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ROCK MASS SEALING

An Assessment of Information and Research Needs

J. Daemen
University of Arizona
NRC-04-78-271

November 1984

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Summary

This assessment of rock mass sealing information needs is intended to identify information gaps that might be encountered by NRC during a HLW repository license application review. Research is suggested that would close such gaps and thereby provide assistance in assuring that the repository sealing requirements are addressed satisfactorily in a license application and that NRC has sufficient information to make findings in this regard.

In the first section, the introduction, the need for sealing and hence for sealing performance predictability is identified, primarily because it is required by 10 CFR 60, and because it is generally considered necessary or desirable by the technical and scientific community. One sealing aspect stressed in this section, because it has not been addressed very much, is the need to prevent repository flooding during operations, i.e. prior to permanent closure.

In the second section an overview is given of ongoing sealing research projects. These projects are only touched on, the major aspects are identified, and a few representative recent references are given to allow the interested reader to identify (the extensive) additional information published on any of these projects.

The third section identifies remaining sealing uncertainties. A separation needs to be made between sealing requirements for salt repositories and sealing requirements for hard rock (basalt, granite, tuff) repositories. For salt repositories operational sealing is considered to be the critical requirement, while permanent closure sealing is likely to be dominated by salt behavior. For hard rock repository sealing it is argued that the principal uncertainty issue

is the influence of the damaged zone surrounding excavations (shafts, tunnels, emplacement rooms and holes), which might form a direct preferential flowpath from waste to aquifers penetrated by shafts. Permanent salt repository (salt creep) and hard rock repository damaged zone influence preferably should be considered in the broad context of the repository thermal-hydrological-chemical-mechanical repository performance, and certainly integrated with overall rock mechanics repository engineering research.

In the fourth section a specific list of detailed sealing research needs is presented. The list is intentionally split up into numerous subsections in order to facilitate an NRC prioritization among various subissues. For reasons explained in the third section a complete separation is made between sealing issues and research recommendations for hard rock and for salt repositories.

For hard rock repositories it is argued that a critical unknown issue remains the damaged zone around excavations. While the potential for this zone to become a preferential flowpath points out its significance within the sealing context, an improved predictability of the damaged zone extent and of its characteristics (e.g. hydraulic conductivity, porosity, strength) is equally important, possibly more so, for a number of other licensing issues: retrievability; disturbed zone definition; canister loading; repository stability; in-situ (e.g. exploratory shaft) measurements, monitoring, and interpretation thereof. It is concluded that damaged zone studies, whether programatically focused very narrowly within the sealing context, or, preferably, more broadly addressing the listed rock mechanics licensing issues, deserves a high research support priority. Subsidiary topics of importance in this context include remedial action (grouting), and preventive action (rock bolting). It also would seem desirable to maintain some activity in borehole sealing studies, primarily to allow completion of testing at elevated temperatures, to extend the time length for experimental performance assessments, to allow the development of a broader data basis, and to resolve remaining key uncertainties, particularly with regard to field installation procedures and testing.

For salt repository sealing it is essential to distinguish between operational sealing requirements, probably the most cricital aspect, and permanent sealing requirements. Permanent salt sealing is primarily determined by salt behavior, and research in this area would be closely related to various salt creep studies, and should concentrate on salt behavior (closure), on salt as a sealing material, and on other proposed salt sealing products (cement, concrete, earthen-clay meaterials). Operational sealing research should concentrate on sealing aquitard penetrations, i.e. sealing of shaft interfaces with anhydrite and salt, of inclusions (anomalies) that might connect the salt formation to nearby aquifers, of anhydrite, and probably with less emphasis on aquitards such as shale, dolomite, limestone.

The last section of this assessment presents a brief summary of University of Arizona capabilities in the areas discussed, and of a continued contribution that could be made here in support of NRC license application review information requirements. The prioritized research topics discussed there are:

1. Damaged zone predictability assessments.
2. Rock mass sealing (fracture grouting).
3. Borehole plugging.
4. Rock bolting.

A more detailed discussion of possibilities for damaged zone studies is given in Appendix A.

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This assessment has been prepared at the request of NRC, Research. It provides a summary of the current status of rock mass sealing information, and of information needs likely to develop in the context of NRC evaluations of HLW repository license applications.

Because this review has been prepared at fairly short notice, it is not comprehensive, but highlights critical areas of concern. Only a few representative references are included, aimed at identifying major ongoing research areas as well as problem areas, but not sufficient to provide a comprehensive state-of-the-art review. More detailed discussions as well as numerous additional references on various topics can be found in reports submitted to NRC as part of Contract NRC-04-78-271.

1. Introduction: Need for Repository Sealing

The requirement to seal manmade penetrations of the rock surrounding a repository (e.g. shafts, boreholes) is stated explicitly in 10 CFR 60, §60.133, Design of shafts and seals for shafts and boreholes. Additional sections of 10 CFR 60 that address the sealing issue include §60.132, a, 2; g, 5, 6 and §60.142, a, d. The regulatory requirements for sealing are established uambiguously, and hence the requirements for the license applicant to provide reasonable assurance that sealing is feasible, and for NRC to evaluate whether reasonable assurance has been provided.

The sealing requirements have been discussed extensively in the technical literature. A brief summary of references in which the sealing needs are identified or discussed has been given in our last annual report (NUREG/CR-3473, Daemen et al., 1983, p. 7, third and fourth paragraphs). The literature referenced there can be summarized by stating that the majority of the authors believe that high quality sealing (low hydraulic conductivity, adequate strength, durability) is necessary or desirable, that multiple not entirely compatible performance requirements suggest the need for multiple components in the sealing system, and that sealing performance needs to be demonstrated. A few authors do not believe sealing to be necessary or important, although even they recognize that sealing would provide a desirable redundancy in the waste containment system. Only a very small number of formal performance assessments have specifically addressed the sealing issue, and all the ones I am aware of include extreme simplifications, e.g. in driving mechanisms, in failure scenarios, in geometry, etc.

Given that the flowpath from emplacement hole to emplacement room to access tunnels and to shafts/boreholes forms an obvious and direct connection from (through) the disturbed zone to the surface, and given the unavoidable presence of two opposing waterflow driving forces, i.e. gravity and thermal, it is clear that waterflow towards and waterflow away from the repository is a possibility. Whether inward or outward flow (or flow through a repository) occurs at any particular moment in time can be determined only by simulations of the entire system, including pre-construction conditions, construction-induced changes, waste-induced changes, etc., i.e. requiring comprehensive thermal-mechanical-hydrological modeling. The reliability of such simulations depends on the reliability of the modeling and of the site characterization.

An aspect which has received surprisingly little attention in the sealing literature is the requirement to prevent repository flooding during operations, from an NRC (radiological hazard) point of view primarily after the first waste has been lowered into the repository, and up to the end of the retrievability period. Among several repository hazard scenarios (that include such aspects as dropping canisters during hoisting, canister failures, etc.), the flooding risk has not been addressed (to my knowledge. I only have a superficial familiarity with these risk assessments). It would appear that the risk of flooding, at least in principle, is a very real one, in light of the numerous floods of mines and of underground construction projects that have occurred in the past, especially in salt mines and in mines and underground construction projects at great depth below the water table. (A large number of papers on water inflow problems in mines and underground structures is included for example in the Proceedings of the SIAMOS-78 conference (Fernando-Rubio, 1978)). Even though it is recognized that repository construction is likely to produce much less ground disturbance than mining, and hence less risk of major water inflows, it is difficult to understand why this issue is not of major concern. Flooding during operations, i.e. with waste in various positions within the repository, clearly could have major implications for direct radiological releases, but even more so for retrieval and repository recovery operations. For this reason, within the context of the present review, prevention of flooding during operations is deemed to be an important aspect of rock mass sealing.

2. Ongoing Sealing Research

Because the need for sealing repository penetrations has been recognized from very early on in most programs for HLW disposal in geological media, sealing studies have been initiated as part of various HLW repository projects. A workshop organized jointly by the U.S. Department of Energy and the OECD Nuclear Energy Agency in Columbus, Ohio, 1980, resulted in a volume of proceedings (OECD, 1980), which provides an excellent overview of the sealing programs active at that time:

- WIPP sealing program

  SNL, Sandia National Laboratory, for laboratory and field testing; subcontracts with S^3 (Science, Systems and Software) for field testing of borehole plugs and data analysis, with WES (Waterways Experiment Station), for grout design, grout characterization, lab testing, field emplacement.

- ONWI sealing program

  Subcontractors PSU, Pennsylvania State University, for grout design, materials studies, durability (longevity) studies; WES, same topics as PSU and also field emplacement; D'Appolonia, for conceptual designs of borehole shaft, tunnel and room seals; Terra Tek, Inc. for laboratory testing of plug performance (hydraulic conductivity, strength) and of drilling damage.

- BWIP sealing program

Woodward Clyde subcontractor for materials studies, laboratory seal testing, D'Appolonia for conceptual design studies, PSU for materials studies.

- German salt sealing program

Shaft and tunnel seal designs, material selection (cement, concrete, earthen materials), characterization, testing.

- Swedish granite sealing program

Precompacted bentonite.

- Canadian granite sealing program

Strong emphasis on minimizing damaged zone around excavations, methods for preventing this zone from becoming a preferential flow path.

Prior to the Columbus, Ohio, 1980, meeting a sealing study had been completed for NRC (NUREG/CR-0495, Koplik et al., 1979), and Contract NRC-04-78-271 had been awarded by the NRC to the University of Arizona with the objective to provide the NRC with an independent experimental assessment of the sealing performance that could be obtained with existing technology.

Since the Columbus meeting most of the above listed sealing projects have been continued, and a large number of reports have been issued on various sealing topics. Because no single centralized information source exists, and because no general meeting on sealing has been held recently, it is not easy to determine the present status of all programs. To the best of my knowledge, the following sealing projects presently are active:

- ONWI: subcontractors as per above. In addition, a contract with Golder Associates requires in-situ testing of at least two plugs in salt. It is my understanding that a major RFP on sealing has been issued several months ago. CSM (Colorado School of Mines) studies on damaged zone around excavations, in hard rock, with emphasis on blasting.

- BWIP: active program on crushed basalt/bentonite powder mixes has been mentioned repeatedly. D'Appolonia has contract on conceptual seal design.

- WIPP: contracts with WES, PSU, D'Appolonia, and in-house.

- Swedish granite sealing: continuing large-scale intensive studies on bentonite (University of Lulea).

- Canadian granite sealing: Ontario Hydro is performing extensive materials characterization studies (has published on bentonite).

- British program: damaged zone around excavations studies.

- German salt sealing program: large in-situ tests planned (possibly in progress by now).

- Japan: cement studies in progress.

- Switzerland: damaged zone studies in progress.

A few references have been included on these programs, selected primarily because they are very recent and provide further references to previous work from these projects (e.g. Langton and Roy, 1983 - ONWI Contract; Garrity, 1983 - British program; Chan, 1982; Allison and Lake, 1982 - Canadian program; Christensen et al., 1982 - SNL Program; Tsunoda et al., 1982 - Japanese program). As stated earlier, it would be beyond the scope of this review to provide a comprehensive bibliography on sealing reports issued within recent years.

3. Information-Research Needs - A General HLW Repository Licensing Needs Assessment

Manmade repository penetrations provide a direct flowpath between a repository and nearby aquifers. If such flowpaths have a detrimental effect on waste containment and isolation they need to be sealed. The detrimental effects can be a consequence of flow into the repository, especially during the operations, and flow out of (or through) the repository, espcecially after waste emplacement has started. 10 CFR 60 requires shaft and borehole sealing.

The first information need that follows directly is an assessment of the sealing requirements, i.e. of the quality of sealing that needs to be accomplished. Such assessments need to be realistic, i.e.

taking into account all waterflow driving mechanisms and potential flowpaths.

Based on past experience in underground construction and mining, it is obvious that repository flooding during operations is a realistic possibility. Several salt mines, underground hard rock mines at great depth below the watertable, and underground construction projects have been inundated (e.g. Kupfer, 1980; Cousens and Garrett, 1970; Auld, 1983). Recovery operations typically are length and costly, and, in the case of mining, frequently have proved economically unjustifiable and hence been abandoned. Repository flooding during operations would present a major obstacle to retrieval. Whether it could present an associated radiological release hazard would require a canister and hydrological evaluation.

Long-term sealing performance addresses two issues, waterflow into the repository and outflow of radionuclide contaminated water from the repository. For the first one, waterflow into the repository, a distinction needs to be made between repositories in salt and repositories in rock not subject to dissolution. In salt, water inflow and resulting dissolution historically is the cause of virtually all salt mine floods and losses. Prevention of water inflow therefore is crucial, at least for as long as retrieval is required. In repositories in rock not subject to rapid dissolution (e.g. basalt, tuff, granite), inflow into the repository or flow out of the repository might or might not have detrimental consequences (e.g. canister corrosion, engineered barrier changes). Determination of whether inflow or outflow will predominate, and over what period of time beyond waste emplacement and permanent closure requires comprehensive site characterization and modeling. For a repository below the water table (in a saturated rock mass), the fundamental laws governing flow are sufficiently well understood, so that modeling should be feasible assuming the site is sufficiently well known, and assuming the thermal-mechanical-hydrological rock mass response can be predicted. For a repository above the water table, the predictability of waterflow towards or away from the repository remains less certain, and consequently, so are the sealing requirements.

In summary, short-term sealing for a salt repository is an essential requirement. For other repositories identifying sealing requirements requires comprehensive assessments. Long-term sealing performance for salt presumably will rely predominantly on salt itself, for other repositories on seals installed in penetrations.

It appears appropriate, for the above reasons, to make a clear distinction between sealing information needs for salt repositories and sealing studies for other (e.g. hard rock) repositories. Additional arguments in support of such a distinction include differences in materials types (e.g. conventional cement vs. brine resistant cement, conventional earthen-clay-rock mixtures vs. brine-saturated clays, etc.).

In order to assess in-situ performance of seals, it is essential to consider the total seal system. Therefore, a comprehensive sealing performance study requires consideration of:

- seal materials
- installation procedures.

  The characteristics (e.g. strength, permeability, porosity) of all presently considered sealing materials (cementitious and earthen materials) depend greatly on the emplacement procedures used. (One of the four major recommendations from the general conceptual design study of a high level radioactive waste repository in a granite formation, Commission of the European Communities, 1982, Vol. 1, Ch. 5, Conclusions and Recommendations, reads "defining and optimizing experimentally the infill material and its placement methods.")

- rock-seal interface

  For most underground plug installations the interface between the rock and the plug is a preferential flowpath, unless it is treated with extreme care (e.g. by means of repeated pressure grouting).

- rock surrounding the seal

  For most underground plug installations waterflow bypass through the rock surrounding the seal is a critical factor, usually the principal determinant of minimum required seal length.

In order for NRC to make a finding as to whether reasonable assurance has been provided by a license applicant that the sealing plans are adequate, it will be necessary to have a data basis confirming that the various items identified above have been addressed satisfactorily. From the research viewpoint, work is ongoing in all of the above areas within the DOE program, as well as in foreign programs, although with a strong emphasis on the first topic, i.e. seal material characterization (permeability, strength, porosity, durability, viscosity, thermal effects, etc.). Within the DOE program two major studies have addressed the last aspect, i.e. the damaged zone around excavations (Kelsall et al., 1982; Montazer and Hustrulid, 1983) and several scoping studies have been performed in foreign programs (e.g. Canada: Jakubick and de Korompay, 1982; Great Britain: Garritty, 1983). Drilling damage around boreholes has been addressed explicitly in an ONWI-sponsored study by Terra Tek, Inc. (e.g. Lingle et al., 1982). The influence of installation procedures has been tested most directly in the at-depth Bell Canyon test (e.g. Christensen and Peterson, 1981), and in simulated laboratory tests (e.g. Lingle et al., 1982), some of which also have included an explicit experimental assessment of interface flow.

It must be recognized that there is considerable overlap between sealing information needs and other aspects of HLW repository research needs. Typical examples include:

- sealing materials and engineered barrier materials studies, especially with regard to theoretical analysis of longevity
- sealing need indentification and overall hydrological performance assessments
- influence of near-excavation rock damage on isolation and containment, on definition of the disturbed zone, and consequences of the damaged zone for retrievability and for canister loading
- salt creep, the essential driving factor for all long-term salt sealing designs, obviously also is a dominant consideration in all other thermal-mechanical aspects of repository design.

4. Experimental Sealing Research - Recommendations for an NRC Program

As outlined in Section 3, fundamental differences exists between salt repository sealing requirements and sealing requirements for non-salt repositories. This distinction will be carried through in this section, describing specific recommendations for sealing research.

4.1 Sealing issues for hard rock (basalt; granite; tuff) repositories

The two main aspects of penetration sealing are borehole sealing and excavation (shaft, tunnel drift, room) sealing. There is some overlap between the two, primarily in such areas as materials characterization (e.g. bentonite hydraulic conductivity, grout-rock interface flow and strength). There also are considerable differences, primarily with regard to size effects, both for the rock surrounding the seals and for the seals themselves, as well as installation procedure differences.

4.1.1 Borehole sealing

The main objective of continued experimental research on borehole sealing is to resolve some specific uncertainty issues that remain associated with borehole sealing:

- influence of installation procedures - channeling, piping - interface flow

  It has been demonstrated that excellent cement plug performance can be obtained (e.g. relatively high interface strength, very low interface hydraulic conductivity) with optimum tightly controlled laboratory plug installations (e.g. Daemen et al., 1983). However, repeated observations have been made of interface problems (primarily channeling or piping) in cement plugs installed within a water column and in bentonite plugs subjected to even fairly modest water pressure gradients. These problems have been observed sufficiently frequently and are serious enough to warrant further study, and to try to develop an improved understanding of how these detrimental effects are induced and hence on how they might be prevented.

- cement drying

The shrinkage observed on the swelling cements used to date when the cements are allowed to dry, especially for extended periods of time (many months) causes the plug-rock interface to become a strongly preferential flowpath. It would be desirable to test the effectiveness of remedial action, e.g. sand-cement mixes, remedial grouting of leaking plugs, etc.

- bentonite/crushed rock mixes

Virtually no experimental data presently is available for this complex and potentially important sealing and backfill material, although some studies are said to be in progress.

- drilling damage on very large diameter (over 9") boreholes

It has been demonstrated conclusively that drilling damage in small holes (up to 7" diameter) is so minor as to be an unlikely preferential flowpath. It is recommended to close this issue by performing a few detailed microscopic studies on rocks from the walls of large drilled holes (12" to 36" range).

- long-term flow testing

Several seals have been tested for several years. It is recommended to continue these tests in order to extend the information thus obtained over the greatest time length possible.

- long-term cement swelling

A reversal in swelling has been observed on all swelling cements tested. This reduction in volume increase has occurred after periods of 1 to 6 months, and also has been observed by Waterways Experiment Station/Sandia National Laboratory Laboratory with a different (linear expansion) test arrangement, during which they also observed a significant hydraulic conductivity increases (Gulick et al., 1980). This strongly suggests the desirability of continued long-term testing of these plugs in order to identify long-term (i.e. multi-year) behavior changes that might occur.

- field testing

A critical issue in assessing borehole seal performance always will remain the difficulty in extrapolating laboratory data to field (in-situ) performance assessments, primarily because of the potentially predominant influence of installation procedures. For that reason it is highly recommended that the presently ongoing field testing program be maintained.

- durability, longevity

For all seal materials, long-term performance needs to be addressed. It is probable that two different time frames need to be considered: up to the end of retrievability, and isolation and containment period requirements. Even the first period is long compared with conventional mining and underground construction. Accelerated testing and theoretical (geochemical, thermodynamical stability) predictions will be required, the latter hopefully backed up by some successful experimental verification.

4.1.2 Excavation sealing

Some of the results of borehole sealing studies are directly applicable to excavation sealing, e.g. mechanical analyses (Jeffrey, 1980; Stormont and Daemen, 1983), material characterization and some material behavior studies (e.g. seal-rock interface flow). Excavations have problems which, if not unique, are sufficiently different from borehole sealing requirements to warrant separate attention.

The problems associated with excavation (shaft, tunnel) sealing that are particularly important are those responsible for the risk of bypass flow around the seals. (Such problems tend to be less severe for borehole plugs because borehole plugs typically are much longer, i.e. many times their diameter). By-pass flow through the rock surrounding the seals is almost universally recognized as the most severe limitation on shaft and tunnel seals (e.g. National Coal Board, 1982; Garrett and Campbell Pitt, 1961; Auld, 1983; Chamber of Mines of South Africa, 1983; Moller et al., 1983; Misslitz, 1960). Any type of excavation sealing performance assessment will have to address the critical and very difficult issue of seal bypass flow. This issue has been identified, for example, in the LBL March, 1984 meeting on coupled thermo-mechanical-hydro-chemical processes (Tsang and Mangold, 1984, pp. 36, 38, 50, 52, 58) and by the Japanese program (Tsunoda et al., 1982). Generic studies on the problem have been issued by D'Appolonia for ONWI (Kelsall et al., 1982), by Garrity (1983) for the British HLW repository program, and by the Canadian program (e.g. Jakubick and de Korompay, 1982; Gyenge, 1980). Additional issues of concern in this context have been discussed in our previous annual report (Daemen et al., 1983, Ch. 10). A study specifically on blast damage has been performed by Colorado School of Mines for the Office of Nuclear Waste Isolation (e.g. Montazer and Hustrulid, 1983). The study by Kelsall et al. (1982) is particularly important in this context, because it has been referenced extensively in pre-license application DOE documents (e.g. BWIP SCR; EA's for BWIP, Richton, Cypress Creek and Vacherie domes - probably in other EA's as well), even though the extreme uncertainty in the conclusions reached by the report is explicitly emphasized by the "Preliminary" first word of the title, as well as repeatedly in the report itself.

A review of the literature on damaged zones around underground excavations makes it unmistakingly clear that extreme uncertainty exists in the predictability of such zones, and the uncertainty is compounded if one wishes to predict specific characteristics of that broken zone, e.g. hydraulic conductivity, even more so in the presence of thermal effects. A few quotes from the recent literature might strengthen this argument. Hoek and Brown (1980, p. 215), in their text, probably the most widely used engineering reference for underground rock excavation design, state about the predictions of failures in tunnnel walls: "This progressive failure process is very poorly understood at the present time and it constitutes a challenging problem for rock mechanics research workers." Garrity (1983, p. ii), in the summary of his review for the British program of the potential influence of a damaged "proximate rock" zone, concludes that "this (stress redistribution) may lead to zones of fracturing and enhanced permeability around the opening... The effect is, however, difficult to quantify, and the extent of the zone difficult to predict."

Although the present review is written specifically within the context of sealing, it is important to recognize that the uncertainty in damaged zone predictions implies uncertainty in a number of licensing issues:

- retrievability
- disturbed zone estimates
- canister loading, which, if due to emplacement hole failure, is likely to be extremely nonuniform
- repository (shaft, tunnel, room, emplacement hole) stability
- rock support or reinforcement requirements and performance
- stress measurements (e.g. exploratory borehole wall spalling interpretation, and extrapolations to shafts, tunnels, rooms, emplacement holes)
- interpretation of in-situ monitoring (e.g. exploratory shaft site characterization)

It is quite possible, therefore, that damaged zone predictions constitute the major rock mechanics repository performance issue. It is clear that such predictions will be complicated further, as compared to conventional mining and tunneling, by long-term thermal, hydrological and chemical effects.

Two sealing issues related closely to the damaged zone around excavations are those of the effectiveness of remedial action (grouting), and of preventive action (rock bolting, internal supports, e.g. shotcrete, steel sets).

Grouting of the rock surrounding plugs or dams in tunnels, mine drifts or shafts always is necessary in order to obtain satisfactory sealing performance (e.g. Auld, 1983; Chamber of Mines of South Africa, 1983; Moller et al., 1983; National Coal Board, 1982), and the results are extremely unpredictable. As a consequence, it is common practice to grout repeatedly, until satisfactory performance is obtained, satisfactory being determined by a reduction in seal bypass flow to an acceptable level. Such a performance assessment is not attractive for a repository, where actual mobilization of the seals is likely to occur only a long time after emplacement, and should be of little benefit in providing numerical input for performance assessments. Moreover, it would seem highly undesirable to allow permanent closure sealing of a repository to depend critically on a procedure frought with uncertainty, and about which fundamental disagreements exist in the technical community, e.g. with regard to appropriate injection pressures, volume rates, materials, etc. A factor of particular concern in this context is the risk for fracture initiation and propagation (e.g. Wong and Farmer, 1973), re-opening, and/or connecting pre-existing fractures, etc. (This risk associated with grouting is identified explicitly by Baar, 1977, p. 87, as one of the probable causes of some salt mine floods). The contradictory requirements imposed on, and the contradictory results (i.e. beneficial vs. detrimental) that can be obtained from grouting are succinctly stated in the Introduction of the paper by Morgenstern and Vaughn, 1963. Grouting of deep shafts has been particularly difficult, and has caused major difficulties, e.g. in Canadian potash mines (e.g. Link, 1971). Specifically within the repository performance context, the issue of fracture behavior under fluid (e.g. grout) injection has been discussed extensively at the LBL March 1984 meeting of the Panel on Coupled Thermo-Mechanical-Hydro-Chemical Processes (Tsang and Mangold, 1984). A comprehensive experimental study of fracture sealing therefore will address directly a major uncertainty in repository performance, and deserves a very high research priority.

Rock bolting is the most likely rock reinforcement method for repository excavations, and, because of the intimate bolt rock interaction, the most likely system to minimize fracture aperture opening subsequent to excavation. Long-term performance of rock bolts clearly is equally important for maintaining opening stability, i.e. for maintaining retrievability. Hence, a detailed experimental assessment of rock bolt performance will address several licensing information needs, i.e. predictability of rock bolt performance at elevated temperatures and for long periods of time - an uncertainty issue which has been raised repeatedly in repository perforamknce discussions, and about which virtually no information is available, effectiveness of rock bolting in minimizing the development of a damaged zone (with all related licensing issues discussed under damaged zone predictability), and effectiveness of rock bolting in minimizing the hydraulic conductivity of the damaged zone.

4.2 Sealing issues for salt repositories

"The mine opening itself is the greatest cause of problems," (Kupfer, 1980, p. 133).

Sealing issues for salt repositories need to be subdivided into two groups, short-term or operational sealing, i.e. up to the time of permanent closure, and long-term sealing, beyond permanent closure, for isolation and containment purposes.

The predominant significance of short-term sealing for salt repositories arises from the fact that salt mines traditionally have been very susceptible to flooding (e.g. Kupfer, 1980; Baar, 1977, pp. 2, 3, 61, 81, 87, 109, etc.). Most, if not all, salt mine floods have been caused by water infiltration along shafts or by accidental penetrations of the impermeable barriers surrounding the salt, either cause being followed by salt dissolution. It is recognized that the development of chemical seals (e.g. Pence, Jr., 1970) and the use of multiple steel liner with bituminous seals (e.g. Eichmeyer et al., 1980) has improved shaft sealing practice considerably. The problem of accidentally breaching the protective aquitards surrounding the salt formations appears to be primarily an engineering, design and operational problem. Avoiding such breaches is essential, because "External leaks, once started, are almost impossible to stop permanently with present technology," (Kupfer, 1980, p. 134). This is the reason why both the German and the Dutch salt repository programs will allow the drilling of only two explatory holes, along the centerline of the shafts, and will allow only two shafts.

The long-term (post permanent closure) sealing for all salt repositories (ONWI; WIPP; Germany) relies predominantly, if not exclusively, upon salt backfill and salt creep, although all programs call also for concrete and earthen (bentonite) plugs along selected lengths of shafts and drifts.

From a technical viewpoint, salt repository sealing needs to address two different aspects:

- sealing of the aquitard surrounding the salt in order to prevent fresh (or unsaturated brine) inflow and consequent salt dissolution and repository flooding
- sealing of the salt formation itself

4.2.1 Salt aquitard sealing

The primary aquitard near most salt formations consists of anhydrite. Hence, anhydrite sealing probably is the most important aspect of pre-closure sealing requirements. It must be recognized, however, that a large variety of sedimentary formations can surround salt, e.g. shale, limestone, dolomite, gypsum, and various combinations thereof. Salt aquitard sealing studies would be complicated further by the fact that the anhydrite-salt interface often is disturbed, and that the aquitard contains a variety of rock types, suggesting that laboratory studies either need to be performed on rather large, hence difficult to obtain, representative samples, or on a wide range of small samples. Shaft penetration sealing problems essentially are large-scale field problems, which are complex and poorly understood, and difficult, if not impossible, to simulate in a laboratory environment. Almost certainly the highest priority in this area should be to try to develop a better understanding of past salt shaft seal failures. To some extent this could be pursued through literature review, but it would be far preferable to make personal contact with people intimately familiar with such failures. (This might be a difficult task.) A parallel line of investigations that could be very productive would be to perform a systematic parametric sensitivity study, by means of computer programs that allow a comprehensive simulation (i.e. including salt dissolutoning, salt creep, water inflow, etc.) of the seal-ground-water interaction around "typical" salt shafts. Such a parameter study could identify conditions particularly susceptible to sealing failures, the physical validation of which, in turn, could be evaluated in laboratory tests.

4.2.2 Salt sealing

Sealing within the repository itself typically relies upon dual or triple seals, including salt itself (e.g. blocks, recrystallized salts, crushed, granulated), concrete plugs and earthen (e.g. bentonite-salt) mixtures. In all cases heavy reliance is placed on the creep and fracture healing characteristics of salt. Considerable uncertainty remains with respect to salt creep predictions (e.g. Nelson and Kelsall, 1984). Given the very short time frame that remains prior to license application, it seems highly probable that any salt license application will have to rely heavily on generic salt creep data, because time will not permit the development of an extensive site-specific data basis. This is a strong argument in favor of NRC developing its own experimental expertise and data in this area, and to start it up as soon as possible in order to maximize the duration over which data can be gathered prior to license application. Conversely, the argument can be made that the need for an independent NRC experimental performance assessment is less acute for salt because several largely independent programs (e.g. ONWI, WIPP and Germany) already are in progress and will further develop independent data bases, while extensive information also already exists from salt mining, the Strategic Petroleum Reserve and other salt storage projects, and fundamental scientific studies on salt. (The first two categories do not include thermal effects.) Given the predominant influence of salt creep on salt sealing, it is clear that any salt sealing study, if conceived broadly or conducted with sufficient interaction with other salt repository studies, will provide assistance in license application assessments of such issues as retrievability and excavation (e.g. emplacement holes, rooms, access drifts, shafts) stability.

4.2.3 Salt sealing research

The two topics separated above, operational sealing and permanent sealing, can be addressed to some extent by a single research project, although they could readily be separated into two distinct ones, with the first one emphasizing aquitard sealing (although not at the exclusion of salt sealing), while the second one could concentrate almost exclusively on sealing of the salt formation itself, assuming all leaks, if any, between salt formation and aquifers with sufficiently incomplete brine saturation to permit salt dissolution can and will be sealed at the time of permanent closure.

4.2.3.1 Literature studies

It is believed that it could be of considerable assistance in license application evaluations if NRC were to have available comprehensive reviews with crisp integrated summaries of several salt sealing aspects:

- salt creep: laboratory, field, theoretical models
- salt healing
- salt shaft sealing
- salt mine failures (shaft and breach failures)

Especially on the first topic, a huge but widely dispersed literature exists. In light of the fact that a license application for a salt repository is likely to rely heavily on generic data, it would seem desirable for NRC to have ready access to available data and analysis procedures (e.g. creep models). It is critical that such an integrated compilation include salt mining engineering considerations. A purely scientific approach is likely to result in an extensive study of halite, whereas repository problems are likely to be due to non-halite inclusions within the salt repository formation.

4.2.3.2 Experimental studies

Conceptually an experimental assessment of salt repository sealing could proceed along lines very similar to those of ongoing sealing studies (ONWI, WIPP, Germany, Canada, Sweden, NRC-University of Arizona contact), i.e. materials characterization, plug testing, for a range of rock types and seal materials, and considering a range of variables, e.g. pressures, temperatures, sizes, etc. Programmatically, such a project is likely to be more extensive than hard rock sealing, because it includes a considerably wider range of materials, because the primary rock to be sealed (i.e. salt) is far more temperature-, pressure- and time-dependent than other rocks to be sealed, and because it is difficult to assess what in-situ dissolution conditions need to be simulated (i.e. fresh water always will cause failure, saturated brine probably only for inadequate sealing materials). A major simplification for salt repository sealing studies, as compared to hard rock repository sealing, is that a damaged zone around excavations, if any, is likely to be self-healing, hence highly unlikely to form a significant preferential flowpath, and probably does not need to be addressed separately.

Testing procedures for salt sealing studies essentially would consist of various types of flow tests on seals installed in salt and in typical aquitard formations surrounding salt.

A representative material list for a salt sealing test program would include:

- rock types to be sealed
  - rock salt, anhydrite (essential)
  - limestone, dolomite, shale, gypsum (lower priority)
  - impure samples, e.g. a rock salt with anhydrite or gypsum stringers, with clay beds (high priority)
- sealing materials
  - in salt: - salt: granulated (pneumatically emplaced), crushed, precompressed blocks, recrystallized (slurried in)
    - cement, concrete
    - earthen materials: clay, bentonite, mixes
  - anhydrite: cement, concrete, (earthen materials?)
  - limestone, shale, etc.: cement. concrete, clay

A typical test program for salt sealing performance assessments would include:

- installation of sealants (plugs, selected from preceding list) in salt core, salt blocks and, preferably, in-situ (salt mines, holes from surface); in anhydrite, and possibly in other representative aquitard materials
- perform flow and strength tests on plugs.

A test program of this type needs to be performed at a range of temperatures, e.g. 40^{o}C (in-situ temperature), 90^{o}C (below steam formation), and possible in a few steps up to maximum repository temperature (250^{o}C-300^{o}C range, but not finalized yet). It needs to be performed at representative in-situ stress levels and water injection pressures (of the order of magnitude of 3,000 psi and 1,000 psi, respectively). Particularly important in this regard is the sequence in which the load application, water injection pressure application, heating, plug installation, etc. are performed. To simulate actual field conditions would be very difficult for salt (unless extremely expensive pressurized core barrel recovery procedures are used) because with all conventional procedures, salt will be stress relieved for some time prior to repressurization in the laboratory. The sequence of test condition applications could, alternatively, be selected to test the plug performance under the most severe conditions, thereby providing a lower bound estimate on plug performance.

5. University of Arizona Rock Mass Sealing Studies

This section describes in detail a continuation or renewed sealing program that could be performed at the University of Arizona in support of license application assessments. The proposed program is broken down in a number of fairly independent topics such as to facilitate a prioritization by NRC, or development of multiple contracts, or grouping of various subtopics.

In light of the preceding discussions, it is suggested that the following might be an appropriately prioritized list of experimental resarch topics that could be pursued productively at the University of Arizona under the direction of the PI. The prioritization is based exclusively on NRC information needs for license application reviews, as perceived by the PI, within his areas of technical expertise.

1. Damaged zone predictability assessment.

   Recommended is an intensive program with high priority because of the major uncertainties in this area and because of its impact on multiple licensing issues, i.e. retrievability, canister loading, repository stability, interpretation of in-situ monitoring and stress measurements (e.g. exploratory shaft site characterization), excavation plugging and rock sealing.

2. Rock mass sealing (fracture grouting).

   An intensive, integrated effort, the recommended option, would address comprehensively the thermo-mechanical-hydrological-chemical behavior of fractures in hard rock, because only such a comprehensive effort can allow definite statements about fracture performance modifications (e.g. in hydraulic conductivity, aperture, extent), whether beneficial or detrimental, that can be obtained through grouting (broadly analyzed as fluid injection).

3. Borehole sealing

3.1 Basalt, granite

It is recommended that a low-level effort be maintained, primarily to permit completion of field work in progress, to resolve some key remaining uncertainties, and to allow extending the previously initiated data gathering effort over a maximum practical period of time.

3.2 Salt

It is recommended that a low-level but long-term laboratory experimental program be initiated to assess experimentally the sealing effectiveness of the most widely proposed sealing materials (salt, cementitious, earthen) in salt and in anhydrite. This would consist of flow testing in heated, unloaded, and loaded blocks or core. In parallel, an effort, literature review, visits to mines, and computer simulation should be initiated to identify more precisely shaft sealing problems in salt. Sealing studies on other aquitards (e.g. shale, dolomite, etc.) should be initiated if they are relied on for any of the potential repository sites selected for site characterization.

4. Rock bolt performance assessment

Rock bolt performance assessment, similarly to damaged zone predictions, is likely to be a licensing issue for a number of related topics, primarily repository stability and retrievability, as well as damaged zone extent and damage severity (i.e. bolting effectiveness), in addition to its significance for rock mass sealing. Primary issues will be performance at repository room temperatures (especially for resin or cement grouted bolts, types most likely to be used) and longevity. Durability (corrosion) data on bolts is very limited. A realistic evaluation would require an extensive program, because it is essential for such an evaluation that the field bolt loading conditions, which are very complicated, be simulated correctly in the laboratory.

The following sections provide a slightly more detailed description of the type of research programs recommended for each of the major topics.

5.1 Damaged zone predictability assessment

A comprehensive study to assess the predictability of damaged zones around underground excavations, and their extent and properties, would consist of four parallel phases:

1. Experimental laboratory studies
2. Theoretical model compilation, integration and further development
3. Literature searches to identify published case studies
4. Field surveys in tunnels and mines.

Because of its predominant significance within the licensing context, this subject is discussed in more detail in Appendix A.

5.2 Discontinuity grouting in polyaxial stressfields

The probability of encountering discontinuities, either natural, pre-existing, or excavation-induced, about underground cavities is extremely high. In order to reduce the hydraulic conductivity of such discontinuities, grouting frequently is applied. (Grouting also can have a considerable stabilizing influence, and is used often for this purpose, for example, in shaft sinking.)

Presently, the state of the art in grouting is largely empirical, and applications by means of a trial-and-error appraoch are very common. If a first round of grouting proves successful, a second sequence is performed, and so on. Moreover, the performance of grouting, especially in fractured rock, remains highly unpredictable, particularly in terms of the final sealing, i.e. reduction in hydraulic conductivity, that can be expected. While such an empirical approach appears to be reasonably satisfactory for many conventional engineering applications, even though it has on occasion caused very large cost overruns, it is highly undesirable for HLW repositories. Even more serious for such a long-term application is the lack in predictability of performance, in particular because of the occasionally very significant detrimental consequences of grouting, primarily induced fracturing.

The experimental work to be performed for this task addresses the problem of predicting the performance of various grouts and grouting procedures in fractured rock. Variables involved are numerous, e.g. grout type, fracture characteristics, (3-D) stressfield and injection pressure. The primary emphasis will be on the testing of cement/ bentonite grouts, because of their well-established durability. Two types of fractures will be studied, artificially created carefully controlled cuts and natural joints. Stressfields to be applied will simulate expected or likely conditions aound repositories. Performance evluation will include distribution studies, displacements during injection, hydraulic conducitivity prior to and after grouting.

5.3 Borehole sealing

The University of Arizona has developed considerable expertise in experimental borehole sealing studies. Numerous reports have been issued and are in preparation, and a number of major uncertainties have been resolved (e.g. drilling damage, cement plug sealing performance - strength, permeability, dynamic loading - earthquake simulation). For these issues an independent experimental assessment has been provided to NRC, confirming or demonstrating performance standards that can be accepted when used in license applications.

A number of issues remain unresolved, and a number of problem areas have been discovered as part of the ongoing research. This includes, in particular:

- severe detrimental consequences of cement borehole plug drying
- interface problems between cement plugs and rock, in particular piping or channeling along the interface.
- field installation and field instrumentation problems
- scaling up to large diameter plugs
- long-term swelling/hydraulic conductivity/interface strength changes
- drilling damage in very large diameter boreholes
- thermal effects
- performance of bentonite/crushed rock materials

A relatively low-level effort would allow closure of some, if not most, of these issues.

5.4 Bolting of discontinuities

Bolting of reinforcement and stabilization of underground structures and mines has been a widespread practice for over three decades. Although many aspects of bolt mechanics are understood, there remains considerable uncertainty about the interaction between bolts and discontinuities, as well as about the most appropriate design approach (e.g. Lang, 1982). In practice this has frequently led to a trial and error approach to bolt utilization (an approach which is almost universal in mining).

Bolting, at least in principle, could be an extremely valuable method for "sealing" the discontinuities within the disturbed zone. This is especially true when relatively rigid fully grouted bolts intersecting weakness planes are used. Several experimental studies of the interaction between bolts and discontinuities have been performed (e.g. Bjurstrom, 1974; Haas et al., 1974,5,6,8). Such experiments have provided considerable insight in the strengthening mechanisms obtained by rock bolts. They have, however, been quite limited in terms of the range of external loading conditions. Moreover, relatively little attention was paid during these experiments to the normal displacements or aperture changes, a crucial aspect of the sealing performance of bolted rock discontinuities.

The experimental work to be performed will have as its primary objective a detailed study of the sealing performance that can be accomplished by bolting across discontinuities. Clearly, this aspect can not be separated from the reinforcing effect that can be accomplished by means of rock bolts, because the strength, and especially the stiffness, of the bolting system has a direct bearing on the normal displacements (separation and/or closures) during various load applications.

The experimental work will consist of bolting across discontinuities (natural or man-made) intersecting rock blocks, loading and/or unloading the blocks in various polyaxial configurations, while monitoring displacements at multiple positions on the block, strains in the bolt(s), as well as discontinuity apertures. The latter will be measured directly as well as indirectly (e.g. by means of air (gas), fluid (water) and grout injections).

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Appendix A

Damaged Zones about Underground Excavations

A.1 Introduction

The concept that a damaged zone develops around tunnels and shafts has long been accepted as one of the fundamental aspects of the stability analysis of tunnels and shafts. Only recently has the disturbed zone received attention from the point of view of its influence on rock mass isolation capacity. Aside from nuclear waste isolation, where this aspect could be of primordial importance, but where to date very little experimental work has been performed on the topic, the problem has received attention mostly in the context of various underground storage facilities (e.g. hydrocarbons, compressed air, water, sewage). Although this provides very valuable information from a generic performance prediction point of view, it must be recognized that significant differences exist with HLW repository performance assessments. First and foremost, the performance criteria for conventional storage are unlikely to be satisfactory for a HLW repository. Secondly, engineering methods commonly used for conventional storage isolation are unlikely to be acceptable for HLW repositories (e.g. depressurization to assure water inflow, guaranteeing no outflow, or vice versa; semipermanent and continuous pumping and ventilation). Thirdly, overall performance is monitored and determined, usually not detailed separate aspects.

It is proposed that a major project be initiated, within the rock mass sealing context, to establish a solid data basis on damaged or disturbed zones about tunnels. Such a project would consist of a survey to gather factual information about "representative" damage zone thicknesses, damage intensity, its direct influence on potential flow-path development and its indirect influence as a consequence of its effect on opening stability. While the topic has been debated and analyzed theoretically at length, there exists a surprisingly small readily accessible and reliable factual data basis. As a consequence, it is extremely difficult to asses in sufficient detail what is likely to happen around underground excavations.

The proposed study would consist of three major phases, which can progress simultaneously: an in-depth review of past experience, and in-situ measurements and detailed laboratory testing.

A.2 Review and Integration of Past Experience: Development of an Empirical Data Basis.

Although very limited direct damage or disturbance information is available, numerous indirect measurements have been made that provide insight in the extent and intensity of damage about underground excavations. This includes in particular some direct measurements of damage induced by blasting, measurements of stress states about underground excavations, measurements of differential displacements (e.g. borehole extensions and contractions) around openings, grouting intakes, air permeabilities, etc. These types of measurements provide, at least, an indirect indication about where rock mass volume increases (relaxation), discontinuity separations (aperture increases) and fracturing are likely to have occurred.

Even though such measurements have been made frequently, a number of serious difficulties are likely to be encountered with the interpretation and integration of the results. The published data usually are incomplete, because frequently only "typical" or "representative" data are presented. Especially back-up information, e.g. stressfield, rock mass structure, lithology, tunnel support method and installation procedure, excavation methods, often will not be available. Hence it might be desirable to try to gain access to (internal) company or agency files, with attendant difficulties.

In conventional practice field measurements are most likely to be made when severe construction problems are expected or encountered. As a consequence an empirical data base developed from past experience is likely to be biased towards poor quality rock masses, rock which in principle should be avoided for HLW repositories.

It might deserve emphasis that a simple computerized literature search or bibliography, although an essential first step, will not provide an adequate data basis. Considerable interpretation will be necessary to translate raw but indirect data into a useful predictive tool for damage assessment. With all the expressed reservations, it is believed that such an empirical data basis would be of considerable help to NRC in evaluating the likely development of disturbed zones about proposed repository excavations.

The presence of a damaged zone around repository excavations has several regulatory implications within the 10 CFR 60 context. The rules require direct demonstration of isolation feasibility, including "an analysis of the expected performance of the major design structures, systems and components" (10 CFR 60.21.c.1.ii.D), a repository "designed so that the entire inventory of waste could be retrieved on a reasonable schedule" (10 CFR 50.111.a.2), "to provide for structural stability" (10 CFR 60.132.a.2), "orientation, geometry, layout ... enhance containment and isolation ..." (10 CFR 60.132.3), and particulary the explicit design requirements in 60.132.e.1,2,3. An improved understanding of borehole failure development would allow a much better estimate of canister loading. A specific example of the application of damaged zone development would be an interpretation of the borehole wall spalling observed at BWIP. Finally, a clear understanding of failure development will be necessary for an adequate interpretation of field measurements, e.g. in the exploratory shaft test facility.

These are extensive requirements, justifiably imposed on the repository design. It must be recognized, however, that detailed design of underground facilities prior to at-depth site exploration on a large scale remains very difficult. It is likely, therefore, tha decisions on feasibility will have to be made within the very short time between initial full-size excavations at repository depth and initiation of construction. For this reason it would be highly desirable for NRC to develop the state-of-the-art of underground opening design to the fullest. This would include, in the first place, a comprehensive summary of the present knowledge about damaged zones around excavations, interpreted from an isolation performance viewpoint. Preferably it should be accompanied by experimental work to verify various existing theoretical models for predicting tunnel stability, support requirements and failure modes.

A.3 Laboratory Assessment of Damaged Zone Predictability

Task 1. Rock Failure About Underground Excavations

It has become customary in the Nuclear Waste Disposal literature to refer to the rock directly around an underground excavation as the disturbed zone. In more conventional geotechnical practice this zone usually is referred to as the plastic zone, broken zone, failed zone, stress-relieved zone or relaxed zone. It refers to the zone immediately surrounding an excavation, where the rock has been damaged by excavation (blasting) or by excessive stress concentrations. An extensive literature exists on the topic, to which the principal investigator has made several widely quoted contributions. A comprehensive review of theoretical work prior to 1975 is given by Daemen (1975), while Detournay (1980) includes much of the more recent work. A very comprehensive survey of one analytical tool for predicting damaged zones, ground response curves, has been published by Brown et al. (1983). An extremely large number of numerical analyses (e.g. finite elements, finite differences, boundary elements, discrete elements) have been published, but virtually no, if any, systematic comparisons between such theoretical predictions and measured damage. Most of the literature deals with theoretical derivations, and relatively little experimental work has been performed in this area, certainly entirely insufficient to allow an adequate verification of various (at least partially contradictory) theoretical models. An extensive review of the implications of the disturbed zone for potential radionuclide release from a HLW facility is given in Appendix A of D'Appolonia (1981). Examples of laboratory experimental work on the determination of the disturbed zone are Gay (1973 and 1976), Heuer and Hendron (1971), Hobbs (1966), Hoek (1965), Krauland (1970), Senseny and Lindberg (1979 - referenced by Lindberg, 1982), Wallace (1973), York and Reed (1953), Daemen and Fairhurst (1970). Most of this work deals with the failed zone from a stability point of view only, without considering the permeability change consequences. Moreover, most of the work is limited to a relatively small number of specific cases, generally within a fairly narrow range of parameters.

The primary purpose of this task is to allow a careful detailed study of the development and characteristics of the broken zone, and of its consequences for opening stability. This topic, although primarily directed towards identifying whether such a disturbed zone could become a preferential migration path for radionuclides, will inherently lead to conclusions about the stability of openings in rock.

Research will be conducted by performing polyaxial testing on rock blocks and/or artificial rock simulating materials that contain excavations. A testing facility of this type should allow tight control of applied stresses and/or displacements, as well as comprehensive monitoring of strains and displacements, i.e. reaction of the structure.

Task 2. Influence of Discontinuities on Damaged Zones around Underground Rock Excavations

The preceding task will concentrate on the performance of excavations in intact rock. That topic is important because it is likely that plugs (seals) will be installed in the best possible rock formations. Nevertheless, it must be recognized that in virtually all rock masses the behavior of underground structures is strongly influenced, if not dominated, by the presence of discontinuities or weakness planes.

Similarly as for intact rock, there have been considerable developments in the development of theoretical analysis and design methods during the last decade (e.g. Crawford, 1982; Goodman et al., 1973; Goodman et al., 1982; Hoek, 1977; Hoek and Brown, 1980; Shi and Goodman, 1981; Voegele and Fairhurst, 1982) which have not been accompanied by an increasing effort to confirm and/or verify these stability calculations by experimental validation.

A considerable body of literature deals with results of laboratory experimental work on the influence discontinuities have on underground excavations (e.g. Goodman et al., 1973; Hendron et al., 1972; Lindberg, 1982; Wallace, 1973). This valuable work will be reviewed in detail as part of the proposed sealing study. It is clear, however, that past work was concerned primarily with stability, to a lesser extent with displacements. To our knowledge, none of these investigations have addressed directly the consequences of discontinuity displacements for permeability changes (almost certainly permeability increases) within the disturbed zone about underground excavations in discontinuous rock.

Although several field studies have provided some data (e.g. Daemen and Fairhurst, 1977; Okliewicz et al., 1979; Montazer et al., 1982) it is clear that field work, very expensive and time-consuming, while being an essential verification step, does not allow for wide-ranging parametric evaluations.

While the primary focus of the proposed work is radionuclide isolation, this aspect can not be separated from instability, or at least large displacements.

The work proposed for this task will consist of polyaxial testing of rock blocks that include simulated excavations as well as discontinuities (artificial or natural). Tests will include comprehensive strain and displacement monitoring, as well as collapse observations. Back-analysis will consist of comparing the results with a variety of theoretical models such as the ones cited above. Because the primary purpose of the study is to assess the influence of the "disturbed" zone on sealing, particular attention will be paid to the aperture along discontinuities, as a function of applied stress and resulting displacements. This will be complemented by direct flow measurements.

All experimental work to be performed in the proposed testing facility will be static, although dynamic simulations are a refinement which will be considered, primarily because it might provide an improved understanding of failure mechanisms. The basic equipment could be modified accordingly, but at a considerable cost only.

This work can proceed in parallel and concurrent with Task 1, because sample preparation and testing can proceed independently, and will be performed by different people. Clearly this parallel approach will result in optimum utilization of the equipment, because it will allow alternate use.

A.4 Experimental Field Survey

In order to complement the data from the recommended literature survey, especially with regard to detail of observation and with regard to representativeness of good quality rock masses most likely to be used for HLW repositories, it is recommended to initiate an experimental field survey of disturbed zones about existing shafts and tunnels. Such a survey would consist of detailed in-situ determinations of the disturbed zone and of its properties, in extensive sections of tunnels (and shafts wherever possible).

The experimental field survey should include:

- surface methods (i.e. from tunnel or shaft, without drilling: seismic refraction surveys; radar surveys; structure mapping; etc.)

- borehole methods, i.e. in and from holes drilled to a depth of at least three times the largest cross-sectional dimension of the tunnel and shaft: core and hole mapping and logging; cross-hole and in-hole seismic surveys; stress measurements; radial deformation jacking measurements; water, air and grout injection measurements; strength, modulus, density testing of core.

Gaining access for such projects unquestionably will be a serious problem. Ideally, they should be performed in tunnels under construction (this is essentially impossible in shafts). Great care will have to be excercised to locate "representative" situations, e.g. with respect to rock type, stressfield, excavation method, support method, etc. Perfect matching of a repository is not possible and not necessary, but neither should the differences be excessive. Ideally, a fairly broad range of conditions should be covered.

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