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CANADA
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
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OTTAWA

A METHOD FOR MEASUREMENT OF STRESS CHANGES DURING MINING OPERATIONS*

By

J. G. Buchanan, F. W. Marsh, and R. C. A. Thurston**

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INTRODUCTION

Arising from opinions expressed by the Coal Committee of the Provincial Ministers of Mines Conference, by the Alberta Research Council, and by the Nova Scotia Research Foundation, on the desirability of a fundamental study of the causes of "bumps" and "outbursts" in certain Canadian coal mines, an extensive investigation was initiated in the Mines Branch of the Department of Mines and Technical Surveys with the broad objective of providing useful information for the coal mining industry. Collaborating in this project are mining engineers from the

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Fuels Division, engineering physicists from the Physical Metallurgy Division, and a structural geologist from the Geological Survey of Canada. The directions along which the investigation is proceeding, together with some account of the progress made, were presented at a Coal Division Symposium of the C.I.M.M. in 1954 (ref. 1).

The basis of the Mines Branch approach to the problem is essentially of an experimental nature and involves the methodical accumulation of data from direct observations in various mine workings, and their subsequent statistical evaluation. It was felt that this empirical approach would provide the most useful information regarding the behaviour of mine structures, and would assist in proving or disproving some of the many theoretical solutions advanced over the years. Of the various methods developed for obtaining qualitative and quantitative data underground, those with which the authors were directly concerned were designed to measure existing stresses and stress changes in pillars and in solid ground, and involved the use of ultrasonics, electrical resistivity techniques and bonded electrical resistance strain gauges. The first two of these methods have shown promise of providing useful information under certain conditions and will be described and discussed at a later date, but the purpose of the present article is to acquaint mining engineers in general with the potentialities of the strain gauge load cell method and to illustrate these by typical applications.

It must be pointed out that from the commencement of the project the emphasis was essentially on the development of a load cell for installation in coal mines with their associated and inherent safety requirements, but no reason exists why the final product, as described herein, could not be installed and used with equal if not greater success in hard rock mines. In fact, one of the installation networks currently being studied is in a Canadian iron ore mine, and is already giving encouraging results.

The basic requirements of a satisfactory load cell for insertion in coal pillars or in solid coal were considered to be: accuracy, reliability over extended periods, ease of installation, simplicity in taking readings, portability of equipment, and adequate safety precautions. Of these, all but the last apply with equal force to metal mining, the safety precautions being considerably less stringent in so far as the use of electrical devices is concerned due to the absence of methane concentrations. The equipment envisaged originally consisted of a cylindrical metal cell containing a load-bearing member and one or more strain gauges; means for inserting the cell in a bore hole and for transmitting the load from the surrounding coal or rock to the cell; a device for orienting the cell; connecting leads; and the measuring instrument. With minor design changes and materials modifications dictated by laboratory and field experiments, the foregoing system is essentially that now in use in underground installations.

The equipment to be described satisfies the basic requirements outlined above, and has demonstrated its usefulness in the field to such an extent that the authors feel it should be brought to the attention of those interested in the design of mining structures, with the objective of increasing output and minimizing the accompanying hazards. The importance of the problem is emphasized by the vast amount of technical literature that has been published during the years in Europe, South Africa, the United States and the U.S.S.R., and by the continued efforts of numerous groups of investigators in experimental and theoretical approaches. Both the theory of rock or strata pressure in connection with mining excavations, and the stress distribution around single or multiple openings, have been examined by such investigators as Fenner, Duval, Van Iterson, Labasse, Jaeger and others (refs. 2, 3, 4, 5 and 6 respectively) and involve various assumptions. The opinion of the majority of workers in the strata pressure field, however, can be summed up in the words of Weiss (ref. 7) who considers that "the most important first principle is that all instruments must be placed *inside* the rock mass within which the stresses accumulate". It is also the authors' view that progress can best be made through the collection and careful analysis of a multiplicity of experimental data, and it is for these two reasons that the following information regarding the Mines Branch load cell is now published, with the hope that it will commend itself to other workers as a useful, practical tool in the pres-

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why not placed [illegible] to acc. stress.
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sent state of the art. Development work is still in progress and any subsequent improvements will be made available as and when they have proved themselves in underground applications.

DESCRIPTION OF LOAD CELLS AND ASSOCIATED EQUIPMENT

Preliminary experiments with electrical resistance strain-gauges bonded directly to rock and coal specimens indicated that this approach to strain measurement was unsatisfactory. A suitable method of utilizing a strain-sensitive metal structure to which a strain gauge was bonded, was therefore sought. The first so-called "load cell" employed in the investigation consisted simply of a uniaxial strain gauge bonded to a short thin-walled magnesium tube with cylindrical end caps. This load cell was imbedded in plaster of paris at the end of a short hole drilled horizontally into a coal block. The axis of the tube (and strain gauge) was vertical, and the block was compressed in the vertical direction in a universal testing machine. Readings taken from the strain gauge during compression of the block indicated that a linear, consistent relationship existed between strain in the load cell and load on the coal. Further development of a suitable load cell for use in bore holes in mines was therefore undertaken.

At the outset it was obvious that assessment of stress in a single direction in a mine pillar, or in ground adjacent to a mine opening, would be of little value. Since dependable rosette strain gauges which provide a method of measuring the two principal strains, as well as

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their orientation with respect to a fixed datum, in a plane, have been developed and are widely used, a "rectangular" rosette gauge was chosen as the active element for the load cell. This gauge consists of three separate grids, so arranged that two of their axes are at right angles, with the third making an angle of 45° with the other two. A simple but time-consuming set of calculations performed on readings taken from the three grids (strain readings) in conjunction with the elastic constants of the material on which the gauge is mounted, give the magnitudes and signs of the principal stresses and their angular disposition with respect to one of the grid axes. The angle φ is defined as the angle between the horizontal and the major principal stress, σ_1, measured counter-clockwise. A circular metal disc appeared to be the most suitable component for the strain-sensitive element, and proved to be satisfactory in subsequent laboratory tests. A single gauge, having a grid identical to each of those in the rosette, and mounted on the same material as that of the disc, must be maintained free from mechanical strain, and placed in close proximity to the disc, in order to compensate for apparent strains due to thermal changes. A suitable method for orienting the disc, in a bore hole, to a known angle between, say, the vertical and one of the rosette grid axes, is necessary in order to fix the principal strain directions. Finally, since strain readings depend upon a very small electric current in the grids, complete moisture-proofing of the strain gauges and their associated leads is imperative. All these problems, with the exception of the last mentioned, were easily overcome and although a relatively dependable method of moisture-proofing has been developed, better materials are still being sought.

The functioning of the strain-sensitive disc in the load cell depends, of course, upon its being maintained in intimate contact, over its entire periphery, with the matrix whose strain is under observation. This condition was satisfactorily met by placing a quantity of a fairly stiff mix of cold-setting grouting material at the end of a bore hole, and plunging the load cell into it (with the correct disc orientation), ensuring at the same time that adequate material was provided to allow extrusion completely around the load cell. Observations made both in the laboratory and on load cells which were mined out after installation in bore holes up to fifty feet deep, indicate that the method is sound. Several **grouting** materials have been employed, with retarding agents added to delay setting for a suitable length of time, the most satisfactory one discovered to date being a mixture of pulverized natural minerals used in conjunction with a petrifying fluid, and sold under the trade name of "Karlenite".

Strain readings consist of a measurement of the change in resistance in each of the grids of the rosette gauge, the change in resistance being proportional to the change in strain on the disc. It is important to note that the principal strains, determined from these readings, are two-dimensional, in the plane of the disc, and refer to the disc itself, not to the matrix. Stresses in the matrix can only be accurately determined when the relationship between strain in a circular disc of given material imbedded in the matrix, and stress in that matrix, is known. Although this relationship has not yet been accurately determined for the discs and matrices employed so far, both theoretical and experimental work done elsewhere on the problem of circular inclusions (ref. 8, 9) suggest that a reasonable assessment of the stress changes in a matrix can be expected from the strain readings of the load cell. The resistance changes in the grids may be measured with any one of a variety of bridges designed for the purpose, the exact type of bridge and voltage employed being governed by working conditions and safety regulations in the mine under study.

Magnesium Load Cell

Figure 1 shows the general lay-out of a magnesium alloy load cell constructed at the Mines Branch, and Fig. 2 is a photograph of a completed cell with the inserter. A magnesium alloy was used in order to take advantage of its low modulus of elasticity, and thus obtain reasonably high strain-sensitivity with a large loaded area on the disc. Two discs were employed in order to simulate the condition of having the active gauge placed at the centre of a single disc, and thus reduce any anomalous stresses caused by the absence of constraint, in the bore hole, at the outer edge of the disc. The orienting device in this load cell consists of a weighted insulated pendulum, suspended between two contacts placed very close to the pendulum arm. During installation the load cell is oriented by rotating it until the pendulum is free of the contacts, as indicated on a voltmeter in series with a small voltage applied between the pendulum and contacts. Some trouble has been experienced with corrosion of the contacts when the cells are stored for a time before installation, and safety regulations in coal mines dictate the use of a very small voltage. An improved orienting device has therefore been developed, which employs an inverted "U" tube, partially filled with a conducting liquid and carrying a pair of contacts at the highest point of the inverted "U". Before being placed in service, the load cells are roughly calibrated in a small hydraulic press to check their uniformity, and to minimize hysteresis effects. For use in mines where magnesium alloys are forbidden, a steel load cell has been constructed, employing a reduced section for the disc, which is integral with the tube. Electrical cables for the load cells are cut to pre-determined lengths and connected to the gauges and orienting devices, and the cells are then sealed with moisture-resistant compound before shipment to the field. Both magnesium and steel load cells have been installed in concrete blocks to study (a) their behaviour when the blocks are subjected to unidirectional, unconstrained loading; (b) the repeatability of readings for short-term loading; and (c) the effects of the grouting material, during setting, on the strain readings. These laboratory studies have been encouraging. In particular, results of (a) showed that the load cell indicates a major* principal stress proportional to the stress applied to the block, and within a few degrees of its orientation, while the minor* principal stress is approximately zero, as would be expected. Long term stability of an unstrained load cell has been found to be quite satisfactory. Results of these laboratory tests, as well as those obtained from several mine installations, suggest that the load cells provide a promising tool for the assessment of stress variations around mine openings.

Grouting and Installing Tools -

Figure 3 shows a cross section of the device used to deposit grouting material at the end of a bore hole, and a dismantled unit is shown in the photograph, Fig. 4. It consists of a thin-walled steel cylinder large enough to accommodate the required volume of material for satisfactory grouting, and a piston for ejecting the material at the end of the bore hole. The assembly is inserted by means of a set of magnesium alloy or steel rods, joined to the piston rod. When the cylinder reaches the end of the hole, the rods are rotated counter-clockwise until the pin drops through a slot, allowing the piston and stop rod to move forward slightly, the stop rod resting against the back of the bore hole. The cylinder is prevented from turning, during this operation, by teeth cut

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* In this work, compressive stresses are considered to be positive.

in its open end gripping the end of the hole. The cylinder is now withdrawn over the piston, by means of a cord or wire, and then the entire assembly is removed, leaving the grouting material at the end of the hole. The stop rod is incorporated merely to prevent the piston from moving forward and becoming imbedded in the material after the cylinder has been retracted, and thus withdrawing some of the grouting material when the whole assembly is removed. A pair of light, hinged doors arranged to open outwards, is placed at the open end of the cylinder, just inside the teeth, to prevent dust and debris from being picked up during insertion, absorbing moisture from the outer layer of the grouting material, and thus causing partial premature setting of the layer.

The rods used to insert the cylinder assembly are also used for inserting the load cell. Installations made both in the laboratory and in actual bore holes up to 50 feet deep indicate that this installation technique is fairly rapid, simple, and provides the necessary intimate contact between the bore hole and load cell.

APPLICATION OF CELLS TO PROBLEMS OF MEASUREMENT

The limitations of the cells, i. e. (1) their ability to measure in one plane only and (2) the fact that they only record the increase in stress after installation, impose severe restrictions upon the placement of the cells and cause some difficulty in the interpretation of their results. When first examined, these limitations appear to restrict the applications of the cells to a point where they would not be sufficiently useful to justify their installation, but in fact they can be employed to give much helpful engineering information about stresses in mining structures.

The first of these limitations requires that the cell be placed in a hole drilled in such a direction that the plane of the cell lies in the plane in which one is most interested, or, if required, two cells must be placed close to one another but in holes drilled at right angles to one another to give more complete information about the stress at a point. Also, in practice, an attempt is made to keep the plane of the active disc parallel to a principal plane of stress in the ore. This is desirable because of the uncertain effect of stresses falling on the cells at an angle.

The second limitation requires that the cells be installed before the change in stress which is to be measured takes place. Often this is impossible, but each case must be examined individually.

With these two limitations in mind, consider the application of the load cells to the problem of stress around a single, horizontal mine opening. Figure 5 shows three possible ways in which the cells could be placed to measure the influence of a single mine opening. In all cases, of course, there must be an existing mine opening within drilling distance of the region to be studied. Figure 5(a) shows the case where parallel openings are being driven, one in advance of the other, and where the distance between them does not prohibit drilling. Ideally they should be sufficiently far apart so that the region of influence of the existing opening does not overlap the expected stress distribution of the advancing opening. This precaution is difficult to observe because the region of influence before the measurements are made can only be estimated from theoretical considerations. In this example, information will be obtained about the vertical stress, and about the horizontal stress parallel to the axis of the opening, but the horizontal stress perpendicular to the opening will not be measured. Figure 5(b) shows a method whereby the perpendicular stress is measured but the stress parallel to the opening is not. Here, the cells are installed in holes of equal depths drilled from an existing opening which is to be intersected by the opening in question. In practice, the arrangement of Fig. 5(b) gives the most useful information, since the horizontal component perpendicular to the opening is considered to be the governing stress in studies of rock-bursts and coal outbursts (ref. 7). The third example, in Fig. 5(c), is a more complex case, but nevertheless interesting. Here, cells are installed at various depths in holes drilled perpendicularly to the opening to be studied, and subsequently the area comes under the influence of an extensive extraction. The abutment stress due to the large opening, falling upon the narrow opening will distribute itself about the opening and be measured by the cells. There are certain objections to this, for example: (1) the abutment stress is not necessarily of the same nature as the original overburden stress; (2) the abutment stress does not usually distribute itself in the same manner as the original stress. The points in favour of this technique are: (1) the drilling is much shorter, and (2) usually very high stresses are associated with this type of mining, thus ensuring that the cell readings are substantial. Also, of course, there are occasions when precisely the information given by this arrangement (namely, the increases in stress due to the approach of a face) is desired.

Stresses due to extensive extracted areas can be measured in a similar manner to that described above. Figure 6 illustrates two methods by which this can be done for areas lying essentially in the horizontal plane. Figure 6(a) shows a method that can be used to measure the stress influence ahead of a face which is retreating in the direction of the development openings. The cells installed from the opening parallel to the face give the required information, except for the horizontal component perpendicular to the face. If considered necessary, cells could be installed from the opening which runs perpendicularly to the face. In the case of an advancing long wall where no openings exist ahead of the face, there is little that can be done except to drill very long holes ahead of the face. However, in one interesting case, where there is a seam being worked below the area concerned, use can be made of any openings that lie under the area which is to be mined (ref. 10). Figure 6 (b) illustrates how this was done by Dowance and Tincelin in their study of stresses in iron ore mines in France, using extensometers on the side of the opening below the area which was extracted during the course of the test. They observed the advance of the stress abutments and, in addition, observed the reconstitution of stress in the excavated area as the roof settled.

This technique could also have been used with strain gauge load cells.

Although what has been said here applies to horizontal excavations, the same statements would apply to gently dipping deposits. In these cases, the holes are still drilled horizontally (with a slight upward tilt to aid the run-off of drillings). If the holes are drilled along the strike, there is no change from the flat case, but where the cells are installed in holes drilled normal to the strike, they will often terminate either above or below the seam.

As an example of their application, a description is given here of an experimental installation of steel cells in a flat lying coal seam in Western Canada. Figure 7 shows how the cells were installed with respect to the excavated areas, and the progress of the mining. Cells 4, 5, 6, and 8 were installed to measure the stress around the opening marked 7. Cells 9 and 10 were installed as a rough check on the first group in a different portion of the pillar. Cells 2 and 3 were installed to observe the advance of the stress abutment on the other side of the opening. In the system of mining used, the central pillars are not mined, therefore cells 4 to 10 would continue to record the loads on the pillar when the pillar extended as a peninsular abutment into the gob. It was desirable to discover if and when the load on this pillar decreased, thus indicating the commencement of major subsidence.

While a complete analysis of this work cannot be given here, a few interesting results can be presented as examples of the type of information which can be obtained from the cells. Figure 8 shows the results from cell 2 which was installed on the right hand side of 7 Butt at a depth of 5 feet (which depth proved to be within the relatively de-stressed zone). The results are shown plotted against time in days, stress in the steel disc being plotted as an ordinate. The stress condition is described by two principal stresses σ_1 and σ_2 and the angle φ as explained previously. For practical purposes, the dilatational stress-shear stress interpretation is often useful. In this case, the mean line between σ_1 and σ_2 represents the dilatational (hydrostatic) component $\frac{\sigma_1 + \sigma_2}{2}$, whereas half the distance between σ_1 and σ_2 represents the shear stress $\frac{\sigma_1 - \sigma_2}{2}$. An examination of Fig. 7 reveals the history of cell 2; how it was approached by the rooms, and left in a small sacrifice pillar of coal. Examination of the results shows: (1) how the cell was subjected to relatively small stresses until the approach of the extraction; (2) the increase in stress (especially a very high shear stress), accompanied by the changing of the angle φ to values near 90° (vertical loading), when the cell was left in a pillar formed by an outbye room; (3) the decrease in stress (presumably when the pillar failed due to the high shear stress); and, finally, (4) the gradual rise in stress with little shear stress existing. This picture of the failure of a block of coal is consistent with the general ideas formed from theoretical rock pressure studies, i. e. that failure takes place when the shear stress becomes sufficiently high compared with the normal stress (ref. 2). Theoretical work also indicates that the stress reaches a maximum at some distance into the wall of the opening. Although insufficient cells were available to obtain a continuous set of values at various depths into the wall, it was found that the cells that were installed at depths greater than 5 feet were subjected to higher loads than those in the shallow holes. Figures 9 and 10 show the results from cells 6 and 10. The fact that the shear stress is relatively small agrees with the theoretical view that extremely high stresses such as these must consist largely of dilatational stresses as opposed to shear stresses. In the case of cell 6, the stresses quickly exceeded the yield point of the steel, and calculations beyond that point were not made, because of the non-elastic behaviour. This overloading can easily be avoided in future by making cells with thicker discs when they are to be used in high-stress areas.

Referring once more to Fig. 8, which illustrates the results from cell 2; the data obtained showed a distinct unloading effect when the pillar crushed. This illustrates an advantage which cell measurements have over measurements of deformation of the rock or coal itself. When a material is crushed and then unloaded, it does not return to its original size, but the load cell, operating within the elastic range of stresses in the disc, will always show unloading despite the plastic or broken condition of the surrounding material.

The correlation between the stresses in the cell disc and the actual stresses in the rocks has not been explored fully as yet; the laboratory tests performed thus far indicate that the stresses in the rock can be obtained by dividing the stresses in the steel disc by a factor of about 10, the angle φ being unchanged. This factor will change considerably for different cell designs, but it is hoped that a design will be achieved which will be relatively independent of the rock substance.

In the examples quoted here, it is fully understood that the resultant calculated stresses are somewhat removed from the actual stresses existing in the rock, and also that the precise degree of disagreement is not fully known. In addition, of course, there is the limitation that the cells do not read the existing stresses at the time of installation. It is believed, however, that it is still possible by intelligent location of the cells to establish such useful engineering information as:

(1) the extent of influence of large and small excavated areas;

(2) the distance of the peak stress from the boundary of the excavation under various degrees of loading and times of application of load;

(3) information regarding the type of stress which is existing, e.g. the relative amounts of hydrostatic and shear stresses.

With information of this type available it should then be possible to place the design of mining structures upon a more rational basis.

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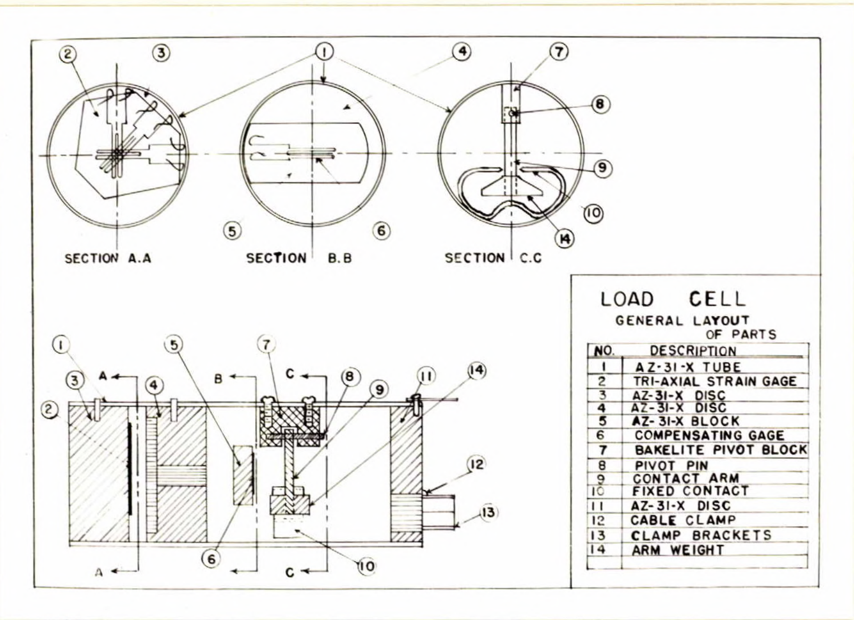
(Figs. 1 to 8 follow,)
(on Pages 20 to 25.)

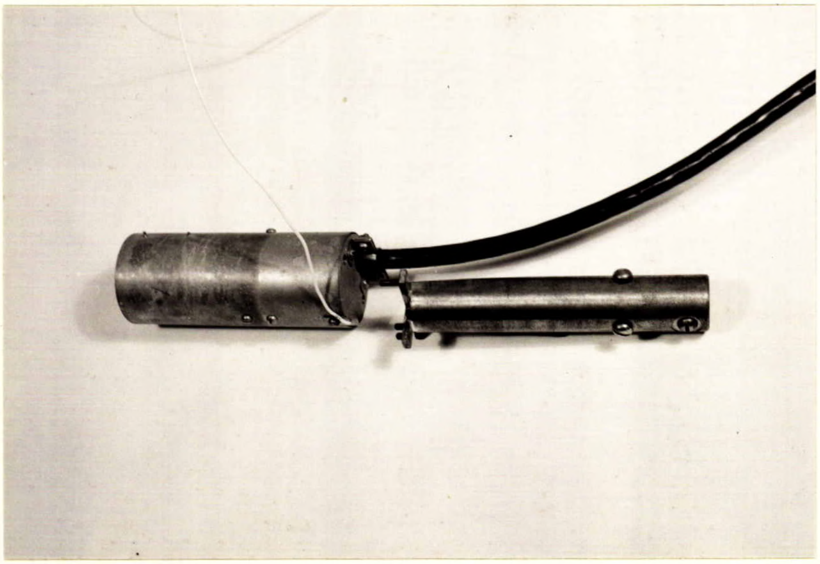
Fig. 1.



NO.	DESCRIPTION
1	AZ-31-X TUBE
2	TRI-AXIAL STRAIN GAGE
3	AZ-31-X DISC
4	AZ-31-X DISC
5	AZ-31-X BLOCK
6	COMPENSATING GAGE
7	BAKELITE PIVOT BLOCK
8	PIVOT PIN
9	CONTACT ARM
10	FIXED CONTACT
11	AZ-31-X DISC
12	CABLE CLAMP
13	CLAMP BRACKETS
14	ARM WEIGHT

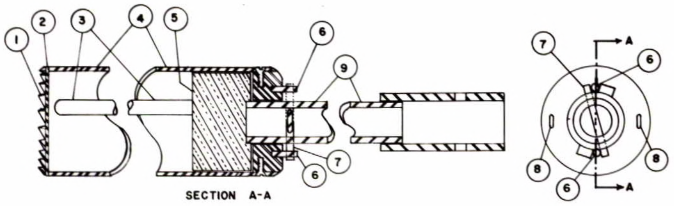
CONSTRUCTION OF MAGNESIUM ALLOY LOAD CELL.

Fig. 2.



MAGNESIUM ALLOY LOAD CELL WITH INSERTER.

Fig. 3.

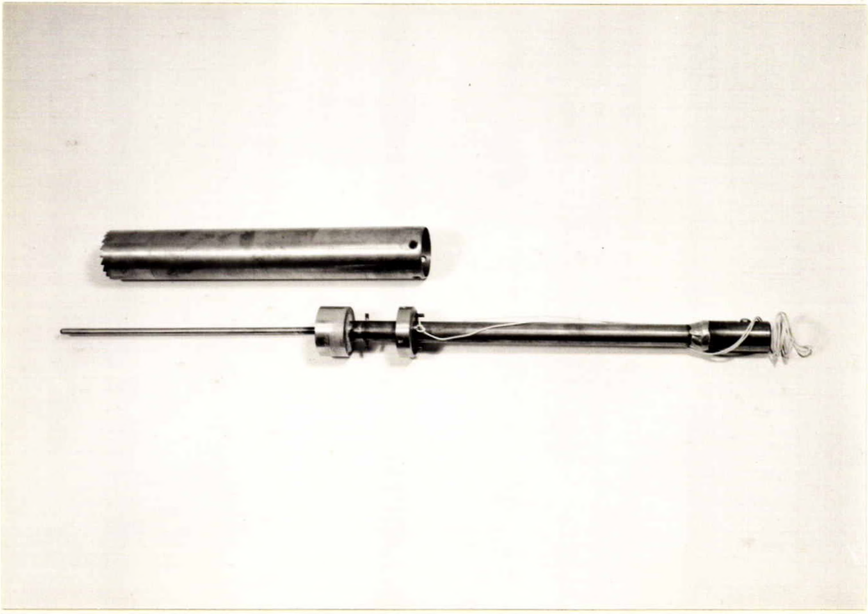


PLASTER CARRIER
GENERAL LAYOUT OF PARTS

NO.	DESCRIPTION
1	Teeth Cut in end of cylinder
2	Hinge pin for doors
3	Stop rod
4	Steel cylinder
5	Brass piston
6	Stops
7	Pin
8	Eyelets for retracting cylinder
9	Piston rod

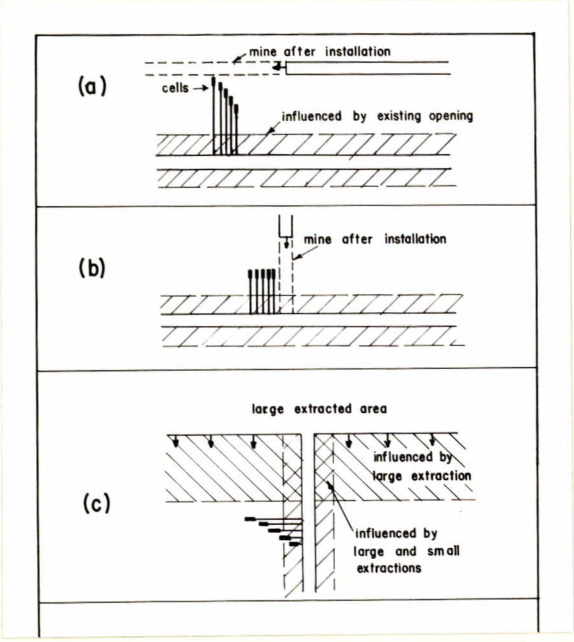
CONSTRUCTION OF GROUTING TOOL.

Fig. 4.



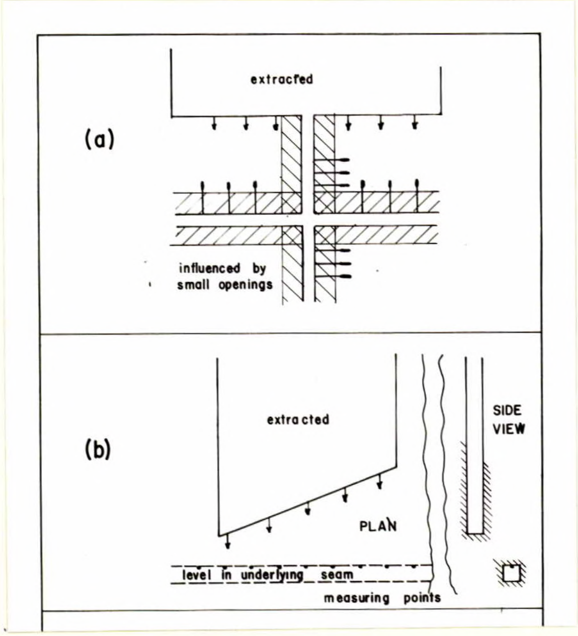
GROUTING TOOL DISMANTLED.

Fig. 5.



PLAN VIEW SHOWING THREE METHODS OF MEASURING STRESS DISTRIBUTION ABOUT A SINGLE HORIZONTAL MINE OPENING.

Fig. 6.



PLAN VIEW SHOWING TWO METHODS OF MEASURING STRESS DISTRIBUTION ABOUT LARGE HORIZONTAL EXTRACTED AREAS.

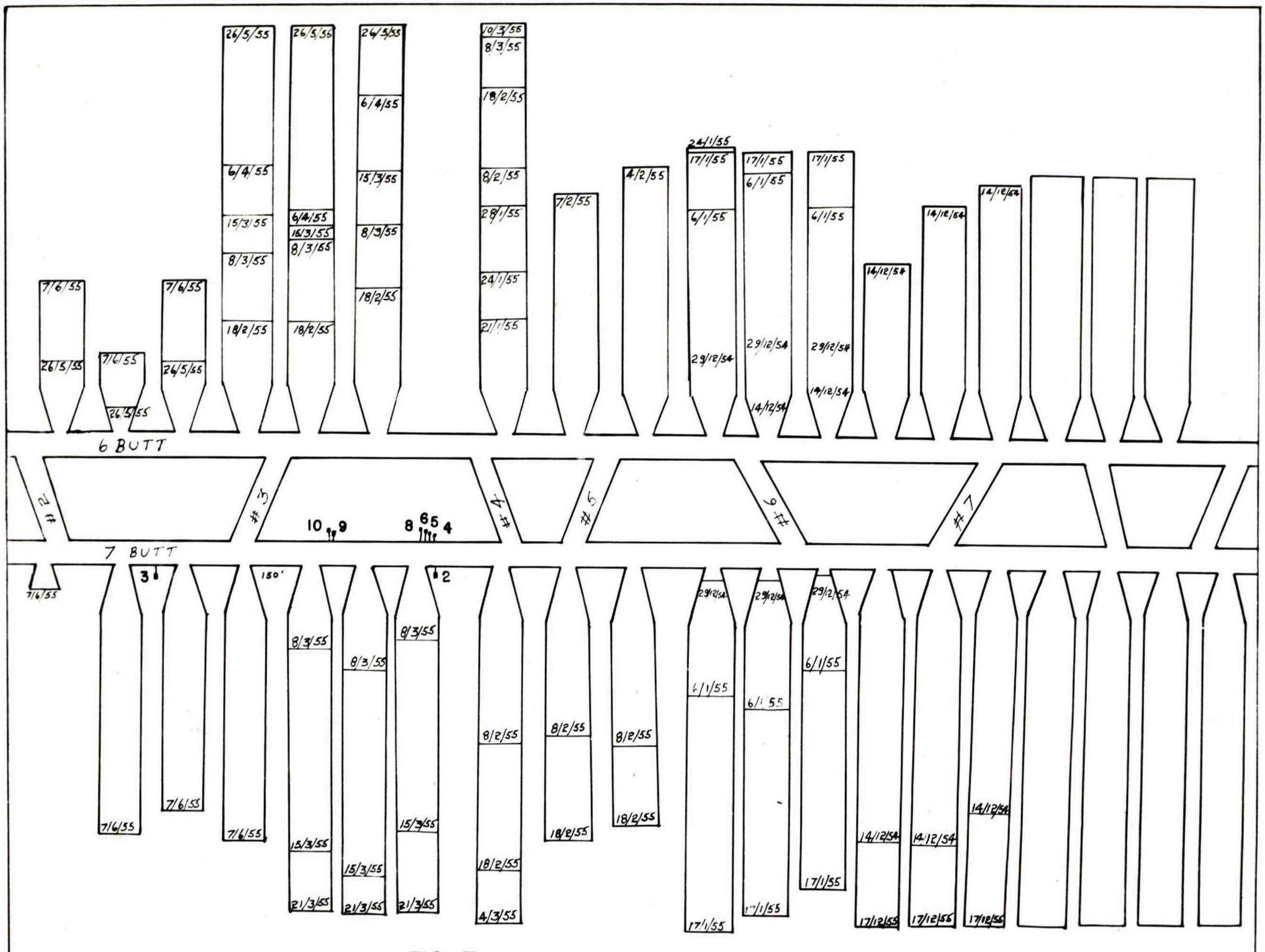
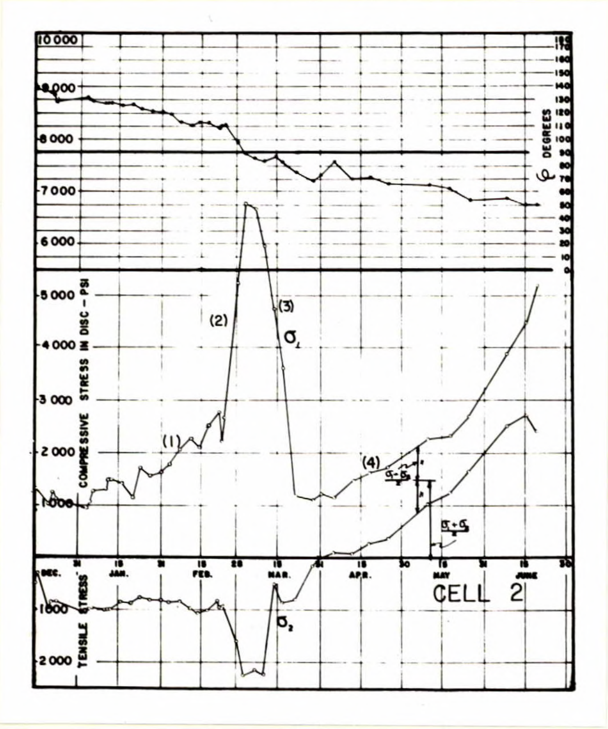


FIG- 7

PLAN VIEW OF MINE SHOWING PLACEMENT OF CELLS AND EXTRACTION HISTORY

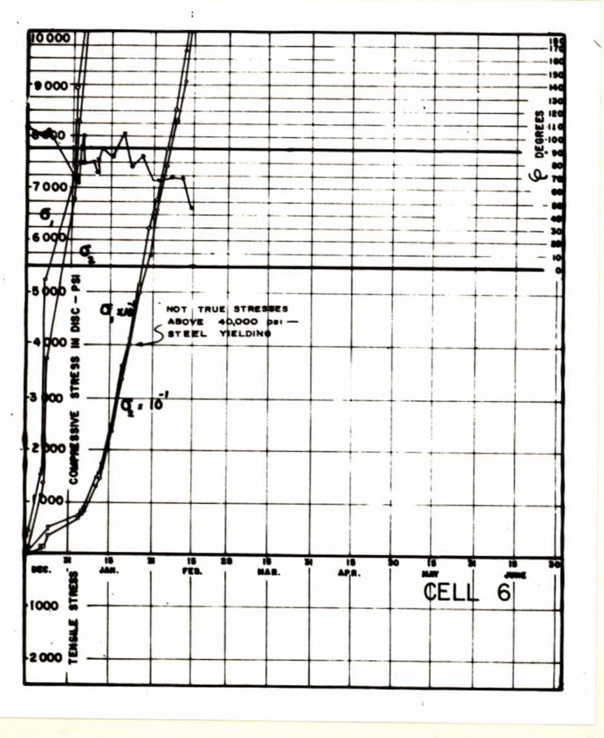
Fig. 7.

Fig. 8.



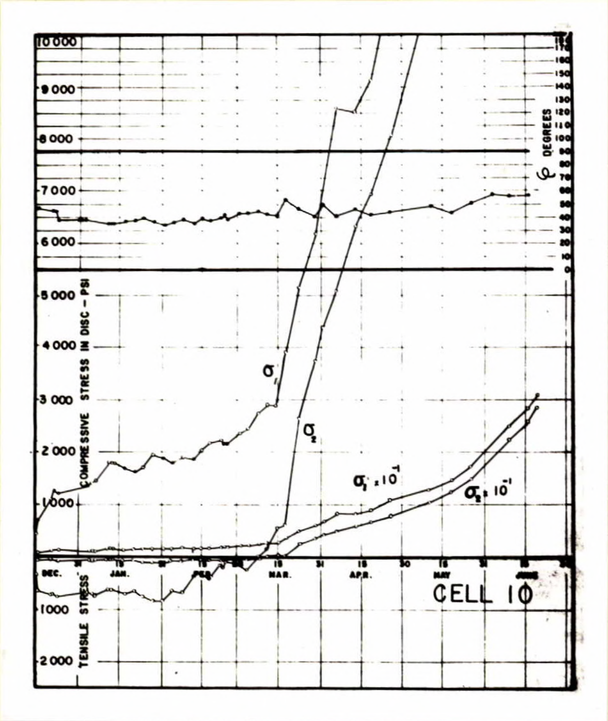
RESULTS FROM LOAD CELL #2.

Fig. 9.



RESULTS FROM LOAD CELL #6.

Fig. 10.



RESULTS FROM LOAD CELL #10.

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