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Comparative Study of Rock Support Systems for a High Level Nuclear Waste Geologic Repository in Tuff

(Interagency Agreement NRC-02-80-075)

U.S. DEPARTMENT OF THE INTERIOR ★ BUREAU OF MINES ★

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DENVER RESEARCH CENTER

COMPARATIVE STUDY OF ROCK SUPPORT SYSTEMS FOR A HIGH LEVEL NUCLEAR WASTE GEOLOGIC REPOSITORY IN TUFF

PREPARED FOR THE U.S. NUCLEAR REGULATORY COMMISSION
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BY

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EXECUTIVE SUMMARY

At the request of the Nuclear Regulatory Commission (NRC), under Interagency Agreement NRC-02-80-075, the U.S. Bureau of Mines (BOM) conducted a study to:

a) describe the state-of-the-art of underground rock support systems that may be applicable in high temperature repository environments,

b) describe relevant high temperature ground support experience in underground mines, especially in tuff,

c) describe candidate site geologies based on a critical review of available literature,

d) describe repository ground support system options and thermal interaction effects using simplified scoping calculations,

e) present a comparative ranking of candidate systems,

f) describe data base deficiencies, and

g) recommend future research.

Significant advancement in rock support technology has been accomplished by the application of high-strength metal in rock bolts and steel sets, and concrete in entry linings. The development of cement and resin grouts to maintain rock bolts in position and provide improved bonding to the rock is another area of significant advancement. Special cement-based grouts can withstand high temperatures and not lose bonding strength. Concrete can withstand high temperatures without significant strength reduction. In addition, installation procedures and special application techniques have been developed for unusual ground conditions. Rock support state-of-the-art is presented in Appendix 3.

Experience at mine operations and research facilities around the world has not produced data specific to rock bolts or other support systems performing in an elevated temperature underground mine environment, as discussed in Appendix 4. Some research into high temperature underground environments has been performed; however, the research did not focus on rock support. Similarly, mine fire accident investigations have not produced specific rock support data and information that could provide complete analysis of support effectiveness. Rock temperatures at operating mines have not exceeded approximately 55° to 65°C (130° to 150°F); this temperature range is significantly lower than the temperature predicted for emplaced canister surfaces, approximately 200°C.

Substantial geologic data exists regarding each repository region. The data is based primarily on information from nearby off-site locations where rock samples were obtained from selected horizons. In addition, upcoming site characterizations will provide horizon-specific rock physical property data. A review of pertinent geologic data is presented in Appendix 5.

In addition, limited information has been developed to determine the effect of high temperatures on the physical and geologic parameters of the rock. It is not known if, or how much, physical properties of horizon rocks will change when subjected to high temperatures. All scoping calculations performed were based on rock properties at ambient temperature. If higher than ambient rock temperature is used, the calculations may be affected significantly.

This report presents analyses of specific ground support systems within a postulated, but previously undeveloped, thermal environment. Verification of the lack of previous information and experience in these areas is presented in Appendix 4.

One of the first tasks performed was to develop a rock mass heat transfer description. This description, referred to as the "thermal pulse," was developed by integrating DOE isotropic-homogeneous rock mass heat diffusion models and BOM developed fractured and layered rock mass heat flow postulates. The resultant integration identified the potential for anomalous and reversible heat flow. Anomalous heat flow, called "hot spots," were further identified as potential sources of disruptive rock mass expansions. These rock mass expansions were estimated to impart, depending on the extent and nature of rock mass fracturing, a wide variety of support system tensional, shearing, and torquing loads. The thermal pulse was also recognized to potentially transfer heat in all directions from the canister equally. This orderly heat transfer mode was estimated to adversely effect bolt anchorages due to drill hole deformation, and bolt effectiveness, due to differential thermal expansion.

Geochemical compatibility of support system materials was identified as a prerequisite to the long-term stability of underground excavations. A support systems corrosion overview is presented in Appendix 2.

Ground control programs are partly based on analyses of the in situ stress conditions and the stress redistributions expected to occur as an opening is created. Overburden stress redistribution around repository openings, and other stresses not accounted for in conventional theory that may result from high temperature zones in the repository, create the possibility of a stress superposition near the canisters. These other stresses could be the result of stress focusing, as depicted by the "pressurization" theory presented in Appendix 1. When stress field focusing is further expanded to include the potential for seismic, dynamic wave, focusing, an additional repository ground stability and support system integrity problem is created. The near canister stress field condition is also important in identifying the potential for creating new fractures, propagating old fractures, and subsequent ground support system effects.

The lack of horizon-specific geologic data, and the uncertainty of stress redistributions in the vicinity of a physically continuous but thermally discontinuous rock mass, did not prevent an investigation of potential thermal pulse and support system interaction effects. The lack of information did, however, greatly limit the assessment of the probability that a given effect would occur.

This report creates differential thermal expansion assessments of support systems in the medium-field rock mass, which identified potentially adverse effects on support system materials. Medium-field, as used in this report, refers to underground excavations 100-250 ft. distant from an emplaced waste canister. The calculations simplify the interaction between a thermal pulse and a ground support system; therefore, the calculations scope, rather than define, the problem. Although bolt-yield and shear failures between the grout and rock are predicted to occur by the calculations, the failure margins are small and indicate that minor design modifications in the support systems may prevent failure.

All aspects of the project were incorporated to create a support systems comparative ranking. The accuracy of this ranking should be understood to be no greater than the weakest of the component parts, i.e., the uncertainty of geologic and geothermic rock mass response data. The comparative ranking refers principally to support system characterizations in the following areas:

- Corrosion susceptibility
- Anchorage stability
- Thermal pulse adaptability

Support system components were assessed and recombined into systems more adaptable to thermal pulse environments. The results of the performance assessments, ranked in order of decreasing long-term effectiveness, were:

1) Continuous, high strength, linings, which include lagged steel sets
2) Cable bolts with long grout anchors
3) Mechanical point anchor bolts with spring loaded bearing plates
4) Long grout anchor Helical bolts
5) Long grout anchor Conway bolts
6) Long grout anchor, rigid, steel bolts
7) Full column grouted bolts
8) Long grout anchor roof trusses

The exposed steel portions of all of the above systems were presumed to be coated or sleeved to resist corrosion.

A wide range of potential rock mass responses to a thermal pulse was developed in the report. The adequacy of support systems under these conditions was reviewed. Deficiencies in horizon-specific geologic data and the lack of knowledge regarding the rock mass geothermic response are noted. Corrosion was identified as an ever present potential problem even in the fairly dry conditions at the site. The development of ground control systems with a high probability of providing adequate support in a thermally pulsed rock mass for a 100-year repository operating life requires further research. Accordingly, the following research recommendations are presented:

1) The stress redistribution process for the repository should be modeled numerically and evaluated in the laboratory. This work should be designed to evaluate the "pressurization" stress focusing theory described in Appendix 1, and quantify, wherever possible, the static and seismic stress effects on the rock mass. Initially, the effects of stress on a simplified, isotropic-homogeneous heated rock mass should be evaluated. Following this evaluation, stress responses for more complex rock masses should be examined. Associated heat transfer variables should also be identified.

2) Rock bolt anchorage investigations are required. Specifically, possible anisotropic expansion and contraction of a thermally pulsed drill hole in a rock mass should be quantified, shear effects in the bolt anchorage from differential thermal expansion should be examined, and selected rock properties and bolt pull-test measurements should be thermally calibrated. These baseline data should then be used to develop a more complete description of the interaction between a thermally pulsed rock mass and bolt ground support system. Where appropriate, internal thermal gradients and stresses on support system

components should also be quantified. Thermal gradients and stress differences within the support systems are the more probable field conditions. The differential contraction effects from blast cooling should also be evaluated.

3) A support materials corrosion study is required for the specific geochemistry of the rock mass. Corrosion rates of support system materials should be quantified, and optional methods to protect support materials by coating or sleeving should be identified.

4) An integration of all support system design parameters in a thermally pulsed repository is required. Corrosion, anchorage effects, thermal gradients, and rock mass thermal response should be combined to prioritize conventional ground support systems suitable for use in a geologic repository. Where appropriate, support systems or system components should be redesigned to provide support hardware more adaptable to a thermal pulse. Emplacement drift ground support problems are similar to medium-field entry ground support problems; however, the problems may be potentially more severe because a considerable increase in temperature, and differential temperature effects may occur. The integrated support system research effort would provide improved understanding of the ground control problems that may occur during retrieval of the waste canisters.

INTRODUCTION

At the request of the Nuclear Regulatory Commission (NRC) the U. S. Bureau of Mines (BOM) has conducted a study to report on the following:

a) describe the state-of-the-art of underground rock support systems that may be applicable in high temperature repository environments,
b) describe relevant high temperature ground support experience in underground mines, especially in salt, tuff, and basalt,
c) describe candidate site geologies based on a critical review of available literature,
d) describe repository ground support system options and thermal interaction effects using simple scoping calculations,
e) present a comparative ranking of candidate ground support systems
f) describe data base deficiencies,
g) recommend future research, and
h) present an executive summary.

The effort was technical; cost considerations were not a factor in ranking the support systems.

OVERVIEW

Ground Control Theory

The first objective of ground control is to reestablish and maintain the structural integrity of a geologic mass where the natural mechanical equilibrium has been disturbed. Current rock support methods result from a combination of theoretical considerations, site-specific geologic knowledge, and a review of trial and error empirical studies. Variables, such as lithology, geology, physical properties, and in situ stresses, combine to yield broadly bounded, non-standardized solutions.

A pressure arch naturally occurs in the rock mass around an underground opening. The arch is a consequence of redirected stress. The redirected stress field compresses a zone of confined rock around the periphery of the opening, which directs vertical and horizontal loads around the opening.

The most straightforward method to control ground failure is to create openings that are inherently stable by virtue of their geometry. In a uniform stress field the inherently stable geometry is circular. A circular opening in an isotropic, homogeneous, rock mass will uniformly strain relieve and allow equal stress redistribution within the surrounding rock mass.

When a high horizontal in situ stress condition exists, i.e., the horizontal stress is at least twice the vertical stress, the uniform strain relief geometry in homogeneous, isotropic rock is an appropriately oriented ellipse. The shorter radii ends of the ellipse are aligned in the maximum principal horizontal stress direction, and the longer radii are oriented in the lower principal horizontal stress direction. Thus, the uniform strain relief criteria are met, and the compressed zone of rock surrounding the opening supports an increased load.

Where vertical loads are significantly greater than horizontal loads, a further variation of opening geometry to that of an upright arch is indicated. The arch variation of the elliptical shape is preferred because vertical loads create horizontally oriented forces with a magnitude of about one third the vertical load. The shorter radii of the top of the arch limits displacement in the highly loaded area, while the lesser curvature of the sides of the arch is subjected to lesser forces. A uniform strain relief is again achieved.

Adequate rock competence is a prerequisite to ground control planning based on geometry alone. If rock is not competent, geometry can be complemented by artificial support to improve stability. A number of theories exist on the mechanics of rock behavior, and a wide variety of hardware is available to implement the theories.

The most common means of artificial rock support currently used in underground workings is the rock bolt. Four basic bolt support theories have been developed, each based on mechanical engineering principles. These theories propose that bolts achieve improved ground control through suspension of loose rock from more competent geologic members, multi-layer beam building, column reinforcement, or block keying.

A bolt suspension system supports sidewall or top rock by anchoring loose surface rock to deeper competent rock. See Figure 1.

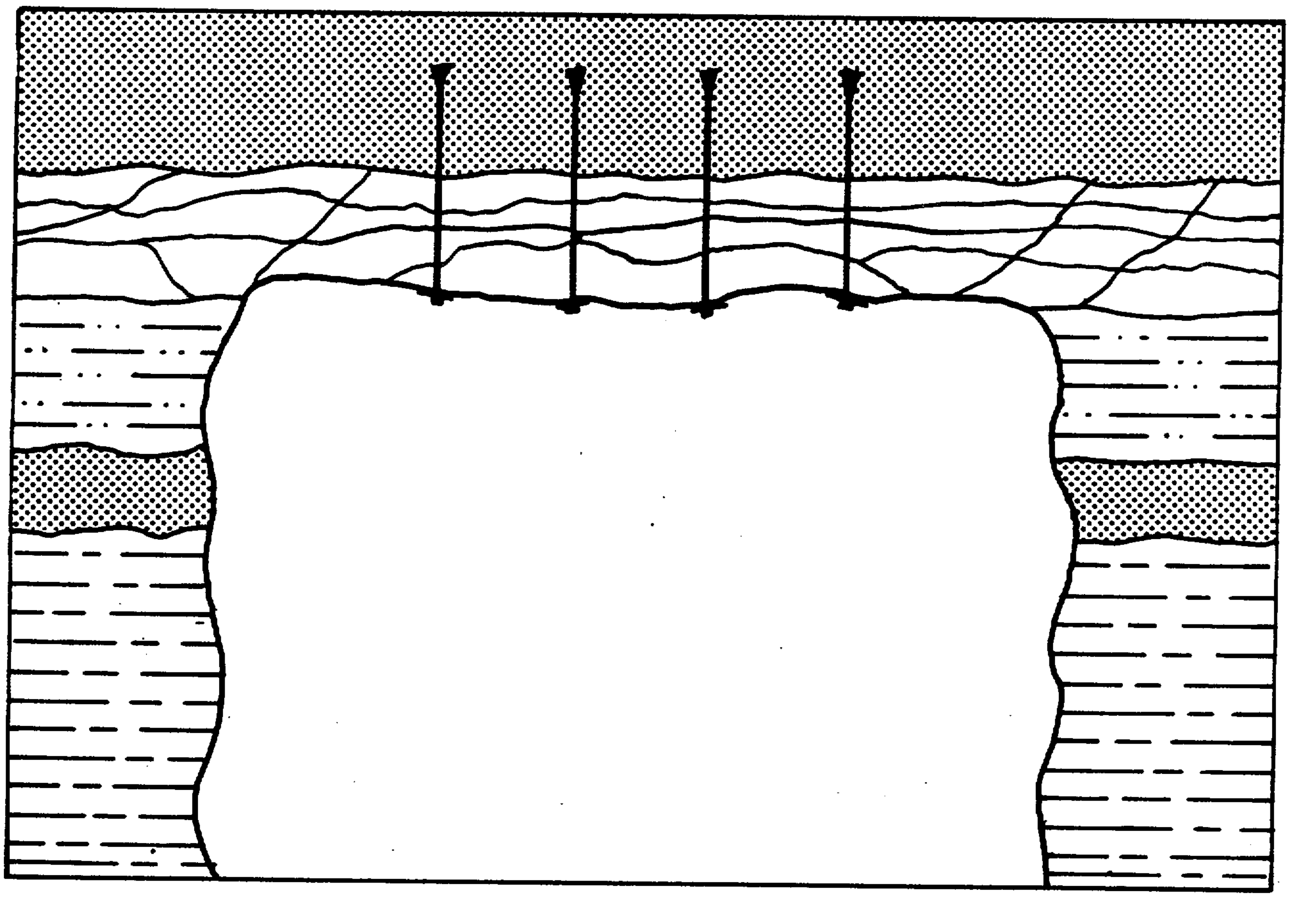


Figure 1. Suspension rock bolting

The beam building support theory increases the integrity of a laminated rock structure by unifying several laminated layers into a single beam-like member by bolting the discrete units together. The enhanced strength of laminated layers bound together is a well established mechanical principle. See Figure 2.

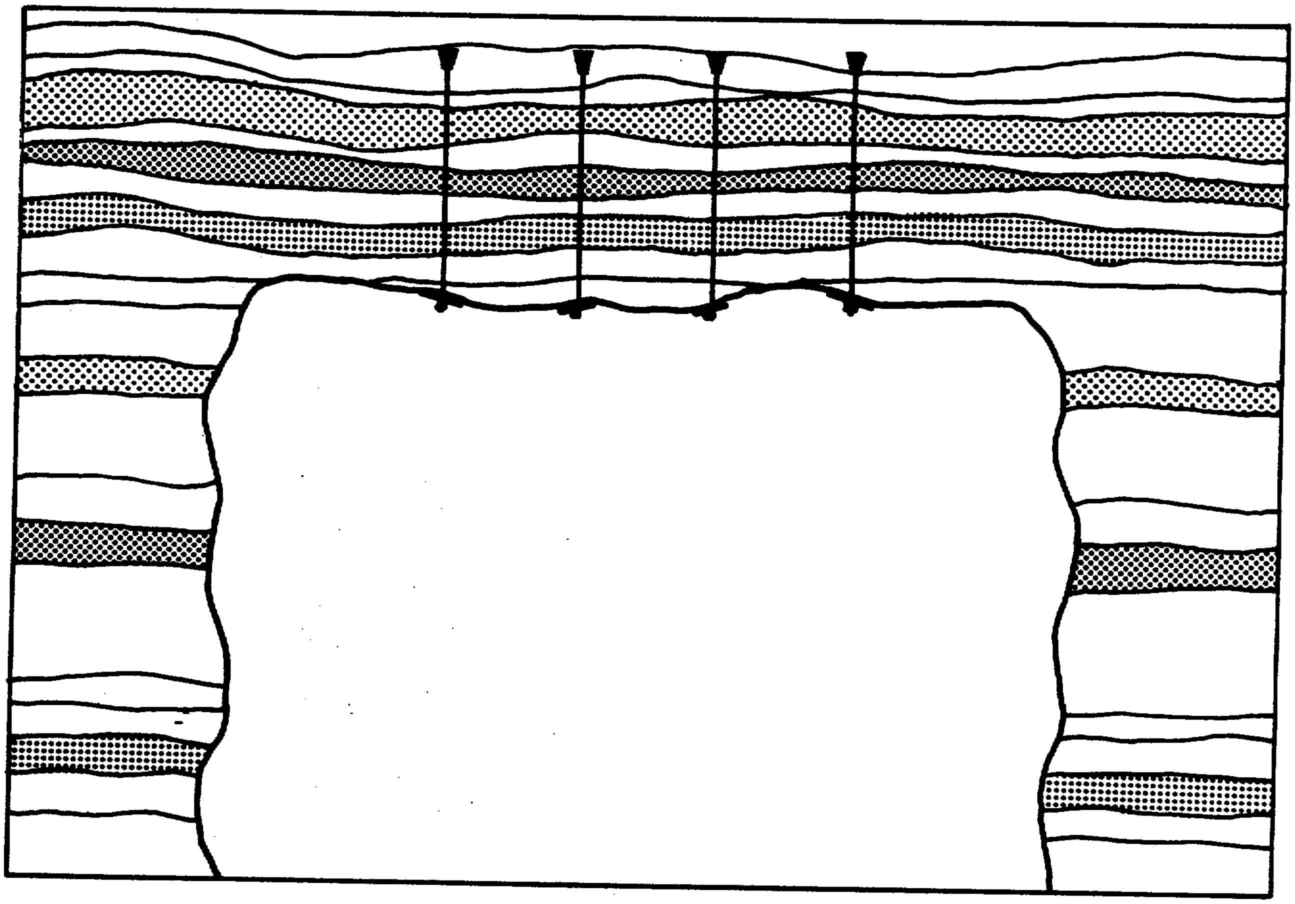


Figure 2. Beam Building Rock Bolting

Column reinforcement bolting, in practice and appearance, is identical to beam building. The distinction between theories lies in the presence of a sufficient in situ horizontal stress field to cause the bound rock laminations to respond as an axially loaded, horizontally oriented, column. The objective of binding the laminations into a structural unit is to create a horizontal column of sufficient cross section to prevent buckling failure.

Block keying was developed to secure blocky, fractured rock structures where a single block falling out of position leads to collapse of a whole system. The bolt is installed so that bolt length and angle of penetration will bind together blocks of rock and form a structurally competent unit of discrete, interlocked, sub-units. See Figure 3.

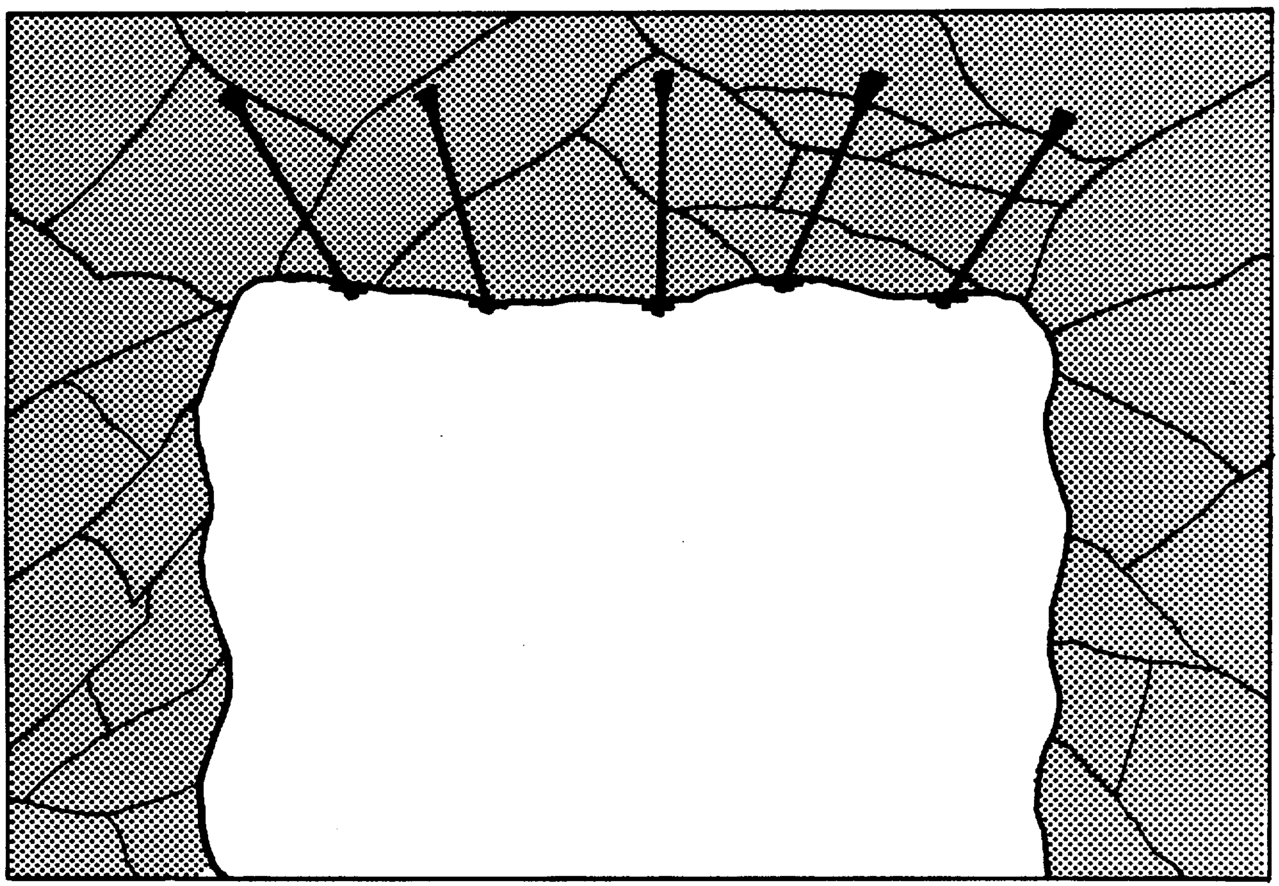


Figure 3. Keyblock Rock Bolting

Tensioned bolts form a zone of compression by overlapping individual compression areas created by each tensioned bolt. The artificially induced pressure zone is effective for both roof or full circumference support. See Figure 4.

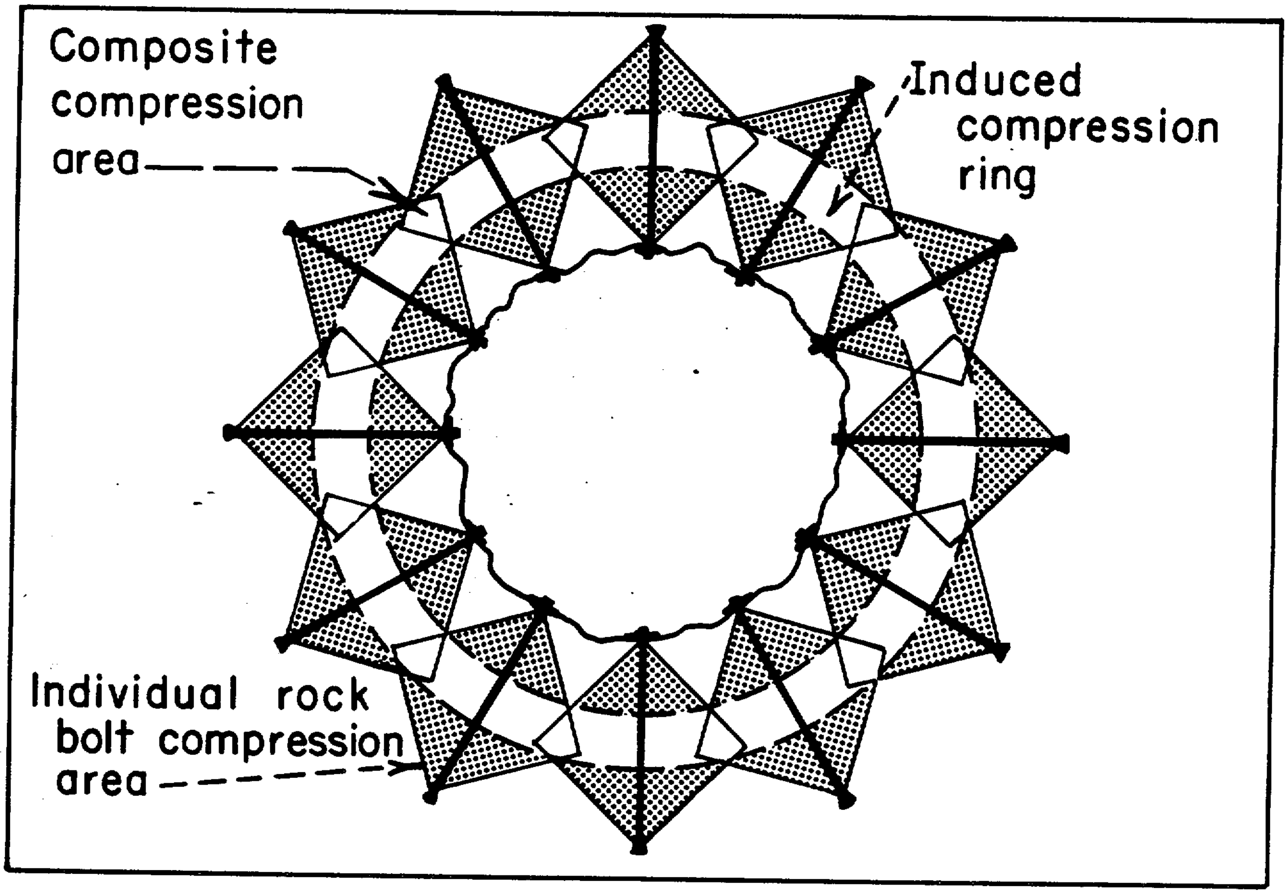


Figure 4. Rock Bolts in Tension

Artificial support may also be obtained with posts. The post base is normally positioned on the floor of the opening; the roof is supported by securing the top of the post to the roof with a cap block and wedges. This system is useful not only because of the support provided, but also because increasing load can be observed in the degree of destruction of the post. Another similar support method is the crib. Cribs are log cabin style stacks of squared lumber or concrete in contact with the floor and roof. Observation of their condition can sometimes indicate increased loading.

In some underground openings, yieldable supports are used when loading conditions are sufficiently intense that it is impractical to attempt to restrain all displacement. Yielding of the supports is essential to maintain control of opening displacements that could cause failure of a rigidly fixed support system. Half-section, nested, steel arches, which are designed to yield in a controlled manner at a predetermined load, are examples of this type of support.

Induced bonding is another type of artificial support where a rock mass is internally strengthened. Cohesion is created in the rock mass by high pressure injection of cement or resin grout through strategically located drill holes. The grout mix is forced to migrate into fracture voids, creating a bonding matrix to secure broken rock. In situ freezing of water-earth-rock compositions is another induced bonding technique. Moisture in the ground crystallizes during freezing and creates load resistent cohesion where lubricated sliding planes were previously present. This approach is sometimes the only feasible solution to excavate extremely wet, unstable ground.

One approach to ground control that is neither an artificial nor natural support method uses stress redistributions at engineered inclusions. An inclusion is defined as a mass with certain physical properties that is fully enclosed in a larger dissimilar mass. The physical property of principal interest relative to the two masses is stiffness. Inclusion stiffness may range from zero in an air-filled void, to the upper limits of stiffness available through state-of-the-art materials science. The effectiveness of the method derives from an optimized interplay of relative stiffness, location, and geometry to create the "engineered" inclusion. The best example of the technique, where a "soft" inclusion is created in a rock mass, is the drilling of destressing drill holes over drifts in the heavy overburden in the Coeur d'Alene, Idaho mining district. Soft inclusions divert load from the immediate vicinity so that drifts can be developed under the inclusion "umbrella" where only a portion of the original overburden induced stress field remains. The same effect could theoretically be created by the formation of a series of hard inclusions created by high pressure injection of a stiff material in areas adjacent to a proposed entry. The highly loaded inclusions relieve the natural stresses in local rock and create an "umbrella" similar to that formed by the drilling of destressing drill holes.

Each approach to ground control may be used alone or in conjunction with any of the other approaches. The principal factors in selecting an approach include opening size and geometry, life of opening, geology, depth of workings, excavation method, and rock mass alterations such as air slaking and groundwater drainage. High in situ stresses acting in a predominant direction may require mine-wide orientation of the workings to minimize exposure of ribs to the maximum principal stress direction.

General Background

Repository designs are presently conceptual in nature. Proposed entry geometries and thermal loadings vary significantly between literature sources (1). In recognition of repository design uncertainties, a literature evaluation has been updated with state-of-the-art repository design descriptions by knowledgeable personnel (2). This aided in development of a simplified repository construction and operations overview.

The development of overview thermal pulse descriptions, ground support system interactions and comparative rankings was based on probable and worst case interaction descriptions. That worst case conditions are described does not imply these conditions are expected to occur. Rather, extreme system interactions were analyzed to develop boundary conditions by which the adequacy of support systems were tested.

The development of "thermal pulse" factors, such as the thermal coefficient of expansion of a fractured rock mass, should be empirically derived and integrated with existing theory and practice. "Thermal pulse," as used throughout the report, is defined as the rock mass temperature change associated with the dispersal of canister generated heat.

Very little literature or experience exists that is pertinent to the ground support problem in a thermally pulsed rock mass (see Appendix 4).

A geologic repository will be designed to include a secure, 100 year, access; other activities include waste canister emplacement and engineered backfilling (3). Observation of repository performance, and, if warranted, retrieval of the waste, are also potential activities.

Principal accesses, including shafts and main or sub-main drifts, are best maintained by minimizing extraction of adjacent ground and providing continuous linings to resist overburden weight and thermal pulse effects. The main and sub-main drifts are estimated to receive moderate thermal pulses of 30-50°C above ambient temperature at the rib during a 100 year operating lifetime (2). Figure 5 provides a general repository underground design and selected terminology (1, 4).

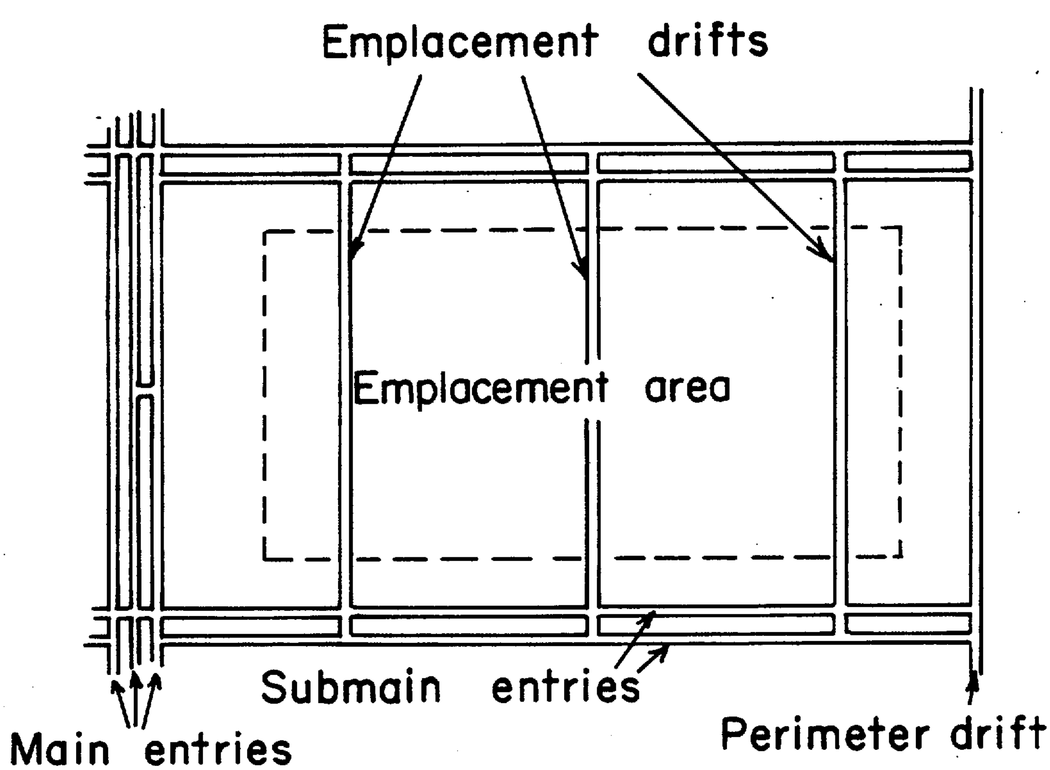


Figure 5. Undimensioned Repository Layout (1)

Immediate, temporary ground support may be required in the emplacement drifts prior to waste canister placement. Emplacement drifts are planned as short duration openings and scheduled for "immediate" backfilling (2). However, for use in this report, neither literature reviewed nor personnel contacted clarified the timing associated with the term "immediate."

The highest predicted rock temperatures will occur in the emplacement drifts closest to the canisters. Significantly elevated temperatures, 50°C or more above ambient temperature, are not expected to occur at the emplacement drift ribs until after backfilling (2,4). However, heating rate anomalies, along with associated rock mass thermoelastic responses, are a major study within the context of the report. The anomalies can cause significant rock mass displacement in advance of observable temperature changes.

The NRC has directed this study away from a "severest" thermal pulse analysis (2), i.e., 200°C tuff immediately adjacent to the canisters, . Should such a "severest" temperature differential study be required, the marginal adequacies of known support materials and designs may become more apparent.

Some ventilation drifts could receive significant hot exhaust air exposures (1). Drift perimeter insulation is a practical way to minimize potentially disruptive air to rock or air to metal heat exchanges.

By law, canister retrieval is an option that must be engineered into the original repository design. "Severest" thermal pulse ground conditions must be assumed to exist in a retrieval effort (5). Canister retrieval, whether through fill or new accesses, is a major design problem; its detailed analysis is not within the scope the report.

Design Specific Background

Gravity, sometimes accompanied by the destructive atmospheric alteration of rock structure, i.e., slaking, precipitates excavation filling. The rate and method of excavation filling is dependent on site-specific characteristics. An increase in void span or depth of a given span requires greater inherent rock mass strength to prevent opening failure. Gravity induced, excavation, failure mechanisms, such as slowly forming fracture systems (6), rock mass creep, or explosive rock bursts, can be controlled by the installation of adequate artificial support.(7)

Ground control plans for underground excavations are usually based on pilot drifts and closely spaced drilling along the planned routes. Information obtained will alert tunnel designers of undetected faults, ground shatter, saturated ground, discontinuous bedding, and altered rock strength. Anomalous zones are of special concern in that a ground support system developed for one rock mass condition is usually found to be inappropriate for an altered rock mass.

Geologic characterization of the proposed repository sites has largely been extrapolated from similar rock types in the immediate vicinity of the sites (3). Core from the sites has been classified by rock type and fracture detail and microscopically examined for mineralogic detail. Core samples have been tested for unconfined rock strength, Poisson's ratio, wet and dry thermal conductivities, and other thermal properties, but usually without thermal calibration. Critically important fracture data, including spatial orientation, frequency, strike, dip, roughness, and filling characterizations, are presently unavailable; these data are scheduled for development during the site characterization phase. (3)

Discussion

Waste canisters will supply internally generated heat to the surrounding rock mass (5). Approximate temperatures for the very-near-field canister area, near-field emplacement zone, medium-field sub-main and main entries, and far-field shaft areas have been numerically modeled by the Department of Energy and private contractors (1, 4). Figure 6 illustrates the adopted distance terminology related to the canister location. Heat transfer simulations generalize the site geology and usually assume an isotropic, homogeneous rock mass. This facilitates time and spacial approximation of the thermal pulse magnitude.

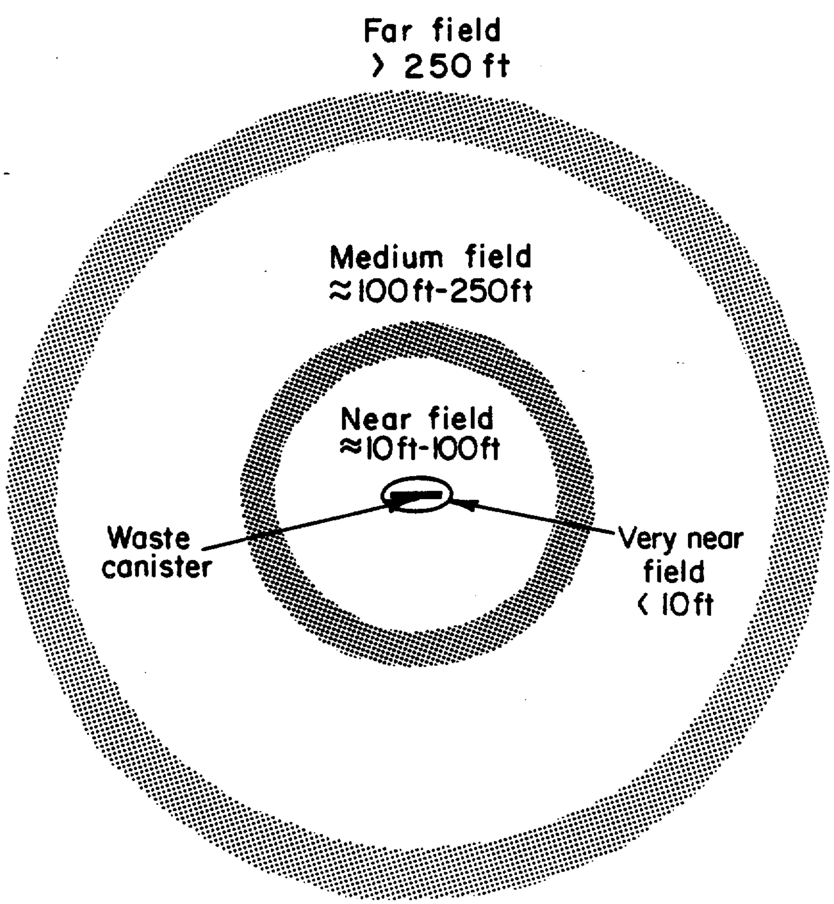


Figure 6. Field Designations

Heat will disperse from the canister by one of two mechanisms; 1) the formation of water vapor that migrates through adjacent fractures, condenses and thereby releases its heat of vaporization, and 2) thermal conduction through the rock mass. Heat transfer through a fractured, nearly dry rock mass is the expected condition. Existing numerical modeling programs that estimate thermal diffusion by conduction only for an isotropic, homogeneous rock mass may, therefore, be misleading since the vapor transport mechanism is ignored.

Unconfined rock will expand when heated. Rock mass joint and fracture fillings, depending on mineralogy and moisture content, may expand or contract. Vapor porosity characteristics of rock mass joints and fracture fillings may change with prolonged heating, repeated condensation, or physical protrusions from surrounding blocks of rock. Heat can theoretically move great distances in short times through steam-channel mechanisms in rock fractures, relative to conventional rock conductive diffusion. Heat transfer through convection systems can result in anomalous "heat planes" or "hot spots" within a larger, cooler, rock mass.

Heat flow prediction is also difficult in layered rock. Stratigraphic interbedding may provide moisture vaporization, condensation, and liquid gravity return. Patterns of mineralogic alteration may cause the thermal pulse to be directionally erratic since the altered rocks may be thermally conductive. See Appendix 5 for a more detailed geologic description.

Heat, moisture, and pressure can be vented through intersecting, unsealed entries. Air gaps in fractures or between rock layers are heat conduction barriers, and anomalous heat build-up on the "hot" side of an air gap can be expected. Substantial disturbances in heat flow could cause conductive temperature fronts to develop erratically, at greater rates and in other directions than existing numerical models product (4). The severity of temperature change of a hot spot, and its probability of occurrence at different distances from the heat source, requires quantification of undefined rock mass heat transfer mechanisms. Although temperature extremes of 100°C are unlikely to migrate the many hundreds of feet between a canister heat source and sub-main or main entries, physical mechanisms enabling such anisotropic heat flow can be either present or, at times, created. Moisture filled faults, or newly formed fractures resulting from rock mass expansion in the very near field, are potentially two of the most significant conditions affecting heat flow.

Ground Support System Interaction

Prior to heating, ground support in repository workings will be achieved by natural support, including key-blocked rock mass arches and inherently strong roof layers spanning entries, and artificial support, where natural support is insufficient to provide adequate ground stability. A fractured or layered rock mass would be strengthened by installing artificial supports; for example, grouted or friction stabilized bolts would create keyblocked or beam suspension composites.

Artificial ground supports are normally a type of bolt or compression member. These supports can be, by design, either rigid or yielding. Bolt systems support a rock mass through keying, beam building, suspension, compression, and combinations of the same. Bolt systems are often used with steel landing mats, straps, slings, or wire mesh between bolts to provide support between bolts. Compression members include gunite lining, continuous reinforced concrete or steel linings, posts, cribs, and steel sets. Load bearing compression members prevent layer separation and control key blocks; continuous linings are load bearing members that also prevent air slacking of the entry free face. Pressure grouting internally strengthens a rock mass by filling voids in rock fractures or between separated rock layers.

The transfer of thermal energy within the rock mass can be erratic, especially where layered and fractured materials are present. Consequently, it is difficult to predict the thermal pulse direction and rate of advance.

Repository rock mass discontinuities and inhomogeneities, such as fractures or layers, could be inconsequential as heat transfer mechanisms. However, the probability of creating a spherical or cylindrical thermal pulse away from the source canister zone is unlikely, where jointing, fracturing, layering, and mineralogic variabilities are present.

The major effects of heat on the stability of repository workings that were identified are:

1) rock or support system alterations, resulting in physical property changes;

2) macrogeologic effects, e.g., creation of new fracture systems or thermoelastic deformations;
3) corrosion between rock mass and support materials; and
4) differential thermal expansion loading resulting from dissimilar materials.

All of the above heat effects act together as a system. Certain effects can be isolated and analyzed to describe and quantify simplified failure modes. This simplification procedure, although technically deficient, identifies the failure sensitivity of the rock mass and support system components. Failure sensitivities of individual components were recombined to produce a support system comparative ranking. Research recommendations were then developed to validate the comparative ranking.

A critical thermomechanical problem that must be addressed to provide stable repository workings is the interaction between the variably strong rock mass surrounding the entries and the thermally induced forces that can, due to erractic heat dispersal, impose loads from any direction. For example, pressure created by thermal expansion of rock blocks behind a keyblocked roof or sidewall could induce failure of what was a stable, gravity resistive, arch. Conversely, a key block in the arch, if anomalously heated, could expand and tighten the arch. Thermal effects on supports, such as bolt shearing, liner bending, beam flexure, cap and post compression, bolt tension, and anchor slippage, could occur, depending on the size, orientation, and location of rock fractures, layer interfaces, and heated rock expansion centers. Variations in load imposition timing and reversibility add another set of complicating factors. Floor heaves could also disrupt natural and composite keyblock and beam construction ground control systems.

The above mechanisms do not identify all of the potential thermal interactions; rather, they are examples of some of the possible methods to thermally fail or strengthen an opening. Prediction of the inward displacement of an entry perimeter is related to the "stiffness" of the surrounding mass. Rock mass stiffness, as opposed to rock speciman stiffness, is difficult to quantify under the simplest of circumstances.

Under gravity only loading conditions, rock bolt mechanical anchors can partially unload by the process of uneven gravity settlement of the drill hole. Drill hole settlement, a closure process. is dependent on stress relief of the rock mass. Bolt re-torquing is commonly practiced to regain bolt tension.

A thermal pulse may initiate additional ground movement in the bolt anchorage zone. When the potential for joint expansion is liberal and the temperature pulse is large, a drill hole may expand. When the potential for joint expansion is minimal, such as when rock is confined, rock expansion may be forced towards the free face of the drill hole and the drill hole would contract.

Thermally induced hole closure onto a grout anchor or grout column can improve bolt anchorage. The anchoring plug is squeezed more tightly by the surrounding rock. However, longitudinally differential thermal expansion shear forces could cause either a grout or rock material failure. The subsequent rubblization may not necessarily create an anchorage failure since the broken grout pieces interact to provide pull out resistance (8). Grout, as used above, and, unless otherwise noted, throughout the report, refers to a cement-based mixture.

The thermal pulse creates a rock mass expansion force which is confined; hence, in situ "pressurization" occurs. Stress redistribution around underground opening (soft inclusion) theory may potentially mirror image stress redistributions around a thermal "pressurization" center (hard inclusion). The implication of such a stress redistribution relationship is a stress focusing into the hottest portions of the repository. Such a stress field alteration would be important knowledge for repository designers. "Pressurization" theory is further explained in Appendix 1.

SIMPLIFIED SCOPING CALCULATIONS

Discussion

Differential thermal expansion effects of a bolt in a rock mass for some of the more commonly used rock bolt types can be quantified mathematically using a "scoping calculation." Scoping calculations were simplified by assuming the advancing thermal pulse in the area of the bolt is uniform and the bolt anchorage is fixed. Another simplification assumes an unfractured rock mass. The differential thermal expansion effects examined were limited to tension, compression, and linear shear. The rock mass contains a bolt hole, bolt and, where appropriate, grout. In one case heat removal by ventilation is assumed. By simplifying the thermal pulse and assuming fixed anchorages, thermal expansion loadings can be quantified using a scoping calculation.

Anomalous heating in or behind the rib, roof, or floor can create rock thermal expansions that locally impinge on the drift. Localized, hot spot heating creates shearing, torquing, and tensional stresses on ground support hardware. Gravity loads combine with the induced stresses, potentially creating a need for ground support where none was previously required, such as a behind-the-rib expansion where a key block is dislodged. See Figure 7 for a sequential pictorial depiction, A through D, of "hot spot" induced failure; heated canister and steam heat transfer channels are indicated by the arrows.

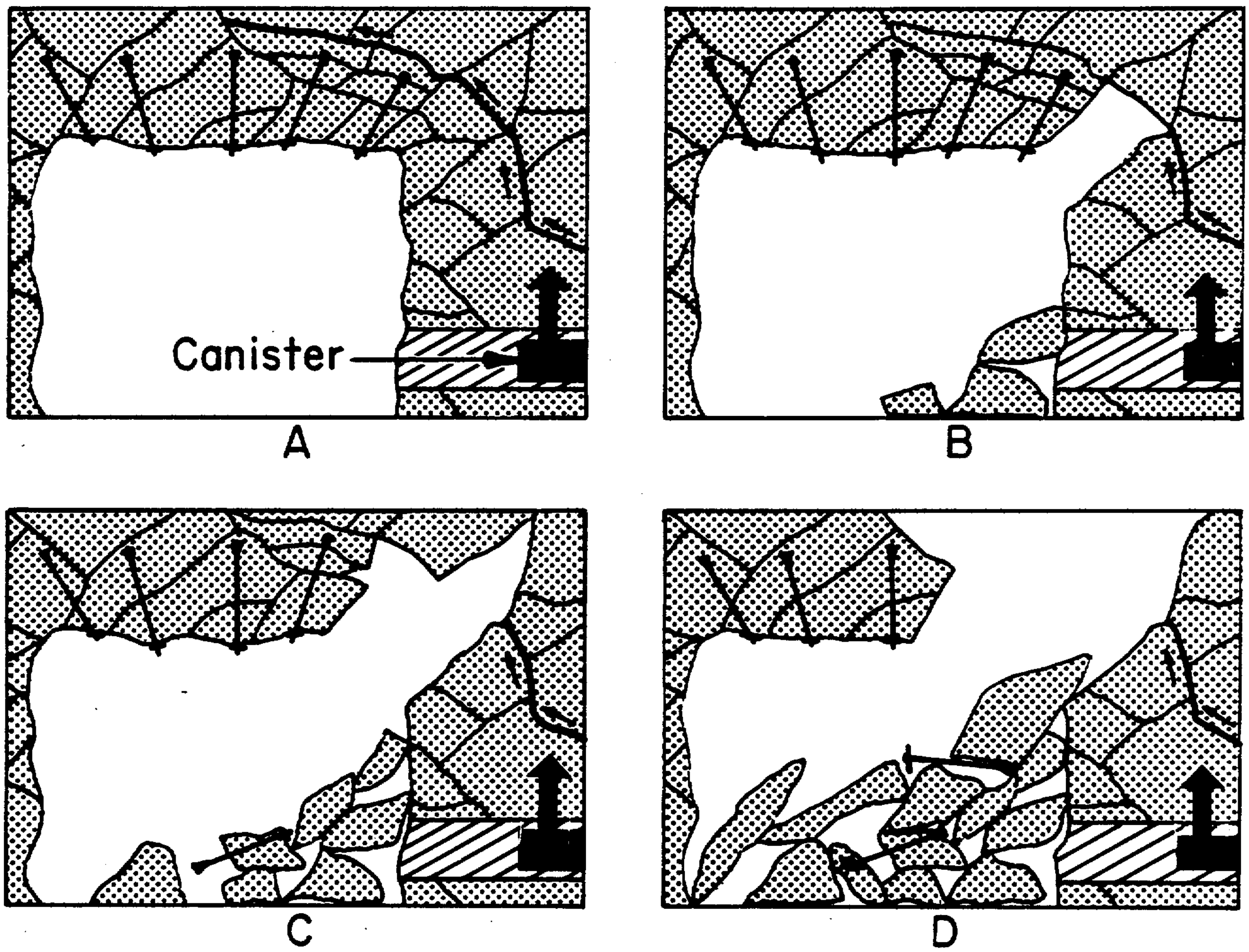


Figure 7. Behind-the-keyblock "Hot Spot" rock mass expansion causing a keyblock dislodgement failure.

The combination of bending, torquing, and tensional stresses on rock support hardware can be physically described but is difficult to quantify. Determining the adequacy of support materials under these stress conditions requires a complex laboratory analysis of the support materials alone and interacting with a heated rock mass. However, this analysis is beyond the scope of the report.

Rock fractures are, by definition, partings. The magnitude of rock separation and the nature of any fracture filling are factors in determining thermal displacements at the free face. Considerable geologic data are required before credible displacement predictions can be developed, but these data are not presently available. In general, displacement magnitude is a function of rock column length. Thus, integral, unfractured rock, when heated, will exhibit a maximum free face rock displacement. Conversely, rock containing many fractures, when heated, should exhibit a minimal free face displacement.

Thermal gradients within a rock bolt or other support system member, which undoubtedly exist, will not be addressed in the simplified scoping calculations. The thermal gradients imposed on rock and support system materials by blast cooling can result in materials failures and, therefore, can cause an overall ground support system failure. Internal thermal gradients of support systems, such as a hot bolt with a ventilation cooled faceplate end, a mid-section heated bolt with cool ends, or a continuous lining with cool interior and hot exterior sides, create complex stress fields and corresponding deformations. Future ground support proposals should analyze the complex thermal effects on artificial support systems that are likely to occur in a geologic repository.

Differential expansion axial overloading of long bolts, such as cable bolts, described in Appendix 3, is less likely than typical 4-12 ft rock bolts because increased length provides increased elastic flexibility. The displacement of a rigidly anchored bolt is a linear function of bolt length; therefore, a microinch displacement imparts 10 times more load on a 5 ft bolt than on a 50 ft bolt (12).

Drill hole confinement, a critical bolt effectiveness parameter, is dependent on the proximity and tightness of expansion accommodative fractures around the drill hole. Minimal drill hole confinement is analogous to a thin wall cylinder in that the rock mass response to heating is an expansion of the drill hole diameter and the surrounding rock mass. Infinite drill hole confinement would approximate a heated fixed-boundary plate with a small hole in the center, where the hole diameter will decrease prior to plate buckling. Drill hole deformations can vary along the length of the hole. Drill hole expansions can break ordinary grouts, unload mechanical anchors with non-flexing bearing plates, and unload friction stabilized bolts, depending on the bolt type. See Appendix 3 for detailed descriptions of the various bolt types available.

Simplified scoping calculations are presented using DOE rock mass heating projections increased by approximately 50%. This increase better illustrates the adverse medium-field thermal loading that could, in a worst case scenario, occur in non-isotropic, non-homogeneous rock. A list of assumptions and a definition of terms is included. Also, a tabulation of host rock physical properties and a brief description of the repository horizon are shown in Table 1.

Sample scoping calculations are presented for:

1) A grouted point anchor bolt with ventilation cooling effects,
2) A mechanical point anchor bolt with ventilation cooling and bolt pre-tensioning effects,
3) A full column grouted bolt with induced tension effects, and
4) A full column grouted bolt with tension and shear effects.

Scoping Calculation Assumptions and Definitions

Differential Thermal Expansion Tensioning of an Installed Rock Bolt

Assumptions Used

- Rigid anchor
- Infinite confinement except in direction of drift
- Rock & material physical properties chosen from end-of-range which emphasize failure mode under review (see Appendices 3 and 5)
- Simplified geology and thermal pulse descriptions
- Simplified loading theory applications

Definition of Terms

α = thermal coefficient of expansion

E = deformation modulus = stress/strain

ϕ = diameter

σ_1, σ_2, σ_3 = principal stresses

σ_N = Normal stress

τ = Shear stress

ΔT = Temperature difference

F = Force = stress x area

ξ = strain = in/in deformation

σ_V = vertical stress

R = rock

G = grout

B = bolt

C = temperature in Celsius

L = load in psi

F = force in lbs.

A = cross-sectional area, unless otherwise noted

L_0 = original length

ℓ = change in length

Host Rock Physical Properties

The candidate repository horizon zone selected for the tuff is a zone of densely welded rhyolitic tuff of the Topopah Spring Member of the Paintbrush Tuff. The zone lies about 1000 to 1200 feet below the surface and 300 to 500 feet above the water table. The data gathered to date, as described in detail in Appendix 5, was primarily extracted from the NNWSI Site Characterization Plan "SCP" - Chapter 2: Draft 17 - Mar-86. The detailed results of the laboratory mechanical property test results on samples from drill holes in Yucca Mountain and G-Tunnel at Rainier Mesa revealed a range for physical properties presented in the table and described in more detail in Appendix 5. In situ stress information is included in the table and is described in greater detail in the Appendix.

Table 1. Range of Tuff Physical Properties

PHYSICAL PROPERTIES	RANGE English	Metric
Overburden Depth	1000 - 1200 (ft)	305 - 366 (m)
Water Table Depth	1500 (ft)	457 m.
Cohesion	2500 - 13300 (psi)	17.24 - 91.70 x 10^3 (kPa)
Angle of Friction	23 - 67 (deg)	23 - 67 (deg)
Young's Modulus	3.48 - 5.51 x 10^6 (psi)	24 - 38 x 10^6 (kPa)
Poissons Ratio	0.12 - 0.32	0.12 - 0.32
Unconfined Compressive Strength	7975 - 41615 (psi)	55 - 286 x 10^3 (kPa)
Tensile Strength	120 - 4000 (psi)	.83 - 27.58 x 10^3 (kPa)
In Situ Stress: N33°E	580 - 1450 (psi)	4 - 10 x 10^3 (kPa)
Matrix Porosity (%)	6 - 19	6 - 19
Thermal Conductivity at ambient to 100°C	86 - 123 (BTU/HR•Ft•°F)	1.5 - 2.1 (W/m-°C)
Coefficient of Thermal Expansion	5 - 6.9 (10^{-6}/°F)	9.0 - 12.4 (10^{-6}/°C)

General Solution: Rock - Bolt Differential Thermal Expansion

- Rock thermal expansion > steel thermal expansion
- No expansion absorption by intersecting joints
- Rock - bolt temperature changes are equal
- Rock column length equals bearing plate to bolt anchor length

Where no restraint is present, the linear expansion of the rock column parallel to the bolt will be greater than the bolt expansion per degree of temperature change. However, the rock mass is constrained by the bolt rigidity. The result is the rock mass expands less than it would if unconstrained, and the bolt is stretched beyond its untensioned length by resultant constraint forces. The constraint represents a quantifiable force acting over the bolt stem cross-sectional area creating an induced tensional stress.

The change in length of an unconstrained bolt due to thermal expansion is $\alpha_B \Delta T_B L_o$. (13)

The bolt change of length due to bearing plate constraint is

$$\frac{F}{A_B E_B} L_o \qquad \text{(Note: } \sigma/\epsilon = E,\ \sigma/F_{AB},\ \text{and } \epsilon = \ell/L_o\text{)}$$

The change in length of an unconstrained rock column due to thermal expansion is $\alpha_R \Delta T_R L_o$.

The rock column is constrained from full expansion by bearing plate pressure. The constraint force acts over the faceplate area, hence, the change of length is

$$\frac{-F}{A_R E_R} L_o$$

The rock column and bolt begin with equal lengths and remain equal in length during heating, therefore:

$$\xi_B = \xi_R$$

$$\xi_B = \alpha_B \Delta T + \left[\frac{F}{A_B}\right]\left[\frac{1}{E_b}\right] \quad L_o$$

$$\xi_R = \alpha_R \Delta T - \left[\frac{F}{A_R}\right]\left[\frac{1}{E_R}\right] \quad L_o$$

Factoring out the original lengths and equal temperature changes, and solving for F yields:

$$F = \frac{(\alpha_R - \alpha_B)(\Delta T)(A_B)(E_B)}{1 + \frac{A_B E_B}{A_R E_R}}$$

This differential thermal expansion constraint force is the induced bolt tension. The bolt can fail if the induced tension is large enough.

Point Anchor Bolts

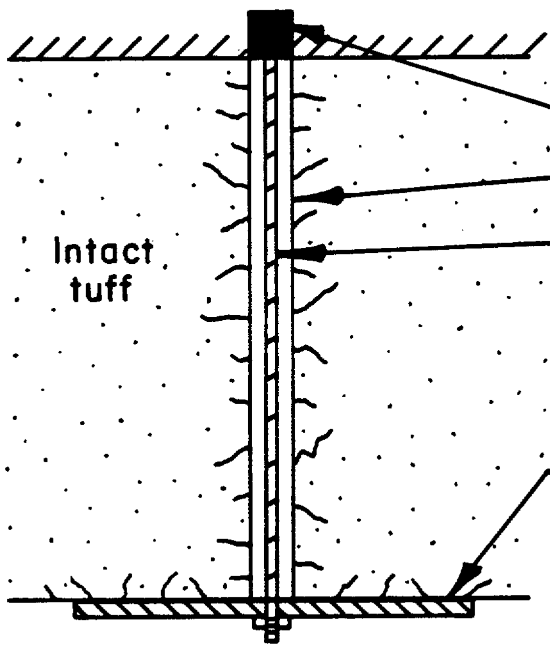


Figure 8. Differential Thermal Expansion of a Point Anchor Bolt

Case 1: $\Delta T_{Rock} = 75°C$; $\Delta T_{Bolt} = 25°C$: A condition predicted to possibly occur for main and sub-main entries if bolts are ungrouted and air exchanges in the bolt hole and at the bearing plate keep the bolt at 50°C.

Case 1 represents an induced, discontinuous, bolt tension where the rock and bolt expand together, although slightly differently, from T = 25°C to T = 50°C. However, from T = 50°C to T = 100°C, the rock alone expands and consequently stretches the bolt.

Hence,

$$F_{25\rightarrow 50°C} = \frac{(\alpha_R - \alpha_B)\ (\Delta T)\ (A_B)(E_B)}{1 + \frac{A_B\ E_B}{A_R\ E_R}}$$

However, dissimilar heating for rock temperatures 50°C and above requires temperature term refactoring, as follows:

$$F_{50\to100°\to} = \frac{(\alpha_R \Delta T_R - \alpha_B \Delta T_B)(A_B)(E_B)}{1 + \frac{A_B\ E_B}{A_R\ E_R}}$$

The stress induced in the bolt is the sum of the calculated loads divided by the load bearing area. See Figure 9 for a plot of the Case 1 induced tensional loads.

Case 2: ΔT_R = 75°C; ΔT_B = 25°C; mechanical point anchor bolt with pre-tension equal to 12,000 psi.

Again, the induced tension from differential thermal expansion is a discontinuous function breaking at 50°C. Furthermore, the Case 2 mechanical point anchor bolt is mechanically pre-tensioned to 12,000 psi. The thermally induced tension is superimposed on the initial bolt tension.

Pre-tensioning a bolt is a special condition whereby a rock mass is compressed by mechanically reducing the length of bolt between a fixed anchor point and a mobile bearing plate. If the tensioned portion of the bolt returns to its pre-tensioned length without adding other loads, the pre-tension load is relieved. If the change in bolt length from pretensioning is completely offset by bolt thermal expansion, the bolt will unload. In this case, pretension unload = 12000 psi = (9.8 in/in/°C x 10^{-6})(ΔT)(30 x 10^6 psi), when ΔT = 32°C. This is the expected condition for a hot bolt in cooler rock.

Since pressure induced by rock expansion is present and, due to differential thermal expansion, increasing throughout the temperature range under investigation, Case 2 is identical to Case 1 but adjusted upward 12000 psi because of the pre-tensioning. See Figure 9 for the graphical presentation.

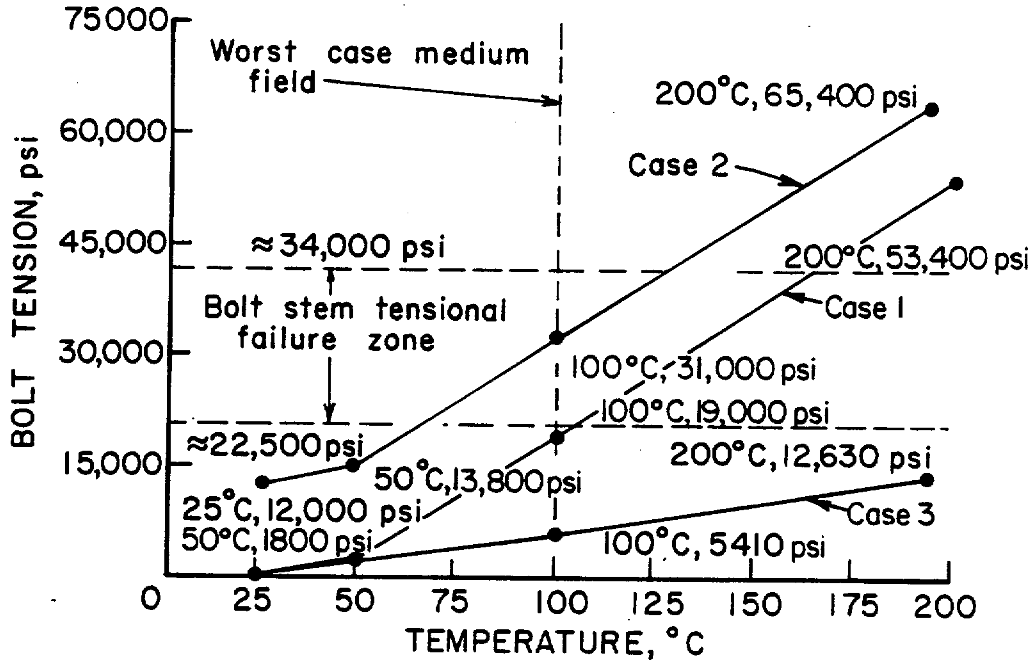


Figure 9. Rock Bolt Differential Thermal Expansion Loadings

Case 1: from $T_{AMB} = 25°C = T_B = T_R$ to $\Delta T_R = 75°C$, $\Delta T_B = 25°C$;

Case 2: from $T_{AMB} = 25°C = T_B = T_R$ to $\Delta T_R = 75°C$, $\Delta T_B = 75°C$
pretension = 12000 psi (mechanical anchor bolt)

Case 3: from $T_{AMB} = 25°C = T_B = T_R$ to $\Delta T_R = \Delta T_B = 75°C$ (column grouted bolt)

Full Column Grout Anchor Bolts

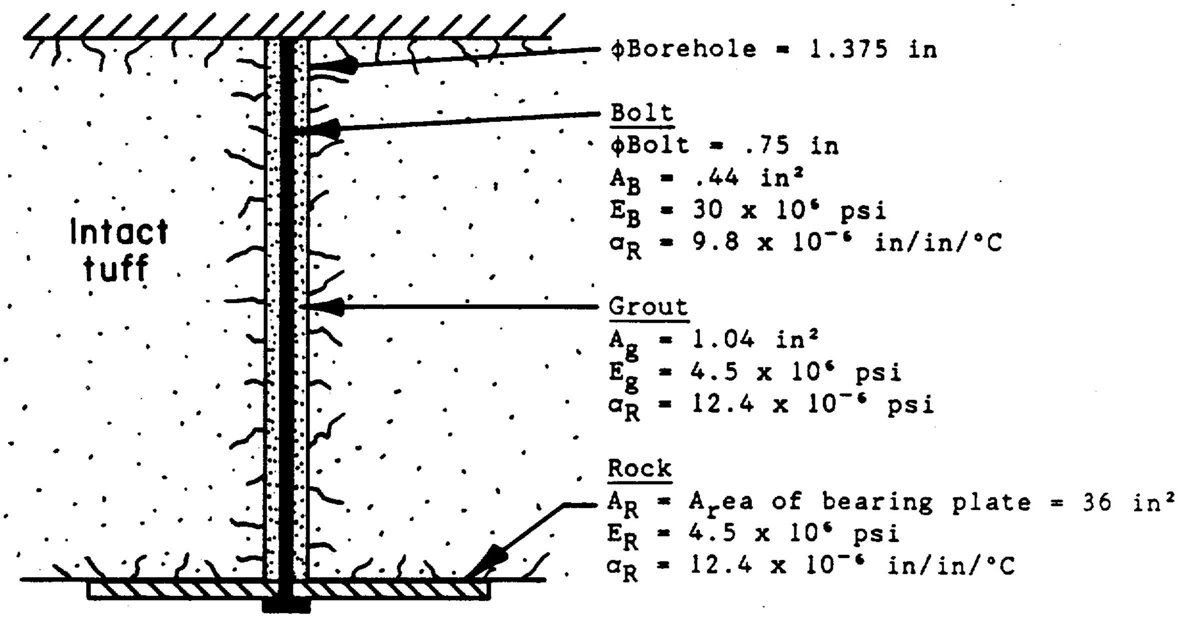


Figure 10. Differential Thermal Expansion of a Full Column Grouted Bolt

Case 3: $\Delta T_{Rock} = \Delta T_{Bolt} = 75°C$: A condition predicted for grouted bolts where rock to steel heat transfer is efficient and steel heat loss is restricted to bearing plate zone heat transfer. No pre-tensioning.

- Grout enables efficient heat transfer from the rock to the steel where:

$$\Delta T_R = \Delta T_B = \Delta T_G$$

- Grout has minimal tensile strength; therefore, the bolt carries the induced tension load. (10)

Using the previously developed equation for induced tension due to differential thermal expansion where ΔT for the bolt and rock are identical,

$$F = \frac{(\alpha_R - \alpha_B)(\Delta T)(A_B)(E_B)}{1 + \frac{A_B E_B}{A_R E_R}}$$

As shown in Figure 9, for the predicted "worst case" medium field condition; i.e., $T_R = T_B = T_G = 100°C$, the induced stress of 5400 psi is well below the bolt yield stress.

However, the bolt-grout and grout-rock interfaces are critical to maintain support, and the anchorage fails if:

- Differential thermal expansion loading exceeds shear strength of bolt, grout, or rock materials
- Bolt-grout or grout-rock bond is broken by thermo-chemical deterioration or thermo-mechanical failure.

Full column grout anchor bolts fail by either bond slip, where the bolt pulls out of the grout or the grout pulls out of the rock, or internal shear of grout or rock. However, analysis of bond strengths was not within the scope of a simplified calculation of differential thermal expansion failure. A simplified shear failure evaluation was considered reasonable.

Approximations of the Mohr-Coulomb shear stress failure envelopes were generalized for grout (14, 15) and tuff (16), as given in Figure 12 . When the calculated and plotted Case 3 shear stresses, shown as $\Delta T = 10°C$ and $\Delta T = 30°C$, are greater than the materials shear strength envelopes, a shear failure is predicted.

The heating of a grouted bolt creates tensional forces in the bolt stem, as shown in previous calculations. Tensional forces are transferred to the bolt-grout and grout-rock interfaces. In the base case of a 3/4" bolt and a 1 3/8" drill hole, tensional forces are transferred to a 2.36 in^2 bolt-grout interface area/linear inch of bolt, and a 4.32 in^2 grout-rock interface area/linear inch of bolt. The bolt load decays with distance into the rock along a full column grouted bolt.(17,18,19,20) This implies a similar distribution of load is transferred to the bolt-grout and grout-rock interfaces. The load transfer distance is dependent on rock hardness.(19) Load transfer decay mechanisms are complex, and empirically generated curves are required for different grout and rock types. Since these data are not available, an assumption of equal load distribution along the bolt length was used in the Case 3 calculation. The vertical stress is identified as σ_V in these calculations.

Confinement prevents radial thermal expansion of materials, hence, internal stress is induced. See Figure 11. Rigid confinement is an extremely important assumption. If confinement is minimal, drill hole expansion and subsequent grout failure in tension may occur. The internal stress induced by the confined thermal expansion is referred to as σ_N in the report.

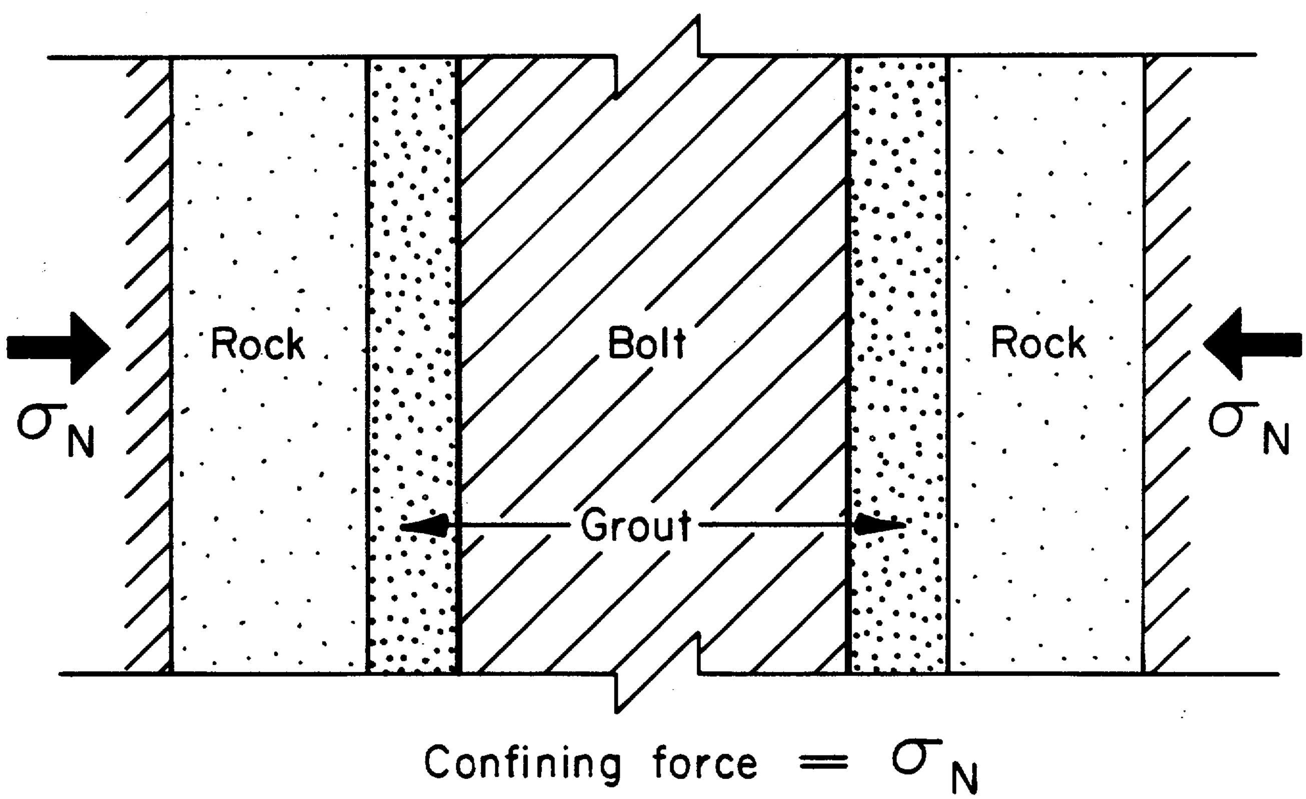


Figure 11. Thermally Induced Lateral Confining Force

Hence, $$\sigma_{N_{B/g}} = \sigma_{N_{g/R}} = \alpha_R \Delta T E_R + \alpha_B \Delta T E_B + \alpha_g \Delta T E_g \qquad (\underline{13})$$

For $\Delta T = 1°C$

$$\sigma_N = (12.4)(1)(4.5) + (9.8)(1)(30) + (10)(1)(4.5)$$

$$\sigma_N = 394.8 \text{ psi/°C}$$

Also for $\Delta T = 1°C$

The vertical stress equals the induced tension, 31.7 lb/°C given in the induced tension calculation, divided by the load transfer surface area;

therefore, $\sigma_{v_{B/G}} = 31.7 \text{ lb}/2.36 \text{ in}^2 = 13.4 \text{ psi/°C}$ (tension)

and, $\sigma_{v_{G/R}} = 31.7 \text{ lb}/4.32 \text{ in}^2 = 7.4 \text{ psi/°C}$ (tension)

Case 3 stress data for $\Delta T = 10°C$ and $\Delta T = 30°C$, i.e., $\sigma_N = \sigma_1$ and $\sigma_r = \sigma_3$, were then plotted onto a Mohr-Coulomb diagram of grout and tuff strengths. See Figure 12.

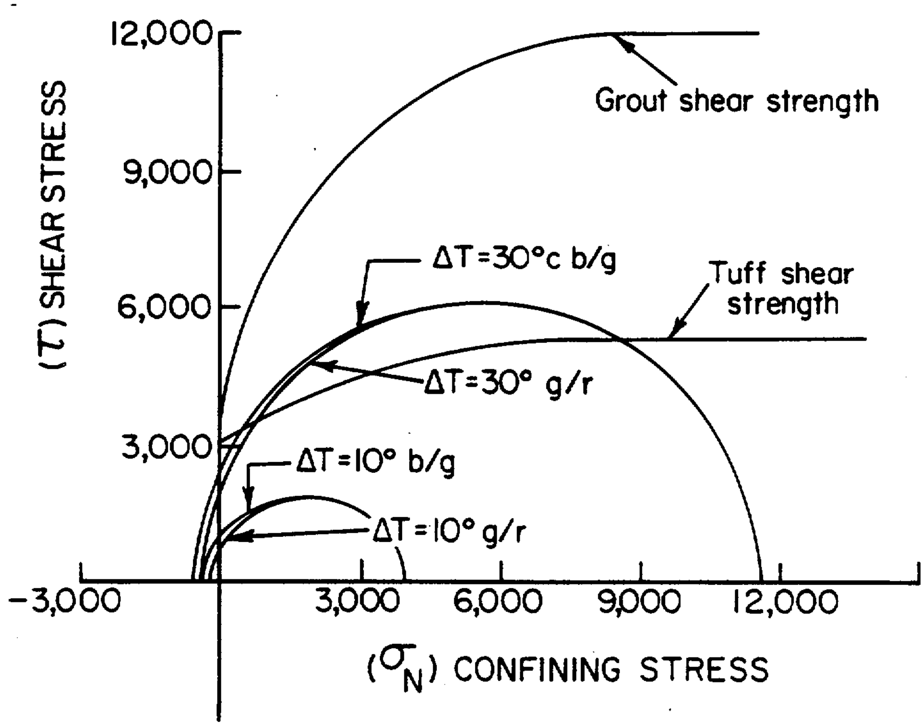


Figure 12. Mohr-Coulomb Failure Envelopes and Base Case Shear

As shown in the Mohr Circle shear strength envelope, tuff fails in shear at the grout bond at a temperature of approximately 20-30°C. Testing has shown that anchorage would be maintained by a mechanical interlocking of sheared rock fragments. The grout-bolt interface is predicted to fail due to grout shear at $\Delta T \approx 60°C$. However, mechanical interlocking of rock fragments should again become a predominant anchorage mechanism.

Quantified, the new anchorage capacities would be:

$$\text{bolt in grout} = \sigma_N(f_{B/G})$$

$$\text{grout in rock} = \sigma_N(f_{G/R})$$

However, the interface friction factors, $f_{B/G}$ and $f_{G/R}$, are non-quantifiable except through empirical, pull-out tests.

Scoping Calculations Conclusions

The scoping calculations have shown, in a greatly simplified manner, the effects of differential thermal expansion on some of the more commonly used rock bolt types. Rock mass expansions are considered as the least understood complicating factor. Methods to treat fracture geometries as a support system design variable and develop geothermic rock mass response principles are, accordingly, identified as research recommendations.

Grouted bolts have significant corrosion resistance compared to bolts with unprotected steel surfaces. The integrity of grout-bolt and grout-rock interface bonds in a thermally pulsed environment is uncertain and requires further evaluation.

OTHER FACTORS

Full Column Friction Anchor Bolts

Tension is created in friction stabilized bolts by differential thermal expansion, as described previously in the scoping calculations. Frictional anchorage is enhanced by increased contact areas, increases in normal stress from hole closure, and increased hole sinuosity and roughness. Elliptical and Split-Set bolts rely on the mechanical setting of a radial spring load, in combination with rock-metal friction, to secure the bolt anchor. The Swellex bolt relies on rock-metal friction developed from plastic deformation of a metal tube to fit the drill hole shape.

Thermal pulse impact on a drill hole is related to the expansion accommodation of adjacent fractures and the ease of rock flexure. Thermal expansion of a confined rock mass will force adjacent rock into the drill hole; however, expansion of a fractured rock mass may allow the drill hole perimeter to expand. Anisotropic drill hole deformations, inward and outward, may occur frequently along the drill hole length.

An expanding drill hole will adversely affect the anchorage of full column friction bolts; a contracting hole will enhance friction bolt anchorages. Rock block expansions that increase sinuosity will increase pull-out resistance of friction anchor bolts.

Yielding of friction anchor bolts will be controlled by either anchor slippage or bolt cross-sectional failure. Medium field temperature changes are not expected to cause a cross-sectional bolt failure, even with extreme differences in coefficients of thermal expansion. Thin walled bolts, e.g., the Swellex bolt, can, however, tolerate little corrosion before bolt cross-sectional area losses do result in an increased risk of yielding.

Load Reversals

Heat transfer through formation, travel, and condensation of water vapor in rock fractures is dependent on the porosity of fracture fill material and the travel path clearance; this transfer mechanism is expected to be more erratic in magnitude and duration than conductive heat transfer through a homogeneous rock mass. Bolt or rock mass heating-cooling cycles may occur and render certain support systems ineffective. For example, deformable support systems, e.g., yieldable bolts, can be deformed by an expanded rock block, and later unloaded if the rock block cools and contracts or the block is forced back towards its original position.

Anomalous bolt heating may occur at the intercept between a bolt and a heated rock fracture, particularly if the bolt is not grouted. Expansion of the bolt relative to the adjacent rock causes pretensional unloading of a mechanical anchor bolt and possibly even a bearing plate separation from the rock face. Such events would normally require bolt re-torquing. However, caution must be employed; if the bolt cools and contracts, an increased load commensurate with the degree of re-torquing could be incurred and the bolt may fail. Load reversals due to thermal cycling of a bolt is a distinct possibility within the operating life of the repository.

Radial spring seated bolts, such as Split-set and elliptical bolts, would be expected to elastically reset for most expansion-contraction deformations. Swellex bolts can be repressurized as an offset to expansion-contraction unloading.

The response of a grouted bolt to anomalous heating is difficult to predict. Grout or rock shear may occur due to a differential expansion of metal grout and rock, and create a rubble zone. Thus, the bearing plate may separate from the rock face. When cooled, the bolt may or may not contract to its original length since rubble zone keying may create contraction resistance. Contact between the bearing plate and the rock mass, which provides essential confinement, may be irrevocably lost if bolt contraction is impaired.

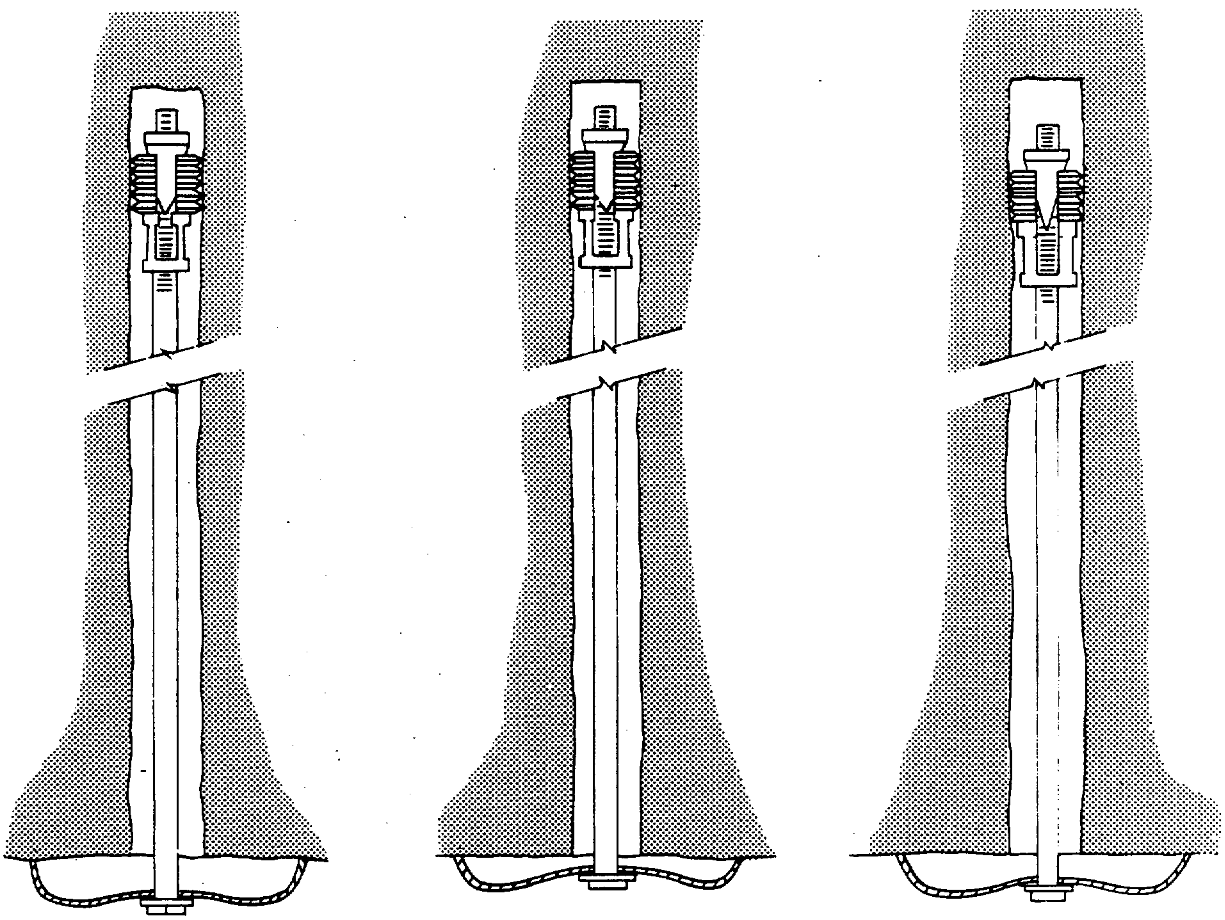
An ungrouted helical bolt (9), as shown in Figure 14 in Appendix 3, appears to be adaptable to possible heating/cooling cycles. Thermal linear expansion of the bolt will produce less bearing plate movement than a conventionally shaped bolt. The bolt will return to its original shape when cooled and, therefore, retain usefulness.

A cable bolt provides a larger thermal storage capacity than conventional bolts and possible smaller temperature variations for most anomalous heatings. Therefore, bearing plate disturbances due to thermal expansion effects may be less likely to occur.

Bearing Plates

Bearing plate buckling, particularly failure at the bolt intercept, is almost entirely a function of the plate thickness. Doubling or tripling the plate thickness, by overlaying multiple plates during installation, is a practical, approach to prevent failure.

Some bearing plates have curled corners that provide some flexibility; if set properly, plate corners should maintain contact with adjacent rock, even during anomalous bolt heating. The plates are strong enough, when used with a mechanical point anchor, to pull the anchor plug through the anchor leaves. Anchor slippage due to gravity, thermal drill hole deformations, and thermal cycles that load and unload the system can be absorbed. See Figure 13.



(a) (b) (c)

Figure 13. The Spring-Loaded Bearing Plate:

a) As set

b) Rock mass expansion greater than steel expansion

c) Anchor Slip/Reset Mode

Corrosion

The corrosion discussion in Appendix 2 provides a comprehensive discussion of corrosion concerns in a geologic repository. The following observations assisted in support systems rankings but are recognized to be preliminary.

The repository environment at the Yucca Mountain site is discussed in DOE/RW-0073 (3). Water flux is described as extremely low. Chemistry of water in the host rock is assumed to be similar to that of samples taken from drill holes at Yucca Mountain. The pH of this water is nearly neutral. Chloride ion concentration is very low, on the order of 6 ppm. Dissolved oxygen is expected to be in equilibrium with air at ambient temperature.

Under these conditions, uniform corrosion should be the significant factor in reducing the strength of plain carbon and HSLA steels. Corrosion rates could vary from essentially zero to as high as 15 mils (.015 inch) per year (mpy). The latter rate assumes dissolved oxygen is in equilibrium with air at a temperature of 80°C. Higher temperatures will result in a lower dissolved oxygen concentration in an open system, with a corresponding reduction in the rate of corrosion. Since a low concentration of Cl^- is present, neither pitting nor crevice corrosion is expected to occur. Possible corrosion of metal portions of a support system is considered critical, particularly when bolt supports are used.

COMPARATIVE RANKING

Discussion

The effectiveness of a support system may not be adequately described by any single failure analysis. The nature and severity of interactions between a thermal pulse and a support system depend on the temperature and geology. Since available knowledge of site-specific geology and geothermic response is limited, a variety of thermal pulse and support system interactions are possible. In addition, thermal heating and cooling of the rock mass and support system may impart differing loads to bolt, grout, and rock materials, all of which impact the support system effectiveness.

Interaction analyses of a thermal pulse and support systems in the medium field, i.e., main and sub-main entries, are emphasized in this report. The project de-emphasized the following, principally emplacement area, considerations:

a) temperature extremes greater than 75°C above ambient rock temperature, as might occur immediately adjacent to the canisters,

b) temporary ground support approaches or techniques, and

c) the compatibility of a selected ground support system with repository re-entry techniques, principally the excavation of backfill.

The principal concerns of a medium-field comparative ranking are:

a) drill hole expansion, contraction, or both, and the resulting effects on bolt anchorage;

b) differential expansion loading of support hardware and rock mass, and adaptability of the hardware to a reversible thermal pulse; and

c) geochemical and geothermic material degradation of support hardware.

Possible methods to reduce the effects of the four above concerns are, in order:

a) A longer bolt anchorage is more likely to be anchored in the surrounding rock mass if only a drill hole section contracts with rock mass heating. Long anchors are less likely to be located exclusively within a rock expansion zone where tensional failure of a grouted point anchor bolt or unloading of a mechanical point anchor bolt could occur. A spring-loaded bearing plate can be used to compensate for mechanical anchor movement. Selected bolt types, principally cable bolts, could be anchored outside the thermally pulsed zone.

b) Rock, grout, and steel thermal expansion coefficients should be as equal as possible. Bolt unloadings, due to lower rock mass displacement relative to steel expansion, are correctable by re-torquing. Re-torqued bolts may require mechanical torque unloading if additional thermal pulses occur. In heavily fractured ground that exhibits a low rock mass coefficient of thermal expansion, low thermal expansion steels could be incorporated.

c) Most organic resin, epoxy, and fiberglass grouts, while relatively stable at temperatures of 100°C, may weaken over a 30-year plus period when exposed to moderate, 70-100°C, temperatures. Most thin walled steel bolts, such as the Split-set, elliptical, and Swellex bolt types have a large surface area to load resistance ratio. Therefore, corrosion attack of the surface area has a large effect on the bolt load carrying capacity. Pull-out resistance is reduced proportionate to any corrosion detached sections. However, in some rock masses, minor corrosion has enhanced support effectiveness (21).

Inorganic grouts do not corrode. However, a loss of moisture weakens the mix. In the temperature environment under review, concrete moisture loss is not predicted to cause a large reduction in strength. Portland and calcium-aluminate cements alter the near bolt pH which inhibits corrosion.

Support System Components

The descriptions of support hardware given in Appendix 3 and site geology given in Appendix 5 provide background for the following discussion.

Mechanical Point Anchors

Drill hole deformations, including expansions, contractions, and offsets may unload mechanical point anchors. The anchor can be reset by bolt torquing; however, re-torqued bolts may yield if the rock mass heating cycle reverses. Anchor metal in intimate rock mass contact may be susceptible to corrosion. Mechanical point anchor bolts with spring-loaded bearing plates are apparently compatible with thermal pulse unloading because the anchor will automatically reset.

Grout Point Anchors

Drill hole closure enhances grout point anchorage, while excessive drill hole expansion will fail the anchor as the grout fails in tension (10). A grout point anchor bolt can be retensioned by tightening the nut against the bearing plate in the event that the rock mass differentially contracts. If moisture is introduced, grout provides a beneficial alkaline pH, i.e., corrosion protection, for the encapsulated portions of the bolt.

Full Column Grout Anchors

Anisotropic drill hole deformation, i.e., alternating drill hole expansion and contraction, is less likely to cause unloading of full column grout anchors than point anchors. The adaptability of full column grout bolts to a thermal pulse is questionable; thermal expansion shear forces may reduce intact grout to rubble, which either destroys bolt anchorage or creates an alternate, interlocking fragment anchorage. Grout-steel differential expansion can expose small sections of an encapsulated bolt to possible corrosion. Cable bolts can be anchored with long sections of grout and achieve the same advantages as full column grout anchor bolts.

Full Column Friction Anchors

Full column friction anchored bolts do not unload with drill hole contraction. Drill hole expansion may unload Swellex bolts, but elliptical and Split-set radial spring bolts can adapt to moderate drill hole expansions. Swellex bolts can be repressurized to restore friction anchorage. Radial spring bolts do not provide the original anchorage after drill hole expansion because some radial tension is lost in an expanded hole. Full column friction bolts are highly adaptable to thermal load reversing, but their thin wall construction is less resistant to corrosion weakening compared with full column grout bolts.

Fiberglass Bolts

Fiberglass bolts have high tensional strength, elasticity, corrosion resistance, and present minimal interference to remining. Incremental loss of strength may occur due to time-temperature volatilization of critical polymer components and thereby reduce long-term stability. However, reliable time-temperature-strength curves are not yet developed.

Carbon Steel Bolts

High strength carbon steel bolts are available with thermal expansion-contraction coefficients compatible with the rock mass and Portland or aluminum-silicate grout. Steel is an appropriate rock mass support material for repositories. Grout encapsulation, to the extent possible, is important for corrosion protection.

Yieldable Bolts

A resetting mechanism is integrated in the design of some yieldable steel bolts that permits bolt expansion and contraction in excess of normal changes in bolt length due to thermal effects. If rock mass expansions are greater than steel expansions and the thermal cycle is reversed, some non-yieldable bolts would be useless since bearing plate gouging or thread stripping is not reversible. The BOM-Conway (11) bolt is an example of a yieldable bolt that can be reset for rock expansion or contraction. Helical bolts can freely to expand or contract in the drill hole and are inherently reversible. Yieldable steel bolts may become non-yieldable if the resetting mechanism is corroded.

Wooden Dowel Bolts

Wooden dowel bolts will likely degrade with heat and time and, therefore, are unsuitable for entries with 70-90 year life.

Ground Support System Comparative Ranking

The development of a comparative ranking of ground support systems for thermally pulsed Topopah Springs tuff must be very preliminary since site-specific information is largely undeveloped.

Anomalous heat transfer by water vapor travelling through rock fractures, possibly in a cyclical manner, could cause erratic bolt heatings. Bolts that can be re-torqued, un-torqued, and reset are preferred in these circumstances. Any system that has enough thermal mass to accept anomalous heating with a minimum of temperature change and differential expansion is favored. Bearing plates that have two-way movement to maintain pressure when the bolt expands and contracts is also preferred.

Drill hole deformation resulting from a thermal pulse is difficult to predict, and confinement is believed to be the key variable in predicting either inward or outward displacement. For most point anchorage supports, drill hole deformation is critical to the long-term effectiveness of the support hardware. A long grout anchor is preferred if the nature of drill hole deformation is uncertain, since better anchorage is achieved if the drill hole contracts and contracting drill hole sections are more likely to intersect part of the long anchor. A mechanical anchor bolt that adjusts for moderate drill hole expansion or contraction is another feasible anchoring method. A spring-loaded bearing plate would pull a plug through a mechanical anchor and re-seat the anchor against the drill hole in the event of anchor slippage.

Rock mass fracturing and consequent thermal expansion accommodation will usually result in greater bolt-grout expansion than rock mass expansion. If this differential expansion shears the grout or the rock, the bolt may provide inadequate support, particularly if the thermal cycle reverses. Rubblization of grout or rock may not allow the bolt to completely contract when cooled and return to its original length and seating. Matching the thermal coefficient of expansion of bolt and grout is a preferred method to avoid a grout-metal shear failure.

Grout encapsulation of bolts is preliminarily identified as important for corrosion protection. Therefore, the suitability of full column grouting must be further researched, possibly through grout mix modification, to better maintain contact between bearing plates and rock. Corrosion protection by the development of metal coating and sleeving options is, however, another approach to solving the problem.

A number of the ground support systems or system components reviewed for this project can achieve improved thermal pulse adaptability with only minor modification. These modifications were less involved with the basic design of the system than alteration of an aspect of the system relative to its conventional use. Some pertinent examples are: long grout anchors on cable bolts that essentially provide a partial grouted column, roof truss spacer blocks that conform to uneven rock surfaces and allow use in a crowned drift, increased curvature of the corners of a conventional bearing plate to create the spring-load, and the extension of the Conway bolt threads to allow retensioning, hence, more yielding. All of the adaptations are based on expected repository conditions. Support design modifications are beyond the immediate scope of the project; however, proving the merit of these system adaptations is the basis of several proposed research recommendations.

The following comparative ranking provides a measure of the overall adaptability and effectiveness of available ground support systems relative to all reviewed conditions. It is conservative in estimation and preliminary to basic research required to understand the interactions between a thermal pulse and a ground support system.

Continuous, High Strength Lining

Continuous, high strength linings, including reinforced concrete or lagged steel sets, achieve complete perimeter displacement control. Warning of high gravity or thermal loadings is provided by limited deformation of the lining before complete failure. Corrosion protection and initial support thickness provide long-term control of material degradation. Floor heave, should it occur, can be controlled by placement of transverse beams adjacent to the floor.

Cable Bolts with Long Grout Anchors

Cable bolts should have state-of-the-art "birdcage" wire stranding (see Appendix 3) and be anchored in areas outside the thermally pulsed zone where possible. The flexibility inherent with a long bolt length and the large mass to retain and dissipate heat make cable bolts one of the best for expanding and contracting thermally pulsed ground. The susceptibility of exposed steel to corrosion is a negative factor which could be overcome by shielding cables with a plastic sleeve, rope coating, or other methods.

Mechanical Point Anchor Bolts with Spring Loaded Bearing Plates

Spring loaded bearing plates with four curled corners should be tested against the tensional strength of tuff at different temperatures. Assuming rock strength is sufficient, a mechanical point anchor bolt with this bearing plate will maintain compressive forces on the rock mass when: rock expansion is greater than bolt expansion, bolt expansion is greater than rock expansion, or the combination of both in a thermal cycle. Automatic resetting of mechanical anchor pressure by a spring load pulling on a plug through leaves is crucial to maintain anchorage. Corrosion of exposed steel is a concern, but should be controllable through plastic sleeving, metal coating, or other protective methods.

Long Grout Anchor Helical Bolts

Secure anchorage and two-way movement for expansion and contraction of the rock mass are achieved with long grout anchor helical bolts. The helical bolt has had little field use, and the systems tested had undue flexibility, relative to the types and magnitudes of displacements anticipated in a repository. In principle, a tighter coil and a more rigid bar would provide the support desired for the expansion and contraction expected in the repository. The problem of exposed steel corrosion should be solvable.

Long Grout Anchor Conway Bolts

Like the helical bolt, the long grout anchor Conway bolt has had little field use. The bolt is resettable, as required, for either expansion or contraction of the rock mass. The problem of exposed steel corrosion should be solvable.

Long Grout Anchor Rigid Bolts

Long grout anchor, rigid bolts will unload due to differential thermal expansion if the rock mass coefficient of thermal expansion is appreciably less than the steel coefficient of thermal expansion. Re-torquing or un-torquing bolts is required to maintain sufficient internal rock compression as the rock mass expands or contracts without failure of the grout anchor. All bolt torque adjustments must be made at the bearing plate end because the anchorage is not accessible. Prevention of exposed steel corrosion along the bolt length should, as previously noted, be addressed by the future development of protective coatings or sleeves.

Full Column Grouted Bolts

Differential thermal expansion is possible between either the rock mass and grout or the grout and steel. If the shear stress induced by differential expansion exceeds either the rock or grout shear strength, a rubble zone of unpredictable anchorage strength and little flexibility could be formed at the bolt anchor; therefore, the load capacity of the bolt is questionable. Full column grouting provides the best initial protection against bolt corrosion, but shear failure of the grout could leave sections of the bolt exposed and susceptible to corrosion.

Long Grout Anchor Roof Trusses

When retrofitted with roof or rib adapted spacer blocks, long grout anchor roof trusses can provide substantial support and considerable flexibility through turnbuckle tensioning. The system takes up fractionally more space in an entry, which should be considered if vertical or horizontal clearances are crucial. Trusses can be difficult to install in confined areas, and increasing entry dimensions to accommodate truss supports would be a disadvantage.

Full Column Friction Anchor Bolts

Full column friction anchor bolts should provide continuous anchorage for initial and reversing thermal pulses, with only small variations in load capacity. Swellex bolts should be repressurized if drill hole expansion occurs. A major problem of full column friction bolts is the susceptibility to corrosion, due to the thin wall design. If adequate corrosion protection can be developed, the bolt could become significantly useful.

Others

Mechanical point anchor, Meypo yieldable, and Ortlepp yieldable bolts with flat bearing plates are generally unadaptive to anisotropic, expanding drill hole deformation and a thermally pulsed rock mass.

Gunite and pressure grouts are rigid support systems that provide limited resistance to rock movement. If the grout strength is exceeded by induced loads from thermal or thermal-gravitational rock block expansions or rotations, it is irreversibly damaged.

Yieldable steel sets and arches with continuous liner laggings, when used conventionally, will deform with entry closure. A re-setting technique could possibly be developed to provide continuous contact and support if erratic thermal pulse effects cause the drift periphery to locally displace out, i.e., for the rock to withdraw contact from the support. The likelihood of such outward displacement was not developed for this report.

RESEARCH RECOMMENDATIONS

Background

The focus of the project has been to identify and describe the geologic and ground support system response to the predicted thermal energy affected medium-field area of a geologic repository. The analysis was complicated by certain, largely data base deficiency, circumstances; specifically:

a) A detailed geotechnical description of the geologic horizon for the repository was unavailable. Thermally calibrated rock properties, such as Young's Modulus, Poisson's ratio, and thermal conductivity, were generally unavailable.

b) Heading dimensions, canister stand-off distances, emplacement mode, and other repository construction specifics are presently conceptual and may undergo further change.

c) Operating parameters, such "immediate" backfilling of emplacement drifts and re-entry using blast-cooling to inspect or retrieve canisters, created ground control concerns that could not be addressed without further definition.

In view of the lack of design specifics and geologic uncertainties, the project considered a wide range of potentially significant ground support variables and possible interactions. The broadness of the effort proved to be advantageous in that it facilitated a basic review of the problem and recognized potential thermal pulse disruptions that might have escaped scrutiny in a more boundary defined analysis.

Near-field emplacement drifts will experience the largest temperature increase, and conventional ground support techniques and hardware, without modification, may be inadequate to maintain opening integrity. Considerable additional study of ground conditions and support systems in emplacement drifts is required if opening integrity is to be designed with any assurance.

Use of blast cooling to re-enter any severely thermally pulsed area, either on a one-time or repeated basis, raises questions of differential thermal contraction and possible failure of support systems.

Research recommendations are written to obtain deliverable results during a 3-10 year period. The most difficult problems may require 5-6 years to develop theory, design test parameters, perform laboratory and field tests, and publish results.

Recommendations

The following recommendations emphasize the need to investigate geology, ground support system materials, and fundamental interacting relationships to provide reliable ground support designs for the medium field and, if possible, for the near-field.

Expanding Inclusions

The BOM has developed numerical models to examine the effects of hard or pressurized inclusions in a rock mass as part of its research on overburden stress redistribution around underground openings. One of the methods identified to pressurize rock was in situ rock heating, which emplaced nuclear waste canisters appear to provide. The pioneering work performed to date, indicates that stress focusing of the overburden load and in situ stress on a confined, heated, rock mass will occur. Stress focusing of dynamic waves, such as the nuclear detonation pulses that travel within the Nevada test site, is also implied.

The relationship between thermal pressurization and stress focusing presently exists only as a numerically modeled theory. The model configuration and boundary conditions are not identical to the repository. However, the model is believed to provide a reasonable beginning for developing theory and physical models that simulate the in situ heating process and predict thermomechanical strain and stress redistributions.

Stress focusing theory and suggested validation reasoning are presented in detail in Appendix 1 of this report.

Rock Mass and Support Systems Thermo-Mechanics

Legal mandates behind the repository development clearly present the need for safe operations. However, experience and available literature on the potential effects of a thermal pulse on the stability of underground workings are almost non-existent. The need for increased knowledge of thermally impacted rock structures is obvious.

The proposed research would be directed toward understanding rock mass responses to heating and cooling, as measured by displacements, temperature, acoustic emission activity, and differential stress measurements. Of special importance will be to quantify rock mass fracture creations, magnitudes, and orientations around thermal expansion areas for variable, externally imposed, stress conditions. Other areas significant to ground control design that could be quantified in the laboratory include:

a) validation of static and dynamic stress wave focusing,

b) rock bolt anchorage responses for thermally pulsed ground,

c) rock mass fracture geometries and thermal pulse displacement resistive keyblock stiffness, and

d) ground support system design guidelines adaptive to a thermal pulse for a variety of ground conditions.

Strength and Thermal Properties Study

Shear tests, unconfined and confined compression tests, and direct and indirect tension tests are typical of the rock mechanics parameters used to characterize the strength and elasticity of rock specimens. The specimens can also be thermally characterized by diffusion, conductivity, expansion, and specific heat. A thorough knowledge of the thermal effects on strength and competence of the host rock is essential to the integrity of the repository.

Torquing, tension and compression loading, and bending will induce stresses and strains in rock bolts. These induced stresses and strains may significantly affect the bolt thermal loading response. A thorough strength of materials review is required to understand the relationship between increased stress, increased temperature, and bolt strength. Interactions that may result in rock or support materials failure, such as load timing vs. changing physical constants and temperature vs. strength should be assessed.

The effects of increased stress and increased temperature on the strength of grout, resin, and host rocks should be defined. A pressurized triaxial tester could be adapted to evaluate the thermal parameters of the materials alone or as a composite.

Elevated Temperature Rock Bolt Pull-Tests

Conventional support systems may be inadequate for the repository main and sub-main drifts. Emplacement drifts, after a short time, will become severely thermally-pulsed and conventional ground support techniques and hardware will probably be inadequate to maintain opening integrity. Considering the expected thermal conditions, a critical need exists to develop design criteria for rock support materials in a high temperature environment.

Pull tests on a large variety of rock bolts should be performed using a variety of anchoring methods in a high rock temperature environment. Critical parameters should be measured and recorded on a continuous basis. To perform these tests, rock samples up to 3 feet square or 7 feet long, and weighing up to 4000 pounds should be obtained and directionally heated up to 200°C (392°F). Loads should be applied to the sample, before and during heating, to approximate the stresses encountered at depths up to 3000 feet. At any time one face of the test sample must be available to measure the effects of "blast cooling" on the rock support system under test.

Pull tests could be conducted on rock bolts installed in the rock samples during or after the heating phase. The pull apparatus must be capable of exerting a variable pulling force twice the yield strength of any bolt tested and should continuously record the force exerted. Instrumentation must continuously measure and record temperature, stress, and horizontal and vertical forces at several points in the rock sample and on the support tested. Any movement of the rock support system must also be measured and recorded during testing.

Preparing rock samples and support systems for testing will be required, and appropriate equipment must be available to perform these functions. Rock samples must be cut to dimensions, smoothed, and drilled with various size holes for the support system under test and for installation of appropriate instrumentation. The bolt system and instrumentation must be installed, verified, and prepared for testing.

Corrosion Studies

Metals, as load bearing members in ground support systems, must retain integrity for the duration of the repository operating life. Any ground support system will be subject to increasing gravitational and thermal stresses that will likely be severe. Stress-temperature conditions in the repository will be conducive to metal corrosion.

Metal support system components may be loaded in tension or compression, and they may be torqued, twisted, or bent. Integral components that are also in direct contact with the host rock will be subject to corrosion. A program of corrosion and loss-of-strength testing should be performed for all metal, fiberglass, plastic, grout and other materials that may be used in the repository.

When metals are bent or loaded, they become more susceptible to corrosion, possibly hydrogen embrittlement; an integral part of the corrosion studies should address this problem.

"Hot Spot" Identification

Thermal "hot spots" can exert expansion loads that can result in entry failure. The failure would be uniquely difficult to address since ambient temperature rock would fall and high temperature rock would be exposed. The installation of ground support hardware into rock faces of 120-140°F is very unusual and for temperatures greater than 140°F would be unprecedented. Ground failure near a "hot spot" or diffusively heated rock are possible, especially in the emplacement drifts. The difficulty in controlling hot rock damage may be minimized if hot spots in the rock mass could be detected early.

Early detection could possible be performed using remote sensing techniques. Remote sensing of fractures and other discontinuities in a rock mass is only a developing science. Some high-resolution mapping, 1-2 feet deep, and low-resolution mapping, 50 feet deep, of the internal structure of a rock mass has been recently achieved.

The presence of a hot spot may be indicated by anomalous heat, rock expansion, and moisture migration. Warning devices or observational criteria could potentially be developed for the early identification of hot spot development, thus alerting ground control engineers to potential resupporting needs.

REFERENCES

1. Wallace, K. G., Jr. Ventilation Planning for a Prospective Nuclear Waste Repository. Soc. Min. Eng. AIME preprint 87-151, 1987, 10 pp.

2. Nuclear Regulatory Commission Staff. Private communication, Nov, 1986. Available upon request from J. A. Lombardi, BuMines, Denver, CO.

3. U. S. Office of Civilian Radioactive Waste Management. Environmental Assessment - Yucca Mountain Site, Nevada Research and Development Area, Nevada. Dept. of Energy, DOE/RW-0073, v. 1, 2, and 3, May 1986.

4. Flores, R. J. Retrievability: Strategy for Compliance Demonstration. Sandia Natl. Laboratories, Albuquerque, NM. Sandia Rep. SAND 84-2242, 64 pp.

5. DeMarco, M. J. (BuMines, DRC technical assistance to NRC) Underground Nuclear Waste Repositories. Briefing pres. in orientation meeting at BuMines, Denver Research Center, Denver, CO, Aug. 1986; available upon request from M. J. DeMarco, BuMines, Denver, CO.

6. Hill, F. G. and H. G. Denkhaus. Rock Mechanics Research in South Africa, with Special Reference to Rockbursts and Strata Movement in Deep Level Gold Mines. Paper in Transactions of the Seventh Commonwealth Mining and Metallurgical Congress. South African Inst. Min. and Metall. (Johannesburg), v. 2, 1961, pp. 805-829.

7. Hoek, E. and E. T. Brown. Underground Excavations in Rock. Inst. Min. and Metall. (London), 1980, 527 pp.

8. James, E. L. and K. G. Stagg. A Further Investigation of a Method of Temporarily Anchoring a Cable in a Borehole. Paper in Proceedings of the Second Congress of the International Society for Rock Mechanics. Beograd, Yugoslavia, v. 3., 1970, pp. 183-188.

9. Babcock, C. O. A Flexible Helical Rock bolt. BuMines RI 8300, 1978, 26 pp.

10. Gonnerman, H. F. Concrete. Chap. in Textbook of the Materials of Engineering, ed. by H. F. Moore and M. B. Moore. McGraw-Hill, 8th ed., 1953, pp. 225-285.

11. Conway, J. P., S. M. Dar, J. H. Stears, P. C. McWilliams. Laboratory Studies of Yielding Rock Bolts. BuMines RI 8058, 1975, 40 pp.

12. MacGregor, C. W. Mechanical Properties of Materials. Chap. in Handbook of Experimental Stress Analysis, ed. by M. Hetenyi. Wiley, 1950, pp. 1-27.

13. Faupel, J. H. (ed.). Thermal Stress, Creep, and Stress Rupture. Chap. in Engineering Design. Wiley, 1964, pp. 799-910.

14. Woodruff, S. D. (ed.). Types of Rock Fracture. Chap. in Methods of Working Coal and Metal Mines. Pergamon, v. 1, 1966, pp. 138-148.

15. Kelly, J. W. Strength of Concrete, Chap. in Composition and Properties of Concrete, ed. by G. E. Troxell and H. E. Davis. McGraw-Hill, 1956, pp. 172-195.

16. Obert, L. (U.S. BuMines Applied Physics Lab., College Park, MD). Operations Nougat and Storax - In Situ Stresses in Rock, Rainier Mesa, Nevada Test Site. Clearinghouse for Federal Scientific and Technical Information, N.B.S., Springfield, VA, WT-1869, 1964, 95 pp.

17. Tadolini, S.C. Anchorage Capacities in Thick Coal Roof. BuMines IC 9058, 1986, 15 pp.

18. Farmer, I. W. Stress Distribution along a Resin Grouted Rock Anchor. Int. J. Rock mech. Min. Sci. and Geomech. Abstr. Pergamon, v. 12, 1975, pp. 347-351.

19. Snyder, V. W., J. C. Gerdeen, and G. L. Viegelahn. Factors Governing the Effectiveness of Roof Bolting Systems Using Fully Resin-Grouted Nontensioned Bolts. Pres. at 20th U.S. Symp. on Rock Mechanics, Austin, TX, June 4-6, 1979, pp. 607-613; available from Dr. Ken Gray, U. of Texas at Austin, Petroleum Engineering Dept.

20. Coates, D. F. and Y. S. Yu. Rock Anchor Design Mechanics. Can. Dept. Energy, Mines and Resour. Mines Branch Res. Rep. R233, Jan. 1971, 13 pp.

21. Ingersoll-Rand. Many Uses for Split Set Rock Stabilizers. Compressed Air, v. 87, no. 4, April 1982, pp. 28-30.

APPENDIX 1

THERMAL PRESSURIZATION: BACKGROUND

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UNDERGROUND OPENING SUPPORT

Maintaining the integrity of underground openings through support of the surrounding rock can be divided into two general areas: 1) overburden support, and 2) dead weight support. An analysis of how these support systems function is given in the following few paragraphs.

Overburden Support

Overburden support encompasses systems that control the redistribution of overburden gravity load. With increasing depth and greater loads, this support system becomes of major importance in maintaining underground opening integrity.

Because of the intangible nature of the load redistribution process, it is most easily described and understood by applying a concept of inclusions. Any stiffness discontinuity in a rock mass is considered an inclusion. Load or stress distribution depends on the physical properties of the two materials, (the host rock and the inclusion). An opening, being a less stiff material than the host rock, is a "soft" inclusion. Its perimeter displaces inwardly and signals the overburden load to redistribute to the stiffer, surrounding, host rock. The redistribution of stress is always to the stiffer material whether it is the inclusion or host material.

The confinement of either material, by geometry and/or boundary load, will alter the displacement of the materials and consequently the stiffness of the materials. The complete confinement of a material makes the material very stiff and very strong. Controlling the stiffness of rock at any location is the first step in a controlled redistribution of overburden load. This method of stress control is, of course, only possible where the host material can resist shear.

Further evidence of the load redistribution principles and how they are reflected in underground support problems is shown in Figure 1. This figure illustrates how the stress trajectories, i.e., the plotted stress direction in the rock, are redirected by local changes in stiffness within an elastic rock mass. The overburden load distribution that takes place when circular inclusions of different stiffnesses are placed in rock are illustrated in Figure 1-A and Figure 1-B. Figure 1-A shows an inclusion of reduced stiffness, i.e., a "soft" inclusion, as compared to the host material. The stress is redistributed to the stiffer host material or wallrock. In Figure 1-B, where the inclusion is stiffer than the host material, the stress is redistributed into the stiffer inclusion material.

Figure 2 illustrates the stress distribution for two circular stiffness anomalies when the host material is subjected to a uniform biaxial stress. If the field stress is changed from the illustrated uniform biaxial stress to any other field stress condition, then a different stress distribution in the host and inclusion material will occur. Figure 2-A shows the radial and tangential stress distribution near an open hole (soft inclusion). Figure 2-B shows the stress distribution for a pressurized circular hole (stiff inclusion) where the radial pressurization is two times the vertical load.

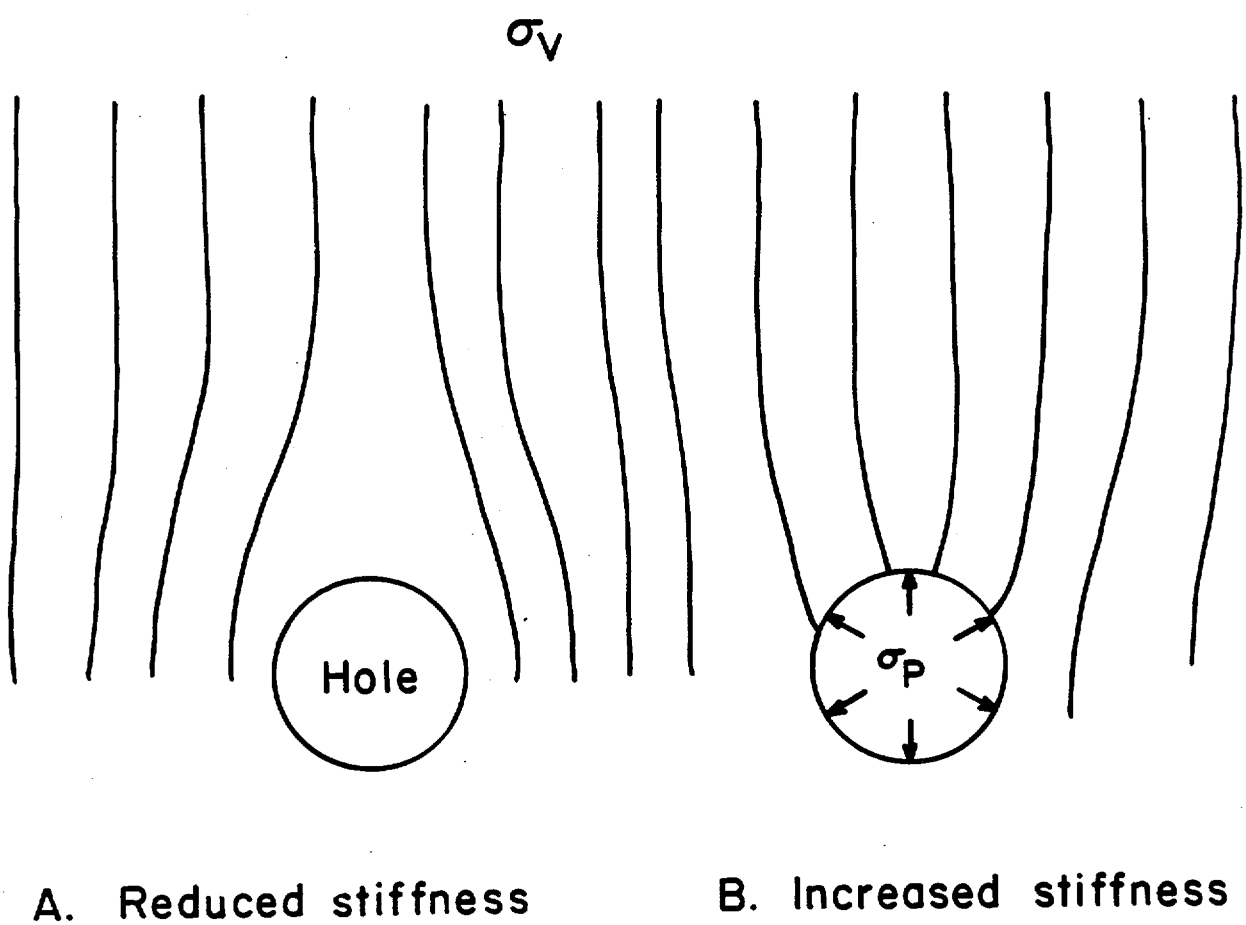

Figure 1. Stress redistribution

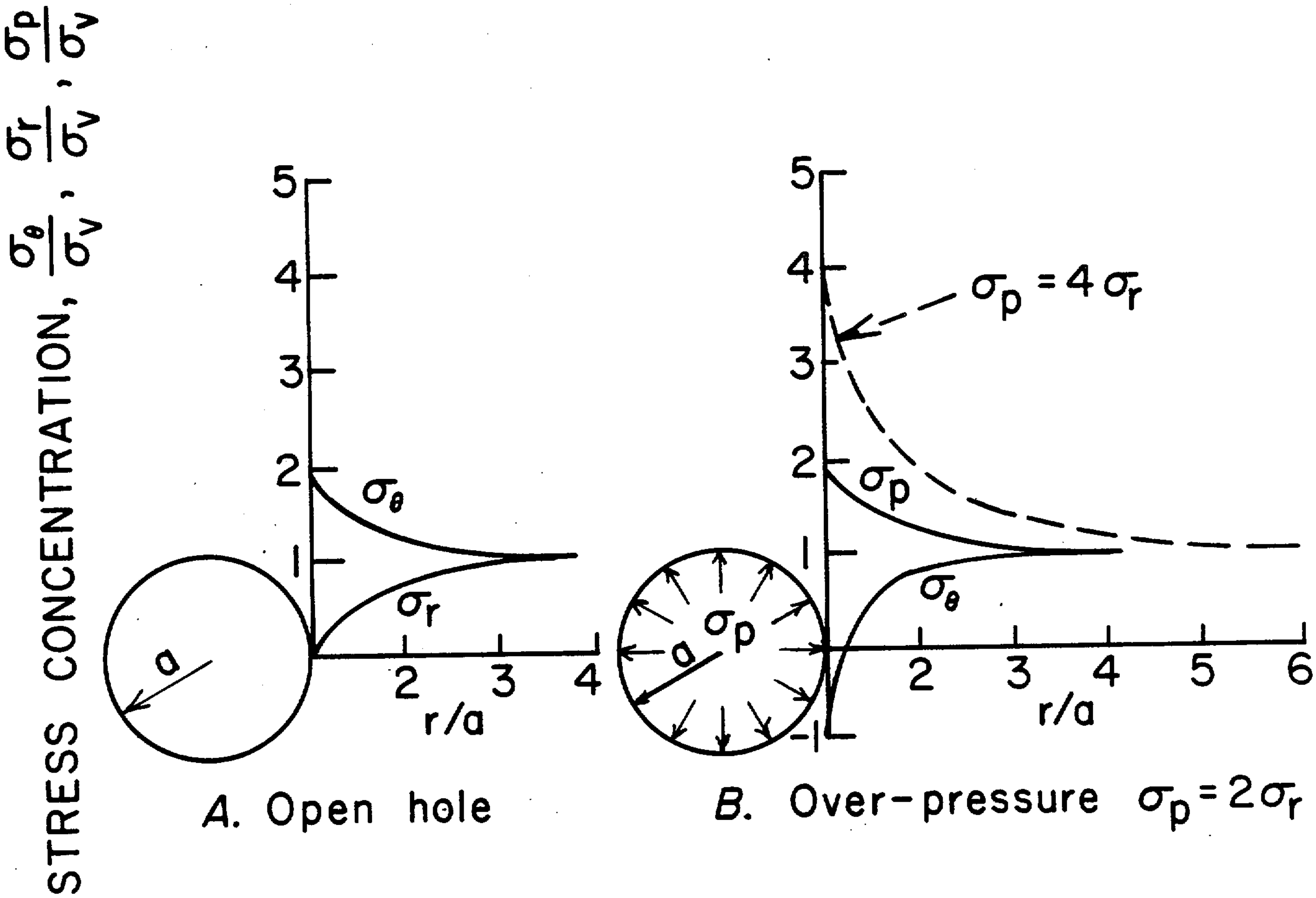

Figure 2. Stress redistribution for two circular inclusions

Illustrated in Figure 3 is what may be called a "stress control spectrum" or curve containing all the stress possibilities existing from extremes of inclusion stiffness to stiffness equal to the host material. To the left of the vertical axis is the less-stiff-inclusion's zone of influence, with an open hole as the extreme least stiff inclusion. To the right of the vertical axis is the zone of influence for the stiffer-than-host material inclusions. This curve was developed from the thick-walled cylinder formulas commonly used in mechanics-of-materials texts. The zone of influence cut-off was taken as 5 percent of the field stress.

Conclusions drawn from this work can be summarized in the statement that the magnitude and location of overburden stress within the rock can be controlled by physically changing the stiffness of selected zones of rock.

Rock expands when heated. Rock, when heated in situ, i.e., in a confined condition, exerts a force against the confining mechanism. This pressure creates a displacement which, in the context of inclusions, is analogous to the "pressurized" inclusion of Figure 2B. The stress distribution around rock heated in situ will then be similar, though not identical, to that shown in Figure 2B (uniform biaxial stress fields do not exist at the site). Hence, overburden stress loads will be concentrated onto the heated rock portions of the repository according to this theory.

Dead weight support

Dead weight support encompasses all of the methods devised to hold in place broken, fractured, loose, and interlocked material within a pressure ring

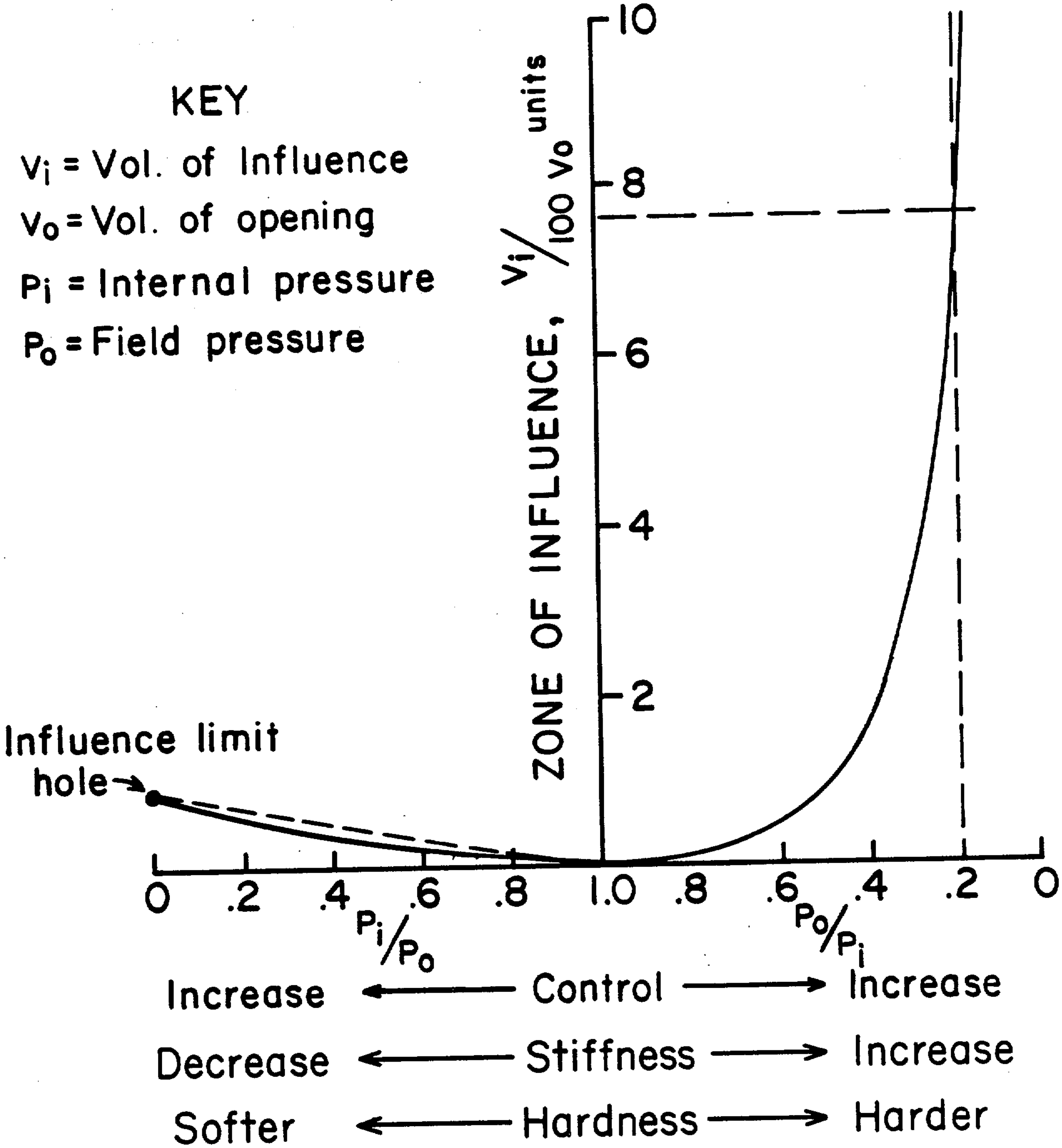

Figure 3. Stress control spectrum

surrounding an underground opening. Very little stress from the overburden load stays within this ring. This is due to inward displacement of the surface rock of an opening into the opening. This yielding diverts the stress to stiffer rock farther away from the opening. Breaking of the rock within this pressure ring occurs in the initial stages of displacement but as the stress shifts farther from the opening, most of the support required is for the dead weight of the rock.

Supports holding this dead weight can either be tension supports or compression supports. Rock bolts and roof trusses are examples of tension supports. These supports hold the rock in place by anchoring into the rock itself. Compression supports are simpler to use in that no holes have to be drilled in the rock. These supports are wedged between the roof and floor. Examples of compression supports are timber posts, cribs, yieldable arches, and other arches.

TESTING SUPPORT SYSTEMS

Models of underground support systems can be employed to design and evaluate prototype systems. Numerical modeling and scaled physical modeling can cross-check results before a full-scale physical model (field tests) is used to obtain the final results. Laboratory testing of support material and supported-systems parts constitute input for the modeling effort. An integral part of any modeling effort is the instrumentation required to determine the models response to loads. The instrumentation pertains to the physical modeling effort and applies to both scaled and prototype models. There is also some instrumentation of the laboratory testing of support-system parts and materials.

A numerical modeling of an underground nuclear waste repository can be carried out using a finite element program having a subroutine to handle materials temperatures. The present ADINA program addresses this type of problem. Physical properties and their magnitudes plus boundary loading and model geometry are the required inputs to the program. Analysis of the model would give estimates of the stress concentrations resulting from the overburden-thermal load interaction.

To determine the validity of numerical modeling results an entirely different modeling technique, i.e., physical modeling, is required. If results vary greatly then a reevaluation of the procedure and instrumentation for the physical model and/or input data for the numerical model is required.

A scaled physical model requires considerable effort in its preparation and instrumentation. It sets the basic requirements for the final full-scale physical model, that of the prototype or field test.

Scaled physical model parametric analysis for a nuclear waste repository would contain, at a minimum, the following physical quantities:

a. Density $FL^{-4}T_2$, ρ

b. Modulus of Elasticity FL^{-2}, E

c. Stress FL^{-2}, σ

d. Time T, T

e. Viscosity (Kinematic) L^2T^{-1}, ν

f. Temperature θ, θ

g. Thermal-expansion Coefficient, θ^{-1}, c

h. Length L, L

i. Poisson's Ratio - v (dimensionless)

Using dimensional analysis to develop the following dimensional products

$$\pi_1 = \frac{\rho L^2}{ET^2} , \quad \pi_3 = \frac{T\nu}{L^2} , \quad \pi_4 = \theta c, \quad \pi_5 = \frac{\sigma\theta c}{E}$$

We will then be able to develop the model equations necessary for scaling the model. The model equations giving the parametric relationships are:

$$\frac{\rho L^2}{\rho_M L^2_M} = \frac{ET^2}{E_M T^2_M} , \quad \frac{T\nu}{T_M \nu_M} = \frac{L^2}{L^2_M}$$

$$\frac{\theta}{\theta_M} = \frac{c_M}{c} , \quad \frac{\sigma\theta c}{\sigma_M \theta_M c_M} = \frac{E}{E_M}$$

From these equations the scaled physical properties of the repository host rock can be determined as a guide for developing the model-material characteristics and also the size scale.

Instrumentation developed for measuring the load distribution and redistributions, as the model is heated and loaded through thermal expansion, may be scaled up at a later date to be used in any prototype testing. Special small extensometers and strain gages must be developed for measuring movements of the model and opening displacements.

APPENDIX 2

CORROSION BEHAVIOR OF UNDERGROUND SUPPORT SYSTEMS

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CORROSION BEHAVIOR OF UNDERGROUND SUPPORT SYSTEMS

INTRODUCTION

The Nuclear Regulatory Commission has engaged the Bureau of Mines to investigate the feasibility of storing radioactive waste materials in underground repositories. The three candidate sites presently under consideration are located in volcanic tuff, bedded salt, and basalt respectively. While it is conceivable that the underground storage area finally chosen might not require ground support, it seems far more likely that some type of support system will be used. The purpose of this report is to consider the corrosion behavior of materials commonly used in the manufacture of mine support hardware in the environments anticipated for the three proposed storage sites.

Corrosion

This report will use the definition of corrosion suggested by Fontana; destruction or deterioration of a material by interaction with its environment (1). Since non-metallic materials are frequently used in some support hardware, this broad definition is preferable to one restricted to the degradation of metals, per se. For reasons of convenience, however, engineering materials such as plastics, ceramics, and rubber will be considered a separate category, and first consideration will be given to the corrosion of metals and alloys.

Thermodynamics

A major part of corrosion engineering is being able to predict whether or not a material will corrode in a specific environment, and at what rate. The first part of this question, whether or not corrosion will occur, can be addressed in terms of thermodynamics. If the corrosion products are chemically more stable than the reactants, i.e., the material and its environment, then a corrosion process is energetically possible. The thermodynamic function most commonly used for processes occurring at constant pressure is the Gibbs free energy

$$G = H - TS$$

where H is the enthalpy, S is the entropy, and T, temperature.

The criterion for whether or not a reaction can occur is that the Gibbs free energy of the corrosion products be greater than the free energy of the material and its environment, i.e.,

$$\Delta G_{products} - \Delta G_{reactants} < 0$$

The relative activities of products and reactants at equilibrium can be derived from the relationship

$$\Delta G = \Delta G^\circ + RT \ln K$$

where R is the universal gas constant and K is the equilibrium constant for that particular reaction.

Since the Gibbs free energy function has the dimensions of energy, it can be related to the concept of electrical work

$$\Delta G° = -nFE°$$

where n is the number of electrons transferred per atom, F is the Faraday number and E° is the EMF at standard condition.

Similarly, an expression can be derived relating the EMF to an equilibrium constant

$$E = E° - \frac{RT}{nF} \ln K$$

This last expression is commonly known as the Nernst equation, and is a basic relationship for the electrochemical study of corrosion. The criterion for a spontaneous reaction is the opposite of that for the Gibbs free energy; i.e., the reaction can occur only if E is positive. It should be noted that any change in the temperature T, will result in a change in the magnitude of E, and possibly in a reversal of sign. The significance of temperature as a variable in corrosion processes will be addressed in a separate section.

Pourbaix Diagrams

Metallic corrosion can and does occur in the gas phase. A more familiar environment, however, is the condensed state. While media such as liquid organics, anhydrous acids, and fused salts are encountered in engineering processes, corrosion in aqueous solutions is the area of broadest interest. The Pourbaix Atlas (13) represents an attempt to define the conditions under which a metal can corrode in aqueous solution. Pourbaix diagrams arbitrarily define corrosion of a metal as occurring when the concentration of that metal's corrosion product in aqueous solution exceeds 10^6 gram atoms per liter. An acidity range of pH 0 to pH 14 is plotted as the abscissa, and EMF for the corrosion reaction appears as the ordinate. Under this system, acidic oxidizing conditions appear at the top left of the plot, and basic reducing conditions are shown at the lower right. While these diagrams have gained wide acceptance, their utility is limited by the actual chemical species for which the Nernst equations can be written; i.e., if the actual corrosion products are different from those used in the calculations of the diagram, the diagram may not indicate the true corrosion behavior of the metal in question.

Pourbaix diagrams, sometimes called phase stability diagrams, show areas in which the corrosion products appear as solid metallic oxides, hydrides, etc. Depending on whether or not the corrosion product is stable in solution, these areas may be shown as not subject to corrosion, or more exactly to be passivated.

Passivation

It has long been observed that the corrosion behavior of metals does not occur in strict accordance with their positions in the electromotive series. In theory, any metal appearing above hydrogen in the Standard EMF series should experience corrosion with the evolution of hydrogen gas. In practice, aluminum, with an oxidation potential of 1.67 volts, shows a corrosion rate of 0-5 mils per year (mpy) in concentrated nitric acid, and is commonly used as a container material for this reagent (2). Similarly, titanium, a reactive metal, is corrosion resistant over almost the entire domain of water stability (14).

Both aluminum and titanium exhibit the behavior of a metal that has been passivated; that is to say, highly protective films of Al_2O_3 and TiO_2, respectively, have formed on the surfaces of the metals and prevented attack on the substrates. Yet another familiar example is the behavior of stainless steels, whose corrosion resistance is due primarily to a protective film of Cr_2O_3.

It should be noted that true passivation films are extremely thin, on the order of tens of Angstroms thick (3). As a consequence, normally protective films can be destroyed mechanically, or by certain chemical species, with resultant attack upon the underlying metal or alloy. Dissolution of oxide layers by chloride ion is an example of passivation destroyed by chemical attack (17). While protection of metals by mineral scales is not strictly a passivation phenomenon, it is again an example of a material being protected from corrosion by interaction with its environment. The Langelier Saturation Index (18) represents an attempt to predict to what extent protective mineral deposits will form from waters of a given chemistry.

Kinetics

While thermodynamics addresses the question of whether or not a certain corrosion reaction is energetically possible, it provides no information concerning the rate at which the reaction will occur. The importance of distinguishing between thermodynamics and kinetics may be seen in the following example: graphitic carbon is thermodynamically more stable at room temperature than diamond, yet such a back conversion is not observed to occur. In addition, many thermodynamically favorable chemical reactions proceed only in the presence of a catalyst, or if sufficient energy of activation is provided to the reactants.

The kinetics of corrosion are determined by similar constraints. If the rate at which a corrosion process proceeds is controlled by the sequence in which certain chemical reactions occur, the process is said to be under activation control (activation polarization). Conversely, if the corrosion rate is determined by the migration of reactants in the electrolyte, the reaction is diffusion controlled (concentration polarization).

Corrosion rates are influenced by many factors; ion mobilities, electrode kinetics, gaseous diffusivities, and surface chemistry to name but a few. The salient point of this discussion is to emphasize the difference between thermodynamics and kinetics. The fact that a corrosive reaction is energetically possible does not necessarily mean that it will take place. Similarly, thermodynamics alone cannot be used to predict the rate at which corrosion will proceed.

CORROSION VARIABLES

The corrosion process has already been defined as the interaction of a metal or alloy of varying composition with an environment of almost boundless variety. Each such combination must be examined on the basis of past corrosion experience with that material in a specific corrosion environment.

Nevertheless, some generalizations can be made about the effect of variables that commonly influence the corrosion process. These examples are provided by way of illustration.

Temperature

As previously noted, the Nernst equation

$$E = E° - \frac{RT}{nF} \ln K$$

contains absolute temperature as a variable. It is immediately evident that a temperature change of sufficient magnitude could result in a reversal of sign in the cell potential E; in other words, metals that were cathodic at a certain temperature could become anodic (or vice-versa) when the original temperature is changed. Uhlig (19) cites such a reversal of polarity between a zinc-iron couple with increasing temperature in aerated water; the net effect being that the normally sacrificial zinc coating became cathodic with resultant corrosion of the base metal.

Rates of corrosion processes on the other hand are frequently controlled by an Arrhenius factor

$$e^{-\Delta H/RT}$$

i.e., the corrosion rate increases exponentially as a function of temperature (4).

In cases where temperature variations produce additional physical or chemical changes in the corrosion environment, overall effects may be difficult to predict; e.g., raising the temperature of aerated water will result in decreased solubility of dissolved oxygen, and as a result lower corrosion rates (20).

Dissolved Oxygen

In general, the presence of dissolved oxygen will increase the corrosion rate of carbon steel, copper, copper alloys, and nickel in acid solutions. On the other hand, metals such as aluminum and stainless steels, whose metal oxides are resistant to these conditions, may show lessened corrosion rates in oxygenated solutions (5).

Oxygen has been mentioned specifically, because of its ubiquitous nature and because of its important role in the corrosion process. Other dissolved gasses can greatly influence corrosion behavior by reacting directly with metals, by being in chemical equilibrium with passivation films or protective scales, or by alterating solution pH. Hydrogen is of particular interest for its ability to cause embrittlement of certain alloys. This mechanism is of sufficient importance that it will be considered in a separate section.

Water Chemistry

The ionic and molecular species present in water, and their concentrations are of primary importance to the corrosion process. Distilled de-ionized water is in effect an insulator, with a dielectric constant of 80 at room temperature. Corrosion rates in such high purity deoxygenated water are extremely low. The addition, however, of even small amounts of compounds producing ionic species in solution dramatically lowers the water resistivity. The resulting electrolyte will readily support a variety of corrosion mechanisms.

Dissolved salts serve to increase the ionic strength of the solution. The overall effect on solution conductivity will be determined by the ionic mobilities of the species present. In addition to increasing conductivity of the aqueous environment, some ionic species may also become involved with the chemistry of the alloy and/or its metal oxide. The presence of Cl^- is particularly deleterious to stainless steels. One mechanism proposed to explain the corrosion behavior of stainless steels in the presence of Cl^- is dissolution of the normally protective Cr_2O_3 film to form stable Cl^- complexes.

A second such example will serve by way of illustration. Gold is a highly noble metal with a standard potential of -1.5 volts, yet is readily attacked by aqua regia. As before, in the presence of an acidic oxidizing medium, stable metal chloride complexes are formed with the resultant dissolution of the gold (35, 15). The fact that a metal or alloy is highly noble according to the EMF series is no guarantee that it will not be readily attacked by a specific chemical reagent. In summary, accurate knowledge of the chemistry of the corrosion environment is required if proper selection of engineering materials is to be made.

FORMS OF CORROSION

As previously noted, the corrosion process is a result of the interaction of a chosen engineering material with a specific environment. The type of corrosion observed and the rate at which it will occur are peculiar to that given combination of material and environment. Nevertheless, it is possible to categorize a number of different types of corrosion, either according to the mechanism responsible for each or the corrosion morphology observed.

For reasons of brevity, only those forms of corrosion that could reasonably be expected to occur in the waste storage environment will be examined. As a case in point, hot corrosion is the term used to describe dissolution of a normally protective superalloy scale by a liquid phase, generally a fused salt. Hot corrosion and other high temperature metal gas reactions are of great importance in the design and maintenance of jet engines and stationary gas turbines. Since, however, these reactions generally occur at temperatures in excess of 700°C they will not be included in a discussion of those forms of corrosion likely to occur in the proposed waste storage environment.

Uniform Corrosion

This type of corrosion is the result of uniform attack over a large surface area. A familiar example is the rust appearing on unprotected steel surfaces exposed to the atmosphere. This corrosion morphology is easily recognizable.

Galvanic Corrosion

As already noted, metals and alloys may be considered as noble or base depending on their position in the EMF series relative to the Standard

Hydrogen Electrode. If two metals, having different standard potentials, are placed in contact with each other, and a current path provided by the presence of an electrolyte, corrosion can occur. The driving force for this reaction is again the difference in Gibbs free energy between the two metals. The less noble of the two metals will become anodic and undergo oxidation, with the accompanying formation of corrosion products. Again it should be stressed that galvanic corrosion cannot occur in the absence of a suitable electrolyte. Of particular interest in the study of galvanic corrosion is the result of an unfavorable area effect. For a given current, corrosion current density is a function of the area of the anode or cathode active in the process. The combination then, of a large cathodic area and a small anode will result in rapid perforation of the less noble metal. A specific example of such a mismatch is the use of steel rivets in copper plates. In sea water, the steel rivets, anodic to the copper will experience rapid corrosion with mechanical failure accompanying loss of the rivets.

Crevice Corrosion

This type of corrosion is characterized by localized attack within crevices or interstices of structures exposed to a corrosive aqueous environment. Specific examples include corrosion occurring under bolt and rivet heads and at metal/gasket interfaces. A peculiar requirement for crevice corrosion is that the opening must be large enough to permit entry of the corrosive liquid, yet at the same time be small enough to restrict convection. Mechanisms proposed to explain crevice corrosion are somewhat complicated, but an important factor is depletion of dissolved oxygen in the crevice because of lessened convection. Because of this oxygen depletion and other associated phenomena, the crevice, in effect, becomes anodic to the exterior surface, which is protected from further corrosion. For this reason, crevice corrosion cannot be detected by a cursory inspection of exterior metal surfaces. The presence of chloride ion is particularly conducive to this form of corrosion.

Pitting

Pitting is a highly localized form of corrosion evidenced by the appearance of small holes in an otherwise undamaged surface. The pits may be closely grouped together or widely distributed. Depth of the holes is generally comparable to their diameter.

An immediate and obvious danger is that corrosion rates determined for uniform attack, cannot be used to predict service life of the material. Because of the highly localized nature of the attack, a metal can be perforated with resulting loss of structural integrity, while showing insignificant weight loss due to corrosion. Obviously, pitting is more of a concern in the case of items of tubular or thin wall construction than for those of solid design.

Pitting, like crevice corrosion, is commonly associated with stagnant liquids and the presence of Cl^-. Not surprisingly, a similar mechanism is proposed to explain pitting behavior. Again, as in crevice corrosion, the pits corrode preferentially to the rest of the metal surface. It is noteworthy that stainless steel alloys in general are more susceptible to both crevice corrosion and pitting than plain carbon steels. The reason for this behavior is believed to be the disruption of the normally protective stainless steel passivation film by chloride ions.

Stress Corrosion Cracking (SCC)

Stress corrosion cracking is defined by Fontana as "...cracking caused by the simultaneous presence of tensile stress and a specific corrosion medium" (6). A similar definition is offered by Uhlig (21). A Characteristic of SCC is that failure of the metal or alloy in the corrosion medium generally occurs well below the normal tensile yield stress, and that the corrosion rate of the unstressed material in that medium is negligibly low. In other words, the effects of tensile stress and a particular corrosion environment become synergistic.

It should be noted that the required stress need not be externally applied. Residual stresses from forming or welding as well as thermal stress may serve to introduce SCC.

A particularly insidious aspect of stress corrosion cracking is that materials affected by it show little physical or mechanical evidence of attack prior to failure. Cracks associated with SCC are frequently too fine to be seen directly, and are more readily detected with a penetrating dye. Such behavior is understandable in that as cracking progresses, specimen area is reduced and final failure occurs when the ultimate tensile strength of the material is exceeded.

The mechanism of stress corrosion cracking is not well understood, and an attempt to summarize what is know in a few paragraphs would be simplistic and misleading. It seems reasonable, however, to report some generalizations based on cumulative experience. First, the number of specific environments that will cause SCC in a given material is relatively small. A representative summary of such combination is given in Fontana (7), and in the Metals Handbook (36). Second, the disruption of normally protective films by mechanical stress or by specific chemical reagents has already been considered in this report. Such a mechanism is consistent with the highly specific nature of the stress corrosion environment and is generally accepted as part of the overall SCC mechanism.

HYDROGEN DAMAGE

Hydrogen is unique in that it is the only gas having significant diffusivity in metal lattices. Furthermore, only atomic or nascent hydrogen, as opposed to the molecular species, is small enough to exhibit this mobility. In addition, hydrogen is capable of reacting with certain metals to form stable hydrides, with resulting adverse effects on the mechanical properties of the metal or alloy (42). As a consequence, several distinct forms of hydrogen attack may be identified. Given reasonable assumptions regarding the repository environment, only two of these forms are thought to warrant consideration.

Hydrogen Blistering

It has already been noted than only atomic hydrogen can diffuse through a metal lattice. Atomic hydrogen present at the surface of a metal will diffuse into its interior. If this species accumulates in a void in the metal, the atomic hydrogen will recombine to form molecular H_2 according to the reaction

$$2H_{(g)} \longrightarrow H_{2(g)}$$

The Gibbs free energy for this reaction is some 48.6 Kcal/mole. at 25°C. Accordingly, the reaction goes strongly as written. The pressures generated in these voids by recombining hydrogen can easily exceed the tensile strength of any metal or alloy.

Hydrogen Embrittlement

Exact mechanisms for all instances of hydrogen embrittlement have not yet been determined. It is known that in some metals hydrogen reacts to form brittle corrosion products. Other mechanisms postulate the accumulation of absorbed hydrogen at dislocation sites. The phenomenon common to all forms of hydrogen embrittlement is a loss of ductility in the metal or alloy.

When sufficiently high external or residual stress is present, loss of ductility due to hydrogen embrittlement can result in failure. Some workers consider such a mode of failure as a distinct form of corrosion , aptly called hydrogen stress cracking (22). It should noted that such a failure mode has been reported for rock bolts at the WIPP site (43).

The hydrogen necessary for any of these forms of attack can be generated in a number of ways. Corrosion processes themselves can produce nascent hydrogen.

Cathodic protection, while effective in combating many types of corrosion including SCC, produces hydrogen. Significantly, a large aqueous phase need not be present. Uhlig reports hydrogen stress cracking as a result of galvanic corrosion occurring in a moist atmosphere (23).

It was stated in the introduction to this section that only the forms of corrosion that could reasonably be expected to occur in the proposed waste storage environment would be considered. The objection could be raised that materials in the repository might be subject to other forms of attack such as weld decay, knife line attack, fretting corrosion, or selective leaching, to name but a few. Similarly, nothing has been said concerning radiation embrittlement, on the assumption that any neutron flux to which support members would be exposed would be insignificant. Oxidation or tarnish will undoubtedly occur in the heated air atmosphere. On the other hand, both the likelihood of a particular type of corrosion and the probability that its occurrence would result in a material failure, were weighed in choosing those forms of corrosion discussed in this report.

CORROSION CONTROL

While the physical and chemical environment anticipated in the waste repository will be examined in detail in another section of this report, some general assumptions are possible. These in turn will place limitations on the types of corrosion control that can reasonably be utilized. For example, aqueous solutions are frequently maintained at low levels of dissolved oxygen by the addition of oxygen scavengers, such as hydrazine. Similarly, many inhibitors are known that reduce corrosion rates by functioning as retarding catalysts or poisoners. In both cases, the materials subject to corrosion are assumed to be in contact with or submerged in relatively large volumes of aqueous solution. Clearly, such will not be the case in the repository environment.

The corrosion control methods described, then, will be those techniques expected to be applicable to the proposed storage site. An additional weighting factor is that conventional support systems will be emplaced in either bedded salt, tuff or basalt. When the practicability of a corrosion prevention scheme is questionable, such as in the case of impressed cathodic protection, the method will be discussed, but with appropriate caveats.

Materials Selection

The simplest and most effective corrosion control practice is selection of a suitable metal or alloy for service in a particular environment. There are a number of materials whose corrosion behavior seems particularly well suited to a certain medium. Aluminum in concentrated nitric acid has already been mentioned, and a number of other "natural" combinations such as lead/dilute sulfuric acid are known.

Only rarely, in actual practice, is the corrosion environment so well defined. Not infrequently, conditions that favor the occurrence of more than one form of corrosion are present. In the absence of exact knowledge of the corrosion environment, materials may be selected on a "worst case scenario" basis, on the theory that whatsoever can go wrong will. There are obviously situations in which the cost of materials failure in human or monetary terms is so great that such an approach is warranted.

Additional constraints affecting materials selection may be fabricability, mechanical properties, aesthetic appearance, and cost. By way of example, most ceramics show excellent corrosion resistance and are relatively inexpensive. Their lack of ductility, however, precludes them from use as engineering materials in many instances. Similarly, gold and platinum are resistant to most corrosion environments, but are low in tensile strength and are prohibitively expensive for most uses. All told, a satisfactory selection of materials is usually a compromise, weighted by the priorities given to these and other factors.

Any survey of material selection would be incomplete without some discussion of corrosion testing. The uncertain nature of the corrosion environment in many cases has already been stressed. The best assurance that a candidate material will perform satisfactorily is a carefully planned program of both laboratory and service corrosion testing. Such tests should model as closely as possible the environment to which the material will be exposed when in use.

In many instances, the diversity of corrosion tests and apparatus has been limited only by the ingenuity of the individual researchers and the particular needs of the areas in which they work. Other test procedures, e.g., Huey test (ASTM A-262) have generally recognized utility, and have become standardized. As a rule, such tests are designed to detect and evaluate susceptibility to a specific form of corrosion, and are not a substitute for in-service or pilot plant tests.

In a similar vein, considerable controversy exists regarding the value of "accelerated" tests. Such procedures extrapolate the long term corrosion behavior of a material from its short term exposure to a more severe environment. While these tests may be of benefit in the preliminary screening of candidate materials, they cannot in generally be relied on to give accurate information concerning long term corrosion rates. The question then arises, how long should corrosion tests be conducted? As a generalization, the lower the corrosion rate of a material tested, the longer the tests should be run. An obvious case in point is stress corrosion cracking. As already noted, a metal or alloy subject to this form of attack, will show little physical or mechanical evidence of corrosion prior to failure. Such tests obviously must be conducted until failure of the specimen occurs.

Environmental Modification

It would seem that the repository as currently conceived would afford little opportunity to modify the corrosion environment to which the support systems will be subjected. For example, rock bolts used for support would be embedded in a massive formation of salt, tuff or basalt, depending on which site is chosen. The heads of these bolts as well as other support members will be exposed to what will be essentially a heated air atmosphere of unknown relative humidity, possibly containing condensation nuclei of unknown composition. The one foreseeable case of environmental modification is the one in which hygroscopic salt absorbs any moisture present in the storage area. This possibility will be examined in more detail in a later section, along with a review of actual conditions in several salt mines.

Cathodic Protection

Corrosion is the result of a metal or alloy undergoing oxidation, defined as the loss of electrons.

$$M \rightarrow M^{+n} + ne$$

As seen earlier, the driving force for current flow is the EMF difference between competing chemical reactions in the medium. Since oxidation occurs at the anode of the electrochemical cell, the corroding metal is said to be anodic to the substance being reduced. If however, a supply of electrons at sufficient current is provided to the corroding metal, the course of the reaction is reversed, and the metal or alloy is said to be cathodically protected.

Cathodic protection can be effected in two ways; 1) by an impressed current from an external power supply or 2) by the use of a sacrificial anode. Cathodic protection by the use of an impressed current will typically consist of an external DC power supply whose negative terminal is connected to the structure to be protected. An inert electrode, frequently graphite or high silicon iron, serves as the anode. Current flow is maintained by the surrounding medium, e.g., in the case of pipeline protection, earth. Current density required for cathodic protection is determined by severity of the corrosion environment and other factors.

Sacrificial anodes serve the same purpose as an impressed current, supplying electrons to the metal to be protected. In this case however, cathodic protection is achieved at the expense of the anode, which undergoes corrosion, Two major requirements for sacrificial anodes are 1) that they be substantially anodic to the structures to be protected, and 2) that they be relatively inexpensive. For these reasons, magnesium and zinc find extensive use as sacrificial anodes. In order for either form of cathodic protection to function, the corrosion medium itself must be able to support the required amount of current. Obviously this condition is met in the case of a hot water tank protected by a magnesium sacrificial anode, where the supporting electrolyte is water. Earth environments also permit the passage of sufficient current to cathodically protect pipelines and storage tanks via an external power source. Cathodic protection has been found to be effective in preventing several types of corrosion, including stress corrosion cracking. On the other hand, hydrogen generated by the inpressed current can cause hydrogen cracking (8, 23). It should be recalled that the failure of 1040 steel roof bolts at the WIPP site was attributed to hydrogen embrittlement.

A final note of caution is in order. Whether or not any of the three geologic environments proposed for the waste storage facility could support adequate current density to provide cathodic protection, has not been determined. The feasibility of cathodic protection in the storage repository will be determined by the materials chosen for support systems, severity of the corrosion environment, and resistivity of the salt, basalt, or tuff lithology.

Anodic Protection

It was shown in an earlier section that a number of metals and alloys exhibited superior corrosion resistance because of the formation of passivating films. In the simplest sense, anodic protection uses an external anodic current to effect the formation and maintenance of such protective films on metals and alloys showing active/passive behavior. Since the passivating films are stable only within a relatively narrow range, voltage of the impressed current is controlled by a potentiostat. Current requirements for anodic protection are generally quite low. An additional advantage is its applicability in highly corrosive media. A comparison of anodic and cathodic protection is given in Fontana (9).

Coatings

Coatings of metallic and nonmetallic materials can be an effective means of corrosion control. Generally, coatings serve one of two purposes: (1) to act as a barrier against the corrosion environment, (2) to function as a sacrificial anode for the underlying material. In addition, highly corrosion resistant metals are frequently used to coat less noble substrate materials.

Metallic Coatings

Metallic coatings are often used to produce corrosion resistant surface properties superior to those of the substrate metal. Nickel and chromium coatings are applied to steel automobile bumpers and plumbing fixtures. Contacts in electronic equipment are gold plated to provide corrosion resistance. Such coatings are commonly applied by electrodeposition. Other means for modifying the surface composition of a metal or alloy include chemical vapor deposition, plasma spray, ion implantation and diffusion coatings. All have in common the fact that the resultant coating is intended to be more corrosion resistant than the substrate.

A second type of metallic coating is sacrificial; that is, the substrate is cathodically protected by corrosion of the surface material. Metals commonly used as sacrificial coatings are zinc and cadmium. Some familiar examples are galvanized iron and steel, and cadmium plated screws. In general, the thicker such coatings are, the longer they will continue to afford cathodic protection.

Depending on the temperature and chemical composition of the corrosion environment, potential reversals are possible, in which the supposedly sacrificial coating becomes cathodic to the substrate metal it was designed to protect (19).

Organic Coatings

The term organic coating is used to comprise a wide variety of paints, varnishes, lacquers, resins, etc., applied to a substrate metal. The common purpose of all such coatings is to provide a barrier between the structure to be protected and the corrosion environment. In general, such coatings should not be used when their failure would result in rapid corrosion of the substrate. Paint coatings are generally thin and the risk that they will be damaged mechanically is always present. On the other hand, thick coatings such as coal tar with reinforcing fibers are abrasion resistant and are frequently used to protect buried pipelines.

Portland Cement

The Pourbaix diagram of iron indicates that in an oxidizing environment, at a pH of from 10 to 13, a passivating film of Fe_2O_3 will form (16), protecting the substrate from further corrosion. Fortunately, Portland cement at a pH of about 11, provides just such an environment. An additional advantage of a Portland cement coating is that its coefficient of expansion closely matches that of steel. Water pipes so protected have been in service for more than 60 years (24). Portland cement coatings are inexpensive and relatively easy to apply, their main disadvantage being their susceptibility to mechanical and thermal shock.

CORROSION BEHAVIOR OF SUPPORT MATERIALS

The purpose of this section will be to provide an overview of the corrosion behavior of the materials from which commercially available rock bolts are fabricated. Some twelve types of rock bolts may be considered. Of that twelve, eleven are made from plain carbon steel, and one from high strength low alloy steel. All the metallic bolts and hardware must conform to ASTM F 432, steel specifications for rock bolts and hardware. In addition, glass fiber/epoxy resin roof bolts are commercially available, but because of their non-metallic construction, will be discussed separately.

Plain Carbon Steels

Steels meeting ASTM F 432 specifications are generically referred to as plain carbon. Their AISI/SAE designation is 10XX, the last two digits of this series indicating the average carbon content in hundredths of a percent, or "points." Carbon content of rock bolts and accessories specified by ASTM F 432 may range from .20 to 1.0 percent, depending on the design use of the finished product. Plain carbon steels used in these components then, will be designated by series 1020 to 1095, with grade 1040 probably being most common. The corrosion of these steels will be considered as a class.

Effect of Metallurgical Variables

In general, as long as oxygen diffusion is the rate controlling step in the corrosion process, the carbon content of series 10XX steels has little if any effect on their overall corrosion resistance. In an aqueous environment, the corrosion process will be under the control of oxygen diffusion over a range of about pH 4 to pH 10. Since the pH range of naturally occurring waters is well within these limits, it can be said that in fresh waters, corrosion resistance of these steels is not affected by variations in carbon content (37, 25). In addition, under these conditions normal compositional variations in elements other than carbon have negligible effect on corrosion rates.

On the other hand, in acidic solutions, the corrosion rate becomes increasingly dependent on the rate of hydrogen evolution. Because of the lower hydrogen overvoltage associated with a cementite Fe_3C phase, corrosion rates increase with higher carbon content (26). Sulphur and phosphorus levels specified by ASTM F 432 are the same regardless of carbon content. For a given carbon content of 10XX steels, however, different manganese compositions are available (38). In acid media, the grade with higher manganese content should show somewhat improved aqueous corrosion resistance (27).

Corrosion Behavior of Plain Carbon Steels

As previously discussed, the corrosion behavior of plain carbon steels in fresh waters is determined by mineral content, pH, dissolved oxygen content, and temperature. Because of wide variations in these conditions in naturally occurring waters, corrosion rates are difficult to predict, and corrosion testing is warranted in most cases. Nevertheless, some generalizations can be made. As long as the corrosion process is controlled by oxygen diffusion, that is, over the pH range from 4.5 to 9.5, the corrosion rate of plain carbon steels is not appreciably pH dependent. Corrosion rates under these conditions, are however, dependent on the dissolved oxygen content of the water. Distilled water at 25°C, in equilibrium with air, will contain some 8 ppm dissolved oxygen. Corrosion rates will in general be linearly related to dissolved oxygen content up to this point. Corrosion rates of plain carbon steel under these conditions will range from effectively no corrosion in the absence of dissolved oxygen, to a steady state value of 2-10 mpy in air saturated water (10, 28, 39). Again, these rates refer to neutral waters at room temperature, and are meant only to be representative of rates expected in service.

As previously discussed, corrosion rates are frequently governed by an Arrhenius factor, $e^{-\Delta H/RT}$. As a consequence, as long as the process remains under diffusion control, the corrosion rate may be expected to double with every 30°C increase in temperature, for a given concentration of dissolved oxygen. At temperatures in excess of about 80°C, deoxygenation of the water becomes significant, and the overall corrosion rate declines. When hydrogen evolution starts to become a significant part of the process, i.e., at pH < 4, corrosion rates become increasingly temperature dependent. Under these conditions, as little as a 20°C temperature rise may result in a doubling of the corrosion rate in acid media.

Dissolved Salts

The effect of dissolved salts on the aqueous corrosion of plain carbon steels is complex, observed corrosion rates being dependent on both the cations and anions present. Anything but a cursory review is beyond the scope of this discussion. Later sections of this report will attempt to determine as closely as possible the expected nature of the corrosion environment at the proposed sites.

Since one of the proposed repository sites is located in bedded salt, some generalizations are possible concerning corrosion in this environment. As previously mentioned, corrosion rates in salt solutions are dependent on the ionic species present. The effect of the chloride ion as a corrosive agent, however, predominates over that of other ions present. In addition, the corrosion rate of plain carbon steel in NaCl solution is dependent on the concentration of the dissolved salt, reaching a maximum at about 3wt%. With increased salt concentration, a decline in the corrosion rate is observed, presumably because of lowered dissolved oxygen content (29). In effect then, a 3wt% NaCl solution may represent a worst case scenario for the salt environment. Seawater contains some 3.4% salt at a pH of about 8. Estimation

of the corrosion behavior of plain carbons steels in the salt repository environment from saltwater data then, would seem reasonable.

Fontana gives a representative value for corrosion of plain carbon steel in quiet seawater of about 5mpy (11). Uhlig (30) cites similar values, as does the ASM Handbook (40). It must be reemphasized that these data are for quiet seawater, containing some 5-10ppm dissolved oxygen, and at a temperature on the order of 20°C. On the other hand, corrosion rates for splash zones, subject to alternative wetting and drying, may be much higher (12). Assuming only atmospheric confining pressure, corrosion rates at higher temperatures could be as much as an order of magnitude greater. For trapped water subject to a confining pressure in excess of 1 atmosphere, corrosion rates at temperatures above the normal boiling point would be difficult to predict, but must be assumed to be unacceptably high.

Pitting

The role of chloride ion in both pitting and crevice corrosion has been discussed previously. In general, plain carbon steels are less susceptible to both pitting and crevice corrosion than are stainless steels or other alloys that depend on a passivation film for corrosion protection. Nevertheless, carbon steels are subject to pitting, and may exhibit penetration rates that are unacceptable, particularly when product design entails thin wall construction. Fontana cites typical penetration rates for carbon steel in quiet seawater as on the order of 30mpy (10). Data appearing in the metals Handbook are consistent with this figure, but in addition show a trend toward increasing penetration rate with length of exposure (40).

Stress Corrosion Cracking

Because of the complex nature of SCC as well as hydrogen stress cracking, only the broadest statements can be made about the susceptibility of plain carbon steel to these types of corrosion. Plain carbon steels generally show less susceptibility to SCC in seawater than do stainless steels. On the other hand, hydrogen embrittlement appears to have contributed to the failure of 1040 steel in the WIPP environment. It should be assumed that the possibility exists for both these forms of corrosion to accompany the use of plain carbon steels in any of the three proposed site environments.

Atmospheric Corrosion

Conditions determining atmospheric corrosion rates are the temperature, relative humidity and composition of the gas phase environment. The presence of even small amounts of extraneous gases such as SO_2 can greatly increase corrosion rates. Consequently, only representative data can be given. Atmospheric corrosion rates at any of the proposed sites will depend not only on temperature, dew point, and relative humidity, but on what if any extraneous gases are present, and on any condensation nuclei in the air. In addition, thermal gradients or periodic temperature variations may result in the presence of a condensed phase.

Such diverse conditions are reflected in the wide range of values reported for atmospheric corrosion of plain carbon steels (41). Conditions ranged from nonpolluted, low humidity environments, to industrial and tropical marine environments. Reported corrosion rates varied from less than .1 mpy to over

200 mpy. Atmospheric corrosion rates of plain carbon steels in any of the proposed sites will be expected to fall within this range of values.

High Strength Low Alloy (HSLA) Steels

As already noted, one type of rock bolt is fabricated not from plain carbon steel, but from HSLA steels. SplitSet^R stabilizers are made from either Exten-H60 or KAI-Well 55. Both alloys differ from plain carbon steel by the presence of low amounts of manganese, vanadium, columbium, and copper. The USBM Rolla Research Center has conducted a series of corrosions tests on Splitset^R stabilizer HSLA steels in various mine environments. (44, 45, 46).

Test conditions comprised dissolved oxygen contents from .1 to 10.5 ppm, and temperatures from 11°C to 53°C. The Langelier index for the various mine waters varied greatly, and lower corrosion rates in a number of instances were attributed to the formation of protective $CaCO_3$ films. Cumulative corrosion rates reported for both HSLA steels over diverse mine environments ranged from less than 1 mpy to 60 mpy. The value of this series of this reports is that it documents corrosion behavior of the HSLA steels in environments reflecting the diversity of conditions that rock stabilizers may be subject to in an actual mine environment.

For purposes of comparison, HSLA steels generally exhibit corrosion rates comparable to their plain carbon counterparts in fresh or salt water (40, 31). They do, however, show improved resistance to atmospheric corrosion, primarily because of the more adherent oxide layer formed when the alloying elements are present (41).

Galvanized Steels

Several rock bolt types are available with a galvanized coating. The function of such sacrificial coatings was discussed in an earlier section. A major assumption in comparing corrosion rates for galvanized steels is that the substrate material is not involved in the corrosion process. The validity of this assumption, however, may depend on the nature of the corrosion environment (32). Cathodic protection of galvanized coatings can be reduced by the formation of hydrous oxides (33).

In seawater, neither of these exceptional conditions occur and steel is cathodically protected by the zinc coating. Uhlig suggests that each mil of zinc coating will provide about 1 year of protection for the substrate (34). The key questions in the use of galvanized coatings then, are (1) is the corrosion environment such that effective cathodic protection will occur, and (2) is the zinc coating sufficiently thick to afford corrosion protection for the design life of the product.

In the same series of tests already mentioned (44, 45, 46) USBM Rolla Research Center determined corrosion rates of galvanized roof bolt steels in a variety of mine waters. Corrosion rates reported ranged from less than 1 mpy to 5 mpy. In some instances, a qualitative evaluation of the pitting potential was made.

Galvanic Coupling of HSLA and Plain Carbon Steels

It has been stated that plain carbon and HSLA steels show comparable corrosion rates in most aqueous media. EMF potentials of the two materials, however, may be dissimilar. If the two materials are in electrical contact in the presence of a supporting electrolyte, galvanic corrosion may occur. Mixing of these or any other metallurgically dissimilar components in a situation where the possibility of galvanic corrosion exists, should be avoided.

Glass Fiber/Epoxy Roof Bolts

These materials have excellent corrosion resistance to a wide range of environments. Their main disadvantage is loss of strength and eventual degradation of the epoxy matrix at elevated temperatures. Since temperatures approaching 200°C are considered possible in the proposed repository, it would appear that support systems made from these materials are not suitable for long term use in the anticipated environment.

CONCLUSION

As stated at the outset, this report was not intended to be a technical exposition of the corrosion process. Other researchers will immediately realize that in many instances broad generalizations have been made; the information presented is accurate, but not comprehensive. The alternative to such an approach is to say nothing. The bibliography on the other hand, is intended as a source book for those wishing an in-depth study of some particular aspect of corrosion science.

REFERENCES

1. Fontana, M. and N. Greene., 1967, Corrosion Engineering, McGraw Hill, p. 2.
2. Op. cit., p. 247.
3. Op. cit., p. 321.
4. Op. cit., p. 21.
5. Op. cit., p. 127.
6. Op. cit., p. 91.
7. Op. cit., p. 100.
8. Op. cit., p. 113.
9. Op. cit., p. 212.
10. Op. cit., p. 271.
11. Op. cit., p. 269.
12. Op. cit., p. 268.
13. Pourbaix, M., 1974, Atlas of Electrochemical Equilibria in Aqueous Solutions, NACE, 644 pp.
14. Op. cit., p. 79.
15. Op. cit., p. 403.
16. Op. cit., p. 318.
17. Uhlig, H., 1971, Corrosion and Corrosion Control, 2nd Edition, Wiley, p. 75.
18. Op. cit., pp. 116-118.
19. Op. cit., pp. 235-238.
20. Op. cit., p. 97

21. Op. cit., p. 134.

22. Op. cit., p. 141.

23. Op. cit., p. 143.

24. Op. cit., p. 242.

25. Op. cit., pp. 100, 118.

26. Op. cit., pp. 101, 118, 120, 129.

27. Op. cit., p. 121.

28. Op. cit., p. 93.

29. Op. cit., p. 113.

30. Op. cit., p. 101.

31. Op. cit., p. 119.

32. Op. cit., p. 231.

33. Op. cit., p. 236.

34. Op. cit., p. 235.

35. Cotton, F., and G. Wilkinson, 1966, Advanced Inorganic Chemistry, 2nd Edition, Wiley, pp. 1039-1040.

36. American Society for Metals, Metals Handbook, Desk Edition, 1985, ASM, Section 32, p. 26.

37. Op. cit., Section 4, p. 91.

38. Op. cit., Section 4, p. 7.

39. Op. cit., Section 4, p. 92.

40. Op. cit., Section 4, p. 93.

41. Op. cit., Section 4, p. 90.

42. Smith, D., 1948, Hydrogen in Metals, University of Chicago Press, 366 pp.

43. Lucas, J., 1984, Analysis of Rock Bolt Material Failures at the WIPP Site, Sandia Report 84-0224, Sandia National Laboratories, 36 pp.

44. Tilman, M., A. F. Jolly, III, and L. A. Neumeier, 1984, Corrosion of Friction Rock Stabilizers in Selected Uranium and Copper Mine Waters, BuMines RI 8904, 23 pp.

45. Tilman, M., A. F. Jolly, III, and L. A. Neumeier, 1985, Corrosion of Roof Bolt Steels in Missouri Lead and Iron Mine Waters, BuMines IC 9055, 9 pp.

46. Jolly, A. F., III, and L. A. Neumeier, Corrosion of Friction Rock Stabilizer Steels in Underground Coal Mine Waters, BuMines IC to be published.

BIBLIOGRAPHY

Metals Handbook
9th Edition
American Society for Metals, 1978

Modern Electrochemistry
Bockris, J. and A. K. N. Reddy
Plenum Press, 1970

Corrosion Testing Procedures
Champion, F. A.
John Wiley and Sons, 1964

Physical Chemistry
Daniels, F. and R. A. Alberty
John Wiley and Sons, 1963

Environmental Assessment
Deaf Smith County Site, Texas
DOE/RW-0069, Volume 1

Environmental Assessment
Yucca Mountain Site
DOE/RW-0073, Volume 2

Environmental Assessment
Reference Repository Location
DOE/RW-0070, Volume 2

Physical Chemistry
Eggers, D. F., N. W. Gregory, G. D. Halsey Jr., B. S. Rabinovitch
John Wiley and Sons, 1964

The Corrosion and Oxidation of Metals
Evans, U. R.
Edward Arnold (London), 1960

Corrosion Engineering
Fontana, M. G. and N. D. Greene
McGraw-Hill, 1967

Solutions, Minerals and Equilibria
Garrels, R. M. and C. L. Christ
Freeman, Cooper & Company, 1965

Thermodynamics
Lewis, G. N., M. Randall, K. S. Pitzer, L. Brewer
McGraw-Hill, 1961

Cathodic Protection, A Symposium
NACE, 1949

Atlas of Electrochemical Equilibria in Aqueous Solutions
Pourbaix, M.
NACE, 1974

Electrolyte Solutions
Robinson, R. A. and R. H. Stokes
Academic Press, 1959

Hydrogen in Steel
Smialowski, M.
Pergamon Press, 1962

Corrosion, Causes and Prevention
Speller, F. H.
McGraw-Hill, 1951

Fundamental Aspects of Stress Corrosion Cracking
Staehle, R.
NACE, 1969

Corrosion and Corrosion Control
Uhlig, H.
John Wiley and Sons, 1971

Corrosion Handbook
Uhlig, H.
John Wiley and Sons, 1948