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2 October 1986

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U.S. Nuclear Regulatory Commission
Division of Waste Management
Washington, D.C. 20555

"NRC Technical Assistance
for Design Reviews"
Contract No. NRC-02-85-002
FIN D1016

Dear David:

Enclosed is Itasca Review No. 001-02-22, "Evaluation of Damaged Rock Zone Around Repository Openings," Rockwell Hanford Operations Computational Brief No. 573 (March 13, 1986). Please call me if you have any questions.

Sincerely,

Mark Board for

Roger D. Hart
Program Manager

cc: J. Greeves, Engineering Branch
Office of the Director, NMSS
E. Wiggins, Division of Contracts
DWM Document Control Room

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ITASCA DOCUMENT REVIEW

File No.: 001-02-22

Document: "Evaluation of Damaged Rock Zone Around Repository Openings," Rockwell Hanford Operations Computational Brief No. 573 (March 13, 1986)

Reviewer: Itasca Consulting Group, Inc. (M. Board)

Date Approved:

Date Review Completed: 2 October 1986

Significance to NRC Waste Management Program

This document attempts to determine the extent of the damaged or yielded zone around repository openings from analytical and numerical techniques. This work was prompted by comments on the Draft Environmental Assessment regarding the significance of the disturbed zone on post-closure repository performance. The effect of this zone on enhanced groundwater transport from the repository depends, to a large degree, on the radial extent of this zone. This document was referenced extensively in the Final Environmental Assessment.

Summary of the Document

This document presents calculations of the extent of the yield zone surrounding shafts, emplacement holes, and emplacement drifts using analytical and numerical calculation methods. The rock mass is treated as an elastoplastic continuum with properties derived from laboratory test results. The in-situ plasticity properties assigned to the material was derived from Sublette (1983). The cohesion and friction angle were determined from the empirical Hoek and Brown (1980) failure criteria. The resulting values of cohesion and friction angle are 15.1 MPa and 58.3°, respectively, for the dense basalt and 10.9 MPa and 49.5°, respectively, for the internal vesicular zone. These are very high cohesion and friction angle values which, subsequently, had a great effect on the calculations of the yield zone.

Three analytical ground reaction curve methods were used to estimate the extent of yield around circular openings. These are:

- Hoek and Brown (1980)
- Daemen (1975)
- St. John et al (1983)

The first two methods assume a hydrostatic field stress and thus are of limited value in bounding the response at BWIP under the highly deviatoric state.

The numerical model VISCOT (Intera, 1983) was used to examine the case of an emplacement room in the dense interior basalt and the internal vesicular zone (IVZ) of the Cohassett Flow.

The report draws the following conclusions.

- The analyses indicate relatively small zones of yielding around the emplacement rooms, shafts, and emplacement holes. For an emplacement room, under proposed full thermal stress conditions,* a yield zone of 21cm was calculated.
- For an emplacement hole under full thermal stress conditions, yield zones are calculated of 1.3cm and 6.3cm thick for dense basalt and vesicular basalt, respectively.
- The excavations will be generally stable with only minor support.

There are several significant problems associated with these analyses—the greatest being the input material properties. The friction and cohesion assigned to the dense basalt are very high. With a friction angle of 58°, the yield zones are forced to be very small. We feel that a more reasonable value of friction is obtained from measurements on joints. This would put the friction angle in the range of 35°-45° (Sublette, 1986).

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*Rockwell has estimated the mechanical effect of the heating to be the same as the addition of a horizontal far-field stress of 24.7 MPa to the existing stress of 61.5 MPa. This total stress of 86.2 MPa for fully-heated conditions was rounded to 90 MPa for the analysis.

The in-situ stress state used does not cover the full design range specified by the Rockwell expert review panel (St. John and Kim, 1986) and therefore underestimates the peak horizontal design stress by roughly 20%. The method for estimating thermally-induced stresses is also highly simplistic, and it is not obvious if it represents conservative assumptions.

In conclusion, we disagree rather strongly with the conclusions reached by this report. The material properties chosen for the analyses and the underestimation of in-situ stress force the analyses to indicate little yield.

Problems, Limitations and Deficiencies

YIELD ZONE DETERMINATION

Calculation Methods — Four methods are used in this report to determine the radius of the yield zone: the ground reaction curve methods by Hoek and Brown (1980), Daemen (1975) and St. John et al (1983) and the finite element code VISCOT (Intera, 1983).

The Hoek and Brown and Daemen analyses examine the problem of a circular hole (tunnel) in an elastic-perfectly plastic material subjected to hydrostatic stresses at infinity. Both techniques are analytical in nature and allow the determination of the radius of yield zone* based on the internal support pressure in the tunnel. Both methods are essentially the same, with the exception that Hoek and Brown is formulated in terms of an empirical failure criterion while Daemen uses the standard Mohr-Coulomb criterion with provision for dilatency.

The St. John et al (1983) method was developed by Detournay (1983) and examines the problem of a circular hole in an elastic-perfectly plastic (Mohr-Coulomb) rock mass under non-uniform biaxial field stresses. The method is semi-analytic in nature and involves the use of design charts to determine the yield zone radius. The resulting yield zone is therefore not circular but dependent on the deviation in the stress field.

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*Yield zone, here, is identified as the radius to which the rock has undergone inelastic deformations.

The finite element program VISCOT was used to analyze the non-circular (emplacement room) geometry as well as the circular shaft. A Mohr-Coulomb elastic-perfectly plastic constitutive model was used.

Material Properties, Initial Conditions — Two rock types were modeled in these studies: the "dense" interior basalt and the interior vesicular zone of the Cohassett Flow. Values for material constants were obtained from repository design studies by RKE/PB (McElrath, 1984; RKE/PB, 1985). These studies obtained empirical failure constants m and s for the Hoek and Brown (1980) yield criteria from the Rock Mechanics Data Package compiled by Sublette (1983). The design models used in the present analysis require the explicit plasticity parameters c (cohesion) and ϕ (friction). Mitchell (1984) has used an empirical procedure given by Hoek and Brown (1980, p. 515) to determine these properties from the m and s curve fit parameters. The strength envelope for dense basalt is given in Fig. 1 and the corresponding properties in Table 1. The envelope and properties for vesicular basalt are given in Fig. 2 and Table 2, respectively.

As seen in the tables, the values derived for the rock mass friction angle is very high at 58.3° for the dense basalt and 49.5° for the vesicular zone. These values are far higher than generally used in practice for similar hard rocks and is higher than the 35-45° range for joints given by Sublette (1986). The cohesive strength assigned to the rock mass is also quite high at 15.1 MPa. The presence of infilling materials will possibly result in this high value. It is stressed here that these values are not conservative.

The stress values used in the analyses are given in Table 3. The total applied stresses are composed of two parts: the in-situ field stress and the thermally-induced stresses resulting from thermal expansion of the rock mass. The maximum horizontal in-situ stresses cover the complete range given by Kim et al (1986). In a recent document review (Itasca, 1986), it was shown that the most conservative range of stress values from the hydraulic fracturing data presented by Kim et al (1986) is:

$$58.3 < \sigma_{Hmax} < 83.3 \text{ MPa}$$

$$22.0 < \sigma_{v} < 26.4 \text{ MPa}$$

The values of σ_{Hmax} = 61.5 or 72.9 MPa used in these analyses are, again, non-conservative.

Table 1

DENSE INTERIOR MATERIAL PROPERTIES USED IN ANALYSES OF PROGRESSIVE FAILURE

Parameter	Analysis method (see notes)			
	GRC1	GRC2	GRC3	VISCOT
Drift size	2 m radius	2 m radius	2 m radius	2 m radius and 6x3 m placement room
Elastic modulus	38 GPa	38 GPa	38 GPa	38 GPa
Poisson's ratio	.25	.25	.25	.25
Rock mass strength				
UCS	64.6 MPa	106.4 MPa	106.4 MPa	106.4 MPa
c	—	15.1 MPa	—	15.1 MPa
φ	—	58.3°	58.3°	58.3°
m	18.44	—	—	—
s	.0375	—	-	—
Residual strength				
c	—	8.8 MPa	—	—
φ	—	54.5°	—	—
m	9.22	—	—	—
s	0	—	—	—

NOTES: GRC1 = ground reaction curve analysis - Hoek and Brown (1980)
GRC2 = ground reaction curve analysis - Daemen (1975)
GRC3 = ground reaction curve analysis - St. John et al. (1983)
VISCOT = numerical modeling with program VISCOT

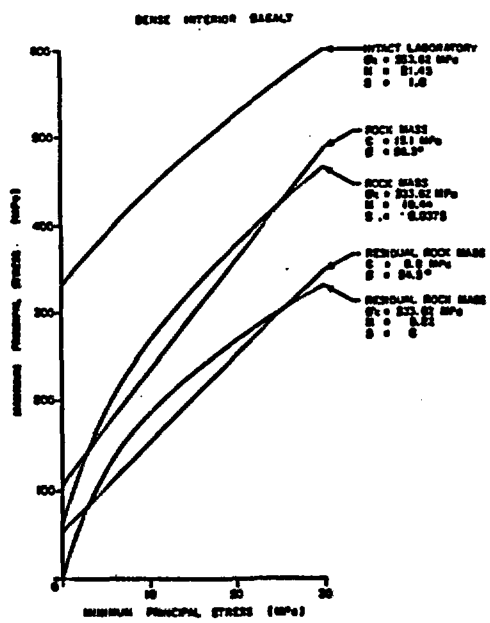

Fig. 1 Hoek and Brown Failure Criteria, Dense Basalt

Table 2

VESICULAR ZONE MATERIAL PROPERTIES USED IN ANALYSES OF PROGRESSIVE FAILURE

Parameter	Analysis method (see notes)			
	GRC1	GRC2	GRC3	VISCOT
Drift size	2 m radius	2 m radius	2 m radius	2 m radius
Elastic modulus	26 GPa	26 GPa	26 GPa	26 GPa
Poisson's ratio	.29	.29	.29	.29
Rock mass strength				
UCS	36.4 MPa	59.1 MPa	59.1 MPa	59.1 MPa
c	—	10.9 MPa	—	10.9 MPa
ϕ	—	49.5°	49.5°	49.5°
m	10.00	—	—	—
s	.0375	—	-	—
Residual strength				
c	—	6.1 MPa	—	—
ϕ	—	45.3°	—	—
m	5.0	—	—	—
s	0	—	—	—

NOTES: GRC1 = ground reaction curve analysis - Hoek and Brown (1980)
GRC2 = ground reaction curve analysis - Daemen (1975)
GRC3 = ground reaction curve analysis - St. John, et al. (1983)
VISCOT = numerical modeling with program VISCOT

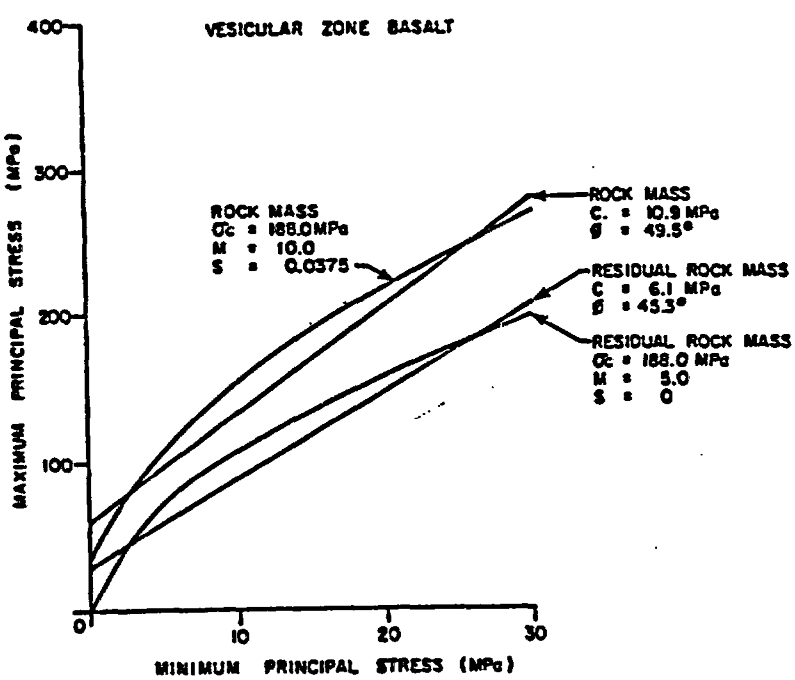

Fig. 2 Hoek and Brown Failure Criteria, Vesicular Basalt

Table 3

IN-SITU STRESSES USED IN PROGRESSIVE FAILURE ANALYSIS

Stress state	Analysis method (see notes)			VISCOT		Comments
	GRC1	GRC2	GRC3	Dense interior	Vesicular	
$\sigma_H = \sigma_V = 33.8$ MPa	X	X	X			Hydrostatic stresses equal to measured minimum horizontal stress in Cohassett
$\sigma_H = 33.8$, $\sigma_V = 24.2$			X			Horizontal stress as above; vertical stress as measured
$\sigma_H = \sigma_V = 61.5$ MPa	X	X	X			Hydrostatic stresses equal to measured maximum horizontal stress in Cohassett
$\sigma_H = 61.5$ MPa, $\sigma_V = 24.2$ MPa			X		X	Measured stresses in Cohassett
$\sigma_H = \sigma_V = 72.9$ MPa	X	X	X			Hydrostatic stresses equal to measured maximum horizontal stress plus two standard deviations
$\sigma_H = 72.9$ MPa, $\sigma_V = 24.2$ MPa			X			Horizontal stress as above; vertical stress as measured
$\sigma_H = \sigma_V = 90.0$ MPa	X	X	X			Hydrostatic stresses equal to expected thermally generated stress
$\sigma_H = 90.0$ MPa, $\sigma_V = 24.2$ MPa			X	X		Horizontal stress as above; vertical stress as measured

NOTES: Stress measurements from Kim et al. (1984)
GRC1 = ground reaction analysis, Hoek and Brown (1980)
GRC2 = ground reaction curve analysis, Daemen (1975)
GRC3 = ground reaction curve analysis, St. John et al. (1983)
VISCOT = numerical modeling with program VISCOT

<u>Results of Calculations</u> — The extent of the yield zone in the dense basalt and vesicular zone as determined by the various methods is shown in Tables 4 and 5. The immediate conclusion from these analyses is the relatively small thickness of the yield zone. This thickness is directly a result of the assumption of material properties, particularly the values of cohesion and friction.

A simple check on these calculations is performed by using the elastic-plastic formula for a hole in an infinite plate under hydrostatic stress developed by Bray (1967, Fig. 3). The radius of the yield zone is given by

$$R = a \left[\frac{2P - q_u + [1 + \tan^2(45+\phi/2)]\, C_j \, \text{Cot}(\phi_j)}{[1 + \tan^2(45+\phi/2)]\, C_j \, \text{Cot}(\phi_j)} \right]^{1/Q}$$

where $Q = (\tan \delta)/\tan(\delta-\phi_j) - 1$, $\delta = 45+\phi/2$

a = tunnel radius

q_u = the unconfined compressive strength = $2C \tan(45+\phi/2)$

C = intact cohesion

ϕ = intact friction angle

C_j, ϕ_j = joint cohesion and friction

P = hydrostatic field stress

Rather than using a numerical model to determine the thermally-induced rock stresses, the author attempts to determine a far-field in-situ stress state which will produce an equivalent stress concentration at the emplacement drift. It is assumed that the rock mass surrounding an opening will undergo an average temperature rise of 108°C from the waste heat. This was derived by thermal studies conducted by RKE/PB (1985). The thermal expansion of this rock mass is resisted by the surrounding cool rock, thus developing thermal stresses. If it is assumed that a "sample" of the rock mass, confined in the horizontal direction, is heated to this average temperature, a horizontal stress component will be induced. Mitchell calculates this induced stress to be 24.7 MPa (p. I.22). This stress is subsequently added to the existing horizontal field stress to produce an equivalent thermal-field stress for the non-thermal analyses.

This methodology is exceedingly simplistic, ignoring the contribution of thermal gradient and vertical confinement of the rock mass. It is not obvious that this simplification will produce proper stress concentrations around the openings nor is it clear what effect the determination of an equivalent linear thermal stress change applied as a boundary condition will have when examining yield behavior around an opening.* The reliance of BWIP design efforts on these simplistic assumptions can be seen not only in the present report and the conceptual design but in the recent study by Barton (1986) which determined rock support requirements.

One final note regarding the stress conditions used in the present analysis: a consistent value of the pre-existing σ_{Hmax} was not used in the "thermal" and non-thermal simulations. The non-thermal studies use a σ_{Hmax} of 65 and 72.9 MPa, whereas the "thermal" analysis uses the least conservative value of 65 MPa only.

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*BWIP's design methodology is not clear. It appears that one portion of their program is investing a great deal of time in acquisition and development of thermomechanical codes while the actual designers are using simplistic analysis techniques with unrelated methods.

Table 4

EXTENT OF YIELDED (PLASTIC) ZONE (in cm) IN DENSE INTERIOR

AS CALCULATED BY PROGRESSIVE FAILURE ANALYSES

Stress state	Analysis method (see notes)				
	GRC1	GRC2	CRC2A	GRC3	VISCOT (circle)
$\sigma_H = \sigma_V$ = 33.8 MPa	16.7	--	--	3.3	--
σ_H = 33.8 MPa σ_V = 24.2 MPa	--	--	--	R = F = 6.8 S = 0	--
$\sigma_H = \sigma_V$ = 61.5 MPa	34.3	36.2	19.8	19.8	--
σ_H = 61.5 MPa σ_V = 24.2 MPa	--	--	--	R = F = 25.3 S = 0	R = F = 25 S = 0
$\sigma_H = \sigma_V$ = 72.9 MPa	41.1	45.2	25.0	25.1	--
σ_H = 72.9 MPa σ_V = 24.2 MPa	--	--	--	R = F = 30.2 S = 0	--
$\sigma_H = \sigma_V$ = 90.0 MPa	51.1	56.6	31.8	31.9	--
σ_H = 90.0 MPa σ_V = 24.2 MPa	--	--	--	R = F = 36.1 S = 0	--

NOTES: Stress measurements from Kim et al. (1984)
GRC1 = ground reaction curve analysis, Hoek and Brown (1980)
GRC2 = ground reaction curve analysis, Daemen (1975)
GRC2A = ground reaction curve analysis with perfectly plastic residual behavior, Daemen (1975)
GRC3 = ground reaction curve analysis, St. John et al. (1983)
VISCOT = numerical modeling with program VISCOT
R = roof
F = floor
S = sidewall

Table 5

EXTENT OF YIELDED (PLASTIC) ZONE (in cm) IN VESICULAR ZONE AS CALCULATED BY PROGRESSIVE FAILURE ANALYSES

Stress state	Analysis method (see notes)					
	GRC1	GRC2	GRC2A	GRC3	VISCOT (Circle)	VISCOT Placement room
$\sigma_H = \sigma_V = 33.8$ MPa	1.8	--	--	0	--	--
$\sigma_H = 33.8$ MPa $\sigma_V = 24.2$ MPa	--	--	--	0	--	--
$\sigma_H = \sigma_V = 61.5$ MPa	9.5	4.2	2.2	2.2	--	--
$\sigma_H = 61.5$ MPa $\sigma_V = 24.2$ MPa	--	--	--	R = F = 5.3 S = 0	--	--
$\sigma_H = \sigma_V = 72.9$ MPa	11.8	9.0	4.8	4.9	--	--
$\sigma_H = 72.9$ MPa $\sigma_V = 24.2$ MPa	--	--	--	R = F = 7.8 S = 0	--	--
$\sigma_H = \sigma_V = 90.0$ MPa	15.2	14.8	8.2	8.3	--	--
$\sigma_H = 90.0$ MPa $\sigma_V = 24.2$ MPa	--	--	--	R = F = 11.0 S = 0	R = F = 12 S = 12[a]	R = 21 F = 69 (max.) S = 33 (max.)

NOTES: Stress measurements from Kim et al. (1984)
GRC1 = ground reaction analysis, Hoek and Brown (1980)
GRC2 = ground reaction curve analysis, Daemen (1975)
GRC2A = ground reaction curve analysis with perfectly plastic residual behavior, Daemen (1975)
GRC3 = ground reaction curve analysis, St. John et al. (1983)
VISCOT = numerical modeling with program VISCOT
R = roof
F = floor
S = sidewall

[a]Sidewall failure in this case probably due to indeterminacy of problem.

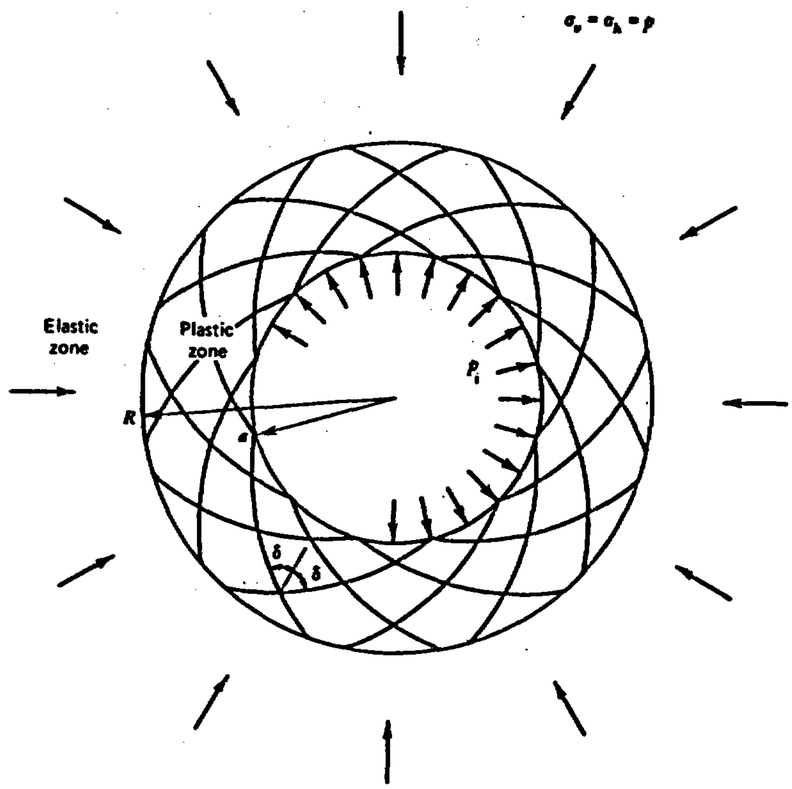

Fig. 3 Nomenclature for the Bray Elasto-Plastic Solution

Calculations using this formula are summarized in Table 6. For the same input properties, Bray's solution (1967) checks well with Mitchell's results. We wish to vary the rock mass properties to illustrate the lack of conservatism in the analyses. As seen in this table, the effect of varying the internal friction angle of the material is quite significant. Normally, when the rock mass is considered to be a continuum, a conservative analysis will assign mass plasticity properties to be those of the joints. If the friction angle of the mass is reduced from 58.3° to 35° (a typical value assumed in scoping studies), the thickness of the yield zone will increase by a factor of 8 using the standard plasticity formulae. If conservative stresses are selected, the thickness of the yield zone can become significant.

In reality, the damaged zone will likely be characterized by shearing along joint surfaces and thus be structurally controlled. Structural control may be particularly important in columnar basalt, resulting in a highly non-uniform yield zone.

The analysis of the emplacement room using the VISCOT program indicates similar problems. Using the intact friction angle (58.3°), the results are biased, giving a small (<1m) yield zone.

This does not seem sensible from a practical standpoint and would suggest that little or no rock support would be required of the emplacement rooms. This is at odds with the physical evidence of borehole spalling and disking, experience in deep mines, and Barton's (1986) classification which rated the rock mass as "extremely poor to poor", with a colonnade design range in the "very poor to poor" category. This classification resulted in a recommendation of systematic grouted bolting on 0.8 to 1m centers with 2.5 to 5.0cm of mesh-reinforced shotcrete or quite heavy ground support. Thus, from a practical standpoint, it is difficult to place a great deal of credence on the VISCOT calculations.

The program FLAC (non-thermal version) was used to analyze a single emplacement room geometry for conservative rock mass properties and stress conditions. This is done in contrast to the VISCOT analyses present earlier. The following conditions were assumed:

$$\sigma_{Hmax} = 97.9 \text{ MPa}$$

$$\sigma_{V} = 24.2 \text{ MPa}$$

$$\text{cohesion} = 15 \text{ MPa}$$

$$\text{friction angle} = 35°$$

A Mohr-Coulomb plasticity constitutive law (as in VISCOT) was used for the rock mass. The resulting yield zone for the case of 15 and 5 MPa cohesion is illustrated in Fig. 4 and 5. For the 15 MPa cohesion, a maximum yield zone radius of slightly less than 1 radius is indicated. A reduction of cohesion to 5MPa (not unusual for joints) indicates a yield zone of roughly 1-2 diameters of the opening. Associated plots of shear stress contours and principal stress vectors for the case of a 5 MPa cohesion are given in Figs. 6 and 7.

These calculations were given to illustrate the large effect of choice of plasticity parameters on the apparent disturbed zone about the openings. It seems clear that plasticity parameters obtained from intact rock will result in highly non-conservative answers. Values obtained from non-healed joints will likely yield conservative results. A true determination of the radius of the disturbed zone will not be known until the ES test measurement of full-scale response.

Table 6

COMPARISON OF YIELD ZONE CALCULATIONS

USING BRAY'S SOLUTION TO MITCHELL (1986)

a (m)	P (MPa)	C (MPa)	ϕ	C_j (MPa)	ϕ_j	Thickness of Yield Zone (cm) Bray	Mitchell	Comments
2	90	15.1	58.3	15.1	58.3	8.3	8.2	case where intact and joint friction both high
2	90	15.1	35	15.1	35	68.4	—	compare conservative case is assumed to have equivalent joint friction
2	90	15.1	58.3	10.0	35	20.5	—	case where joint and intact properties different
2	97.9	15.1	58.3	15.1	58.3	9.7	—	conservative range of σ_{Hmax} from Kim (1986) +25 MPa thermal
2	97.9	15.1	35	15.1	35	76.3	—	
2	97.9	15.1	58.3	10.0	35	24.4	—	
2	107.3	15.1	58.3	10.0	35	28.8	—	most conservative stresses from Itasca review of Kim (1986)
2	107.3	15.1	35	10.0	35	113	—	σ_{Hmax}=82.3 MPa + 25 MPa thermal stress

JOB TITLE : Emplacement room, cohesion = 15 MPa fric = 35 deg

FLAC (Version 1.0)

LEGEND

1/ 1/1980 0: 8
step 1001
-2.000E+00 < x < 2.810E+01
1.000E-01 < y < 3.010E+01

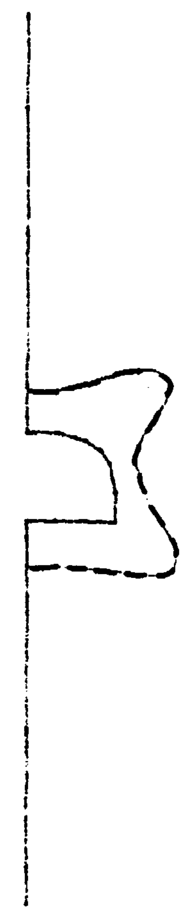

Fig. 4 Yield Zone Radius Determined by FLAC For the Case of 15 MPa Cohesion

JOB TITLE : Emplacement room, cohesion = 5 MPa fric = 35 deg

FLAC (Version 1.0)

LEGEND

1/ 1/1980 0: 8
step 1001
-2.000E+00 < x < 2.810E+01
1.000E-01 < y < 3.010E+01

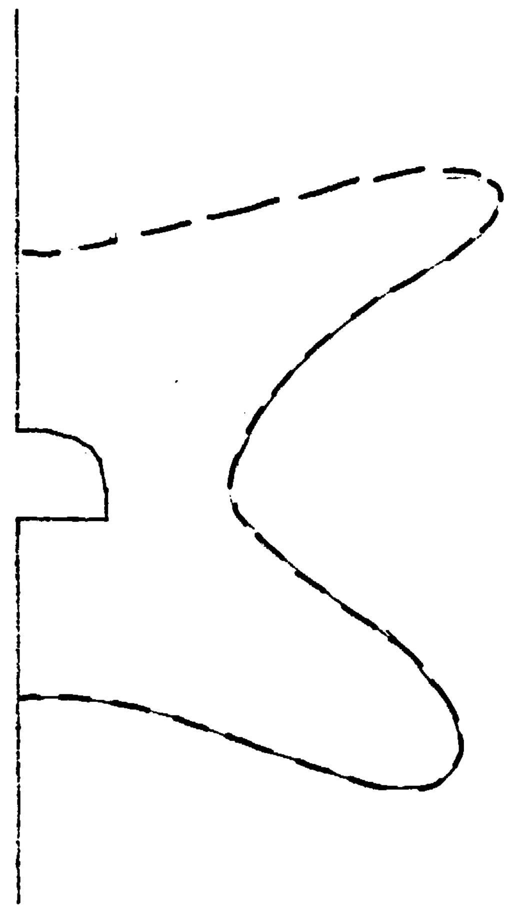

Fig. 5 Yield Zone Determined By FLAC For Case of 5 MPa Cohesion

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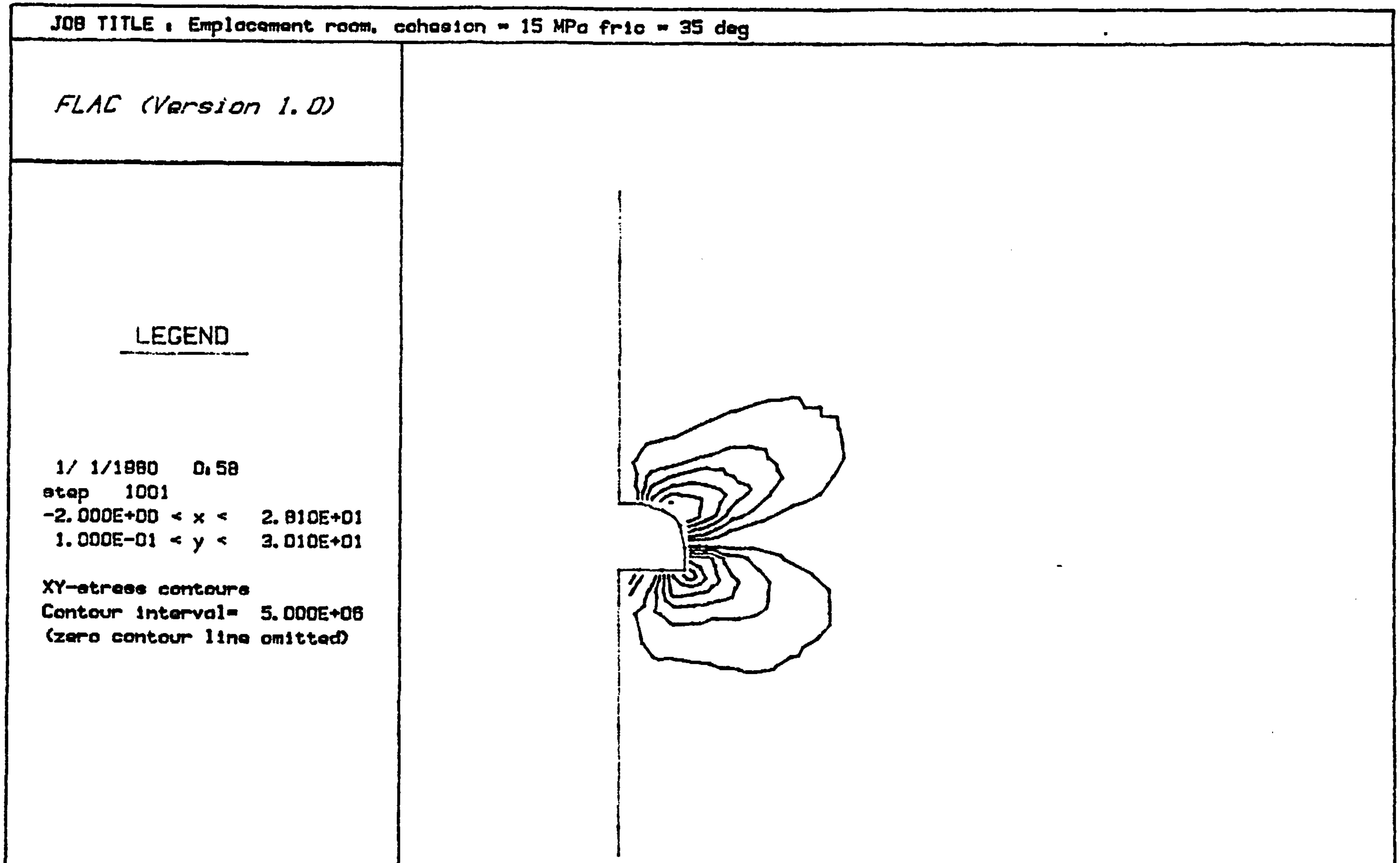

Fig. 6 Shear Stress Contours For Case of 15 MPa Cohesion

JOB TITLE : Emplacement room, cohesion = 15 MPa fric = 35 deg

FLAC (Version 1.0)

LEGEND

1/ 1/1980 0:50
step 1001
-2.000E+00 < x < 2.810E+01
1.000E-01 < y < 3.010E+01

Principal stresses
Max. Stress= 1.377E+08

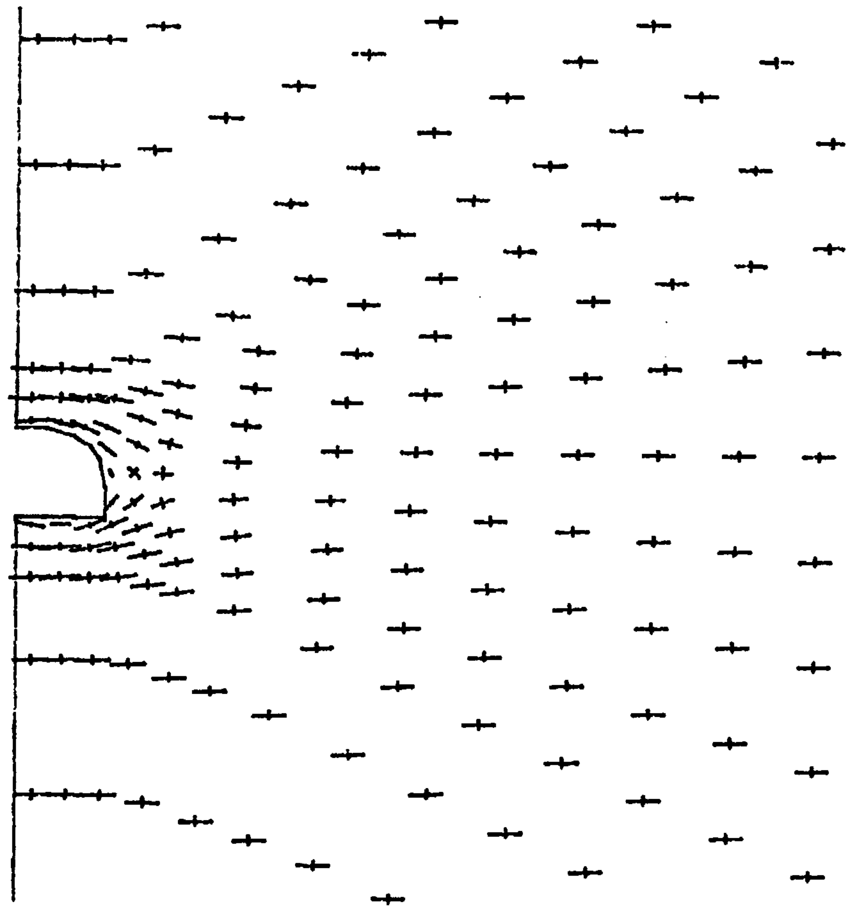

Fig. 7 Principal Stress Vectors For Case of 15 MPa Cohesion

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A second portion of the report examines the potential for thermally-induced fracturing of basalt due to thermal expansion of fluid in vesicles in the basalt. In the simple analysis given, the most conservative conditions of a fluid-filled vesicle near a waste canister is considered to undergo a temperature change of 153°C. The temperature rise is given by RKE/PB (1985) using the DOT heat transfer code. The analysis illustrates that a maximum fluid pressure of 13.6 MPa is developed. Considering the in-situ stress state at Hanford (and making use of hydraulic fracturing measurements), a stress of 29.1 MPa in dense basalt, or 24.7 MPa in vesicular basalt, would be required for tensile fracturing to occur. Thus, even at the most conservative level of analysis, there appears to be little possibility of fracturing to fluid expansion. We can agree with these conclusions.

CONCLUDING REMARKS

The analysis presented by Mitchell (1986) for determination of the extent of the damaged zone are highly non-conservative. This is a result of the choice of intact cohesion and friction values as well as non-conservative choice of in-situ and thermally-induced stresses. Calculations were presented which show that the choice of these parameters can greatly affect the resulting yield zone radii. In our opinion, the damaged zone radii calculated in this report are not conservative and are not supported by practical evidence of spalling and disking or empirical evidence from mines under similar conditions. The conclusions of the report will probably not be representative of the actual conditions to be encountered at depth.

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