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TECHNICAL SUPPORT DOCUMENTATION

FOR THE

SITING REQUIREMENTS

IN

USNRC

10 CFR PART 60

DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTES IN GEOLOGIC REPOSITORIES

* * *

This Document is a working draft presently being reviewed and edited.

PREFACE

The siting requirements discussed in this document are a part of a much broader regulatory framework under development for the disposal of high-level radioactive wastes. In order to fully appreciate the siting requirements, and the discussion of their development, some familiarity with the overall regulatory framework is essential. This section briefly summarizes those aspects of the overall regulatory framework which bear on the development of the siting requirements.

I. EPA Role

The Environmental Protection Agency (EPA) is responsible for developing an overall environmental standard for permissible radiation exposures to the general public from radioactive wastes. The EPA is presently developing a standard entitled: 40 CFR Part 191, Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes. The key aspects of the standard are as follows:

(1) The standard will establish general principles and projected long-term performance requirements.

(2) The standard will set forth the major performance objective in terms of radioactive release limits and acceptable probabilities of releases. The standard basically defines an upper limit to acceptable risk.

(3) The standard requires a comprehensive performance assessment to demonstrate the performance objectives are achieved, i.e., an analysis of radionuclide releases and their likelihood based on conditions, events, and processes that may affect the repository over the long term.

(4) A reasonable expectation is required that release limits specified in the standard for radionuclides will be satisfied over a period of 10,000 years.

(5) The standard defines release limits in terms of releases to the accessible environment. The accessible environment is defined as those portions of the environment directly in contact with or readily available for use by human beings. It includes the air, land surface, surface waters, oceans, and usable sources of groundwater which are more than one mile from the geologic repository.

(6) The standard requires an assumption that active human controls will not persist for more than 100 years.

(7) Recognizing the uncertainty associated with assessing repository performance over the long term, the standard requires: (a) the repository be sited and constructed such that there are multiple barriers, both natural and engineered, that will isolate and/or inhibit the movement of radioactive nuclides, (b) the repository be sited to avoid future adverse human activities, such as the exploration for resources at depth, which may effect the repository's performance, and (c) the Nuclear Regulatory Commission (NRC) to implement the standard in a way which reduces risks below the upper bound in the EPA standard to the extent reasonably achievable.

The EPA standard is presently in draft form and subject to change.* The NRC has been working with the EPA, and the NRC siting requirements have been developed cognizant of the developing EPA standard.

II. NRC Role

As noted above, the NRC is charged with assuring the EPA standard is satisfied and with establishing additional standards to protect the public. The NRC is presently developing a regulation for radioactive waste disposal entitled: 10 CFR Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories. The regulation at present is in two parts. The procedural portion which encompasses subparts A through D was published as a proposed rule for comment on December 6, 1979 in the Federal Register. The procedural portion basically contains the administrative and licensing procedural requirements. With regard to the siting requirements, the important elements of the procedural rule are contained in subpart B - Licenses. This subpart sets forth a multistep licensing process which includes site characterization, construction authorization, issuance of a license to receive waste and decommissioning. Contained in this subpart are general site information and licensing requirements. The second part of the regulation contains technical and associated requirements and encompasses subparts E through I. This portion of the regulation is in draft and is expected to be published initially as an advanced notice to seek comment prior to being promulgated as a proposed rule.

*The material summarized above is contained in the Draft EPA Standard dated 2/15/80.

The key technical requirements in subpart E are:

(1) The EPA standard is taken as the overall performance objective;

(2) A geologic repository is viewed as a system of multiple barriers, and performance objectives are stipulated for the major components which include: the waste package, overall repository design and the repository site. Key engineering long-term performance objectives bearing on siting are: a resilient waste package capable of lasting a thousand years or more under expected processes and events; an overall repository design capable of severely limiting releases after decommissioning under expected processes and events and keeping open a 50-year option to retrieve waste following emplacement.

(3) Detail technical requirements are also included for siting; design, construction, operation and decommmissioning; the waste package; and monitoring.

Thus, the siting requirements were developed in context of the EPA standard, and the procedural and other technical aspects of the developing NRC regulation. Key aspects influencing the development of the siting requirements are:

(1) The overall performance objective is meeting the EPA standard as an upper bound and to the extent achievable releases to the accessible environment which are lower. The time span of significance is the next 10,000 years. Performance will be assessed through the use of a comprehensive performance analysis. The uncertainties associated with such analysis require a conservative and compensating approach.

(2) The siting requirements must fit into a multistep licensing process which will involve evolving information and reanalyses.

(3) The site performance objectives must be complementary to the performance objectives on the design and waste package and must help assure that uncertainties are compensated.

(4) Siting requirements must provide information for design and must, along with the site performance objectives, assure the EPA standard is satisfactorily achieved.

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1.0 SUMMARY

1.1 Explanation

This document attempts to summarize the many deliberations and judgments and the intent behind the technical aspects of the siting objectives and requirements contained in the draft dated March 24, 1980, USNRC regulation, 10 CFR Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories, Subpart E. The effort here has been to review and assess the technical literature and to summarize in an integrated fashion the many technical aspects involved in site exploration, investigation, evaluation, analyses and repository performance as they bear on the formulation of the siting requirements. It should be stressed that the siting requirements and information described represent only a part of ongoing deliberations.

Because of the nature of this effort, the author takes full responsibility for the information contained in this document and relieves others and the USNRC. The author in developing this documentation has strived for diligence; however, suggestions or commentary for improvement or the identification of areas needing correction will be appreciated.

1.2 Summary of the Siting Requirements

Appendix A contains the draft siting requirements which when finalized will be used as the basis for findings at the different geologic repository licensing stages. The site of a geologic repository and its environs are critical to inhibiting radionuclide migration if wastes are released from the engineered waste isolation system. The site parameters associated with radionuclide migration are numerous and difficult to measure. Siting considerations for a repository are complex, variable, and uncertain; moreover, the state-of-the-art in the many earth science fields that are involved is quite limited. Therefore, the siting criteria were developed in consideration of the following:

1. An extensive level of siting investigations and evaluations are needed to reduce uncertainty to the point that licensing findings can be made.

2. As more detailed site information becomes available in the course of investigations and testing, it must be used to check less detailed, less certain information on which earlier licensing findings may have been based.

3. Site evaluations often involve expert judgment. While latitude must be allowed for such judgment, specific criteria are needed to assure a degree of conservatism that is appropriate given the nature of the hazard and uncertainties involved.

4. Site evaluations should be performed with emphasis on those processes and events which could adversely affect the long-term function of the repository. In general, those events and processes would most likely be determined through investigation of those processes that are now active or were recently active.

5. At best, analytic modelling of site related events and processes will be highly uncertain. Therefore, adverse natural conditions or human activities that are difficult to evaluate and add to the inherent level of uncertainty are best avoided.

The site performance objectives and requirements are summarized below:

1.2.1 Site Performance Objectives

(i) The future stability of the site is of paramount importance. It is the cornerstone of the concept of geologic disposal. Site stability is the main thread of every guideline on site suitability. It is of paramount importance in terms of limiting releases. If it could be shown that the initial site conditions along with the engineered elements provide retardation and other properties that would keep releases within acceptable limits, future stability of the site provides the margin of confidence that the repository will indeed perform as anticipated over the long term.

Past or present stability cannot guarantee future stability nor can stability in and of itself assure that releases will be within acceptable limits. However, site stability is judged to be essential in providing confidence in calculations of predicted releases.

Stability is relative. The regulation requires that the site's present stability will not significantly decrease over the long term given both natural processes and the influences of the emplaced waste. In geology, perhaps, the only thing that can be guaranteed is change. Some change to a site in the future can be anticipated. Of importance here is the rate and magnitude of changes as determined by examination of the past and the present in consideration of possible future influences, e.g., climatic change. In terms of the past and present, the site should be relatively stable and have been relatively stable in the recent geologic past. To show this requires that the rate and magnitude of processes acting in the area around the site in the recent geologic past are, on a relative basis with other areas, on the low end of the scale.

(ii) The site and its environs are the ultimate barrier to radionuclide migration. As such, they must significantly contribute to retarding radionuclide migration. Regardless of host rock permeability and depth, there is sufficient time for groundwater to penetrate the repository and return biologically significant radionuclides to the accessible environment. However, the geochemical system has the major impact on retarding the rate of release to the accessible environment. Therefore, it is essential that a site exhibit geochemcial properties that significantly retard radionuclide migration. Unfortunately, the geochemical system is the least understood site component. Thus in order to have adequate confidence in release predictions, the other components of the site must provide a significant margin of safety. The rule requires that the site be selected with properties that promote isolation of the waste and that the present capability of the site to isolate waste not decrease over the long term.

(iii) The third site performance objective, in context of the two above, provides a coupling between the site and the engineered barriers. It requires that the site supplement the engineered elements, particularly during the time period when the fission products are present.

This objective requires a site be chosen with the idea of achieving no releases to the accessible environment under expected processes, assuming the engineered barriers may fail during the first thousand years. It indirectly, but intentionally, sets a minimum radionuclide travel time from the repository to the accessible environment of 1,000 years. Performance studies indicate such a minimum travel time should result in releases approaching background radiation levels. Additionally, such a travel time, coupled with the time it would take for repository resaturation and delays brought about by the engineered barriers, will provide a degree of confidence that during the time period when the hazard and complexities in assessment are greatest releases can be kept within acceptable limits.

1.2.2 General Requirements

Identified in this section are basic principles and requirements that guide site selection, investigation and evaluation. Unusual complexity in the geologic, hydrologic, or geochemical characteristics of the site could make it impossible to determine whether the performance objectives can be met. Therefore, the rule requires that sites be selected that are simple enough to allow thorough investigation and evaluation of important characteristics.

An attempt has been made to provide guidance as to the scope of the site investigations. The geographic area to be investigated must include the geologic and hydrologic features and conditions as well as human activities that can affect performance of the geologic repository. In general such features, conditions, and activities would be found within a distance of about 100 km from the site.

It has been judged that the most significant period for evaluating the performance of the site to be the most recent geologic period, the Quaternary Period. Behavior of the site during this period, a period extending about 2 million years into the past, should best exemplify the site behavior that might reasonably be expected during this period of time for which waste isolation is required. As for the latter period, this has been taken to be a period of about 10,000 yars. Over a 10,000 year period the biological dangers to human health presented by the radionuclides in spent fuel would be reduced to about the same level as that presented by an equivalent ore body. For other high-level waste that period is much shorter.

The repository will need to be designed, constructed, operated, decommissioned, and functional after decommissioning in consideration of a number of potentially disruptive natural processes and human events. Some such processes and/or events could even be induced by the emplacement of waste. The rule requires that investigations be conducted that properly assess these various processes and events.

Some of the required investigations are inherently destructive to some degree and could themselves adversely affect performance of the repository. Therefore the rule requires that the investigatory program be conducted in a way that minimizes adverse effects on the repository.

The rule requires that the analyses and mathematical modelling that will be a necessary part of assessing future performance of the repository be validated and verified to the extent practicable to increase confidence in that assessment.

Because the greatest uncertainty in analysis will be introduced in a volume of rock near the repository that will be disrupted by the presence of the repository, the rule requires a determination of the extent of repository/site interactions. The rule further specifies information that will be needed to make that determination. It is expected that the determination of extent will be somewhat uncertain and therefore the rule requires that a minimum volume be assumed even if analysis showed the volume to be less.

1.2.3 Adverse Conditions

This section includes criteria that apply to adverse conditions within the potentially disturbed volume of rock and to specified other locations with respect to different phenomena. The criteria are based on several factors: (1) the need to avoid adverse conditions in the near-field of the repository which are difficult to evaluate; (2) difficulties that have arisen in the past in assessing similar conditions in the siting of nuclear facilities; and (3) doubt as to whether one could demonstrate achievement of the performance objectives at a satisfactory level of confidence, if such adverse conditions existed at or near a site.

Application of the criteria will require judgment. They are intended to be applied on a case-by-case basis. Not all the descriptions of adverse conditions are completely specific; some require analysis as to reasonable potential, reasonable evidence, or the like. It is not the intent of the section to require absolute proof but, rather, a reasonable demonstration, using state-of-the-art methods that the adverse condition is not present.

The listed conditions are those that are expected to be particularly difficult to analyze and which could contribute an unmanageable degree of uncertainty to assessments of the long-term function of the repository. If a listed adverse condition is present, the site will be presumed unsuitable for a geologic repository. Proof to the contrary must meet several stringent criteria. Thus, it is the intent of this section that any of the listed adverse conditions can be present only if it can convincingly demonstrate, using conservative assumptions and analyses, that the condition will neither prevent the performance objectives from being achieved nor unduly increase the uncertainty in assessing long-term repository performance. In this demonstration, the compensating effects of favorable conditions may be included.

(i) Adverse Human Activities. This paragraph deals with human activities which could adversely affect the long-term performance of the geologic repository or threaten worker safety during repository operation. An attempt has been made to identify existing activities or conditions which suggest future activity that could both compromise the geologic repository and be difficult to evaluate with sufficient confidence to make a licensing decision. The rule presumes sites near these activities or conditions to be unsuitable. Thus the rule could proscribe sites near the following: (1) valuable subsurface resources that could encourage activities related to exploration or recovery; (2) potential impoundments; and (3) areas of high population.

(ii) Adverse Natural Geologic and Tectonic Conditions. This section deals with geologic and tectonic conditions and processes which could adversely effect the long-term performance of the geologic repository. Historically, geology has been a descriptive rather than a predictive science. Projections of many kinds of geologic and tectonic activity and processes into the long-term future can be done only with great uncertainty. An attempt has been made to identify conditions or processes of that kind which could also compromise respository performance. Also, the activity of some geologic and tectonic features are particularly difficult to assess given the present state of knowledge. In this section, such features are identified as well.

(iii) Adverse Natural Conditions-Hydrologic. The principal mechanism for transporting radionuclides to the accessible environment would generally be the movement of groundwater. In this section, conditions are identified which suggest adverse changes in the groundwater flow system and which would be difficult to evaluate.

(iv) Adverse Natural Conditions-Geochemical. Geochemical retardation is expected to be the principle mechanism for isolation of radionuclides by the site. In this section, the rule identifies the lack of substantive geochemical properties to significantly retard radionuclide migration to carry with it the presumption of site unsuitability.

1.2.4 Favorable Characteristics

Favorable site characteristics are to be sought at a site, in its immediate environs and in the area surrounding a site. Favorable characteristics identified in the siting requirements are intended to assure the site and its environs possess natural barrier characteristics. In terms of natural barriers, the requirements were developed to provide for a significant level of redundancy with respect to site properties pertaining to inhibiting radionuclide migration, the distribution of such properties in space and with respect to natural barriers compensating or withstanding adverse conditions to which the site may be subject.

The favorable characteristics identified are qualitatively expressed in the rule. It is expected that a site and its environs will not possess all the favorable siting factors specified. However, it is expected that sites will be selected in a way that attempts to optimize these preferred siting conditions.

1.3 Summary of Support Information

The siting requirements were largely drawn from documents produced by experts in the earth sciences and related fields, such as those developed by the National Academy of Sciences, the International Atomic Energy Agency (IAEA), NRC sponsored reviews and others. Such documents were considered in light of previous NRC experience in the siting of nuclear facilities. Particular regard was given to difficulties that have been encountered in past siting decisions.

The support information following Section 2.0 (which describes the full purpose of this document, background and major issues arising in the development of the siting requirements) tracks the draft requirements in order as contained in Appendix A. Section 3.0 describes the siting objectives and their underlying principles, as well as the role of the site as part of a multiple barrier system. Of particular importance here is the identification of the nature of the many uncertainties involved. Section 4.0 discusses the need for and describes the anticipated comprehensive program of investigations, evaluations, and analyses. Contained here, as well, is a summary of the types, extent, and magnitude of potential repository/site interactions and the need for in situ testing to ascertain information to bound them. Section 5.0 summarizes potentially adverse human activities and natural conditions which may affect a site and which may compound uncertainty and increase the difficulty in demonstrating long-term performance. Particular attention has been given to assessing the magnitude, nature, and extent of impacts that may be caused by adverse conditions. Section 6.0 summarizes favorable characteristics necessary for performance and needed to compensate for uncertainty and building confidence. Described are the functions of favorable characteristics and how they contribute to inhibiting radionuclide migration. Section 7.0 contains conclusions drawn from this review. The major conclusion drawn is the need for a very conservative approach for demonstration drawing heavily on the weight of a diversity of information and engineered repository elements. Section 8.0 contains references cited. Appendix A contains the siting requirements as of this writing.

2.0 INTRODUCTION

2.1 Purpose of Document

This document discusses the technical siting requirements contained in subpart E of the NRC regulation 10 CFR Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories. A copy of the requirements are contained in Appendix A.* The pertinent requirements encompass site performance objectives: detailed siting requirements dealing with evaluations, investigations, analyses and tests; adverse condition criteria; favorable site characteristics; and monitoring. Other general siting requirements dealing with information needs and licensing procedures are contained in subpart B of the regulation and are not treated here. The discussion here also does not treat requirements for site ownership and control and environmental considerations which are covered in other sections of the regulation or by other NRC regulations.

This document constitutes a summary of the development and supporting information that went into deriving the siting requirements. The purpose of this document is several fold:

(1) To describe in detail the bases for the siting requirements, including the staff judgments, technical support information, and intent of requirements, so as to produce a comprehensive and traceable logic behind the requirements. The compilation of such a rationale has been requested both in the course of

*At the present time, the siting requirements discussed here and contained in appendix A are in draft form and are soon scheduled to be issued as a draft for public comment.

internal NRC review and in comments by review groups on various draft versions of the regulation;

(2) To identify issues associated with requirements to help focus public comment on the regulation when proposed;

(3) To establish a framework to consider comments and potential modifications to requirements as the regulation proceeds through the rulemaking process;

(4) To establish material for the preamble (Supplementary Information Statement) that will accompany the rule upon publication; and

(5) To provide information useful for an environmental impact statement that is being developed and that will be available when the regulation is proposed;

2.2 Background

The development of the siting requirements has been an evolving one, tied to the development of the overall regulatory framework for the disposal of high-level radioactive wastes, i.e., the developing EPA standard, NRC licensing procedures and technical performance objectives, and National Program as described in the Interagency Review Group Report (IRG, 1979). The development of the requirements has entailed considerable deliberations by various NRC working groups over the last several years. Fundamental to these deliberations has been the application of staff judgment in consideration of the following:

(1) Various versions of the siting requirements have been subject to formal and informal peer review. Several workshops, attended by state representatives and a broad spectrum of the technical community, to consider siting requirements have been held (See: McGrath and others (1978), USNRC (1977, 1978), TRW (1978), Craig (1979), University of Arizona (1980, in preparation). Discussions have also been held with the U.S. Department of Energy (DOE), the U.S. Geological Survey (USGS), EPA and others to obtain comment on the technical aspects of the regulation. In part, and importantly, the siting criteria are an outgrowth of considering comments received.

(2) The development of the siting requirements has entailed the review of recommendations in the literature on siting guidelines, NAS/NRC (1979), IAEA (1977), see Goad (1979) for summary. The NRC has also sponsored studies to recommend criteria, NAS/NRC (1978), LLL (1979).

(3) Considerable attention has been paid to ascertaining the state-of-the-art in the pertinent fields associated with repository development to gain a perspective on the uncertainties that are involved and the level of conservatism that should be built into the siting requirements. Efforts here have involved meetings with experts (e.g., See O'Donnell and others (1979), and peer review reports cited above); discussions with DOE personnel and DOE contractors; assessments of broad scale state-of-the-art reviews (IRG (1978), DOE/USGS (1979), EPA ad hoc (1977), USGS (1978), LBL (1978)); consideration of the state-of-the-art in important technical areas such as in the geotechnical and geomechanical area (Wawersik (1978), in the geochemical area (Ames and Rai

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(1976)), in the field of hydrologic modeling (Bachmat and others (1978)), and in radiological performance assessment capability (See specific references cited in text).

(4) The NRC has been sponsoring research and technical support work to develop insights and analytical tools for licensing at Lawrence Livermore Laboratory, Sandia Laboratory, and elsewhere. A considerable amount of technical literature has evolved from these programs (e.g., see Heckman and Minichino (1979)). Moreover, through DOE EPA and USGS sponsorship a voluminous amount of technical literature has evolved. An attempt to be cognizant of and to draw upon technical literature has been made in developing the siting requirements.

(5) Importantly, the siting requirements have been developed in consideration of past NRC nuclear power plant licensing experience and problems which have arisen, particularly in the earth science area (see Robbins and Budge (1979)). Of particular concern here is the establishment of requirements which will help to facilitate the licensing process, decisionmaking and confidence in making findings on site suitability.

Thus, the siting requirements are largely the result of staff judgments in consideration of establishing an effective licensing process, the views of experts, the state-of-the-art, and information derived from the technical literature.

2.3 Issues Arising in the Development of the Siting Criteria

A number of broad issues have arisen during the course of developing the siting requirements. These are briefly described here in order to provide focus and perspective as to the merits of the technical requirements and the decisions reached in their formulation.

2.3.1 Level of Specificity

The siting requirements are intended to be generic in their application, i.e., applicable to all potential host rocks in consideration of different waste types and forms, and repository designs.* Perhaps the most difficult issue that has arisen in deriving the requirements has been determining an appropriate level of specificity to be incorporated in the requirements in terms of scope, emphasis and the inclusion of numerical criteria. This difficulty is reflected in past versions of the siting requirements which differ mostly from the present version in terms of the degree of specificity (some are more specific, some are less so).

There are several key factors that bear on the degree of specificity of requirements. The requirements establish the technical and legal framework for licensing. They must be necessary for implementing the EPA standard and

*In terms of applicability, it should be emphasized that the siting requirements were developed with deep underground constructed geologic repositories in mind. They were not developed for, nor are they intended to discourage other radioactive waste disposal concepts, such as vadose zone disposal, seabed disposal, etc. Application of the siting requirements to other modes of geologic disposal may require exceptions and different requirements.

the protection of public health and safety. They must be specific enough to facilitate decisionmaking. As noted in several peer reviews (see TRW (1978), Craig (1979)), the requirements must provide substantive guidance to DOE. The same holds true in terms of providing substantial guidance to the NRC licensing staff. The requirements must consider the source, composition, and form of waste so that they are not unduly restrictive or inadequate (TRW (1978)). The requirements must consider site specific characteristics which are difficult to generalize (USNRC (1977)). Also, the requirements must consider the nature of the hazard and the performance of the entire repository system (IRG (1978)). Importantly, the requirements must take into account what the technology will bear. They must also consider uncertainties that are involved from many sources, the compensation of uncertainties in order to demonstrate performance and the specification of what is acceptable. Particularly, in the application of the earth sciences, consideration must be given to the application of professional judgment and warranted latitude.

In reviewing various versions of siting guidelines, such as the IAEA (1977), NAS/NRC (1979), NAS/NRC (1978), and those developed by contractors to the NRC, e.g., LLL (1979), Golder (1978b), it is immediately apparent that most are rather general (see Goad, 1979, for summary comparison). Siting guidelines in the literature more than anything else reflect general consensus views on what constitutes sound siting practice in terms of what is needed by way of investigations and tests, and what are favorable and unfavorable site characteristics. There appears several reasons why guidelines are rather general. They reflect the difficulty in trying to codify earth science considerations which are very much judgmental in nature due to limitations in knowledge of earth processes. They reflect the site specific nature of factors to consider which are difficult to quantify generically. They also reflect a systems view that requires consideration of the site as part of a larger system. Such a view requires no single factor be treated in isolation of other factors (IRG, 1978), and requires a site specific weighing and balancing of factors. Consideration of a site as part of a multiple barrier system requires the site to perform in concert with other elements of the system in terms of complementing and supplementing performance so that an acceptable overall performance is achieved. As illustrated in Golder (1978b), in the application of generic siting criteria, different requirements will better be met by different host rocks and hydrogeologic environments and, as such, allowance must be made for considering overall performance.

In assessing the technology of radioactive waste disposal in geologic repositories for purposes of drafting siting requirements, several important factors become apparent. Most technical studies are relatively fundamental in nature. That is, repository development is in a research mode and a gamut of research is underway to understand the very basic aspects of repository performance. Many outstanding questions are still to be resolved. Most efforts have been associated with bedded salt as a repository host rock, although studies on other potential host rocks have been and are being conducted. Importantly, radiological performance analyses performed to date are computer simulations on generic sites. Such studies have used different analytical or numerical models, assumptions, boundary conditions, and input data. Although, as noted in such studies, attempts have been made to assess "real world" conditions, they are in fact simplifications of "real world" conditions. Such studies are useful, through the application of sensitivity and uncertainty analysis, in defining the nature of the hazard, what parameters or conditions are important, and are helpful in placing bounds on the problem. Thus, such studies are an aid in defining where emphasis should be placed in terms of demonstrating operational and long-term performance. However, because of their generic nature and limitations, such studies have only a qualitative utility in specifying requirements. Given the present-day technology and limited experience, there is a need for a conservative approach in siting. However, the technology will bear only so much in terms of quantifying this approach.

In terms of the benefits of quantitative requirements, Rogers and others (1979) discuss some of the benefits to be gained. Quantitative criteria can facilitate the licensing process in several ways. It is easier to develop procedures to satisfy a quantitative requirement. Such a requirement helps reduce ambiguity in decisionmaking. It is easier to determine if a quantitative requirement is met. Quantitative requirements permit specification, either explicity or implicity, as to the level of conservatism desired. Particularly, in the earth science area, as past licensing experience indicates, often endless technical and legal debate ensues in grappling with earth science questions which the technology cannot answer one way or another. It has been recommended that the siting requirements be quantitative and specified in relation to repository performance, Craig (1979).

The siting requirements discussed here are an attempt to resolve the question of specificity. The requirements have been developed for generic application. They were developed to provide substantive guidance. They were developed to allow judgment in their application and structured latitude to assure they are neither unduly restrictive nor inadequate. The siting requirements constitute a set of criterion which in combination and along with other requirements should assure with confidence that the overall performance objectives are attained. Emphasis has been placed on important system parameters and compensating for uncertainty.

2.3.2 Reliance on Systems Analysis

A major issue that has arisen in the course of developing the siting requirements is the question of how much reliance can be placed on a comprehensive performance analysis, i.e., on modeling long-term performance. Considerable attention has been paid to deriving siting requirements that are consistent with assessing, through a comprehensive performance analysis, the overall performance of the repository over the long term. Additionally, as required in the EPA standard, considerable attention has gone into deriving requirements which would result in the site and environs being a major barrier in the isolation of radionuclides in concert with the other technical performance objectives and the multiple barrier approach. As noted previously, and in a latter section in detail, various performance assessments have been considered in deriving the siting requirements. The bulk of NRC contract support work has gone into the development of insights and models for licensing (see Campbell and others (1978), and Heckman and others (1979)). There is no question that consideration of repository performance over the long term will require modeling. However, there is considerable question regarding the confidence one can place in such models. There are many factors involved in assessing this question and details are covered in sections to follow. As noted in IRG (1978): "Given the uncertainties associated with our predictive capabilities in the earth sciences, with mathematical oversimplification of complex processes and with the variability of rock properties and hydrogeologic characteristics, a precise risk assessment...may never be possible." Similar views have been expressed elsewhere in the technical literature. In dealing with this question, one must weigh such views in context of the state-of-the-art in modeling and the technologies involved, the magnitude of uncertainties involved, the nature of the hazard, and in context of a regulatory process where decisions will be made.

The use of performance analysis bears on every aspect of the siting requirements. It bears on data to be collected and analyzed, on the level of conservatism to be applied, on latitude permitted in light of an analysis of overall performance, on incorporating the traditional judgmental nature of much of the sciences involved and consensus views. Of particular concern is the compensation of uncertainty in the performance analysis and making allowance for exceptions in criteria if the performance analysis indicates exceptions are warranted. The siting requirements are an attempt at a conservative approach in dealing with this question. Requirements have been developed to help simplify the performance analysis and thus gain confidence in results. Additionally, requirements have been developed to assure the application of sound practices in siting. Latitude in meeting requirements requires not just the performance analysis indicating it is warranted, but also that sound practice and the weight of information support such exception.

2.3.3 Adverse Human Activities

As noted in EPA Ad Hoc (1977), "Man's unpredictability far outstrips most of the imagined geologic hazards we can foresee." This view is widely held in the technical literature and is compounded by studies which reveal that release mechanisms for radionuclide migration induced by exploration activities and repository construction, Berman and others (1978), and by future repository penetrations by subsurface human activities, Cloninger (1979), appears to be of far greater concern than escape pathways created by natural processes. Thus, two major issues have arisen in dealing with human activities. The first relates to repository development and minimizing adverse impacts on the repository site. A paradox is created here in that a significant amount of information characterizing a site is essential; yet at the same time the attainment of such information is limited because of potential adverse impacts due to such activities as drilling and the limited state-of-the-art in sealing subsurface penetrations. The siting requirements attempt to deal with this issue by requiring careful attention to site investigations. Ultimately, some sort of weighing must be done.

The second issue dealing with future human activities is perhaps the most confounding problem to deal with. There is no precedent in dealing with human activities in the distant future. Although many past and present human activities effect the future, none has been given the type of consideration that is being given in dealing with radioactive wastes. The EPA standard requires the assumption that active human controls not be assumed to last for more than 100 years. Thus, there is a significant burden in siting and designing a repository to reduce potential inadvertent human intrusion in the future. The siting requirements attempt to deal with this problem by requiring a repository be sited such that it is less prone to adverse future human activities, particularly in dealing with the exploration and exploitation of resources. Of particular emphasis here is consideration of past and present human activities and present-day technologies for the purposes of forecasting. It is believed futile at best to consider future human motivations and technologies.

2.3.4 Overall Performance Assessment

As noted previously, an attempt has been made to relate the siting requirements to overall performance. However, at present, the siting requirements have not been fully assessed as to their bearing on overall performance. Such a study is contemplated in context of viewing all the technical requirements in relation to the EPA standard and is anticipated to be completed prior to proposing the technical requirements.

Thus, the siting requirements, based on the judgment of the NRC staff in consideration of a broad range of information, are an attempt at balancing many factors. They are an attempt to balance such factors as: general requirements vs. very quantitative requirements; quanititive assessments vs. judgmental considerations; reliance on performance modeling vs. reliance on more traditional practices; being conservative in light of uncertainties vs. allowing flexibility in light of performance. It is anticipated that the siting requirements will be supplemented by more specific guidance in the form of Regulatory Guides. Also, given the research and development mode that the sciences dealing with repository development are in, the requirements may be revised as new information and experience is gained.

3.0 SITING OBJECTIVES AND PRINCIPLES

This section describes the bases and underlying principles for the site performance objectives and siting requirements. Of particular importance here is the role of the site in radioactive waste isolation, i.e., what are its important features in isolating waste, what is its role in complementing and supplementing design features and what is its role in providing a margin of assurance in demonstrating that overall repository performance is achieved. Consideration is given in this section to viewing the site as part of a multiple barrier system and the site as a system of multiple barriers. Some material briefly described here goes somewhat beyond the scope of this document and is only included for perspective.

3.1 Purpose of Geologic Disposal

Substantial quantities of radioactive waste exist and continue to be produced from the national defense program and commercial nuclear power plants. Detailed assessments have been made concerning the amounts and types of waste being temporarily stored and that are being and may be generated in the future, USDOE (1979), ADL (1979a). Studies have been conducted to assess various means of permanently disposing of waste, IRG (1978), Altomare and others (1979). On February 12, 1979, the President in an address to Congress established a comprehensive radioactive waste management program base on recommendations of the Interagency Review Group on Radioactive Waste Management (see recommendations in IRG (1979)). The objective of this program is to isolate existing and future

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radioactive waste such that it poses no significant threat to public health and safety. The main thrust of the national program is to dispose of waste in mined geologic repositories.

As noted in IAEA (1977), the major principle behind geologic disposal is that geologic formations have existed relatively undisturbed for many millions of years and, as such, there is a high probability they will remain so in the future. Radioactive waste deeply emplaced in such formations should then remain relatively undisturbed and isolated. However, due to many factors, including the disturbance of geologic formations in emplacing waste, deleterious waste/rock interactions, and considerations spaning thousands of years into the future, the most serious difficulty, as discussed in Golder (1977), will in all likelihood be related to adequately demonstrating that wastes are sufficiently isolated in consideration of the suitability of a site and repository design.

3.2 Role of a Geologic Repository

The role then of a geologic repository is twofold: (1) to perform in a way that isolates radioactive waste such that the radionuclides pose no significant hazard, and (2) to be amenable to assure an adequate demonstration of (1). In terms of factor (1), the EPA standard (presently in draft) defines the upper limit as to what constitutes "no significant hazard." The developing NRC regulation and licensing process basically deal with factor (2) in defining what is needed for an adequate demonstration that the EPA standard is satisfactorily achieved.

3.2.1 The Elements of a Geologic Repository

Conceptual designs and studies of a geologic repository envision a series of shafts leading down from the surface several hundred meters to a series of lateral drifts, perhaps at a number of horizons, in a host rock where waste packages will be brought and emplaced, CWI (1978a). Various estimates have been considered in the literature for the size of a geologic repository. This largely depends upon the amount of waste to be disposed, the configuration of waste emplacement and the geology of the site. Surface facilities can be expected to cover an area of about 200 acres (1 sq. Km), CWI (1978a). Estimates on the subsurface volume of rock necessary to accommodate a repository range from about 1 to 10 Cu. Kms, Cook (1977), ERDA (1976). Estimates on the volume of the repository (drifts) are generally up to several million cubic meters, Cook 1977, NRC/NAS 1978. In terms of subsurface area, figures range from about 2 to 8 sq. Kms., IAEA (1977), Cook (1977), CWI (1978a). In general, most analyses assume a repository subsurface radius of about 1 to 2 kilometers.

A repository can be considered to consist of three major components: waste packages, the repository structure and the site. Each component has a function both during operation and over the long term. During operation the waste packages provide a means to transport and shield the waste. The repository structure provides the skeleton to emplace the waste and support for shafts and drifts. The site provides mechanical stability and physical subsurface isolation. Emphasis in waste isolation is on the long term following backfilling of the repository.

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3.2.2 The Repository as a Multiple Barrier

Over the long term the three components of a repository act as a system of barriers in isolating radionuclides from the accessible environment. A number of studies have been conducted to assess and analyze generic repository systems. As described in Cloninger (1979), and in other studies, the repository system provides isolation by preventing or limiting:

(1) the penetration of the repository by groundwater;

(2) the failure of waste packages;

(3) the leaching of radionuclides from waste packages, and

(4) the transport of nuclides through the geology to the accessible environment.

Thus, protection could be achieved by totally isolating the waste, isolating the waste for sufficient time to allow radioactive decay to reduce the hazardous radionuclides to innocuous levels prior to discharge to the accessible environment, limiting the rate of release of radionuclides to the accessible environment and diluting the radionuclides to very low concentrations.

In order to reasonably demonstrate the sufficient isolation of radioactive waste, each of the three components of the repository system must contribute to:

(1) significantly inhibiting radionuclide migration;

(2) compensating for deficiencies in the other components and enhancing the performance of the other components;

(3) providing a margin of assurance that there is reasonable expectation of long-term system performance by compensating for uncertainties and reducing the complexities of the problem.

The above factors basically constitute the multiple barrier approach. The long-term function of the three major repository components is to act as a multiple barrier system to isolate waste. The engineered controls for isolation basically hing on two key factors: (1) the waste material and its resistance to transport (this includes the type of waste, type of container package, resistance to leaching, solubility of the leached material); and (2) the design of the facility to achieve maximum isolation from the environment (this includes inhibiting groundwater migration; providing a controlled environment to inhibit radionuclide migration through sorption, solubility limits, and reactions; mitigating adverse waste/rock interactions through controlling the distribution and thermal loading of waste (packages), ADL (1979b), Byrne and others (1979)).

3.3 The Role of the Site

Like the engineered elements, the site must contribute to the above four factors that provide isolation, and to the three factors that provide for demonstration of isolation. The discussion here focuses on how the site contributes to the multiple barrier approach.

3.3.1 Elements of the Site

In terms of radionuclide isolation, the site and its environs can be divided into four major components. These are a geologic framework, a geomechanical framework, a groundwater flow system, and a geochemical system. These four components, like the repository components, can act as a multiple barrier system to inhibit radionuclide migration. It is these four critical components that determine the site's contribution to the repository multiple barrier system.

The geologic framework consists of the geologic setting of the site in terms of geologic materials present, the geometry of the site and major natural processes which may act on the site. Its major contribution to isolating waste is providing physical isolation, e.g., through depth. The geomechanical framework consists of the mechanical properties of the site, e.g., the thermal properties, stress field, and fracture distributions. The geomechanical framework significantly influences the construction of the repository and the response of the site to waste/rock interactions. The geologic and geomechanical framework contribute to defining the groundwater flow system. The groundwater flow system basically describes the movement of groundwater. Important properties here are: porosity, permeability, hydraulic gradient, dispersivity, and rates and distances of flow. It is well accepted that groundwater flow will be the predominant mechanism for radionuclide movement. All the previous components significantly influence the geochemical system. The geochemical system consists of the chemical environment produced by interactions between groundwater and rocks. Some important characteristics here are: the oxidization-reduction potential (eh), acidity (ph), ionic strength of the groundwater and sorption characteristics of rocks. Performance studies and sensitivity analyses indicate, over the long term under reasonable conditions, it is primarily the geochemical system that will determine the rate of release of radionuclides to the accessible environment, De Marsily and others (1977), ADL (1979c), Heckman and others (1979), Cloninger (1979), Hill (1979). This is brought about by a series of complex chemical processes, as described by

Isherwood (1978), beginning with radionuclides entering the groundwater in concentrations determined by the dissolution or leach rate of the waste package, solubility of the radionuclides, and volume flow of the groundwater. As the groundwater leaves the engineered repository structure, various conditions such as Eh and ph will determine which radionuclide species are stable (e.g., TcO_4^- or TcO_2). As nuclides move along interstitial grain boundaries and fractures, reactions will take place between the radionuclide species and the rocks, such as adsorption, ion filtration, percipitation, ion exchange. It is reactions such as these that retard the movement of radionuclides.

3.3.2 The Performance of the Site in the Multiple Barrier System

The combination of site components can influence the isolation of radionuclides in several ways as discussed to some extent above. In terms of the repository system performance, the site can contribute in varying degrees to the following:

(1) physically isolating the repository from adverse human activities and adverse surface and subsurface natural conditions through location and depth;

(2) inhibiting groundwater into and out of the repository structure by providing physical barriers to groundwater flow;

(3) depending on the chemistry of the groundwater which enters the repository and anticipated reactions with engineered elements (the waste package, waste form, backfill), maintaining a low leach rate of the waste;

(4) controlling the initial concentration of radionuclides leached from the waste through groundwater flow velocity, and through chemical conditions (such as Eh), the solubility of radionuclides;

(3) inhibiting the movement of radionuclides that have escaped the repository structure by:

(a) providing physical barriers to movement.

(b) providing chemical barriers to movement.

Thus, the site can contribute to decreasing population and individual exposures by increasing the geographic distance between the waste and the accessible environment; by increasing the isolation time to allow radioactive decay through (1) protecting the repository structure from groundwater, (2) increasing the waste leach time (or decreasing the waste leach rate) directly and indirectly, (3) increasing groundwater travel time (either through decreasing the groundwater flow rate or increasing path length), and (4) increasing radionuclide travel time by providing a reactive geochemical system (high retardation); and through dispersion decreasing concentrations of radionuclides that may enter the accessible environment, Towse (1978).

A major question that arises is how much reliance can be placed on the site in its role as a contributor to the multiple barrier system? This depends on a number of factors including what will constitute sufficient isolation as determined by the EPA standard. Because of the long time frame of consideration, some 10,000 years, and limitations in confidence that engineered structures can be built to perform as desired over such a time frame, it has been suggested in the literature that the major reliance in isolating the waste must be placed on the site. Performance analyses to date, sponsored by the NRC and others, indicate that of the three components of the repository, it is the site and its environs under most reasonable conditions (the biggest exception being human subsurface penetration) that will contribute most to isolating the waste. However, as discussed below, unless a very conservative approach is taken in siting, considerable difficulty will arise in demonstrating long-term performance due to the nature of uncertainties.

3.3.3 The Nature of Uncertainties in Site Performance

The technical literature dealing with nuclear waste disposal in geologic repositories literally abounds with citations noting technical uncertainties and the need for further research. There are several reasons why this is the case. First, substantive uncertainties do indeed exist. Second, at the present time repository development is in a research mode and, as such, researchers are very cognizant of identifying questions that need to be answered. Third, sensitivity and uncertainty analyses are being conducted to assess the significance of parameters and data uncertainties with respect to overall performance and isolation. As such, uncertainties are being identified. The NRC has sponsored considerable research here as well, e.g., GEI (1978), Evenson and others (1979), Golder (1977). Fourth, because of the novel consideration that is being given to waste disposal, i.e., consideration spanning thousands of years, and the rigorous pursuit of trying to quantify the complex process of isolation, there is a perception problem as to the nature of the hazard and what evidence is necessary for demonstration that the job is indeed done. As such, a major question arises as to when is enough, enough. This section focuses on the nature of uncertainties, primarily in siting, and what is needed to compensate for these uncertainties.

As noted in the Earth Science Technical Plan (DOE/USGS (November 1979, draft), the development of geologic repositories for radioactive waste requires an improvement in the state of the art in most areas in the earth sciences. As described in the IRG (1978), deficiencies or the major causes of uncertainty can be categorized into four classes. These are:

(1) lack of data;

(2) lack of experience;

(3) limitations in characterizing a natural environment due to natural variations in properties;

(4) limitations in the ability to predict natural conditions and processes, human activities and repository performance over the long term.

3.3.3.1 Lack of data

Included in the discussion here are limitations in data per se, technologies to collect pertinent data and the understanding of processes and conditions the data describe. Studies have indicated that some two dozen types of parameters are needed in modeling regional radionuclide migration and most of these parameters are not well understood, Evenson and others (1979). In terms of the four components of the site, the geologic framework, geomechanical framework, groundwater system and geochemical system, data limitations are most severe in the latter three.

In the geologic area, the characterization of geologic parameters, particularly when complexities arise, has always been a formidable task. Questions arise regarding the transferability of data from site to site. Considerable difficulty has arisen in trying to characterize and quantify adverse geologic conditions, such as fault zones.

In the geomechanical area, there are limitations in testing and exploration technology, particularly in characterizing thermal response, such as the thermomechanical properties, time dependent properties, distribution and influences of fractures, movement of gaseous or liquid inclusions, in situ stress, the validation of laboratory and in situ experiments, the development of instrumentation for monitoring, Wawersik (1978).

In the groundwater system, field techniques for measuring and characterizing important parameters, such as permeabilities in low permeable rocks, dispersion and fracture flow are not well developed nor are these parameters well understood, IEC (1979), Golder (1977).

As borne out in sensitivity analyses, Heckman and others (1979), the geochemical system is perhaps the most important of all the site components in isolating waste, yet it is the least understood, Isherwood (1978). There is a wide disparity in our knowledge of the chemistry and geochemistry of radionuclides, EPA ad hoc (1978). There are some 30 to 45 significant radionuclide isotopes in spent fuel or high-level waste, Cloninger (1979), Heckman (1979), ADL (1979c). Of these, studies reveal the major potential contributors to radiological dose (under more favorable conditions) appear to be ^{99}Tc, ^{129}I, ^{237}Np, and ^{226}Ra, Hill (1979), ADL (1979c). Also, under circumstances where path length is short, groundwater velocity high, or sorption low other nuclides such as ^{90}Sr, ^{126}SN, ^{234}U, ^{239}Pu, ^{240}Pu, ^{243}Am, and ^{245}Cm have been identified as being potentially significant contributors to dose. Thus, understanding the geochemical system requires understanding the behavior of a number of elements which tends to complicate the problem. Additionally, a number of these elements have no naturally occurring isotopes which adds additional complexity.

In consideration of data collected on these elements and others with respect to waste isolation, questions have been raised regarding the usefulness of data collected in the past due to ill-defined experiments and lack of systematic evaluation, Ames and Rai (1978). The difficulties in obtaining meaningful measurements of retardation (Rf, Kd, Ka) in the laboratory are many and formidable, Relyea and others (1978). Measurements of such factors as distribution coefficients (Kd) used in describing the retardation process in models vary significantly from experiment to experiment, Apps and others (1977). Variations of several times to orders of magnitude in values of distribution coefficients for the same nuclides and same rocks measured in different laboratories have been reported, Serne and others (1979). The applicability of data obtained in laboratory experiments over sho t times and using small sample sizes to geologic situations over long time periods and path lengths of kilometers has not been conclusively shown, Serne (1977). Additionally, little work has been done at elevated temperature regarding retardation. Thus, little work is applicable to the near field of a repository. Compounding the problem are questions regarding characterizing the geochemical system in the field. The compounding aspect here is defining the behavior of a number of nuclides with respect to a number of rocks and in context of different groundwater chemistries. Significant variations in sorption in the same rock taken from different depths in boreholes has been reported, Erdal and others (1978). Significant questions are arising regarding the theory underlying much of the retardation work that is currently being pursued. Necessary thermodynamic data to predict the stability fields of nuclide species are limited in terms of their paucity and accuracy, Ames and Rai (1978), Rai and Serne (1978). Predictions of concentrations based on different thermodynamic data vary by several orders of magnitude, Rai and Serne (1978). Present theory in use (simple chromatography theory) is coming under question. The migration of nuclides in rocks appears to exhibit a much more complex behavior than predicted by present theory which basically ignores kinetics, Seitz and others (1979). Questions are arising as to whether the assumption of equilibrium which underlies the theory behind retardation values is truly applicable, Dosch and Lynch (1978). Additionally, new effects on the oxidization state of nuclides which effect retardation are being found, such as the influence of radiation, Fried and others (1979). Significant here also is work revealing that retardation may be controlled by minor rock components, Hinkebein and Hlava (1977). Thus, retardation may vary by orders of magnitude over a few meters and may only be characterized in situ, if at all. Finally, little work to date has been pursued in developing techniques for measuring, performing measurements and quantifying radionuclide migration in situ in the field, Isherwood (1979a).

3.3.3.2 Lack of experience

Many facets of the concept of geologic disposal in geologic repositories are unique and without precedent. Earth scientists are being called upon to assess and quantify factors never before done and in ways almost opposite to their experience. Geologists who have primarily been focusing on the past and present are now being called upon to make projections into the far distant future. Groundwater hydrologists are being called upon to assess low permeable rocks when their experience has largely been in the search and understanding of groundwater in highly permeable rocks. In both cases, both the tools and the theory are presently limited. Two significant areas here, relating to the lack of experience and siting and uncertainties, deal with the engineered features and thermal effects.

Of all the waste/rock interaction effects that are of concern, it is the thermal effects produced by the thermal loading of the waste from radioactive decay that is the most far reaching in potentially compromising an otherwise good site. Potential effects from the thermal loading will be complex. Weaver (1979), in assessing the thermal effects on shales and clays, notes a number of complex effects which include: dehydration and hydration of minerals, porosity and permeability changes, changes to the porewater chemistry, effects on retardation capacity, pressure buildup, fracturing, expansion, contraction, and gas generation from organics. These same effects in varying degrees will occur at any site in any host rock. Additional effects anticipated include chemical reactions and large scale perturbations to the groundwater flow system. The lack of experience in assessing thermal effects has been well noted in the literature, EPA ad hoc (1978), Golder (1977), Wawersik (1978) and others. As considered by Wawersik (1978) in reviewing the state of the art in rock mechanics as it relates to repository development, he notes that the development of a repository involves problems without precedent in the history of deep underground construction. He cites the two most significant being evaluations for periods of thousands of years, and the short- and long-term effects of elevated temperature due to the waste, and concludes existing information concerning the mechanical, thermal, and chemical properties of rock masses are insufficient to make such evaluations.

Another critical area where experience is limited is in borehole and shaft sealing technology. Of prime concern in the development of a repository is sealing drifts, shafts and exploratory boreholes. Although there is considerable time over the next several decades while repositories are under construction and in operation to develop effective seals, consideration must be given now to whether seals can be effective over the long term at a particular site. It appears, however, based on available data, that information is of limited value and inadequate to judge long-term performance of borehole and shaft seals, Koplik and others (1979), ONWI (1979). Included here is even the question of importance of seals on long-term performance, ONWI (1979). Past experience has indicated that many borehole seals that are in use have indeed failed over relatively short time periods, GEI (1978).

3.3.3.3 Natural variations

In consideration of identifying sites 25 sq. Kms on the surface has been used, DOE/USGS (1979 draft). As discussed earlier, the volume of rock necessary to accommodate a repository ranges from about 1 to 10 cu. Kms. Regional studies related to siting will extend tens of kilometers from a site. In modeling the migration of radionuclides, generic assessments have considered distances on the order of kilometers to tens of kilometers, e.g., ADL (1979c), Naymik and Thorson (1978). Depth considerations may extend to several kilometers. Out to such distances and to such depths, and in the volume of rock to be assessed, variations in geologic properties, even in the same rock units, can be anticipated. Some properties may vary by several percent, some by orders of magnitude. As such, natural variations in parameter values and conditions can be anticipated. As previously discussed, some two dozen types of parameters for modeling will be necessary to perform a rigorous analysis. This is compounded by the number of geologic formations present, discontinuities and heterogenities. Present technology and resources will not permit complete knowledge of a site and its environs. Additionally, because of the need for limited borings so as to not compromise the site, limitations are placed on data collection and assessing the extent of variations. Thus, both natural variations and limitations in exploration will create uncertainties in assessing the site.

3.3.3.4 Limitations in prediction

Considerable research activity is being sponsored by EPA, DOE, and NRC and others in developing computer analysis techniques in an attempt to develop tools for long-term prediction. Bachmat and others (1978) have reviewed the state of the art of hydrologic and transport models. As they note, this field is relatively new and models are only in the developmental stage. Models, although they may represent sophisticated computer technology, are only simplified representations of complex real world conditions. As yet, the testing of transport models is very limited. Of particular note are problems associated with institutional acceptance of models and the difficulties that arise in their application in a legal framework.

In terms of model prediction, this involves coupling of physical and chemical processes in context of the likelihood of natural events and human activities, i.e., the probability of events, over a long time span, into the future. As described in Stottlemyre and others (1978), Carpenter and others (1979), and others, the assessment of long-term performance is very complex involving identifying potential disruptive phenomena, assessing phenomena and interrelationships, assessing the impact on and response of the geology and hydrology and assessing the impact on releases. Experience in siting critical facilities reveals considerable difficulty in making such assessments in the

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earth sciences over the short term. This is primarily due to the lack of knowledge of processes and the paucity of data, both in amount and over time. Coupling the making of long-term predictions with the previously cited uncertainties in the sections above considerably compounds the problem. The ability to predict geologic processes in any but the most general way over time spans of thousands of years is believed to be generally poor, EPA ad hoc (1977). Considerable research has been called for to develop predictive tools, EPA ad hoc (1977), USGS (1978), DOE/USGS (1979 Draft). However, as noted previously, a precise risk assessment may never be possible.

The problem of long-term prediction is compounded by consideration of future human activities which may disrupt the repository. It is believed not possible to envisage measures capable of protecting a repository against human activities, IAEA (1977). In terms of probability analysis, human unpredictability far outstrips the most imagined geologic hazards that can be foreseen and it is doubtful that human actions in the distant future are amenable to such analysis, EPA ad hoc (1977). Assuming the loss of active administrative control, it is only possible to try and minimize adverse and inadvertent human activities in the future, Golder (1977). This can only be done through conservatively siting a repository where, based on present technology, human subsurface activities are not likely.

3.3.3.5 Compensation of uncertainties

As discussed above, considerable uncertainty exists and will create difficulty in reasonably demonstrating long-term performance. As noted in

McGrath and others (1978), repositories will be sited despite the presence of uncertainties in available data and lack of full knowledge of important factors, and despite these uncertainties, the national program is going forward.

A number of things can and are being done to compensate for uncertainty. Considerable research is underway to try and answer many of the questions raised above (e.g., DOE/USGS (1979 draft)) and to try and quantitatively assess the impacts of uncertainty. Certain important questions must be answered before adequate performance can be assured, NAS/NRC (1979). A conservative approach now to repository development is needed. As recommended, a repository must consist of a series of backup systems, i.e., multiple barriers, IRG (1978), Craig (1979).

In terms of siting, a conservative approach must be taken. A stable and predictable geology is necessary, Golder (1978b). It is important to select sites with characteristics that are relatively easy to characterize and model accurately, Rogers and others (1979). Significant complexities should be avoided because they introduce considerable uncertainty in model calculations and available models may not be able to represent such complexities; this also increases the possibility of overlooking anomalies, Rogers and others (1979). Sites must be selected which possess as many favorable conditions as possible to compensate for uncertainties and any adverse conditions found. Reliable and accurate geotechnical information must be obtained and can only be obtained by observation and measurement taken at a particular site and on geologic material collected from that site, IEC (1979).

In dealing with long-term assessments, natural analogues provide the element of "time" and must be drawn upon as part of the weight of technical evidence. The application of models to past geologic thermal events, Norton and Knight (1977), and transport processes, Norton and Knapp (1977), provides a means to verify predictions over the long term. Comparisons of processes and conditions related to a repository with natural conditions, Brookins (1978a,b), Walton and Cowan (1975), Cowan (1978), provides a means to bound the problem on a first principle basis.

A considerable subjective element exists in the earth sciences. Despite the fact that such subjectivity, i.e., expert opinion, is considered by some not to be suitable for a comprehensive safety evaluation tool, Greenborg and others (1978), such subjectivity, and the sound siting practices that have evolved through the years from it, must play a considerable role in safety considerations in siting.

3.4 Site Performance Objectives

3.4.1 Underlying Principles

The achievement of the EPA standard requires three main factors: (1) the numerical release standards, as a minimum, be met through a comprehensive performance assessment; (2) there is "reasonable expectation" that the performance standards are met; and (3) to compensate for uncertainty, the repository be composed of multiple barriers.

In consideration of achieving the EPA standard, and in consideration of the above discussion, as well as information to follow, a number of principles have emerged which underlie the siting requirements, i.e., the site performance objectives and the individual siting requirements. In relation to the above factors, these are:

3.4.1.1 Performance assessment

In conducting the performance assessment, three things are necessary: (1) simplifying the problem through avoiding complexities; (2) bounding the problem through using bounding assumptions and parameter values; and (3) thoroughly investigating a site to obtain as thorough a knowledge of conditions and representative data as possible. This latter principle cannot be more stressed. As summarized by Dowding (1979), in engineering disciplines other than those related to the earth sciences, material properties are defined a priori and are controlled by manufacturing. At a site, nature has manufactured the material properties and they can only be revealed by thorough investigation. The conveyance of the overriding importance of exploration to other disciplines is a difficult one. Here, with regard to a repository, investigations become even more important because long-term performance cannot be measured over the long term but only assessed on the basis of short-term tests and investigations.

3.4.1.2 Reasonable expectation

Reasonable expectation of site performance requires not only a computer simulation but also the following: (1) the weight of technical evidence based on "first" principles, derived from the observational sciences involved, and the consensus of peers, (2) verification of models; (3) professional latitude and judgment in terms of neither being unduly restrictive nor inadequate, and (4) that the level of decisions reached corresponds to the level of information available.

3.4.1.3 Multiple barrier approach

Compliance with the multiple barrier approach requires: (1) the site to complement and supplement the engineered barriers not in just simply and marginally making up deficiencies but also in providing a margin of safety; (2) each of the site components to provide a margin of safety and this requires the site to possess as many favorable characteristics as possible and as few adverse conditions as possible.

From these principles, the three site performance objectives below and the siting requirements described in the sections to follow have been derived.

3.4.2 Stability of the Site and Environs

The future stability of the site is of paramount importance. It is the cornerstone of the concept of geologic disposal. Site stability is the main thread of every guideline on site suitability, e.g., NAS/NRC (1978), NAS/NRC (1979), IAEA (1977), IRG (1978), USNRC (1977, 1978), McGrath and others (1978). It is of paramount importance in terms of limiting releases, Cloninger (1979). Based on a performance analysis, assuming that along with the engineered elements, the initial site conditions provide retardation and other properties that show the EPA standard is achieved, future stability of the site provides the margin of safety and confidence that the repository will indeed perform as anticipated over the long term. Future stability provides protection to the engineered elements from both man's activities and natural processes. It allows simplification of and provides additional confidence in the performance forecasting.

The nature of future stability is a relative one. What is required is that the site's present stability will not significantly decrease over at least the next 10,000 years, both under natural processes and influences of the emplaced waste. In geology, perhaps, the only thing that can be guaranteed is change. As such, some change to a site in the future can be anticipated. Of importance here is the rate and magnitude of change as determined by examination of the past and the present, in consideration of possible future influences, e.g., climatic change. In terms of the past and present, it is necessary to show that the site is relatively stable and has been relatively stable in the recent geologic past in terms of such things as tectonic stability, hydrologic stability. That is, it is necessary to show that the four components of the site have not significantly changed over the recent geologic past. To do this requires that the rate and magnitude of processes acting in the area around the site in the recent geologic past are, on a relative basis with other areas, on the low end of the scale.

There is some discussion in the literature about siting repositories in very active areas, such as near an active volcano such that volcanic ash would help bury a site and keep humans away, or on the down thrown block of a fault such that with time the repository would become more deeply buried. At present, neither the characterization or prediction of the close-in effects of these phenomena can be made with any real certainty to make predictions over short time spans, let alone the next 10,000 years; and neither phenomena has had any real effect on where humans in the past and at present congregate. These suggestions also go against the main body of recommendations in the literature.

As noted in the literature, De Marsily and others (1977), past (or present) stability cannot guarantee future stability, nor are they sufficient to assure that there is reasonable expectation of meeting the EPA standard. Such a condition(s) is, however, essential. Additionally, the following objective must be achieved.

3.4.3 Inhibiting Radionuclide Migration

The site and its environs must significantly contribute to retarding radionuclide migration and it is necessary that this capability not significantly decrease with time. Much of the discussion above applies here and will not be repeated. As indicated in previous sections, over the long term the site will be the major contributor to isolating waste, excepting human activities which may short circuit the site and catastrophic geologic events which meeting the first objective and the engineering objectives should minimize. As indicated in a number of studies, De Marsily and others (1977), Altomare and others (1979), regardless of host rock low permeability and depth, there is sufficient time for groundwater to penetrate the repository and return biologically significant radionuclides to the accessible environment. As noted previously, it is the geochemical system that has the major impact on retarding the rate of release of radionuclides to the accessible environment; therefore, it is essential that a site exhibit geochemical properties that significantly retard radionuclide migration. However, the geochemical system is the least understood site component. As such, this requires the other components of the site to provide a significant margin of safety. That is, the hydrologic system alone must provide very long travel times (see section 6.0). The geological and geomechanical framework of a site and its environs must provide a significant physical barrier to groundwater movement and circulation. Each of the components must be shown to provide a margin of safety and significantly contribute to assuring the EPA standard is met. What constitutes a margin of safety in toto would be the site preventing any releases to the accessible environment for 10,000 years under reasonably likely natural processes. This should be the goal, but it is not required, because it goes beyond the EPA standard and may not be reasonably achievable. However, reasonable predictions indicating that this may be attained would provide a significant margin of safety. What is required is assurance that the initial conditions exhibited by a site to inhibit radionuclide migration and that are used in forecasting radionuclide migration in the future, remain relatively unchanged and don't decrease in the next 10,000 years. The task of characterizing these properties at a site and of quantifying them to determine present conditions, given such things as variations in natural properties, the questionable relevance of laboratory measurements on samples from a site, the lack of in situ techniques, will be formidable and in and of itself highly uncertain. Anticipation of significant variations from the initial conditions would basically lead to a situation of limited to no confidence.

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3.4.4 Minimum Release Time

The third site performance objective, in context of the two above, provides a coupling between the site and the engineered repository elements. It basically requires as a performance objective that the site provide a certain level of redundancy and supplementation to the engineered elements, particularly during the time period when the hazard is the greatest. Analyses of the potential hazard of the waste indicate that the hazard significantly decays with time and that it is the most intense within the first 1,000 years. As noted by Heckman and others (1979), the initial condition of the repository must be such that no significant releases occur during this period because radioactive decay has not substantially reduced the hazard. It is also approximately within this time frame and out to several thousands of years that waste/rock interaction effects will be the most intense on the site, in the far field, Wang and others (1979), ADL (1979b). Thus, within this time frame, the hazard and the complexity of analysis will be the greatest. Within this time frame, then, demonstration of performance will tend to be the most difficult.

In general, the performance objectives for the engineering elements provide two major things: protection against human intrusion which would short circuit the site, and compensation of the many uncertainties associated with the site. The third site performance objective provides needed backup to the engineered elements during the most significant time period with respect to difficulties in analysis and the hazard. This objective requires a site be chosen with the idea of achieving no releases to the accessible environment under expected processes and reasonably foreseeable events, assuming the engineered barriers may fail during the first thousand years, when the hazard is greatest. It indirectly, but intentionally, sets a minimum radionuclide travel time from the repository to the accessible environment of 1,000 years. Performance studies indicate such a minimum travel time should result in releases approaching background radiation levels. Additionally, such a travel time, coupled with the time it takes for repository resaturation (estimated to range from decades to hundreds to perhaps a thousand years depending on permeability and other factors, Heckman and others (1979)) and delays in initiating travel (a thousand years or more) brought about by the engineered barriers, will provide a significant factor of safety in assuring that at least over a significant percentage of the 10,000 years and during the time period when the hazard and complexities are greatest, the EPA release standards will be achieved.

The use of a travel time per se as a performance objective was chosen for several important reasons. First, it allows consideration of the combination of site parameters in keeping with a systems approach. That is, different sites could achieve this objective through different combinations of site parameters. As such, it does not place undue restrictions in the choice of a site which might result from placing overemphasis on a single site condition. Second, such a performance objective allows a certain de[illegible] of independent check on performance modeling. This can be achieved through the dating of groundwater movement by multiple approaches and the assessment of the chemical evolution of the groundwater, Davis (1979), Fritz and others (1979). Comparisons, then, can be made between measured flow characteristics and predicted flow characteristics. Third, if the radionuclide travel time to the accessible environment is equated to just the groundwater travel time (as further discussed in section 6), it helps to relieve considerable uncertainty which is brought about by heavy reliance on the uncertain and complex geochemical system. In this case, the geochemical system just becomes an additional safety factor and it only requires marginal retardation (effective retardation factors between 1 and 10) to assure the EPA release standard is achieved under reasonable likely events and processes. This third element is not required as a performance objective but is a favorable characteristic siting requirement. Finally, the use of a travel time is considered a type of objective that can be readily determined early-on in site screening, both in terms of field tests and associated analyses and in carryout performance modeling. As such, it should help in making early site suitability determinations.

4.0 SITE EVALUATION

This section, as well as Sections 5 and 6 to follow, describe the bases behind the siting requirements in the draft regulation (See appendix A). The siting requirements as a whole define and provide more detail as to what is acceptable in terms of site characteristics and the assessments that need to be performed in context of meeting the site performance objectives and the EPA release standards. The previously defined principles that underlie the site performance objectives underlie these requirements as well. Of particular importance, here, is the application of professional judgment and latitude. It is anticipated that a site may not meet all of the siting requirements but still meet the site performance objectives and the EPA standard. As such, exceptions to individual requirements may be warranted so as not to be unduly restrictive. However, the requirements have implicitly associated with them a level of conservatism the NRC staff believes is appropriate and necessary for meeting the site performance objectives and the EPA standard. Thus, exceptions will not come readily. The requirements, as discussed in sections 5 and 6, layout the scope of what is necessary to obtain an exception. What is essential is the maintaining of about the same implicit level of conservatism that would be associated with having met all of the siting requirements.

4.1 The Scope of Site Evaluation

The site evaluation requirements refer to the general siting requirements and site-related monitoring requirements in the regulation. Following on the recommendations in NAS/NRC (1979), the site evaluation requirements establish a framework for a comprehensive data acquisition and analysis program that is based on extensive exploration, experimentation in the laboratory and in the field, and large-scale in situ testing. They establish a process that will continue and build through the licensing stages. They also establish the foundation for the development of regulatory guides which will provide more specialized and detailed guidance, and the licensing review process. As noted previously, site evaluation is the cornerstone of applied earth science fields. Because of the importance of site evaluation, and particular importance with respect to assessing long-term repository performance, site evaluation requirements have been included in the regulation.

There are three essential aspects to site evaluation. These are: (1) exploration, which includes performing investigations and tests to determine site conditions for the purposes of design and long-term performance projection; (2) analysis, which includes, based on (1), such things as identifying past, present and future natural conditions and processes and their magnitudes, rates and likelihood, i.e., scenarios for modeling, evaluating waste/rock interactions, and conducting performance modeling; and (3) verification, which includes validating models as well as monitoring to confirm performance and predictions. None of these aspects are mutually exclusive. Individual site evaluation requirements to some extent encompass all three aspects. However, in the following discussion these three aspects are treated somewhat separately. Additionally, repository/site interaction effects which bear significantly on the application of the adverse condition requirements are also treated separately below.

4.2 Exploration Requirements

The development of a repository is unique in several ways. In addition to those examples previously cited, such as evaluations extending thousands of years into the future, the development of a repository has lead to federal regulations and standards that explicitly deal with risk and calls for a comprehensive and integrated approach. There is little precedent for the type of integrated approach that is being taken in developing a repository. This is particularly true in the applied earth science area where geotechnical information is obtained and is provided to design engineers for design input. Although in repository development this still holds, much more is required because of the importance of the site, the unique types of evaluations involved and the integration of the many factors that are involved via systems modeling. Thus, it becomes imperative that site exploration be conducted in an integrated way and that those conducting exploration be cognizant of the essentials involved. The siting requirements dealing with investigations, evaluations and tests were developed with this in mind. The essentials involved and their bearing on exploration are discussed below.

4.2.1 Reducing Complexity

One must keep in mind that the analysis of repository performance is very complex and demonstration of performance will be very involved. Given limitations in modeling capabilities and limitations in conducting investigations near a site to prevent adverse effects (e.g., due to boreholes), in site exploration one must consider, in context of present capabilities and these limitations, whether a site is too complex to be thoroughly investigated and evaluated. This assessment is an important requirement. As to whether a site is too complex or not is a relative judgment. It involves considerations of many factors but, in particular, considerations of confidence. This in turn involves, from an exploration standpoint: whether site conditions can be described with a high degree of confidence; whether there exists complex geologic structures and active processes; and whether there may be significantly different but just as sound interpretations of past and present conditions which could lead to orders of magnitude variations in consideration of future conditions.

4.2.2 Extent of Investigations

The extent of investigations, in terms of defining the spacial and temporal framework of a site, will be dictated by site specific conditions, i.e., whatever it takes to define the dynamics of the system and possible variations at a particular site, TRW (1978). However, based on past licensing experience and difficulties that have arisen (see Robbins and Budge (1979)) and the uniqueness of assessments related to repository development, several minimum requirements have emerged. These bear on defining the spacial framework and temporal framework (i.e., the past, present, and the future) of the site and its environs.

4.2.2.1 Spacial framework

In consideration of the spacial framework one must ask the question: How far out from a site should "detailed" investigations extend? Without some guidance here, the answer to this question could either lead to a situation where "detailed" considerations extend to distances on the order of thousands of kilometers from a site (e.g., on the extreme, the entire North American plate) to distances of only a few kilometers from a site. The knowledge of earth processes is such that there is no real formula to make a decision such as this. From a licensing perspective, this could lead to a situation where one is trying to answer the impossible, where considerable "endless" debate will ensue and where information may be obtained which either is of questionable relevance or doesn't go far enough. In fact, this has indeed happened in past licensing cases.

In terms of the geographic extent of past investigations conducted for critical facilities, this has largely been dictated by seismic considerations, Slemmons (1977). Although there are certain common threads, there is no real consistency in the geographic extent of past investigations for critical facilities, Robbins and others (1979). Although far-field seismic considerations are important in repository development, such as in the design of surface structures, in defining the tectonic region around a site, and in assessing the likelihood of seismic events in the future, they are not as important for a repository over the long term as for the design of other types of critical structures over the short term, Koplik and others (1979), KBS (1978), Carpenter and Towse (1979), Pratt and others (1978). With regard to groundwater assessments, these have largely focused on present and short-term future considerations.

Assessments of groundwater conditions in the geologic past comparable to assessments made of tectonic conditions (for purposes of defining present day conditions for design applications) appears scarce. Much of the past effort here appears largely academic in nature. That is, there is no precedent for the type of considerations that must be made here (i.e., "quantitatively" defining the extent of paleo-groundwater systems and future groundwater systems on a geologic time scale).

Given the above problems there is no specific answer to the stated question and one can envision this situation arising even at a specific site. The answer to this question will be formidable. However, there are several factors that should be kept in mind and that have led to setting a minimum (but generally acceptable) distance of a radius of a hundred kilome ers from a site for purposes of investigation. These are:

(1) Emphasis must be placed on unraveling the future through unraveling the recent past and present. Thus, one must not just look for conditions which help define the past and the present but the future as well. This is helpful not just for input to model predictions but to help validate such predictions on a first principle basis.

(2) Emphasis must be placed on not just mmediate site conditions but on a much larger area to assess whether more remote conditions could influence the site in the future or be useful in unraveling past, present and future conditions in the immediate area around a site. That is, correlations and similarities must be sought.

(3) The search for information must become more intense closer toward the site and at points were radionuclide releases to the accessible environment may occur. Particular focus must be placed on site properties which may influence the extent and magnitude of repository/site interactions, e.g., properties bearing on convective groundwater flow.

(4) Emphasis must be placed on those conditions, events and processes that are truly important. Of particular concern here is bounding the nature and extent of conditions, events and processes, i.e., defining their geometric extent, temporal extent, rates, magnitudes and likelihood.

Consideration of these factors and the above discussion went into the judgment behind the 100 km minimum (with respect to details on factor 4, see section 5). This numerical requirement appears reasonable from several respects. Considerations in terms of defining the region around a repository site span about 10^3 to 10^5 square miles (or square kilometers), DOE/USGS (1979 draft), or a radius of about 30 to 300 kilometers. The geometric extent of geologic features and tectonic features are usually in the range of tens of kilometers. A distance is necessary to encompass these features. Studies to assess such features in critial facility siting are usually on the order of a hundred to several hundred kilometers, Slemmons (1977). Distances traveled by deep groundwaters before they reach surface waters or shallow aquifers are noted as being usually in the range of 10 to 1,000 kms., Hill (1979). Given, the approximate travel times of such deep water, a site meeting the favorable characteristics in the regulation and modeling studies performed, e.g., Naymik and Thorsen (1978), detailed considerations of flow paths beyond tens to a hundred kilometers appears unreasonable. A number of conditions may extend way beyond the 100 kilometer minimum. These include conditions dealing with glaciation which have had impacts spanning thousands of kilometers, such as that resulting from major reorientations of river drainage patterns, Flint (1971). Tectonic features such as large-scale geologic structural provinces, may also span thousands of kilometers, Rodgers (1970). Putting these in some perceptive, tectonic conditions far removed from a site have been noted to be of questionable relevance in assessing present day site conditions, Robbins and Budge (1979), Hadley and Devine (1974), let alone conditions thousands of years hence. It is questionable whether glacial processes far removed from a site are relevant and whether they require detailed considerations that cannot be obtained closer in. It is thought unreasonable to require detailed assessments beyond a hundred kilometers, unless there is something major to be gained. On the other side is the question as to whether the hundred kilometers is too large. As stated previously, geologic and hydrologic conditions of interest span tens of kilometers, so that considerations at a minimum would have to encompass such a distance. Geologic processes have rates on the order of millimeters per year to centimeters per year in most cases, and migratory geologic phenomena are conservatively bound by the hundred kilometers. The same holds true for hydrologic processes.

4.2.2.2 Temporal framework

4.2.2.2.1 Past and present

Both the past and the present are handles on the future, but there is a question as to where emphasis should be placed. As noted previously, much emphasis in the siting of critical facilities, particularly in the east, has focused on paleozoic (about 350 to 600 millon years ago) tectonics and is of questionable relevance in assessing the present, let alone the near-term geologic future. Questions have also been raised about the relevance of looking back into the past beyond 10 million years because too many conditions have changed, TRW (1978). We are presently in the Quaternary geologic period which began some 2 million years ago. This period has been largely characterized by tectonic conditions extending from somewhat earlier periods, and cyclic episodes of major glaciation on the order of every hundred thousand years, with interglacial periods like the present period lasting on the order of 10,000 to 20,000 years. The height of the last glaciation occurred some 23,000 to 18,000 years ago; the present interglacial began about 10,000 years ago. The present climate may be in a cooling off period and, in any case, glaciation in the next several thousand to ten thousand years can be anticipated.

Consideration of the operational period of a repository requires emphasis on the present. Consideration of long-term performance requires emphasis on the near geologic future. For both, in dealing with the past, emphasis must be on those elements of the past that bear on processes acting today and that may be acting in the near future, that is, the present geologic period that we are in: the Quaternary period. Therefore, investigations of the site and its environs must be geared to emphasizing the Quaternary period. Information must be obtained at a site and near a site that details what happened since the Quaternary period began. Focus must be given to obtaining information that will be useful in predicting the future, particularly those that deal with perturbations on the site's four components or support the lack of perturbations.

As noted, emphasis in investigations is required to be placed on conditions, events and processes which have been active since the start of the Quaternary period. However, considerations for the more distant past will also be necessary.

In some places Quaternary stratigraphy may be absent or scarce and consideration must be given to periods extending further back into the past. Additionally, older geologic conditions must be assessed to unravel stratigraphy and the plate tectonic evolution of a site and its environs.

4.2.2.2.2 Future

The EPA Standard requires performance analysis out to 10,000 years into the future. A question arises as to whether it is reasonably achievable to require assessments, which includes investigations to look beyond this time period. This depends on three factors: (1) the nature of the hazard, (2) the precision that can be achieved in predicting the future and this includes assessing the past, and (3) given the time evolution of the hazard due to radioactive decay, whether the 10,000 years is enough time to evaluate what might happen to the waste in the future. The EPA has evaluated these factors and has concluded that 10,000 years is sufficient.

In developing the siting requirements consideration has also been given to this problem as it strictly relates to site investigations and analyses and to the ALARA concept (that is as low as reasonably achievable concept). The hazard due to radioactive waste decays with time. Assessments reveal that between 1,000 to 10,000 years the risk posed by the waste is reduced to a level that is about the same as that posed by unmined uranium ore. However, certain differences exist: the waste is more concentrated; it is not in a naturally produced geological or chemical environment; and different elements are present, a number of which are long-lived and considered biologically significant, e.g., ^{239}Pu. In regard to these differences, consideration has been given to requiring site evaluations for periods extending beyond 10,000 years, e.g., to 250,000 years. The literature contains reference to a number of time periods, such as up to 100,000 years, NAS/NRC (1978), IAEA (1977), hundreds of thousands of years, USDOE (1979), and even several millions of years. Different time periods basically stem from considerations of different nuclides, e.g., 250,000 years representing ten half lives of ^{239}Pu, several thousands to several millions of years representing the buildup of alpha emitting daughters (e.g., ^{226}Ra), IRG (1978). Several references discuss the problems in making a rational case in setting limits between a hundred thousand to 10 million years, e.g., Gera (1975), and in using an individual nuclide, e.g., APS (1978). From strictly a siting perspective, making any future predictions, even spanning decades as in the case of the siting of critical facilities, is a difficult and sometimes almost impossible task. Quantitative assessments over a period of 10,000 years, although only representing at a minimum one hundredth of the time period in the past investigated, will be formidable, given many of the previously cited uncertainties. Assessments of geologic conditions used in siting critical facilities, for example in using probabilistic analysis to derive design earthquakes, approach 10^{-3} to 10^{-4} events per year. However, it is recognized that data are scarce and only represent a small time window into the past, present and future. Although such assessments only apply to facilities having short lifetimes, significant reliance on engineered safety margins are included to compensate for siting and other uncertainties. In the case of a repository, then, from a siting standpoint, it is highly questionable, given the limitations in confidence at 10,000 years, whether anything quantitative can be said with any meaning beyond that period; and even at that period, in parallel with other facilities, considerable safety margin must be incorporated via the engineered barriers. Beyond this period, reliance must heavily be placed on such things as the resilience of the waste form and packaging as noted in IAEA (1977).

Thus, it is highly doubtful that quantitative site assessments beyond 10,000 years will be meaningful. However, because of the potential adverse impacts due to glaciation, effects of glaciation warrant consideration. Additionally, it is expected that, based on qualitative considerations, no highly probable catastrophic geologic events should be anticipated shortly beyond the 10,000 years. Built into this latter consideration is meeting the favorable and adverse condition criteria.

4.2.3 The Objectives of Investigations

Many studies have dwelled on the general types of information needed for design and for performance assessments, e.g., IAEA (1977), NAS/NRC (1979), LLL (1979), on more specific information dealing with specific subject areas, e.g., Ames and Rai (1978), Isherwood (1978), LBL (1978), and the types of investigative methods available, e.g., IEC (1979). Table 4.1 lists some of the more important information needed to assess a site. Details covering such material will be the subject of future regulatory guides and will not be discussed here. Considered here, however, are the objectives behind the requirements for investigations and several important types of investigations that must be made. The required objectives are sixfold:

4.2.3.1 Investigations for design

Investigations must be conducted for both short-term and long-term considerations bearing on design, construction, operation, and decommissioning. Important investigative considerations here deal with making determinations on site suitability in context of a site specific design. This includes the design of excavations, methods of excavation, size and geometry of a repository, waste emplacement, backfilling and monitoring, Wawersik (1978). Included here

Table 4.1 Examples of Important Site Parameters

1.0 Geologic Framework

1.1 Conditions

Geometry
Stratigraphy (composition, thickness, lateral extent)
Depth to host rock
Geothermal gradient
Tectonic framework
Climatologic framework
Distribution and extent of resources

1.2 Processes

Extent, magnitude, and rate of:

Surficial geologic processes (erosion)
Tectonic processes (earthquakes)
Dissolutioning
Uplift
Subsidence

1.3 Events

Extent, magnitude, rate, liklihood of:

volcanism
fault'ng

2.0 Geomechanical Framework

2.1 Mechanical Conditions

Distribution of heterogeneities and discontinuities (fractures, faults)
Quality of rock conditions
Stress conditions
Strength
Modulii
Plasticity

2.2 Thermomechanical properties

Thermal conductivity
Expansion coefficients
Thermal alteration properties
Specific heat
Density
Conduction and convection characteristics
Pore water pressures

3.0 Groundwater System

3.1 Flow Framework

Locations and rates of recharge and discharge
Depth to the water table
Hydrostratigraphy (aquifers, aquicludes)
Aquifer capacities
Directions of flow
Velocity of flow
Travel times of flow
Gradients

3.2 Flow Properties

Interstitial flow
Fracture flow
Primary and secondary porosity (effective porosity)
Permeability (hydraulic conductivity and intrinsic permeability)
Groundwater age (using multiple approaches)
Dispersivity

4.0 Geochemical System

4.1 Rock properties (in all potentially travelled rocks)
Mineralogy
Petrology
Alteration processes and products
Retardation properties for nuclides and species of importance (bulk rock and mineral retardation, mass and surface distribution coefficients, ion exchange, adsorption and desorption, absorption, ion filtration, osmotic effects, kinetic factors, equilibrium factors, temperature and pressure effects, characteristics effecting oxidization/reduction and acidity)
Organic content

4.2 Nuclide properties (in all potentially travelled rocks)
concentrations
stability fields of species (at temperature, pressure)
solubility
reactions
complexing

4.3 Groundwater chemistry (in all potentially travelled rocks)
Oxidization/reduction potential
Acidity
Trace and bulk chemistry (ionic strength, inorganic and organic composition)
Hydrogeologic evolution

POOR ORIGINAL

5.0 Human System

Past and present activities
Population distribution (including growth trends)
Extent, magnitude and distribution of subsurface activities (exploration drilling, resource mining and drilling, water well drilling, subsurface waste or waste water disposal, underground storage, underground construction)
Military activities
Transportation

also is determining design basis events for surface and possible subsurface and interconnecting facilities. These include natural events, such as earthquakes and meteorologic phenomena, and consideration of human activities near a site. Another important investigative design consideration that must be made is early indications that site conditions are such that the repository can be effectively sealed. Early consideration must also be given to investigating discontinuities, heterogeneties, such things as brine pockets, gas pockets, and poor rock conditions needed for determinations regarding safety-related design modifications, or the possible retrieval of waste, or which have a bearing on site suitability.

4.2.3.2 Investigations for stability

Investigations must focus on determining the relative stability of the site over the long term, i.e., the relative stability of the four site components. As previously stated, this requires emphasis on the recent geologic past. Considerations here must be given to establishing site conditions in context of plate tectonics and global climatology, McGrath and others (1978), Potter (1979). Of particular concern is performing investigations which cast light on the paleohydrology and past chemical conditions of the site and its environs. Consideration here must also be given to identifying parameters and conditions important in assessing repository/site interactions. Important here, as well, is defining the rates, magnitudes, extent and likelihood of processes and events active today and in the recent past.

4.2.3.3 Investigations for migration

Investigations must focus on those conditions that bear on the isolation of radionuclides, i.e., defining the contributions of the four site components in isolating waste, the margins of safety they provide, how they complement one another and supplement one another. Again, considerations in investigations must focus on repository/site interactions, i.e., both the effects on the site and in turn the site's effect on the engineered barriers.

4.2.3.4 Investigation of system dynamics

In conducting investigations as well as evaluations, consideration must be given to the dynamics involved, i.e., interactions and superpositions of many variables in space and time. As an example, in investigating site properties with respect to borehole sealing, it is not enough to just determine ambient conditions. Consideration must be given to the location of the borehole with respect to the repository; the anticipated heat flux in the vicinity of the borehole, and its changes in time and magnitude; changes in groundwater chemistry and flow in the vicinity of the borehole with time; changes to stress conditions in the vicinity of the borehole due to uplift or lateral expansion from the heat load; changes to pore water pressure; natural conditions, processes and events, when they might occur in time and their magnitude at the borehole location. Thus, in investigating conditions at the site of a borehole or at the location of a potential shaft, one must obtain information that goes beyond just identifying ambient conditions. Again, investigations must give consideration to the dynamics involved and this includes combined consideration of natural processes, human activities, construction of the repository and waste/rock/water interactions.

4.2.3.5 Investigations for representative and bounding values

In terms of characterizing site conditions, both natural and those related to human activities, the obtainment of both representative and bounding values are necessary. In terms of representative values, characteristics related particularly to bulk groundwater flow and retardation are essential for the long-term performance assessment. In terms of obtaining bounding values, this is essential in assessing confidence. A significant aspect of the comprehensive performance assessment will entail sensitivity analysis, i.e., the assessment of what conditions at a site are particularly important, and uncertainty analysis, i.e., the assessment of the impact of uncertainties associated with input data on radionuclide release calculations. This requires investigations to seek out the extent of variations in site conditions, and to define bounds on variations. Because of the interpretative nature of site assessments, due consideration must be given to reporting interpretations that not only support a position but also those that may not.

4.2.3.6 Minimizing adverse effects

Finally, in terms of investigations, care must be taken to minimize potential adverse effects, EPA ad hoc (1977), NAS/NRC (1979). Of particular concern here are the sinking of an exploratory shaft, development of exploratory drifts, and the drilling of boreholes which could result in creating pathways for groundwater and radionuclide movement and could short circuit the site's isolation properties. This could either come about through creating additional pathways via the shaft, drift, or borehole, or creating fractures into the surrounding rock. This may be particularly troublesome in penetrating soluble rocks such as salt and limestone because of the possibilities of inducing dissolutioning, Carpenter and others (1979). Consideration must be given to both the state-of-the-art of sealing boreholes which is limited, and the system dynamics as discussed above which will be complex. Investigations entailing subsurface penetrations must give prior consideration to possible effects on long-term performance. Obviously, trade-offs are involved here and this must be carefully assessed. Consideration must also be given to the use and resolution of remote sensing techniques. What is required, then, is a demonstration that a reasonable attempt has been made in assessing and bounding impacts, in weighing impacts against what is gained, and that impacts do not have a significant effect on long-term performances nor in meeting the site performance objectives, the other technical objectives in the regulation and the EPA release standard.

4.3 Required Analyses for Long-Term Performance

As noted in IRG (1978), the degree of long-term isolation can only be assessed through mathematical modeling. Extensive efforts are underway to develop such computer models, Stottlemyre and others (1978), Dillon and others (1978), Campbell and others (1978), Iman and others (1978). Sensitivity analyses have been conducted to assess what properties of the repository system are important and when, Hill (1979), Cloninger (1979), APS (1978). Studies are being conducted to identify scenarios that may lead to releases, Carpenter and others (1979), Campbell and others (1978), ADL (1977), Stottlemyre and others (1978). This section, drawing upon the above references and emphasizing the site, discusses the scope and objectives of the requirements dealing with evaluations and performing analyses. The next section will discuss verification of analyses.

4.3.1 Scope of Analyses

The analysis of repository performance requires a comprehensive performance assessment, i.e., an analyses of the magnitude and likelihood of radionuclide releases to the accessible environment. To perfom such an analysis requires the following factors, as derived from site investigations, to be defined:

Table 4.2. Events, Processes and Conditions Requiring Long-term Performance Consideration for Scenario Analyses

Condition, Event, Process	Influences of Particular Concern
1.0 Natural and Slow Continuous Processes:	1.0 Evolving framework for analyses
1.1 Processes Initiating on the Surface	
1.1.1 Sea Level Fluctuations	1.1.1 Changes to groundwater flow and chemistry
1.1.2 Denudation and Stream Erosion	1.1.2 Exhumation of waste and changes to recharge and discharge locations
1.1.3 Climatic Fluctuations	1.1.3 Increasing recharge and discharge, aquifer capacity
1.1.4 Sedimentation	1.1.4 Brittle fracturing due to sediment loading, increasing porosity and permeability, creating natural impoundments
1.1.5 Glaciation	1.1.4 Gamut of potential effects including exhumation due to erosion, isotatic adjustments resulting in brittle fracturing and increasing porosity and permeability, changes in the regional flow system boundary conditions, affects on dissolutioning rates, creation of natural impoundments
1.2 Subsurface and Broadscale Processes	
1.2.1 Regional Uplift and Subsidence	1.2.1 Brittle fracturing, generation of earthquakes
1.2.2 Dissolutioning	1.2.2 Increasing rate of waste leaching, creating pathways for radionuclide migration
1.2.3 Diapirism	1.2.3 Creation of fractures, changes to repository geometry and effects on engineered structures

Table 4.2. (Continued)

Condition, Event, Process	Influences of Particular Concern
2.0 Disruptive Natural Events	2.0 Disruption of engineered elements and ambient site conditions
2.1 Volcanic Activity (including extrusive and intrusive activity)	2.1 Creation of natural impoundments, earthquake activity, creation of pathways, exhumation of waste, changes in groundwater chemistry
2.2 Faulting	2.2 Creation of pathways, disruption of engineered repository elements to inhibit groundwater and radionuclide migration, short circuiting the site properties to inhibit migration
2.3 Earthquakes and Associated Effects	2.3 Disruption of emplaced engineered materials (seal failures)
3.0 Human-Induced Phenomena	3.0 Disruptions to ambient conditions and repository elements
3.1 Repository Related	
3.1.1 Subsistence and Caving	3.1.1 Creation of fractures
3.1.2 Shaft and Borehole Seal Failures	3.1.2 Decreasing path length
3.1.3 Fluid Inclusion Migration	3.1.3 Increasing dissolutioning of waste
3.1.4 Thermal Effects	3.1.4 Changes to groundwater flow including circulation pattern and rates, chemical changes to groundwater and retardation capacity of rocks, physical changes in geology including expansion/contraction, including stress and fracturing, pressure changes, failure of seals, chemical reactions.

Table 4.2. (Continued)

Condition, Event, Process	Influences of Particular Concern
3.1.5 Radiation Effects	3.1.5 Production of gases, physical changes to material properties
3.1.6 Chemical Effects	3.1.6 Adverse effects on retardation properties
3.2 <u>Nonrepository Related</u>	
3.2.1 Inadvertent Intrusion Into Repository Due to Exploration (drilling)	3.2.1 Decrease path lengths, increasing dissolution of rocks (salt), disruption of engineered elements, creation of additional fractures
3.2.2 Mining Activities (for resources or storage)	3.2.2 Decrease path lengths, creation of fractures, changes to groundwater chemistry, dissolution of host rock (salt)
3.2.3 Subsurface Water Use (wells and waste disposal)	3.2.3 Decrease path lengths, creation of fractures, adverse changes to groundwater chemistry, local effects on groundwater flow (effects on gradients)
3.2.4 Human Activities on Surface (military use, impoundments, population center establishment)	3.2.4 Creation of fractures, modification of groundwater flow system (effects on gradients, recharge, and discharge)
4.0 <u>Undetected Conditions</u>	4.0 Creation of uncertainty
4.1 <u>Hydrogeologic Conditions</u> (includes faults, breccia pipes, gas and brine pockets, fractures, voids, discontinuities, heterogeneities, valuable resources)	4.1 See above influences
4.2 <u>Human Induced Conditions</u> (includes undiscovered boreholes and mines)	4.2 See above influences

dealing with a particular event, process, or condition should be performed. It is expected that this will be conservatively approached.

It should be noted that three types of conditions have been left off the list which are included on others. These are: consideration of nuclear warfare, meteorite impacts and intentional future human activities. With regard to nuclear warfare in the future, surely the catastrophy brought about by both the surface dispersion of radionuclides and major disruption to society makes consideration of repository failure somewhat a moot point in comparison. Meteorite impacts of the size to cause damage to a repository have a very low likelihood of hitting a repository, and a repository site has less chance of being hit by such a meteorite than a major city (due to area) where destruction and death would be many, many orders of magnitude greater and yet, it is of little concern. In terms of "intentional" human intrusion in the distant future, in context of the site, little can really be done here.

4.3.1.2 Sensitivity analysis

Because factors are largely site specific, analysis must be performed to determine, at a specific site, what are the important site conditions and their influences on releases. Thus, a sensitivity study is necessitated. Important here are the assessments of the four key factors previously stated that could result in increasing releases. That is, analysis must not just focus on those things which would result in exceeding the EPA standard but on those conditions, processes, and events which may have a major impact on releases.

4.3.1.3 Uncertainity analysis

As with sensitivity analysis which is site specific, an assessment of the uncertainties in input data and how they influence releases must be performed. Particular attention must be given to bounding values, to alternative interpretations of data, and to whether the model used appropropriately propagates errors. Of particular concern here is assessing uncertainties in the geochemical system, i.e., retardation, which is critical for isolation.

4.3.1.4 Incorporating limitations in the state-of-the-art

In performing analysis attention must be paid to incorporating the limited current understanding of processes, the limitations in experimental and in situ data, and the subjectivity of many of the aspects of the sciences involved. Peer review and consensus is essential. Consideration in performing analysis must be given to what models represent, i.e., only simulations of very complex processes, and where they are limited. Consideration must be given to the institutional difficulties associated with model use which may arise in proceeding through the licensing process (Bachmat and others (1978)), concerns regarding the confidence in models and concerns regarding either intentional or inadvertent manipulation of models such that they only provide one sided answers. An open and conservative approach which heavily relies on sound practices cannot be more stressed and is required.

4.4 Verification Requirements

There are three types of verification requirements contained in the regulation bearing on siting. They are in addition to general quality assurance requirements which apply to all safety related features of the repository. The three types of requirements deal with (1) validating analyses, particularly overall performance analyses, (2) monitoring, and (3) establishing a program to continuously verify and assess changes in site conditions. In keeping with recommendations of NAS/NRC (1979), verification criteria require a continuous process of evaluation during all the licensing stages. The bases behind these requirements are discussed below.

4.4.1 Validation of Analyses

Ultimately, technical determinations on site suitability will be made on the bases of the weight of the technical evidence. That is, in consideration of such factors as the technical judgments made, investigations performed and the data derived, peer review and analyses, the technical information taken as a whole must support satisfactory performance of the repository to isolate waste from the accessible environment. No single factor dominates this process, although some things are more important than others. Of particular importance here, is the necessary use of models in forecasting long-term performance. Because of the significant reliance on models and the inability to actually view performance over the long-term, a heavy burden is placed on validating models to the extent practicable. That is, determining to what degree do they actually simulate "real world" conditions. There are two critical areas here. These involve assessing the migration of radionuclides which includes assessing groundwater flow, and assessing repository/site interactions, particularly the effects due to the thermal loading. What must be determined, given that models are but simulations of real world conditions, is how well do they represent the real world. Are they conservative representations or underconservative representations? The determination of the degree of validation can only really be assessed through real world application. As noted by Bachmat and others (1978), little test application has been done thus far on the models of interest. Most are in the developmental stage. Although models have been applied to assumed and generic sites, conditions studied are only simplistic representations of the real world. Although models themselves may be based on sound first principles, and in conducting simulations there is an attempt to represent and bound real world conditions, the question remains just how representative are they? An important note, here, particularly with regard to transport models and geochemical models, is whether indeed they are based on sound first principles. Transport models primarily rely on porous flow theory and it is questionable as to how applicable this is for low permeable rocks and in assessing fracture flow. Geochemical models of retardation are primarily based on simple chromatographic theory which appears to be overly simplistic.

Because of the importance of models, tests to validate them are required. These include:

4.4.1.1 Field verification

The application of models to field situations is essential. Included here might be using tracer tests. Because of anticipated low permeable repository site conditions, large-scale field testing in impermeable rocks near a repository may not be possible, but this possibility must be considered. Whether it be at the site or not, or in impermeable or even permeable rocks elsewhere, tests must be performed. This is particularly true with regard to retardation which is fundamentally unverified.

4.4.1.2 Validation using in situ tests

The comparison of predictions based on models with in situ tests is essential. As will be discussed further on, in situ tests at the site of a repository permit the characterization of site bulk rock properties and, importantly, the characterization of discontinuities and heterogeneities which significantly bear on groundwater and radionuclide flow and thermomechanical response. Essential comparisons here between model predictions and test results should be made with regard to such parameters as: gross permeability (as determined by tests in drifts and groundwater dating), fracture permeability, thermal conductivity and thermal response (expansion). Consideration here should not just be given to the host rock per se, but any confining units or rocks that may be important in terms of radionuclide migration and that might be significantly effected by the heat flux.

4.4.1.3 Validation by field-verified laboratory tests

Laboratory tests provide another means of verifying models. Some work in this area has been pursued, Seitz and others (1979). However, laboratory tests themselves may suffer from the same shortcoming as the models, i.e., they require validation with respect to the real world. A significant example, here, is in the area of measuring radionuclide retardation. Thus, the use of laboratory tests in helping to verify models will require that laboratory tests be field-verified.

4.4.1.4 Validation through monitoring

It is important that information obtained through monitoring (see below) be fed back to models not only to make refined predictions based on monitoring data, but also to validate the models themselves. Monitoring data collected during repository development will provide the most representative information available on the response of the site to the emplacement of waste. Also, it will provide a greater element of time, i.e., perhaps decades of information. Although monitoring is required to commence during the early stages of repository development, early model validation will primarily be done using the other tests of validation.

4.4.1.5 Validation using natural analogues

In context of long-term performance forecasting over the next 10,000 years and validating models, all of the above tests have one major shortcoming: they only represent a small window in time. This is also basically true for all tests, investigations and evaluations performed. It appears ironic that geologic disposal being based on geologic continuity has drawn little on geology as a tool in forecasting. Yet, an examination of geologic situations, i.e., natural analogues, offers the element of time. It appears there are many natural analogues which would be useful and must be drawn upon to validate models and bound the problem. Application of models to natural analogues and of natural analogues to bound parameter values in a number of areas can be performed. These include: modeling of the chemical stability of the waste packages in a natural environment, Ringwood (1978); modeling and bounding potential leach rates through examination of natural leach rates, Moreira-Nordemann (1980); modeling of igneous intrusive bodies to ascertain the extent and dynamics of heat flow in a natural environment that may be associated with waste emplacement, Norton and Knight (1977); examining changes in rocks brought about by heat flow due to igneous intrusive bodies particularly as it relates to physical and chemical changes in rock materials, Weaver (1978); modeling the transport of material through fractures, Norton and Knapp (1977); modeling radionuclide transport by searching out for elements which exhibit geochemical coherence to those in the waste and this includes examination of the transport in aquifers and along fractures from ore bodies, the Oklo phenomena, and natural chemical gradients in aquifers. Modeling of the potential for inadvertent criticality of waste material, Brookins (1978b), and reconcentration phenomena (Burkholder and Cloninger (1978)) through examination of natural transport processes. Waste/rock interactions are largely low grade hydrothermal reactions. A good deal of information on natural but analogous hydrothermal reactions exist, e.g., seawater/rock reactions being an anologue to brine/waste/rock reactions. Additionally, one can investigate possible effects of natural events, e.g., glacial loading, on a repository at depth through assessing past effects on ambient conditions subject to the same events. These are but a few examples that can be used not only to validate models, but as part of the weight of the technical evidence. Considerable effort here is not only needed but is required.

4.4.2 Monitoring

As discussed previously, monitoring of repository performance offers a means to validate models. It also offers a means to collect information on actual repository performance and is essential from the siting standard point (as well as design) in verifying whether the site under waste/rock/water interactions is responding as predicted based on previous analyses and information obtained. Again, one must keep in mind, unlike the siting and design of conventional facilities in which previous information and analyses can be confirmed during operation, a repository will function over thousands of years and its functioning cannot be viewed, at least by the designers. Considerations regarding monitoring requirements are only in the early stages. A number of studies have been conducted to assess potential monitoring methods, IEC (1979), EATC (1979). Considerations include the design of a monitoring program to detect and identify possible adverse conditions bearing on worker safety, structural stability, retrieval and containment capability. Considerations also include the use of in situ and remote sensing monitors. Conditions that will require monitoring include:

(a) waste/waste package interactions

(b) waste/waste package/engineered barrier interactions

(c) engineered barrier/rock/water interactions

More specifically from the siting standpoint these include:

(1) Storage room stability

(2) shaft stability

(3) heat flow out of the repository

(4) groundwater flow into and out of the repository

(5) borehole, shaft and tunnel sealing

(6) changes in ambient conditions including stress field changes, fracturing, brine migration, porewater pressure changes, expansion and possible contraction of rocks, chemical and physical changes to rocks, and perturbations to groundwater flow

At the present time three principal requirements regarding monitoring have been developed bearing on siting. These are:

4.4.2.1 Minimizing adverse effects

Like the investigation requirements discussed previously, consideration in establishing a monitoring program must consider potential adverse effects on the repository brought about by the installation and operation of monitors. For example, boreholes possibly drilled from drifts into the wall rock to assess the extent of mine-induced stress using seismic instruments, Kaufman and others (1978), McGarr and others (1978) must take into consideration the possibility of inducing fractures and sealing the boreholes. Electrical instruments emplaced at a site where gas pockets may be encountered must take into consideration spark-ignited explosions.

4.4.2.2 Monitoring baseline conditions

Candidate sites for a repository will primarily be chosen on the bases of favorable ambient conditions. Early extensive monitoring of important ambient conditions, that is, at the commencement of site characterization, is required to obtain details on subsurface conditions and changes to those conditions brought about through the drilling of boreholes, the sinking of exploratory shafts and the developing of exploratory drifts. Important here is monitoring baseline conditions and the extent and magnitude of changes to those conditions so that during construction and operation, further changes can be assessed with respect to the ultimate impacts on radiological performance. Of particular importance here is the assessement of rock stability and groundwater flow. The emplacement of surface and subsurface instrumentation to monitor mine-induced seismic activity and changes in groundwater flow patterns will be essential here. Geodetic leveling to monitor possible subsidence will also be important. Physical observations and observations made with remote sensing instruments to monitor the extent of fracturing due to subsurface excavation will also be needed.

4.4.2.3 Monitoring changes to baseline conditions during construction, operation, and after decommissioning

During construction and operation, much of the previous discussion applies. The decommissioning, i.e., following backfilling of a repository, is decades away. It can be anticipated that much will have been learned and technology will have advanced at the time when the point of decommissioning is reached. Thus, conceptualizing about requirements here is difficult. Nonetheless, the sealing of a repository is essential and consideration of decommissioning must be given early. This includes considerations for monitoring. Questions have been raised regarding the need for monitoring following closure and what it can achieve given that even if there was early leaching of radionuclides from the repository, arrival to the accessible environment should take thousands of years. Important here are several factors. First, is leaving the future the option to monitor a repository if they wish, particularly as it may bear on retrieval. This requires collecting information and establishing the foundations for future monitoring technology now. Second, is establishing the demonstration of sealing of a repository at the point when decommissioning proceedings begin. Required, here, is the prior sealing and monitoring of portions of the repository, perhaps the sealing of several drifts or modules in the case of modular design, early on and monitoring them. Finally, is the question of things not going as anticipated. Conceptually, the act of placing waste in the ground and covering it up is a simple one. However, the hazard is real, the complexities are great and things to do go wrong. Given the above, early consideration must be given to establishing a monitoring program that will be useful after decommissioning.

4.5 The Extent of Repository/Site Interaction Effects

As generally described in USGS (1978), NAS/NRC (1979) and in other overview studies, and as borne out in the more detailed studies that will be discussed, the emplacement of wastes will produce complex mechanical, chemical and thermal disturbances on a site. These disturbances, some perhaps beneficial but most appearing deleterious, will effect all four site components, i.e., the geologic framework, the geomechanical framework, the groundwater system and the geochemical system, as well as the engineered barriers. Effects will vary in magnitude, extent, and duration, and depend on many site specific factors, the nature of the waste and repository design. Effects will be superimposed one on another and interactions will take place leading to complex site response. Complicating the situation will be the further superposition of natural and human-induced events, processes and conditions over time. Most of all, these effects may have very significant impact on the site's (and engineered barrier) capability to inhibit waste migration. Significant here, too, are current limitations to model the complex interactions of effects. From the perspective of siting, required then are several things: keeping these effects to a minimum to reduce impacts, maintain stability and reduce complexities; conservatively bounding these effects in performing analyses; and rigorously investigating the extent of these effects to define them.

This discussion primarily deals with the latter two factors above. Important here is the definition of effected volume of rock, or zone of complexity which is used to reduce uncertainty as an exclusionary zone in the application of the adverse condition requirements discussed in section 5.0. Also important here is the application of tests, particularly in situ tests in defining the very near field of the effected zone.

4.5.1 Definition of the Minimum Extent of Repository/Site Interaction

The siting criteria specify that as a minimum, the repository/site interaction zone be assumed to extend a horizontal distance of 2 kilometers from the edge of subsurface excavations and a vertical distance from the surface to a depth of 1 kilometer below the limits of repository excavation. The bases behind the minimum extent of this zone is twofold: (1) bounding significant construction and waste/water/rock interaction effects, and (2) bounding the more localized adverse conditions. This latter factor, as well as the application of this zone as an exclusionary zone to reduce complexities and adverse impacts, is discussed in section 5. Described here is the bounding of significant construction and waste/water/ rock interaction effects. Although not mutually exclusive, effects are considered in light of the four site components.

4.5.1.1 Extent of effects on the geologic framework

There are basically four types of effects on the broad scale geologic framework. These are: the removal of rock material from the ambient environment, possible subsidence and subsidence-related fracturing, perturbation in the ambient geothermal gradient, and domal uplift due to expansion in response to the heat. The removal of rock materials in the construction of drifts and shafts is bound by the subsurface extent of the geologic repository operations area as a minimum. As noted previously, the estimated volume of excavated rock is in the range of several million cubic meters. The subsurface lateral extent is on the order of a radius of one to two kilometers from the repository center. The depth from the surface is usually taken as about 400 to 600 meters.

Second, associated with excavation is the possible secondary effect of surface subsidence (including propagation of fractures) resulting from the removal of rock material. It is anticipated that this will be held to a minimum. Like most of these effects, subsidence is very site specific. Taking salt as the medium having the highest potential for subsidence, potash mining surface subsidence has been reported to be up to 1 meter, with associate fractures extending from the edge of mine up to the surface at angles usually in the range of 0° to 45° from the vertical, GEI (1978). Taking the repository depth at 400 to 600 meters, effects may laterally extend out to distances comparable with the depth, i.e., 400 to 600 meters from the edge of the excavation. As a note, other mechanical effects will be covered under the section on the geomechanical framework.

The third effect, which is the most felt effect of all, is the change in the ambient temperature gradient brought about by waste generated heat from radioactive decay. A number of studies have been conducted which examine the change in ambient temperature and heat flow in time and space, and other effects resulting from the waste-generated heat. These include: OWI (1978b, c, d), Byrne and others (1979), Wang and other (1979), ADL (1979b), Dillon and others (1978), Cook and others (1979), Campbell and others (1978), Koplik and others (1979), Eaton and others (1979). These studies and others which have been drawn upon are generic in nature, and are but order of magnitude estimates. One finds, in examining these studies and others, that no two appear the same. There are differences with respect to such factors as waste type, planar heat density or thermal loading, geometry of the repository, depth of repository, ambient geology (including differences in stratigraphy, host rock type ambient temperature gradients), ambient groundwater hydrology, thermal properties, models used (including near field or far field, 1D, 2D, or 3D, consideration of the short-term or long-term, consideration of convection or conduction) and results obtained. These differences make any direct comparisons somewhat dubious at best. Additionally, one must also keep in mind that, although attempts have been made to simulate real world conditions, these studies are but generic models. Given that the cited studies and others cover a range of simulated conditions, an attempt has been made to assess reasonable bounds to these conditions and to gleen trends in effects.

Table 4.3 summarizes approximate bounds, ranges, and trends of heat flow calculations, drawn from the above references and other studies where heat flow results have been reported. As noted, heat from the waste is primarily generated by fission product decay having a heat decay rate with a half life of approximately 30 years. Thus, most of the heat will be generated early during the decades of operation. Heat flow during operation primarily depends upon such factors ; ventilation, the conductivity of surrounding rocks, the thermal loading and spacing of the waste and the geometry of the repository, Byrne and others (1979), Koplick and others (1979). With regard to the near field several observations can be made. These are:

(1) Thermal output per canister is the most important factor in determining local temperature, Koplick and others (1979).

(2) For low thermal planar densities (~10-15 W/M²) the maximum temperature for all media, and both HLW and spent fuel is generally below 100°C and is usually attained within a few tens of years (35-100) years, Wang and others (1979),

Table 4.3 Approximate Bounds, Ranges and Trends of Temperature Felt Effects

Geometries:

Slabs, discs
Range of radii - 1,100M to 1,600M
Range of depths - 450 to 650M

Host rock:

Bedded salt, dome salt, granite, shale
Ambient gradients - 20 to 40°C/km

Source term:

Spent fuel/HLW
Thermal loading (planar heat density) range
- 10 W/M^2 to 100 W/M^2 (40 to 400 kw/acre)
- 15 W/M^2 to 50 W/M^2 (usual range)
- 30 W/M^2 (about median and average)

Heat primarily generated by fission product decay and source heat decays with an approximate 30-year half life

Near field extent:

Low thermal loading
All media
HLW and Spent fuel
Max T $\sim$ < 100°C
Max τ $\sim$ tens of years (35-100 years)
Max T of Spent fuel > Max T of HLW $\sim$ 10°C
Max T Shale > Salt > Granite > Basalt

High thermal loading:
Difference amongst parameters increases
Max T $\sim$ up to several hundred degrees °C
Max τ $\sim$ up to several hundred years
Max T of Spent fuel > Max T of HLW $\sim$ tens of degrees
Conduction $\sim$ convection (< 75 years)
Temperature extent from repository: Vertical < 100 M
Horizontal < 10 M

Far field extent:

Near field continues to expand
Max τ for spent fuel $\sim$ 2,000 to 7,000 years
Max τ for HLW $\sim$ 250-2,500 years
Max surface T < 3°C (probably fraction °C)
Max vertical isotherm effect ($\Delta\tau$=5°C)= Several hundred meters to 1 km below repository
Max horizontal isotherm effect ($\Delta\tau$=5°C) $\sim$ within several hundred meters ($\sim$ 1/2 vertical)
Conduction ≠ convection (conduction Max T > convection T)

Effects in general:

Vertical effects are greater than lateral
Effects due to spent fuel are greater in magnitude and duration than HLW

Byrne and others (1979), Koplick and others (1979), Campbell and others (1978). Spent fuel temperatures are generally about 10°C higher than HLW. In terms of media, shale appears to attain the highest temperature, then salt, then granite, and basalt. Of course, this depends upon a number of factors including stratigraphy and thermal conductivity.

(3) As the thermal loading increases (from 10 to 40 W/M²) near field effects and differences appear to become more profound. Maximum temperatures, depending on the host rock type can extend from tens of degrees °C to several hundred degrees C° (as the thermal load changes from 10 to 40 W/M²). It is not clear if the time of maximum temperature is effected. Within a study, increases in the thermal load brought about increases in temperature, but the time of the maximum temperature remained about the same, ADL (1979b). Comparisons between studies, e.g., ADL (1979b) and Wang and others (1979), however, reveal a several hundred year difference. At the higher thermal loads, differences in maximum temperature and time of maximum temperature between spent fuel and HLW become more profound, differing by tens of degrees and somewhat greater than a hundred years (spent fuel being higher both in temperature and time). Also, it would appear at least for the first 75 years, there is little difference in the temperature field whether heat flows by conduction or convection, Dillon and others (1979).

(4) In terms of extent, during the early period, the largest thermal gradient is in the vertical direction. Magnitude of rise decreases sharply

with distance from the repository. Within tens of years, temperature effects can be felt within less than 100 meters above and below the repository and out laterally less than 10 meters.

In terms of the long term and far field, measures defining the extent of temperature effects include: the time of maximum extent of isotherms; time of maximum change to the ambient geothermal gradient; time of peak surface temperature rise; and time and magnitude of peak uplift, the latter being the fourth effect on the broad scale geology. The extent of far field and long-term temperature felt effects are dependent on such site factors as thermal conductivity of rock formations, stratigraphy in terms of formation thicknesses and geometry, and the groundwater hydrology, particularly as it effects conduction and convection. Important repository factors include the waste type, planar heat density or thermal loading and geometry. Several observation here include:

(1) With time, the near field temperature disturbance continues to expand. Again effects are much more extensive in the vertical direction above and below the vertical center line of the repository. Also, the magnitude of felt effects due to spent fuel appears greater than HLW, in terms of both magnitude and time (spent fuel being higher in both).

(2) Maximum felt effects may occur from several hundred years out to somewhat less than ten thousand. Spent fuel appears to have more profound and longer lasting effects. The time of maximum effects, here, appears to extend from several thousand years (~2,000 years) approaching somewhat less than ten

thousand years (7,000 years). Maximum high level waste effects range from about 250 years to several thousand (2,500 years).

(3) Anticipated surface temperature rises appear to range from a fraction of a degree to about 3°C. It would appear increasing depth or decreasing the radius of the repository would lower surface effects, Wang and others (1979).

(4) In terms of geometric extent, considered here with regard to bounding the 5°C (or 10°F) isotherm, temperature effects may extend vertically along the repository center line from near the surface to approximately several hundred meters below the repository in the first few thousand years and may approach over a kilometer below the repository in 10,000 years. The horizontal extent appears well bounded by several hundred meters from the repository edge. The temperature gradient appears to drop off very rapidly from the edge of the repository and comparable isotherms appear to only extend a distance about half of the vertical extent below the repository.

(5) Calculations would indicate significant differences in far field results depending on whether models consider conduction or convection, Campbell and others (1979). Conduction being the more conservative case as far as heat flow is concerned, i.e., temperatures are higher. Convection, perhaps being very significant with regard to waste migration.

Finally, the fourth effect on the geologic framework is broadscale uplift due to expansion in response to the heat. Like the extent of the felt temperature disturbance, the extent of uplift is dependent upon the same factors discussed above. Additionally, coefficients of thermal expansion are important as well as whether the problem is treated in 1D, 2D, or 3D, OWI (1978c), ADL (1979b), Koplick and others (1979). General observations regarding thermal uplift are:

(1) Maximum uplift occurs above the center line of the repository and uplift may extend several hundred meters beyond the radius of the repository (~< 600 meters).

(2) In terms of the magnitude and geologic environment, uplift appears greatest for dome salt, then bedded salt. The magnitudes of uplift of shale, basalt, and granite are several times lower than salt and are all approximately the same.

(3) Uplift may range from several meters to a fraction of a meter. The higher portion of the range may be an artifact of using 1D or 2D models. Effects due to spent fuel are greater than HLW in magnitude and the time when maximum uplift occurs. Uplift resulting from spent fuel disposal is about within one and a half to five times greater than uplift from high level waste disposal, and this would appear to depend on the geologic setting (host rock type) and perhaps, the thermal load. The time at which maximum uplift occurs resulting from high level waste disposal varies from about several hundred to a thousand years and varies with host rock and site stratigraphy. It appears, here, that uplift would occur sooner for salt domes then bedded salt, granite, basalt and shale. For spent fuel maximum uplift appears to occur between two

thousand years and seven thousand years, again depending on the geologic setting. Here, it appears that the time of maximum uplift may occur sooner for shale, then granite, then basalt.

4.5.1.2 Extent of effects on the geomechanical framework

The effects on the geomechanical framework related to waste isolation can be classed into three categories. These are: effects due to excavation, effects related to the geometry of the repository, and thermomechanical effects from the waste generated heat.

With respect to excavation, the effect of concern here is the fracturing of rock around shafts and drifts. The fracturing of rock may directly or indirectly (e.g., promoting dissolution) increase rock permeability, thus increase radionuclide flow. It is anticipated that excavation techniques will be used that minimize fracturing. The extent of fracturing is considered to be generally localized around openings. It has been estimated that the width of a fracture zone around subsurface openings may range from about one to three times the radius of the opening, Isherwood (1979a). Thus, the extent should be within some twenty meters or less ($r \sim 4.5$ meters).

The second category of effect involves mechanical disturbances brought about by the removal of rock material. This relates to the geometry of the repository, particularly the size of drifts and their spacing, as well as the ambient stress field. Effects here involve perturbations to the ambient stress field, possibly resulting in mine collapse, inducing fracturing and inducing faulting and earthquake activity. These effects are also considered to be generally localized, USGS (1978), perhaps with the exception of surface subsidence as discussed previously. Analysis would indicate that perturbations in the stress field, i.e., stress concentrations, depend on the diameter of a drift and spacing of drifts, and interactions become negligible as the ratio between the two decreases, Cook (1977). At a ratio of about .2 or a distance of about 45 meters between drifts (for a 9M diameter drift) effects appear to become negligible. Microearthquake studies of perturbations in the ambient stress field in the vicinity of mines also reveals that effects are localized and within a few tunnel radii away (tens of meters), McGarr and others (1978), Kaufman and others (1978). These effects amount to the establishment of a tensional stress field around openings. Induced microearthquake activity may be anticipated (that is, localized and minor faulting). Very high accelerations have been recorded due to mine induced microearthquakes (> 1g to several g), but of low particle velocity and high frequency, so felt effects are negligible.

The thermal mechanical effects caused by waste generated heat are anticipated to be more extensive than the mechanical effects and the magnitude of effects very much depends upon such site specific factors as the thermal loading, temperatures attained, rock type, and nature of discontinuities and heterogeneities, hydrology and ambient stress field. Also, effects are dynamic in that they will change in magnitude and in time. As summarized in Isherwood (1979a), Weaver (1979), USGS (1978), potential thermomechanical effects include:

(1) decreases in rock strength resulting in mine caving, fracturing and subsidence;

(2) reduction in rock moisture content (particularly in shales) resulting in shrinkage, cracking and reduction in strength;

(3) thermal expansion (as previously discussed) resulting in tensile fractures;

(4) differential expansion resulting in fractures along bedding planes, and the opening of rock/seal contacts;

(5) hydrofracturing by steam (perhaps, unlikely at depth);

(6) increases in porewater pressure causing fault movement and fracturing;

(7) differential heating across faults resulting in movement;

(8) heat induced compressive stresses inducing faulting; and

(9) heat induced creep resulting in fracturing, plastic flow and possibly diapirism.

Thermomechanical effects caused by changes in mineralogy may be initiated at ambient temperatures of only a few tens of degrees above ambient (~> 50°C), thus, effects may extend several hundred meters from the repository, Weaver (1978). Studies of the changes in the ambient state of stress reveal increases in compressive stress within the heated zone and the addition of deviatoric stresses including tensional stresses outside, Cook and others (1979). Preliminary full-scale heater tests in granite simulating the power output of a high-level waste canister reveal induced stresses up to several tens of megapascals in tens of days, in the immediate vicinity of the heater, Cook and Hood (1978). They also reveal the complexities involved in theoretically predicting induced strain and stress bec[illegible] the response of fractures. Simulations of a bedded salt environment, Campbell and others (1979), predict the development of a maximum shear stress and a maximum compressive stress in the salt formation directly above and below the repository horizon, and a maximum radially outward normal stress below the repository (in this case in a shale bed) about one hundred to two hundred meters down. Also, finite stress effects may extend several hundred meters vertically and horizontally from the repository. Maximum induced stresses predicted are on the order of several to a few tens of megapascals (compressive > shear > normal) and are attained in a short period over several decades (~ 50 years). Stresses also appear to reach maximum at about the same time and at about the time of the peak in the nearfield thermal pulse. Simulations of fluid pore pressure changes in shale predict large induced pressures near a repository within a few decades, Eaton and others (1979). Peak predicted pore pressures may well exceed local lithostatic pressure by several hundred bars (~ 600 bars or 60 mpa) in the immediate vicinity of the repository and pore pressures in excess of lithostatic pressure may extend about a hundred meters above the repository. Such pore pressures may produce the generation of tension cracks in the vicinity of the repository. Another consideration, here, may also be the possibility of inducing fault movement through decreasing the effective stress across an inactive fault.

Thus, mechanical effects appear to be limited to several tens of meters from a repository. Thermomechanical effects, although more extensive closer in, may extend several hundred meters from the repository. As illustrated in Cook and Hood (1978), thermomechanical effects will be very much site specific.

4.5.1.3 Extent of effects on the groundwater flow system

Perhaps, the most significant effect that may be brought about by the emplacement of waste is deletorious distortion of the ambient groundwater flow system. Changes in the ambient groundwater flow system could possibly make a site, which is seemingly suitable based on ambient conditions, unsuitable under waste/rock/water interactions. Thus, in investigating a site, it is imperative to keep in mind that ambient conditions will be effected by waste emplacement and one is searching for information to assess the extent of those changes.

Distortion of the groundwater flow system comes about either as a result of effects on the other site components by the waste or effects on groundwater properties per se. Important, here, are potential increases in flow rate and decreases in path length from the repository to the accessible environment, and changes in circulation patterns which may increase exposure of the waste to groundwater. Effects on the groundwater flow system are coupled effects, i.e., the groundwater flow system not only is influenced by changes in the other site components, but also it may influence the response of the other components, e.g., as discussed previously with regard to the influences of convection on perturbations in the ambient thermal gradient, and potentials for fracturing due to increases in pore water pressure. In terms of extent, coupled effects would be in the range of where other site components would be effected, i.e., from the near surface down to hundreds of meters below the repository and within several hundreds of meters laterally from the repository. Potential effects, here, would include the creation of fracture flow paths, increases or decreases in interstitial flow due to compaction or expansion of rocks which may change intrinsic permeability and effective porosity, increases or decreases in fracture flow depending on the relation of fractures to ambient stress (e.g., under compression fractures may close, on the other hand increases in porewater pressure or tensional stresses may expand fractures), increases in flow due to dissolutioning.

In terms of the more microscale properties of groundwater per se, potential decreases to viscosity due to increases in temperature have been discussed, Isherwood (1979a). These effects would tend to be localized probably within the zone of effects on the other site components. Given the inversely proportional relationship between viscosity and hydraulic conductivity, Lohman and others (1972), effects outside of the immediate vicinity of the emplaced waste ($T < 100°C$) should be well bounded within an order of magnitude or less increase in hydraulic conductivity and perhaps within limits of resolution of bulk properties.

The most dramatic effect on the large scale is inducing convection in the groundwater flow system. With respect to temperature, convection will tend to significantly reduce the temperature in the vicinity of the repository, Dillon and others (1978), thus work in reducing temperature impacts on the other site components. On the other hand, convection may change a horizontal flow system into one in which flow permeates vertically from below a repository, removes radionuclides, and transports them vertically to near surface aquifers. The extent of convection, like the other effects, is site specific and depends on the thermal loading, the geometry and properties of the initial flow system and therefore the geology. Simulations of the extent of convection, OWI (1979d), in basalt, shale and granite predict that at high thermal loadings (120 kw/acre-180kw/acre) finite effects may be felt within a couple of kilometers below the repository and somewhat less than 10 kilometers laterally from the repository edge. However, the extent of convection cells is much less on the order of a few kilometers. Additionally, convection effects are asymetric with respect to the recharge and discharge sides of a repository. As noted also, faults providing a permeable pathway may have a significant effect on the rate of flow. Most important of all are predicted vertical travel times from the repository to near surface environs on the order of a couple of hundred years or less during most of the 10,000 year period of concern. Thus, this significantly bears on the need for resilience in engineered barriers to prevent waste dissolutioning and radionuclide migration from the repository structure.

4.5.1.4 Extent of effects on the geochemical system

There are three classes of effects on the geochemical system. These include chemical effects on the country rock surrounding the repository; chemical reactions among the engineered repository elements (including the radionuclides, waste form and packaging material and engineered backfill materials) and the site; and effects on the site's capability to inhibit radionuclide migration due to changes in mineral and groundwater chemistry.

These effects are all largely brought about by the increase in temperature which promotes reactions. Some of these effects may in deed be beneficial because of the formation of reaction products which may absorb radionuclides or promote low solubility of radionuclides. Others, on the other hand, may be deleterious not only on the geochemical system but, as previously described, on the other site components, as well as the engineered repository elements. Thus, considerable investigation is required, particularly in the near field, to ascertain the geochemical peoperties of the site for assessing possible effects and for designing and developing engineered repository elements which are geochemically compatible with the site.

In terms of the first class of effects, this includes fluid inclusion migration, mineral reactions and effects on rocks and minerals due to irradiation. With regard to fluid inclusion migration, this is basically a problem restricted to salt. Both laboratory studies (e.g., Roedder and Belkin (1979a,b)) and modeling studies (e.g., Cheung and others (1979)) are being performed to study fluid inclusion migration because of the possibility of increasing corrosion of the waste package, increasing the rate of dissolutioning of the waste form, and altering thermal and mechanical properties of the host rock. As noted in Roedder and Belkin (1979a), the movement of inclusions is a complex function of many variables including inclusion size, composition of brine, vapor/liquid ratio, growth defects in the salt, strain, grain size, grain broundaries, temperature and the thermal gradient, and as such, there may be too many factors to permit useful modeling. In terms of the extent of effect, based on modeling and laboratory studies, inclusion migration appears localized in the immediate vicinity of the repository in that appreciable movement (mm/year to Cm/year) requires very high temperatures in the range of a hundred to hundreds of degrees °C and/or very high temperature gradients on the order of degrees °C per Cm. As noted in Roedder and Belkin (1979a), examination of inclusions in salt formations which have been subject to small but finite geothermal gradients indicates no movement over periods of hundreds of millions of years. As such, it is anticipated that the effect here is not one of kinetics and is indeed very localized. As summarized in Isherwood (1979b) estimates have been made approximating up to about 40 liters of brine accumulating near canisters in a 10-year period. Assuming inclusions represent 1 percent by volume of the salt, the extent of the effected zone here is approximately 4×10^{6} cm^3 of salt or well with a meter around a typical cylindrical canister. It should be emphasized, although the extent may be localized, the effects on the corrosion of a canister may be substantial and have to be assessed.

In terms of temperature induced mineral reactions in rocks, Weaver (1979), as discussed previously, has described such reactions in shale as dehydration, hydration, changes in ion exchange capacity, generation of gases with respect to organics, decreases in ion exchange capacity, increasing solubility and changes to groundwater chemistry. One anticipates the same types of reactions in any media, but to varying magnitudes. As noted by Isherwood (1978), except for attempts at quantifying re ~rdation, few other types of reactions have been quantitatively assessed with regard to waste isolation. Additionally, reactions will be very site specific. Taking shale as a bounding case, either as the host rock or a confining unit, temperatures attained on the order of tens of degrees above ambient may precipitate reactions. As such, effects may extend out a few hundred meters from a repository and will be more intense with higher temperatures or closer in.

A number of possible effects in surrounding rock have been postulated to be caused by radiation eminating from canisters, e.g., IAEA (1977). These include disordering effects in minerals, the storage of gamma ray energy and the formation of radiolytic products. Consideration of radiation effects, Koplick and others (1979), Golder (1978a) reveal that effects, if they occur at all, will be very localized and overshadowed by other chemical effects. The intensity of radiation appears to decrease many orders of magnitude over a distance within a couple of meters from a canister. Stored energy effects do not appear significant due to thermal annealing and the improbability of rapid energy release. The formation of radiolysis products appears to be confined within the waste package and in terms of amount appears to be far overshadowed by products formed from chemical corrosion. Limited radiation effects are also supported by studies of Oklo, Oran and others (1975), Oran and others (1978), Durrani (1978), Naudet and Renson (1975).

In terms of the second class of chemical reactions, i.e., reactions between engineered elements and the site, included here, is the formation of secondary minerals or contact aureoles extending from the repository, McCarthy and others (1978), which may be beneficial if radionuclides are absorbed in reaction products. As a handle on the extent, here, Naudet (1978) notes the formation of aureoles extending about a meter from Oklo reaction zones. Another type of reaction here includes modifications to site geochemical properties such as Eh or ph or retardation properties caused from the degradation of engineered elements, Winchester (1978). Because of the low permeability of host rocks, the ambient conditions may not dilute these effects until groundwater penetrates higher permeable rocks. Again, these changes may have either a beneficial or deleterious effect in terms of inhibiting migration. Little study appears to have been done here. An additional coupled reaction cited in the literature is the possibility of inadvertent criticality, i.e., the reconcentration of fissionable nuclides by precipitation or some other way to form critical masses. However, as assessed by Brookins (1978b), in consideration of natural analogues, such a reaction does not appear possible.

Finally, with regard to retardation per se and effects on retardation due to repository site interactions, at this point it appears little quantitative information exists. All of the above reactions and effects on other site components will have a coupled and complexing influence on retardation. The complexity is such that full knowledge of effects may not be possible. Difficulty even exists here in even bounding the problem. Most experiments on retardation are performed at ambient surface conditions and do not take into consideration the dynamics involved. Even with regard to something as simple as elevated temperature, it appears little work has been done. And work which has been done at elevated temperature, Erdal and others (1978), Erdal and others (1979), reveals complex variations in retardation properties (Kd). For example, it would appear that for some elements, retardation may increase with increasing temperature. For others, it may decrease or remain the same. Perhaps the bounding condition, here, is the assumption of no retardation in the near field.

4.5.1.5 Summary of the extent of repository/site effects

Table 4.4 summarizes the effects discussed above and their approximate lateral and vertical extent. Several things should be emphasized. The effects discussed are those primarily receiving attention or note in the technical literature. Emphasis, here, is on the site so that in terms of design their may be and are other effects of concern. Again, studies drawn upon are rather generic or fundamental and not site specific. In this regard, computer simulations drawn upon are just that: computer simulations of simulated but approximated sites. Any specific numbers cited in defining effects must be considered in this light.

As previously discussed, and as illustrated in Table 4.4, repository/site interactions will be many and coupled. In all simulations reviewed, although they may include discussion of many effects, they do not assess all combined interactions. It is even questionable whether this can indeed be done given limitations in the state of the art. Important here as well is the observation that the intensity of effects are greater closer in, are primarily in the vertical direction, and may have substantive near field impact on inhibiting waste migration; yet, most studies on radiological releases tend to ignore this and investigate and simulate conditions in the far field out laterally, e.g., Cloninger (1978), Hill (1979). Of particular concern here is the possiblity of orders of magnitude decreases in groundwater travel times to the accessible environment viz-a-viz vertical flow due to convection.

In terms of the extent of effects, most appear to be bound within several hundred meters above and below the repository and somewhat of a lesser

Table 4.4. Summary of the Extent of Repository/Site Effects

Site component	Effect	Vertical extent	Lateral extent
Geologic framework	-removal of several million cubic meters of rock	Encompasses subsurface extent of geologic repository operations area - 400-600M from surface	Encompasses subsurface extent of geologic repository operations area. Radius ~ 1 to 2 km
	-possible subsidence and fracture propagation	From surface to repository horizon ~ 400-600M	Equivalent to depth ~ 400-600M from edge of repository
	-significant change to ambient temperature gradient	From near surface to several hundred to one kilometer below repository	Several hundred meters from repository edge
	-thermal uplift	From surface to repository horizon and possibly below	Several hundred meters from repository edge
Geomechanical framework	<u>Mechanical</u>		
	-excavation fracturing	Less than about twenty meters from excavation openings	Less than about twenty meters from excavation openings
	-stress concentration around openings	Within tens of meters from drifts (few tunnel radii away)	Within tens of meters from drifts (few tunnel radii away)
	<u>Thermomechanical</u>		
	-changes to rock constituents	Within several hundred meters above and below repository	Within a few hundred meters from repository edge
	-induced stress (fracturing, faulting)	Within tens to a couple of hundred meters above and below repository	Within tens to a hundred meters from repository edge
	-induced porewater pressure (fracturing, fault movement)	Within about a hundred meters above and possibly below repository	Less than vertical due to less extensive thermal effects (~within tens to perhaps a hundred meters from edge)

Table 4.4. (Continued)

Site component	Effect	Vertical extent	Lateral extent
Groundwater flow system	-coupled effects with changes in other site components (e.g., creation of fracture flow paths, changes to interstical porosity and intrinsic permeability, induced dissolutioning)	Hundreds of meters above and below repository	Within several hundred meters from repository edge
	-microscale properties (viscosity, hydraulic conductivity)	Within meters to a few tens of meters (<order of magnitude effect in far field) above and below repository	Within meters to a few tens of meters (<order of magnitude effect in far field) from repository edge
	-induced convection (changes in flow pattern)	From the surface to a couple of kilometers below repository (decreases in vertical travel times by several orders of magnitude)	Several kilometers from repository edge
Geochemical system	-repository induced reactions:		
	fluid inclusion migration	Within a meter of canisters	Within a meter of canisters
	mineral reactions (includes dehydration, groundwater chemistry change)	Up to a few hundred meters above and below repository	Out to a few tens to about a hundred meters from repository edge
	radiation effects	Within a couple of meters from a canister	Within a couple of meters from a canister
	-repository/site reactions secondary minerals and contact aureoles	Within a meter from cannister	Within a meter from cannister
	effects on ambient chemistry	Local to near field (?)	Local to near field (?)
	-retardation	Local to near field (?)	Local to near field (?)

distance out laterally, i.e., well within a kilometer in all directions from the repository. Exceptions include some possible finite temperature rise above ambient beyond 1 kilometer particularly below the repository, and potentially in near surface aquifers as the heat spreads out. Additionally, and potentially of great concern, is convection which may extend laterally for kilometers beyond the repository and to several kilometers below the repository, thus making simulations of releases through ambient conditions somewhat dubious. In consideration of low thermal loading or planar heat densities (necessitated for purposes of retrieval, for reducing operational impacts, and for reducing the complexity of the problem) and the time period of concern, i.e., within ten thousand years, the extent of convection should be reduced below those reported in the literature which are for high thermal loadings (120-180kw/acre). It is judged that the extent of significant convection should be reasonably bound within the minimum volume of rock specified in the regulation. It should be kept in mind that the distances specified in the regulation are minimum distances. Additionally, the true extent of significant effects is a site specific problem requiring site specific investigation and analysis, and the limits will depend upon consideration of the significance of effects at a particular site. The discussion that follows treats the question of investigating for the extent of effects, particularly in the near field.

4.5.2 Investigating for the Extent of Repository/Site Effects

Much of the principles and information behind the previous discussion of investigations applies here and will not be repeated. This section primarily focuses on near-field testing and investigations. However, with regard to both the near field and far field, it cannot be more stressed that investigations must focus beyond present day ambient conditions in consideration of future conditions, processes and events both natural and human caused which may effect a site, and changes to ambient conditions brought about by waste/rock/water interactions. Particularly with regard to far field groundwater properties, consideration must be given to obtaining not only ambient properties but to obtaining information useful in assessing changes in groundwater movement resulting from repository/site interactions.

As described previously, most repository/site interactions are within the near field of a site. Their intensity generally increases closer in and are highest in a vertical direction. Because of potential intense interactions and possible orders of magnitude effect on the site's isolation capability, it becomes imperative to perform investigations which obtain representative information on site's near field properties and the site's response to interactions. However, certain limitations in obtaining information exist here. These include: consideration of potential adverse effects on a site caused by exploration, limitations in assessing conditions below a repository at depth given the potential for creating an adverse situation and the limits in resolution of remote techniques, and limitations in testing techniques to define conditions of interest. Because of these limitations it then becomes imperative that consideration be given to defining properties and responses well enough that conservative bounds can be placed on them.

Given the unique nature of the problem, the geotechnical aspects involved, considerations and recommendations that have been made, DOE/USGS (1979 Draft), LBL (1978), LLL (1979), Craig (1979), Rogers and others (1979), IRG (1978) and others, and as borne out in the work of the experimental facility at STRIPA, in situ tests and direct field investigations will have to be performed near a site and at depth to develop reliable information on site properties and response. Consideration here extends somewhat beyond the immediate repository horizon and the near field. It also extends to bounding responses of rocks further away in that bulk properties are sought to bound possible variations over distance and time. It also extends to obtaining important information for design purposes.

Requirements in the regulation here identify as a minimum basically five essential investigations. These are described below.

4.5.2.1 Investigating rock conditions

In terms of the site response, as described previously, the site's physical, chemical and mechanical behavior, as well as its capability to inhibit radionuclide migration, will be very much governed by the pattern, distribution and character of fractures, discontinuities and heterogeneities in the host rock and surrounding rocks. Severe limitations exist in obtaining a three dimensional picture of such information from surface boreholes or remote sensing techniques, although they will aid in characterizing a site. Intended here, is a comprehensive program which includes subsurface mapping, sampling, and remote sensing at depth. Particular attention must be given to attempting to unravel the conditions below a repository.

4.5.2.2 Investigating bulk geomechanical properties and ambient stress

Considered, here, are tests which not only define interstitial geomechanical properties per se obtainable through laboratory tests but that define the larger geomechanical framework; that is, the properties of rocks in context of fractures and discontinuities and those properties necessary to assess site response under the thermal loading, increases in porewater pressure and changes in the state of stress. As noted in LBL (1978), mechanical and thermomechanical analysis or design of a repository must proceeed from knowledge of the ambient state of stress. As noted previously, modifications to the ambient state of stress can be anticipated and may cause rock failure and the development of fractures as well as movement along preexisting faults. Thus, understanding, through in situ testing, bulk geomechanical conditions is essential.

4.5.2.3 Investigating bulk hydrologic properties

Orders of magnitude differences have been reported between laboratory measurements and in situ measurements of permeability, GEI (1978). The differences primarily being due to the influences of fractures, particularly in measuring rocks which have low interstitial permeability. Additionally, the theory to predict fracture flow is limited. It is anticipated that fracture flow will have a significant effect on radionuclide migration. Thus, it becomes important to assess permeability as well as other groundwater properties in situ. Included here are considerations of bulk rock permeability, rates of flow along fractures, effects on the rate of flow due to changes in the geomechanical and geologic framework. Important here as well, is conducting independent tests to help validate model predictions.

4.5.2.4 Investigating geochemical conditions

As noted previously, geochemical studies to date on radionuclide migration are almost all laboratory studies which have not been field verified. Additionally, little work has been done, nor would it appear even conceptualized beyond a preliminary level, on developing techniques for in situ testing of retardation, perhaps the most important parameter of all! Also, almost all retardation assessments confine themselves to far field types of conditions, even though substantial flow to near surface environs may occur in the very near field of a site as discussed previously. There appears no question that analytical chemical techniques are indeed limited in terms of in situ measurement. Nonetheless, in situ measurements will be essential and necessary to gain confidence in retardation values used in performance analysis. Considered important, here, as discussed in section 6, is measurement of the oxidation/reduction potential at depth which bears on solubility limits and the stability field of nuclide species. As discussed in LBL (1978), many problems exist with downhole fluid sampling. Measurement of redox potential at depth (on samples collected directly at depth) will avoid many of these problems. Important here as well is the collection of samples at depth to assess groundwater evolution and groundwater age. Additionally, tracer experiments performed on ambient fractures in conjunction with hydrologic testing should provide better representative retardation values under more representative conditions. Experiments can also be conducted at elevated temperatures. Recognizing time constraints on interstitial rock experiments, due to slow travel times, measurements and sample collection can be performed to ascertain natural chemical gradients. These in turn can be compared to laboratory experiments.

4.5.2.5 Investigating integrated response

The response of the site to waste emplacement will be a coupled one involving simultaneous actions and reactions, primarily due to the generation of heat. Required here are heater tests and experiments under simulated repository conditions to assess in situ response of all four site components. Thus, comparisons can be made between measurements and the predictions of computer simulations to verify models, and to bound the intergrated response of the site. Important, then, are in situ tests that assess simultaneously and in an integrated fashion effects, so that they may be bound. Also, important are tests on possible adverse conditions that may exist at a site, e.g., on areas exhibiting poor rock conditions, fractures, faults.

5.0 ADVERSE CONDITIONS

Many of the previously cited references speak to avoiding various human related and natural conditions which may adversely affect a geologic repository, e.g., active faulting. Listings of such conditions are primarily based on sound siting practices and reflect technical judgments and consensus. It is recognized that no site and its environs will be free of adverse conditions. The type and extent of adverse conditions, as well as favorable conditions, will vary from site to site, Golder (1978b). In consideration of an adverse condition at a particular site, assessments will have to be made to define the condition, its extent and magnitude, and to assess its impact, i.e., likelihood and magnitude, on the site's and the repository's capability to inhibit radionuclide migration. Considerable deliberation has been given to guideline recommendations in the literature in formulating how adverse conditions should be treated in the siting requirements. During the course of deliberations a number of considerations have emerged which have gone into the development of the adverse condition requirements. These are:

(1) The overall objective is meeting the long-term radiological performance objective. Thus, adverse conditions must be viewed in light of impact on long-term radiological performance so as to neither be unduly restrictive nor unduly lax.

(2) Consideration must also be given to potential adverse impacts from adverse conditions during construction and operation on safety related surface

and subsurface facilities. Included here is whether it is possible to design around these adverse conditions.

(3) Consideration must be given to the fact that different adverse conditions may have different degrees of impact and different kinds of impact.

(4) There will be considerable uncertainty associated with performance modeling, from the many sources as previously discussed. Consideration must be given to the extent to which adverse conditions add to this uncertainty and to the complexity of analysis, particularly in light of the limitations in modeling.

(5) Past siting experience associated with the siting of nuclear facilities and other types of critical facilities indicates that considerable limitations exist in assessing many natural adverse conditions from their geometric extent to their casual mechanism to the scarcity of data and to their impact. Given the unique aspects of a repository, particularly considerations spanning far into the future, limitations in dealing with adverse conditions are compounded. Perhaps even more so is the formidable uncertainty associated in dealing with future human activities. Thus, the treatment of an adverse condition must be viewed with respect to the limitations associated with defining the nature of the adverse condition.

(6) As described previously, the repository itself will have considerable impact on the site. Repository/site interactions will be more severe and complex closer to the repository location. Consideration of adverse conditions

requires not only an assessment of their impact on ambient conditions but their impact on repository/site interaction conditions. Included here as well is consideration of the impact of repository/site interactions on an adverse condition. Thus, consideration must be given to the location of an adverse condition with respect to the repository and to the coupling effects, including the increase of complexity and uncertainty involved.

(7) In terms of the impact of adverse conditions on long-term performance, consideration must be given to the extent of impacts on the four site components. This must include whether impacts can be ascertained, whether they are significant, and whether they reduce the margin of safety provided by a site component in terms of its function per se and its function in complementing and supplementing the other site components and engineered elements in (a) providing stability, (b) inhibiting groundwater movement and (c) inhibiting radionuclide migration. In this regard as well, consideration must be given to whether favorable conditions at a site and in its vicinity compensate for impacts brought about by the presence of an adverse condition.

(8) Finally, in dealing with adverse conditions consideration must be given to the application of professional judgment. Given the state of the art, assessments of adverse conditions will require substantive judgment. However, judgments will vary. Thus, consideration must be given to defining a range of latitude that is acceptable.

The adverse condition requirements were developed in light of the above considerations and should be viewed in this light. The application of the adverse condition requirements is described below.

5.1 Application of the Adverse Condition Siting Requirements

In light of the discussion in previous sections and the above listed considerations, three objectives behind the application of the adverse condition requirements have emerged:

(1) The first objective is to assure that long-term performance and the design of safety related facilities can be accomplished with a high degree of certainty. This is accomplished through the presumption that a site is unsuitable if either: (a) there are specified, more localized adverse conditions existing within the volume of rock previously required to be identified, where there will be significant repository/site interactions, or (b) that the site is located in a specified vicinity with respect to certain identified adverse conditions.

With respect to (a) as a minimum, the volume of rock is the previously discussed 2 kilometer lateral radius from the limits of excavation and from the surface to a 1 kilometer depth below the limits of excavation. Given the extent of most repository/site interactions as summarized in Table 4.4, i.e., well within 1 kilometer vertically below and out laterally from the repository, and given the extent of effect of the more localized adverse conditions as summarized in Table 5.1 (as will be discussed in section 5.2.5), i.e., within hundreds of meters, this minimum volume provides a minimum buffer zone between the repository and the more localized adverse conditions in the site vicinity. It also helps to reduce the complexities and uncertainties that will be involved in assessing the impact of a near field adverse condition on the site and

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the impact of repository/site interactions on the adverse condition. The specification of a minimum volume of rock in the requirements permit early evaluation of a site for site selection purposes prior to more rigorous definition of the affected volume determined through in situ testing.

It should be emphasized here that it is the intent of these requirements not to require absolute proof that a specified adverse condition either exists or does not, but to require a reasonably rigorous and state-of-the-art investigation and evaluation. Included here as well is full documentation. That is, in conducting investigations and in arriving at interpretations, reporting should include consideration of all reasonable sides.

With regard to both (a) and (b) above, it should be emphasized although a site may be free of specified adverse conditions, ultimate site suitability will depend on overall performance so that other conditions not specified or specified conditions beyond the minimum volume may be important and may require assessment.

(2) The second objective in the application of the adverse condition requirements is incorporating necessitated latitude due to the site specific nature of the problem, the judgments that will have to be made, and the consideration of satisfactory overall repository system performance despite the presence of an adverse condition. The latter factor may result from either designing around a problem or from a site specific assessment that indicates an adverse condition has little impact or is well compensated for by the presence of favorable conditions. To assure that the first objective is achieved, it is

expected that the adverse condition requirements be applied in a conservative manner. Although exceptions may be permitted, in order not to nullify the requirements and to maintain confidence, restriction has been placed on the range of latitude allowed. This restriction takes the form of necessary demonstrations that indicate not only that the adverse condition does not prevent meeting the performance objectives (i.e., the overall radiological performance objective, the site performance objectives and the engineering performance objectives) but that also it has little influence on meeting the performance objectives. Again, given the uncertainties associated with performance modeling, it is not enough to say a model simultation alone indicates achievement of the overall radiological performance objective. Here it is also intended that model simulations indicate little influence on all the performance objectives. The components of this demonstration include:

(a) A demonstration that the adverse condition has been adequately characterized as to its geometry, its physical, chemical, and mechanical properties, magnitude or rate, as appropriate. Included here also is an assessment as to whether adverse conditions may have been undetected by investigations.

(b) In assessing an adverse condition, a demonstration is essential that the effects of the adverse condition (i.e., the condition on the site and repository/site interactions or the condition) in space and time and on the four site components is well understood. Given the uncertainties inherent in such assessments, it is necessary to place bounds on the problem through using reasonably bounding parameters, assumptions and calculations in demonstrating effects.

(c) Given potential masking out or dampening that may be inherent in a model use to assess adverse impacts, it is necessary to show that the mechanics of a model are inherently sensitive to parameters and conditions of interest; that is, the model per se and other parameters used do not artificially mask or dampen out influences.

(d) If an adverse condition is present, it will be necessary to show that its potential adverse impacts will be well compensated by the presence of favorable characteristics.

(e) Finally, if an adverse condition is present, such that it can be remedied through engineering, this will require a conservative demonstration that indeed this can be done. Again, this necessitates consideration of not just ambient conditions but reasonably bounding conditions under repository/site interactions.

It is judged that the above demonstrations will allow necessary latitude; yet, at the same time, preserve necessary conservatism, given the complexities and uncertainties introduced by the presence of adverse conditions in the vicinity of a site.

(3) The third objective here has been to incorporate recommendations in the technical literature on adverse conditions in such a way that demonstration of performance and confidence in performance can be viewed in two ways. That is, through reliance on modeling and through reliance on sound siting principles and practices. As will be discussed in the sections to follow, the adverse conditions identified have been gleaned from the literature and considered in

light of potential impacts and application in a regulatory framework. For example, it is not enough to say: active faulting should be avoided. Definition is needed as to what is an active fault, its impact and what distance from a fault is acceptable. Without such definition, experience has indicated endless debate may ensue. At the same time, it is recognized that precise definition of conditions is not possible and that assessments are site specific. The level of specificity incorporated in the adverse conditions is such as to indicate intent and implicit level of conservatism desired. However, all of the conditions will require site specific analysis and definition.

Discussion of the specified adverse conditions, the extent of their impacts and their individual application are discussed below.

5.2 Individual Adverse Conditions

In reviewing technical guideline documents and recommendations that deal with identifying natural conditions and human activities that should be avoided in repository siting, one is struck by the number, the subtitles, sometimes contradictions, and sometimes almost impossibilities being suggested. Taking all suggestions emphatically, it would appear no site is suitable. However, guidelines note they are but guidelines, that no site is ideal and that allowances, depending on impacts, should be permitted. An attempt has been made to weigh, through identified natural conditions and human activities, and ascertain the impacts that are of concern. These impacts are those basically noted previously, that is: physically exhuming the waste, increasing the flow of nuclides, decreasing the path length, and increasing the source term. Also, assessments have been made as to whether a recommendation is indeed workable.

Individual adverse conditions specified in the requirements have been classified into four categories: adverse human activities, adverse geologic and tectonic conditions, adverse hydrologic conditions, and adverse geochemical conditions. This discussion focuses on defining the condition and intent beyond the condition, potential impacts, the extent of influence and its application to either the repository/site interaction zone or to a specified vicinity. In viewing these conditions, one must keep in mind the coupling of different identified conditions (as well as favorable characteristics) which should rule out extremes in any individual condition. Also, different specified conditions may deal with different aspects of the same phenomena. At the same time, an individual adverse condition may be applicable to different phenomena. The attempt here has been to define conditions in a way that identifies the impact of concern and that will facilitate assessing the presence or absence and impact of the adverse condition. Overall performance modelling focuses on the future. Focused on here is the past and present as another means to assess performance. Finally, here, it should be noted that the adverse conditions identified focus on protecting the repository. In so doing, isolation should be maintained and thus, protection to the public health and safety should be provided.

5.2.1 Adverse Human Activities

As borne out in a number of performance studies, Berman and others (1978), Cloninger (1978), it would appear that future human activities which probe the subsurface or affect the subsurface may be the most significant adverse conditions to which a repository may be exposed in the future. Human activities which probe or affect the subsurface may result in the direct penetration and exhumation of disposed waste, short circuiting, or decreasing the site's capability to inhibit the movement of nuclides, secondary effects which might increase the rate of dissolution of waste packages or may cause or accelerate the decrepitation of engineered barriers and site barriers. Such impacts, then, may result in direct exposures or increasing the magnitude and rate of release of radionuclides to the accessible environment over the long term. Treatment of adverse future human activities requires consideration of many questions. These include: To what extent can one predict future human activities and their impacts? To what extent can one rely on active institutional controls, or passive controls identifying a site and its significance? To what extent can and should one deal with intentional future activities which may probe a site for whatever purpose, e.g., to exhume the waste for fuel, out of archeological curiosity? To what extent can and should one deal with unintentional future activities which may probe a site for whatever purpose, e.g., in the course of resource exploration? This latter question has implications regarding loss of institutional memory as to the purpose and location of a repository. Implications, such as whether a catastrophy has wiped out institutional memory and in this light whether the hazard posed by the repository is truly of significance, and whether the future will still comprehend the nature of the hazard if exposed? Answers to the above considerations border on ethics, philosophy, and perhaps, even science fiction. This issue again exemplifies the unique types of considerations being given to a repository. Consideration of adverse future human activities as an issue goes way beyond the technical aspects of siting per se. It bears on the viability and acceptability of the concept of a geologic repository, on the technical aspects of design, and on the definition of acceptable risk. However, the resolution of this issue will have significant impact on site suitability, particularly as it bears on resources in the vicinity of a site. As such, early resolution of this issue is essential.

The adverse human activities identified in the siting requirements were developed in an attempt to deal with this issue from a reasoned and technical perspective. A number of premises are behind the adverse conditions identified. These are:

(1) Active institutional controls are assumed not to last for more than a century or so, Rogers and others (1979), and institutional memory of a respository is assumed thereafter lost.

(2) In accordance with assessments in the literature, EPA Ad Hoc (1977), IRG (1978), McGrath and others (1978), IAEA (1977), future human actions are considered unpredictable. This includes future technologies, motivations, and conditions. Thus, the assessment of the future can only rely on past activities, and present activities, technologies and conditions.

(3) It is assumed (from the siting prespective) that little can be done to prevent intentional intrusion into the repository or mitigate potential consequences of such intrusion other than the same types of things that are associated with natural hazards, e.g., in the favorable characteristics are requirements for limited groundwater circulation near a site.

(4) Of concern, then, is future human activities which, without awareness, i.e., unintentionally, may impact on the repository and on releases from the repository.

It is assumed then, that all that can be done in siting with respect to future human activities is reducing the likelihood of unintentional impacts on the respository. The activities identifed attempt to accomplish this by focusing on past and present human activities in consideration of present day technologies and conditions.

It should also be noted that past and present human activities are identified bearing on possible adverse impacts on a repository site during construction and operation, and which may also have long lasting impacts on a site over the long term.

5.2.1.1 Avoiding resource locations

There are several activities identified in the siting requirements which, coupled together, provide a necessary buffer against subsurface resource exploration and exploitation impacts. The term "resource" applies to minerals, hydrocarbons, potable groundwater, geothermal energy and natural building materials. The activities include the following:

5.2.1.1.1 Subsurface mining

A site is considered unsuitable if there has been or is subsurface conventional or in situ mining for resources within the repository/site interaction zone. The presence of a mine or mining near a repository site greatly complexes the problem. Effects are discussed here in terms of impacts on all four repository components.

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In terms of the geologic framework, mining activities can result in considerable subsidence and associated effects, as summarized in GEI (1978). Solution mining has resulted in subsidence zones with diameters from tens to several hundred meters across and subsidenced in meters. Conventional potash mining has also resulted in comparable subsidence. Fractures have been reported propagating upward from mines at angles usually in the range of 0°-45° and with surface fracture widths on the order of about 10 centimeters. As noted in Golder (1977a), subsidence deformation may not only be in overlying strata but in adjacent strata as well. Solution mining in salt can also produce breccias and collapse structures, Anderson and Kirkland (1980).

In terms of the geomechanical framework, as noted previously, subsurface excavations can alter the local stress field. Additionally, in situ mining, e.g., for shale, oil, or coal at elevated temperature, can alter the geomechanical properties of rocks, Golder (1977).

With respect to the groundwater system, mines and associated activities can have a number of influences, Golder (1977). These include: through the creation of fractures, pathways for more rapid groundwater circulation, and changes to horizontal and vertical head gradients through dewatering activities. In situ coal gasification has been reported to increase permeability, effective porosity, and water circulation, Vogwill (1979), Golder (1977), in adjacent rocks.

In terms of the geochemical system, solution mining can change the groundwater chemistry, as well as lead to brine invasion of nearby rocks. Importantly, as noted in Page and others (1956), with respect to uranium, in areas where groundwater has been disturbed by mining, abnormally high uranium concentrations may result. As reported, in uraniferous areas in the U.S., groundwater ordinarily contains about 1-120 ppb uranium. Strong acid waters from mines have ph values around 2.6 and uranium concentrations reported are on the order of 5,000 ppb. Thus, mining activities may result in conditions that increase the solubility of radionuclides. Acid waters could also increase corrosion of engineered barriers and increase waste dissolutioning.

Of course, effects due to mining will be very site specific and vary in extent and magnitude depending on the geology and mining activities. However, given the nature of mining, it is questionable whether sufficient records will exist that characterize the impacts and activities of importance. With respect to abandoned mines the problem is compounded, given difficulties in exploring such mines and ascertaining records on exploratory boreholes and effects on the surrounding rock.

Additionally, one must view mine impacts in terms of the coupling of waste/rock interactions and mine effects during repository operation and over the long-term.

In terms of the future, past mining invites future exploration and exploitation. The history of mining has been one of abandonment and reopening. Case histories reveal some mines have been used off and on over thousands of years, Sandstrom (1968). Even lacking present day technological sophistication, historic mining activity has extended hundreds of feet below the surface and horizontally thousands of feet. As noted in Golder (1977), mining into a repository in the future where the repository is at elevated temperatures could cause trapped steam and other gases to escape and explosions to result.

As considered in NAS/NRC (1978), areas with present or past records of subsurface resource extraction should be avoided. Consideration of the repository/site interaction zone as a buffer is also consistent with a preliminary 2 km mine avoidance distance suggested by Wagoner and Steinborn (1979).

It should be noted that shallow strip mining per se is not intended here because of its surficial nature. However, associated activities, e.g., deep water well or exploratory drilling, would fit into the next activity identified. Additionally, it is recognized that strip mining may extend to considerable depths, e.g., strip mining of coal may be carried to depths as great at 100' below the surface, Strahler and Strahler (1973). The more extensive the strip mining in general, the more likely there will be subsurface impacts. Again, if impacts are those below, the site will be presumed unsuitable.

5.2.1.1.2 Drilling

Of all the human activities that may effect a repository site, given the depth of a repository, drilling is perhaps the most profound. Drilling may lead to direct penetrations of a repository and exhumation of waste. Drilling may also have a number of secondary effects as well which may perturb a repository site over the long term. It has been recommended that repository sites be located where there has been minimal drilling, Golder (1978b), and others. Considered here in terms of explicit unsuitability is drilling within the repository/site interaction zone that has penetrated to depths below the lower limit of the accessible environment, i.e., to depths below the nearest useable aquifer above the waste emplacement horizon. Drilling to such depths has several implications.* These are: (1) the creation of groundwater pathways between the repository host rock and the accessible environment via drill holes; (2) past and present deep drilling implies that future drilling to such depths is likely and that the repository may be penetrated in the future; and (3) deep drilling may have significant effects on the ambient site components and thus influence the migration of radionuclides (such effects may have already happened, be happening or may happen in the future). Again, it is important, here, to keep in mind the additional complications that may result from the impacts of deep drilling coupled with repository/site interactions.

It should be noted that this restriction does not apply to more shallow drilling per se, although such drilling may have radiological implications with respect to the consumption of contaminated groundwater and may effect the groundwater conditions. In terms of long-term performance and as part of analyzing scenarios, such conditions will be assessed and will have to be shown to be not of significance.

A number of technical studies have considered drilling and possible impacts on a site. In considering drilling, one must also consider the purposes for drilling. These include: the extraction of oil and gas, the extraction of geothermal energy, the withdrawal of water, in situ solution

*It should be recalled that the EPA standard deals with cumulative releases to the accessible environment. Thus, the limiting case in assessing releases is releases into the nearest useable aquifer above the repository.

mining, for exploration, for waste water or other fluid disposal. The impacts of drilling are considered in light of the purpose of drilling.

Solution mining which entails drilling has been associated with subsidence extending several hundred meters in diameter and vertical subsidence at the surface on the order of meters, GEI (1978). As noted previously, solution mining and associated drilling may result in other deformations and deleterious effects on all four site components. Particularly in soluble rocks such as salt, drilling may initiate or accelerate dissolutioning, Carpenter and others (1979).

A number of deleterious drilling effects bearing on a repository have been associated with the extraction of oil and gas. Again, perhaps the most dramatic is far reaching subsidence, GEI (1978). Reports of subsidence indicate it may range up to several meters over areas ranging from a few hundred meters to hundreds of kilometers over time periods measured in tens of years, GEI (1978), Bolt and others (1975). It would appear that the more extensive effects are associated with major oil and gas fields, Strahler and Strahler (1973), Bolt and others (1975), which the next criterion would rule out. It is interesting to note that remedial actions that may be taken to prevent subsidence, such as water injection into deep wells, Strahler and Strahler (1973), may, from a repository perspective, be deleterious in several ways, e.g., changing vertical and hydraulic gradients. It would appear that most observed cases of surface subsidence occur where oil and gas are withdrawn fairly close to the surface, i.e., depths less than about 1,000 to 2,000M, Bolt and others (1977). Thus, given repository depths (400 to 600M) a repository site in such areas could be extensively affected. As noted in Golder (1977), the withdrawal of gas and oil results in fluid pressure reduction and, depending on the location of a repository, could result in either increasing the flow of water into or out of a repository. Another potential problem associated with oil and gas drilling is potential hydrofracturing at depth, thus increasing fracture pathways for groundwater and radionuclide migration.

Abandoned oil and gas boreholes and wells in and of themselves may generate deleterious effects. As reported in GEI (1978), deleterious effects include boreholes connecting aquifers and acting as conduits for oil and brine migration which may leak into a repository. Fluids migrating from old wells have been reported to have moved up to 500 meters and more away. Also, fractures may be associated with drilling.

Many of the effects discussed above are also associated with the exploitation and drilling for geothermal energy, deep water wells and fluid injection and will not be repeated. Associated with all deep wells and boreholes is the question of sealing them. To do this first requires locating them. Although, as noted by Koplik and others (1979), it would appear that available records would permit locating most past boreholes, difficulties may arise in locating small diameter exploratory holes which may be drilled to great depth. Additionally, there is a question, if such boreholes are important, as to whether they can be effectively sealed.

In terms of the future, areas not possessing previously drilled deep holes have implication, based on investigations elsewhere, or surface investigations, or economics, etc., that the deep geologic and hydrologic framework is such that it is not suitable for subsurface exploitation. As such, this should help reduce the likelihood of subsurface perturbations which may affect a repository. However, the pressing use of resources today is raising the level of subsurface exploration and exploitation. As summarized by Meyerhoff (1980), in 1979, there were some 48,800 oil and gas wells drilled in the U.S. with an alltime footage record of 240 million feet (average of 1,500 M/well). Deep holes are also being drilled (the deepest in 1979 was some 6,000 meters). Groundwater use is also on the rise for domestic, industrial, and geothermal energy purposes. Although most water wells have been relatively shallow in the range of 15 to 60 meters, several percent are over 150 meters. Groundwater (xxxx). In arid regions, especially, wells are relatively deep on the order of 150 to 180 meters, McGrath and others (1977). Injection wells, on the other hand, range from about 90 to 3,600 meters and appear to average between about 300 to about 1,800 meters, South (1979), Groundwater (xxxx). Usually, injection wells extend to porous rock and are drilled about 60 meters below the deepest freshwater aquifer, South (1979). As such, they may be drilled through a repository, increase pressures below a repository thus driving water up, or introduce chemicals having adverse effects on ambient and engineered retardation properties.

Although it has been suggested to avoid areas with extensive fresh groundwater IAEA (1977), even in areas where nonpotable aquifers exist, considerations are being given to the use of nonpotable aquifers for chemical waste disposal, Brown and others (1979). Such uses again may have similar results as those above. Even in areas with essentially no water, they still may be potential locations for dry rock geothermal energy drilling.

Of course, the impacts of drilling will vary depending on site specific conditions. Some areas, such as in sedimentary basins where oil and gas are generally found, have been more susceptible and impacts appear greater. However, it would appear all locations are suceptible to some extent. It also seems that present depths contemplated (400-600 meters) for a repository do not appear to provide much protection from drilling in the distant future given present depths of drilling. Even then, unless repositories are below 2,000 meters or so, little appears to be gained with respect to protection from future drilling. However, such depths may pose serious construction problems, particularly with salt host rocks. Also, at such depths, because of higher ambient temperatures, repositories over the long term may reach higher temperatures which, in turn, may increase the extent of repository/site interactions.

It appears then, with respect to drilling, past and present drilling greatly confounds the problem and must be avoided. With respect to the future, it would appear that all that can be done in terms of siting is the reduction of the likelihood of penetrating a repository. In terms of evaluation of the long term it would appear that drilling into a repository should be assumed likely. Also, consideration must be given to not only the "hit" but "misses" and their potential impacts, and impacts of the various purposes of drilling.

5.2.1.1.3 Economically exploitable resources

The avoidance of resources has been highlighted in every collection of siting guidelines reviewed. It is not the resources per se that cause a problem, but their attractiveness with respect to future exploitation and exploration. As such, they may attract future activities which could cause disturbance of a repository site through mining or drilling. Both of these have already been covered previously. However, the condition defined here and the following one are an attempt to define what is acceptable in terms of "avoidance of resources."

Considerations in the literature on this subject are relatively general. However, several refinements have been offered. These include: avoid present or predictable resources, NAS/NRC (1978); avoid foreseeable future economically desireable resources, LLL (1979); avoid mineral or element concentrations or locations which are like locations where mineral concentrations are found elsewhere, APS (1978); avoid locations where there are mineral or element concentrations greater than average crustal abundances or where there is monomineralic rocks; avoid host rocks which are valuable resources, Golder (1978b); avoid areas where mineral concentrations are greater than regional averages, McGrath and others (1978). The objective of these considerations boils down to defining resources in such a way that if resources as defined are avoided, a site will rank low with respect to being a future prospect for exploration. Deliberations on this subject included considerations regarding the definition of resources, whether the problem can be approached in an absolute way or a relative way, and whether future activities and resource needs can be predicted now with any meaning.

The probl . ..as been approached in both an absolute way and relative way. Also, the problem has been approached from the point of view of present day technology and conditions with the premise that we cannot predict the needs nor the technology of the future. However, it is judged that the likelihood of future disturbance of a repository due to resource exploration will be low, assuming the future assesses resources in a similar fashion as they do today.

In consideration of the extent of potential perturbations to a repository from mining and drilling as previously discussed, the following condition applies to the repository/site interaction zone. A site is assumed unsuitable if, in the repository/site interaction zone, there are economically exploitable resources based on existinr technology and under present market conditions. This condition is geared to a situation where there may not be present knowledge of the existence of resources because either there has not been exploration or resources have not been found given investigations to date, and during evaluation for a repository they are encountered. It is assumed that if there are known exploitable resources, there will have been drilling or mining and these are covered under previous conditions.

5.2.1.1.4 Relative resource assessment

Coupled with the previous condition is a relative one, requiring an assessment and comparison of the resource endowment of the repository/site interaction zone and similar sized areas in the geologic province in which the site is located. Here resources apply to presently recognized and used mineral, hydrocarbon, water, and natural building materials. Although these resources at the site may not be economically exploitable at present, what is required is an estimate of the gross resource endowment of the repository/site interaction zone and similar sized areas in the geologic province in which the repository is located. Also required, in consideration of development, extraction, and marketing costs, is an estimate of the net resource endowment of the respository/site interaction zone and similar sized areas in the geologic province in which the repository is located. In making both assessments, consideration is required to be given to both known and estimates of undiscovered deposits of all resources within the geologic province that (1) have been or are being exploited or (2) have not been exploited but are exploitable and, for whatever reason are not being worked, e.g., resources being held in reserve. A site will be presumed unsuitable if based on either the gross or net resource estimates, the site has a greater than average resource endowment relative to the other similar sized areas. The objective here is to demonstrate that in searching for resources a site has about the same or less chance of being explored, particularly via drilling, than any other nearby area.

Taking all four previous conditions together, the first three strive to define a site that is in a relatively low resource area, and one that has not been complicated or is being complicated by resource activities. The fourth condition strives to define a site that on a relative basis has just as likely or less chance of being explored in the future as any other areas nearby. Again, this all assumes the presence and the purpose of the repository is unknown in the future.

5.2.1.2 Failure of human-made impoundments

As considered in TRW (1978), NAS/NRC (1978) and Campbell and others (1978), the presence of a large dam in the vicinity of a repository may have several deleterious effects. Failure of such impoundments may lead to flooding of the geologic repository operations area during operation. Such impoundments may have large areal effects on the groundwater system, e.g., they may influence the magnitude and direction of groundwater flow and hydraulic gradients. Also, such impoundments may affect the areal stress field through increasing pore water pressure or through adding to the lithostatic load, Bolt and others (1975). Induced earthquakes, thus induced faulting, have been associated with large impoundments.

The presence of a large dam near a repository complexes the assessment of performance in several ways. First, it complexes the definition of natural ambient conditions given that ambient conditions have been affected by the impoundment. Second, in analyzing effects over the long term, one must assume that for whatever reason the dam is removed. Thus one must attempt to assess conditions back to natural ambient. Third, the presence of a dam today on a river implies that other dams may be built and again changes to ambient conditions will have to be assessed over space and in time. Fourth, the presence of a dam implies the presence or the possibilities of other human activities which may result in subsurface penetration, e.g., the dam may encourage development and industry which in turn may lead to subsurface waste water disposal. Thus, the presence of a dam may lead to having to assess many complex and uncertain scenarios for long-term performance analysis.

This problem has been treated in two coupled parts with regard to the present and the long term in order to simplify and gain confidence in the long-term assessment. Here, it is presumed a site is unsuitable if prior to decommissioning there is a reasonable potential that the geologic repository operations area may be flooded by failure of human-made impoundments. The effect of this condition is threefold: it assures that a repository during operation will not be flooded by dam failure which has a number of safety implications during operation. Second, it assures a repository will not be sited at least nearby and downstream from a dam. This should help simplify the performance analysis. Third, it should also effect the siting of a repository with respect to rivers, i.e., potential nearby discharge points.

5.2.1.3 Impoundments over the long term

This condition deals with impoundments over the long term. Given the complexities described above, this condition presumes that a site is unsuitable if, based on the type of present state-of-the-art analysis that would be associated with dam development, there is a reasonable potential for the construction of a large dam that may influence the regional groundwater flow system of which the site is a part. One must keep in mind that waste isolation entails regional considerations. Additionally, repository/site interaction effects considerably add to the complexity of the problem.

5.2.1.4 Significant perturbations to the hydrogeologic framework

This condition here is a broad one in dealing with all present or reasonably anticipated human activities. It is intended to apply to all nonrepository related human activities and is intended to immeasurably reduce scenario analysis. It basically is presumed here that a site is unsuitable if any human activities can have an order of magnitude type of effect on the hydrogeologic framework within the repository/site interaction zone. What is of concern here is the maintaining of ambient conditions and the reduction of additional superimposed complexities in assessing repository/site interactions. Also what is of concern is the siting of a repository in a location that acts as a buffer against potential deleterious human activities. The assessments of site are immeasurably reduced if one but shows that individual human activities do not have a significant influence on the hydrogeologic framework. Given all the potential influences previously cited and the uncertainties dealing with future human activities, and the difficulties that will arise in analyzing individual activities and permutations and combinations in context of repository/site interactions, superimposed natural conditions, events and processes, changes in space and time, the analysis of a repository may be endless. Sites must be chosen not with the idea of analyzing problems away but with the idea of reducing the problem as much as possible. What is sought here are such sites.

5.2.2 Adverse Geologic and Tectonic Conditions

Coupled together, the objective of avoidance of the geologic and tectonic conditions discussed below is to assure over the long term that a site is very stable on a relative basis. That is, one in which conditions, processes, and events may affect a repository over the long term have a very low likelihood of occurring at a magnitude that they would be significant. As such, confidence in the performance analysis can be gained. The conditions, processes and events identified, if present at a site given the state of the art, will be very difficult to analyze with a high degree of confidence, particularly in combination with repository/site interactions.

5.2.2.1 Extreme bedrock incision

Geologic and tectonic processes have rates usually in the range of millimeters per year or less to centimeters per year, NAS/NRC (1978). Thus, on the low end of the scale, such processes will be insignificant with respect to perturbing a repository site. In the centimeter range or greater over the long term, effects may be significant. Processes of concern here are those that may traverse the area near a site and incise the bedrock to significant depths and as such, either on the extreme, exhume the waste to the surface or significantly affect the hydrogeologic framework through dramatically changing the surficial character of the site and its environs, e.g., exposing rocks that are subject to dissolutioning. Studies would indicate there are basically two processes of concern here. These are river incision and glacial scouring.

Erosion rates, in general, have been noted to average less than a millimeter per year worldwide, Campbell and others (1978). The average rate of denudation in the United States has been reported to be about .063 millimeters per year and varies up to about a factor of 75, EPA ad hoc (1975). Rates of erosion have been reported to be higher in steep mountainous terrains (up to about a millimeter per year) than flat terrains (within hundreths of a millimeter per year), Wagoner and Steinborn (1979), IAEA (1977). Erosion rates in New England integrated over the last million years or so have been reported to be about .03 millimeters per year, Doherty and Lyons (1980), Wagoner and Steinborn (1979).

Rates of erosion will vary depending on climate; this must be considered over the long term. The work of Moreira-Nordemann (1980) in Brazil, which represents a humid tropical climate where chemical weathering is active, is the case of more humid conditions. Estimates of weathering here are on the order of .03 millimeters/year or 100 tons/km^2/year (2.5 x 10-^{5}gm/cm^2 day). That is still rather low. On the other extreme is cold climates during glacial periods where glaciers are the profound mechanism of erosion. As noted in Flint (1971), the rate of glacial erosion depends on such factors as the thickness of ice, rate of movement, abundance, shape, and hardness of rock particles at the base, and the erodibility of ground beneath. Glaciers erode through working down in joints and the depth would depend on at what depths joints become tight enough to inhibit glacial action. Depths of areal glacier scouring have been reported to be in the range of several meters, EPA ad hoc (1977), to a few tens of meters, Wagoner and Steinborn (1979). Present rates of glacial erosion in Iceland have been reported to be in the range of about .68 to 5.5 millimeters per year, Flint (1971).

Thus, on a regional scale, it would appear rates of erosion are very low with respect to exhuming waste or having significant impact. However, one also has to look at the depth of penetration of chemical and physical denudation effects. Here again it would appear that in most cases depth penetration is very low. Flint (1971) reports glacial grooves reaching 1 to 2 meters in depth and lengths of 50 to 100 meters, and on the more extreme end, giant grooves reach depths of 30 meters and lengths of 1.5 kilometers. Depths of weathering in crystalline terrains have been reported to range from about 1.5 to 15 meters and may extend to depths somewhat greater than 90 meters, Golder (1978b). Thus, here again, impacts appear insignificant to relatively minor.

It is on the extreme end of the erosion scale that effects may be significant. In the case of river incision, for example, taking the Niagara River as a bounding case, erosion (the falls) extends to a depth of some 50 meters and the falls have been traversing about a meter a year averaged over the last 10,000 years, Stokes (1966). Such actions not only physically erode, but also may have extensive subsurface effects, such as affecting oxidation, increasing dissolutioning of soluble rocks, and may shorten the path length between the repository and the accessible environment. In consideration of glaciers, mountain valley scouring has been reported to extend to depths of 330 to 600 meters and at rates of 2 centimeters per year averaged over 30,000 years, NAS/NRC (1978), Wagoner and Steinborn, Flint (1971). As noted by Flint (1971), the great magnitude here is due to steep preglacial gradients, high velocity of ice flow, concentrations of ice in a narrow valley and frost wedging.

In consideration of the coupled siting restrictions of not siting where a dam may flood a repository and as will be discussed within a flood plan and where active geomorphic and geologic processes are occurring, sites will not be located where extreme conditions are presently active. However, in consideration of the future through assessing the past, an additional restriction is necessary. That is, sites are presumed unsuitable if there is evidence of processes within the repository/site interaction zone that have caused extreme incision since the start of the Quaternary period. If there is evidence of extreme bedrock incision ($\sim>$ 50 meters) due to past stream erosion and glacial scouring, or based on an analysis of the processes associated with such extreme conditions, these processes have existed, although may not in the past have caused extensive incision, may cause extensive incision in the future. Given present inactive conditions and the slow nature of tectonic forces, in all likelihood, if extensive erosion was to occur in the future, it would either result from glacial scouring or the rerouting of streams due to glaciation. This would take thousands of years to initiate and, if incision was taking place outside of the repository/site interaction zone, a thousand to several thousands of years to traverse to the site. Thus, the minimum exclusionary distance of 2 kilometers appears reasonable with respect to the level of the hazard at the time when extensive incision might affect a site in the future.

5.2.2.2 Dissolutioning

Dissolutioning and associated effects such as the formation of breccia pipes, collapse structures, and brine pockets have been cited in the literature as being, perhaps, the most deleterious natural condition that can affect repositories in salt host rocks, Carpenter and others (1979a), Anderson and Kirkland (1980), LLL (1979). Dissolutioning can also occur in other soluble rocks such as gypsum and limestone. Effects of dissolutioning can be far reaching and include: the creation of pathways for groundwater migration, and the creation of geochemical conditions that increase corrosion of waste packages and nullify retardation. The effects of dissolution may also go beyond the host rock and into overlying and underlying formations, causing collapse, and fracturing which, under repository/site interactions, may substantially increase groundwater flow to and from the waste, and again nullify retardation properties.

As discussed previously, fluid inclusion migration, which is a microscopic form of dissolutioning, depends on may factors and, perhaps, too many to assess confidently through modeling. Dissolutioning here refers to macroscopic effects; however, these effects depend on the same factors as fluid inclusion migration and more. To a large part, as noted by Campbell and others (1978), the rate of dissolutioning depends on the availability of water and flow paths. Dissolutioning rates reported in the literature range from about 1.5 millimeters per year for dissolution fronts, Wagoner and Steinborn (1979) to hundreths to tenths of millimeters a year for vertical dissolutioning, Golder (1978b). Although these rates are low, it is difficult to comprehend the meaning of rates of dissolutioning. Dissolutioning is a solubility process, depending on the volume of water present and flow, the temperature, and the amount of material in contact with the water (which is a function of fracture geometry) and the solubility of material. The process of dissolutioning is a time dependent one as well, involving continuous changing boundary conditions as material is dissolved. It is also a function of surface groundwater conditions. Although rates of dissolutioning can be derived in a laboratory at different temperatures, dissolutioning is a site specific problem involving the macroscopic parameters of a site, and will be difficult to assess, particularly in consideration of the permutations resulting from construction activities and repository/site interactions over the long term. Perhaps the only confident handle one can have in dealing with dissolutioning and its magnitude is reliance on observations in the field, and comparisons of site conditions with conditions elsewhere, that is natural analogues. As such, as a minimum, if dissolutioning has occurred at a site it indicates the availability of water and the presence of flow paths in the past or at present, and under waste rock interactions, it is hard to imagine conditions not getting worse. Although it can be argued that the heat of a repository can cause fractures to heal, thus diminishing the potential for dissolutioning, it also increases the solubility and would appear to increase convective flow, thus increasing dissolutioning.

As a minimum, then, a site is presumed unsuitable if there is past evidence of dissolutioning within the repository/site interaction zone. The lack of past dissolutioning adds confidence that under ambient conditions no substantive groundwater paths have existed and if such conditions are maintained then future dissolutioning will not occur. A major question that arises here bears on the extent of dissolutioning intended, recognizing that some water is present in soluble rocks and recrystallization occurs. There is no answer quantitatively. What is sought are indications of substantive dissolution as indicated by large Karst features such as sinkholes and caves, and by the presence of breccia pipes, collapse structures, and a layer of insoluable residues.

5.2.2.3 Active geologic and tectonic processes

The condition identified here is a broad one. It has been recommended in the technical literature to avoid areas of tectonic instability, IAEA (1977), and others. The condition here is an attempt to define the extent of instability to be avoided. The condition applies to geologic or tectonic processes that are active at present and may be resulting in present deformation in the repository/site interaction zone. The presumption, here, is that a site is unsuitable if there is evidence of presently ongoing structural deformations. As stated previously, rates of geologic processes range on the order of millimeters per year to centimeters per year. The objective here is to find that ambient processes to begin with are occurring at a rate that is on the very low end of the scale (i.e., ~ fractions of a millimeter per year or the low end relative to the phenomena). Sites with presently active processes, to begin with, will be complicated to assess and indicate ambient instability which probably can only get worse when subject to repository/site interactions; thus, this complicates and creates uncertainties in assessing performance over the long term. The causes of many geologic and tectonic processes are not well understood, thus preventing the identification of specific processes of interest. Rather, the identification of attributes of such processes is called for, e.g., uplift, subsidence, diapirism, folding, faulting, and formation of fracture zones. The implications of such attributes can be severe and are discussed below.

5.2.2.3.1 Uplift

Uplift may be associated with many geological processes, such as faulting, or impending faulting, isostatic adjustments due to crustal unloading from the retreat of glaciers, warping in the crust due to large-scale tectonic stresses. Ascertaining the exact causes of uplift often is speculative but such uplift does indicate some type of instability. Uplift from faulting may be very rapid and very widespread as in the case of faulting causing large earthquakes. On the extreme end, for example, as noted in Bolt and others (1975), uplift associated with the March 27, 1964 magnitude 8.6 Alaska earthquake extended over 50,000 square miles (≅ 128,000 square km) and up to 35 feet (≅ 10 meters). Less spectacular, but of concern, is the uplift ongoing on the Palmdale bulge, with a magnitude of 1 meter in 10 years, Campbell and others (1978). Its cause remains a mystery but would be of concern regarding possible faulting and near field ground motion. Reports of uplift in the Adirondacks is on the order of 3.7 mm/yr, EPA ad hoc (1977), and could result in 37 meters of uplift at a site in 10,000 years, increased erosion, possible effects on the groundwater hydrology, implications regarding faulting, fracturing and thus radionuclide transport. Basin and range faulting has been reported to average a few millimeters per year, APS (1978), and although low enough not to be a problem with respect to exhumation of waste, it implies unstable stress conditions and pathways for nuclide migration. Uplift complicates considerations of repository/site interactions with respect to inducing faulting due to changes in ambient porewater pressures and the ambient stress field. Considerations of uplift with respect to faulting would require a complex scenario analysis. As illustrated in Isherwood (1979a), scenarios would have to consider changing effects on fracture permeability during the period as stress builds up, during the period as stress opens fractures, when faulting occurs, and then with respect to new boundary conditions as the cycle repeats.

Uplift associated with deglaciation carries with it many complex implications that appear difficult to deal with. The following discussion gives some perspective here. It is known that uplift rates (glacial rebound) vary with distance from the margins of ice sheets and the date of deglaciation, Fillon (1974). It also appears that uplift decreases about exponentially with time, being rapid soon after deglaciation, Farrand (1974). Estimated uplift rates range from about 300 meters in the last 10,000 years (average of 3 centimeters per year) at North Bay, to about 5 millimeters per year at Lake Superior, and less going into the U.S., Farrand (1974), King (1965). Studies of the Scandinavian peninsula reveal that subsidence was about 250 meters relative to the present under an ice sheet of 2 kilometers in thickness and that the crust was depressed many kilometers beyond the ice margin, [illegible] and others (1975). Studies by

Bloom (1974) in southwest Maine indicate a complex history of subsidence and uplift, emergence and submergence with relative movements in the range of tens of meters. Isobase studies, as summarized in Flint (1971), indicate uplift on the order of 20 to 10 meters or less in the continental U.S. since the retreat of the glaciers, or average rates of uplift of less than about 2 millimeters per year. From the above discussion it would appear that the impact of glaciation would be relatively minor with respect to uplift and its significance. However, a number of questions arise. Given active uplift and assuming it can be related to glacial rebound, what can be said regarding ongoing possible faulting due to uplift? What can be said regarding indications of future glaciation, the magnitude of loading and depression in the future and the possibilities of inducing differential stresses, faulting, and weakening of borehole and shaft seals during loading and uplift? Can one assume that all of the deformation is restricted to the mantle? What can be said about ascertaining these effects with confidence given complex histories? It would appear from the cited studies, effects may go out many kilometers beyond the glacial front and what can be said with regard to crustal deformations here? Finally, what can be said with respect to the addition of repository/site interactions? This author has seen little work on this subject pursued.

5.2.2.3.2 Subsidence

Subsidence like uplift may be caused by the same processes and has associated with it similar types of possible deformations and impacts. With respect to sedimentation and subsidence, sedimentation at a reasonable rate may effect the distribution of surface water and increase static loading on a site, Campbell and others (1978). This will be a cause for concern regarding the location of future discharge points, regarding future human activities associated with surface water and possible impacts on the repository regarding the possibility of subsidence induced stresses causing earthquakes and faulting, and regarding subsidence induced effects on shaft and borehole seals.

5.2.2.3.3 Diapirism

The literature speaks to diapirism in relation to salt domes. Recommendations have been made about avoiding domes which exhibit active diapirism, LLL (1979), IAEA (1977). It would appear the rate of diapirism ranges up to about .3 to 2 millimeters per year, Golder (1978b). Thus, left to themselves over a 10,000 year period, uplift may extend only about 20 meters. However, as noted in NAS/NRC (1978), diapirism may be influenced by mechanical, thermal, and chemical stresses brought about by construction and operation. As to whether this can cause significant acceleration in diapirism is uncertain, although, as calculations indicate, the upper portion of a dome above the repository may be substantially uplifted, perhaps up to several meters due to thermal expansion, ADL (1979b). Thus, the problem here is not one of exhumation. What is of concern is indications of active diapirism which imply internal instability and strain that can be accelerated by repository/site interactions, particularly the heat. It would appear that salt flows plastically at temperatures about or greater than 200°C. Such temperatures are confined to the very near vicinity of canisters, Golder (1978b). Given the large shear zones surrounding domes, there is a question as to whether at lower temperatures and in an unstable situation, additional shear deformation could occur. One can speculate that such deformation could result in the propagation of fractures and thus connect the repository with shear zones, increase dissolution, and increase water migration into and out of a repository. Thus, indications of active diapirism may substantially complex the problem and may be a problem.

With respect to the other attributes--folding, faulting or fracture [illegible]es--these will be discussed subsequently in other sections. The objective then of this identified condition is, again, to reduce the complexity in analysis and gain additional confidence. Having significant ongoing processes at a site will, in all likelihood, lead to a situation of "paralysis by analysis." Additionally, although present stability does not guarantee future stability, it does significantly add confidence that waste repository/site interactions over the next few thousand years will not be made more complex by the superpositions of significant ambient processes.

5.2.2.4 Active faulting

Site suitability guideline studies all recommend avoiding active faults. In terms of more definition, recommendations have been made regarding avoiding faults which have exhibited movement during the Quaternary Period, NAS/NRC (1978), Altomare and others (1979). Problems associated with faulting are severalfold. Faulting may rupture the engineered containment, McGrath and others (1978), thus short circuiting the engineered barriers. Faulting may provide pathways and thus short circuit the site barriers to migration, and, as discussed previously, lead to complex time-dependent scenarios. Additionally, active faulting near a site implies considerable stresses and may result in complexing repository/site interactions, e.g., more intensive fracture development, induced fault movement.

Faulting produces earthquakes which may effect surface structures. However, within wide limits, this can be designed around. With respect to the subsurface during the operational period, it would appear from assessments of mine and tunnel damage, due to earthquakes outside of the epicenter region, that damage is relatively slight to negligible, Pratt and others (1978), Carpenter and Towse (1979), Koplick and others (1979). Effects associated with nearfield earthquakes amounts to vibration, rock spalling, and caving. As reported in Carpenter and Towse (1979), severe damage in tunnels in epicenter regions occurs at about ground motion accelerations of .4 g and velocities greater than 60 centimeters/second, the most severe damage being associated with movement along a fault that cuts a tunnel. As noted in Pratt and others (1978), subsurface damage occurs where surface ground accelerations exceed .5 g and damage appears to be associated with high frequency motions (in the range of 50 to 100 Hz). With respect to the long term, once sealed, it is believed that effects of even large earthquakes are likely to be negligible, EPA ad hoc (1978), NAS/NRC (1978). Considerations of possible effects on backfill due to large magnitude earthquakes indicate low temporary stresses, and the risk of damage to backfill appears negligible, KBS (1978).

In dealing with active faulting in the siting of nuclear facilities in the past, considerable difficulty has arisen given limitations in the state of the art. This problem becomes more severe closer to the proximity of a fault. Considerable difficulty arises in assessing the geometry of an active fault zone. In the case of a repository, additional difficulty arises in having to assess the hydrogeology and geochemical properties, and other properties necessary to assess repository/site interactions. With respect to future movement per se, although empirical relations have been derived, they are highly uncertain. With respect to predicting earthquake ground motion in close proximity to a fault (i.e., both with respect to designing the surface facilities and in consideration of possible damage during operations, as noted in Swanger and others (1979), present techniques applicable to the nearfield are very limited due to paucity of nearfield data and deficiencies in understanding nearfield processes.

In consideration of the above discussion in dealing with active faulting, the following condition has been identified. A site is presumed unsuitable if the geologic repository operations area lies within the nearfield of a fault that has been active any time since the start of the Quaternary Period. Thus, this condition should provide for ample protection and amenable analysis. Intended here are tectonically driven faults as opposed to near surface deformations. In terms of defining the near field, this is relatively site specific and depends primarily on the fault or rupture length. Nearfield has been defined as a distance within a few wavelengths of the source, Swanger and others (1979). Intended here is a distance between 10 to 20 kilometers from the geologic repository operations area (that is, from the limits of excavation).

5.2.2.5 Seismic activity

As with the previous condition, siting guideline studies speak to avoiding high seismic risk zones. Again, outside of the nearfield of a fault, surface structures, and if need be, interconnecting facilities and subsurface structures can be designed to withstand earthquakes. However, earthquakes, perhaps more than anything else, indicate crustal instability, high stresses, and ongoing deformation, i.e., folding or faulting. Often the nature of the deformation or causitive mechanism for earthquakes cannot be ascertained, particularly outside of areas where surface faulting is evident, York and Oliver (1976), Hadley and Devine (1974), Hinze and others (1977). The assessment of such intraplate earthquakes usually entails consideration of their magnitude, frequency, spacial relation with geologic structures, and possible cause in context of plate tectonics. One finds in any given region, clusters of earthquakes and earthquakes which appear randomly. Additionally, at times clusters of earthquakes on an observational basis appear geographically associated with some geologic structures, e.g., large folds, intrusive bodies, etc. Given the lack of understanding of the causitive mechanisms of earthquakes, if earthquakes in a geologic region are associated with some portion of a geologic structure then the same type of seismic activity, although it may not be evident, is assumed to occur anywhere near that geologic structure or near similar nearby geologic structures. Given the present state of the art, recommendations to avoid high seismic zones, and the instability indicated by seismic activity (which repository/site interactions will compound), the following condition has been identified. Based on a study of the region around a site (≅100 km), a site will be assumed unsuitable if (1) the repository/site interaction zone appears to fall within an identified zone or concentration of seismicity, or (2) there are indications, based on the distribution or trend and frequency of occurrence of earthquakes, as well as considerations of correlations between earthquakes and nearby structures in context of tectonic processes, features or reasonable plate tectonic interpretations, that it is reasonable to assume earthquakes will be concentrated near the geologic repository operations area. It is recognized that some earthquakes occur randomly, there are uncertainties in locating earthquakes, and it is possible to record microearthquakes of some finite size, perhaps almost anywhere.

What is intended, here, is a reasoned approach in consideration of analyses and the views of experts in the geologic and seismologic community.

5.2.2.6 Volcanic activity

Another prevalent view in the literature is avoidance of active volcanism. Recent volcanism in the conterminous United States is confined to the west and northwest and is potentially hazardous enough to be considered in long term land use planning, Mullineaux (1976). Problems associated with volcanism are profound and many. In terms of the short term, nearby volcanism poses many geologic hazards including earthquakes, lava flows, mud flows, poison gases, ash falls, etc., Bolt and others (1975). However, as noted in Mullineaux (1976), volcanic events in the conterminous United States are relatively infrequent; thus, the risk is low. Furthermore, severe destructive effects appear to be limited to areas within a few tens of kilometers down valley or downwind of a volcano. Because most volcanic activity is concentrated at large central vents, whether a location may be effected can be predicted reasonably accurately; however, the predictions of the timing of future eruptions and magnitude are not at present reliable. Thus, reliance must be placed on the historic and geologic record.

In terms of the long term, as noted by Mullineaux (1976), in the Cascade Range moderate volcanic eruptions may occur as often as once every 1,000-2,000 years. Very large eruptions may occur once every 10,000 years. Thus, sites in the vicinity of active volcanic terrains would have to consider volcanism. In addition to central vents, it should be noted that some eruptions occur at widely scattered vents and, as noted by Mullineaux (1976), the sites of future eruptions from scattered vents appear unpredictible. Again, all one can say is that the risk decreases as distance increases from major vents. Over the long term volcanism poses several problems. Volcanism may produce natural dams and thus large scale impoundments which may effect a site (see adverse hydrologic conditions). As noted in McGrath and others (1978), volcanic fields often have resource potential (geothermal energy or hydrothermal mineral deposits) and, as such, invite potential human intrusion (see adverse human conditions). With the exception of natural impoundments, surficial volcanism over the long term does not appear to be a problem, although it may result in loading over the repository, and changes to groundwater chemistry. As such, it may compound repository/site interactions.

Subsurface volcanic effects in terms of the long term have been stressed in the literature. Associated with volcanism are subsurface intrusions, such as dikes and sills, which are of concern if they penetrate into the repository, APS (1978). As summarized in Golder (1978b), volcanism can also lead to the formation of pathways for groundwater and radionuclide transp rt, e.g., intrusions may cause folding, faulting, and fracturing. Volcanic terrains, in general, are characterized by successive lava flows which contain voids between flows. joints caused by cooling, lava tubes, breccia zones.

As with faulting, recommendations have been made regarding avoiding areas exhibiting Quaternary volcansim, NRC/NAS (1978), Wagoner and Steinborn (1979). Various adverse conditions previously discussed and that will be discussed deal with different attributes of volcanism, i.e., the resource issue, natural impoundments, current instability, etc. Here, in consideration of the long term and in context of the above discussion, intrusive igneous activity is covered. With regard to the future, reliance must be placed on the geologic record. Thus, a site is presumed unsuitable if there is evidence of intrusive igneous activity since the start of the Quaternary Period within the repository/site interaction zone.

5.2.2.7 High and anomolous geothermal gradient

A number of studies have discussed avoiding areas with abnormally high geothermal gradients, e.g., Altomare and others (1979), NAS/NRC (1978). The geothermal gradient of an area depends on a number of factors, particularly, rock or sediment conductivity, the concentration of radioactive elements in rocks, and whether there is a subsurface volcanic source. The average geothermal gradient is about 30°C/kilometer and in areas of high geothermal gradients about 80° to 100°C/kilometer, IAEA (1977). Consideration of geothermal gradients with respect to repositories has several implications. The lower the geothermal gradient, the lower the induced temperatures that will be attained, everything else being equal. However, except on the extreme case, the geothermal gradient does not vary by that much, and lower temperatures could be attained via lowering the planar heat density. High geothermal gradients may imply subsurface volcanism and thus either imply potential future subsurface igneous intrusion or other active processes and stresses in the site vicinity which may be compounded by the addition of repository/site interactions. High geothermal gradients also imply potential future subsurface drilling for geothermal energy and thus a potential for repository penetration or subsurface disturbance which may increase the movement of radionuclides to the accessible environment. It is recognized that the geothermal gradient, through heat flow studies, can be readily determined early-on to make site suitability assessments. In consideration of the above combined impacts, an identified condition dealing with geothermal gradients appears appropriate. However, geothermal gradients are relative in a region and will vary, e.g., over a pluton it may be higher than over surrounding metamorphic terrain, and it may be somewhat higher in one area relative to another. What we are interested in here are significantly high and anomolous gradients in consideration of variations in a region. That is, does the site and its environs stand out above the normal variations in geothermal gradients encountered. In this regard, is the identified condition that a site is presumed unsuitable if based on a study of and comparison with the region, the repository/site interaction zone has a high and anomolous ambient geothermal gradient. As a note, there has been some discussion of "hiding" a repository in an area that already has a high geothermal gradient. However, in consideration of both potential adverse human activities in such areas and potential adverse natural conditions, this is thought to create more problems than it solves.

5.2.3 Adverse Hydrologic Conditions

Coupled together the hydrologic adverse conditions identified stress the need for stable hydrologic conditions, conditions amenable to analysis and conditions which are considered important to be avoided because of their likelihood in decreasing the travel time of groundwater and radionuclides to the accessible environment.

5.2.3.1 Stable paleohydrology

As with stable geology, stable ambient groundwater hydrology is important, particularly in gaining confidence for long-term extrapolations. Recognizing the potential magnitude or impact on the present groundwater hydrology due to repository/site interactions as previously discussed, significant past natural perturbations in the groundwater system in the vicinity of a site will (1) make the evaluation of ambient conditions difficult and considerably uncertain, and (2) compound the analysis of future conditions in consideration of the superposition of varying past conditions and varying repository/site interactions. Perhaps, the most significant natural perturbation in the recent geologic past on surface hydrology and groundwater flow has come about and could come about viz-a-viz glaciation. As noted in EPA ad hoc (1977) and other studies, glaciation brings about marked changes in mean precipitation and evaporation, in geomorphic land forms, in sea level. All of these may have significant effects on the groundwater hydrology and even the geochemistry (e.g., changing oxidation conditions, brine flooding which neutralizes retardation). One can envision a myriad of scenarios that would have to be assessed. Although analysis will be performed regarding possible changes to groundwater conditions, having had effects already basically makes future effects likely, and given the precision with which these things can be assessed, uncertainty is created. Thus, what is required here is first a paleohydrologic evaluation. The work by Schumm (1965) illustrates the type of surface paleohydrologic work to be performed involving assessments of precipitation, runoff, etc. Fritz and others (1979) illustrate the types of assessments to be conducted in evaluating the evolution of groundwater. Important here would be dating of groundwater. Based on such studies, if there are indications that significant (≅ order of magnitude) changes occurred during and since the last glacial period on groundwater properties important to the assessment of future conditions in the repository/site interaction zone, a site is presumed unsuitable.

5.2.3.2 Flood plains

A number of recommendations have been made regarding a repository not being located where it may be subject to surface flooding, IAEA (1977), Golder (1978b). Surface flooding per se has both long-term and short-term implications. From a short-term environmental standpoint, Executive Order 11988 prohibits the siting of federal facilities in a 100-year flood plain. From a safety standpoint, during operation, flooding may be designed against. However, given not only the hydrologic but geologic safety problems, e.g., settlement potential liquifaction that may be associated with flood plains, and the addition of another consideration for protection of the underground facility, siting in a flood plain seems somewhat needless and complicated. Over the long term, siting in a flood plain implies the possibility of being very close to a discharge location. Also, as discussed in IAEA (1977), over the long term, surface streams may be expected to undergo radical change and provide the possibility of deep erosion. In consideration of previously identified conditions which cover the long-term, the stress here is on the short term. Thus, a site is presumed unsuitable if the geologic repository operations area is located within a flood plain. The 100-year flood plain has been chosen for this restriction.

5.2.3.3 Natural impoundments

As discussed previously under adverse human activities, surface impoundments may have a significant impact on the regional groundwater flow system. Basically, the same discussion applies here, except that the consideration is for the possibility of natural impoundments. What is required, using present day conditions, is an assessment of the region around the site as to whether natural impoundments can be formed by such phenomena as landslides, subsidence, or volcanic activity. If so, a further assessment is called for to determine whether such impoundments could significantly impact the regional groundwater flow system. A site is assumed unsuitable if there is such a reasonable potential. Basically, what is sought here, barring human activities and until perhaps the glaciers return several thousands of years from now, is as much stability and reduction in complexity as possible. The regional groundwater flow system being immuned from natural disturbances adds to the margin of safety. This is brought about through investigating a site and the region and, having shown that present conditions which have been well characterized and are used in long-term performance analyses, will not significantly change, at least by the addition of natural impoundments, for the next several thousands of years.

5.2.3.4 Fault and fracture zone pathways

As discussed previously, a site is presumed unsuitable if there is a nearby active fault. However, it is anticipated, based on past nuclear power plant experience and the large subsurface extent of a repository, that inactive faults and ancient fracture zones will be encountered. Such features pose several problems. In terms of repository design, studies indicate that not only are minor faults on the order of tens of feet difficult to detect but they can have a significant structural impact, Byrne and others (1979). Fault or fracture zones may represent poor rock conditions and may require considerable design modifications. One must consider this in light of changing the emplacement mode and resulting ramifications in analysis of repository/site interactions. Encountering poor rock conditions and modifying design may lead to an entire reanalysis of repository/site interactions and radionuclide transport. More profound and stressed here are faults and fracture zones acting as conduits for groundwater. As noted in Byrne and others (1979), flow through fault zones may measure hundreds of gallons per minute. Studies of well yields show dramatic increases along fault zones as compared to distances away. For example, Golder (1977) cites well yields varying from 70 to 100 gpm near a fault zone and 15 gpm in other locations. As noted previously with regard to salt domes, water leakage from boundary shear zones which are substantial conduits for water may extend within 300 feet into the dome, O'Donnell and others (1979). As noted in Golder (1978b) down gradient from a repository fracture zones may reduce transit time and up gradient may reduce resaturation time. As studied in OWI (1978d), fault zones may substantially affect convective flow. Also, given the increases in heat and pore water pressure, as previously discussed, induced movement may occur, thus further increasing groundwater flow.

It would appear, at least for crystalline and metamorphic terrains, that water seepage through faults or fractures is likely unless a repository was at 900 meters or more where pressures would seal them, Golder (1977). Even in salt formations which are characterized by very low intrinsic permeability, fractures exist and may act as conduits to groundwater flow, IEC (1979). The extent to which an ancient fault or fracture may provide a conduit to groundwater depends on such factors as the geometry, type, distribution, spacing, width of opening, degree of interconnections, fluid pressure, rock stress. Although these are all site specific, one general rule usually holds. The larger the fault or fracture, the greater the problem. This is not only with respect to increasing or perturbing groundwater flow but also with respect to increasing the difficulty in characterizing the nature of the fault or fracture zone. Rarely, if at all, are large fractures or faults planer. They often consist of a complex array of interconnecting or in echelon elements.

A number of recommendations have been made about avoiding areas with a large fracture or fault or where there is a high density of them, IAEA (1977), Wagoner and Steinborn (1979). A priori there is no specific formula here. However, in consideration of possibly designing ground minor faults or fractures, that the problem increases as faults or fracture zones increase in size and in regard to making early site suitability assessments viz-a-viz using air-photo imagery, widely spaced boreholes, surface investigations, avoidance of faults or fracture zones several hundred meters long appears appropriate and amenable to early assessment. It is recognized here that some ancient faults on fracture zones may indeed be well solidified, such that they posed no problem. However, the presumption here is that a site is unsuitable if there exists in the repository/site interaction zone a fault or fracture zone, irrespective of age of formation or last movement, which has a horizontal extent of more than a few hundred meters. Proof to the contrary requires the previously stated series of demonstrations.

5.2.4 Adverse Geochemical Conditions

As discussed previously, the geochemical properties of a site are considered to provide the most significant barrier to radionuclide movement. Simulations involving changes in sorption, retardation factors, indicate orders of magnitude effects on transient times can result, DeMarsily and others (1977), Naymik and Thorson (1978). Every guideline study reviewed speaks of a site possessing high sorption properties. Considerations have been given to host rocks possessing high sorption, confining units possessing high sorption or sites not possessing certain properties that may reduce sorption, e.g., organic materials, complexing agents. Given the importance of site geochemical properties, a number of adverse conditions to be avoided have been considered. However, given the nuclide specific nature of sorption, a bounding condition appears appropriate. It has been recommended, UA (1980 draft, in preparation) that a site not be considered suitable without geochemical properties that significantly inhibit radionuclide migration. Although a number of geochemical properties have effects on migration, in terms of the rate of movement, sorption is of concern. However, in terms of sorption, studies would indicate that the rate of movement of some nuclides, such as iodine and technetium, are little affected by site sorption properties, although (as will be discussed later on) other geochemical properties may inhibit migration in other ways. In terms of movement, the bounding condition here is that a site is presumed unsuitable if geochemical properties do not provide a major barrier to the movement (i.e., low rates of movement) of most radionuclides between the repository and the accessible environment. That is, along travel paths between the repository and the accessible environment no matter where they extend over the time frame of interest. Again, as stated previously, given the uncertainties associated with sorption, it is considered appropriate to rely on sorption as a dubious but necessary safety margin.

5.2.5 Summary of Adverse Conditions

Table 5.1 is a qualitative summary of the adverse conditions previously discussed. Identified are the conditions, the primary adverse influence(s), assessment of the magnitude and extent, and information on the application, i.e., whether it applies to the past, present, or future and spacially where it applies. Taken together, the avoidance of the adverse natural conditions should rule out extremes in any natural phenomena. Additionally, substantial confidence can be gained through assessments that indicate past site and regional conditions have remained stable and by and large are relatively immuned to disturbance. This adds weight that present site properties and characteristics are truly representative with respect to future extrapolations. Of all adverse conditions, human subsurface penetrations appear the most severe. This is not only with respect to exhumation of waste but also in perturbing a site so that the site properties to inhibit waste migration over the long term are nullified or severely impacted.

With respect to the avoidance distance per se, this is truly site specific. In consideration of ruling out extremes (e.g., a site will not be within a major oil or gas field) and in consideration of the extent of repository/site interactions, and that their magnitude is more extensive toward the repository, it is judged that for most adverse conditions, a laterial avoidance distance of 2 kilometers from the geologic repository operations area appears appropriate (i.e., up to about 1 kilometer for most repository/site interactions and an additional buffer distance of 1 kilometer considering effects of adverse conditions extending laterally hundreds of meters). Although not discussed, engineered barriers should significantly add to decreasing the adverse impacts of conditions as well. Thus, in this light, also, such a distance is judged to be appropriate.

Again, it should be stated that exceptions to these conditions may be warranted and may be granted. However, substantial restriction has been placed on the granting of exceptions to assure a high level of confidence and will require a high level of demonstration based on the weight of technical evidence.

Although a site may ideally not possess any of these adverse conditions, because of repository/site interactions which may significantly change ambient conditions and because ambient conditions may still permit substantial radionuclide movement, it is necessary that a site possess a number of favorable characteristics as well. Such favorable characteristics also are necessary to compensate for anticipated adverse conditions. Required favorable characteristics are discussed next.

Table 5.1 SUMMARY OF ADVERSE CONDITIONS

Condition	Influences			Application	
	Primary	Magnitude	Extent	Time	Space
5.2.1 Adverse Human Activities					
5.2.1.1 Resources Locations					
5.1.1.1.1 Subsurface Mining	subsidence, collapse structures, fracturing, stress field changes, alteration of geomechanical properties, head changes, permeability changes, brine invasion, acidification, future exploration	severe	radius of hundreds of meters	past, present	repository/site interaction zone
5.2.1.1.2 Drilling	exhumation of waste, pathways-direct, fracture pathways, future exploration, subsidence, head changes, permeability changes, leakage pathways, sealing, chemical changes, accelerate dis-solutioning, short circuit site barrier properties, brine invasion	very severe oil and gas, - thousands of meters depth injection wells - hundreds to several thousand meters depth water wells - tens to a few hundred meters depth	radius of hundreds of meters (on extreme kilometers to tens of kilometers)	past, present	repository/site interaction zone (deep drilling)

Table 5.1 (continued)

Condition	Influences: Primary	Influences: Magnitude	Influences: Extent	Application: Time	Application: Space
5.2.1.1.3 Economically Exploitable Resources	future exploration and potential for above effects			present	repository/site interaction zone
5.2.1.1.4 Relative Resource Endowment	" "			present	repository/site interaction zone relative to surrounding areas
5.2.1.2 Failure of Impoundments	flooding-operation, perturbers ambient stress field and ground water hydrology	severe	areal	present	geologic repository operations area
5.2.1.3 Impoundments Over the Long Term	perturbs ambient groundwater flow system, perturbs ambient stress field - faulting, earthquakes	extensive	regional	present	region
5.2.1.4 Perturbations to the Hydrogeologic Framework	all types - gradients, magnitudes of flow, chemical changes, etc.	significant - order of magnitude	local to regional	present, anticipated future	repository/site interaction zone
5.2.2 Adverse Geologic and Tectonic					
5.2.2.1 Extreme Bedrock Incision	exhume waste, changes in hydrology (discharge locations)	severe glacial - 300 to 600 meters	areal (valleys)	past, present	repository/site interaction zone
	chemical effects, dissolution	stream incision -tens of meters	areal valleys - may extend kilometers	past, present	respository/site interaction zone

Table 5.1 (continued)

Condition	Influences: Primary	Influences: Magnitude	Influences: Extent	Application: Time	Application: Space
5.2.2.2 Dissolutioning	large scale features- breccia pipes, collapse structures, brine pockets, sink holes, caving, corrosion of waste packages, nullify retardation, host rock and surrounding rock effects, increase flow.	severe	local to areal (rates low?)	past, present	repository/site interaction zones
5.2.2.3 Active Processes	complicating, uplift, subsidence, folding, faulting, diapirism, instability.	significant - millimeters to centimeters per year	local	present	geologic/repository operations area
5.2.2.4 Active Faulting	rupture of engineered barriers, short circuiting site barrier properties, near field earthquakes and repository damage, pathways for groundwater flow, difficult to assess, amenable analysis.	severe - meters to hundreds of meters through time	areal	since Quaternary Period	near field (10 to 20 kilometers)
5.2.2.5 Seismic Activity	instability, complicating	significant - macroearthquakes	local	historic record and geologic record	regional as it bears on the repository/site interaction zone

Table 5.1 (continued)

Condition	Influences: Primary	Influences: Magnitude	Influences: Extent	Application: Time	Application: Space
5.2.2.6 Volcanic Activity	geologic hazards for operation, igneous intrusions dikes, sills (intrusion into repository), pathways for flow- fractures, joints, bedding planes, lava tubes, breccia zones, resources (drilling).	severe	areal to regional	since Quaternary Period	repository/site interaction zone
5.2.2.7 High & Anomolous Geothermal Gradient	possible insta- bility, volcanism, geothermal resources	significant to possibly severe (penetrations)	-	present	repository/site interaction zone
5.2.3 Adverse Hydrologic					
5.2.3.1 Stable Paleohydrology	complicating analysis	significant to severe (order of magnitude effects)	-	recent past through present	repository/site interaction zone
5.2.3.2 Flood Plains	operational hazards, long term-near discharge, deep erosion	significant to severe	local	present, historic past	geologic reposi- tory operation area
5.2.3.3 Natural Impoundments	same as 5.2.1.3	extensive	regional	present	region
5.2.3.4 Fault and Fracture Zone Pathways	pathways for flow, complicating, design assessments, induced fault movement, changing flow patterns under repository/site interactions	extensive to severe	local	past through present	repository/site interaction zone

Table 5.1 (continued)

Condition	Influences			Application	
	Primary	Magnitude	Extent	Time	Space
5.2.4 Adverse Geochemical Limited Sorption	rate of movement of nuclides	extensive to severe	local to regional	present	repository to accessible environment

6.0 FAVORABLE CHARACTERISTICS

Section 3.0 described the role of the repository in isolating waste and the role and contributions the site can make to the multibarrier system. Also, discussion focused on the nature of uncertainties involved. Section 4.0, among other things, considered repository/site interactions and their deleterious effects, the difficulties that may arise in assessing interactions and effects, and the uncertainties here. The last section focused on adverse human activities and natural conditions that may contribute further to uncertainty, lack of confidence and, importantly, releases of radionuclides. Given the difficulties, uncertainties, and potential deleterious impacts cited, it is essential that a site (as well as design elements) possess as many favorable and compensating characteristics as practicable.

In consideration of various favorable characteristics that may contribute to inhibiting radionuclide migration, a number of paradoxes are encountered. For example, rocks which exhibit low porosity and permeability from the perspective of groundwater flow may appear ideal. However, from a heat flow perspective, limited groundwater flow may inhibit convection and would result in higher temperatures, Campbell and others (1978), and may result in more far-reaching repository/site interactions. However, high permeability increases the likelihood of waste being leached and transported. Additionally, the velocity of nuclides is inversely proportional to porosity, i.e., the lower the porosity, the higher the velocity. Low permeability would result, if nuclides escaped, in higher concentrations and lower dispersion. However, low porosity results in low circulation and low permeability results in low velocity and increasing transient times. It is highly doubtful that one can find a site that optimizes all these paradoxes and more. Thus, considerations in dealing with high-level waste disposal (as discussed in Rogers and others (1979)), involves trade offs. In terms of requiring favorable site characteristics, a number of trade offs have been made. These involve considerations that go beyond siting per se and include the engineered elements and the EPA standard. It should be recalled, overall long-term performance will be based on cumulative releases and their likelihood over the next 10,000 years. Thus, what is important from a siting standpoint with respect to overall performance is the reduction of the likelihood of adverse conditions (and thus releases) and decreasing the rate of releases, i.e., inhibiting the rate of radionuclide migration. With respect to the engineered elements, requirements being developed are focusing on containment for as long as achievable (e.g., through requiring a 1,000 year waste package and restricting the rate of releases from the repository through design and engineered barriers that inhibit groundwater and radionuclide movement). Since minimizing the rate of release is of concern, the site contributes to the engineered elements through (1) inhibiting groundwater circulation and increasing repository resaturation time, (2) possessing characteristics amenable to drift and shaft sealing, (3) maintaining a non-corrosive chemical environment that may degrade the engineered barriers, and (4) possessing a local and far field environment that in turn compensates for possible deficiencies in design, i.e., site properties to inhibit the rate of nuclide movement. With respect to waste/rock interactions, it would appear since the heat is the most significant problem, low planar heat densities are necessary. The requirements in the favorable characteristics section were developed in consideration of the above. From a tradeoff standpoint, characteristics that inhibit groundwater circulation, the rate of movement of groundwater, and rate of movement of radionuclides is preferred.

The judgments behind the favorable chara cteristics requirements are the same as those previously discussed in the introduction to the adverse conditions. Requirements here focus on simplifying the problem, adding confidence with respect to the long-term performance analysis, compensating for site deficiencies, and adding assurance that the site will provide multiple physical and chemical barriers to radionuclide migration.

In this light it is expected that a site chosen for a repository will possess many favorable characteristics. It is recognized that a site may still perform satisfactorily, in consideration of the design elements, so that possessing all of the characteristics identified may not be necessary. However, given their importance, an analysis is required to show to what degree a site possesses favorable characteristics and to what degree they (1) contributa to assuring stability; and (2) the isolation of waste by restricting (a) the access of groundwater to the waste, (b) the rate of dissolution of waste, and (3) the migration of radionuclides from the geologic repository. Again, conservative analyses are called for, as well as full documentation. Also, an assessment is necessary regarding the degree to which the favorable characteristics have been characterized in consideration of the resolution of investigative techniques used.

The discussion which follows focuses on the favorable characteristics and what they are intended to achieve with respect to radiological performance. As discussed in the introduction, at the present time no simulated radiological analysis of the requirements have been performed. Consideration is being given to performing such an analysis in context of all the technical aspects of the regulation, i.e., including the design and waste package requirements and further development of the EPA standard. A number of qualitative comparisons, however, are made here with studies of simulated conditions. Again, the previous caveats on modeling are appropriate.

6.1 Favorable Candidate Area Characteristics

The requirements here focus on the area around the site and the subsurface extension of the host rock and confining units from the geologic repository operations area out to some areal distance beyond.

6.1.1 Stability Since the Quaternary Period

As noted previously, in one way or another, siting guidelines stress stability. Relative stability is a site performance objective. For the long term, past and present surface and subsurface stability adds confidence that data collected today will be representative with respect to the future. As a favorable characteristic, surface and subsurface geologic, geochemical, tectonic, and hydrologic relative stability is sort in a wide area around a site and desired since the beginning of the Quaternary period.

6.1.2 Favorable Areal Characteristics of the Host Rock and Confining Units

With the exception of the geomechanical framework which is of greatest importance in the site vicinity (and to be discussed later on), the other three site components, i.e., the broad geologic framework, groundwater flow system, and the geochemical system maintain importance in terms of inhibiting radionuclide migration a considerable distance beyond the immediate vicinity of a site. Focusing on the host rock and confining units and the above three site components, described below is a series of required favorable characteristics necessary to inhibit the release of radionuclides to the accessible environment.

6.1.2.1 Favorable areal geologic framework

Except for direct exhumation of the waste via drilling, the flow of groundwater will be the mechanism that carries radionuclides to the accessible environment. Thus, the rate of flow of radionuclides will be proportional to the rate of groundwater flow. This carries with it that the residence time between when radionuclides are leached from the repository to when they enter the accessible environment will be proportional to the groundwater residence time. Having a geologic framework that provides long groundwater residence times and long flow paths has been identified as a favorable characteristic, IRG (1978), Golder (1978a), and others. To achieve this requires minimizing deleterious repository/site interactions and having a host rock (and confining units) that are vertically and laterally extensive and continuous, LLL (1979) IAEA (1977). Although one can envision certain impermeable discontinuities, e.g., facies changes, providing a bulkwork to groundwater flow, thus increasing residence time, they also increase the complexity of characterizing a site and analysis to be performed, Carpenter and others (1979a).

In consideration of long residence times and flow paths, a question arises here. That is, how long is long? There are several considerations involved in answering this question which the siting aspects are only but a part. Considerations here involve: the meeting of the EPA standard; the time it takes for repository saturation; the resilience of the waste packages (their leach rate); the contributions the engineered facility makes in inhibiting groundwater flow, waste migration, and the rate at which nuclides may escape from the engineered structure; the contributions the site can make as part of the multiple barrier system in inhibiting radionuclide movement given retardation, groundwater flow, perturbations brought about by repository/site interactions and adverse conditions; and the confidence and uncertainties involved in long-term prediction, thus the margin of safety desired. Additionally, one must look at the nature of the hazard, and what does long residence times and flow paths and other factors contribute. This has been simulated viz a viz sensitivity analyses, e.g., De Marsily and others (1977), Cloninger (1979), Heckman and others (1979), Hill (1979), and ADL (1979c).

On a first principal basis one can almost state the following:

(1) Since the hazard is from the radioactive decay of nuclides, the longer the isolation (that is, the longer the flow path and residence time), the lesser the hazard.

(2) Some elements in HLW and spent fuel have very long half lives; i.e., millions to billions of years. Some of these are naturally occurring, such as U-238, U-235, Th-232 and some are not, such as Np-237, Cm-247, Pu-244, and I-129. Although they may be isolated from the accessible environment for very long times due to engineered and site components, the fate of these elements over very long time spans approaching anywhere near their half lives will be impossible to predict. They may, in fact, be isolated for such time periods, as evidenced by Oklo, or they may be retrieved by humans, or they may work themselves naturally back to the accessible environment.

(3) For nuclides with shorter lived half lives, the amount of isolation from the accessible environment will depend on how much greater the isolation time is with respect to the half life. For example, for a nuclide with a 10 year half life, a residence time of 200 years (20 half lives) will result in a reduction of the original amount of a nuclide by a factor of a million.

(4) With respect to combining leaching from the repository and site travel time to the accessible environment, the following can be said. If the travel time to the accessible environment is very low, compared to the half life of a nuclide, and leach time very long, the leach time will control the rate at which nuclides enter the accessible environment. If on the other hand, the travel time is very long with respect to the half life, but leach time is very short, the travel time will govern the rate of release into the accessible environment. For intermediate times, the combined rate of the two will determine the rate of release.

(5) All other things being equal, the longer the travel time, the more dispersion that occurs and, as such, the lower the concentration per time that reaches the accessible environment.

The sensitivity studies noted above consider the total hazard, i.e., the hazard of the combination of the nuclides present, in consideration of their different rates of movement in the environment due to different amounts of retardation, and in context of different site properties, i.e., using and changing boundary conditions (e.g., permeability). All of the studies predict, based on a range of "reasonable" circumstances, that travel times approaching hundreds to thousands of years, result in very low releases, approximating background or less, except under very adverse circumstances.

It is just such adverse circumstances that are of concern here. That is, deleterious effects in the near field due to repository/site interactions, such as fracturing and fracture flow, low retardation brought about by high temperature or fracture flow or other effects (included here as well is the uncertainty in characterizing retardation), human intrusion into the repository and possible secondary effects. As such conservatism is warranted with respect to the ambient host rock and confining units providing long groundwater residence times and long flow paths. Although what constitutes long will be site specific, in consideration of the previous stated factors, it has been suggested as a desirable flow path length, distances on the order of tens of kilometers, IRG (1978). Thus, required here is an ambient geologic framework that provides such long residence times and long flow paths.

6.1.2.2 Favorable areal groundwater flow characteristics

A number of favorable ambient groundwater flow characteristics in the area of a site have been identified in the literature. These deal with having inactive groundwater circulation within the host rock and surrounding confining units and little hydraulic communication between the host rock and nearby aquifers. These characteristics provide protection to the repository-engineered elements from groundwater, slow-up resaturation time, and, if nuclides escape, inhibit their movement and their reaching aquifers. These characteristics also, with the exception of lowering planar heat density, more than anything else, restrict convection, particularly water entering from below the repository and traveling vertically upward, as previously discussed. One must also recall convection may be far reaching laterally as well and can have a dramatic effect on ambient conditions. Thus, restriction to groundwater calculation must extend laterally beyond and vertically above and below the repository horizon.

The restriction of groundwater circulation is basically defined by the thickness of rocks, i.e., the distance groundwater must travel, and both bulk mass permeability and fracture permeability. Hydraulic gradient is also important but will be discussed later on. In terms of permeability per se, the permeability of individual host rock types ranges over several orders of magnitude, Isherwood (1979), Giuffre and others (1979). Low permeability is usually classified in the range of about 10^{-7} cm/sec or less. The more fracture the rock, in general, the higher the permeability. To illustrate the effects of host rock permeability, Heckman and others (1979), in performing resaturation time calculations for a simulated mined repository report, everything else being held constant, that resaturation time ranged from 20 years to 100 years to 1,000 years as host rock permeability varied from 10^{-8} to 10^{-9} to 10^{-10} cm/sec. Heckman and others (1979) have also summarized the range and average permeability of fractured rocks derived from producing wells and pump tests. These range on the average of 10^{-4} to 10^{-5} cm/sec. Thus, one can see dramatic orders of magnitude differences in permeability between unfractured and fractured rocks. One should note the velocity of groundwater, thus, radionuclide movement, holding everything else constant, is directly proportional to permeability. In terms of thickness, it has been suggested that a host rock be surrounded by low permeable rocks that separate the repository from circulating water by about 300 meters or more, IAEA (1977). As discussed previously with respect to salt domes, this is also a rule of thumb.

Given the gains to be made, the requirements specify that the host rock and surrounding confining units be characterized by inactive groundwater circulation and little hydraulic communication with adjacent hydrogeologic units. Here, again, the degree will be site specific, but should represent the low end of the scale.

6.1.2.3 Favorable areal geochemical characteristics

Multiple lines of information reveal that low Eh, neutral ph, and a lack of complexing agents can significantly promote a low rate of corrosion of the engineered elements, low solubility of nuclides and high sorption. Simulations of releases reveal orders of magnitude decreases in both the magnitude and rate of releases can be brought about through a favorable geochemical environment, ADL (1979c). As previously discussed, there are many factors that compiex the quantitative determination of retardation. However, the three broad environmental factors identified, based on laboratory experiments, thermodynamic data and natural analogues, i.e., multiple lines of evidence, appear to significantly contribute to immobilizing many of the radionuclides of long-term dose significance.

6.1.2.3.1 Low redox (Eh) potential

The redox (Eh) potential can basically be defined as an environment's ability to promote an oxidation or reduction reaction (high Eh is oxidizing, low Eh is reducing). In low Eh environments, elements having multiple oxidization states are reduced to lower valence species (e.g., $Ur^{+6} \rightarrow Ur^{+4}$). As indicated in a number of studies, for elements having multiple oxidization states, lower oxidization states have higher retardation and/or lower solubility, Ames and Rai (1978), Nishita (1979). This is particularly true for the actinides, e.g., Ur, Pu and Np. Also, studies reveal Tc may be reduced in low Eh environments from the very mobile pertechnate, (TcO_4^-) which is highly soluble in oxidizing environments, Wildung and others (1979), to technetium dioxide (TcO_2) which is highly insoluble, Bondietti and Francis (1979), Francis and Bondietti (1979). Thus, in a reducing environment, the source term of actinides and technetium can be significantly reduced and restricted by solubility limitations. Additionally, studies by Fried and others (1978), and Bird and Lapata (1979) on engineered barriers reveal a number of reduced mineral types (e.g., cuprous sulfide, ferrous sulfide, plumbous oxide and sulfide) can significantly absorb Tc and I, and reduce their mobility. Such reduced minerals, however, require a low Eh environment for stability.

In addition to laboratory studies, studies of uranium deposits also bear on how reducing conditions result in the immobility of nuclides, Qidwai and Jensen (1979). As discussed in KBS (1978), uranium rollfront deposits result from the precipitation of Ur in the approximate Eh range of -72 millivolts to -195 millivolts. This is important in that spent fuel is more than 95 percent uranium dioxide. Thermodynamic studies relevant to uranium immobility, Langmuir (1978), indicate at a normal ph range (phZ7) and low Eh, reduced forms of uranium are predicted, thus making uranium essentially immobile. Perhaps, on a more analogous vein with a repository, studies of Oklo bear out thermodynamic predictions and the immobility of uranium and the actinides as well as most of the fission products over 2 billion years, Brookins and others (1975), Brookins

(1978a), Walton and Cowan (1975), Duffy (1978), Naudet and Renson (1975), Naudet (1978), Cowan (1978), and Cowan and Norris (1978). Estimated Eh and ph conditions in the reaction zones at Oklo are on the order of Eh -50 millivolts to -450 millivolts, and ph of 7 to 8.5, Brookins (1978a). It should be noted that temperature estimates at Oklo during the several hundred thousand year fission activity period are on the order of 450°C at core boundaries to 600°C at core centers, Vidale (1978). In comparison, the temperatures of a repository will be much lower and much shorter lived. Thus, borne out here is the order of magnitude contribution low Eh (as well as neutral ph) can make to immobilizing radionuclides.

In terms of achieving low Eh conditions, Apps and others (1977) report most groundwater is in the range of + 400 Mv to -400 Mv (ph6-9). The Eh is a function of a number of factors, e.g., bacterial action, dissolved oxygen content, composition of the rock. At STRIPA studies have been conducted and reveal a decrease in Eh with depth. Although this decrease is not straightforward. Eh values reported in deep waters decrease to about -100 millivolts, Fritz and others (1979), KBS (1978). Of course, roll front Ur deposits are an indication of the existence of low Eh environments at fairly shallow depths, approximately 400M, KBS (1978). In addition to the discussions above, low Eh implies low oxygen content, thus less direct corrosion of canisters due to oxidization.

In consideration of the above discussion in terms of limiting solubility and promoting retardation both with respect to the engineered elements and the host rock and confining units, low Eh appears essential and has been identified as a required favorable characteristic.

6.1.2.3.2 Neutral ph

A neutral (or slightly alkaline) environment appears to also significantly contribute to promoting retardation, low solubility of nuclides, and limiting corrosion of engineered elements. As Page and others (1956) report, acid groundwaters may have several orders of magnitude higher concentrations of uranium than more neutral groundwaters indicating a significant increase in the dissolutioning of uranium. With regard to retardation per se, Ames and Rai (1978), Dosch and Lynch (1978), Isherwood (1978) have summarized effects. These include changing the stability field (as a function of Eh and ph) of chemical species, and changing the adsorption characteristics of minerals as well, both of which affect retardation. Because extreme ph conditions are more reactive, they tend to complicate assessments as well. It would appear from the above summaries and enperimental work reviewed, particularly with regard to the actinides, that everything else being equal, sorption appears to maximize near neutral ph. As such, a neutral ph is identified here as a favorable characteristic of the host rock and confining units.

6.1.2.3.3 Complexing agents

Complexing agents, here, are applied in the broad sense to organic constituents which complex with nuclides and may decrease retention (deleterious complexing agents (e.g., EDTA) that might be introduced from the degradation of the waste and that might interfere with the site's retardation properties are covered in the design selection of the requirements), and to solutions having high ionic strength which introduce competing ions in terms of ion exchange. Both organic constitutents and high ionic strength have been identified as factors that significantly affect retardation, Isherwood (1978), Ames and Rai (1978). As a general rule with regard to trends of influence, it would appear that groundwater that has high ionic strength will result in low retardation, Ames and Rai (1978). The effects of organic materials that might be anticipated at depth appears complex by and large uncertain, and lacking in study. Given the complexity in defining retardation in the field, the lack of complexing agents in the host rock and confining units has been identified as a favorable characteristic.

6.2 Favorable Repository/Site Interaction Zone Characteristics

The characteristics identified here apply to the volume of rock that may be affected by repository/site interactions, i.e., as a minimum, from the surface to 1 kilometer below the subsurface extent of the excavations and laterally to a 2 kilometer radius from the limits of excavations.

6.2.1 Incorporation of Favorable Areal Characteristics

The characteristics previously described are confined to the host rock and confining units. Here, those same characteristics are seen as favorable characteristics in the entire near field, extending to rocks above and below the repository and out laterally. In consideration of repository/site interactions and anticipated perturbations in the ambient site conditions, the previous favorable characteristics are viewed as essential means to compensate or buffer deleterious interactions. Particularly important is ascertaining the favorable characteristics above and below the repository that inhibit vertical upward groundwater flow. Additionally, it is essential to identify the favorable geochemical characteristics in the rocks above the repository in which groundwater may flow.

6.2.2 Favorable Geologic Characteristics for Repository Development

The general favorable characteristics identified here bear on the geologic aspects of sealing the repository, subsurface mine stability and depth of repository development. With respect to sealing as noted previously, present long-term sealing technology is limited. Thus, it is necessary to find a site whose geologic properties do not compound the problem, and that promote sealing. For example, with respect to sealing vertical shafts, thick and uniform formations permit better characterization and require less diversity in seals. Having a lot of thin formations may require very complicated and multilayered seals. The same is true for complex folded structures that may be penetrated. A significant problem identified in the literature dealing with seals is the possibility in salt of dissolutioning occurring behind grout curtains or seals, Carpenter and others (1979). The geology should permit excavations to be as far as possible from circulating groundwater. As noted in Byrne and others (1979), properties of the host rock, in particular, should inhibit or prevent fracturing around openings.

In terms of the excavation of a stable subsurface opening, it has been recommended that gentle dips less than a few degrees will contribute to the ease of mining, IAEA (1977), thus, contribute to reducing potential adverse impacts of excavation. Here, too, uniform and predictable geologic properties should help assure well-controlled construction. Friable rocks may lead to caving and the development of fractures during excavation. Sites in salt should be free from nearby brine pockets. Such features may lead to sudden inflows of brine, Byrne and others (1979). Temperature effects must be given consideration here as well, regarding pressure buildup.

With respect to the depth of waste emplacement, a number of factors have been considered here. With regard to physical isolation from subsurface drilling, given the depths of drilling previously cited, it would appear a depth of a few hundred meters would avoid most water well drilling. However, it would take several thousand meters to avoid injection wells and oil and gas wells. Such depths pose a number of problems, however. As noted in Golder (1978a), and Wagoner and Steinborn (1979), mechanical constraints (particularly in salt) such as creep and spalling, are encountered which may pose problems for retrievability. As noted in Altomare and others (1979), the greater the depth, the hotter are ambient temperatures. This would result in lowering heat dissipation from the waste and higher temperatures will be reached, thus, extending and amplifying repository/site interactions. Thus, from a drilling standpoint, it would appear feasible to avoid most water wells at a few hundred meters depth. With regard to oil or gas well drilling, injection wells and exploration drilling, it is judged that location rather than depth would have more of an impact in terms of the likelihood of penetration. Even then, however, it would appear designing for drilling would be appropriate.

Most of the literature on depth speak to separating the repository from surficial material processes, LLL (1979), NAS/NRC (1978). As noted previously, in the discussion of adverse conditions, requirements have been developed as a means to assure no extreme surficial conditions will exist at a site. Thus, extreme bedrock incision is judged not likely. Assuming a high rate of physical erosion as a worst case, such as 5 mm/year, in 10,000 years, ground leveling would only be 50 meters. Thus, several hundred meters to avoid water wells should still bound physical erosion.

Chemical weathering and surface water percolating down open fractures have been indicated to extend down to 200 to 300 meters, IAEA (1977). It has been reported that in crystalline terrain, poor water circulation occurs at depths less than 100 meters, Golder (1978b). The depth of penetration of surface water is important in terms of repository resaturation time, i.e., the lower the depth, the lower the fracture permeability. It also is important in terms of achieving a reducing environment. It would appear that here as well, a few hundred meters would be bounding.

Of course, the depth at a particular site depends on many factors and will be site specific (not considered above, but essential will be assuring a site is in a regional groundwater flow system). However, a minimum depth appears appropriate to assure separation of the repository from surficial processes discussed, particularly in consideration of the uncertainties in making long-term prediction. A depth of several hundred meters appears appropriate. Most recommendations are around 300 meters, NAS/NRC (1978), Golder (1978a), Altomare and others (1977) and this has been taken as a minimum.

6.2.3 Favorable Near Field Groundwater Flow Characteristics

In addition to the more broad scale characteristics discussed above, identified here are a series of favorable groundwater flow characteristics that in combination are judged to provide a needed and very restrictive near field groundwater flow regime. The objective of this restricted groundwater flow regime is to severely delay releases, to severely restrict upward flow, and flow to potentially usable aquifers above the repository, and to channel any releases to a long horizontal flow path.

6.2.3.1 Unsaturated host rock (very low water content)

As noted in IAEA (1977), a dry host rock or one that has little or no movement of groundwater is preferred. It is recognized that no rock is completely dry. However, an unsaturated condition or a host rock with very low water content provides a significant barrier to groundwater circulation. If a rock can be shown to be unsaturated or have been unsaturated over geologic time, and if repository/site interactions are kept low, i.e., a low planar heat density, one is basically assured, barring future human activities, that unsaturated conditions will remain for at least thousands of years. Radionuclides will be essentially immobilized until the rock becomes saturated. Saturation would require vast climatologic changes and may or may not come about during the next glacial period. Thus, it would appear thousands of years of isolation, barring human activity, are assured.

6.2.3.2 Limited intrusion and circulation of groundwater

A number of studies identify limited groundwater circulation in the host rock and characteristics that limit intrusion of groundwater into the host rock as preferred characteristics, IAEA (1977), LLL (1979), Golder (1978b). These favorable characteristics cannot be more stressed. They imply a host rock with a very low fracture density and low intrinsic bulk permeability, a thick host rock and a host rock surrounded by thick confining units.

6.2.3.3 Restricted upward flow

Intended here are groundwater characteristics that restrict upward flow between hydrogeologic units or along subsurface penetrations. As previously discussed, vertical flow due to induced convection may severely reduce travel times to near surface aquifers. Thus, it becomes imperative that vertical permeability be very low both above and below the repository. Additionally, given the problems with sealing, it is also necessary that groundwater flow characteristics are such so as to severely restrict groundwater movement to shafts, drifts and bore holes and if penetrated by groundwater, hydraulic gradients should prevent upward flow.

6.2.3.4 Low hydraulic gradients

With respect to the magnitude of hydraulic gradients per se, low gradients in the host rock and surrounding confining units are favored. Low gradients imply lateral continuity or homogeneity and reduced driving forces for groundwater flow.

6.2.3.5 Horizontal or downward hydraulic gradients

With respect to direction of hydraulic gradients in the host rock and confining units, ambient horizontal or downward gradients are preferred, IRG (1978). This helps to assure long horizontal travel paths and pathways directed away from potential near surface aquifers.

6.2.3.6 1000 year minimum groundwater residence time

As noted earlier, coupled with the engineered components is a site performance objective to achieve as a minimum a radionuclide residence time to the accessible environment of 1,000 years. In consideration of the uncertainties with respect to the characterization of radionuclide retardation, a groundwater flow residence time of 1,000 years or longer is a favorable characteristic. Thus, retardation during the early period when the hazard is greatest becomes a safety factor. Taking retardation factors as reported in ADL (1979c) and Hill (1979) as representative, values for retardation for the long lived apparently dose significant isotopes range from a low of 1 (TcI) to a high of 10^4 (Pu). The retardation factor is defined as the ratio of the velocity of groundwater to the velocity of the radionuclide (taking Pu for example, a retardation factor of 10^4 means the groundwater travels 10^4 times as fast as the Pu, or for a given distance it takes the Pu 10^4 times as long to arrive as the groundwater). Assuming these values remain constant during repository/site interactions or decrease, perhaps, by an order of magnitude or two (the limiting case being $R_f=1$), a preserved groundwater residence time of 1,000 years will essentially assure no isotopes reach the accessible environment for 1,000 years, and, given the safety margin of retardation, the delay time due to the engineered repository and resilent waste packages, for thousands of years longer.

6.2.4 Nearfield Favorable Geomechanical Properties

In terms of the geomechanics of a site with respect to construction and operation and the long term, a variety of general favorable site characteristics has been identified in the literature. All of them are basically geared to maintaining stability. These include low ambient stresses, predictible mechanical properties, resilience with respect to the thermal loading, an ambient state of stress such that there is a significant resistance to slip along planes in the presence of induced stress and changes in pore water pressure, resistance to creep, high thermal conductivity, etc., NAS/NRC (1978) NAS/NRC (1979), IAEA (1977), Golder (1978b), etc. Given the critical importance of the geomechanical properties in the near field, it is expected that sites will possess many of these favorable characteristics or high degrees of them.

6.2.5 Low Population Density

As a general consideration, low population densities in the site vicinity and distance from population centers have been recommended. From a technical and siting standpoint, there are several reasons for avoiding areas of high population density and population centers. Given either present or the growing use of groundwater, and the effects on ambient conditions, analysis of ambient conditions are complexed. Past and present subsurface injection waste wells, which would be associated with industrial centers, may be difficult to identify, get records of and to assess with respect to the nature of materials disposed, and their potential effects over the long term. Although predictions of human activities over the long term are dubious, present activities are at least a guide. As such, given population growth, expansion of population centers, trends of groundwater and subsurface use, being near a population would seem to make the problem more difficult and complex and substantive impacts on the repository can be envisioned. With respect to radiological impact, due to operation or accidents near a site, regulations on transportation, surface facilities, and applicable standards in the design sections apply here.

As to what constitutes an acceptable low population density in the site vicinity or distance from population centers is further being pursued. Various draft versions of the siting sections have contained specific numerical quantities, these being based on aspects of reactor siting. Thus far, no satisfactory resolution has been found. It is judged a this time that a site specific assessment would be made as to impacts. However, as general guidance, a low population density in the near field of a site has been identified.

7.0 CONCLUSIONS

Appendix A contains the siting requirements and excerpts of the monitoring requirements that have been derived in consideration of the previous discussion. It should be noted the requirements, as of this writing, are in draft and comments are sought. It is also anticipated that subsequent changes will be made in both language and in text as the requirements proceed through development.

Through the course of deliberations on the requirements and in developing this documentation, a number of considerations stand out. These are listed below as conclusions drawn.

(1) Perhaps foremost, major difficulty exists and will exist in the demonstration of the long-term performance of the repository. Given uncertainties, complexities, limitations in the state of the art, the novelty of considerations, etc. To resolve this difficulty will require a very conservative, comprehensive, and stepwise approach that seeks out the full weight of information. Reliance on systems modeling alone, will not be sufficient. Major reliance on the site will not be sufficient. Given the opportunity to control engineering, significant emphasis must be placed on engineering for compensation and demonstration. Margins of safety with respect to the long term and building in multibarriers must be compounded.

(2) It is recognized that repository development is in a research mode and many years of development are ahead. As gleaned from the literature, nothing will take the place of in situ and field testing at a specific repository site. Early initiation of such testing is essential.

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(2) It is recognized that repository development is in a research mode and many years of development are ahead. As gleaned from the literature, nothing will take the place of in situ and field testing at a specific repository site. Early initiation of such testing is essential.

(3) It is recognized that with time the hazard decays. But it must be also recognized that with time the uncertainties increase. As to whether the two cancel is uncertain. Proclamations of repository performance over thousands of years, hundreds of thousands of years, millions of years with an air of anything approaching certainty must be guarded against. One must keep in mind, simulations are but simulations.

(4) Many judgments have gone into the siting requirements and many judgments will have to be made in meeting them and ascertaining whether they are met. Professional and reasoned judgments, perhaps more than anything else, will determine an acceptable demonstration of performance; that is, reasoned consensus will be necessary. The siting requirements themselves are only a framework to make the initial judgments in the years ahead. They do not stand by themselves and will require a comprehensive licensing process. Given the years ahead, it is anticipated as experience is gained, the requirements may change.

(5) In terms of evaluations of future performance, one can envision now a myriad of scenarios. The siting requirements, although calling for much in the way of analysis, attempt to simplify the problem, to break it up into its parts. Proof that a repository, through simulations, can withstand extremes, the extraordinary, the near impossible, adds nothing to confidence, nor demonstration, but just complexes and compounds the already bewildering nature of performance projection. The key here is a reasoned approach. Given, a particular site, the judgments of knowledgeable professionals is essential in defining what is reasonable.

(6) Of all the technical areas involved, the geochemical area appears the most sorely lacking. Although there is room for improvement, given the complexity here, it is highly doubtful that the full, comprehensive, and quantitative characterization of geochemical properties being sort in the literature will ever be achieved. Laboratory measurements and computer analysis only will go so far. Recognizing the importance of the geochemical system and present problems, it is essential that the scope of problems be conveyed to those performing long-term analysis. Bounding the problem here would also appear essential. Finally, leaving the laboratory, and getting out to field to search for natural analogues, to perform field experiments, to develop field measuring techniques at specific sites cannot wait and must be rigorously pursued NOW.

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APPENDIX A

Excerpts from the 3/24/80 Draft* of 10 CFR Part 60, Subpart E, Disposal of High-Level Radioactive Wastes in Geologic Repositories.

60.111 - Site Performance Objectives

60.122 - Siting Requirements

60.137 - Monitoring Programs

*Modifications of this draft in terms of editing and text is anticipated. The actual advanced notice that is finally published may differ from this draft and reviewers should be aware of possible changes.

60.111 Site Performance

(i) The site and environs shall be chosen to provide reasonable assurance that the degree of stability exhibited at present will not significantly decrease over the long term.

(ii) The site and environs shall be chosen to exhibit properties and conditions that promote isolation and to provide reasonable assurance that their present capability to inhibit the migration of radionuclides will not significantly decrease over the long term.

(iii) The site and environs shall be chosen with hydrologic and geochemical properties of the host rock and surrounding confining units that provide reasonable assurance that radionuclides will not reach the accessible environment during the first 1,000 years* after decommissioning even assuming degradation of the engineered barriers due to expected processes and events.

*Comment particularly sought.

60.122 Siting

(a) General Requirements

(1) The site and environs shall be selected so that they are not so complex as to preclude thorough investigation and evaluation of the site characteristics that are important to demostrating that the performance objectives of §60.111 will be met.

(2) The Department shall investigate and evaluate the geologic, tectonic, hydrologic, and climatologic conditions and processes and human activities that can reasonably be expected to affect the design, construction, operation, and decommissioning of the geologic repository operations area, as well as the stability of the geologic repository and the isolation of radionuclides after decommissioning.

(i) The horizontal extent of the investigations shall be on the order of 100 kilometers radius from the geologic repository operations area,

(ii) Emphasis shall be placed on those processes active anytime since the start of the Quaternary Period, and

(iii) Emphasis on predictions of changes in natural conditions and the performance of the geologic repository shall be placed on the first 10,000 years following decommissioning.

(3) The Department shall conduct investigations that adequately characterize and provide representative and bounding values for those human activities and natural events and conditions that may affect any of the following:

(i) The design, construction, operation, and decommissioning of the geologic repository operations area.

(ii) Demonstration of the stability of the geologic repository after decommissioning.

(iii) Demonstration of the isolation of radionuclides from the accessible environment after decommissioning.

(4) The siting investigations and evaluations shall be performed taking into account reasonably likely future variations in the site characteristics which may result from natural processes, human activities, construction of the repository, or waste/rock/water interactions.

(5) The site investigations shall be conducted in such a manner as to obtain the required information with minimal adverse effects on the long-term performance of the geologic repository.

(6) Analyses and modelling of future conditions and changes in site characteristics shall, to the extent practicable, be validated by field tests, in situ tests, field-verified laboratory tests, monitoring data, and natural analog studies.

(7) The Department shall continuously verify and assess any changes in site conditions which pertain to whether the performance objectives will be met.

(8) The Department shall determine by appropriate analyses the extent of the volume of rock within which the geologic framework, ground water flow, ground water chemistry, or geomechanical properties are anticipated to be significantly affected by construction of the geologic repository or by the presence of the emplaced wastes, particularly by the thermal loading of the latter. In order to do the analyses required in this paragraph, the department shall at a minimum conduct investigations and tests to provide the following:

(i) The pattern and distribution of fractures, discontinuities, and heterogeneities in the host rock and surrounding confining units;

(ii) The bulk geomechanical properties and ambient stress conditions of the host rock and surrounding confining units in situ;

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(iii) The bulk hydrogeologic properties of the host rock and surrounding confining units in situ;

(iv) The bulk geochemical conditions, particularly the Redox potential, of the host rock and surrounding confining units in situ;

(v) The bulk response of the host rock and surrounding confining units to the anticipated thermal loading given the in situ pattern of fractures and other discontinuities and the heat transfer properties of the rock mass.

As a minimum, the volume shall be assumed to extend a horizontal distance of 2 kilometers* and a vertical distance from the surface to a depth of 1 kilometer* below the limits of the repository excavation.

(b) Potentially Adverse Conditions

The criteria in this section apply, unless otherwise stated, to the volume of rock determined by the Department in Paragraph 60.122(a)(3) above.

*Comment particularly sought

Paragraphs 60.122(b)(1) through 60.122(b)(4) below describe human activities or natural conditions which can adversely affect the stability of the repository site, increase the migration of radionuclides from the repository, or provide pathways to the accessible environment. The Department shall demonstrate whether any of the potentially adverse human activities or natural conditions are present. All investigations shall be fully documented. The presence of any of the potentially adverse human activities or natural conditions shall give rise to a presumption that the geologic repository will not meet the performance objectives.

Proof of the contrary shall require a demonstration that the presence of the potentially adverse human activity or natural condition does not prevent the geologic repository from meeting or have a significant influence on the ability of the geologic repository to meet the performance objectives. In order to provide this proof, the Department shall first demonstrate that:

(1) The potentially adverse human activity or natural condition has been adequately characterized, including the extent to which the particular feature may be present and still be undetected given the degree of resolution achieved by the investigations;

(2) The direct and indirect, near field and far field, and short term and long term effects of the potentially adverse human activity or natural condition on the geologic framework,

groundwater flow, groundwater chemistry, and geomechanical integrity of the site and environs have been evaluated by use of conservative assumptions and analyses;

(3) the method of evaluation used in (2) is sensitive to the potentially adverse human activity or natural condition:

(4) The potentially adverse human activity or natural conditon is compensated by the presence of favorable characteristics in Paragraph 60.122(c) of this Section;

(5) The potentially adverse human activity or natural condition can be remedied during construction, operation, or decommissioning of the repository.

The specific potentially adverse conditions are the following:

(1) Potentially Adverse Human Activities

(i) There is or has been conventional or in situ subsurface mining for resources.

(ii) There is or has been drilling for whatever purpose, except holes drilled for investigations of the geologic repository, to depths below the lower limit of the accessible environment.

(iii) There are resources which are economically exploitable using existing technology under present market conditions.

(iv) Based on a resource assessment, there are resources that have either higher gross or net value than the average for other areas of similar size in the geologic province in which the geologic repository is located. Determinations of net value shall consider development, extraction, and marketing costs. The resource assessment shall include both known and undiscovered deposits of all resources within the geologic province that includes the site and that (1) have been or are being exploited or (2) have not been exploited but are exploitable under present technology and market conditions.

(v) There is reasonable potential that failure of human-made impoundments could cause flooding of the geologic repository operations area prior to decommissioning.

(vi) Existing topographic, geomorphic, stratigraphic, hydrogeoloic, and climatologic characteristics suggest a reasonable potential for construction of large-scale impoundments which may affect the regional groundwater flow system.

(vii) There is indication of present or reasonably anticipatable human activities that can significantly affect the hydrogeologic framework such as groundwater withdrawals, subsurface injection of fluids, underground pumped storage facilities or underground military activities.

(2) Potentially Adverse Natural Conditions - Geologic and Tectonic

(i) There is evidence of processes which have caused extreme bedrock incision since the start of the Quaternary Period.

(ii) There is evidence of dissolutioning, such as karstic features, breccia pipes, or insoluable residues.

(iii) There is evidence of processes which may result in structural deformation such as uplift, diapirism, subsidence, folding, faulting, or fracture zones.

(iv) The geologic repository operations area lies within the near field of a fault that has been active since the start of the Quaternary Period.

(v) There is a fault or fracture zone, irrespective of age of last movement, which has a horizontal extent of more than a few hundreds of meters.*

*Comment particularly sought.

(vi) There is a concentration of earthquake activity relative to the regional distribution of earthquakes or there are indications that earthquake activity may be concentrated in the future based on either the distribution and frequency of occurrence of earthquakes or the correlation of earthquakes with tectonic processes and features.

(vii) There is evidence of intrusive igneous activity since the start of the Quaternary Period.

(viii) There is a high and anamalous geothermal gradient relative to the regional geothermal gradient.

(3) Potentially Adverse Natural Conditions - Hydrologic

(i) There is, based on a paleohydrologic evaluation, reasonable potential for significant changes in hydraulic gradients, average pore velocities, storativities, permeabilities and natural discharge.

(ii) The geological repository operations area, or any part thereof, is within the 100-year* flood plain.

(iii) Based on evaluation of the existing topographic, geomorphic, stratigraphic, hydrogeologic, climatologic characteristics,

*Comment particularly sought.

and geomechanical properties of the rock units, there is reasonable potential for natural phenomena such as landslides, subsidence, or volcanic activity to create large-scale impoundments that may affect the regional groundwater flow system.

(4) Potentially Adverse Natural Conditions - Geochemical

There is an absence of geochemical properties that provide a major barrier to the movement of most radionuclides between the repository and accessible environment.

(c) Favorable Characteristics

Each of the following characteristics represent human activities or natural conditions which enhance the ability of the geologic repository to meet the performance objectives.

The Department shall demonstrate the degree to which each favorable characteristic listed in Paragraphs 60.122(c)(1) and 60.122(c)(2) below is present. All investigations shall be fully documented. Evaluations shall be performed to demonstrate to what extent the favorable characteristic contributes to assuring the stability of the site and/or the isolation of the waste by restricting the access of groundwater to the waste, the rate of dissolution of the waste, or the migration of radionuclides from the geologic repository. The analyses used to demonstrate the significance of the favorable characteristics shall be conservative, shall be based upon conservative assumptions, and shall include evaluation of the degree to which the favorable characteristic has been adequately characterized, given the degree of resolution achieved by the investigations.

The specific favorable characteristics are the following:

(1) The site shall be selected so that to the extent practicable the candidate area

(i) exhibits demonstrable surface and subsurface geologic, geochemical, tectonic, and hydrologic stability since the beginning of the Quaternary Period.

(ii) contains a host rock and surrounding confining units that provide:

(a) a geologic framework, such as extensive vertical and lateral continuity, that provides long groundwater residence times and long flow paths prior to entering the accessible environment.

(b) groundwater flow characteristics, such as low intrinsic permeability of the rock mass, including low fracture permeability, that result in (1) inactive groundwater circulation within the host rock and surrounding confining units, and (2) little hydraulic communication with adjacent hydrogeologic units.

(c) geochemical properties, such as (1) reducing conditions which result in low solubility of radionuclides, and (2) non-extreme pH or a lack of complexing agents that promote high retardation of radionuclides.

(2) The site shall be selected so that to the extent practicable the site and environs:

( ) possess the favorable characteristics described above.

(ii) possess a geologic framework that permits effective sealing of shafts, drifts, and boreholes, and that permits excavation of a stable subsurface opening, and the emplacement of waste at a minimum depth of 300 meters* from the ground surface.

(iii) possess groundwater flow characteristics that:

(a) provide an unsaturated host rock.

(b) prevent groundwater intrusion or circulation of groundwater in the host rock.

(c) prevent significant upward groundwater flow between hydrostratigraphic units or along shafts, drifts, and boreholes.

*Comment particularly sought.

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(d) result in low hydraulic gradients in the host rock and surrounding confining units.

(e) result in horizontal or downward hydraulic gradients in the host rock and surrounding confining units.

(f) result in groundwater residence times, between the repository and the accessible environment, that exceed 1000 years.

(iv) possess geomechanical properties that provide stability during construction, operation, and under the influences of thermal load or other waste/rock/water interactions.

(v) possess a low population density.

60.137 Monitoring Programs

The department shall initiate a system of monitors during site characterization. The system of monitors shall be maintained and supplemented, as appropriate, throughout the period of institutional control. The system of monitors shall be designed to verify that the performance objectives of Section 60.111 are being achieved.

(a) Monitoring systems shall not adversely affect the natural and engineered elements of the geologic repository.

(b) Monitoring systems shall be established at a candidate site to obtain baseline information on those parameters and natural processes pertaining to the safety of the site and perturbations at the site that may be caused by site characterization activities.

(c) Monitoring systems shall be established at the site of the geologic repository to monitor changes from baseline condition of parameters which could affect the performance of the site's natural or engineered barriers to radionuclide migration during construction, operation, and after decommissioning.