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FRACTURE-INDUCED PERMEABILITY:
PRESENT SITUATION AND PROSPECTS FOR COAL

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FRACTURE-INDUCED PERMEABILITY: PRESENT SITUATION AND PROSPECTS FOR COAL

Abstract

Creation of permeability by explosive fracturing is considered. Experimental or inferred in situ permeabilities from nuclear explosive events fall into two groups: very low (≤ 0.3 md) permeability creation in the events in sandstone and much higher (5 md to 1 d) permeability enhancement in naturally fractured media (granodiorite, dolomite, and granite). Permeability data correlate well with R/R_c , where R_c is the cavity radius, or with failure shear strain (ϵ_f). Simultaneous detonations are quantitatively predicted to produce much flatter permeability distributions than for single or sequential detonation.

The projected permeability distribution for HE fracturing by chemical explosive emplaced in an array of drilled holes has serious consequences for the LLL in situ coal gasification concept. Permeabilities are expected to vary by a factor of 50 over $4 R_c$, even for simultaneous detonations. Bypassing of at least some coal appears likely. Experimental data for k vs R/R_c or ϵ_f are vitally needed to determine the permeability variations with range. The coal outcrop experiments are expected to be definitive in this regard. Realistic gasification calculations are needed to indicate whether the predicted permeability distributions are acceptable for our concept or whether modifications or alternate solutions must be found.

Introduction

Knowledge of permeability as a function of distance from an explosive source is needed for many of the LLL energy and resource projects. It is vital to the LLL in situ coal gasification program. We plan to emplace chemical explosives in an array of drilled holes within a coal seam, detonate the explosive, and then gasify the fractured coal with steam and oxygen with a vertically moving reaction zone. It is unlikely that a rubble pile (similar to a nuclear explosive-produced chimney) will be formed; rather, we anticipate that a network of permeable, intersecting fractures will be produced which will be suitable for our in situ gasification concept.¹

In this report I first review three models for fracture-induced permeability, then review a current LLL model and present my own views, present the limited experimental or inferred data available on the subject, fit the Hardhat data to a "failure shear-strain" parameter, present a prediction of permeability as a function of radius for the coal-outcrop and coal-field fracture experiments, and finally discuss some of the programmatic implications of the predicted permeability distributions.

Theory

A. Packed-Bed Model

The simplest model that leads to a quantitative prediction of permeability is the Kozeny-Carman equation, valid for packed beds^{2,3}:

$$k = \frac{d^2 \eta^3}{180(1 - \eta)^2}, \quad (1)$$

where k = permeability, η = porosity, and d = mean particle diameter.

The factor 180 in Eq. (1) was chosen as a best fit to empirical data. Other models could have been discussed,² but the Kozeny-Carman model is the simplest and approximately as accurate as more complex treatments. The principal limitation of this model is that it considers the final state to be a packed bed of particles with mean diameter d . It may be valid for rubble within a nuclear chimney (see Ref. 4) but probably is not correct for fractures beyond a chimney wall or HE borehole.

B. Capillary-Tube Model

Starting from the Hagen-Poiseuille equation, valid for laminar flow,⁵ and considering a straight circular capillary tube of diameter D ,

$$Q = -\frac{\pi D^4}{128 \mu} \frac{dp}{dx}$$

where Q = volumetric flow rate, μ = viscosity, and $\frac{dp}{dx}$ = pressure gradient.

If there are N such tubes per unit area, normal to the direction of flow, then:

$$\frac{Q}{A} = -\frac{N \pi D^4}{128 \mu} \frac{dp}{dx}. \quad (2)$$

However, Darcy's law is:

$$\frac{Q}{A} = \frac{k}{\mu} \frac{dp}{dx}, \quad (3)$$

where

$$k = \frac{N \pi D^4}{128}. \quad (4)$$

This model may be valid for many media, but is probably invalid for explosively-induced permeability.

C. Crack Model

For a medium containing a single crack of width b , bounded by parallel impermeable planes, the solution to the Navier-Stokes equation is³:

$$u = \frac{b^2}{12\mu} \frac{dP}{dx} \quad (5)$$

where

u = velocity.

For a network of cracks, all of width " b " and spaced distance " a " apart, with $b \ll a$ (valid for narrow cracks):

$$\frac{Q}{A} = \frac{b}{a} u = \frac{b^3}{12a\mu} \frac{dP}{dx} \quad (6)$$

and

$$k = \frac{b^3}{12a} \quad (7)$$

This is probably the most representative model for fracture-produced permeability.

Current LLL Model for Fracture-Induced Permeability

The current LLL model for explosively-produced permeability is based on the two dimensionless ratios (k/k_0) and (R/R_c) , where k_0 is the initial permeability of the medium, k is the postshot permeability, R is radial distance from the shotpoint, and R_c is the cavity radius produced by the shot.

$$\text{Thus } \frac{k}{k_0} = f\left(\frac{R}{R_c}\right).$$

The model most widely quoted⁶⁻⁹ is shown in Fig. 1, where k/k_0 is essentially infinite from $R/R_c = 0$ to 1.0 (no pressure drop in the chimney), $k/k_0 = 33$ for $1 \leq R/R_c \leq 2.75$, k/k_0 decreases to 1.0 linearly from $R/R_c = 2.75$ to 3.0, and $k/k_0 = 1.0$ at $R/R_c \geq 3.0$. This model was developed to fit the Rulison gas-flow data.

A persuasive argument for scaling R by R_c has been made by Borg.¹⁰ Figure 2 shows that "horizontal fracture radii, as judged by in situ permeability measurements, observed microfracturing in postshot cores, chimney pressurization tests, and macrofracturing in cores and tunnels, tend to be $2.7 R_c$ to $3.5 R_c$ in competent rocks" (Ref. 10). Use of R_c as scaling parameter tends to quantitatively account for yield and the mechanical properties of the medium. The cavity radius is also one of the parameters which is calculable with some confidence using the LLL finite-difference codes SOC and TENSOR and easily estimated by several empirical formulae. A new failure parameter defined as failure shear strain (ϵ_f) has been developed by Schatz.¹¹ When more firmly verified, failure shear strain may well replace R/R_c as a suitable scaling parameter. Use of ϵ_f in interpreting postshot Hardhat permeabilities is discussed later.

Fig. 1. Permeability enhancement model for Rulison gas flow.

Fig. 2. Horizontal fracture radii as a function of cavity radii. Points 1, 2, and 3 are granodiorite; 4 and 5 are salt; 6 is tuff; 7 is dolomite; 8 and 9 are sandstone/shale. Range in estimate is indicated by line joining similar symbols.¹⁰

In contrast, k/k_0 should not be used as a predictive parameter. It is a dangerous and misleading ratio, since k_0 itself is irrelevant for the explosive fracturing process.¹² Consider the most likely model for explosive permeability enhancement, the crack model.

$$k = \frac{b^3}{12a}, \quad (7)$$

where b = mean crack width and a = mean crack spacing.

Now consider a number of cases as follows:

Case A. Initially Impermeable Medium ($k_0 = 0$)

In this case an explosion produces a nonzero $k(r)$, and for all ranges where permeability is produced by the blast, $k(r)/k_0$ is equal to infinity.

Case B. Initial Permeability of Medium is Due to Capillary Tubes

In this case,

$$k_0 = \frac{N\pi D^4}{128}. \quad (4)$$

For a given radius from the explosive source,

$$\frac{k}{k_0} = \frac{b^3/12a}{N\pi D^4/128} = \frac{3.40b^3}{aND^4} \quad (8)$$

Certainly this ratio, including, at a given radius from the shot, the cube of the mean crack width (b), the mean spacing between cracks (a), the number of capillary tubes per unit area (N), and the fourth power of the mean capillary tube diameter (D), cannot be extrapolated from one medium to another.

Case C. Initial Permeability of Medium is Due to Cracks

In this case

$$k_0 = \frac{b_0^3}{12a_0} \quad \text{and} \quad \frac{k}{k_0} = \frac{(b/b_0)^3}{a/a_0}. \quad (9)$$

Again, as in Eq. (8), this ratio involves initial properties of the medium and cannot safely be extrapolated from one medium to another.

In conclusion, I claim that the use of k/k_0 has no extrapolative value. Permeability should be plotted directly versus scaled range (R/R_c) [or failure shear strain (ϵ_f)], as is done in the next section. If there is any validity in extrapolating fracturing results from one medium to another, it will be found in this way.

Experimental and Inferred In Situ Permeabilities for Single Detonations

Very little in situ permeability data of a quantitative nature are available. All are for point-source detonations. Much of the qualitative evidence has been contributed by Borg¹⁰ and Boardman.¹³ Permeabilities measured in the laboratory are of limited value in this regard, because such k values are one or more orders of magnitude lower than the actual field measurements. The small laboratory samples cannot, of course, duplicate the natural inhomogeneities of the host rock, such as the joint system. Thus laboratory-determined data are represented as matrix permeability; the permeability of the intact, flaw-free medium.

Quantitative information is discussed below.

A. Sandstones

To my knowledge, no experimental in situ permeability measurements have been made for postshot Gasbuggy, Rulison, or Rio Blanco. All results have been inferred by adjustment of an assumed $k(R)$ function until a good fit was obtained to postshot gas flow test.⁷ These inferred permeability distributions are shown in Fig. 3, where the fits were taken as follows: Rulison (Ref. 7), Gasbuggy (Ref. 14), and Rio Blanco-Montan (unpublished). The Rio Blanco case considers effects from the top explosive only. Certain fine structure in the inferred Gasbuggy permeability distribution between R/R_c values of 2.5 and 3.5 was omitted. Relevant data are shown below:

	Initial permeability (k_0), μd	Productive section (h), m	Cavity radius, m
Gasbuggy	6.6	46.3	24.4
Rulison	9.1	23	23.2
Rio Blanco	15	30.5	20.1

Note that the Gasbuggy and Rio Blanco inferred permeability curves are similar, while the permeability distribution for Rulison is different from and greater than for the other two shots. The reason for these differences is not known.

A real difficulty with such inferred permeabilities is that the calculations are insensitive to the assumed shape of the $k(R)$ distributions. For example, an exponential decay curve could probably be fitted to the Rulison data just as well as the one shown in Fig. 3. In addition, permeabilities at $R/R_c = 1$ could be in error by a factor of two or more (Montan, private communications).

With these qualifications, it is important to note the very low permeabilities, 0.3 md and less, for these initially impermeable sandstones. If coal scales with these types of plots, permeability will be enhanced very little by explosive fracture. However, the initial permeability of coal is in the millidarcy and higher range; coal is generally a naturally fractured medium. Next we examine permeability enhancement in naturally fractured media.

Fig. 3. Inferred permeability distributions for three sandstone shots.

B. Granodiorite and Dolomite

Some in situ permeability data are available for the Handcar Event (dolomite), Hardhat and Piledriver (Climax stock granodiorite), and French nuclear events in Hoggar granite. These are field in situ permeability data and show considerable scatter due to the inhomogeneous nature of permeabilities due to fractures. In addition, explosion-induced permeabilities are probably not isotropic, and the orientation of the borehole and flow during the permeability tests can affect the measurements.

Results for Hardhat,¹⁵ Piledriver,^{16,17} Handcar¹⁸ and the Hoggar shots¹⁹ are shown in Fig. 4. The French data shown are for horizontal drill holes only. Few data are available for Handcar: a preshot permeability of 130-300 md and a permeability of 1.2 d near the chimney. The Hardhat and Piledriver permeabilities do not agree well with each other except at $R/R_c = 1.0$. The Hardhat points in parentheses are considered less reliable because they were measured near free surfaces which may have experienced enhanced fracturing due to tensile-wave rarefaction. These measurements would appear to be upper bounds of the permeabilities at those ranges.

Slant-range distances for the Piledriver data were obtained from Borg (unpublished). These data are given in the appendix.

It is interesting to note that all three U.S. shots produced a permeability of 1-2 d at the cavity wall. Whether this is a general rule or a coincidence should be investigated. The reported French close-in permeability of 2 md is very low.

There is some evidence that the process of drilling the holes for the permeability measurements may have at least partially plugged the fractures.^{15,17} Therefore, some of these measured permeabilities may be minimum values.

In the case of the granodiorite, the close-in permeability was increased two to three orders of magnitude by the detonation.

Thus field experimental and inferred permeability data for nuclear events appear to fall into two groups: very low fracture permeabilities (≤ 0.3 md) for initially impermeable sandstones and much higher values (up to 1 d) for the naturally fractured media granites and dolomite. We hope that stimulation of coal will produce results similar to those of the naturally fractured media. In subsequent sections I will use these data for predictions of fracturing using HE in cylindrical boreholes, notwithstanding the fact that HE, not nuclear explosives, is to be used; cylindrical geometry, not a point source, is planned; and the response of coal is, of course, not yet known.

Failure Shear-Strain Considerations

It is of interest to fit the Hardhat permeability distribution to Schatz's¹¹ concept of failure shear strain. Consider:

$$k = f(\epsilon_f)$$

Fig. 4. Postshot permeabilities of naturally fractured media.

Schatz interpreted ϵ_f^* rather loosely as $\Delta\ell/\ell$, where ℓ is the crack length and $\Delta\ell$ is the motion to crack failure. Then, one can approximately correlate $\Delta\ell$ with b , the mean crack width created by the crack motion. If this is so, one can expect that:

$$k = \frac{b^3}{12a} \sim \alpha \epsilon_f^3,$$

where α = a constant.

Using Schatz's data for $\epsilon_f(r)$, k is plotted against ϵ_f with the results shown in Fig. 5. Note that the fit from $0.001 \leq 0.019$ is $k = 6300 \epsilon_f^{2.3}$, not a cubic. However, the scatter in the experimental k values is considerable. There also appears to be a region $0.019 \leq \epsilon_f \leq 0.3$ where k is insensitive to ϵ_f , $k \sim \epsilon_f^{0.17}$. Clearly, more in situ data and failure shear-strain calculations are needed to evaluate $\epsilon_f(r)$ for use in predicting $k(r)$.

Possible Effect of Multiple Detonations

No data appear to be available for the effect of multiple detonations on permeability distributions. In this section I estimate the effect of multiple detonations using the calculations of Terhune and Shaw.²⁰

Terhune and Shaw used the crack number as a parameter related to fracturing as permeability enhancement. The crack number relates the number of times a zone in the finite-difference code has exceeded the failure criterion.

The first conclusion to be drawn from Ref. 20 is that sequential detonation is not a desirable mode for the coal program. Sequential detonation depends upon an impedance mismatch at a previously produced chimney to produce a tensile rarefaction wave and consequent enhanced fracturing. The impedance mismatch between rock or coal fractured by HE is likely to be small, and sequential detonations probably would be ineffective.

Terhune and Shaw used a sandstone equation of state in a series of calculations to derive enhanced crack numbers with range for simultaneous detonations. Limitations in applying these calculations to other cases include:

- Point-source calculations are applied to cylindrical geometry.
- The crack number is medium dependent.
- The crack number is zone-size dependent.
- The calculations are for explosives displaced vertically, not horizontally, as for example, an array of drilled holes.

* $\epsilon_f \equiv (K - K_0)/G\tau_m$, where K_0 is the "equilibrium" value of K , the deviatoric stress, G is the shear modulus and τ_m is the Maxwell relaxation time. See Ref. 11.

Fig. 5. Correlation of Hardhat permeabilities with failure shear strain.

The procedures I followed to derive a permeability distribution for simultaneous detonations were to assume that:

$$k = f(\text{crack number}) = f(\text{CKN}),$$

and

$$k(r/r_c) = f[\text{CKN}(r/r_c)].$$

I then used Terhune and Shaw's results for simultaneous detonations spaced $8R_c$ apart. Terhune and Shaw found that:

$$\text{CKN}(r/r_c) = \text{CKN}'[K(r/r_c)],$$

where

CKN = crack number for a single detonation,

CKN' = crack number for simultaneous detonation,

and

K = a constant, almost independent of r/r_c and CKN, about 1.5 to 1.6.

Results for TENSOR calculations (two-dimensional finite-difference code) are shown below.

Crack No. (TENSOR)	Single detonation R/R_c	Simultaneous detonations R/R_c	K
3	2	3.2	1.6
2	2.67	4.0	1.5

For Hardhat which was, of course, a single detonation, permeabilities corresponding to 2.0 and 2.67 R/R_c , from Fig. 4 are 0.82 and 0.44 d, respectively. From the above Table, if $k = f[\text{crack No.}]$, then for the same k values, the corresponding R/R_c for simultaneous detonations are 3.2 and 4.0. These inferences are plotted on a linear scale, in Fig. 6, along with Hardhat and Piledriver data. For simultaneous detonations spaced $8R_c$ apart, there is a mirror plane for k at $4R_c$. Therefore it appears that for simultaneous detonations at $8R_c$ spacing and a Hardhat-like induced-permeability distribution, permeabilities would not drop below about 0.4 d. For single (sequential) explosions also spaced $8R_c$ apart, the minimum permeability for a Hardhat distribution could be 0.04 d (40 md). Therefore, if the assumptions in this section are even approximately correct, simultaneous detonations should produce a much flatter and, therefore, more desirable permeability distribution than would single detonations.

Fig. 6. Smoothed permeability distribution for Hardhat and Piledriver and estimate for simultaneous detonations.

Estimate of Borehole Permeability

An estimate should also be made of the permeability of $R/R_c < 1.0$, i. e., within the "chimney." This borehole permeability was estimated via the Kozeny-Carman equation with an assumed mean particle diameter of 0.5 cm and a porosity of 5%. This estimated value is 20 d (not shown in Fig. 6) and is, of course, a very uncertain number. The borehole permeability would be 700 d for a mean particle diameter of 1.0 cm and a porosity of 10%.

The average fracture porosity and crack width near the Hardhat chimney can also be estimated. The permeability there is 1 d and using Eq. (7) with an assumed crack spacing of 30 cm (1 ft) one calculates the crack width as only 0.015 cm (0.006 in.). With 10 cm spacing, the crack width is calculated to be 0.007 cm (0.003 in.). The permeability is apparently due to very narrow cracks. The porosity induced by such fractures can also be readily estimated; it is $\eta = b/a$, or 0.05%. Therefore, the porosity is also very low. Both the crack width and porosity, of course, decrease with decreasing permeability and, therefore, with scaled range.

Prediction for the Coal Outcrop Experiment

We plan to execute a number of small-scale HE experiments on Kemmerer Coal Company property. We plan to use 100-mm (4-in.) boreholes filled with HE at depths from 12.2 to 18.3 m (40 to 60 ft). The primary objectives of the experiment are to determine the permeability distribution and extent of fracturing from the shots and to compare them with preshot prediction. My predictions, both for single and simultaneous shots, are shown in Fig. 7. The upper scale is for the coal outcrop experiment while the lower scale is for 0.61-m (2 ft) diameter HE holes at depths of 305 m (1000 ft) — the full-scale field fracture experiments. Figure 6 was used for these predictions using cavity radii calculated by Butkovich.^{21,22} The HE equations of state were nitromethane²¹ and PETN.²² Butkovich calculated the cavity radius for the 100-mm (4-in.) diameter borehole to be 0.33-m (1.07 ft) and to be 0.82-m (4 ft) for the 0.61-m (2 ft) diameter borehole.

I would estimate from the preceding section that the borehole permeability would be 20 to 700 d.

Permeability Distribution: Implication for In Situ Coal Gasification

The consequences of a fracture-produced, permeability distribution as shown in Fig. 3 for the sandstone events are very grave for any type of in situ processing. These low permeabilities produce, in turn, very large pressure drops for a flowing system. It is hoped that the much higher fracture permeabilities found for the granites and dolomite are more representative for coal.

Fig. 7. Predicted permeability distributions for HE-fractured coal. Lower scale on abscissa is for 0.61-m (2-ft) diam HE holes at 305-m (1000-ft) depth. Upper scale is for 100-mm (4-in.) diam HE holes at 15.2-m (50-ft) depth.

This discussion will be limited to the LLL concept for in situ coal gasification, which is to use chemical explosives emplaced in an array of drilled holes to fracture a coal bed and gasify the resultant permeable region with steam and oxygen.

Gregg²³ shows for a similar situation (flamefront stability due to spatial inequalities) that a permeability distribution such as shown in Fig. 6 leads to incomplete resource recovery. Gregg treated a case for uniform bed permeability but point or area injection and withdrawal of reactants and products.

Qualitatively, one expects preferential flow in the high-permeability region at and near the borehole, with decreasing flow radially as $k(r)$ decreases. For example, at constant pressure gradient:

$$\frac{\Delta P}{\Delta x} = \text{constant} = \frac{\mu}{k(r)} v(r)$$

$$v(r) \propto k(r)$$

where

$v(r)$ = superficial gas velocity at position R .

Further, if one assumes, as Gregg did, that the flame-front propagation is proportional to $v(r)$, then the flame-front velocity is proportional to $k(r)$. (The assumption that flame-front velocity is proportional to flow velocity assumes, in effect, that flame-front propagation is proportional to mean flow of oxygen to the zone; i. e., kinetics are neglected.)

Homsy²⁴ has refined these calculations. He notes that Darcy's law (Eq. 3) must be applied with care to the case of a moving flame front, even in steady state, and that the flame-front kinetics should not be neglected. I would add that the effects of natural convection, especially in vertical gasification downward, would tend to minimize this flame-front instability. Also, in a narrow, high-permeability region, heat transfer to the cooler surrounding coal would decrease the temperature and tend to extinguish the flame.

Conclusions

The limitations of this analysis have been stated but are worth restating:

- Use of point-source explosions to model cylindrical detonations.
- Use of nuclear explosions to model chemical explosive detonations.
- Medium dependencies.
- Uncertain extrapolations.
- Untested models.
- Kinetics, heat transfer neglected.
- Gravity (natural convection) neglected.
- Constant pressure drop assumed.

These are very serious assumptions, but the conclusions are clear: (1) The flame front will break through first at the highest permeability zones, causing bypassing of coal and combustion of products. Even for the most favorable case found—a Hardhat-like permeability distribution, optimistic estimation of the effect of simultaneous detonations, and a minimum estimate of borehole permeability—one still expects a permeability variation from 0.4 to 20 d within $4R_c$, which is a factor of 50. (2) Experimental data are vitally needed to actually determine $k(R/R_c)$ or $k(\epsilon_f)$ for single and multiple detonations. These experimental data must include in situ permeability measurements. The coal outcrop and full-scale field fracture experiments should be definitive in this regard. (3) Realistic gasification calculations are needed with these predicted permeability distributions. If these calculations show poor resource recovery due to the variable permeabilities, then modifications or alternate solutions must be found.

One modification that makes sense involved "killing" the presumed high-permeability boreholes. Then the projected permeabilities for simultaneous detonation should vary by a factor of only three, rather than 50 or more. Of course, care must be taken not to plug the permeability outside the borehole; otherwise, the desired effects of explosive fracturing would be negated. Drilling mud, foams, smoke, or even a light grout could be considered, depending upon the actual permeability of the borehole.

Appendix

Piledriver Permeability Data

Permeability data were obtained from McMullen and Pasternak¹⁷ and slant range from the working point from Borg (private communication). The data are shown below.

Permeability (k), md	Slant range, m (ft)		$(R/R_c)^a$
47-58	104	(340)	2.59
110	105	(345)	2.63
14	108	(355)	2.70
19	111	(365)	2.77
5.5	113	(370)	2.81

^a $R_c = 40.1$ m (131.5 ft). In addition to these data, Boardman¹⁶ reported permeabilities of 1.1-1.9 d at the cavity boundary.

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