown to be stable with regard to overall geologic processes, it also can be expected to be stable with regard to groundwater hydrology."

3.4.4 Rock Properties

In addition to locating a repository in a stable geologic setting with low hydraulic gradients, there is an extensive set of rock material properties that will influence the degree of containment possible. Somewhat loosely we can place these properties in four categories: mechanical, thermal, hydrological, and chemical. The relative merits of alternate burial media may largely depend on an objective evaluation of these categories of properties. Obviously, site selection will be directed toward media types and particular locations where the rock properties are the most favorable. Luckily, as pointed out in Ref. 53, "A site need not satisfy all the selection guidelines. It is unlikely that any one site will need to provide all the idealized sought-for characteristics."

Mechanical properties include deformation characteristics (stress-strain parameters) and strength characteristics under various types of loading conditions. These properties will determine the ability of the medium to resist erosion, fracture formation, and the pressures of deep burial. Trade-offs do exist between rigid and deformable media; each has distinct advantages. Mechanical properties can be determined for small samples in laboratory experiments, both static and dynamic (for instance, to study creep in salt).

Thermal properties include conductivity, expansion coefficients, and heat capacity. These properties are used in studies to ascertain the ability of the host medium to dissipate the thermal input provided by the radioactive waste and to alleviate thermal stresses. Thermal properties, too, are readily measured; consequently our understanding of the thermal response of burial media is very good (Ref. 73).

Hydrologic properties determine the potential for fluid flow and involve permeability, hydraulic gradient, moisture content, and porosity. Laboratory tests on small specimens, in situ borehole tests, and age dating of groundwater, can all give the necessary hydraulic information.

The list of desired rock chemical properties may be less well defined and studied. In general, a medium that is passive with respect to promoting canister corrosion is preferable. Similarly, one would like to have the medium plus groundwater convert ions of radioactive species to an insoluble form -- e.g., a reducing solution for uranium -- or otherwise retard radionuclide migration by ion exchange or surface adsorption properties. The chemical aspects of waste-rock interactions are currently under study.

3.4.5 Containment and Isolation Depth

This subject has been treated in Section 3.3. Depth of isolation is to provide a barrier of geologic materials between the waste and biosphere and also to protect the repository from surface environmental processes and from intrusion by man. Considerable flexibility exists to select the depth for optimum containment.

3.4.6 Avoidance of Resources

The repository site should be in an area of low resource potential to avoid the risk of future accidental exposure of the repository. In addition, a sufficient area surrounding the site should be free from man's activities such as borings, mines, wells, and land development which could endanger the short- and long-term integrity of the waste facilities. Conflicts between demonstrably stable sites and sites with a potential resource content may occur, but the capability exists to make such trade-offs on a rational basis.

3.4.7 A Systematic Approach to Siting

Based on the various selection criteria discussed in the previous sections, a systematic, logical approach to site selection will result in a safe repository. As stated in Ref. 53 the steps in the selection evolve from the general to the specific according to the process:

1. Identification of a region in which potentially favorable geologic environments are thought to be present;
2. Selection of one or more specific sites within that region for detailed examination; and

3. Characterization of such sites to determine whether they are suitable for a repository.

A similar, though not identical, sequence is recommended in Ref. 67:

1. Regional Reconnaissance
2. Feasibility Study
3. Detailed Engineering Investigation.

The essence of both plans is to begin with required characterization based on literature surveys, aerial photographs, remote-sensing, analysis of geophysical data, and limited borehole and laboratory testing. An illustration of the screening process currently underway are the Paradox Basin studies in Utah and Colorado (Ref. 74) under the National Waste Terminal Storage Progam.

After completion of the first phase, geologic feasibility is established and the selection then proceeds to relatively detailed investigation of a small number of sites in various media. In this second phase detailed characterization of the subsurface geology and hydrology at each site take place, with greater emphasis on borehole drilling, water age dating, and determination of mechanical, thermal, hydrologic, and chemical properties in the laboratory.

Phase III continues to narrow the choice of sites, building on confirmation of earlier findings but also searching for flaws, testing <u>in situ</u>, and providing data needed for engineering designs. Waste Isolation Pilot Plant site characterization in New Mexico salt beds exemplifies stage 2 and stage 3 type work.

This systematic approach to site selection assures, in the early stages, that no reasonable candidate sites will be overlooked, and assures, in the later stages, that the fittest candidate sites are indeed safe through intensive characterizations.

3.4.8 Summary

Conservatism in siting provides an assurance that risk to the public is small. Such assurance can be given because:

- Those properties of the hydrology and the geology that impact safety are understood and positive evidence for stability can be found in many geologic media and locations
- The physical properties of the rocks in specific sites can be well characterized, including the type and location of flaws
- Plans for systematic screening and selection of sites are well accepted.

3.5 EVIDENCE FROM PAST EXPERIMENTS

In addition to the analytical modeling, engineering design, and site selection procedures discussed in the preceding sections, there is a growing body of experimental evidence that provides confidence in the safety of deep geologic burial. Conceptually we can divide the arenas for data acquisiton into three categories. These are: laboratory experiments, field experiments, and in situ experiments.

Laboratory experiments, for the most part, involve reasonably small waste or rock specimens for the purpose of determining specific properties needed for input to risk prediction models or to support the site selection process. As we have already touched on laboratory experiments in Section 2.4, this section will emphasize field and in situ experiments and tests.

Field experiments and tests involve characterization at a particular site in the local geology and hydrology, with emphasis, if possible, on the potential interaction with radioactive nuclear waste. Generally, the extent of the experiment will encompass many times the amount of rock available to laboratory experiments; thus some of the heterogeneous structure in the rock can be included. Also, the difficulties often associated with understanding the response of small-scale laboratory samples are not encountered.

Field experiments may be conducted at or near the surface of the earth. The configuration of such an experiment, however, does not replicate a repository closely, nor is it supposed to. The intent is to obtain data on a well chosen, simplified test system that is comprehensible and that is located within a realistic geologic setting.

In situ experiments go one step further and attempt to reproduce the behavior of a portion of an actual repository design in a deep burial chamber. For instance, waste canister dimensions, spacings, and thermal output might be simulated as well as burial room characteristics.

In this section, we describe many of those past and on-going field and in situ tests of deep geologic waste disposal that have already contributed or that have the potential for contributing in a major way to safety assurance. A portion of that assurance is derived from the acquisition of high quality and necessary data; another portion is obtained whenever there is reasonable agreement between test results and model predictions. The list of tests does not purport to be exhaustive or complete.

The following in situ programs are discussed: Project Salt Vault, Stripa, and Avery Island.

The following field test programs are discussed: Chalk River, Swedish migration experiments, Conasuaga Shale, Savannah River, and Snake River.

3.5.1 Project Salt Vault

Project Salt Vault (Ref. 73) was a test of the disposal of high-level radioactive waste solids in an inactive salt mine in Lyons, Kansas. It is the only in situ vault test to have been completed in the United States. The project was conducted from 1965 to 1967 under the auspices of the AEC by ORNL personnel to demonstrate the feasibility and safety of underground disposal and to demonstrate the techniques and equipment that might be used in an actual disposal facility.

Spent fuel assemblies from the Engineering Test Reactor at Idaho Falls provided sources of radioactivity. These were supplemented with electrical heaters to simulate decay heat that would be generated by real wastes. The main objective of this experiment was to collect data on the properties and behavior of in situ salt for design purposes. The heating elements were located in an array of holes in the floor of newly mined rooms at a depth of about 1000 ft. Fuel assemblies and electric heaters were separated, but otherwise identically arranged in order to elucidate the effects of radiation on salt.

In the area of rock mechanics and thermal effects many vital properties of the salt formation were successfully measured; these included thermal conductivity, heat capacity, thermal expansion coefficients, stress-strain characteristics, elastic and plastic constants, and creep behavior. Of special interest were stresses and stress changes in pillars, accelerated plastic deformation at elevated temperature, and expansion of the salt due to temperature increases, all effects that may affect the integrity of the mine structure. The information derived from those measurements has provided a basis for the design of a bedded salt repository. A current view is expressed in Ref. 70: "Project Salt Vault (PSV) provided one of the first demonstrations of the effects of thermal loading imposed on a salt mine. It is of interest to note that the PSV results have been reproduced analytically through specific independent computer simulations."

A second topic of importance is brine migration as studied in Project Salt Vault (Refs. 52 and 70). Brine inflow rates to buried canisters were measured and compared to predicted migration rates based on a diffusion model and laboratory data on heated salt crystals. Reasonable agreement was noted; and insight into the role of temperature and temperature gradients on the rate of brine migration was obtained. This work has led to the conclusion that brine inflows for small (approximately 1%) volume fractions of inclusions are not large (Ref. 75).

Effects of radiation on salt were found to be negligible, both in terms of the thermal and mechanical properties of the salt and in terms of energy storage and release due to formation of lattice defects. At temperatures in excess of 150°C annealing was found to occur, a process that suppresses energy storage and removes it as a topic for concern.

An excellent summary of the value of Project Salt Vault found in Ref. 73 and also quoted in Refs. 75 and 76 is:

> "With the completion of this experiment, it can be concluded that most of the major technical problems pertinent to the disposal of highly radioactive wastes in salt have been resolved. Project Salt Vault successfully demonstrated the feasibility and safety of handling highly radioactive materials in an underground environment. The stability of the salt under the effects of heat and radiation has been shown, as well as the capability of solving minor structural problems by standard mining techniques. The data obtained on the deformational characteristics of salt have made it possible to arrive at a suitable design for a mine disposal facility."

Similarly the GEIS (Ref. 7) has noted: "This experiment obtained data on the properties of salt at elevated temperatures and indicated that there were no immediate detrimental effects on the stability of the salt as a result of exposure to heat or radiation."

3.5.2 Chalk River

The ability of a glass matrix to inhibit the leaching of radioactive wastes contained in the glass structure is an important element to the multi-barrier concept. Canada is the only country to have field tested nuclear waste stored in glass.

In June 1960 at Chalk River 25 pieces of nepheline syenite glass in the form of small hemispheres were placed in sand beneath the water table without any additional barrier so that they were exposed to flowing groundwater. Each block contained mixed fission products including 20 curies of ^{90}Sr. Leach rates were determined through monitoring the ^{90}Sr in the groundwater downstream radiochemically. This test was subsequent to an earlier (1958) experiment which produced leach rates too low to measure (See Refs. 77 through 79).

During the first fifteen years of the experiment, leach rates were found to drop by a factor of one thousand from a starting value of 4×10^{-8} g/cm^2-day, indeed a favorable result. The most recent data estimates an even lower leach rate - from 8 to 9×10^{-14} g/cm^2-day (Ref. 78). Furthermore, a sampling in 1971 showed that the leached strontium had migrated 33 m from the glass blocks, in good agreement with earlier predictions. It should be noted that the long-term leach rate of glass assumed by most safety assessment studies (see Chapter 1) is one million times the rate measured at Chalk River. Even the low ambient temperatures of the Chalk River experiment cannot account for these large differences.

The Chalk River experience has provided considerable confidence in the ability to contain wastes in glass for substantial periods of time in a severe environment -- direct exposure to flowing groundwater. It has furthermore corroborated our ability to predict migration rates in a real geologic field setting and augmented our understanding of the mechanisms for glass leaching in flowing water.

3.5.3 Stripa Experiments

In Stripa, Sweden, a series of experiments has been carried out to investigate various aspects of radioactive waste storage in granite (Ref. 80). The program, a joint technical effort between the United States and Sweden, was initiated in 1977 and is being conducted in a region over 1000 ft underground adjacent to an abandoned iron mine. The Stripa work represents the first in situ focus on hard crystalline rock as a burial medium for nuclear waste.

The Swedish portion of the program (Ref. 5) under the direction of the Swedish Nuclear Supply Company (SKBF) involves a number of important investigations:

- Rock characterization, including fracture network mapping, core surveys, and water injection tests
- Rock stress measurements of the primary stress state
- Mechanical and physical properties of the Stripa granite
- Rock permeability as a function of pressure and temperature
- Thermal stress changes due to local heating
- Water analysis.

The American portion of the cooperative program has been performed by the Lawrence Berkeley Laboratory (LBL) (Ref. 81). The LBL work, in addition to certain instrumentation and data handling support activities, has been concentrated in three areas:

- Full-scale heater experiments that investigate short-term temperature effects
- Time-scaled heater experiments that examine the long-term thermal loading effect by reducing the linear dimensions of the experiment
- Assessment of the hydrological conditions of fractured granite for various pressures and temperatures.

The KBS Stripa studies have provided highly useful information for their safety studies, in particular indication that Swedish granite is <u>highly impervious</u> (Ref. 11). Measurements of rock stress are in close agreeement with theoretical values (Ref. 5). Mechanical and thermal properties of the Stripa granite are found to be typical of other common granites; this fact enhances confidence in models that utilize granite data. Results of water analyses, such as pH and chemical composition, are valuable for leaching, corrosion, and nuclide migration studies.

The U.S. work has not been fully completed, owing to the long duration of the heater tests. Preliminary results have, however, been obtained. According to Ref. 81:

> "The predicted temperature fields for both experiments were calculated before turning on the heaters using only a laboratory measurement of the thermal diffusivity and a mathematical model appropriate for the known geometry and boundary condition. The agreement between predicted and measured temperature fields over the past several months since these experiments started is excellent. This is true for both full-scale and time-scaled results, and is a good indication that in designing waste repositories there should be no problem in predicting the thermal response."

The measured mechanical response (displacements) of Stripa rock adjacent to heaters has yielded very valuable data. Predicted displacements were larger than measured values (a conservative result) owing to the presence of fracture discontinuities in the rock. Hydrology work is still underway.

3.5.4 Swedish Migration Experiments

Field tests concerning retardation effects were conducted at Studsvik, Sweden, for the National Council on Radioactive Waste Management (Ref. 5). In these tests, tracers were injected into boreholes in fissured rock with heavy water flow. The transit time of the water was determined with the aid of a water tracer. The test confirmed the retardation effect on strontium and cesium.

In a later study, which was commissioned by KBS, the tests were repeated after the same rock sections had been sealed with bentonite grouting. The tests are still in progress, but it can be noted that strontium added to the water had not (after 4 months) arrived at the metering point located 50 meters from the borehole where it was injected. The transit time of the groundwater over this distance, for comparison, was about 10 hours prior to sealing.

Another aspect of the Studsvik work regarding the dispersion process for radionuclides is quoted in Ref. 5:

> "On the basis of the measurements at Studsvik, where inter alia strontium was used as a tracer nuclide, a broadening of the front was noted in agreement with the model which was used."

3.5.5 Other Field Experiments

In this section we mention, briefly, a number of other test programs conducted in the field that to date have made only fragmentary, although potentially valuable, contributions to the state-of-the-art of deep burial technology and its safety implications, principally owing to their on-going nature or to their limited goals.

- Conasauga Shale. A near-surface heater experiment was conducted in the Conasauga Shale formation of the Oak Ridge Reservation in Tennessee (Ref. 82) by Sandia Laboratories under the direction of the Office of Nuclear Waste Isolation. These tests were initiated in 1977 and concluded late in 1978. A significant result of the Conasauga efforts, according to Ref. 45 is:

  "The observed cooling rates for thermocouples lying adjacent to or below the heater were satisfactorily predicted by the CINDA model of the experiment."

- Snake River. Studies are underway at the Radioactive Waste Management Complex, Idaho of subsurface migration of radionuclides away from disposed radioactive wastes (Ref. 83). Samples of subsurface material have been obtained over the past nine years from ore borings and analyzed for radionuclide content. The number of predicted positive results has compared very closely with the number of observed positive results. Based on core drilling and subpit sampling data, "it appears that radionuclide migration has been restricted to a few centimeters below the waste and apparently poses no hazard to the Snake River Plain Aquifer."

- Savannah River. A program is underway at the Savannah River Plant (SRP) to sample and analyze earthen trenches containing transuranium (TRU) nuclides buried unencapsulted (Ref. 84). The purpose of this program is to determine TRU migration in the soil and the chemical species and mineral association of plutonium leached by natural groundwaters.

  Current results from a survey coring of the waste trenches show that leaching and migration of plutonium in acidic SRP soils has been minimal over the 15 to 25 years the wastes have been buried. A favorable conclusion from this work, quoting Ref. 84, is: "Thus the buried plutonium is not expected to move rapidly into the groundwater systems at the SRP site."

- Avery Island. At Avery Island, Louisiana, in situ tests to acquire data to be used in model development are continuing. The overall objective of these tests is to reconfirm and validate the Project Salt Vault results for dome salt deposits. Electrical heaters are used to simulate the thermal characteristics of radioactive waste. Data will eventually be obtained on brine migration, temperature distributions, stresses in and stability of salt, and corrosion of candidate sleeve materials (Ref. 82). According to Ref. 45,

> no unexplicable anomalies have been discovered in the measured temperature, stress, and displacement responses. No results from brine movement experiments are, however, yet available. It is highly likely that these experiments, as mentioned in the IRG report (Ref. 53), will augment our knowledge of salt rock mechanics.

3.5.6 Summary

In situ and field test experiments have been highly successful. In particular the Salt Vault and Stripa experiences have made large contributions to our knowledge of thermal effects, rock mechanics, hydrology, and excavation technology. There have been no serious discrepancies between observed and predicted phenomena; this fact tends to give confidence that our understanding of the fundamentals is adequate enough to design an acceptable repository. Because of these successes and because of the need to characterize potential burial sites in alternate media, we may expect an increasing reliance on large-scale experimental evaluations in the future.

3.6 SUMMARY

This chapter has dealt at some length with two important concepts and their relationship: confidence and conservatism (as they relate to the safe disposal of nuclear wastes). Confidence that deep geologic disposal does not expose the public to undue, unnecessary risks has to be obtained predominately by exercising technology competently and extensively. Most particularly, that aspect of technology most relevant to sound judgments of confidence is risk assessment.

Risk assessments, if sound, require a substantial amount of input information in the form of basic scientific knowledge and experimental data. Such information is combined in safety analyses, which predict the performance of waste disposal schemes. Obviously analyses contain inherent uncertainties; uncertainties may certainly affect confidence in the safety of waste disposal if they are unduly large.

Technical experts in the field of waste disposal are mandated to reduce uncertainties in long-term risk predictions. The general approach to date has been one of conservatism. In this context conservatism has a multiplicity of meanings. Conservatism implies:

- Performing analyses employing well understood, verified models and using parameter values that tend to give pessimistic (higher risk) results
- Providing repository designs that minimize the impact on the local geology and minimize the likelihood of egress of the contained waste
- Providing waste form packages that maintain integrity for a sufficient period of time
- Selecting repository sites with a well characterized, relatively homogeneous, and stable geologic-hydrologic structure
- Acquiring data over a wide variety of test conditions, both nominal and extreme, in laboratory, field, and *in situ* environments.

The scientific community has been responsive and responsible in applying conservatism to the technology of nuclear waste disposal. The bottom line of these technical efforts is conceptualized in the so-called multi-barrier approach. Between buried nuclear waste and man, many natural and engineered barriers exist that retard or even prevent the passage of radioactive materials. The barriers consist of the waste form, the repository, the geology, and the biosphere (of which man is part). The existence of these barriers provides defense-in-depth and a resulting confidence that the containment of nuclear waste is technically feasible and can be performed with completely negligible risks to future generations.

4. CONCLUSIONS

This volume presents a basis for confidence that disposal of spent nuclear fuel can be accomplished safely. Confidence is based on positive findings in three key areas:

- The results of quantitative assessments of nuclear waste disposal safety
- Understanding of issues affecting confidence in long-term performance predictions
- The technical basis, i.e., the scientific and engineering information that justifies acceptance of the assessments as conservative estimates of safety.

Safety Assessment - Safety assessments employ mathematical modeling techniques to predict the long-term consequences to the public following disposal of nuclear wastes. Safety assessment analyses support the contention that deep geologic disposal can be achieved with negligible risks to future generations. The most realistic and reliable analyses predict doses which are a fraction of the variations in natural background radiation even under conditions which assume partial failure of engineered and geologic barriers. Such impacts occur at times from hundreds of thousands to millions of years in the future. The most conservative and pessimistic analyses predict levels of radiation that are no greater than those experienced from some naturally deposited uranium ore bodies. These worst-case but credible analyses bound the maximum level of potential dose to man. It can be concluded from these studies that for a reasonably engineered repository and an appropriate site no significant impacts to future generations are to be expected.

Safety assessment analyses are based on physical data that have been gathered over the years by geologists, geochemists, hydrologists, geotechnical engineers, mining engineers, and others. From this body of data it may be concluded that numerous sites exist that would provide the conditions desirable for waste isolation and containment. Furthermore, the capability to properly design and construct the repository is supported by the judgment of geotechnical and mining engineers. These conclusions regarding the expected safety of the geologic disposal concept and confidence in the implementation of the concept have been supported by several prestigious review groups from the American Physical Society, the National Academy of Sciences, and the American Nuclear Society. Safety assessment work, therefore, has provided confidence that safe disposal can be achieved.

Issues in Prediction of Repository Performance - Confidence in the adequacy of long-term safety results can be based on comparisons to natural radioactive and non-radioactive hazardous materials. There are many natural substances whose toxicity is comparable to that of aged nuclear wastes. Nuclear wastes will be buried with great care is specially chosen locations and with engineered barriers to prevent or reduce release to the environment. Natural hazardous materials are not located with such care. Deposits of toxic ores can be located within flowing groundwater systems and can be present at or near the earth's surface; yet even so their effects on human health are rarely significant. Additional confidence is obtained from a natural analog to a waste repository: the Oklo reactor in Africa. Oklo demonstrates clearly the high degree of containment possible by geologic media.

Uncertainty in predictions of long-term safety by mathematical modeling techniques stems from several sources.

The principal source of modeling uncertainty is the specification of future scenarios for the release of waste to the biosphere and estimation of their probability of occurrence. Scenarios which could impair performance of a repository have been comprehensively identified. Although it is by no means certain that all repository failure modes have been identified, the scenarios already studied bound the consequences of repository failure.

Although some uncertainties can be expected to be resolved during site-specific studies and by more sophisticated modeling efforts, other uncertainties by their very nature can never be resolved. The existence of residual uncertainty is inherent in the risk assessment process. The issue at stake here is whether existing uncertainties are <u>significant</u>. Analyses to date strongly support the position that the degree of risk from nuclear waste disposal can be reliably <u>bounded</u> by safety analyses. Uncertainties in safety predictions do exist, but are not sufficiently large to undermine confidence in the ultimate safety of waste disposal. This confidence is based on:

- The very small risks predicted by current studies
- Conservatism in the choice of scenarios analyzed and the parameter values employed in the analysis
- The large number of potential mitigating mechanisms, both natural and engineered, which have not been taken into account in past safety analyses. Many analyses assume, for example, direct and immediate contact of waste with groundwater and do not give credit to waste package integrity or to the likely isolation of the repository from groundwater flows.

Proper assessment of repository performance requires the systems approach. A repository system (waste package, repository design, and geologic surrounding) which is predicted to perform acceptably need not be optimal in all respects. It is the system as a whole which must perform reliably and effectively. For example, while we know enough to find many fully acceptable sites, we will never know enough to find optimal sites. Nor should we try. The objective is to locate a site and then to design a repository so that the overall system will provide the necessary degree of isolation and containment. Short-sighted focusing on any single element of the system is not justified.

Technical Basis for Confidence - Current scientific and engineering understanding supports the viewpoint that nuclear waste can be disposed of safely. The following conclusions can be drawn from available information:

- Conservatism is the appropriate approach to modeling repository performance; it implies employing well understood, verified models and using parameter values that tend to give pessimistic (higher risk) results. Safety analyses have, to date, followed a conservative approach to risk assessment.
- The existence of natural and man-made barriers provides a defense-in-depth and a resulting confidence that containment of nuclear waste is technically feasible.
- Engineered barriers should be emphasized, including repository designs that minimize impact on the local geology and minimize the likelihood of egress of the contained waste. Waste form packages that maintain integrity for a sufficient period of time contribute to a conservative approach. Engineered barriers that can achieve an adequate level of performance can be developed.

- Suitable repository sites with a well characterized, relatively homogeneous and stable geologic-hydrologic structure can be found.

- Additional confidence is derived from the acquisition of needed data over a wide variety of test conditions, both nominal and extreme, in laboratory, field, and in situ environments. Such data, while necessary for implementation of the geologic disposal option, is not necessary to provide confidence that safe disposal can be achieved. Enough is known now to conclude that safe disposal is possible.

This volume shows that there is extensive information available on all technical factors relevant to disposal safety. Perhaps the most compelling aspect of the technical basis for confidence in disposal safety is the fact that all information, from all technical sectors, indicates that reasonable prudence, regulation, and conservatism will attain safe disposal. In other words, there is no evidence that heroic efforts, technical breakthroughs, or extreme regulatory action is necessary.

The extensive information base now available has already been used to evaluate conceptual repository systems. These efforts have all shown that reasonable conservatism in siting and designing the repositories, coupled with an effective regulatory review process, will assure long-term safety.

APPENDIX A
BIBLIOGRAPHY

This chapter provides a comprehensive listing of pertinent literature, with annotations concerning content that particularly relevant to the establishment of a basis of confidence for waste disposal safety. A ready reference summary table (Table A-1) is provided to permit a quick topical cross-referencing of the literature reviewed. Among the subjects classified are the following:

- Development of hazard indices for radioactive waste
- Comparison of nuclear waste hazards with those of other substances
- Handling of uncertainty in data or models
- Testing and research -- in situ characterization
- Conservatism in analyses
- Conservatism in engineered features
- Use of the multiple-barrier concept.

TABLE A-1
CATEGORICAL BREAKDOWN OF LITERATURE REVIEWED

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	Type of Study		Topics						
	A Safety Analysis	Developmental Work or Review	Development of Hazard Indices	Comparison to Non-HLW Hazards	Treatment of Uncertainty	In Situ Characterization	Conservatism in Analyses	Conservatism in Engineered Features	Multiple Barrier Concept
1) APS Study		X					X		
2) Arthur D. Little (EPA)	X	X	X						X
3) Berman, et al.; Cohen, J. J.	X		X		X				X
4) Bradley & Corey; NAS (Savannah)		X				X			
5) Bredehoeft, et al., (USGS)		X							X
6) Burkholder; Schneider & Platt	X				X		X		X
7) California Energy Commission		X							
8) Campbell, et al.; Dillon; Iman		X			X				X
9) Claiborne & Gera	X						X		
10) Cohen, B. L.	X		X	X			X		
11) de Marsily, et al.	X								X
12) GEIS (DOE)	X		X	X	X		X	X	X
13) WIPP EIS (DOE)	X					X	X		X
14) Girardi, [illegible], et al.	X			X			X		
15) Hill & Grimwood; Hill	X				X			X	X
16) IRG Report		X							
17) JPL Report		X							
18) KBS Studies	X			X	X	X		X	X
19) Logan & Berbano (EPA)	X					X	X		
20) McGrath		X	X	X	X				
21) NAS Report		X						X	
22) Pigford & Choi		X	X	X			X		X
23) Tonnessen & Cohen	X		X	X					

1) "Report to the American Physical Society by the Study Group on Nuclear Fuel Cycles and Waste Management," Reviews of Modern Physics, Vol. 50, No. 1, Part II, January 1978.

This study provides a major independent assessment of the technical issues in waste management and their principal economic, environmental, and safety implications.

The principal conclusions drawn are: 1) many feasible sites exist for satisfactory isolation of radioactive waste, 2) current knowlege and technology are adequate to design and locate a suitable waste repository of the conventional mined type, and 3) groundwater is the only transport medium of importance for radioactive waste emplaced in a repository.

Supportive analysis is included for waste transport in a typical groundwater basin. A reference case and a scenario where a major fault exists near the contaminant source are studied. In both cases no release occurs within 800,000 years. Because neither radioactive decay nor retardation of radionuclides in the rock are considered, these results are conservative. The model, however, assumes that all the boreholes and shafts in the repository region are adequately sealed. This may not be the case over such long periods. The possible failure of these seals is considered in Berman, et al.

2) "Technical Support of Standards for High-Level Radioactive Waste Management," (3 Vols.), Arthur D. Little, Inc., for the U.S. Environmental Protection Agency, Office of Radiation Programs, Report No. EPA 520/4-79-007A, 1977.

As part of its task of developing and promulgating environmental standards for the disposal of high-level radioactive wastes in deep geological repositories, the U.S. Environmental Protection Agency (EPA) contracted with Arthur D. Little, Inc., to do a technical-support study for waste management standards. The study is divided into four tasks: source term characterization and definition, effectiveness of engineering controls, assessment of migration pathways, and assessment of accidental pathways.

The quantities and characteristics of high-level wastes from several alternative nuclear-power fuel cycles are determined. An analysis of the technology necessary for engineering effective barriers to radionuclide transport in geomedia is presented. Finally, generalized models are developed to form a conceptual background for the analysis of radionuclide migration from the repository, through geologic media to the biosphere, and through various pathways to man.

3) Berman, L.E., Ensminger, D.A., Giuffre, M.S., Koplik, C.M., Oston, S.G., Pollak, G.D., and Ross, B.I., "Analysis of Some Nuclear Waste management Options," The Analytic Sciences Corporation, Report No. UCRL-13917, October 1978.

*Cohen, J.J., et al., "Determination of Performance Criteria for High-Level Solidified Nuclear Waste," Lawrence Livermore Laboratory, Report No. NUREG-0279, July 1977.

The models developed and applied in Berman, et al., represent a comprehensive approach to the long-term generic assessment of mined disposal of nuclear wastes. This work was carried out by The Analytic Sciences Corporation (TASC) in association with the Lawrence Livermore Laboratory, Golder Associates (a mining engineering firm), and Geotechnical Engineers, Inc. The objective of this study was to construct a flexible and efficient model for the analysis of both generic and potential repository sites.

On the basis of previous studies (Cohen, J.J., et al., Claiborne and Gera, and Schneider and Platt), it was determined that the primary means of escape of radionuclides from a decommissioned repository would be transport in groundwater. Models are therefore constructed for mechanisms which would permit transport of waste in groundwater and in surface water systems, and for the dose to humans that would result.

Two generic repositories having shale and salt as emplacement media are studied. Both repositories are assumed to have an aquifer below under pressure and another aquifer above -- a condition which makes release upward through the repository relatively likely. Ranges of values for the parameters describing the repository sites are determined by the participating geologists. Sensitivity and uncertainty studies are used to assess the effect of parameter variation on model results.

The NUTRAN (NUclear TRANsport) program is used by Berman, et al. to assess post-emplacement risk from waste in the two generic repositories. This program consists of a subsurface waste transport model (WASTE), a biosphere and dose simulation routine (BIODOSE), and an isotope generation and depletion code (ORIGEN). Stream tubes are used to model flow path segments and a one-dimensional waste transport equation (identical to that used by deMarsily and Logan and Berbano) is

*Cohen, et al., contains an early scoping analysis by TASC whose purpose was to delineate a methodological approach to the risk assessment problem. This early work was superseded by Berman, et al.

solved within each segment. An extremely fast and efficient Green's function solution technique is used which permits simulations with many stream tube segments.

The major conclusion of Berman, et al., is that the dose to an individual resulting from leakage of high-level nuclear waste from a deep geologic repository can be held to a small fraction of background, unless a water well is drilled in the repository area.

4) Bradley, R.F., and Corey, J.C., "Technical Assessment of Bedrock Waste Storage at the Savannah River Plant," E.I. DuPont De Nemours and Co., Savannah River Laboratory, Report No. DP-1438, November 1976.

"An Evaluation of the Concept of Storing Radioactive Wastes in Bedrock Below the Savannah River Plant Site," Committee on Radioactive Waste Management, National Academy of Sciences, Washington D.C., 1972.

Long before significant attempts were made to assess the risks from disposal of commercial wastes, analyses were performed on the disposal of radioactive military wastes. As early as 1960, studies were conducted on the feasibility of long-term storage of liquid and sold defense wastes in the bedrock beneath the Savannah River Plant. These nuclear wastes were to be disposed of in their original condition with no view towards conversion to another waste form.

The safety analysis and in situ studies cited above were performed by E.I. duPont de Nemours Co., which runs the Savannah River Plant. Their studies were under continual review and evaluation by an advisory committee of the National Acedemy of Sciences.

The proposed concept was eventually put aside, primarily because of the concern voiced over the proximity of the site to both the Tuscaloosa aquifer and the Savannah River. An important problem was the possible contamination of the very large and prolific fresh water aquifer which overlay the disposal site. Nevertheless, this early work provides a considerable body of information which advances the understanding of long-term disposal risks.

5) Bredehoeft, J.D., England, A.W., Stewart, D.B., Trask, N.J., and Winograd, I.J., "Geologic Disposal of High-Level Radioactive Wastes -- Earth-Science Perspectives," U.S. Department of the Interior, Geological Survey, Circular 779, 1978.

This monograph deals with the earth-science viewpoints of the difficulties and uncertainties connected with the geologic disposal of high-level radioactive waste. The behavior of host rocks under thermal, mechanical, and chemical stresses is said to be sufficiently uncertain to make the short-term retrievability of waste from the repository a design requirement. The report also suggests that a systematic examination of alternate media be carried out to identify sites that meet broad criteria for tectonic stability, slow groundwater movement, and long flow paths to the surface. Characterization of groundwater transport systems around potential repositories is deemed important, with special emphasis placed on the gathering of empirical data on fracture flow and sorption-desorption phenomena.

The concept of the multiple-barrier or "defense-in-depth" philosophy for radionuclide containment is upheld, and research directions are suggested. Some of these recommendations have already been fulfilled in the literature reviewed here (cf., Berman, et al., Burkholder, et al., Hill and Grimwood, KBS).

6) Burkholder, H.C., et al., "Incentives for Partitioning High-Level Waste," Battelle Pacific Northwest Laboratory, Report No. BNWL-1927, November 1975.

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

Schneider, K.J. and Platt, A.M., eds., "High-Level Radioactive Waste Management Alternatives," Report No. BNWL-1900, Battelle Pacific Northwest Laboratory, May 1974.

A sequence of reports by Battelle Pacific Northwest Laboratory describes the development of a risk assessment method for analyzing geologic disposal of radioactive wastes.

The authors estimate the consequences from release of radioactive materials from a high-level waste repository into an aquifer. Groundwater is assumed to transport the radionuclides into a major river. The waste form and the surrounding geologic, hydrogeologic, and geochemical environment are analyzed, and doses are calculated for individuals living within the region of influence of the site at various times after disposal. By varying the values of important parameters, the sensitivity of the dose consequences to the degree of effectiveness of multiple barriers is estimated. The results shown that for "reasonable" isolation conditions the potential maximum incremental radiation doses are of the same order as or less than doses from natural sources. The parametric variations show that the dose results are 1) strongly sensitive to the radioisotope inventory of the waste and to the effectiveness of chemical retardation on radionuclide transport, 2) moderately sensitive to the leach rate, and 3) weakly sensitive to the time when initial contact of groundwater and the waste occurs (particularly after the first 1000 years).

7) "Status of Nuclear Fuel Reprocessing, Spent Fuel Storage, and High-Level Waste Disposal" (DRAFT), Nuclear Fuel Cycle Committee, California Energy Commission, January 1978.

In June 1976 the California Legislature passed three bills in response to the public debate over nuclear power. Among other things, these required that it be determined whether or not a demonstrated technology or means for permanent, terminal disposal of high-level nuclear waste exists. The California Energy Resources Conservation and Development Commission (ERCDC) was charged with making this determination.

Citing the JPL Report (English, Miller, et al.) and other sources, the ERCDC reached the following controversial conclusion: "...a technology for the permanent and terminal disposal of high-level waste has not been developed and demonstrated". This finding is based on the conclusion that "in situ, large-scale, and laboratory data from controlled experiments" are required in order to "demonstrate" safety. It is important to note, however, that several key studies, some of which are reviewed in this appendix, have emerged since the ERCDC report was published. These studies have demonstrated enhanced confidence in several issues of waste disposal addressed by the ERCDC. These include assessment of the potential for escape of waste through boreholes and shafts (Berman, et al.), in situ testing for responses and reactions of the media (KBS studies), and agreement on specific criteria for the characteristics sought in a geological formation (NAS report).

8) Campbell, J.E., et al., "Risk Methodology for Geologic Disposal of Radioactive Waste: Interim Report," Sandia Laboratories, Report No. NUREG/CR-0458, October 1978.

Dillon, R.T., Lantz, R.B., and Pahwa, S.B., "Risk Methodology for Geologic Disposal of Radioactive Waste: The Sandia Waste Isolation Flow and Transport (SWIFT) Model," Sandia Laboratories, Report No. NUREG/CR-0424, October 1978.

Iman, R.L., et al., "Risk Methodology for Geologic Disposal of Radioactive Wastes: Sensitivity Analysis Techniques," Sandia Laboratories, Report No. NUREG/CR-0394, October 1978.

The report by Campbell, et al. and two related reports by Dillon, et al., and Iman, et al., summarize the status of research performed at Sandia Laboratories for the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission. The objective of this research is to develop analytical methods for risk assessment for use by the NRC in licensing waste repositories. Although no assessments of potential risk are made, the report is nonetheless important because of its unique approach to simulation modeling.

The overall problem is divided into four natural components: local waste release due to initiating processes or events, groundwater transport to the biosphere, movement and accumulation in the environment and man, and health effects. The waste release scenarios involve either self-induced processes (e.g., thermal stresses on host rock) or externally-induced processes (e.g., faulting or borehole drilling). The former are deterministically modeled using the DYNAMO code, while the latter are probabilistically modeled. Groundwater transport is simulated by the three-dimensional SWIFT code originally developed for the U.S. Geological Survey. The code was modified to include radioactive decay and radionuclide sorption. The Sandia environmental transport model is a highly sophisticated and flexible multicompartment model for determining the long-term distribution and accumulation of nuclides in the environment. The model is very similar in form to those developed in other studies (Berman, et al., KBS, and particularly Logan, et al.). A unique feature of the model is the capability of directly handling radionuclide production from a parent radionuclide.

9) Claiborne, H.C. and Gera, F., "Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico," Oak Ridge National Laboratory, Report No. ORNL-TM-4639, October 1974.

In this study, potential failure mechanisms and their consequences are analyzed for a repository in bedded salt in New Mexico. Probabilities are also estimated for a number of events that could affect containment. Containment failure mechanisms considered are: sabotage, nuclear warfare, drilling, deterioration of borehole and shaft seals, impact by a meteor, vulcanism, faulting, tectonic activity, erosion, salt dissolution by groundwater, and the existence of an undiscovered permeable fracture zone. Sabotage is dismissed as being too difficult to achieve a release of radioactive wastes from the repository. Nuclear warfare as a means of excavating the waste is dismissed because of the extremely high nuclear yield which would be required. The consequences of drilling into the repository are felt to be minor.

Consequences are calculated in a conservative manner for meteorite impact and faulting. Impact by a giant meteorite directly into the waste repository is identified as the event with the most serious potential consequences. However, the likelihood that such an event would occur is so small (1.6×10^{-13}/yr) that it can readily be dismissed as insignificant. Faulting is identified as a more likely means of waste containment failure and subsequent contact of the waste directly with circulating groundwater. However even if a major fault occurs, fault healing and other factors are shown to mitigate the biological effects on man.

Based on their analysis of failure events and potential consequences, Claiborne and Gera conclude that disposal of high-level waste at this site will result in negligible risks to future individuals or populations. This study stands as a competent and important piece of work upon which many later, more sophisticated analyses are based.

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

This paper presents a highly original and intuitive assessment of the long-term risks from the mined disposal of high-level wastes. The approach avoids all the complex and detailed modeling on which other studies are based. Instead, Cohen argues that an atom of buried waste is no more likely to reach man than an average atom of radium or uranium in the rock or soil above it. The hazard of the waste can then be determined quite easily by comparing the average quantities of natural radium in rock to that in man.

The calculation of risk is carried out in three steps. First, Cohen computes, as a function of time after disposal, the number of possible cancers resulting from ingestion of all the HLW from 400 GWe-yr of nuclear electricity. He then multiplies the computed cancer risk by the average probability of an atom of waste being ingested by man (4×10^{-13}/yr). This probability was calculated by comparing the amount of radium in the soil to the amount of radium actually measured in human bone. (Cohen also obtained the same probability by an analogous procedure based on the observed concentration of radium in surface waters.) Finally the resultant risk versus time curve is integrated from the time waste is first assumed to reach man out to one million years. This gives the total number of eventual deaths (0.4) that may be expected within one million years from 400 GWe-yr of high-level nuclear waste. This study does an excellent job of placing the long-term risks of high-level waste in perspective.

11) de Marsily, G., Ledoux, E., Barbreau, A., and Margot, J., "Nuclear Waste Disposal: Can the Geologist Guarantee Isolation?," Science, Vol. 197, No. 4303, 5 August 1977, pp. 519-527.

This study examines the migration of radionuclides from solidified high-level reprocessing wastes in geologic formations. Five geologic media with properties ranging from highly effective to poorly effective in chemical retardation of radionuclides are considered. Results of the study are expressed as concentrations of radionuclides in groundwater discharging at the earth's surface. The major parameter varied in the study is the leach rate of the waste.

Release calculations are only performed for I-129, Np-237, and Pu-239 even though, under some assumptions, the transfer time to the earth's surface is only a few years. Other actinides, Tc-99, and some shorter-lived fission products should have been included to get more comprehensive results.

12) "Draft Environmental Impact Statement. Management of Commercially Generated Radioactive Waste," U.S. Department of Energy, Report No. DOE/EIS-0046-D, April 1979.

"Environmental Aspects of Commercial Radioactive Waste Management," U.S. Department of Energy, Report No. DOE/ET-0029, May 1979.

"Technology for Commercial Radioactive Waste Management," U.S. Department of Energy, Report No. DOE/ET-0028, May 1979.

The first document cited above is one of two draft environmental impact statements issued by the Department of Energy in April 1979 concerning the disposal of radioactive waste. This document, in compliance with the NEPA, assesses the environmental impacts associated with ten alternatives for managing high-level and TRU wastes. The analysis presented is supported by eight additional but separate volumes on the technology and environmental aspects of waste disposal. These are contained in the second and third documents cited above. Taken together, these reports strongly support the DOE proposal for conventional waste disposal in geologic formations -- i.e., mined repositories.

Detailed assessments of long-term environmental impacts are carried out only for the conventional disposal option. The conclusion drawn is that long-term environmental impacts are negligible for a properly located and designed repository. This conclusion is based on two principal factors:

- Favorable assessments of relative safety based on hazard indices
- Low risk levels calculated by consequence analyses of unlikely, worst-case accident scenarios.

13) "Draft Environmental Impact Statement. Waste Isolation Pilot Plant," U.S. Department of Energy, Report No. DOE/EIS-0026-D, April 1979.

In the draft environmental impact statement for the Waste Isolation Pilot Plant (WIPP), a facility to be located in New Mexico, an analysis is presented of potential long-term radiological impacts. Five release scenarios are chosen for detailed analysis. They are representative of the types of events that might occur as a result of human actions or natural geologic events. One scenario deals with the consequences of a drill shaft directly penetrating a waste canister. The other four scenarios deal with groundwater transport of waste and include: 1) direct connection of the aquifers above and below the repository by an unsealed borehole, 2) water inflow from the upper aquifer through the repository and back through a large wellbore, 3) molecular diffusion of waste upward from the repository to the aquifer through an open vertical fault, and 4) diversion of the upper aquifer's flow directly through the repository.

The conclusion is reached that impacts are insignificant even for the worst-case scenarios with the exception, however unlikely, of direct intrusion into the repository by man. The most likely long-term impact is zero due to the expected integrity of the massive and impermeable salt beds which contain the waste.

14) Girardi, F., Bertozzi, G., and D'Alessandro, M., "Long-Term Risk Assessment of Radioactive Waste Disposal in Geological Formations," Commission of the European Communities, Report No. EUR 5902.e, Ispra, Italy, 1977.

Bertozzi, G., et al., "Evaluation of the Safety of Storing Radioactive Wastes in Geological Formations: A Preliminary Application of the Fault Tree Analysis to Salt Formations," Proceedings: Workshop Organized Jointly by the OECD Nuclear Energy Agency and the Commission of the European Communities, Ispra, Italy, 23-27 May 1977.

This work was performed in Italy for the Commission of the European Communities. Girardi presents in some detail a fault-tree methodology for assessing the failure of the geologic barrier layer. Estimates are made of probabilities for initiating events in both salt domes and bedded salt as a function of time. Exhumation of the waste by man is identified as the most likely cause of failure during the first 10,000 years. After 10,000 years, release is predicted to occur primarily by circulating groundwater. No chemical retardation of the radionuclides is assumed.

The critical and in fact the only parameter affecting release in this model is the estimated leach rate for the vitrified waste. Following release from the glass, the waste is diluted by the water in the river. A biosphere transport model accounts for transfer of radionuclides to man by various pathways such as drinking water, air, vegetables, and animal products. The maximum projected doses for high-level wastes are on the order of 2-5% of natural radiation sources. TRU wastes were also included in the study and were found to cause slightly higher doses. Radionuclide buildup in the topsoil accounts, in part, for Girardi's conservative finding that inhalation of resuspended topsoil is a large contributor to dose.

15) Hill, M.D. and Grimwood, P.H., "Preliminary Assessment of the Radiological Protection Aspects of Disposal of High-Level Waste in Geologic Formations," National Radiological Protection Board, Report No. NRPB-R69, Harwell, U.K., January 1978.

Hill, M.D., "Analysis of the Effect of Variations in Parameter Values on the Predicted Radiological Consequences of Geologic Disposal of High-Level Waste," National Radiological Protection Board, Report No. NRPB-R86, Harwell, U.K., June 1979.

These two studies were carried out under contract to the United Kingdom Atomic Energy Authority on behalf of the Commission of the European Communties. The first is a preliminary assessment of the radiological consequences of geologic disposal of high-level waste. The second is an analysis of the sensitivity of the results of the preliminary assessment to the assumptions made and the values of the parameters used.

The first report by Hill and Grimwood is divided into two sections. In the first section, potential mechanisms that could lead to the release of waste are described and the probabilities of several of these events (a volcano, seismic activity, and a meteorite impact) are estimated. Release of waste due to circulating groundwater is identified as by far the most likely failure mode. In the second section, the consequences of groundwater circulation through the buried waste are analyzed. Doses to individuals and the population are found to occur primarily by the drinking water pathway. The maximum projected doses are on the order of 2 to 5% of natural radiation sources.

Preliminary sensitivity calculations are performed for five of the geologic transport parameters. These calculations show that both the nuclide transport and leach resistances are important controllers of the projected doses for the situations investigated. Although the data available to Hill and Grimwood were uncertain, the uncertainties generally tended in the direction of lower expected doses. Thus, conservatism in the analyses is a significant feature of the study.

The second report examines in more detail some of the assumptions made in the previous report and determines the sensitivity of the results to the values chosen for the more important parameters. The sensitivity analysis shows the relative importance of the waste canisters, the waste form, and the geologic barrier to radionuclide migration in determining potential doses. Peak doses are seen to be strongly dependent on groundwater velocity, path length, and sorption constants, but are only marginally affected by the rate of release of radionuclides into groundwater. It would, therefore, appear that the main barrier to the return of activity to man's environment is that provided by slow migration through the geosphere, while the leach resistance of the waste form is relatively unimportant. This conclusion is based on the fact that (for the parameters considered) dispersion generally contributes more to reducing the waste concentration in groundwater than does leaching.

16) "Report to the President by the Interagency Review Group on Nuclear Waste Management," Washington, D.C., Report No. TID-29442, March 1979.

In 1978 President Carter established the Interagency Review Group (IRG) to help in formulating an administrative policy toward the management of nuclear wastes and related programs. This report summarizes the IRG's principal findings and recommendations.

The report addresses the general issues of planning and decision-making, technical strategies for high-level (and other) waste management, and institutional and management considerations. Of especial relevance is the section reviewing the status of knowledge on mined repositories. In the review the IRG identifies a number of important technical findings that it believes to represent the views of a majority of informed technical experts. The systems approach is recommended for use in selecting the geologic environment, repository site, and waste form from a set of alternative options. The use of analytical modeling is upheld for assessing the viability of long-term waste isolation. Substantial further effort in risk assessment is suggested. The most likely means for release of waste is identified as the transport of radionuclides in the groundwater to a river, lake, well, or other point of discharge at the surface. A technically conservative approach is recommended for pursuing the development of mined repositories for high-level waste.

17) English T., Miller, C., et al., "An Analysis of the Technical Status of High-Level Radioactive Waste and Spent Fuel Management Systems," Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, Report No. 5030-90, September 1977.

This report was written to assist the members and staff of the California Energy Resources Conservation and Development Commission, whose objective was to identify the major unsolved technical or scientific questions surrounding the issue of high-level waste disposal. This report analyzes the technical status of both the "old U.S. mainline program" for high-level radioactive nuclear waste management and the newly developed program for disposal of unreprocessed spent fuel. The method of long-term containment for both of these waste forms is considered to be deep geologic isolation in bedded salt. Each major component of both waste management system is analyzed in terms of its scientific feasibility, technical achievability, and engineering achievability. It is concluded that, while the scientific feasibility of deep geological disposal of encapsulated high-level waste in bedded salt has not been proven, there is no reason to anticipate that future work will not reduce uncertainties to acceptably low levels.

18) "Handling of Spent Nuclear Fuel and Final Storage of Vitrified High-Level Reprocessing Waste," (5 Vols.). Nuclear Fuel Safety Project, Kärn-Bränsle-Säkerhet, Stockholm, Sweden, 1978.

"Handling and Final Storage of Unprocessed Spent Nuclear Fuel," (2 Vols.), Nuclear Fuel Safety Project, Kärn-Bränsle-Säkerhet, Stockholm, Sweden, 1978.

In April 1977, the Swedish Parliament passed a law which required that new nuclear power reactors not be operated until the owner is able to demonstrate that terminal disposal of the nuclear wastes generated can be accomplished with absolute safety. In response to this, the Swedish power utilities formed the Nuclear Fuel Safety Project (KBS). Their investigations have led to two major reports on the handling and final storage of both vitrified high-level reprocessing waste and spent nuclear fuel. These two reports are supplemented by approximately 120 individual technical reports.

In the first report the Swedish Nuclear Fuel Safety Group estimates the dose consequences of groundwater intrusion into a high-level waste repository in Swedish granite. Three types of discharge to the biosphere are assumed: 1) lake, 2) underground well, and 3) Baltic Sea. The safety of the geologic disposal system is based on a set of multiple and independent barriers to the release of waste, with special emphasis placed on the potential for engineered barriers to insure long-term safety. Circulation f the natural groundwaters is stated as the only important mode for release of radioactive materials. Transport of radioactivity through the geologic environment is modeled using a variant of the computer code applied by Burkholder, et al.; projected doses are greatest in the well case with values on the order of one-tenth of natural radiation sources.

In the second report a safety analysis for spent fuel is presented, based on the same set of geologic, transport, and dose models described in the first report. The major difference for spent fuel is in the canister design and in the leaching properties of the uranium dioxide fuel pellets. The rate of dssolution of spent fuel is considered to be limited by the solubility of uranium in the groundwater. This conclusion is supported by studies of natural uranium ores under similar groundwater conditions. The hazard from the burial of spent fuel in this case is seen to be equivalent to the disposal of an equivalent quantity of natural uranium.

The results presented in both KBS studies are based on a set of assumptions that can be viewed conservative. The KBS studies represent the first comprehensive assessment of risk from geologic disposal at a specific site and are superior in scope, thoroughness, and quality to anything previously done in the U.S. What distinguishes them from prior studies and what makes their conclusions so convincing are their site-specific nature, their experimental justification of many of the models and assumptions employed, and their relative completeness.

19) Logan, S.E., and Berbano, M.C., "Development and Application of a Risk Assessment Method for Radioactive Waste Management," U.S. Environmental Protection Agency, Report No. EPA 520/6-78-005, July 1978.

This four-volume report, prepared by the University of New Mexico for the Environmental Protection Agency, develops a methodology for evaluating the environmental adequacy of proposed waste management alternatives. The methodology is applied, for purely illustrative purposes, to a reference repository in a bedded salt formation near the proposed Waste Isolation Pilot Plant (WIPP) in New Mexico.

The model described in Logan and Berbano is composed of a modular set of linked computer programs. These consist of a program to generate radionuclide inventories (ORIGEN), a fault-tree routine, a release model which defines the fraction of waste released as a function of time, an environmental transport and pathway-to-man model, and an economic and health effects model. Release events are assumed to occur either at specified times or to be distributed over time according to their probability of occurrence. Some inconsistencies appear to exist in the manner in which expected releases are predicted and in the algorithm by which radionuclide concentrations in groundwater are calculated. Additionally, conservatively high estimates are made of the amount of radioactive material at the surface available for resuspension in air.

From a consequence standpoint this study would appear to be highly conservative. The overall risk assessment methodology which has been developed is good and with some improvements should be capable of providing useful results. The systems analysis approach used is flexible and can be easily modified and updated.

20) McGrath, P.E., "Radioactive Waste Management: Potentials and Hazards from a Risk Point of View," Kernforschungscentrum Karlsruhe (Gesellschaft für Kernforschung), Karlsruhe, Germany, June 1974.

This paper outlines the general problem of radioactive waste management, illustrates its magnitude and importance, and serves as a preliminary report of the activities in this field. Means by which the various waste disposal procedures can be evaluated and compared in a realistic fashion are described. The approach is from a risk point of view.

The components and elements of risk analysis are reviewed, followed by an exposition on the various indices of the hazard of disposed waste used in these analyses. Hazard indices for several fuel-cycle and waste-disposal options are presented and compared. An iterative systems approach to waste management is suggested in order to assess, for example, the effects of radiation exposure limits on waste treatment and disposal options. The paper concludes with the assertion that there will not be a single optimum waste-management strategy, but rather a combination of strategies based on the systems approach.

21) "Geologic Criteria for Repositories for High-Level Radioactive Wastes," National Academy of Sciences, Committee on Radioactive Waste Management, August 1978.

This report, prepared in response to a request from the U.S. Nuclear Regulatory Commission, presents a summary of the general criteria needed to determine the suitability of geologic sites for the storage and disposal of solidified high-level radioactive wastes. The study's principal assumption is that it is possible to predict an upper limit to the rate of transport of radionuclides in a specific geological media based on accepted physical principles.

Among the geologic and geo-economic criteria suggested for repositories are:

- Locational criteria (minimum repository depth, size and distance from resource-bearing media)
- Long-term stability criteria (avoidance of tectonic boundaries, faults, and high geothermal gradients near repositories; use of proper techniques for backfilling and sealing of the mined cavity)
- Hydrological criteria (setting upper allowable limits on fluid transport in the geosphere based on prescribed radiological limits; observing site climatology over the long run)
- Geochemical criteria (avoidance of excessive thermal and radiation stress in the host rock; minimization of the waste form's leach rate; maximization of the sorptive capacity of the surrounding media).

22) Pigford, T.H. and Choi, J.S., "Effect of Fuel Cycle Alternatives on Nuclear Waste Management," Proceedings of the Symposium on Waste Management, Tuscon, Arizona, ERDA, CONF-761020, 1976, 39-57.

This paper presents a discussion of hazard indices in the context of the regulatory process. A toxicity index for the ingestion of high-level wastes (HLW) is discussed. This toxicity index represents the total volume of water required to dilute the wastes to public drinking-water standards. Toxicity indices from the HLW produced in four different fuel cycles are plotted aginst time. The toxicity of the HLW is seen to fall below the toxicity of the original ore body after a period of about 600 years. It is stressed, however, that this comparison by itself may not be a meaningful criterion for assessing the hazards of radioactive management. For instance, leachability and sorption characteristics assume a greater importance for HLW than for ore bodies. The paper concludes with a call for more realistic analyses of the hazards from geologically isolated radioactive wastes.

23) Tonnessen, K.A., and Cohen, J.J., "Survey of Naturally Occurring Hazardous Materials in Deep Geologic Formations: A Perspective on the Relative Hazard of Deep Burial of Nuclear Wastes," Lawrence Livermore Laboratory, Report No. UCRL-52199, January 1977.

This report considers the hazards associated with deep burial of solidified nuclear waste with reference to toxic elements in naturally occurring ore deposits. The problem is put into perspective by relating the hazard of a radioactive waste repository to that of naturally occurring geologic formations. The basis for comparison derives from a consideration of safe drinking-water levels. Calculations for relative toxicity of fast-breeder reactor waste and light-water reactor waste in an underground repository are compared with the relative toxicity indices obtained for average-concentration ore deposits. Results indicate that, over time, nuclear-waste toxicity decreases to levels below those of naturally occurring hazardous materials.

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