U.S NUCLEAR REGULATORY COMMISSION
DIVISION OF WASTE MANAGEMENT

# REVIEW OF "MODIFICATION OF ROCK MASS PERMEABILITY IN THE ZONE SURROUNDING A SHAFT IN FRACTURED, WELDED TUFF"

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(SAND86-7001)

TECHNICAL ASSISTANCE IN HYDROGEOLOGY
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## 1.0 INTRODUCTION

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| WWLNUM: | 295 |
| DOCUMENT NO.: | SAND86-7001 |
| TITLE: | "Modification of Rock Mass Permeability in the Zone Surrounding a Shaft in Fractured, Welded Tuff" |
| AUTHORS: | John B. Case and Peter C. Kelsall |
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| REVIEWERS: | David B. McWhorter, Lyle A. Davis, Thomas L. Sniff, Water, Waste and Land, Inc., and Adrian Brown, Nuclear Waste Consultants |
| DATE REVIEW COMPLETED: | August 31, 1987 |
| SCOPE: | Reviewed from the standpoint of performance assessment in regard to the NRC evaluation of shaft construction and design. The following three specific requests were raised by the NRC in their letter directing WWL to review the document: |

1) Conduct a brief review of the bibliography cited in the report to determine if any major references have been omitted.

2) Determine if there is adequate and sufficient basis to defend the model.

3) Evaluate whether the model is better (in a regulatory sense) than an earlier model identified in a Department of Energy letter on "Exploratory Shaft Performance Analysis Study" dated July 15, 1985.

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| KEY WORDS: | Permeability, stress analysis, blasting damage, fracture permeability |
| DATE APPROVED: | |

## 2.0 SUMMARY OF DOCUMENT AND REVIEW CONCLUSIONS

### 2.1 SUMMARY OF DOCUMENT

This report presents results of a study which investigated whether the vertical shafts to be constructed during site characterization and repository construction will create preferential pathways for water or air to enter (or leave) the repository after sealing. The possible pathways are divided into three zones: the seal material, the interface between the seal material and the host rock, and a modified permeability zone surrounding the original opening. The report considers only the modified permeability zone, with an emphasis on the Topopah Spring unit (and the Tiva Canyon unit which has similar hydrologic and mechanical properties according to the authors). Stress relief calculations are also performed for the nonwelded Calico Hills unit which underlies the Topopah Spring unit.

The two processes which are considered as dominant in the modification of permeability near the openings are stress redistribution and rock damage due to blasting. Stress redistribution around the shaft will occur regardless of the method of excavation employed. This redistribution of stresses may alter the rock mass by creating new fractures. In addition, changes in stress caused by a shaft may result in the opening or closing of existing fractures. Blasting will damage the rock adjacent to the excavation wall which will probably lead to increased fracturing and, therefore, larger permeability.

#### 2.1.1 Stress Modification Effects

The effects of stress redistribution on the alteration of permeability around a shaft opening are manifested on the fracture system, either by creating new fractures or altering existing fractures. Excessive compressive or tensile stresses can cause fracturing of originally intact rock. In addition, changes in the stress field can cause opening or closing of the pre-existing fractures, altering the fracture permeability.

To evaluate the potential for additional fracturing, tangential stress at the shaft wall where it is a maximum was determined using the Kirsch equation. This equation is for a circular opening and assumes that the rock is homogeneous, isotropic and linearly elastic. To estimate the maximum and minimum far-field (undisturbed) <u>in situ</u> stresses required for the Kirsch equation, predicted and measured values of the ratio of horizontal to vertical stress, $K_0$, were utilized. The predicted values of $K_0$, obtained with finite element modeling to evaluate gravitational effects, ranged from 0.2 to 0.4 due to topographic variations at Yucca Mountain. Data collected during actual hydrofracturing tests in boreholes resulted in $K_0$ values ranging from 0.4 to 0.8 indicating that tectonic or residual stress may be contributing to the total horizontal stress. The minimum far-field stress was therefore set to 0.25 times the vertical stress which was calculated based on the overburden weight. The maximum far-field stress was taken as equal to the vertical stress. The analysis was conducted for a shaft depth of 310 m (1020 ft), which is the approximate depth of the repository at the location of the exploratory shaft. The calculated tangential stress ranged from a minimum of -1.72 MPa (tension) to a maximum of 18.82 MPa (compression). By comparing the results of this analysis to the mean intact rock strengths for Topopah Spring welded tuff (tensile strength of 16.9 MPa and compressive strength of 171 MPa) as reported by Nimick et al. (1984), the authors concluded that fracturing of intact rock due to stress redistribution around a shaft is unlikely.

Although it was concluded that shaft emplacement would not cause fracturing of intact rock, the effects of changes in local stress were evaluated with respect to existing fractures. As a conceptual model, the authors point out that fracture permeability should be increased where normal stresses are reduced across fractures or shear stresses are increased. On the other hand, fracture permeability should be reduced where normal stresses are increased. The following assumptions were used to simplify the problem to allow the analyses to be performed:

1. Prior to excavation, in situ stress state is isotropic and the normal stress acting across each fracture is equal to the average far-field value.

2. The only stresses which effect fracture aperture are those which act in the radial or tangential directions. Shear stresses are neglected.

3. After excavation, the stress acting across each fracture can be estimated as the radial stress which occurs at any distance from the shaft wall.

The authors assert that these assumptions are conservative, or tend to over predict permeability increases, for an isotropic stress state.

The rock-mass response to excavation of a shaft can be either elastic (completely reversible) or plastic. When the response is elastic, the radial stress is reduced and the permeability of fractures which are tangential to the shaft should increase. Under elastic conditions, the tangential stresses are expected to increase relative to the in situ stress and the permeability of radial fractures should be reduced. When the rock-mass response is plastic, both tangential and radial stresses are expected to be reduced in the plastic zone near the shaft so that the permeabilities of both tangential and radial fractures will be increased. Outside the plastic zone, elastic response is predicted and the mode of stress redistribution is termed elastoplastic.

Within the elastic zone, the analysis of stresses and displacements is based upon the Kirsch solution as described by Jaeger and Cook (1976). For this solution, both radial and tangential stresses are functions only of the shaft radius, far-field hydrostatic stress, and radius to the point for which the calculations are being performed. The solution predicts that the radial stress at the shaft wall will be reduced to zero while the tangential stress at the shaft wall will be equal to twice the far-field hydrostatic stress. When the stress at the shaft wall exceeds the unconfined compressive strength of the rock, failure is predicted and the analysis must be conducted using the elastoplastic approach.

The method of Hoek and Brown (1980) was used for the elastoplastic analysis. This method of analysis requires that the radial distance to the boundary between the plastic and elastic zones be determined. Within the plastic zone, radial stress is a function of shaft radius, rock mass properties (e.g. unconfined compressive strength), and internal support stress as well as radius to the point for which the calculations are being performed. In the analyses presented, internal support stress was set to zero simulating an unlined shaft or one in which the liner is placed after stress redistribution has occurred. The tangential stress is a function of radial stress and rock mass properties. In the elastic zone (which is located outside the plastic zone) the stresses are calculated with equations which are similar to the Kirsh solution but which have been normalized to stress conditions which exist at the plastic-elastic boundary.

Estimates of rock mass mechanical properties were required to perform the analyses described in the previous paragraphs. Since these parameters have not been measured directly in welded tuff, comparative methods were used to obtain the estimates. Methods proposed by Hoek and Brown (1980) and Protodyakonov (1964) were utilized with the former being emphasized. The method of Hoek and Brown (1980) is a somewhat subjective method by which the Rock Mass Rating (RMR) is estimated based on the unconfined compressive strength of intact rock, rock quality designation, joint frequency, joint condition, and groundwater condition. For each of these parameters, except groundwater condition which was set to the maximum since unsaturated conditions are expected, a range of values were estimated based on currently available laboratory and field data. As a result three RMR values were obtained for the Topopah Spring welded tuff — an upper bound estimate of 84, an expected value of 65, and a lower bound estimate of 48 — and two RMR values were obtained for the Calico Hills nonwelded tuff — an upper bound estimate of 71 and a lower bound estimate of 49. These RMR values were then coupled with an estimated range of unconfined compressive strength for intact rock as determined by laboratory measurement.

A range of in situ horizontal stresses were estimated based on both theoretical concepts and field measurements. According to theory and a rock mass Poisson's ratio of 0.25 as estimated by Nimick et al. (1984) a value of the ratio of horizontal to vertical stress, $K_0$, of 0.25 can be calculated. As described earlier, finite element modeling and field measurements indicate that $K_0$ is in the range of 0.2 to 0.8. Therefore, the authors selected a range of $K_0$ values corresponding to the RMR ranges described in the previous paragraph. The lower bound estimate of $K_0$ was set to 0.25 while the expected value was set to 0.6 and the upper bound estimate was set to 1.0. Vertical stresses were estimated based on overburden weight as calculated using the unit weight of 2250 $kg/m^3$ for the Topopah Spring welded tuff as reported by Nimick et al. (1984).

The results of the stress redistribution analyses indicate "that a wide variation in rock mass behavior might be observed depending on depth, in situ stress and rock properties." Elastic response is predicted at depths of both 100 meters and 310 meters when upper bound and expected values of rock mass properties and lower bound and expected values of horizontal stress are used in the calculations. At both depths, the response is elastoplastic when lower bound rock mass properties and upper bound horizontal stress (equal to vertical stress) are used in the calculations. Based on these results, the authors conclude that the expected response is elastic in nonlithophysal zones of welded tuff, but plastic response may occur in lithophysal zones or intensely fractured zones where strength is lower. Plastic behavior is expected for the nonwelded Calico Hills. For the nonwelded Paintbrush tuff, which overlies the Topopah Spring unit, the behavior may be elastic or plastic depending on in situ stresses and rock mass strength. The authors also point out that inelastic deformation can be limited by rapid placement of the shaft liner after excavation.

Since matrix permeabilities of the tuff units at Yucca Mountain tend to be small, the authors assume that stress redistribution will effect only fracture permeability. Therefore, the model employed to relate fracture permeability to stress is based on the cubic law which states that permeability is proportional to aperture cubed. By assuming that the fractured welded tuff system can be represented as a parallel array of fractures the authors show that relative permeability, defined as permeability at in situ stress levels divided by permeability at a decreased level of stress, is a function of aperture width at the two stress levels.

Laboratory studies performed on single fractures in core samples as reported by Peters et al. (1984) provided the basis for relating stress to fracture permeability. The report under review considered only results from the unloading cycle from the peak confining pressure. Peters et al. (1984) concluded that fracture permeability is inversely proportional to effective normal stress, although each sample showed different changes in relative permeability as compared to stress. For the sample which showed the most permeability variation with stress, the relative permeability varied between 1 for an effective normal stress of 12 MPa to almost 100 for an effective normal stress of 0 MPa. For the sample which showed the least variation, the maximum relative permeability was less than 10 (no effective normal stress) and was reduced to 1 at an effective normal stress of about 6 MPa. Field permeability tests performed in a single fracture found in the G-Tunnel, which is located on the Nevada Test Site, also showed that fracture permeability is inversely related to normal stress. These studies also showed that fracture permeability shows little or no stress dependence when the effective normal stress exceeded the pre-existing stress of about 3 MPa.

The results of the laboratory and field studies were used to develop upper and likely estimates of relative permeability as a function of effective normal stress at depths of 100 and 310 meters. For a depth of 100 meters, the upper estimate predicts that relative permeability will vary between 1 and about 100 for stresses of about 2 MPa and 0 MPa, respectively. The likely case for a 100 meter depth predicts a relative permeability range between 1 and about 30 for stresses of 1.5 MPa and 0 MPa, respectively. At the 310 meter depth, the likely estimate of relative permeability ranges from 1 at an effective normal stress of about 4 MPa to about 30 for zero effective normal stress. The upper estimate at this depth ranges from 1 at an effective normal stress of about 7 MPa to nearly 100 for zero effective normal stress.

The rock mass stress-permeability relationships described in the previous paragraph were combined with calculated stress distributions to develop predictions for rock mass permeability near a shaft. The results are presented as graphs of relative permeability as a function of normalized distance from the shaft as calculated for Topopah Spring welded tuff at depths of 100 meters and 310 meters. For both depths, both upper and likely estimates are presented. These graphs indicate that stress redistribution should not effect relative permeability beyond a distance of about six to seven shaft radii from the wall. At a depth of 100 meters, most of the permeability change occurs within one radius of the shaft wall while at 310 meters, significant change may occur up to a distance of about 2 radii from the wall.

### 2.1.2 Blasting Effects

As currently planned, the majority of the shafts at Yucca Mountain will be excavated by blasting, which can damage the rock adjacent to the excavation wall. The authors of the reviewed report have divided the damaged area around a blast hole into three zones. Immediately around the blast hole, a crushed annulus is formed. The middle zone is the blast fractured zone where a pattern of radial cracks form. The third and outermost zone is described as the extended seismic zone where tensile or shear failure may occur. In a real system the effects of blasting will be influenced by rock strengths as well as heterogeneities which may exist in the rock. Six case histories which describe rock damage and permeability changes due to blasting during tunnel construction were provided. A generalized relationship between charge density and blasting damage for tunnel blasting conditions is available for granitic rocks. These data suggest that blast effects are dependent on charge density and independent of excavation size.

Based on the literature review, which included approximately 60 documents, the authors concluded that blast damage would be limited to about 0.5 meter from the shaft wall, assuming that controlled blasting techniques are utilized. As an upper range estimate, it was concluded that blast damage would not extend beyond one meter from the shaft wall. Within the blast damage zone, it was assumed that fracture frequency is increased by a factor of three. It was further assumed that fractures created by blasting are similar in nature to pre-existing fractures. As a result it is predicted that the permeability in the blast damaged zone will increase by a factor of three over the increase that occurs due to stress relief.

### 2.1.3 Modified Permeability Zone Model

The changes in the rock mass permeability due to the stress redistribution and blast damage were summarized for two cases, the expected and the upper bound. The changes were evaluated at depths of 100 meters and 310 meters in the Topopah Spring unit. For expected conditions at both depths, the equivalent rock mass permeability, which is an average permeability over an annulus one shaft radius wide, is 20 times the permeability of the undamaged rock mass. For the upper bound case, the equivalent rock mass permeability is predicted to be 40 times larger than in situ permeability at a depth of 100 meters. For a depth of 310 meters, the upper bound rock mass permeability is predicted to be 80 times larger than the in situ permeability.

## 2.2 SUMMARY OF REVIEW CONCLUSIONS

From a geomechanics point of view, the only aspect of this model that has other than empirical support is the failure computations. The direct measurements of the permeability of fractured tuff under various stress conditions are very limited, and do not include one direct measurement of permeability as a function of location in any tuff rock mass adjacent to an excavated opening. Accordingly the model of the expected permeability around the shaft is not validated by the process described. However, the approach used to develop the permeability model described in the report is reasonable and the results obtained (an equivalent permeability increase of between 20 and 80 times) seem consistent with changes that would be expected under careful excavation techniques.

Therefore, it is concluded that the model for permeability as a function of distance from the shaft wall presented in this report is reasonable. However, it is based almost entirely on theoretical concepts and should be regarded as an untested, theoretical model. The model is certainly adequate to conclude that permeability increases are likely to be quite significant and may require corrective measures (e.g. grouting).

## 3.0 SIGNIFICANCE TO THE NRC WASTE MANAGEMENT PROGRAM

The amount of radioactivity which can be released to the accessible environment following repository closure is specified in 40 CFR 191. As part of the licensing process, the NRC must independently assess the ability of the repository, including both engineered and natural systems, to meet those standards. Site characterization will include the sinking of an exploratory shaft and several shafts will be necessary to allow waste materials to be emplaced. The potential exists that these shafts may provide a preferential pathway for the escape of radionuclides. An important aspect of performance assessment will include evaluation of how the shafts may effect isolation of the wastes in the repository.

The repository, as currently envisioned, will be located in the unsaturated zone. Therefore, it is unlikely that shaft sinking will have any effect on normal groundwater flow since it is thought that this flow occurs in the matrix with the fractures remaining essentially dry. However, zones of modified permeability around shafts may be important with respect to evaluation of impacts due to unforseen flooding from surface waters. Further, vapor and gaseous transport of radionuclides may be enhanced in such zones. With these considerations in mind, a model which can describe the variations in rock mass permeability near shafts will be required to allow performance assessment calculations to be performed.

## 4.0 MAJOR REVIEW COMMENTS (PROBLEMS, DEFICIENCIES, AND LIMITATIONS)

### 4.1 STRESS ANALYSIS

The analysis is the standard evaluation of stress around a circular opening in a homogeneous, elastic medium. While little discussion is provided in the report about the fact that the stress analysis is being performed in a material that is highly fractured, it would appear that the development of a generic position on this matter is only reasonable under the simplifying assumption of homogeneous stress conditions. However, this assumption appears to be nonconservative with respect to stress changes induced by the excavation of the shaft. Based on this assumption, the report concludes that no new fractures will be created by stress changes resulting from excavation. This evaluation is weakened by the omission of the direct consideration of the effects of shear stresses in the vicinity of the shaft. It is possible that shear stresses will be the determining consideration in the stability of the rock in the vicinity of the shaft, and that fracturing is possible under the shear stresses induced. No attempt is made to check this possibility in the report.

The authors state that results of modeling studies indicate a horizontal to vertical stress ratio of 0.2 to 0.4 while direct measurements indicate that the ratio is between 0.4 and 0.8. The greater values obtained with the direct measurements are attributed to tectonic or residual stresses. It seems possible, therefore, that the assumption of an isotropic <u>in situ</u> stress field is inappropriate. A USGS report (Ellis and Swolfs, 1983), which was not included in the references or bibliography, indicated that the minimum horizontal principal stress in the welded tuff units above the static water level at USW-G1 may be less than half that of the vertical stress. Ellis and Swolfs (1983) considered the most significant feature observed on the borehole televiewer log to be the borehole ellipticity. As described, borehole ellipticity occurs when stress concentrations around the drill hole are sufficient to exceed the local <u>in situ</u> shear strength of the rock, causing spalling of the borehole walls. Borehole ellipticity was observed in a consistent east-west orientation throughout most of the logged section of drill hole USW G-1. Although the values of horizontal stress ratio used in the analysis considered in the report under review (0.25 and 1.0) are conservative with respect to cited values (0.2 to 0.8), the effects of an anisotropic <u>in</u>

situ stress field on permeability were not investigated. Because of this, the results obtained may not be conservative but development of a model which accounts for an anisotropic stress field may be difficult, if not impossible, at this time.

## 4.2 FRACTURE STRESS/PERMEABILITY RELATIONSHIP

The entire development of the rock mass stress-permeability relationship is based upon the simplifying assumption that the fractures in the system are parallel and have a constant aperture. Case and Kelsall used the cubic law and a relationship from Snow (1968) for a parallel array of planar joints to determine rock mass permeability. Using this approach, an equation is derived which shows that the change in rock mass permeability as a function of stress is independent of the fracture frequency given the assumption that the frequency does not change in response to stress changes. The parallel array model is an oversimplification and there is no significant discussion in the report as to how the model can be modified to consider radial fractures.

As described previously, the authors rely on one laboratory study (Peters et al., 1984) and one field study (Zimmerman, et al., 1985) as support for development of the constitutive relationship between permeability and stress. Two envelope curves, based on data collected during the laboratory study, are used to relate permeability to stress. These envelopes do not take any cognizance of the apparent importance of in situ stress levels, which is clearly suggested by the field test data, on the relationship between stress and permeability. The procedures used to develop the stress/permeability relationship appears to be highly empirical. It depends strongly on the very low stress permeability condition, which is shown in field tests to be highly dependent on both the method of stress reduction and the nature of the fracture being tested. Nonetheless, it would seem that little better can be done until additional data regarding permeability as a function of stress is collected.

## 4.3 BLASTING EFFECTS

The change in permeability as a result of damage from blasting operations was estimated based on a review of available literature. Of the 60 or so relevant citations in the report, apparently only two reported actual permeability as a function of distance from the point of blasting. Based on the literature review, the authors assume that blasting damage will be limited to 0.5 meter for the likely case to 1.0 meter for the upper bound case. It is further assumed that, within the damaged zone, fracture frequency (and therefore permeability) is increased by a factor of three and that the fractures created by blasting are identical to natural fractures. While the studies cited tend to support the assumed extent of damage, evidence supporting the assumption that fracture frequency would be increased by a factor of three could not be located. However, these assumptions seem reasonable, especially given the precision of other aspects of the analysis.

## 5.0 SPECIFIC REVIEW COMMENTS

This section of the document review is dedicated to addressing the specific questions raised by the NRC in their request to review this document. Each of their questions is addressed in the following sections.

### 5.1 REVIEW OF BIBLIOGRAPHY

The response to the question of completeness of the bibliography has been divided into three categories: blasting damage, fracture permeability relationships, and reports dealing with Yucca Mountain data. Each of these topics are discussed in the following paragraphs.

In general, the bibliography dedicated to rock damage due to blasting (Appendix B) appears to be complete. As part of the review process, we searched a computerized data base which contains mining references. The search was limited to blasting damage as it relates to tunnel and shaft excavation. The search identified eight references which may be important with respect to evaluation of final plans for construction of the exploratory shaft. It does not appear that the references which were discovered through this search contain data which refutes the contention that blast damage, under controlled conditions, will be limited to an annular region between 0.5 and 1.0 meters from the shaft wall. Nonetheless, in the interests of completeness, the NRC staff may wish to add these references to their library. A listing of the references along with the abstract provided by the computerized search are provided in Appendix A.

With respect to fracture permeability, two areas of general references appear to be weak. The first is the group of papers and dissertations describing the pioneering work in the area of the relationship between permeability, fracture geometry, and stress (for example, Sharp, 1970; and Louis, 1969). The second is the provision of a bibliography of the recent work in the same area, which is referred to in passing in the report, but not dwelt upon.

The final category of references which we reviewed for completeness concerned reports which provide site specific data for the Yucca Mountain site. We reviewed both the bibliography (Appendix B) and the References section of the report and identified those publications which appear to present actual mechanical (and thermal) data for the Yucca Mountain site. We then compared this list with the publication data base maintained by WWL. Based on this comparison, we have identified five documents which we currently do not have in our data base. A listing of these documents is provided in Appendix B.

## 5.2 MODEL ADEQUACY

Based on our review, it is our opinion that there is adequate and sufficient basis to defend the model. The model has been developed using a reasonable approach:

a. stress changes modify apertures which modifies permeability;

b. blasting causes additional fractures, further enhancing permeability;

c. the effects can be combined.

The experimental basis for the quantification of the model appears to be weak, although it may be adequate for licensing purposes if (as seems likely based on the 1985 document) the enhanced permeability zone is of limited importance in the performance of a repository in tuff. This could be dramatically improved by direct measurement of an actual blasted drift/shaft in tuff, which could be conducted as part of the Exploratory Shaft activities.

## 5.3 COMPARISON WITH EARLIER MODEL

This model is better than the earlier model presented by the DOE in July of 1985. The new model is based on a scientifically rational approach, using accepted principles of stress analysis and fluid mechanics, supported with at least some laboratory and in situ data. The model can be calibrated against actual experience in tuff during construction of the Exploratory Shaft and thus allows appropriately accurate evaluations of the performance of the repository.

## 6.0 REFERENCES

Ellis, W.L. and Swolfs, H.S., 1983. "Preliminary Assessment of In-Situ Geomechanical Characteristics in Drill Hole USW G-1, Yucca Mountain, Nevada," USGS-OFR-83-401, U.S. Geologic Survey, Denver, Colorado.

Hoek, E. and Brown, E.T., 1980. Underground Excavations in Rock, Institution of Mining and Metallurgy, London, England, 527 pp.

Jaeger, J.C. and Cook, N.G.W, 1976. Fundamentals of Rock Mechanics, Halsted Press, London, England, 583 pp.

Louis, C., 1969. A Study of Groundwater Flow in Jointed Rock and its Influence on the Stability of Rock Mases, Doctoral Thesis, University of Karlsruhe, English translation Imperial College Rock Mechanics Research Report #10, London, England.

Nimick, F.B., Bauer, S.J. and Tillerson, J.R., 1984. "Recommended Matrix and Rock-Mass Bulk, Mechanical, and Thermal Properties for Thermomechanical Stratigraphy of Yucca Mountain, Keystone Document No. 6310-85-1 (Memorandum to T.O. Hunter), Sandia National Laboratories, Albuquerque, New Mexico.

Peters, R.R., Klavetter, E.A., Hall, I.J., Blair, S.C. Heller, P.R. and Gee, G.W., 1984. "Fracture and Matrix Hydrologic Characteristics of Tuffaceous Materials from Yucca Mountain, Nye County, Nevada", SAND84-1471, Sandia National Laboratories, Albuquerque, New Mexico.

Protodyakonov, M.M., 1964. "The Size Effect in Investigations of Rock and Coal", Proceedings of the International Conference on Stress in the Earth's Crust, Henry Krumb School of Mining, New York, NY, Unpaginated Addendum.

Sharp, J.C., 1970. Fluid Flow Through Fissured Media, Ph.D. Thesis, University of London [Imperial College].

Snow, D.T., 1968. "Rock Fracture Spacings, Openings, and Porosities", J. Soil Mech. Found. Div., Proc. Amer. Soc. Civil Engrs., Vol. 94, pp. 73-91.

Zimmerman, R.M., Wilson, M.L., Board, M.P., Hall, M.E., and Schuch, R.L., 1985. "Thermal-Cycle Testing of the G-Tunnel Heated Block", Proceedings 26th U.S. Symposium on Rock Mechanics, A. A. Balkema, Boston, Massachusetts, Vol. 2, pp. 749-758.

# APPENDIX A

## ADDITIONAL REFERENCES

## ROCK DAMAGE CAUSED BY BLASTING

Rustan, A., Naarttijaervi, T., Ludvig, B., 1985. CONTROLLED BLASTING IN HARD INTENSE JOINTED ROCK IN TUNNELS. CIM Bulletin v 78, n 884, Dec., 1985, p 63-68, Lulea Univ of Technology, Lulea, Swed.

Full-scale tests have been done at LKAB in hard intense jointed magnetite ore. Four different types of perimeter charges have been tested: tube charges, ANFO mixed with plastic beads, detonating cord and linear-shaped charges. Three types of initiation of the perimeter holes have been used: conventional (half-second delay detonators), instantaneous and ultra short cutblasting initiation (1.5 ms delay). Cutblasting with detonating cord in the perimeter holes gave the smallest damage to the surrounding rock. A new classification system for controlled blasting regarding the damage to the surrounding rock has been devised. (Edited author abstract)

Konya, C. J., Britton, R., Lukovic, S., 1984. REMOVING SOME OF THE MYSTERY FROM PRESPLIT BLASTING. Journal of Explosives Engineering v 2, n 1, p 20-22.

Increased highway construction and structured rock engineering during the last two decades promoted presplit applications. Basic research has not kept pace. Researchers are still looking for better ways to control explosive induced fractures, especially in geologically complicated rock. Techniques developed in the last century, such as borehole notching, may be suitably adapted to increase further the efficiency of modern-day methods.

Chertkov, V. Y., 1983. THEORETICAL EVALUATION OF THE CHARACTERISTICS OF INCREASED MICROCRACK ABUNDANCE IN EXPLOSIVE BREAKING OF BLOCK STONE. Soviet Mining Science (English translation of Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh) v 19, n 3, May-Jun 1983 p 197-202.

On the basis of kinetic concepts of destruction, theoretical estimates are made of: (1) the maximum amplitude pressure of the blast pulse on the blast-hole walls in a medium with a certain initial microcrack density corresponding to the condition of absence of crushing and crumbling; (2) the size of an enhanced microcrack concentration zone; (3) the microcrack distribution in that zone; and (4) the possible size and number of initial radial cracks in the blast-hole walls. 8 refs.

Spivak, A. A., Kondrat'ev, Yu. V., 1979. INFLUENCE OF CHARGING DENSITY ON BLASTING PARAMETERS IN A SOLID MEDIUM. Soviet Mining Science (English translation of Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh) v 15 n 1 Jan-Feb 1979 p 29-35.

This article gives the results of a laboratory investigation of the explosion of compact charges with densities of 0.4 and 1.0 g/cm**3 (loose and pressed singly precipitated PETN) and 0.5 g/cm**3 (loose double-precipitated PETN), as well as the comparative characteristics of explosions of a compact charge and of a charge in an air cavity. Using repeatedly remelted sodium thiosulfate as the model medium, it is shown that a decrease in the effective charging density can reduce the extent of the zone of overcrushing of the material by blasting. 9 refs.

Tregubov, B. G., Taran, E. P., Balagur, Y. A., Trufakin, N. E., 1981. EXPERIMENTAL INVESTIGATION OF A CONTAINED EXPLOSION OF ELONGATED CHARGES. Soviet Mining Science (English translation of Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh) v 17, n 6, Nov-Dec 1981 p 532-538.

It is shown that the best material for stemming is hard rock chips, with coarseness 3-10 mm. The length of stemming which can remain unejected from the borehole amounts to 140-150 $r_0$, but this length can be reduced somewhat, as even in the case of ejection of the stemming the zone of shattering is almost unchanged, but destruction of the mouth of the borehole occurs. The average radius of the zone of crushing in hard rock amounts to approximately 9 $r_0$, and the radius of intense fracture formation attains 18 $r_0$. Fracturing of the rock mass decreases in inverse proportion to the square of the distance from the axis of the charge. With the interaction between contained charges arranged at an optimum distance of 15-20 $r_0$, the zone of shattering is increased by a factor of approximately one and a half in comparison with a single charge. 7 refs.

Isakov, A. L., Sher, E. N., 1983. PROBLEM OF THE DYNAMICS FOR DEVELOPMENT OF DIRECTIONAL CRACKS DURING BLAST-HOLE FIRING. Soviet Mining Science (English translation of Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh) v 19, n 3, p 189-196.

A comprative analysis is made of three proposed theoretical solutions of the problem of propagation of two diametrically directed radial cracks during firing of a blast-hole charge without tamping in a uniform brittle material. It is shown that a quasi-static approach with a time lag is suitable for describing the test process over the whole range of radial crack movement velocities. It is established that (a) the size of the embryonic cracks (notches) has practically no effect on the final dimension of the radial cracks developing from them; (b) the value of the polytropic factor for detonation products used in the calculation also has no apparent effect on the final result; (c) in contrast to zonal problems for breakdown, an increase in the scale of explosion leads to a marked increase in the relative dimensions of radial cracks; (d) the value of the critical stress intensity factor has a weak effect on the final result, whence it follows that the accuracy of determining calculated values of $K_{Ic}$ in this problem does not have to be high; (e) a reduction in the initial pressure in the blast-hole to several kilobars by intoducing an annular air gap around the explosive charge causes practically no reduction in the final dimensions of the cracks obtained in this way, and this is what makes it desirable to use higher-power explosive charges during directional breakdown of rock by blasting. 7 refs.

Fourney, W. L., Dally, J. W., Holloway, D. C., 1978. CONTROLLED BLASTING WITH LIGAMENTED CHARGE HOLDERS. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts v 15, n 3, p 121-129.

A series of experiments, which demonstrate that fracture control can be achieved in a blasting process, are described. Fracture was produced in polymeric and rock models along specified radial planes to form control planes and/or fragments. Fracture control was achieved by utilizing a ligamented split tube for charge containment. The split tube, under the action of the gases from the explosive, produces highly concentrated stresses on the borehole at the slit locations. These concentrated stresses initiate cracks which propagate radially outward to form the controlled fracture plane. The mechanisms involved in fracture control were examined by using dynamic photoelasticity and high-speed recording methods. Photoelastic records which show the dynamic state of stress and propagating cracks are described. These results were employed in evaluating the effectiveness of the charge holders in controlling the fracture process in blasting. 5 refs.

Dolgov, K. A., 1976. INFLUENCE OF JOINTING ON THE EFFICIENCY OF ROCK CRUSHING BY BLASTING. Soviet Mining Science (English translation of Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh) v 12, n 4, p 454-457.

On comparing the blasting efficiencies, it is seen that the greatest influence on the results of blasting is exerted in markedly jointed and very markedly jointed rocks. In these rocks the degree of crushing by the blast is less, and the blasting efficiencies are less by 20 and 28% respectively than in slightly jointed rocks. The calculated values are, of course, valid only for the given blasting conditions. In practice, for a given value of $d_f$ for markedly jointed and very markedly jointed rocks, in order to increase the blasting efficiency the specific explosives consumption and the cost of drilling and blasting are reduced. 5 refs.

## APPENDIX B

## REPORTS/PUBLICATIONS WHICH CONTAIN DATA FOR THE YUCCA MOUNTAIN SITE WHICH ARE NOT CONTAINED IN THE WATER, WASTE AND LAND, INC. PUBLICATION DATA BASE

Bauer, S.J., Holland, J.F. and Parrish, D.K., 1985. "Implications about Insitu Stess at Yucca Mountain", Proceedings of the 265h U.S. Symposium on Rock Mechanics, A. A. Blakema, Boston, Massachusetts, Vol. 2, pp. 1113-1120.

Langkopf, B.S. and Gnirk, P.R., 1986. "Rock Mass Classification of Candidate Repository Units at Yucca Mountain, Nye County, Nevada", SAND82-2034, Sandia National Laboratories, Albuquerque, New Mexico.

Nimick, F.B., Bauer, S.J. and Tillerson, J.R., 1984. "Recommended Matrix and Rock-Mass Bulk, Mechanical, and Thermal Properties for Thermomechanical Stratigraphy of Yucca Mountain, Keystone Document No. 6310-85-1 (Memorandum to T.O. Hunter), Sandia National Laboratories, Albuquerque, New Mexico.

Price, R.H., 1983. "Analysis of Rock Mechanics Properties of Volcanic Tuff Units from Yucca Mountain, Nevada Test Site", SAND82-1315, Sandia National Laboratories, Albuquerque, New Mexico.

Price, R.H. and Bauer, S.J., 1985. "Analysis of the Elastic and Strength Properties of Yucca Mountain Tuff, Nevada", Proceedings of the 26th U.S. Symposium on Rock Mechanics, A.A. Balkema, Boston, Massachusetts, Vol. 1. pp. 89-94.