Initial laboratory studies of the cavity completion process

by

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ABSTRACT

Stimulation of coalbed methane wells using cavity completions offers the prospect of more efficient and economic gas production. We report here on fundamental studies of the cavitation process. Theoretical studies of gas flow confirm that rapid pressure reduction in a borehole can induce mechanical failure, provided that the pressure reduction is sufficiently rapid. Physical model experiments on equivalent materials demonstrate that highly nonlinear failure processes take place during cavitation. Coal failure criteria for cavitation is being studied using core specimens cavitated under controlled stress conditions. Experimental venting of pressurized strings of instrumented drill rods is providing data for assessment of wellbore pressure transients.

INTRODUCTION

Improvements to existing stimulation technology, development of new stimulation methods, and adaptation to local coal conditions, are coalbed methane industry priorities as the Australian industry moves towards economic viability. Internationally, the most widely used method of stimulation is hydraulic fracturing. It has been developed in the conventional oil and gas industry over several decades. More recently, hydraulic fracturing has been the subject of extensive and detailed research for coalbed methane stimulation. In Australia, current research efforts are exemplified by Jeffrey *et al.* (1992).

In the past seven years a new method of stimulation has provided spectacularly successful results in certain instances. This stimulation method is only applicable to coal. Known as openhole cavity completion, the method was first demonstrated by Meridian Oil in the San Juan Basin of southern Colorado/northern New Mexico. Many hundreds of cavity wells have now been completed in the US with very variable results. Some treatments have improved well production rates by an order of magnitude or more when compared to hydrofracture. However, the vast majority of wells have been completed with little or no efforts at seam characterization. Consequently there is little fundamental information as to the reasons for success or lack of it. Only recently have the results of systematic research begun to reveal the fundamental mechanisms of cavitation and the interaction of cavity wells with coalbed methane reservoirs (Palmer, 1992; Mavor, 1992).

At the time of writing, cavity completion has not yet been attempted in Australia. However, the apparently strong dependence of success upon selection of suitable target seam conditions dictates that research must be conducted to characterize the seams with respect to intrinsic properties, including structure and in situ stress conditions. Furthermore, an understanding of the cavitation process and its interaction with these conditions must be achieved to underpin the development of appropriate cavitation technology is specific areas. The research need is to develop quantitative empirical and analytical models for the design and implementation of treatments suitable for a wide variety of conditions. Changes to the treatment strategy which make the cavity method work in an extended range of conditions would have worldwide application.

We report here on theoretical and laboratory studies to provide a better understanding cavity formation in different environments. This work is based on theoretical studies of fluid flow in porous media and poroelasticity. These studies have considered the role of pore fluid in inducing tensile effective stresses in the region of the wellbore during fluid depressurization. The work described in this paper concerns:

(i) cavitation mechanisms and production of cavities under controlled experimental conditions in the laboratory;

(ii) coal failure criteria under cavitation conditions and experiments to study the concept of an index strength for coal, using core specimen cavitation under controlled stress conditions;

(iii) wellbore effects on the depressurization rate of cavities and experiments to simulate wellbore pressure transients.

THEORETICAL CONCEPTS AND PHYSICAL IMPLICATIONS

Rapid gas depressurization in a borehole can induce mechanical failure in the porous medium surrounding the borehole. Failure can be violent, with the ejection of material from the borehole, as has been observed in full scale cavitation stimulations of methane wells.

In contrast to borehole failures induced by high in situ stress or by hydraulic fracturing in impermeable rock, cavitation failures must be analysed in terms of fluid flow within the coal. The stress and failure induced by the flow of liquids into boreholes has been theoretically studied by Paslay and Cheatham (1963) and Risnes *et al.* (1982), but stress induced by gas flow has not received the same attention. Gas is highly compressible, which provides pressure and stress profiles significantly different from those that occur with liquids. The compressibility of gas also means that the equation to be solved to describe the flow is highly nonlinear. This is unlike the linear equation that describes the flow of an incompressible liquid. It is this difficulty that has restricted solutions for gas flow to small pressure changes or other restrictive conditions so that linear approximations can be made.

Chan *et al.* (1992) have recently analysed the transient flow of an ideal gas initially at pressure p_i from a porous rock under uniform external stress σ, into a cylindrical borehole of radius a. It was assumed for this analysis that at time $t = 0$ the pressure in the borehole is instantaneously dropped to zero. This is an idealization, and represents the extreme case. In reality, in the field, it will take at least some seconds to evacuate the borehole. For small time, the pressure at radius r is given by: (1)

$$p(R,T) = \sqrt{1 - \exp\left[\frac{-0.776\,(R-1)}{\sqrt{T}} - \frac{0.152\,(R-1)^2}{T}\right]}$$

where,

$$R = \frac{r}{a} \quad \text{and} \quad T = \frac{kp_i}{\phi\mu a^2}$$

are dimensionless radius and time. Here k is the rock permeability, ϕ is porosity and μ is the gas viscosity. It can be seen from this equation for pressure decay that the group $\phi\mu a^2/kp_i$ provides a natural time constant. For methane ($\mu \cong 10^{-5}$ Pa.s, $p_i \cong 5 \times 10^6$ Pa) flowing into a typical wellbore ($a \cong 0.1$ m) from a coal seam ($k \cong 1$ millidarcy $\cong 10^{-15}$ m^2, $\phi \cong 0.04$), the characteristic time for the movement of the depressurization front is 0.8 seconds.

From equation (1) the effective stress can be calculated. Geertsma (1985) gives the equations for the total stress in the vicinity of a borehole as (2)

$$\sigma_r = \frac{C_1}{r^2} + 2C_2 - \frac{A}{r^2}\int_a^r p(\rho)\rho d\rho$$

and (3)

$$\sigma_\theta = -\frac{C_1}{r^2} + 2C_2 + \frac{A}{r^2}\int_a^r p(\rho)\rho d\rho - Ap\,.$$

In these expressions, A is the poroelastic material property given by

$$A = \frac{(1 - c_r/c_b)(1 - 2\nu)}{1 - \nu}$$

where ν is the Poisson's ratio of bulk material and c_r and c_b represent in-situ rock matrix and rock compressibility, respectively. The value for A for reservoir rocks is generally between 0.4 and 0.7. C_1 and C_2 are constants determined from the boundary conditions.

The Terzaghi effective stress is normally assumed to control failure in both compression and tension (Detournay and Cheng, 1988). Terzaghi effective stress σ' is given by (4)

$$\sigma'_{ij} = \sigma_{ij} + \delta_{ij}p\,.$$

Note that here we have followed the convention that stress s is positive in tension and negative in compression. Solutions using equations (1), (2), (3) and (4) can generally only be obtained numerically. A plot of a solution is shown in Figure 1, demonstrating the zone near the borehole that is in effective tension at that time. Insertion of actual values indicates that the period of time in which material failure can take place is only short, in the range of several seconds to several tens of seconds. For laboratory experiments on a reduced length and pressure scale, an even shorter characteristic time between 0.1 and 1.0 seconds applies.

It is recognized that the solution represents the initial cavitation condition. Assuming a new failure surface is created, the process could repeat itself on a progressively diminishing basis as the gas pressure gradient within the intact coal decreases. This could be visualized as an "onion skin" effect.

The implications of the analysis are that cavitation efficiency will be enhanced by increasing both the rate and magnitude of depressurization. For a coal of given physical properties, there will be a cut-off rate and magnitude below which cavitation will not occur. It is of interest to note that the theoretical model indicates that low permeability will enhance the time that effective tension exists in the coal, thus increasing the efficiency of cavitation, providing other factors are constant. This is supported by the observation from underground coal mines that outbursts tend to be associated with tight coal. However, while low permeability might assist the development of high pressure gradients it is often associated with stronger coal, which works against cavitation. Although a cavity might be formed, the overriding consideration is that low permeability will inhibit gas production rate. This is obviously undesirable.

PHYSICAL MODEL EXPERIMENTS

Small scale physical model experiments have been conducted to simulate cavitation in porous solids. This has been initially for comparison with the theoretical model and to gain insights into the cavitation mechanism. Physical models can provide observational and quantitative data, obtained with well defined boundary conditions and material properties, for validation of theoretical concepts. They enable a range of conditions to be simulated, for instance *in situ* stress conditions, and are an adjunct to field observation and measurement. They are particularly useful in simulating failure behaviour, which may sometimes be beyond the scope of theory, as is the case here. Physical models have been used in the coal mining industry for many years (eg. Wold, 1986).

Laboratory cavitation has been produced in models constructed of so-called equivalent materials, specially developed for the purpose and having low tensile strengths in the range 50 to 100 kPa. In this initial study, cylindrical sand-plaster models of 500 mm diameter and 70 mm thickness were confined in a pressure chamber with the model ends sealed (Figure 2). The porous models were pressurized with nitrogen in the range 0 to 800 kPa. Cavitation was induced around a central axial hole of 20 mm diameter, by sudden release of gas pressure from the hole. Successful cavitation was accompanied by the violent ejection of material from the hole. The gas pressure history at the hole collar and at the outer boundary of the model were recorded by pressure transducers and a high speed data acquisition system. Cavity geometry was recorded by the casting of a low melting point metal alloy (Wood's metal) into the cavity.

For the experiments reported here, cavities were formed when depressurization times were in the range 0.2 to 0.4 s, depending on the strength of the material. With slower pressure reduction rates, of the order of seconds, cavities were not induced. This is consistent with the mechanism hypothesized.

Cavity geometry was generally complex, whether formed in one depressurization step or in several (Figure 3). The complex geometry indicates nonlinearity and instability in the formation mechanism, and is clearly influenced by material heterogeneity. In a model with a bonded layer type of construction, a ramified dendritic cavity geometry was formed along apparent planes of weakness (Figure 4). Similar irregular geometries have been observed at gas outburst sites in coal mines. These cavities can contain a narrow neck which leads into a larger void further into the coal. Rugose cavities associated with interbedded sediments in the coal seams have also been reported from geophysical logs of openhole cavity wells (Palmer, 1992).

The observed geometrical complexity is much greater than has been predicted by the relatively simple theory developed so far, and warrants further investigation. It may be of fundamental significance in interpretation of connectivity of the cavitated wellbore with the reservoir, as discussed by Mavor (1992).

CAVITATION FAILURE CRITERION FOR COAL

Implicit in the theory and experiments presented above is the notion that the cavitating medium has a strength which resists the effective tensile stress generated by the depressurizing gas, and that the relationship of these two factors will govern the initiation of fracture. Coal has a dual porosity nature, with flow possible in both macropores (cleats) and micropores. It is assumed here that as far as cavity formation is concerned, only flow in the cleats is relevant, because of the short periods of time involved.

It is likely that cleat structure also governs the effective resistance to tensile failure. Tensile strength of brittle materials is highly dependent on structural discontinuities and mode of loading, and is notoriously difficult to measure as an absolute property. Nevertheless, as a hypothesis it is assumed that the coal may have a consistently measurable index of resistance to the cavitational (tensile) mode of failure, and that measurement of this index may provide a useful parameter for prediction of cavity performance.

A prototype apparatus has been developed for the cavitation testing of coal core while under externally applied uniform biaxial stress (Figure 5). The apparatus allows the measurement (using additional equipment) of intrinsic permeability as a function of externally applied stress, followed by cavitation as functions of applied stress and depressurization rate. Currently this can be performed on N size core, but could be adapted for any size.

Initially this work has provided data for the physical modelling investigations and validation of the theoretical concepts. These tests have been carried out using low strength equivalent materials and low operating pressures. A pressure decay curve which cavitated a low strength material under confined stress conditions is shown in Figure 6. Superimposed is the system pressure decay curve, obtained using a steel blank in place of the core. The small slope difference between the two curves is a function of the porosity and permeability of the equivalent material, which are high in this case. Currently the apparatus is being further developed for use on coal specimens at insitu conditions of stress and fluid pressure. Using the apparatus, coal specimens can be characterized in terms of porosity, and permeability as a function of stress. They will be cavitated by gases of known viscosity and temperature at controlled pressure decay rates. The method allows depth of cavitation to be measured and the fracture morphology to be examined. Using oriented core drilling from surface coal exposures, directional structural effects can also be investigated.

WELLBORE GAS TRANSIENT EFFECTS

Theory, experiment and field experience confirm that rapid depressurization of the wellbore seam interval is required for cavitation to occur. A measure of the rate required in terms of the coal seam and gas pressure variables is provided in Figure 1. In practice, two "external" factors may act to limit the effective rate of pressure reduction;

(a) the volume and throughput capacity of the wellbore and wellhead, and any equipment in it;

(b) the volume of the cavity as produced by previous cavitation cycles.

Experiments have been carried out in strings of drill rods, pressurized with air to simulate a cased borehole during cavitation. Low pressures have been used to begin with (< 800 kPa) The drill strings were instrumented at intervals along their lengths to measure instantaneous pressure as a function of time during venting. The cavity was simulated by a pressure chamber at the end of the rods. By positioning the high speed valve at various positions in the rod string the effect of wellbore gas volume was evident. As wellbore volume increased, pressure decay rate decreased (Figure 7).

Comparison of the pressure decay curve in the cavity with the critical decay curve for cavitation of the coal provides an approach for predicting cavitation performance. If the pressure decay rate required for cavitation to occur in a core specimen under specified stress and gas pressure conditions (eg. Figure 6) is greater than that of the wellbore (eg. Figure 7), cavitation might not be expected. The experimental curves provide a basis for improving the theoretical model (Section 2, above). Empirical curve fitting indicates that in many cases, the pressure decay curve is exponential. Replacement of the instantaneous pressure step function with an exponential function will provide a refinement to the numerical solution for duration and extent of tensile stress zones.

For full scale cavity wells, the results suggest that wellbore effects and cavity volume will limit the pressure decay rate achievable. As the cavity volume increases during repeated cavitation cycles, the pressure decay rate will decrease. This will lead ultimately to a stabilized cavity in which further cavitation is not induced. Field measurements indicate stable cavity radii of the order of 1.5 m (Mavor, 1992). It was also reported that gas production rate was not further enhanced by continued cavitation cycles beyond a certain limit. The results discussed in this paper are consistent with these field observations.

CONCLUSIONS

A fundamental understanding of cavitation mechanisms is important for the efficient implementation of cavity stimulations in the coalbed methane industry worldwide. We have undertaken initial theoretical and laboratory studies with the following conclusions.

1. Theory predicts that gas pressure reduction within a borehole can induce mechanical failure and for a cavity, provided that the pressure reduction is sufficiently large and rapid.

2. Laboratory cavitation models confirm that rapid pressure reduction can create cavities in a porous material. Failure modes have been demonstrated to be highly nonlinear and dependent on structural features in the material.

3. Prototype equipment has been developed for the testing of core for cavitation strength under controlled gas and external stress conditions.

4. Tests observing pressure decay in instrumented drill strings indicate that wellbore effects and cavity volume limit the maximum rate of pressure drop obtained. In practice this will act to limit the maximum size of cavity achievable for a given borehole diameter and valve arrangement.

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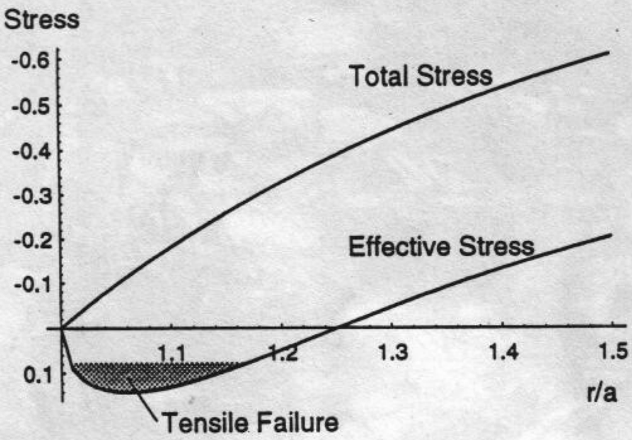

Figure 1. **Calculated total radial stress and effective radial stress as a function of distance *r/a* from a wellbore of radius *a*. These are shown at a very short time after the pressure in the wellbore had been dropped instantaneously to zero. This demonstrates that at small values of time, the effective radial stress can exceed the tensile strength of the porous material**

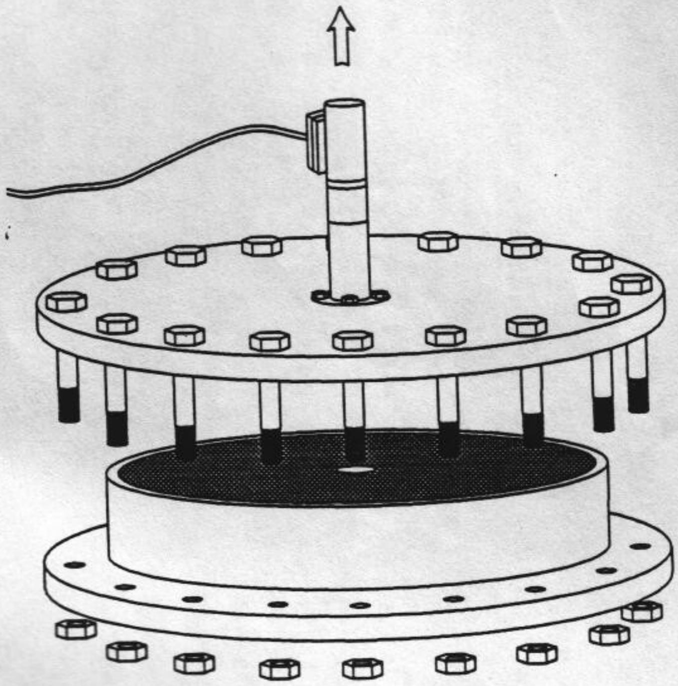

Figure 2. **A schematic diagram of the laboratory pressure chamber for physical model cavitation experiments**

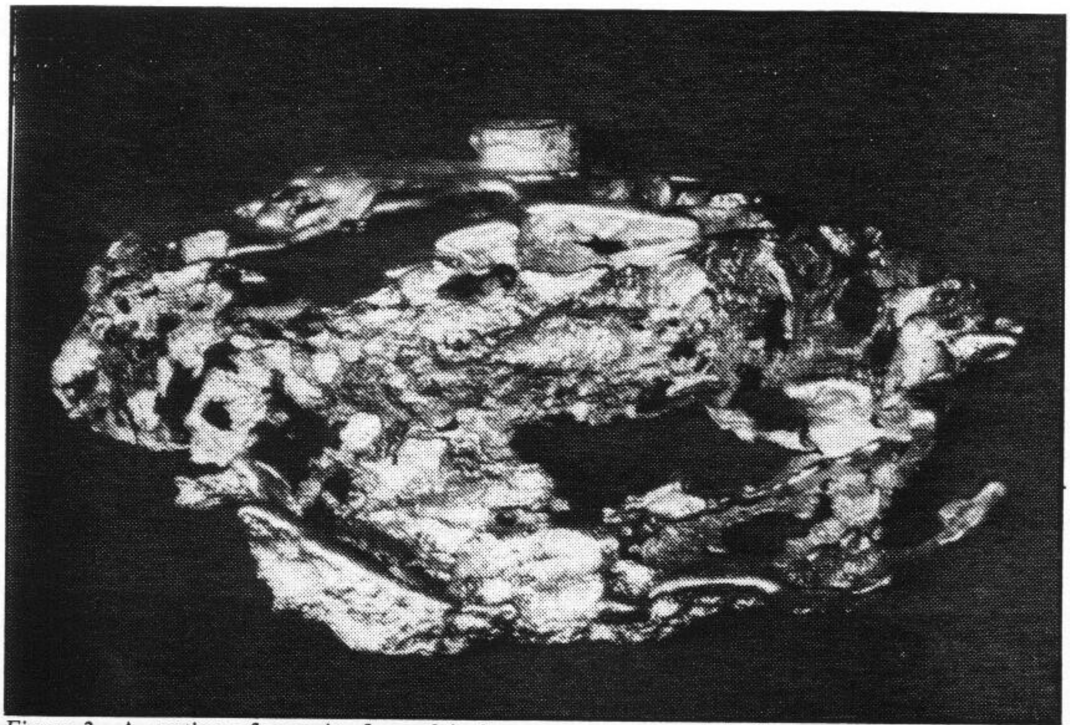

Figure 3. A casting of a cavity formed in homogeneous material after two cavitation cycles in the laboratory pressure chamber. A cavitation cycle is produced when high pressure is dropped suddenly via an orifice at the end of the borehole.

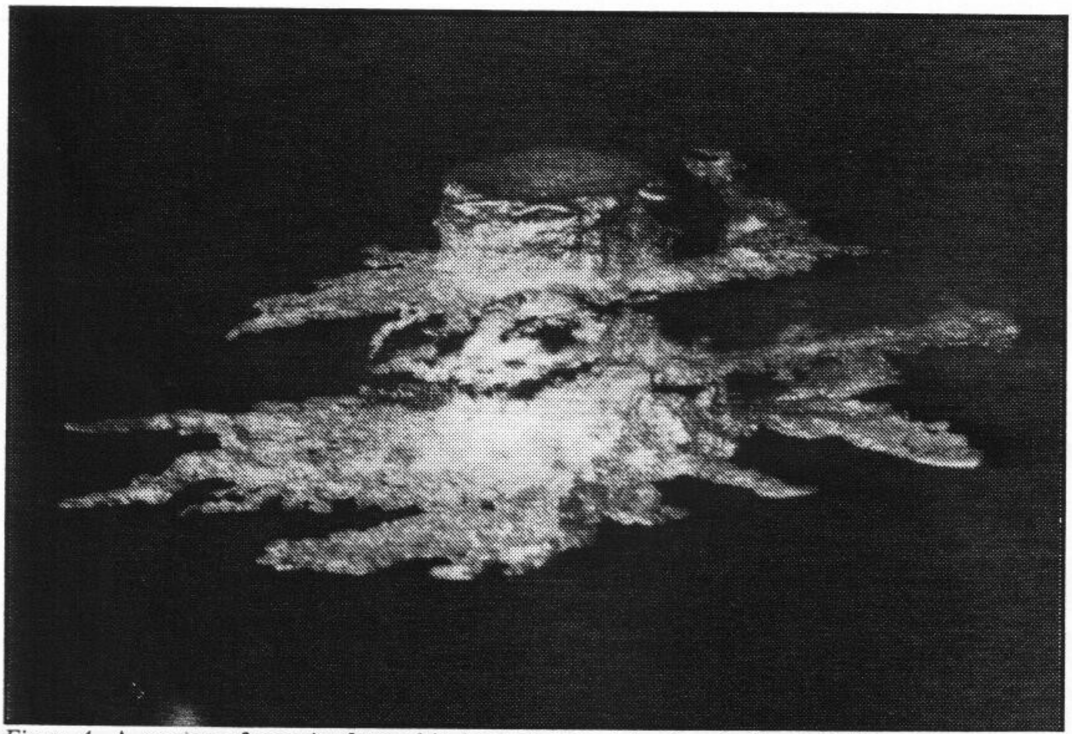

Figure 4. A casting of a cavity formed in layered material using single cavitation cycle

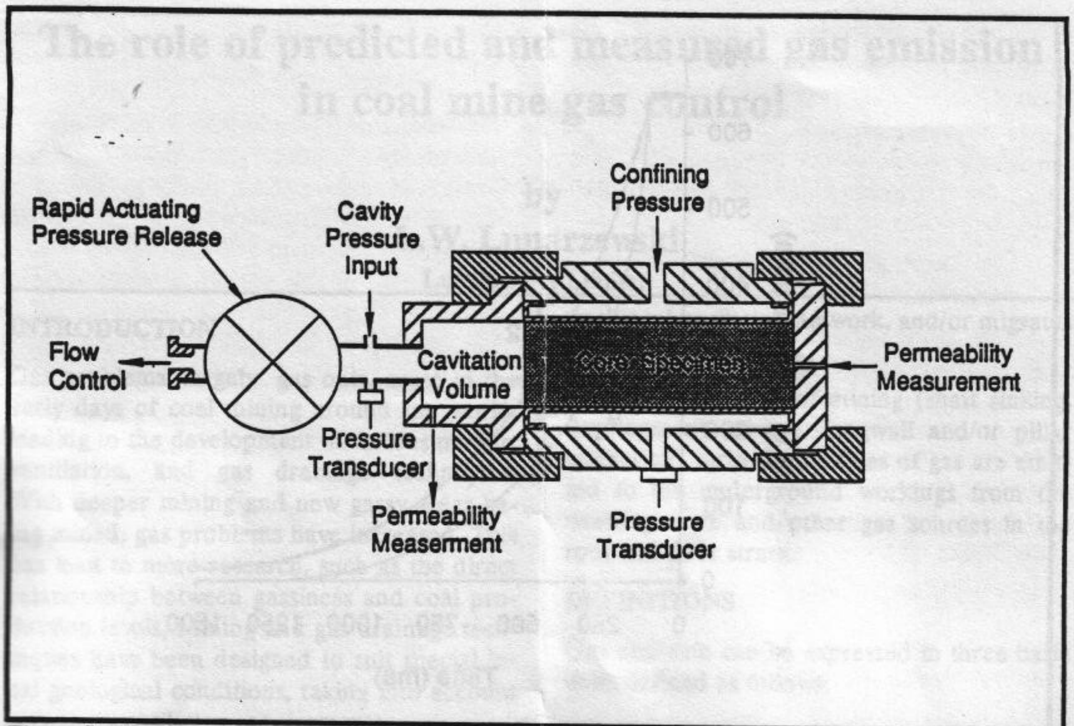

Figure 5. **A schematic diagram of a cell for cavitation of core specimens under confining pressure**

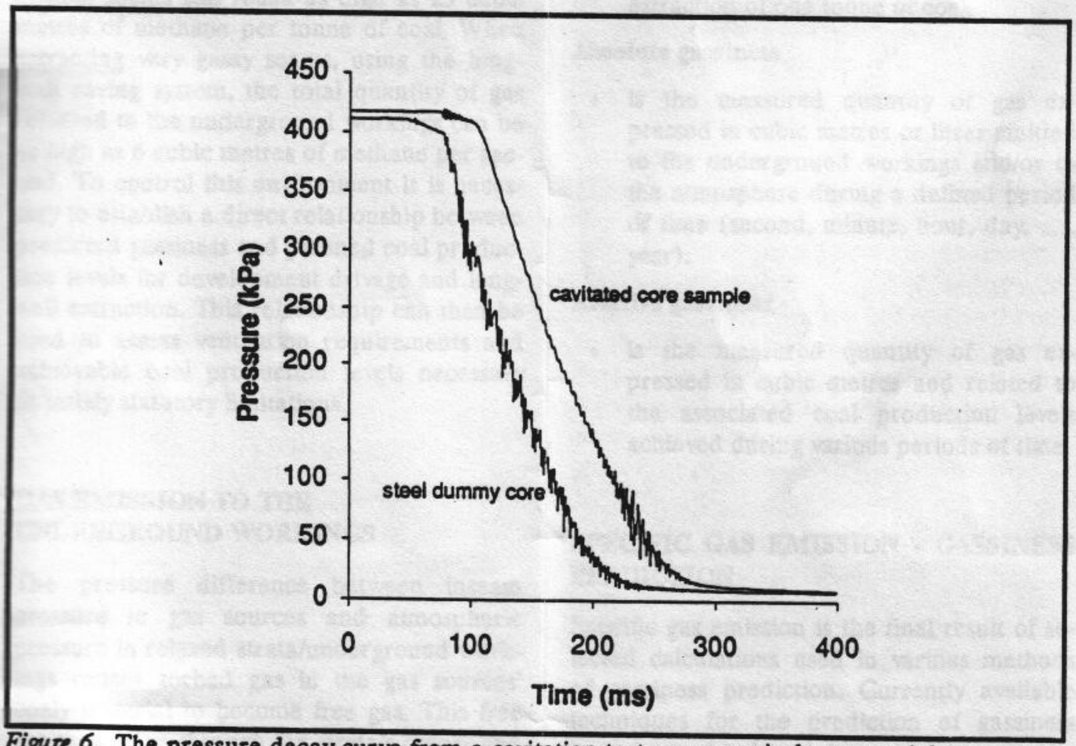

Figure 6. **The pressure decay curve from a cavitation test on an equivalent material core specimen. Also shown is the system pressure decay curve, obtained using a steel blank in place of the core**

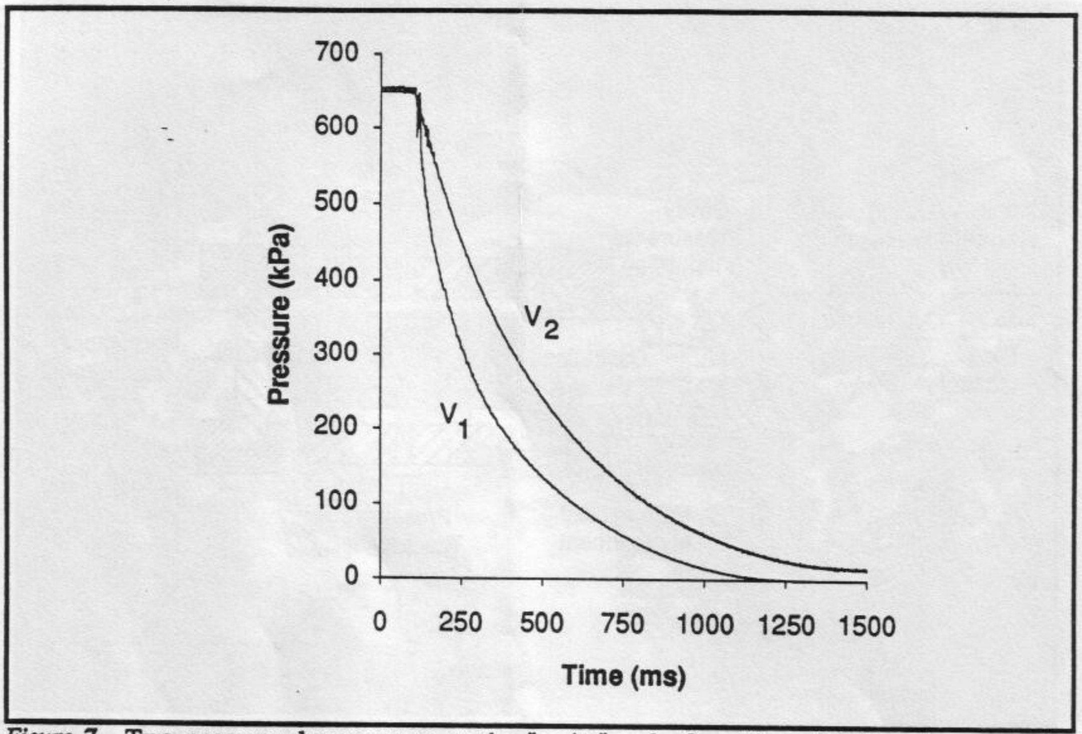

Figure 7. Two pressure decay curves at the "cavity" end of a string of drill rods undergoing depressurization. Two separate cavity and rod volumes were used with V_2 greater than V_1. The rate of pressure decay decreases with increasing volume