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Development and use of a high pressure packer for measuring horizontal stress using the hydraulic fracturing method

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ABSTRACT: Research conducted by the National Institute for Occupational Safety and Health (NIOSH) has shown that knowledge of the direction and magnitude of the in situ horizontal stress can be critical to the success of many underground mining operations. One technique employed by NIOSH for determining in situ stress has been hydraulic fracturing from boreholes drilled in mine. However, in some cases the combined rock strength and stress magnitude have been too high to allow successful stress determination using available hydraulic fracturing equipment. NIOSH developed high pressure straddle and impression packers capable of operating at pressures up to 103 MPa in a 51 mm diameter borehole. The high pressure hydraulic fracturing system was used to measure horizontal and vertical stresses in a western Pennsylvania limestone mine with a high incidence of stress related roof failures. Breakdown pressures ranged from 43.9 to 95.7 MPa and in two cases the rock could not be broken down even at the maximum system pressure, 103 MPa. The estimated ranges for the maximum horizontal principal stresses were 27.2 to 65.9 MPa. The measured vertical stress was 3.8 MPa. The calculated K ratio was between 7 and 17. The stress directions, determined from the crack directions in roof and floor holes, were N76°E and N66°E, respectively. Because of the high breakdown pressures required to initiate the fractures, neither of the horizontal stress measurements could have been made with any other existing hydraulic fracturing equipment. The author believes the packers represent a significant improvement in the state of the art of in situ stress measurement under near mine conditions.

1 INTRODUCTION

Research conducted by the National Institute for Occupational Safety and Health (NIOSH) over the last decade has shown that horizontal stress can have a significant effect upon the success or failure of underground mines (Molinda et al. 1992, Mark & Mucho 1994). Recent studies by NIOSH have documented cases in both coal (Dolinar et al. 2000) and limestone (Iannacchione et al. 1998) mines where understanding and mitigating the effects of horizontal stress have been critical to the safety and continued operation of mines. Research (Agapito et al. 1980, Mark & Mucho 1994) has also shown that horizontal stresses in the range of 10 to 30 MPa, at mining depths from a few tens of meters to well below 1000 m, once characterized as "high" are actually a predictable consequence of plate tectonics (Zoback & Zoback, 1989).

An important part of NIOSH's recent research efforts has been the development of methods to identify the conditions under which horizontal stress adversely affects mining operations, and making the mining industry aware of both the effects of horizontal stress and the means of mitigating these effects. NIOSH and others have used several techniques to measure horizontal stress and assess its potential for causing ground control problems, including the "stress mapping" technique (Mucho & Mark 1994), direct measurement of strain, generally through overcoring and the technique of interest in this paper, the hydraulic fracturing method. This technique is sufficiently well documented to be standardized under ASTM Designation D 4645-87.

Although ASTM D 4645-87 is applicable to any depth, the standard is primarily concerned with stress measurements conducted in vertical boreholes drilled from the surface, rather than from underground mine sites, from which most of NIOSH's stress testing has been conducted. Most of the equipment used for conducting hydraulic fracturing stress measurements has been developed as an outgrowth of the oilfield technique of hydraulic fracturing to increase oil and gas production and is of a size commensurate with oilfield operations. The author is aware of only one manufacturer currently building a hydraulic fracturing system sized for in mine use. Unlike equipment designed for oilfield use, systems appropriate for use in mines can be designed much lighter and can be hand inserted into the relatively shallow boreholes.

Hydraulic fracturing systems for in mine use generally consist of a straddle packer to isolate the test interval, two skid mounted hand pumps, one for packer inflation and the other for pressurizing the test interval, flexible tubing or hoses to transmit hydraulic fluid to the packer, and rigid tubing or rods for inserting the packer in the hole. They also require valves for shutting in the packers and test interval, and pressure gauges and/or recorders. The systems used by NIOSH are not equipped with flowmeters to measure pumping rates.

Although hydraulic fracturing equipment for in mine use can be lighter than the equipment used in vertical boreholes, the required pressure ranges are not necessarily lower. In fact, because the boreholes are usually at atmospheric pressure, the differential pressures across the packers are usually greater than they would be in water or mud filled vertical holes. Nor are the rock strengths and breakdown pressures necessarily lower. Breakdown pressures in the range of 30 to 60 MPa are normal. The currently available commercial system, manufactured in Australia, is designed for use in 38 mm boreholes and for pressures up to 40 MPa. NIOSH has typically operated the system at pressures up to 69 MPa, the maximum rated pressure of the pumps, hoses, tubing and fittings. The packers are sensitive to small variations in hole size and at those pressures damage to the packers from the high pressures and from overinflation in even slightly oversize holes can severely reduce their operational life. In addition, even 69 MPa has frequently been insufficient to initiate fractures.

2 MINE CASE HISTORY

NIOSH has been studying the ground control problems of limestone mines since the mid-1990's. In particular the effects of horizontal stress have been studied in detail in a southwestern Pennsylvania mine because of the high incidence of horizontal stress related roof failures. The mine extracts the roughly 21 m thick Loyalhanna limestone, which is overlain by soft claystones and shales. The Loyalhanna limestone is a sandy moderately crossbedded limestone. The bedding is generally not highly developed and is laterally non-persistent. Physical properties data have not been obtained from the study mine, but data were obtained from a mine 35 km away with similar conditions. The average uniaxial compressive strength was 136 MPa, with a standard deviation of 79 MPa. The average indirect tensile strength was 13 MPa, with a standard deviation of 3 MPa. Modulus of elasticity values for the samples averaged 77 GPa, with a standard deviation of 11 GPa. These values confirm the field observations of high limestone strength and stiffness.

The mine is developed with 13.7 m wide by 7.6 high entries and 10.7 m square pillars. The entries are oriented nearly north-south and east-west, except at the study site where an experiment had been conducted to test the effects of reorienting the mine and changing pillar sizes. The limestone roof averages 2 to 3 m in thickness, but locally can be up to 5 m. After the initial development an additional 10.7 m bench of limestone is extracted in some areas. The mine operates within 1,200 m of outcrop and the maximum mining depth is about 150 m.

The mine has a history of roof falls, generally trending either northwest to southeast, perpendicular to the assumed maximum horizontal stress direction, or north-south, following the entry directions. In 1996 NIOSH began monitoring a northwest to southeast trending zone of roof failure (Fig. 1) which grew slowly toward the northwest over a period of several months (Iannacchione et al. 1998). The failure took place under an overburden of 60 to 90 m. The failure zone was characterized by a narrow zone of crushed rock, indicating compressional or shearing failure of the rock at the surface of the roof. Extensometer data from the site indicated that vertical roof movement (sag) took place in a relatively narrow zone on either side of the visible failure and extended 3 to 5 m into the roof. Within that narrow zone, roof sag could increase rapidly to several centimeters, generally culminating in a roof fall or series of falls. At distances of 5 to 10 m from the crushed zone extensometers measured maximum total sag on the order of a half centimeter, extending to depths of 5 m into the roof. At these distances from the crushed zone the sag generally stabilized and did not lead to a roof fall. The overall behavior of the roof was similar to the growth of roof cutters observed in coal mines, a phenomenon associated with high horizontal stress, but the rock affected was much stronger than typical coal mine roof rock.

When it became apparent that the ground control problems experienced by the mine were caused by horizontal stress, NIOSH attempted to determine the direction and magnitude of the horizontal stress using hydraulic fracturing equipment. Hydraulic fracturing was chosen because it can be performed in boreholes drilled by mining equipment and because it was logistically difficult to set up drills in the high mine entries to use the strain measuring type instruments. Although some measurements were successfully made (Iannacchione et al., 1998), many measurement attempts failed because of the high pressures required to initiate a fracture. A series of 11 tests conducted in 1996 using the "low pressure" system produced estimates of the horizontal stress ranging from 10 to 60 MPa with an average 25 MPa. The direction of the maximum stress was estimated to be N60°E. Of the 5 unsuccessful tests, three failed because the maximum packer pressure, 68

MPa, was insufficient to initiate a fracture. A 1998 series of tests failed to produce any useful measurements and caused the destruction of a new packer in just two days of testing. At that point consideration was given to purchasing packers with a higher pressure capacity.

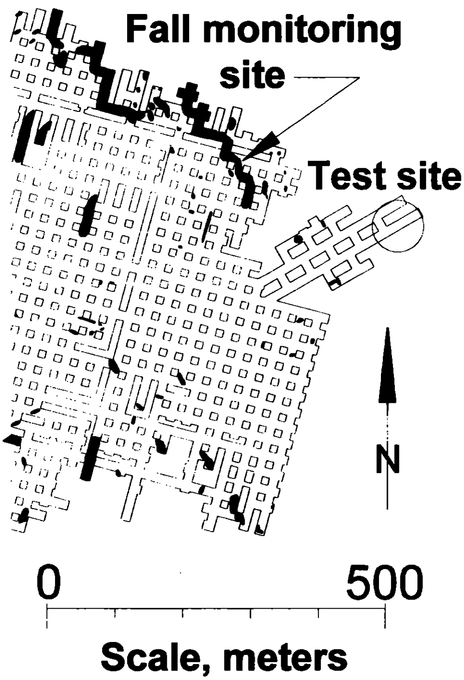

Figure 1. Map of a portion of the southwestern Pennsylvania limestone mine showing the test site, mapped roof falls and the roof fall area monitored using extensometers

3 HYDRAULIC FRACTURING SYSTEM

3.1 *Straddle and Impression Packers*

In early 1998 NIOSH began to look for packers capable of operating at up to 103 MPa. Preliminary calculations indicated that this pressure range could be achieved with a packer designed for a nominal 51-mm hole.

The straddle and impression packers eventually purchased are shown in Figure 2. The straddle packer assembly is 1.71 m long, not including removable tubing adaptors, and 46 mm in diameter. The elements are interchangeable and are each 648 mm in length, of which 434 mm is the rubber coated sealing element. The hydraulic connections are coned type fittings machined into the top packer sub. The mechanical connection to the insertion rods is a 5/8-18 UNF bolt thread. The impression packer was designed from a single straddle packer element and is 1003 mm long with an effective impression interval of 444 mm. In use the straddle packer is wrapped with semi-cured rubber supplied by the manufacturer (not shown in Fig. 2).

3.2 *Pumps, Tubing, Hoses and Fittings*

It was necessary to design a complete system of hydraulic pumps, valves, pressure gauges, hoses and in-hole hydraulic lines to the packers (Fig. 3). The high pressures made it necessary to use coned tubing type fittings, which are rated to 400 MPa.

Only two pumps were found in the 100 MPa range, both rated to 275 MPa. The lower cost of the two was chosen, although in field use they were found to be subject to corrosion damage from the low viscosity 95% water-5% soluble oil hydraulic fluid originally used. After several field tests and a year of use the pumps began to fail and both had to be overhauled. After repair it was found that the pumps would work well with oil, but not with the water-oil emulsion, and it was necessary to permanently switch to hydraulic oil. The pump reservoirs are too small to complete most tests, so the pumps were modified to allow filling and fluid return to a large (19,000 cm^3) auxiliary reservoir.

To make field set up easier a 20 mm diameter hose, rated at 124 MPa, was used to transmit hydraulic fluid from the pumps to the borehole. Because the hoses with their connectors were too large to fit in a 51 mm borehole, it was necessary to switch to high pressure 1/4-inch steel tubing at the borehole. Straight 1.5 m lengths of tubing with coned tubing connections were used. Although the coned tubing fittings are excellent for permanent connections, they are easily damaged during makeup by overtightening and must be replaced frequently.

The system included a pair of mechanical pressure gauges and pressure transducers. A datalogger was used to collect the pressure data,

Figure 2. High pressure straddle and impression packers. Packer diameters 46 mm.

which were graphed on the screen of a laptop computer in real time during a test.

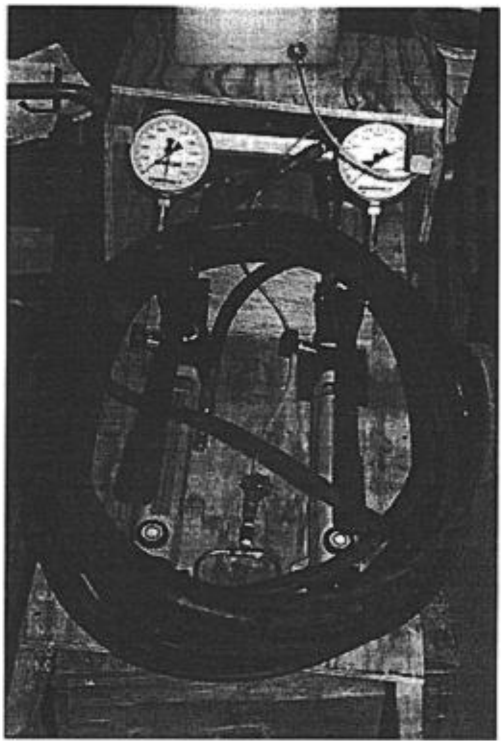

Figure 3. Portable skid with high pressure pumps, pressure gauges, pressure transducers, valves, fittings and hoses.

3.3 *Packer Service Life*

The manufacturer estimated the life of the packer to be about 20 inflations to maximum pressure. The actual operating history of the packers included some 65 successful operating cycles in drilled boreholes. The life of the packer was probably shortened because the borehole being tested at the time of failure was oversized. The hole diameter was estimated to be approximately 57 mm. Both packer elements failed by tearing of the elements at the points nearest to the test interval where the elements begin to expand during packer inflation.

4 STRESS MEASUREMENTS

Two boreholes were tested at the mine. Both holes were approximately 5 m deep and drilled vertically at the same site (Fig. 4), one into the roof and the other into the floor, within a few meters of each other. The limiting factor to hole depth was the length of drill steel, which was provided by the mine and could not be coupled together to drill deeper holes.

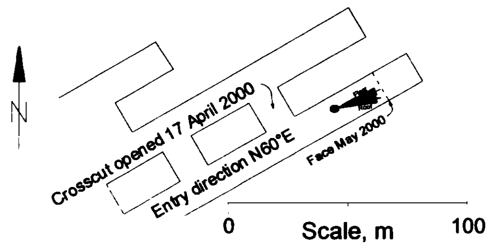

Figure 4. Study site map. The symbols represent hole locations and the fracture directions, with the uncertainty in the directions indicated.

Both holes were examined before and after testing, using a borehole video camera, to look for bed separations, cracks, fractures, changes in lithology and, after testing, the induced fractures. The after test examination of the roof hole and both examinations of the floor hole were video taped. Both holes appeared to be free of features which would have precluded testing any particular interval and all of the rock was competent limestone. In both holes the video camera showed quantities of fine drill cuttings partially coating the wall of the hole. Although the coating did not prevent obtaining an adequate view of the hole conditions, it was of concern because of the possibility that the cuttings might adversely affect the test results.

The breakdown pressures, test intervals and test results are summarized in table 1. Of the twelve tests attempted in the two holes, six required pressures above 69 MPa to initiate a fracture, one appeared to initiate a horizontal fracture at 56.3 MPa and two tests appear to have reopened fractures created during earlier tests. In two of the tests fractures could not be initiated at the maximum packer working pressure. The two tests for which horizontal stress magnitudes and directions were obtained required breakdown pressures of 82.2 and 95.7 MPa. These pressures could not have been achieved with any other existing hydraulic fracturing equipment.

4.1 *Roof Hole*

The first test broke down at 56.3 MPa and produced a shut in pressure of 3.8 MPa. The test was interpreted as a horizontal fracture, indicating a vertical stress of 3.8 MPa. The overburden at the site was estimated to be 120 m, and the average vertical stress at that depth would be expected to be about 3 MPa.

Table 1. Test Results

Test	Test Depths, m	Breakdown Pressure, MPa	Test Result
			Roof hole
1	3.81 - 4.24	56.3	Horizontal fracture. σ_3 = 3.8 MPa
2	3.35 - 3.78	N/A	Communication to test 1 interval under packer
3	2.90 - 3.33	82.2	Good test. Stress results computed
4	2.44 - 2.87	93.1	Inconclusive results
5	1.98 - 2.41	54.6	Inconclusive, could not establish pumping rate
6	1.52 - 1.96	43.9	Fluid leak to preexisting crack or bed separation
			Floor hole
1	3.66 - 4.09	63.3	Inconclusive
2	3.20 - 3.63	95.7	Good test.
3	2.74 - 3.17[1]	N/A	Pumped into Test 2 interval
4	2.29 - 2.72	102.12	No breakdown, test terminated
5	2.06 - 2.49	102.62	No breakdown, test terminated
6	1.37 - 1.80	77.4	Packer failure

[1]Actual tested interval 3.20 - 3.33 m
[2]Maximum pressure, no breakdown
N/A= Not observed or not applicable

Table 2. Computed stresses

Test	Test Depths, m	Test Cycle	Reopen Pressure, MPa	Shut-in Pressure, MPa	Horizontal Stress σ_1, MPa	Horizontal Stress σ_2, MPa	Ratio, σ_1/σ_2
				Roof Hole			
3	2.90 - 3.33	4	42.9	32.6	54.8	32.6	1.68
3	2.90 - 3.33	5	42.4	30.7	49.6	30.7	1.62
				Floor Hole			
2	3.20 - 3.63	4	46.4	34.4	56.8	34.4	1.65
2	3.20 - 3.63	6	49.1	30.4	42.1	30.4	1.38
2	3.20 - 3.63	7	44.5	34.4	58.8	34.4	1.71
2	3.20 - 3.63	8	39.1	35	65.9	35	1.88
3	2.74 - 3.17	5	31.9	19.7	27.2	19.7	1.38
3	2.74 - 3.17	6	28.7	22.9	40	22.9	1.75

Nominal depth of floor hole test 3, 2.74 to 3.17 m, tested depths 3.20 to 3.33 m
Roof hole σ_1 direction N76°E. Floor hole σ_1 direction N66°E.

The second test produced what appeared to be typical reopening cycle test records, but no initial breakdown was observed and no vertical fracture was observed in the video record. This test may have been pumping into the horizontal fracture of test 1, with the 17.2 MPa difference between the shut in pressures in the two tests being the resistence to fluid migration under the packer. The results of the test were considered inconclusive.

The record for the third test is shown in Figure 5. The test appeared to be normal, with good breakdown and shut in pressures and the reopening pressure reducing from cycle to cycle, apparently as the fracture was extended. The fourth and fifth cycles were chosen for computation of horizontal stresses, which are shown in table 2. The direction of the maximum principal stress was determined, from both the impression packer and the video camera record, to be N76°E. In both cases the directions were measured using a magnetic compass. The fracture was observed to extend from 2.90 to 2.95 m in the video and from 2.90 to 2.97 m on the impression record.

The remaining tests gave inconclusive results due to inconsistent shut in pressures and difficulties in establishing consistent pumping rates. In the sixth test shut in pressures continually declined without changes in slope which would indicate crack closure. Test 6 was very close to the mine roof and the test was interpreted as pumping into a preexisting crack or bed separation. No vertical or horizontal fractures were noted in the borehole video camera record in test intervals 3 through 6 and no fractures traces were found in the impression packer record made in the interval of test 6.

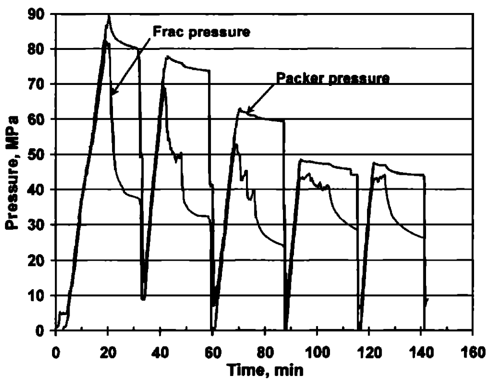

Figure 5. Pressure record for roof hole test 3. Test depths 2.90 to 3.33 m above roof.

4.2 *Floor Hole*

Difficulties similar to those experienced in the roof hole were experienced in the first test in obtaining consistent reopening and shut in pressure and in pumping into the interval and the test was terminated.

The second test appeared to give a good breakdown pressure at 95.7 MPa and a shut in at 21.3 MPa (Fig. 6). Seven additional cycles were conducted, with the reopening pressure stabilizing around 39 to 49 MPa. Fluid was pumped to extend the fracture during cycles 2, 4, and 5 through 8.

The typical test procedure during reopening cycles is to reopen the fracture, pump fluid for 5 to 10 minutes, then isolate the test interval and wait for the pressure to drop until the crack closes. At crack closure the rate of pressure decline decreases, and the pressure at the inflection point is taken to be equal to σ_2. In this hole, using the normal test procedure, pressures did not decline, suggesting either very low permeability, or that the crack was blocked. However, experimentation showed that it was possible to obtain what appeared to be a valid shut in pressure by reversing the usual test order and shutting in the hole immediately after reopening the crack. After the shut in pressure was obtained, pumping would be resumed to extend the fracture.

Data from several cycles of test 2 were used to compute stresses. The resulting computations produced a wide range of stress values, with σ_1 ranging from 42.1 to 65.9 MPa and σ_2 from 30.4 to 35.0 MPa (table 2). The direction of the principal horizontal stress was determined using the video camera. An obvious vertical crack was observed from 3.20 to 3.33 m. The crack was not present in the pre-test video. An impression packer run was not considered necessary in this test interval. The fracture direction was N66°E, 10° north of the direction measured in the roof hole.

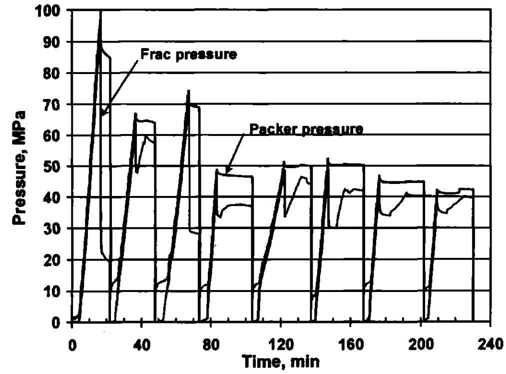

Figure 6. Pressure record for floor hole test 2. Test depth 3.20 to 3.63 m below solid floor rock.

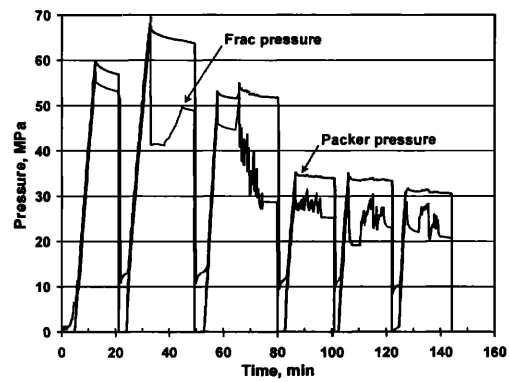

Figure 7. Pressure record for floor hole test 3. Packer depth 2.74 to 3.17 m. Tested depth 3.20 to 3.33 m

The third test did not appear to break down normally and the reopening pressures appeared abnormally high (Fig. 7). However the test was continued and during the fourth through sixth cycles the reopening and shut in pressures became both much lower and more consistent. It also became easier to pump into the interval during the later cycles. During the video inspection, after testing, no indication of a vertical fracture was found. It is believed that instead of initiating a new fracture, fluid from this test was forced under the packer and into the crack opened during test 2. It is believed that the fracture grew vertically upward toward the test 3 interval until the remaining length of packer, about 0.03 m, no longer provided resistance to flow under the packer. The reductions in reopening pressure and easier pumping after cycle 3 suggest that the additional pressure cycles conducted during test 3 may have finally extended the fracture of test 2 far enough to give accurate stress values. Additional estimates of the horizontal stresses for the fracture created between 3.20 and 3.33 m were made using test 3 data and are shown in table 2.

The fourth and fifth tests failed to initiate fractures at the pump maximum working pressure. A breakdown was achieved in the sixth test interval at a pressure of 77.4 MPa. However, it became obvious that the packer had failed when immediately after breakdown the fracture interval pressure began to increase, the packer pressure began to decrease and the two pressures appeared to be approaching equilibrium.

5 DISCUSSION OF TEST RESULTS

The results of the tests were two measurements of horizontal stress, one each from the roof and floor holes and a measurement of the vertical stress from the roof hole. Values of σ_1 ranged from 27.2 to 65.9 MPa, and σ_2 values ranged from 19.7 to 35 MPa. The measured vertical stress was 3.8 MPa, which compares favorably to the 3 MPa computed from overburden stress at the test depth of 120 m. The measured directions of σ_1 from the roof and floor holes were N76°E and N66°E, respectively. The measurements suggest that the direction of the horizontal stresses is relatively consistent between the roof and floor and with regional predictions for the northern Appalachian region (Zoback & Zoback 1989). K (σ_1/σ_v) ratios between 7 and 17 were computed. The σ_1/σ_2 ratios ranged from 1.38 to 1.75, and are consistent with the observations of directional roof damage at the mine.

The magnitudes of the stresses and K values were confirmed to be considerably higher than published near surface horizontal stress values from the northern Appalachian region (Hoek & Brown 1980). Reported values of σ_1 have ranged between 9 and 26 MPa (Agapito et al. 1980, Campoli et al. 1990, Mark & Mucho, 1994).

One explanation for the high measured horizontal stresses may be a stress concentration effect due to the high modulus (77 GPa) of the Loyalhanna limestone. Another possibility is that since all measurements made to date have been close to the mine opening they may have been affected by stress concentration around the opening. Because there is typically no more than 5 m of roof limestone and above the limestone is soft claystone, it has not been possible to conduct tests in the roof away from the influence of the mine opening, which is typically 7 to 8 m high and 13 to 14 m wide. The floor hole tests described in this report were an attempt to conduct tests away from the influence of the mine opening. However, because the available drilling equipment could not drill holes much beyond a depth of 5 m, it was not possible to take advantage of the minimum of 11 m of available floor limestone.

6 DISCUSSION OF SYSTEM PERFORMANCE

Analysis of field operations using the high pressure hydraulic system leads to several conclusions concerning the performance and future use of the system.

- Hole size: It was assumed that the high pressure system was sufficiently robust that maintaining tight control of the hole diameter was not critical. It now appears that the high pressure packer can be adversely affected by an oversized hole and that some means of determining hole size and avoiding operations in oversize holes is critical to maximizing the operational life of the packer.
- Test intervals: Attempts made to maximize the number of test zones by decreasing the length of the test intervals led to communication between zones in two of the tests. In order to reduce the likelihood of communication it appears that greater distances between intervals are necessary.
- Impression packer: Wrapping the packer, eliminating air bubbles from under the impression rubber and removing the old rubber prior to rewrapping the packer were all found to be difficult and time consuming. Removing the old rubber typically required 4 to 8 hours. In many cases the borehole video camera was more effective in identifying fractures and determining their orientation than the packer and gave additional information on hole conditions. The impression packer is now considered a backup means of determining fracture directions.
- Hydraulic fluid: The original fluid used with the high pressure system was a low viscosity water-oil emulsion. The mixture was found to damage the pumps and it was necessary to switch to hydraulic oil.
- Pressure fittings: The coned type pressure fittings have very high pressure ratings and seal very well when new. They are not designed for frequent assembly and disassembly and great care is required to prevent their damage in use. It also appears useful to have tools and spare parts available for repair and replacement of damaged fittings and tubing.

Several tests failed to produce horizontal stress measurements either because horizontal fractures were created or because of preexisting cracks or fractures (table 1). The remaining tests failed for unknown reasons. One possible reason for the unsuccessful results may have been the presence of fine drill cuttings in the hole. The cuttings are estimated to have ranged in size from sand sized particles down to dust. These particles may have entered and blocked the fractures during testing, leading to the ambiguous results.

The results of floor hole tests 2 and 3 suggest that longer pumping times and/or more test cycles may be required in order to insure valid test results. It would probably have been worthwhile to attempt additional cycles in the cases of roof hole tests 4 and 5 and floor hole test 1. However, the primary reason these tests were not continued was time limitations and further testing of one interval would have meant less available time for another interval.

7 CONCLUSIONS

A high pressure hydraulic fracturing system was developed to increase the probability of initiating fractures in high strength or highly stressed rock. Field tests of the system show that it has been successful in extending the pressure range at which stress measurements can be obtained. In a southwestern Pennsylvania limestone mine, use of the high pressure system lead to stress measurements that could not have been made with any other existing hydraulic fracturing equipment. The author believes that the packer represents a significant improvement in the state of the art of hydraulic fracturing for stress measurement under near mine conditions.

The test results have confirmed earlier measurements and observations of roof damage, which indicated that the horizontal stresses were extremely high. The measured stress directions agreed with the generally accepted regional trend based upon global tectonics. The test results also show that horizontal stresses can be extremely high in competent rock, even at locations very close to the surface and to outcrop.

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