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RADIOACTIVE WASTE MANAGEMENT

Part II

Managing Uncertainty: Establishing Design Criteria Through Defense in Depth

by

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I. INTRODUCTION

Prepared in response to increasing interest in the nuclear waste problem by the Administration, Congress, and the public, a number of review papers have identified a myriad of unresolved technical issues relating to the disposal of radioactive wastes, particularly disposal in geologic media.[1-11] The implications of each of these technical uncertainties for achieving an acceptable waste disposal plan depend, first, on defining a comprehensive set of criteria that must be met before the plan is considered acceptable, and second, on the process by which the plan is judged against these criteria.

In the previous phase of NRDC's study of geologic disposal of radioactive waste, three fundamental criteria for geologic disposal of radioactive waste were presented along with the basis for their development. The main goal of these criteria is to promote a nuclear waste management program which is fair to future generations. The first phase of this study showed how a policy of neutrality toward the future is the most fair way to proceed. This policy's practical embodiment is a disposal system producing no more risks to the future than would have been produced by original uranium ore bodies utilized in nuclear power, assuming they had remained unmined.

The objective of this phase of the NRDC waste study is to assess technological uncertainties, identified in the reports cited above, in relation to the fundamental waste disposal criteria developed under Phase I. But first it is essential to identify the regulatory process by which a waste disposal plan should be judged against the fundamental criteria. To set the stage for this, the next section of this report offers a simple thought experiment to assist in conceptualizing the disposal problem. This is followed by a presentation of the proposed regulatory process, which will be recognized as an application of the defense-in-depth philosophy utilized in the licensing of nuclear power plants. The differences between this approach for managing technological uncertainties, and an alternative approach based on extensive use of risk-consequence modelling are then discussed. Here, it is shown that of the two approaches, the defense-in-depth approach is the only acceptable one. The final section of this report examines the implications of the proposed criteria and regulatory process on key technological uncertainties. In this regard, this phase of the study is not intended as simply another review of technological uncertainties related to geological disposal of radioactive waste; rather, the intent is to narrow down these uncertainties, and to focus on those of primary significance. The third phase of the NRDC waste study will discuss the nature of the R&D program required to resolve the technical uncertainties identified here, and will indicate those milestones that are dictated by the criteria.

II. CONCEPTUALIZING THE DISPOSAL PROBLEM

A simple thought experiment helps in conceptualizing the radioactive waste disposal problem: suppose it were possible to take radioactive wastes, to instantaneously convert them into an exact duplicate of the original ore body from whence they came, and to emplace the resultant ore body underground in a duplicate of the original ore body's geologic environment.

The risks to future generations from waste emplaced in this way would be identical to those posed by the original ore body, because the emplaced wastes would be identical to the original body. In these circumstances, elaborate modelling exercises that estimate risks to future generations would be needless and possibly misleading, because two identical arrangements would be expected to perform identically over time. This expectation is adopted as a basic postulate: identical waste disposal mechanisms, in identical geologic environments, will produce an identical field of risks to future generations.

Under this postulate, NRDC Criterion 1 would be satisfied by emplacing wastes in an artificial "ore body" whose characteristics are identical to unmined ore bodies. The process employed here in principal, and to a large degree in practice as well, requires only comparisons between measurable attributes of reference ore bodies and waste disposal plans.

Admittedly, the ideal state of perfect equivalency to a reference ore body is unattainable. Any solutions aiming at equivalency will to a greater or lesser degree suffer some short-comings as a result of the basic differences in radionuclide composition between wastes and source ore.

Source ore contains primarily uranium-238, a very long lived isotope of uranium, and its decay products, such as thorium, radium, and radon. Because of the uranium isotope's long half-life, source ore radiotoxicity changes little over spans of tens of millions of years and so can be viewed as a steady-state variable over extremely long time periods. Radioactive waste, on the other hand, is a highly complex mixture of artificial and natural radionuclides, most of which undergo some decay activity and produce daughter products which may also be radioactive. The exact mixture at any point in time depends on details of initial fuel composition, irradiation variables, post-irradiation processing, and time elapsed since irradiation.

Figure 1[12/] compares an ingestion hazards index of radioactive waste over time to that of source ore expressed in terms of the amount of waste necessary to dilute a unit of waste, or ore, in order to meet current Federal radiation protection standards. This figure shows how the toxicity of radioactive waste resulting from various fuel utilization programs changes over time. Since the goal is to mimic the reference ore hazard over time, the waste disposal plan, in terms of its capability to prevent movement of the activity

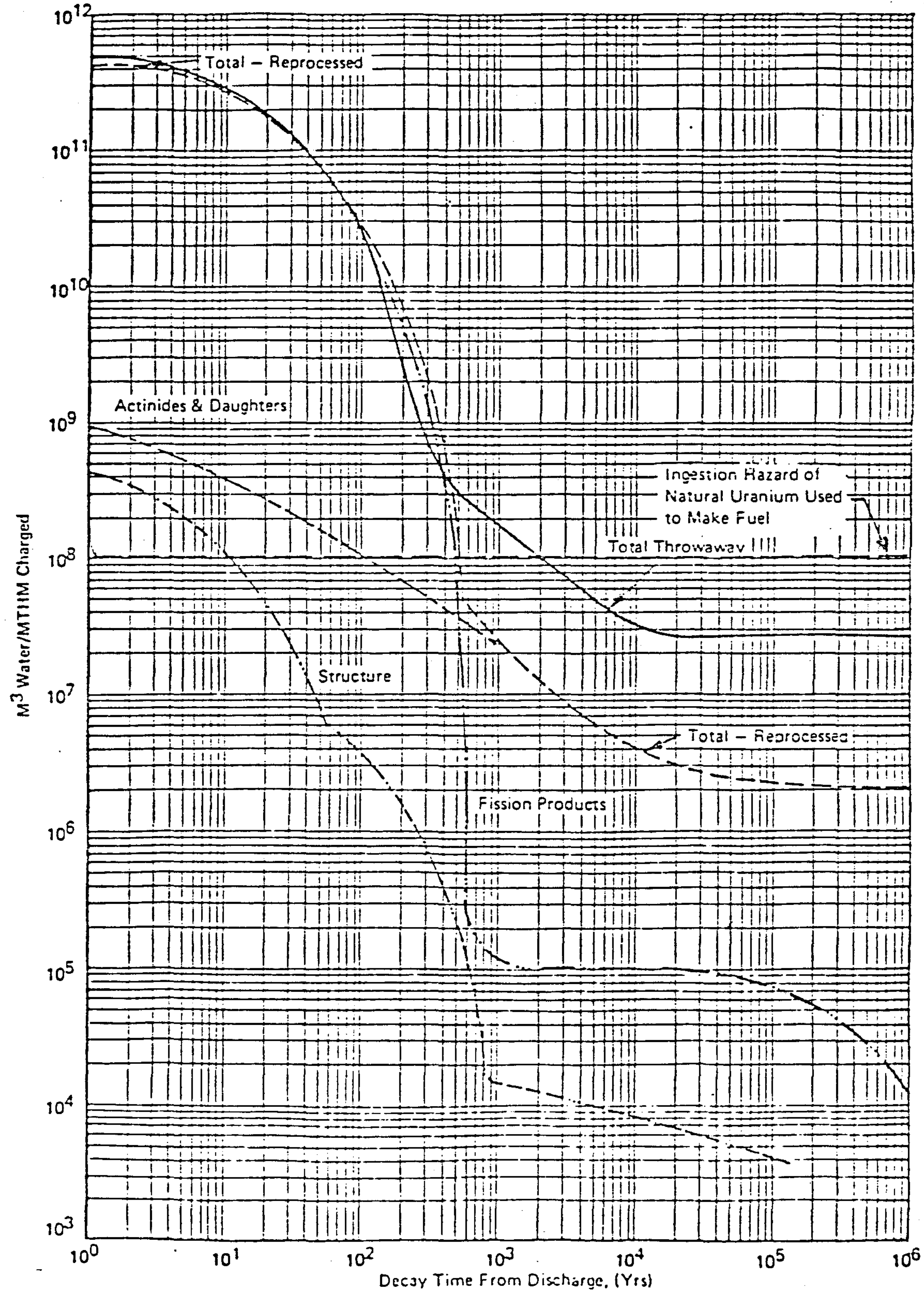

FIGURE 1 INGESTION HAZARD INDEX (THROWAWAY VS. REPROCESSED AND RECYCLED LWR FUEL)

to the biosphere, must have higher performance standards applied over the first 2,000 years or so than in later years. (As will be discussed, a rulemaking proceeding should determine exactly what performance is required over time.)

Exactly how characteristics of waste plans may be compared and judged identical to those of natural ore bodies is a complex matter when viewed in detail. Further, it should be clear that although perfect equivalency with ore bodies is a worthy goal, it is impossible to obtain with absolute certainty. Differences between radioactive waste and source ore combine with other incommensurables to inject some doubt as to the future performance of disposal plans, no matter how closely the presently measurable characteristics of the plan match those of natural ore bodies.

To make a philosophical point, the basic uncertainty common to all predictions of what will occur in the future is bound to infect any waste disposal plan aimed at meeting given standards; however, of the two alternative approaches for managing this problem, one (risk/consequence modelling) is likely to increase the doubt that a waste plan will meet desired goals, while the other (defense-in-depth) diminishes uncertainty.

The defense-in-depth design philosophy embodied in nuclear reactor licensing procedures of the U.S. Nuclear Regulatory Commission (USNRC) is described in detail in the following section. This approach implicitly acknowledges that things rarely go as one would like, especially with complex plans. To manage uncertainty, it uses the ideas of independence and redundancy to assure that the plan will meet its goals. Under this philosophy, the plan will be designed around multiple independent components, the operation of any one of which is sufficient to meet the basic goals even if the other parts are arbitrarily assumed to have failed. In other words, under this philosophy, failure of all the components must occur for the overall plan to fail.

Uncertainty still occurs, of course, as a result of possible common mode failure, and as a result of residual uncertainties that each component, on its own, really is sufficient if the others are arbitrarily assumed to have failed. Nonetheless, as will be subsequently demonstrated, the application of defense-in-depth as a design philosophy can diminish the uncertainty of reaching one's goals.

The second approach - one favored by some Government agencies, but which is shown to be unacceptable - might best be described as systems analysis using risk/consequence modelling. To judge whether a given waste disposal plan is acceptable under this philosophy, the entire plan, as a unit, from waste form to general site, is plugged into a mathematical model purported to function as an analog to the real world. The model yields what is taken to be an accurate or a conservative (in terms of safety) simulation of the behavior of the waste disposal plan over time. If the predicted behavior is within limits, the waste plan passes; if not, it fails.

This approach can lead to increased uncertainty; first, because failure of a single key component could jeopardize the entire plan, and second, because in addition to the probabilistic output of the model, one is faced with the very real uncertainty of whether or not the model accurately represents all of the many things which might occur over hundreds of thousands of years; that is, whether the model represents the real world, or simply represents what its author thinks the real world is.

III. ESTABLISHING DESIGN CRITERIA

Design criteria are essential as goals for the various aspects of a waste disposal R&D program. Moreover, as regulatory requirements, they are essential guidelines for the process that will lead to the licensing of a radioactive waste repository. As indicated above, two approaches are being suggested for the establishment of these criteria. One approach is based upon defense-in-depth and the other upon systems analysis. In the following, each of these is discussed separately and it is shown that the defense-in-depth approach must be employed because it reduces uncertainties while systems analysis increases uncertainties. Moreover, the systems analysis approach offers little guidance for R&D programs.

A. DEFENSE-IN-DEPTH

The standard nuclear facility design practice of the nuclear industry is to follow the "single failure criterion." This is embodied in the USNRC regulations.[13/] In practice, single failure criteria require that all critical safety systems be designed in such a way that the consequences of a single failure in any component or system will not result in the loss of capability of the other safety systems to perform their safety functions. As a result of this concept, a common design practice is to use multiple barriers to guard against the release of radioactive materials to the environment. In an operating nuclear reactor, the multiple barriers consist of fabricating the fuel material itself into ceramic form, enclosing it with metallic cladding, containing the fuel in a pressure vessel, which in turn is enclosed in the reactor protective containment.

NRC licensing proceedings will provide the Administrative setting for reviewing waste disposal plans under any set of waste disposal criteria. Consequently, to insure compliance with the fundamental NRDC waste criteria in licensing proceedings, NRC rule making proceedings must first establish more specific waste repository design criteria analagous to the nuclear power plant design criteria recorded in 10 CFR 50, Appendix A. The waste repository design criteria should reflect NRC's strong historical emphasis on the single failure criterion; accordingly, their development should proceed under the defense-in-depth philosophy.

Thus, the process should begin by resolving the proposed waste disposal plan into a few carefully chosen parts, each of which can be regarded as an independent component. The keystone of this proposed licensing process is that each component of the waste management plan must be sufficient to duplicate the isolation performance of the natural state (reference ore body) even if all other parts of the waste management system are arbitrarily assumed to have failed to perform.

There are a number of components of a waste disposal system that have been likened to "barriers" in the nuclear waste isolation literature.[*/] These include:

(1) The primary waste form - Individual radionuclides are isolated within a specific material such as glass or ceramic.

(2) The waste-form matrix - The primary waste form itself (glass or ceramic beads) could be coated with a secondary material such as pyrolytic carbon. These coated beads could then be dispersed into a third material and cast into cylinders. Thus, the waste form and waste-form matrix may consist of more than one independent barrier.

(3) The waste container - A number of canister materials have been proposed, including alloy steel or copper. The principal purpose of the canister is to facilitate handling the waste.

(4) Backfill material - The individual containers can be surrounded by a reactive material which can absorb the radionuclides that are leached from the primary waste form.

[*/] While the waste isolation literature makes extensive use of the word "barriers", it is often used to imply a medium which merely retards the movement of emplaced materials. This report takes the different approach of acknowledging that each distinguishable aspect of proposed repositories' physical design is in fact a complicated assembly of structures. For example, the overlying strata may consist of many different media and formations; however, the entire set of these media and formations is hoped to accomplish the function of isolating the repository from the biosphere. We call the set of media and formations a "component" and specify this component in terms of its desired function. Thus, by establishing desired functional standards (i.e., performance objectives) for the components in waste disposal plans, we can naturally evolve performance standards useful in licensing procedures.

(5) The host geologic formation - This is the rock formation in which the repository will be located.

(6) Surrounding geological strata - This is the surrounding, overlying and underlying geological strata associated with the host rock formation.

For purposes of establishing design objectives or criteria, the 6 "barriers" can be grouped into three independent components. The first, which will be referred to as the waste component, would consist of the waste form, the waste-form matrix, the canister, and the backfill material. The second component would be the host geological formation, and the third, the surrounding geological strata.

In the defense-in-depth approach, each of these components must be assigned specific criteria or performance standards that are independent of the other components. In addition, there is needed a set of criteria related to repository design, construction, operation and closure. These latter criteria will have the function of maintaining the integrity of the repository during the operational and post-operational phases.

The defense-in-depth approach thus requires specific and verifiable criteria for independent components (barriers) of the waste disposal system. This is quite different from the approach (a systems analysis) being suggested by the U.S. Environmental Protection Agency (USEPA) and the U.S. Interagency Group (USIRG). In the following section, it is shown that this systems approach leads to increased uncertainties and, as a consequence, is unacceptable as a licensing approach for a waste disposal system or as guidance for an R&D program.

B. SYSTEMS ANALYSIS

The USEPA has also proposed that the multiple barrier concept be applied in the storage of radioactive wastes:

> Controls for radioactive wastes are of three general types: engineered barriers, natural barriers, and institutional mechanisms. Engineered barriers such as containers or structures generally can be considered only as interim measures for containment, despite the fact that some structures have survived intact through the ages. Stable geologic media are an example of natural barriers. Institutional controls are those which depend on some social order to prevent humans from coming in contact with wastes, such as controlling site boundaries, guarding a structure, land use policies, record-keeping, monitoring, etc. 14/

Likewise, the USIRG on Waste Management also favors this approach:

> Reliance upon redundant natural and/or engineered barriers to inhibit both the likelihood and consequences of release of radionuclides to the biosphere is a key element in the current waste management program. Moreover, the current program assumes that conservatism would be applied in repository design and operation. 15/

However, the USEPA and USIRG approach to defining, choosing, and utilizing barriers in a waste disposal plan is inappropriate. Instead of focusing on independence and redundancy, the USEPA interrelates barrier mechanisms and views the entire plan as a single retardation system. Both the USEPA and USIRG suggest barrier structures be combined in a systems analysis in this way in order to evaluate the integrity of the overall system. As stated by the USIRG:

> The systems appraoch recognizes that a large number of factors can influence the security of waste isolation and that these factors might have complex interrelationships. Thus, no single factor (such as thermal or hydraulic conductivity of a medium) is treated in isolation of other factors in assessing the possibility of release and movement of radionuclides from the site of emplacement. 16/

Later the USIRG states:

> Recognition of the fact that none of the three basic aspects discussed above -- source term, groundwater transport, and geochemical retardation -- are sufficiently well known at this time to warrant total reliance on only one of them has led to an emphasis on the "multiple barrier" concept. In this concept the principal barrier is a sufficiently long "travel time" for radionuclides to be transported by ground water. 17/

Under this approach, the validity of each of the system's components is not of essence, the key determinant being whether or not the overall coordination of the system, as proven by modelling, can produce acceptable performance under conditions conceivable to the analyst.

What is being proposed by USEPA and USIRG is an elaborate modelling program (a systems analysis) as a substitute for well considered design objectives and criteria. They propose this modelling exercise although it is recognized that this approach is little more than a sophisticated mathematical facade. The USIRG states:

> Transport models useful for the analysis of radioactive waste isolation are necessarily complex and difficult to validate. 18/

Public confidence in any radioactive waste disposal system will not be created by substituting mathematical modelling exercises that are impossible to validate for objective and verifiable design criteria.

It is not suggested here that systems analysis and modelling are not useful analytic tools, and their use is encouraged where appropriate. In the case of waste management studies, systems analysis is important in that it brings into focus the context in which a given waste plan component is analyzed, but the methodology itself should not be extended into domains where it cannot be validated. "Engineering judgment," that is, best guesses of modelling assumptions, and model parameters, should not be substituted for collecting basic scientific data and conservatively applying these data. In sum, substituting verifiable criteria with conclusions derived from complex mathematical models will not encourage public confidence in radioactive waste disposal systems. On the other hand, by applying the philosophy of defense-in-depth, and insuring that the test of each component against its independent criteria can be validated with basic scientific data, public confidence in waste disposal systems should be improved. Management of uncertainty through applications of defense-in-depth is a better way to proceed than an exclusive reliance on modelling.

A further drawback to a licensing process whereby the adequacy of the waste plan is measured by modelling the entire plan as a single system relates to its effect on the R&D program. Without independent criteria for separate components, it is impossible to meaningfully define goals, or to meaaure the progress of the R&D. One would not know, for example, what is required of the waste form until the site is selected, carefully surveyed and modelled. In contrast, under the defense-in-depth approach, research managers working on waste component development would have a concrete set of standards as performance goals, and could work toward those goals without waiting for progress on site selection.

Similarly, there would be comprehensive site selection criteria, and the adequacy of the site would be determined independent of progress on wast form R&D.

IV. THE UNCERTAINTIES

The various references cited in this report discuss a large number of uncertainties or unknowns related to the disposal of radioactive wastes. However, these reports were prepared in a vacuum so far as radioactive waste disposal criteria are concerned. As a consequence, the R&D program which these reports would support could be likened to a vast or limitless inquiry into all things physical, chemical and geological.

At the same time, these reports also discuss a number of facts and phenomena related to radioactive waste disposal that are known or understood. Had the cited references been prepared with specific waste disposal criteria in mind, they would have been able to focus on specifics rather than present a general catalog of relevant and irrelevant problems.

In this section, the NRDC criteria developed in the first phase of this study will be utilized together with the defense-in-depth approach to narrow down these uncertainties and to focus attention on those of primary significance. This discussion will be presented in 3 parts:

A. The Waste Form - This represents an independent barrier in the defense-in-depth approach.

B. The Site Selection - This includes two independent barriers in the defense-in-depth approach (the host geological formation and the surrounding geological strata).

C. The Operational Phase - This involves those aspects of repository design, construction, operation and closure that relate to the long term integrity of the repository.

A. THE WASTE COMPONENT

The waste component represents the first line of defense in protecting the environment from radioactive contamination. As indicated above, the waste component would be represented by the waste form, waste-form matrix, the canister into which it is put and the possible special materials packed around the canister. In essence, the waste component can be likened to an artificial ore body.

Utilizing the multiple barrier, single failure criterion, it must be assumed that the other components of the repository have failed and that the repository is flooded with water. Under these circumstances, it must be assumed that this contaminated water quickly reaches the biosphere. NRDC Criterion 1 then requires that the waste form be such that the overall hazard to future generations be no greater than that which would have been presented by original unmined ore bodies.

It is proposed that the precise definition of this hazard be derived in a rule making proceeding. A logical choice is that the hazard be defined in terms of the concentration of the radionuclides in waste. This has become a common practice in waste disposal studies where the hazard is evaluated as an ingestion hazard index (the volume of water required to dilute the wastes to 10 CFR 20 limits)(see Figure 1).

It is thus anticipated that the result of the rulemaking proceedings would be the establishment of maximum permissible radiotoxicity in the water contaminated by the radioactive wastes. For example, this might be concentrations of the various radionuclides from the wastes whose composite radiotoxicity is equivalent to the average radiotoxicity of the radium and other ore radioisotopes found in surface and ground water in the vicinity of a reference ore body.

Whatever allowable concentration is adopted, the waste form must be capable of maintaining the radiotoxicity of the water in a flooded repository at or below this concentration. This will depend upon the leachability of the waste form itself and to the extent possible, upon the ability of the backfill materials to absorb the leached radionuclides by ion exchange and other processes.

At the present time, an accepted waste form or forms has not been determined. Considerable experimental study has been conducted on borosilicate glass but these studies are inadequate to determine its acceptability.19, 20/ Other candidate forms such as ceramics, oxides and synthetic natural materials such as feldspar have been suggested.21, 22/

Clearly much more research and development work is required to find acceptable waste forms. These forms must be tested and shown acceptable under the conditions expected in a flooded repository. The nature of this R&D program will be discussed in Phase 3 of this study.

B. THE SITE SELECTION

The site of a nuclear waste repository represents a column of earth extending from below the repository to the surface. As stated above, the site must contain two independent barriers: the host geological formation and the surrounding, overlying and underlying geological strata.

1. The Host Geological Formation

Application of defense-in-depth and referencing to natural ore bodies is less clear when considering the remaining two components of the waste disposal plan. In some cases, there may be no clear distinction between the "host rock" and "overlying strata" (for example, if both are part of the same geologic medium). This problem can be avoided since these two components are not intended to serve as geologic labels; instead, they represent two independent functions in the isolation of the wastes. For the sake of applying standards, the host component, or "host rock", in such cases should be defined as that section of rock contained within a given closed surface surrounding the repository.

The host component's function, in the case where the other two components are arbitrarily assumed to have failed, is to isolate wastes within the host rock from significant aquifers that could serve as potential sources of water supply. Here, it is arbitrarily assumed that a) the waste component would leach readily if in contact with water, and b) the site has significant aquifers, although criteria relevant to those other two components will be designed to insure that this is not the case. Performance standards for the host should be written with this function in mind, including, for example, standards insuring that the host rock itself is free from significant water and that it does not crack under thermal stresses associated with emplaced wastes to the extent that it would allow significant movement of water. As before, the precise nature of these criteria would have to be determined by rulemaking proceedings.

2. The Surrounding Geological Strata

Similarly, the site component functions as an independent barrier in addition to those barriers provided by the waste and host components. Performance standards aimed at fulfulling this function under defense-in-depth would emphasize the need for an insoluble, impermeable repository site which is free from aquifers proximate to the host rock enclosing the repository. Here, "aquifer" refers to potable ground water. If one arbitrarily assumes that the waste and host components have failed, the surrounding geological component is the last component isolating waste from the biosphere and should contain no significant aquifers, so that waste free from the first two components cannot be transported to the biosphere. As noted previously the site should allow the construction of a repository in an impermeable, dry rock.

Other performance standards supporting the surrounding geological component's function should be aimed at insuring long term geologic stability of the site and the repository and prevent the alteration of water flow patterns. To insure the long term integrity of the above barriers, it is essential that the site be located in an area of long term seismic stability, the site be free of diaparism and volcanism, and the repository be sufficiently deep to be free from significant effects of glaciation.

3. Proposed and Preferred Sites

Perhaps the weakest link in making sure that the site component fulfills its function is the possibility of unintentional future human disruption of waste disposal plans. Although geologic projections might retain some credibility over a few thousand or even a few hundred thousand years, human behavior is unpredictable over spans of mere decades.

For this reason, NRDC Criterion #2 is fundamental to the selection of a repository site:

> The geologic medium and site selected for geologic disposal should be selected to minimize the possibility of future human intrusion, particularly during periods after which the permanence of records can no longer be expected. Hence, the medium should not be located in an area where valuable materials have been or are likely to be mined. The geologic medium of choice should be a plentiful material such that should it become a useful resource to future generations, its widespread availability will make it unlikely to be mined at the waste disposal site.

The host rock should not be a valuable material and neither the host rock nor the site should contain scarce or potentially valuable materials (including materials of known value which are not at present economically exploitable), much less materials which have already been sought for their value. Likewise, candidate sites and media should possess no geologic structures generally associated with valuable or potentially valuable materials, because even though there may be no valuable materials present, future generations might drill into the repository in search of resources which they suspect to be present. It is important to recognize that potable ground water must be included in the envelope of valuable resources. "Here potable refers to the quality of water which is now being consumed or eventually may be consumed by humans." [23]

There have been 4 basic rock types suggested as potential host rock for a repository. These are salt, basalt, shale and granite. Of these salt has received the major attention over the years. Because of this, salt has been selected for the first so-called "demonstration" facility. This is the Waste Isolation Pilot Plant (WIPP) proposed for a salt deposit near Carlsbad, New Mexico.

The use of salt as a repository should be ruled out on the basis of NRDC Criterion #2. Salt has been, is and will continue to be a valuable resource. Mining of salt deposits has occurred and will continue to occur, probably at an accelerated rate.

The EPA Ad Hoc Panel states:

> Salt is a valuable mineral resource, but worldwide reserves are virtually limitless, so there is no logical reason why a single dome should not be perpetually withdrawn and dedicated to HLW disposal. The possibility of human intrusion at a far future time cannot, however, be discounted. [24]

Since institutional controls have a limited effective life time, the far distant future referenced above might be only a couple of hundred years away. This is particularly true when the salt deposits in question are in areas now inhabited by significant numbers of humans and likely to be so inhabited in the future.

There are additional problems with salt. Most salt deposits are not dry and all are soluble in water. Salt, therefore, eliminates an important barrier - that supplied by the host rock itself. Salt deposits have no integrity of their own, and would have to depend solely upon the integrity of the surrounding non-salt media to isolate them and the contained radioactivity from the environment. Salt deposits simply do not meet the necessary waste disposal criteria.

The various reports referenced above express significant concern over the uncertainties, as well as the known characteristics, of shale and basalt as host rocks for a repository. Both of these materials are interbedded with potential aquifers. Concerning shale the IRG states:

> The composition of the water in shales varies widely, and in some areas even may be quite saline. 25/

The EPA Ad Hoc Panel states:

> Since approximately 70% of the sedimentary rocks of the earth are shales, it is not surprising to find a great many thick shale sections. Yet it is extraordinarily difficult to find one that is uninterrupted by interbeds of other, generally more permeable lithologies. 26/

It may also prove difficult to meet NRDC Criterion #3 with a repository in shale. This criterion requires that the repository operate in a retrievable mode until it is shown with high confidence that all criteria are met. Concerning shale, the IRG Report states:

> A characteristic of shale which must be viewed as a potential drawback is the difficulties associated with mining and keeping the tunnels open. Inhomogenities in shale that significantly affect its structural characteristics are difficult to identify in advance of mining. An example of such effects can be found in the Eleana argillite at the Nevada Test Site. Based upon core drilling there, it is estimated that about 20 percent of the volume of the shale is a highly plastic material that readily deforms to close unconstrained openings. 27/

Basalt formations are typically successive thin layers (10m to 50m thick) of relatively impermeable basalt separated by more permeable strata qualifying as aquifers. Moreover, because of their volcanic origin, they occur in seismically active areas. The major basalt formation considered for possible use as a repository is the Columbia Plateau. Concerning this area, the USEPA Ad Hoc Panel states:

> The typical basalt flow of the Coumibia and Snake River plateaus ranges from 10m to 45m in thickness, and is often separated from the overlying and underlying flows by an aquifer. Lower columnar and upper fan-type jointing of each individual flow is characteristic, and most lavas have a 5m thick vesicular zone at the top, and a 1m think vesicular zone at the base of each flow. Thus it seems that, on the average, basalt should be far more porous and permeable than granite, and that it would also offer a higher risk of contaminating the ground water if used as an HLW repository. 28/

Similarly, the USIRG Report states:

> Basalt on the Columbia Plateau commonly has zones of columnar joints or rubble that are potential channels for water movement. Water bearing sedimentary inter eds within the basalt section are common. 29/

The above discussion suggests excluding basalt as a potential host rock for a radioactive waste repository because of seismicity as well as the proximity of aquifers. Shale on the other hand, cannot be eliminated a priori. However, it is clear from the various referenced reports that shale presents a myriad of problems and thus it will require a long and extensive research program to resolve objections to its use as a host rock.

All of the above referenced documents consider granite to be a likely candidate for the host rock of a radioactive waste repository. The USEPA Ad Hoc Panel states:

> It is the Panel's opinion, and apparently that of several foreign countries as well, that a sizable body of granite underlying a hydrologic basin of appropriate dimensions may prove, in the long run, to be an excellent underground repository. We know of no reasons, as yet, to rule it out. Research on granites should be pushed vigorously, particularly because there may be either socio-political or geological reasons why burial in salt may be ruled out. In this case it appears that we have no fall-back position, and granite is an obvious alternative. 30/

Granite is a rock type that has low pososity and permeability. The water is transported through the rock in fractures and faults. However, at depths in the range of 600-900 meters these fractures are closed and the rock becomes dry and essentially impermeable.[31, 32/] In some areas of the United States these rocks have been stable for 2.5 billion years and in other areas for 100 million years.[33]

It thus appears that deep lying granite rock is the most promising host rock for a radioactive waste repository. At the same time, it is important to note that much of the information on granite has been obtained as a result of mining activities (to considerable depths) in such bodies.[34] Therefore, it is essential that the site be selected in a region which assures that future mining activities will not jeopardize the integrity of the repository.

4. Site Exploration

Having selected a host rock, a problem develops in selecting locations for the repositories. The USEPA Ad Hoc Panel points out a paradox associated with selecting the location for the site:

> There is a fundamental paradox to be encountered in the design and construction of a "closed" repository. It is desirable to avoid disturbance of the rock mass by exploration drilling as this provides extra pathways for the HLW to reach the surface. However, one must determine very precisely the geometric distribution of rock properties throughout the future repository site and its immediate surroundings. Prior to excavation, only careful examination of many drill cores can possibly delineate these properties. These two contradictory demands must somehow be resolved. Proper assessment may have to await excavation of shafts and adits, despite the high risk of the capital investment should the site then be found to be unsuitable. [35]

This is a concern expressed in most of the above referenced reports. It arises from the consideration of placing radioactive wastes in or near water bearing and transmitting strata or media. The problem arises because these media are not homogeneous. The data derived from an individual borehole relates only to the conditions in the immediate vicinity of the hold and not to the overall area. Therefore, if the purpose is to ascertain that there are no short or rapid paths of water flow, a large number of closely placed boreholes are required. In other words, the need for these intrusions into the potential repository is to derive data for modelling the transport of radionuclides by groundwater. As referenced earlier, the IRG states:

> Transport models useful for the analysis of radioactive waste isolation are necessarily complex and difficult to validate. 36/

Thus it appears that (if mathematical modelling of the ground water transport of radionuclides is to be used as an important feature in repository selection) attempts to reduce the uncertainties in these models will only create additional uncertainties. Short of selecting sites that are not so dependent on the use of these models, there is no way out of this dilemma at the present time. The EPA Ad Hoc Panel states:

> As noted in the text, there are also several questions, notably the determination of real permeabilities and porosities in the rocks at a site, or the nature of the long-term monitoring systems, answers to which must await the intervention of new technology. The time scale for such research is much less readily determined. 37/

It, therefore, appears that, if site selection were to depend upon the mathematical modelling of radionuclide transport, selection of such sites must be deferred to the indefinite future.

C. OPERATIONAL PHASE

NRDC Criterion #3 is fundamental to the operational phase of a radioactive waste repository:

> The radioactive waste should be stored in a retrievable manner for the period during which the repository is open, or until it can be assured with high confidence that all waste disposal criteria are met, whichever is the longer period.

The operational phase would begin with the sinking of adits and shafts after the site location had been selected. The early operational phase would have the purpose of determining that host rock properties are adequate for a radioactive waste repository. The IRG Report states:

> Once excavation for the repository begins, direct mapping of shaft and other underground openings will provide extensive information on rock mass characteristics and on the presence of previously undetected faults, fractures, or other possibly adverse features. In addition, geophysical techniques like high resolution acoustics and short pulse radar might be able to detect fractures and other near-field details not actually visible in the walls of the excavation. Some uncertainties resulting from a lack of data in the assessment of long term risk associated with the proposed repository, are expected to be reduced by information obtained during repository construction. 38/

Following this exploratory or confirmatory stage, the placement of wastes in the repository would begin. It is here that a major uncertainty with repository design is encountered. The decay of the radioactive waste is a source of heat. Depending upon the amount of waste deposited, temperatures at the walls of the repository could increase by hundreds of degrees centigrade. The USIRG Report states:

> As the National Academy of Sciences and others have stated, the design of a waste repository constitutes a major challenge for rock mechanics, principally because of this thermal pulse which has the potential to alter both the structure and the stress state of the surrounding rocks. 39/

This thermal pulse or temperature rise can cause expansion, fracturing and slipping of the host rock. In addition, in some rock types, it can cause chemical changes and the release of water. Such changes could alter the hydrological characteristics of the repository and lead to the contamination of ground water.

For other than salt, our knowledge of the potential effects is almost nil. The EPA Ad Hoc Panel states:

> Because the need for underground isolation of HLW has been recognized for some 30 years, the long postponement of pertinent research on rock other than salt is unfortunate. The problems will not be solved quickly. The research is inherently time-consuming because the critical data are attainable only from creep tests of months-long duration. Furthermore, the required testing machines (to accommodate 10-cm specimens, at temperatures of 500°C, under pressure of 200 bars, and for a duration of several thousand hours) do not even exist. It may take a major research effort of 5 years to build the necessary laboratory facilities; to collect adequate data; to develop realistic, three-dimensional, nonlinear, large deformation codes; and to validate predictions in the field. 40/

Since our understanding of these thermomechanical problems is so poorly developed, the period of retrievability required by NRDC Criterion #3 is uncertain. The USIRG Report states:

> It should be emphasized that models validated by _in situ_ testing for short-term (operational period) and near-field mechanical effects cannot be validated for long-term and far-field effects because of the great length of time required for measurable mechanical effects to be realized at large distances from the repository. Confidence in the ability of such models to predict far-field deformations over long periods of time must necessarily be based on the accuracy of short-term predictions and on increased understanding of long-term processes. Monitoring, for some period yet to be determined, will be useful to assure the accuracy of the predictive models for the short-term, and to provide an early warning should the models prove to be unreliable. 41/

The final phase of the repository would involve the sealing of the adits and shafts. These openings, like the site selection boreholes discussed perviously, can become short circuits to ground water supplies. Little work has been done on the problem. The sealing of these boreholes, adits and shafts that penetrate the repository may prove to be the ultimate uncertainty associated with radioactive waste repositories.

V. SUMMARY

Part I of NRDC's study on radioactive waste management developed three fundamental waste disposal criteria and presented the rationale for their development.

This report, part II of the study, interprets these fundamental criteria through the defense-in-depth design philosophy in order to derive specific guidance for designing, developing, and licensing a radioactive waste repository. Part of this derivation involves contrasting the two approaches suggested for the establishment of design criteria and licensing requirements. One approach, defense-in-depth through multiple independent barriers, is currently applied in reactor licensing. The other approach, suggested by the USEPA and USIRG, is systems analysis through risk/consequence modelling. This report shows how of the two approaches, only the defense-in-depth path leads to reduced uncertainties and to adequate guidance for research and development programs.

This report defines three independent functional components, which are intended to act as independent barriers under defense-in-depth assumptions:

1) The waste component - this includes the primary waste form, the waste form matrix, the canister and the backfill material.
2) The host geological formation - this is the host rock in which the repository is located.

3) The surrounding geological strata - this is the surrounding, overlying and underlying strata associated with the host geological formation.

Each of these barriers require specific and verifiable criteria that are to be determined in rule making proceedings. A set of design, construction and operational criteria are also required.

Finally, the NRDC criteria are considered together with the defense-in-depth concept and components in a discussion of the technological uncertainties related to a waste disposal system. Here it is concluded (1) an acceptable waste component has not been demonstrated, (2) of the 4 major host rocks being considered, salt and basalt should be eliminated, (3) shale can not be eliminated *a priori*, (4) deep lying, dry granite is the most promising host rock, (5) in the operational phase, the major uncertainties involve the allowable heat loading of the repository, and the techniques required to seal the exploratory boreholes and the adits and shafts required for operating the repository.

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