IN-SEAM SEISMIC METHODS FOR THE PREDICTION OF OUTBURSTS IN COAL SEAMS

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ABSTRACT

Recent field experiments in the United Kingdom (Buchanan, 1979) have shown that the in-seam technique is capable of detecting a 1m fault in a 3m seam, at a range of 280m and with a resolution of ±40m. Comparable tests in Australian collieries are proceeding. Although the practicality of an implementation of the technique on a routine basis remains to be demonstrated, the potential of the technique for the prediction of outbursts clearly warrants detailed examination. This potential will depend, *inter alia,* on the level and scale of variations in elastic (and anelastic) properties of bodies of coal undergoing stresses associated with mining. Available data, mainly from studies of the seismic properties of gas saturated reservoir rocks, confirm the intuitive view that stress increases give rise to increases in seismic wave velocity and decreases in wave attenuation, markedly at low stresses (as pore spaces close with little resistance) but less so as stress increases. Such increases are of the same order as anisotropic effects, but should provide impedance contrast sufficient for detection by in-seam seismic methods. At higher stresses, cracks form within the rock mass. Results from research on earthquake prediction provide some clues to the behaviour of sedimentary rocks subjected to large stresses. In particular, the dilatancy model suggests that stress can induce significant, but transitory reductions in compressional (but not shear) wave seismic velocities by the formation of "dry" cracks. Notwithstanding the physical basis for a seismic (and electromagnetic) expression of potential outbursts in coal seams, there remain many difficulties in designing and implementing an active in-seam seismic technique capable of reliable and unambiguous detection and location of any manifestation of a potential outburst; the difficulties span data collection, processing, interpretation, and benefit-cost. In-seam methods are better suited to long term prediction (by structural association) than shorter term prediction. Stress induced variations in electrical conductivity may provide a basis of short term prediction by electromagnetic reflection profiling.

INTRODUCTION

Recent results from both the U.K. (Ziolkowski and Lerwill, 1979; Ziolkowski, 1979) and Australia (Rutter and Harman, 1980) have affirmed the role of seismic reflection methods in coal exploration and mine planning. However the fact that reflection methods sample coal seams remotely through an absorptive and highly variable straticulate sequence imposes a severe limitation on the vertical and lateral resolution attainable. The coal mining industry has evinced a need for a means of predicting potential obstacles to mining which

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are beyond the resolution of surface seismic reflection methods. In-seam seismic techniques, in which seismic waves are generated and detected *within* a coal seam, are being developed in response to this need (see Buchanan, 1979; Mason, Buchanan and Booer, 1980; King and Greenhalgh, 1980). Although in-seam methods are beset by technical as well as interpretational difficulties, recent results from research groups in the United Kingdom (Buchanan *et al.*, 1980) and Germany (Klinge *et al.*, 1979) give good cause for optimism. It is timely to explore whether in-seam methods could be used for the prediction of outbursts in coal mines. In the present paper we examine the possibility that potential outbursts may be manifest as seismic "obstacles".

THE NATURE OF OUTBURSTS AND MICROSEISMIC NOISE

Coal mining operations result in a redistribution of stress within the coal and surrounding rock. Depending on the rate of advance, the weight of overlying strata and the geological environment (e.g. presence of residual stresses, faults, pressure of contained gas) this stress re-distribution may cause sudden fractures and explosive ejection of material from the most strongly stressed or mechanically weakest zone of rock near the face.

Microseismic noise (or seismo-acoustic emission) within a coal seam is produced by a similar but less violent stress-relief mechanism involving cracking or separation of the plies of coal. This fracturing in itself expends some energy but also weakens the rock involved, thus decreasing further elastic build up of strain.

PASSIVE MICROSEISMIC NOISE MONITORING

Anomalous increases in the microseismic level, generally expressed in events per hour, have been observed prior to outbursts in coal seams in various parts of the world (Antsyferov, 1966; Blake, Leighton and Duvall, 1974; Hardy, 1975; Howarth, 1977). This has led to the development of passive seismo-acoustic methods as a monitor and predictor of potentially dangerous mining conditions. However, attempts to predict the time and location of outbursts have not always been successful, and no diagnostic precursory sequence of events has been identified.

Part of the problem is that not all microseismic noise is measurable. This may be due to transmission losses, equipment sensitivity limitations, or the problem of separating natural seismo-acoustic noise from ambient machine and cultural noise within the mine. A further problem is that not all releases of accumulated strain energy lead to perceptible outbursts. If the coal is not gas bearing, or though gas bearing has a low rate of gas emission, then spalling rather than outbursting occurs. Alternatively, the stresses may be contained or redistributed within adjacent strata, or they may be released by plastic deformation during mining. At present, therefore, passive microseismic monitoring can serve only as a *warning* of possible outburst occurrences.

To be effective, microseismic monitoring must be used in conjunction with other methods of monitoring mine stability, such as geological surveys, measurements of face and roadway movements, gas volume measurements, in situ elastic stress determinations, and other geophysical remote sensing techniques.

In the present paper we consider *active* as opposed to *passive* seismic methods; active methods make use of seismic impulses which are generated artificially (e.g. explosion, mechanical or magnetostrictive impulses) and coupled to the coal. The active methods offer the advantage that they allow, in principal at least, the regions of increased stress concentration and gas accumulations to be indirectly detected, and possibly located from measurements of seismic wave travel time, velocity and attenuation.

PHYSICAL BASIS FOR ACTIVE IN-SEAM SEISMIC METHODS

Effect of Stress on Seismic Wave Velocity

For most rocks the propagation velocities of seismic waves increase with increasing stress. This had been demonstrated for sedimentary rocks by Hugues and Jones (1951), Hughes and Kelly (1952), Wyllie, Gregory and Gardner (1956, 1958), Toksöz, Johnston and Timur (1979), and others (see Fig. 1).

The propogation velocities under various methods of compression (hydrostatic, triaxial, uniaxial) are not significantly different except when velocity is measured in a direction perpendicular to the stress under a uniaxial stress in which case velocities may be up to 10% lower.

The velocity increase with stress is more pronounced in less consolidated rocks like coal than in cemented sediments and igneous rocks. Also, it has been found that the velocity gradient is much greater at lower stress than at higher stress. For the sandstone represented in Fig. 1, velocities increase by 15% to 30% of their intitial value over the stress range 0 to 500 bars.

We remark that it is not the total overburden stress which determines the velocity, but rather the effective stress (differential pressure), which is the difference between total stress and the pore fluid pressure. In a coal mine situation, effective stress differences of up to 100 bars and more are to be expected.

Effect of Stress on Seismic Wave Attenuation

Attenuation measurements have been carried out on rock cores in the laboratory using different techniques over a wide frequency range (for a review of the subject, see Toksöz, Johnston and Timur, 1979, and Johnston, Toksöz and Timur, 1979). Seismic wave attenuation is generally expressed in terms of dissipation factors Q^{-1}; $2\Pi Q^{-1}$ is the fraction of total strain energy dissipated per cycle. Observations show that attenuation decreases (Q increases) with increasing confining pressure. As with velocity behaviour, this is usually interpreted as the closing of cracks in the rock.

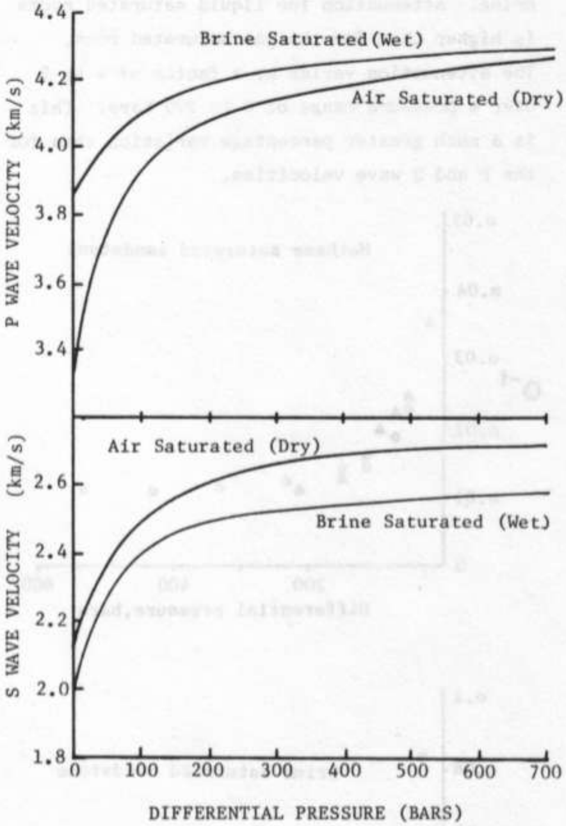

Fig. 1 - Compressional and shear wave velocities as a function of differential pressure in dry and brine saturated sandstone (Data from Toksöz, Johnston and Timur, 1979).

Figure 2 displays Q^{-1} values for P and S waves as a function of differential pressure for a sandstone saturated with methane or with brine. Attenuation for liquid saturated rocks is higher than for the gas saturated rock. The attenuation varies by a factor of 4 to 5 over a pressure range of 0 to 270 bars. This is a much greater percentage variation than for the P and S wave velocities.

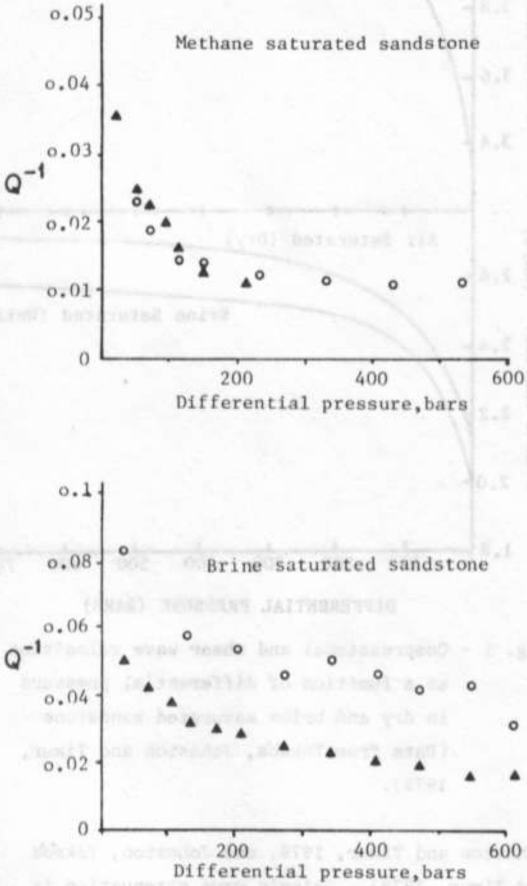

Fig. 2 - Attenuation (Q^{-1}) values of P (▲ symbols) and S (O symbols) waves as a function of differential pressure in methane saturated and brine saturated sandstone. (Data from Toksöz, Johnston and Timur, 1979).

For directed uniaxial stress. the attenuation is reported to be anisotropic, with lowest attenuation normal to the axis of maximum compression.

Effect of Partial Gas Saturation on Seismic Wave Velocity

The effect of gas saturation on the velocity of seismic waves is dependent on pressure. Laboratory tests (Hughes and Kelly, 1952; Wyllie, Gregory and Gardner, 1956; Hicks and Berry, 1956) indicate that when the gas increases from zero percent (water saturated) to 100 percent, the velocity decreases smoothly.

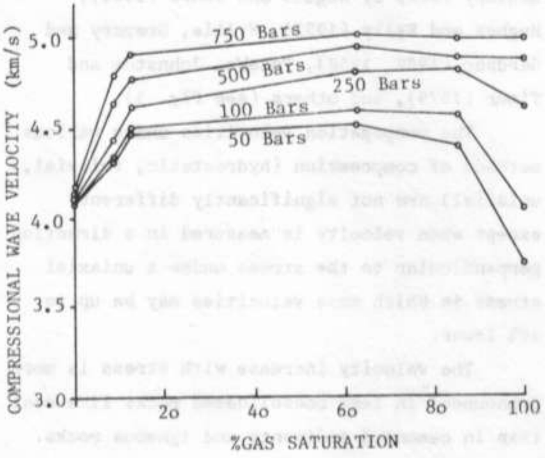

Fig. 3 - Compressional wave velocity vs gas saturation for various pressure in a sandstone at 25°C. (Data from Hughes and Kelly, 1952).

At low pressures (see Fig. 3, say 100 bars) the velocity rises sharply at small gas saturations (0-10%), remains constant with gas saturation from 10 to 90%, and then decreases as complete gas saturation is approached. As the pressure is increased, the fall at high gas saturations decreases - at 500 bars it disappears. At these high external pressures, the velocity is almost constant beyond 10% gas saturation; from 0-10% gas saturation, velocity increases rapidly.

These results can be explained in terms of effective stress. For gas saturation of 10% to 100% the water in the rock is under relatively low stress and the framework under high stress. For zero gas saturation, the rock is completely wet, with the pore water under high pressure and the framework under low pressure.

Effect of Partial Gas Saturation on Seismic Wave Attenuation

Figure 2 displays attenuation data for a sandstone sample, either completely dry (100% gas saturation) or completely wet (0% gas saturation). For partially saturated conditions it has been found (Gardner *et al.* 1966) that the Q value decreases sharply (i.e. attenuation increases) over the range 0 to 20% gas saturaion, but then remains essentially constant out to 80% saturation. Dutta and Ode (1979) have formulated an exact theory of attenuation and dispersion of compressional waves in porous rock containing spherical gas pockets. The loss mechanism is essentially viscous in nature and is due to the relative motion of fluid with respect to the rock matrix.

From this theory we have computed phase velocity and attenuation versus gas pocket separation for a frequency of 1 Khz and gas saturations of 1%, 10% and 45%; results are shown in Fig. 4 and Fig. 5. From these graphs, we observe that velocity increases by 27%, and attenuation increases by an order of magnitude, as the gas saturation decreases over the stated range.

DILATANCY THEORY OF EARTHQUAKE PREDICTION

To date, efforts at outburst prediction have been directed towards finding correlations between outbursts and plausibly related phenomena such as changes in the coal colour or lustre, crumbling of coal, formation of dust clouds, and microseismic noise increases within the seam. We find no reference to an explicit unifying physical model. It would appear, however, that a workable and applicable physical model is available from the extensive research on earthquake prediction, *viz.* the dilatancy model (Hammond, 1971; Nur, 1972; Healy, 1975; Wyss, 1973). Before describing the model, we need to note that it has long been accepted that fracture strength of a rock and resistance to sliding along a fault is inversely related to pore pressure in the rock. Thus raising the fluid pressure will lower the point at which the rock will fracture under stress.

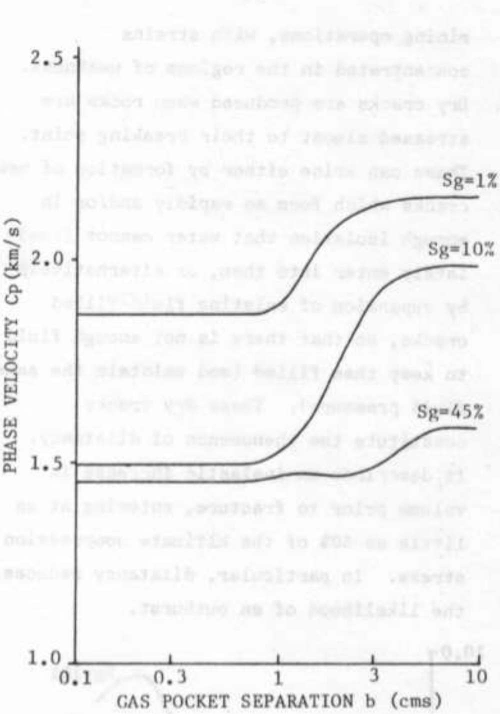

Fig. 4 - Compressional wave phase velocity C_p vs gas pocket separation b for a 1 KHz wave propagating in porous media of various gas saturations S_g. The radius of the spherical gas pockets a is equal to b $S_g^{1/3}$.

The dilatancy model invokes three steps:

I. Elastic stresses and strains build up in the region. These are generally tectonic in origin, or in the case of coal, due to mining operations, with strains concentrated in the regions of weakness.

II. Dry cracks are produced when rocks are stressed almost to their breaking point. These can arise either by formation of new cracks which form so rapidly and/or in enough isolation that water cannot immediately enter into them, or alternatively by expansion of existing fluid-filled cracks, so that there is not enough fluid to keep them filled (and maintain the same fluid pressure). These dry cracks constitute the phenomenon of dilatancy. It describes an inelastic increase in volume prior to fracture, entering at as little as 50% of the ultimate compression stress. In particular, dilatancy reduces the likelihood of an outburst.

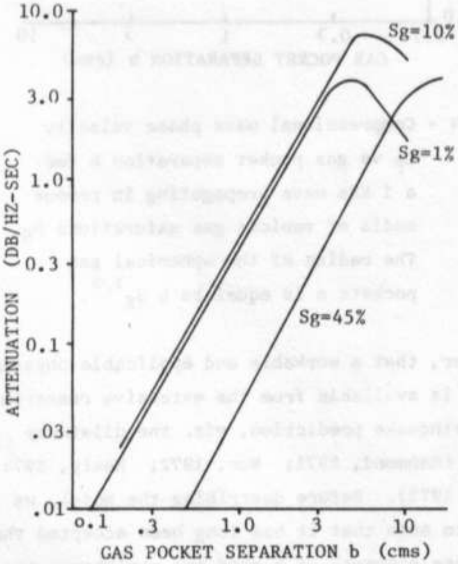

Fig. 5 - Attenuation coefficient α (= $Q^{-1}.\Pi/\lambda$ where λ = wavelength) of the P wave vs gas pocket separation b for a 1 KHz wave propagation in porous media of various gas saturations S_g. The radius of the spherical gas pocket a is equal to b $S_g^{1/3}$.

III. Eventually, pore fluid works its way into the dry cracks. Meanwhile, local stresses have been continuing to accumulate, with mining, so that now we have higher stresses plus well lubricated pores, thus favouring a violent brittle fracture or outburst on both counts.

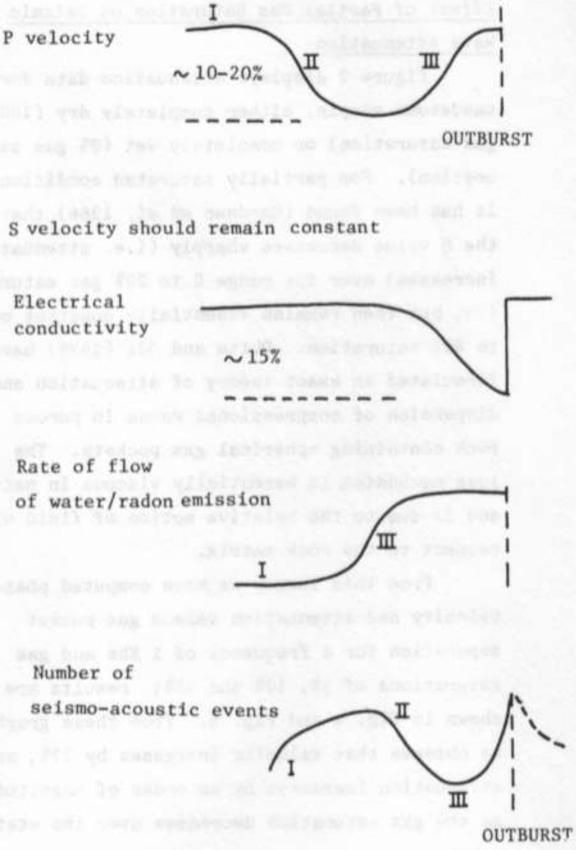

Fig. 6 - Effects of dilatancy model of earthquake prediction schematically illustrated for the coal outburst situation.

I = elastic strain buildup;
II = dilatancy buildup;
III = influx of pore water.

The effects of this three stage process will be manifest in several ways, as illustrated schematically in Fig. 6. In particular P wave velocity and electrical conductivity fall during stage II by up to 20% of their initial value, but then rise during stage III prior to the outburst. The microseismic noise level and the amount of radon emission should also rise during this interval. Shear wave velocity remains unaffected.

POSSIBILITIES AND LIMITATIONS FOR AN IN-SEAM SEISMIC MONITORING METHOD

Perspective

We have now established a physical basis for active seismic testing of coal seams. The velocity anomalies of interest (*viz.* regions of increased stress and/or gas concentration) are likely to be of the order of 3 to 20%. Corresponding attenuation anomalies will be significantly higher, as much as 200%. Anomalies of this size give some cause for optimism; in several cases they have in fact been measured. Mason (1980) carried out velocity measurements in the High Hazles seam of Thoresby Colliery, Great Britain, and found a correlation between the velocity field and the stress field caused by subsidence. Velocities in the seam above old workings are 7% lower than in the unmined areas. Blake (1971) made a study of velocity in a deep metalliferous mine in Idaho, before and after destressing by blasting. Maximum velocity measured before destressing was 5800 m/s; after destressing this value dropped to 4,900 m/s. Antsyferov (1966) has reported on active seismo-acoustic experiment to predict spalling of rocks in underground workings in the Sovient Union. No appreciable change in the velocity or amplitude of the seismic waves was observed until 2-3 hours before the beginning of intense fracturing.

Channel Wave Seismology

The continuity of coal seams is often disturbed by obstacles such as faults, changes in lithology, washouts, clay dykes and old workings. These obstacles adversely affect the efficient recovery of coal as well as present serious safety hazards. In many cases, outburst phenomena are directly associated with these obstacles. For example, a clay vein may act as a barrier to methane drainage. When the vein is mined, large quantities of methane will be encountered.

The exceptionally low velocity and density of coal, compared to neighbouring rocks (Table 1), makes entrapment of seismic energy within a coal seam theoretically possible. Energy is largely prevented from escaping from the channel because of repeated reflection at the top and bottom channel boundaries or because seismic rays which tend to escape are ent toward the channel by increasing velocity away from it in either direction.

Table 1.

Typical Elastic Properties of Coal and Host Rock

	P-wave velocity (km/s)	S-wave velocity (km/s)	Density (g/cm^3)
Coal	1.4 - 2.3	.7 - 1.6	1.2-1.4
Rock (sandstone, Shale)	2.5 - 4.5	1.4 - 2.6	2.3-2.8

Channel waves can be either of the Rayleigh type (P-SV) or Love type (SH), depending on the particle motion in the wave. Each type can be derived from interferences between multipli-reflected P, SV and SH waves in the seam, and can be interpreted in terms of modes (Tolstoy and Usdin, 1953; Lagasse and Mason, (1975).

Krey (1963) first suggested that channel waves could be used to certify seam continuity and to locate any obstacles. Since the pioneering work of Krey there have been a number of studies carried out (Krey, 1976; Hasbrouk and Hadsell, 1976, Dresen and Freystätter, 1976; Buchanan, 1979; Reeves, 1979; *inter alia*). Typical rates of working dictate that for optimum planning, discontinuities must be detected a few hundred metres in advance. This condition is easily fulfilled as channel waves can readily propagate to distances of 1.5 km. The principal advantages in using channel waves, as opposed to body waves, as a means of investigating faulting are that they are essentially confined to the seam, generally "see" larger impedence contrasts, and are of large amplitude. There is therefore one less dimension and less error in locating any discontinuities.

Channel waves may be exploited by way of transmission or reflection surveys (Fig. 7). Reflection surveys are inherently superior to transmission surveys insofar as faults or other obstacles can in theory be located, rather than simply detected. In both types of survey, difficulties arise in practice because channel waves are dispersive.

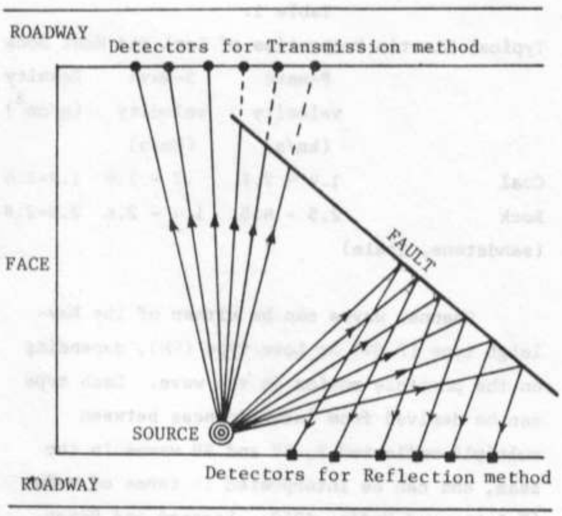

Fig. 7 - Possible configuration of in-seam reflection and transmission probing of a fault cutting a coal panel. The fault modifies the transmitted waves at 3 of the 6 detectors.

It is beyond the scope of the present paper to detail the various aspects of channel wave seismology; the reader is referred to Krey (1976), Mason, Buchanan & Booer (1980), and King and Greenhalgh (1980) for review articles and comprehensive reference lists.

Since 1966, over 300 in-seam surveys have been carried out, mainly in Germany and Britain but also in Czechoslovakia and the U.S.A. According to Krey (1976), 90% of all transmission surveys and 75% of all reflection surveys checked out with excavation and drilling results were found to be correct. Perhaps the most impressive published result is from the National Coal Board in Britain (Buchanan, 1979); Buchanan used a holographic imaging technique to detect a 1 metre fault in a 3 metre seam at a range of 280m, and with a precision of ± 40 metres. The in-seam technique, although still under development, clearly deserves more attention in the Australian context. Preliminary experiments are planned for the Leichhardt Colliery during early 1980.

Potential Difficulties for the Prediction of Outbursts

In this section we investigate some of the potential difficulties that might be encountered in using the in-seam method for detecting and locating potential outbursts. The first consideration is one of target range and resolution. Studies conducted in the Soviet Union (Antsyferov, 1966) have established that the zone of increased pressure and the sources of seismo-acoustic noise occur within a distance range of 2-16 m from the face. Moreover, the spatial extent of the outburst prone area is quite small. For adequate seismic delineation of these small target obstacles it is necessary to employ an elastic wave source capable of generating frequencies typically in the range 1 KHz to 10 KHz. Also, a densely spaced array of receivers must be laid out to capture the transmitted and reflected waves in sufficient detail. Space limitations on the working face may preclude configuration of an array of suitable geometry. In addition, the working face may be rough, presenting coupling problems and reducing wavefront coherence. Absorption in the spalled zone, unless avoided by placing all sources and receivers in drill holes penetrating it, might swamp out the variation we are looking for deeper in the coal panel.

Seismic waves respond to changes in the acoustic impedance of rocks along the propagation path. Unfortunately, in the present context, pressure and gas concentration are not the only factors influencing impedance and absorption. Other factors such as stratification, texture, porosity and temperature also contribute. Velocities tend to decrease with increasing porosity (Rinehart and Burgin, 1961); a 10% variation in porosity may produce a 20% variation in velocity. Temperature also leads to a decrease in velocity. Rinehart and Burgin (1961) predict a velocity change of 5 to 15 percent for a temperature variation of 0 to 100°C. Attenuation, on the other hand, is generally independent of temperature for temperatures low relative to the melting point.

Perhaps the most serious factor to consider in the coal situation is anisotrophy. Velocity measured along layers or cleavages in a coal seam is higher than the velocity perpendicular to layers or cleavages. Differences are typically of the order of 12% (Terry, 1958), i.e. the same order as the putative anomalies. In practice it is difficult to see how the various effects could be separated. Interpretation of velocity anomalies in terms of pressure or gas concentrations would be seriously non-unique.

Problems of benefit-cost compound the above mentioned difficulties. Locating hazardous areas within a coal mine is a short term prediction problem. The transition from a safe zone (where bursts do not occur) to a danger zone takes place over a distance of just a few metres; this corresponds to only a few days production. Thus, to be effective seismic surveys would need to be carried out on a daily basis with possibly several tests per day. Conducting seismic operations of this frequency and on this scale with minimal disruption to normal mining activities would be expensive as well as logistically difficult. On the spot interpretation would be madatory. Some form of machinery shut down would seem unavoidable to overcome the background noise problem; experience suggests this is unlikely to be acceptable to mine management.

If the mine is prone to outbursts then it is not a safe or desirable environment in which to be continually drilling and carrying out seismic tests, particularly with explosive sources. The instrumentation would need to be portable and fire-damp proof, with real-time processing capability. Not least of the difficulties is that undue responsibility (and safety risk) would be placed on the seismic survey party.

A less expensive, and simpler, alternative approach to the short-term outburst prediction problem would seem to us to be a ground probing radar system designed to detect changes in electrical conductivity entailed by the dilatancy phenomenon. Ground probing radar methodology is more suitable for the detection and recognition of transitory anomalies than in-seam sesimic methodology. Extensive tests carried out by Cook (1974) and Coons, Shafer and Fowler (1979) have shown that it is possible to detect transmitted and reflected short pulse radar signals (frequency 10-100 MHz) from discontinuities in coal seams at distances of up to 17m.

CONCLUSIONS

We have established a physical basis for a seismic (and electro-magnetic) expression of potential outbursts in coal seams. There remain many difficulties in designing and implementing an active in-seam seismic technique capable of reliable and unambiguous detection and location of any manifestation of a potential outburst.

The difficulties span data collection, processing, interpretation, and benefit-cost. Notwithstanding these difficulties, there are sufficient incentives for the development of a practical implementation of the in-seam technique in Australian mines to encourage a major research effort. In-seam techniques have the potential for probing several hundred metres ahead of a working face; such long long-range" probing has an important bearing on the prediction of outbursts by way of structural associations. It is important that extensive exmperimental data are collected in Australian mines.

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