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CANADIAN GROUND STRESS INVESTIGATIONS

by

A. BROWN

Fuels Division

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A. Brown*

ABSTRACT

Investigations into the phenomena of rock stress in underground mine workings are being conducted by the Department of Mines and Technical Surveys, Ottawa, Canada, for the purpose of learning additional facts about the behaviour of ground under stress. It is hoped that a more fundamental knowledge of the factors involved may prove beneficial to the mining industry and assist in the optimum recovery of Canadian mineral resources.

For the conduct of such studies the Department has assembled a small group of mining engineers and physicists who are aided on specific problems by Department geologists. Co-operative studies are also promoted in certain Canadian universities and provincial research groups. Considerable importance is placed on observations within the mine workings, supplemented by laboratory based studies leading to the development of dependable field apparatus. Laboratory investigations are also conducted into the physical properties of rocks and minerals.

Field investigations are being conducted with a variety of dynamometer and convergence measuring apparatus in the open workings, and devices for observing stress changes within the "solid" are being developed. Some of these latter have had fairly extensive field trials. The laboratory investigations into rock properties were initially based on short period uniaxial compression testing of unconfined specimens and a considerable body of data has been secured on Canadian and some foreign mine rocks. More recently, apparatus has been devised and is now in routine use for observing the effects of time-strain. Currently, equipment is being constructed for triaxial testing.

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INTRODUCTION

The ever increasing depths to which mining operations are being carried have been accompanied by greater stresses in the underground workings that increase the hazards to mining personnel and hinder the orderly and economical recovery of the mineral. Such stress manifests itself in a variety of ways, ranging from a slow extrusion of rock and mineral into the roadways to violent disturbances known to the coal miner as "bumps" and "outbursts of gas and coal" and to the metal miner as "rock bursts". A bump or rock burst causes sudden destruction of extensive portions of the mine workings, usually without warning, and is frequently associated with large areas of mineral extraction. An outburst of gas and coal is most frequently encountered in narrow roadways penetrating virgin areas of a coal seam and is a large scale expulsion of broken coal into the roadways accompanied, generally, by an enormous release of gas. In this latter type of disturbance the roof and floor strata are rarely damaged. Although these violent manifestations of stress relief are extremely hazardous to personnel they represent only the more spectacular phases of a general problem that usually expresses itself by a slower but continuous deterioration of mine workings.

The Mines Branch of the Department of Mines and Technical Surveys has undertaken a study into the various manifestations of ground stress relief in underground workings in the hope of increasing the knowledge concerning them and thereby contribute toward the optimum recovery of Canadian mineral resources. The need for such study grows with the rapidly rising world demand for mineral products which accelerates depletion of the more readily accessible ores, particularly those of premium grade. For some of our new Canadian mining fields severe problems of ground stress are still in the future but much of our mineral output comes from the older, well established mines which have already reached considerable depths. It must also be anticipated that the depletion of premium grade deposits will eventually necessitate the mining, at competitive cost, of low grade material, and unsolved problems of ground control can very materially increase costs. A study into the phenomena of ground stress in underground workings is therefore considered to be a present-day necessity, especially since such an investigation must be undertaken as a long term effort because of the very complex nature of the problem and the difficulty of making full-scale observations.

Mines Branch investigations into this and related subjects are conducted by a small team of mining engineers and physicists who, with assistance from geologists, endeavour to pool their special skills in an integrated program of study. These Canadian investigations combine field and laboratory approaches, and have been planned along the following lines of study:

1. Structural geology, lithology, and seismology
2. Mechanical properties of rocks and minerals
3. Studies into the association of coal and its sorbed gases
4. Laboratory studies of models
5. Measurements in mine workings.

STRUCTURAL GEOLOGY, LITHOLOGY, AND SEISMOLOGY

A study of regional geology and the projection of the influences of regional structure into the smaller area of the mines is considered necessary to obtain a clearer concept of the character of the geological forces involved in a given mining district and the weakening effect of such forces upon the rock and mineral masses. As part of these geological investigations, studies are also being made into the characteristics of rock failure as exhibited by mining induced fractures on extraction faces and adjacent roadways (1) (2).

In collaboration with the Seismological Division of the Dominion Observatory an effort has also been made to learn whether tremors, due to local or regional seismicity, are associated with violent stress relief in mine workings. Such studies were also intended to supply a better record of the bumps or bursts occurring in each mining field, many of which are not noticeable in the active workings and hence not reported by the mines concerned. A continuous record of such events would enable their incidence to be more closely related to the mining operations. For an initial exploration of the subject, seismographs were installed in the coal mining centres at Fernie and Coleman in the Crowsnest Pass coal field of Western Canada (3). Later, in Eastern Canada, a seismograph was installed in the Springhill coal field to record the tremors occurring in the area and to study their association with the mining operations. In very brief summary of the findings of this study there seems to be no correlation between earthquakes and bumps. Following an earthquake tremor the number of recorded bumps did not increase. There appears, however, to be a definite relation between the rate of mining activities and the frequency of local tremors, since it was observed, both in the East and in the West, that cessation of mining operations, even for a weekend, causes a substantial reduction in the number of tremors recorded. This would also indicate that the ground tremors observed are principally due to strata readjustments associated with the current working faces and much less to long term ground stress relief in the older extracted areas of the underground workings.

MECHANICAL PROPERTIES OF ROCKS AND MINERALS

Laboratory investigations into the physical characteristics of rocks and minerals are considered necessary for understanding how such media behave when subjected to stresses induced by mining and geological forces. The initial phase of these investigations sought to determine the elastic and failure properties by short period, uniaxial stressing of unconfined specimens. The second stage of the laboratory program is concerned with the effects of time-strain, which is a dominant factor in the application of stress in underground mine workings. The third stage of this investigation seeks to observe, within laboratory limitations, the "in situ" behaviour of rock under stress by testing under varying degrees of constraint.

The physical properties observed during uniaxial compression testing were compression modulus, ultimate compressive strength, Poisson's ratio, strain energy at failure, and fracture angle. The apparent specific gravity and Moh's hardness were also observed for a number of specimens. The tests were conducted on right cylindrical specimens prepared from diamond drill cores varying from 7/8 to 2-1/8 inches in diameter. Longitudinal and transverse stress-strain relationships were obtained for stress increments of 1000 lb/in.^{2} up to a maximum stress of 20,000 lb/in.^{2} and from such data the tangent values of compression modulus and Poisson's ratio at 6,000 lb/in.^{2} were obtained by graphical means. Each specimen was then loaded at a constant rate of 200 lb/in.^{2} per second until failure took place and ultimate compressive strength, strain energy at failure and fracture angle were determined.

These investigations are being conducted with rock specimens selected from a representative number of Canadian mines and, for further comparison of results, a number of specimens from European coal and metal mines were included. The procedure and results have been presented in earlier reports (4) (5) and space does not permit adequate treatment in this report.

It was recognized from the outset that the influence of time on the elastic and failure properties of mine rock should be investigated. It was also appreciated that, when compared with short period uniaxial compression testing, a study of these time-dependent properties would present more difficult problems, necessitating the design of special apparatus and technique. Development in this direction has been carried out during the last two years and a time-strain apparatus has been assembled. This apparatus allows the time-dependent characteristics of three separate specimens to be studied simultaneously at loads up to 25,000 pounds.

The third stage of study into the physical properties of mine rocks necessitates investigation into the behaviour of these materials under conditions of triaxial stress. A few initial experiments have already been conducted, principally to secure information required for design of apparatus. A triaxial stressing unit is now being constructed at the Mines Branch and when it is completed, a program of triaxial testing will be initiated.

STUDIES INTO THE ASSOCIATION OF COAL AND ITS SORBED GASES

Laboratory investigations have been directed toward studying the permeability of coal and its sorbing capacity for gas. Observations have also been made of the volume of occluded gases actually held in coal samples selected from various depths in coal seams. These laboratory studies were conducted as part of a program of investigation into the phenomena of outbursts of gas and coal and, for comparison purposes, the tests were carried out on samples selected from "outbursting" and "non-outbursting" seams. A report on the results of this work is under final preparation and an interim review has already been presented (6).

LABORATORY STUDIES OF MODELS

Due to staff limitations this line of study into the phenomena of ground stress has only recently been started, but it is hoped that the studies of models will further the understanding of stress distribution in "mining structures". The data obtained from observations and measurements in the mines and on rock specimens in the laboratory will aid the future studies of models.

MEASUREMENTS IN MINE WORKINGS

The underground measurements were made to obtain quantitative data on the behaviour of stressed ground under actual mining conditions. Although these underground studies lack the control that can be exercised in laboratory work they are vital to an understanding of ground stress problems. They are also useful in providing a basis for laboratory investigations, including studies of models, and in helping to interpret the results of laboratory work in terms significant to the mining industry.

In order to obtain a comprehensive understanding of ground behaviour associated with mineral extraction, it is considered essential to attempt observations in the three zones represented by the extracted area, the production face, and the solid mineral into which the production face is advancing. It is also considered advisable, in order to obtain comparative data, to conduct such observations in mines which are subject to violent relief of stress and in those which are not. Observations in the open workings, as represented by the production face and its servicing roadways, usually include measurements of ground closure and the effect of such closure upon the loading of artificial supports. For such purposes a number of reasonably reliable devices are available. The greatest difficulties lie in designing apparatus for observing stress changes in the solid strata and for remote measuring of closure and the re-establishment of ground loads in totally extracted and inaccessible areas. Since a knowledge of what transpires in these two zones is considered essential to further progress in ground stress investigations, considerable importance is attached to stress analysis studies leading to instrument development. As indicated, the problem of observing stress and stress effects at points remote from the accessible workings of a mine is attended by a considerable number of difficulties. Such difficulties are by no means unique to Canada and, for mutual benefit, the Mines Branch encourages a close liaison with research groups confronted with similar problems in other countries.

Within the limitations of this report it is possible to indicate briefly the object of various underground programs and to present a few examples of what has been observed under a reasonably wide range of Canadian mining conditions.

Locale of Observations

When selecting the mining areas for study it was considered that data obtained under contrasting geological conditions and extraction methods would allow useful comparisons to be made with respect to the behaviour of ground under stress.

In Eastern Canada, observations are being made in the collieries at Springhill, Nova Scotia. The Number 2 Mine of this district has a history of bump occurrences dating back to 1917 and is currently being worked at a depth of approximately 4200 feet. The mining method is longwall retreating along the strike and the practice is to retreat three walls in line, each approximately 350 feet long. No machine cutting or shooting is employed, the coal being dug by hand picks, then hand loaded on to face conveyors. Face support consists of three rows of hardwood chock-block supports built parallel to the coal face. Such supports are built during the two daily coal loading shifts and the rear line is withdrawn during the midnight shift. The goaves are partially packed by 12-foot-wide stone midwalls, which are built forward daily in step with the face advance. The seam dips at 15 degrees and averages 9 feet of strong, well cleated bituminous coal enclosed in competent beds of shales, sandy shales and sandstones of Carboniferous age. The bumps rarely disturb the retreating longwall faces but manifest themselves as violent upthrusts of pavement in the levels leading to the walls. Observations have also been made in the Number 6 Mine at Springhill, which operated in a 5 foot seam of coal at a depth of approximately 2500 feet. Although the mine was not seriously affected by bumps it allowed valuable comparisons to be made regarding ground behaviour in two quite dissimilar operations in the same coal field. As indicated, the seam height and overburden were significantly different. In addition, the wall faces in Number 6 Mine were advancing, not retreating, and they operated on a daily cycle of undercutting, shooting and loading. As an additional variable the face observed in Number 6 Mine was worked as a single unit and not in a combination of three as in the deeper operation. The type of face and gob supports were similar in both mines.

In Western Canada, investigations into mine bumps have been conducted in the Crowsnest Pass coal field of the Rocky Mountain region which has been affected by incidents of violent stress relief since 1907. The mining method generally employed in the thick, pitching seams is a retreating pillar extraction, but a modified form of longwall is used in a few mines where pitches are moderate. No packing is built in the goaves in either method, and total caving is practiced. The enclosing strata, of Lower Cretaceous age, have been heavily faulted by mountain building forces and metamorphosed into usually competent beds of shales, sandstones and conglomerates. The orogenic stresses have also upgraded these Lower Cretaceous coals to medium volatile rank but the accompanying processes of intense folding and extrusion have weakened them structurally and destroyed practically all evidence of bedding planes and cleat. Strata deformations ahead of extraction faces are of much less magnitude than those observed in the Carboniferous measures of Eastern Canada and the less orderly advance of extraction lines tends to obscure trends in strata behaviour. Even well to the rear of the extraction lines, falls of ground are usually limited to the immediate roof beds and it appears likely that long, flat arches are established which extend for considerable but as yet unknown distances into the goaves. A further interesting observation of rock behaviour in the Crowsnest field is that, although the strata are highly faulted, careful measurements have failed to indicate any slippage across such discontinuities even at and behind the extraction faces.

The bumps are characterized by a violent upheaval of the floors and generally occur on or near the pillar extraction line. There have been, however, early incidents in the Fernie area of the Crows-nest coal field where multiple roadways leading to large areas of total extraction were affected at greater distances. Usually, the bumps are associated with broad, totally extracted areas under competent roofs that are able to sustain wide unsupported spans. In some of the earlier occurrences they have been attributed to the failure, over broad areas, of inadequate coal pillars.

In Western Canada, studies are also being made in the mines at Canmore, Alberta, which are affected by the phenomena known as outbursts of gas and coal. The geological history and structure of the Canmore coal basin resemble that of the Crowsnest Pass and the coal, of Lower Cretaceous age, has been upgraded to low volatile bituminous rank. Many local faults, folds and dis-continuities occur in the seams and there is evidence of extensive shearing in the plane of the coal beds. The seam in which most observations have been conducted varies from 7 to 11 feet thick and has an average dip of 20 degrees. Mining is usually conducted by a bord and pillar method. Slopes, cross-cuts and raises, approximately 16 feet wide, are driven to develop the coal into pillars which are later recovered in whole or in part. The outbursts occur during the driving of these development entries.

To assist in the development of measuring methods in a mine free from the geological structure of the Rocky Mountain belt and in strata of low lateral strength, observations have been made in a prairie coal field at Lethbridge, Alberta. The mine selected for study operated in a flat-lying seam of coal, 5 feet thick, at depths of less than 400 feet. The overburden consists of weakly consolidated shales and clays of Upper Cretaceous age, overlain by a thick mantle of glacial drift. A room method of extraction is practiced, with narrow pillars left between adjacent rooms These pillars are not recovered.

The beds of hematite iron ore at Wabana, Newfoundland, are considered to be shallow water sediments of Lower Ordovician age (1). Three mineable beds occur and all outcrop on Bell Island and dip about 8 degrees northwest beneath Conception Bay. The lower bed, in which observations have been conducted to date, ranges from 10 to 30 feet in thickness. The associated rocks are predominantly shales and siltstones with minor sandstone beds and the depth of cover over the current workings is approximately 1200 feet, with an additional 300 feet of water. A room and pillar method is employed and approximately 60 percent of the ore is extracted. The purpose of the study is to investigate the stability of the ore pillars left as supports in these submarine workings.

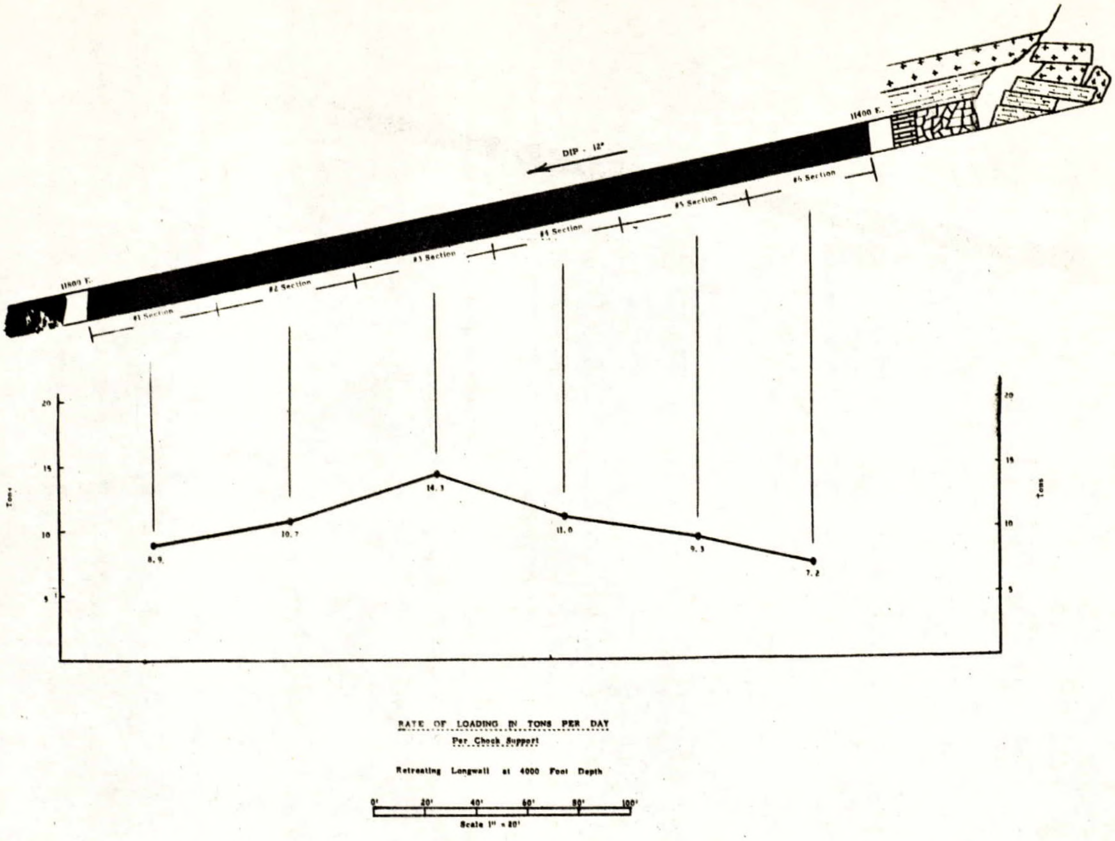


Fig. 1. - Rate of loading in tons per day, No. 2 Mine, Springhill, N.S.

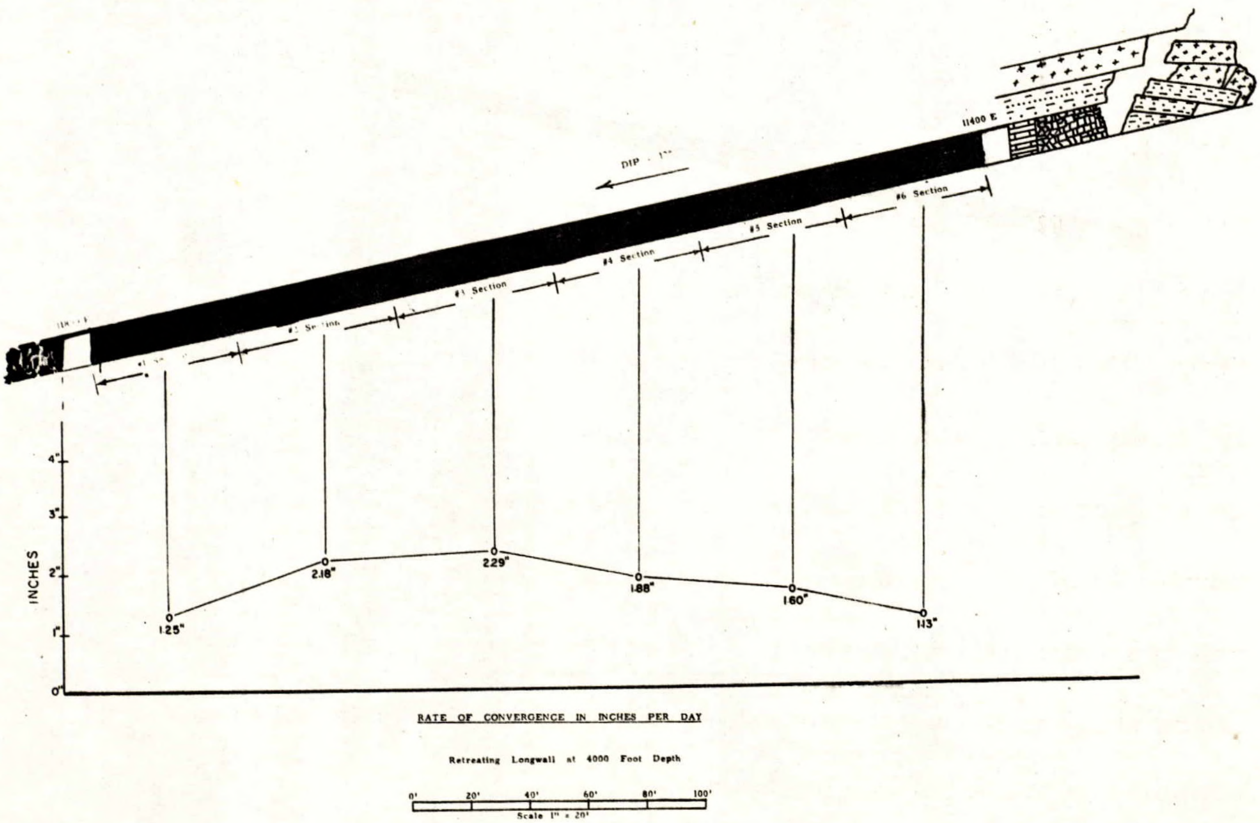


Fig. 2. - Rate of convergence in inches per day, No. 2 Mine, Springhill, N.S.

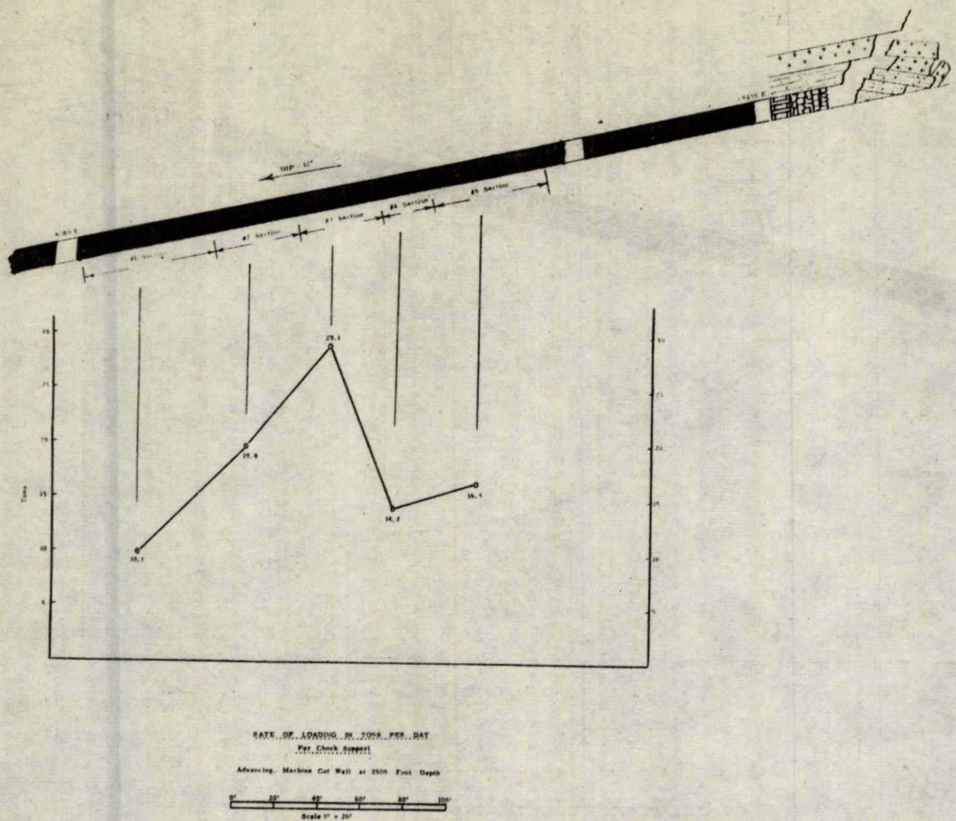


Fig. 3. - Rate of loading in tons per day, No. 6 Mine, Springhill, N.S.

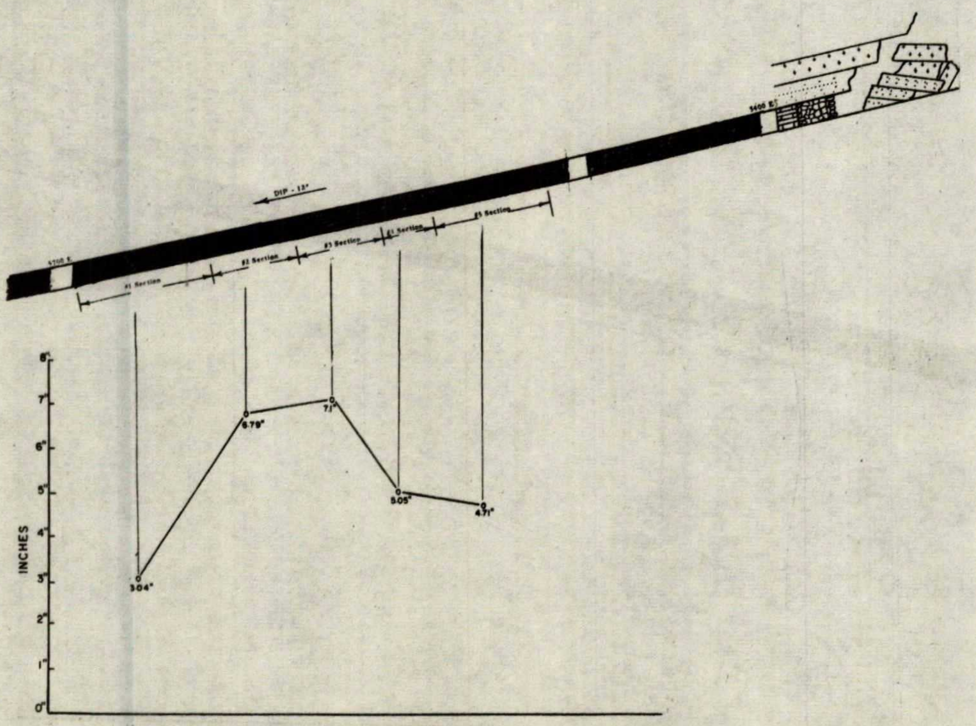


Fig. 4. - Rate of convergence in inches per day, No. 6 Mine, Springhill, N.S.

Ground Behaviour in Open Workings

To deal first with what may be broadly classified as "open workings" observations, these have been undertaken primarily to observe ground behaviour on the edges of solid mineral bordering totally extracted areas. It is considered that a knowledge of wall closures and support loads along such edges is informative of the ground loads imposed upon the solid mineral and also of the manner in which equilibrium is being restored in extracted areas. Such observations have been conducted with a variety of dynamometers and convergence-measuring apparatus.

As indicated earlier, a few examples will be presented of what has been observed under a number of Canadian mining conditions.

Figure 1 is presented as a side view of a longwall face in Number 2 Mine at Springhill, Nova Scotia, with a graph showing the rate of loading upon the artificial supports in different sections of the face. It will be noted that the maximum values occurred approximately one hundred feet above the lower end of the wall. Figure 2 is the same side view, illustrating the observed rates of closure in these same sections. As indicated earlier, other observations were made in the Number 6 Mine at Springhill, but under very different operating conditions and with significant dissimilarities of seam height and depth of cover. Figure 3 is a side view of such a face, with a graph showing the rates of loading upon the supports. Figure 4 illustrates the rates of closure in these same sections along the face. It is interesting to observe that in both mines the highest rate of support loading and the highest rate of convergence occurred in approximately the same position on the working faces.

It is conceivable that the dominant common factor that would bring about such similarity of result under widely different operating conditions could be a substantial similarity in the strength of the rocks enclosing both seams. If rocks are not too dissimilar in their characteristics it is to be expected that they will fail in somewhat the same fashion in extracted areas and set up a recognizably similar pattern of stress in the coal bordering the goaves. Since the total pitch length of the coal block in each mine was approximately the same (about 350 feet), it is also interesting to note that the distance from the edge of the older goaf (which lies on the rise side of the block) to the zone of maximum stress is nearly the same in each case. This distance may indicate the position of an abutment zone set up through the combined influence of the older goaf above and the new void being created by current extraction. The point of particular interest is that, apparently, increased depth did not significantly modify the position of maximum loading on the exposed edge of a massive coal block. Of some significance, also, is the proximity of such an active zone to the level leading to the foot of the upper wall in Number 2 colliery (where three walls are operated in line). It is in this uppermost haulage level that practically all of the bumps in the active workings occur.

A striking parallel to this observed pattern of stress on long extraction faces in Springhill is reported (7) in the Champion Reef Mine of the Kolar gold fields, where a modified form of rill stope is employed with advance along the strike. It is reported that crushing of the upper portion of the block being mined will throw the pressure of the enclosing rock walls on to the bottom of the stope, which may then build up a tremendous amount of strain energy before falling.

Although such face observations were undertaken primarily to observe ground behaviour along the edges of massive coal blocks, the data obtained are also informative of the effects produced by individual mining operations at the coal face. Figure 5 illustrates the development of total convergence and the growth of support loading in Number 2 Mine. It will be observed that convergence increases in a fairly linear fashion and indentations in the curve are due to decreased rate during non-coal-producing shifts. It is apparent that convergence proceeds in unison with removal of coal and is promptly retarded when production ceases. An examination of the curve depicting growth of support load shows a reasonably linear relationship up to approximately 30 tons. Thereafter the rate of loading decreases. Such decrease is considered due to yielding of the supports and floor rock rather than to a decrease of load.

Similarly, the results of face observations in the shallower Number 6 Mine are illustrated in Figure 6. It will be observed that the convergence proceeds in a generally linear fashion between the

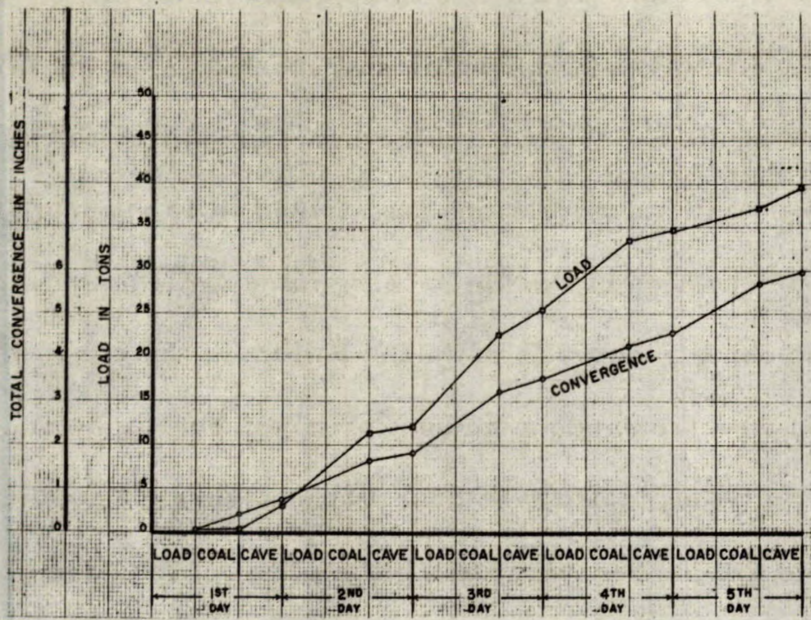


Fig. 5. - Total convergence and support loading in No. 2 Mine, Springhill, N.S.

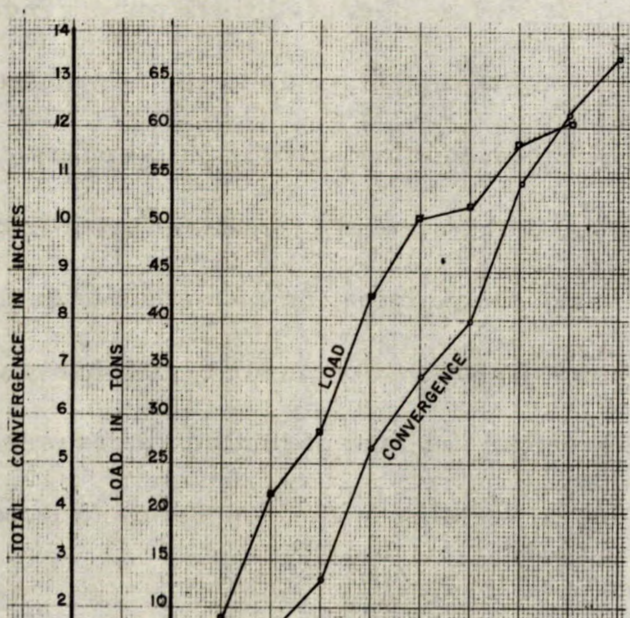


Fig. 6. - Total convergence and support loading in No. 6 Mine, Springhill, N.S.

coal face and the caving line, with appreciably increased rates occurring during the coal-loading shifts. The loading curve is reasonably linear up to a load of 50 tons and thereafter decreases.

Further reference to Figures 5 and 6 reveals that the conditions observed in Number 6 Mine, working at a depth of 2500 feet, were more severe than those observed in Number 2 at about 4000 feet of cover. It is therefore apparent that, under Springhill conditions, depth is not a controlling factor in establishing the rate of wall closure and loading on the face supports. It would appear that a more significant factor is the type of face operations. In regard to speed of advance, the shallower, machine-cut wall advanced six feet per day while the deeper, hand-pick face advanced about four feet. On the basis of convergence per foot of daily advance, the machine-cut wall converged, on the average, 0.75 inch per foot of advance while the corresponding figure for the deeper operation was 0.3 inch. It is useful to compare such values with those obtained in longwall operations by B. Schwartz (8) in French mines and by N. S. Stephenson and S. Lewis (9) in United Kingdom collieries. Schwartz reports a daily convergence of 0.44 inch per foot of daily advance, while a value of 0.62 inch was obtained by Stephenson and Lewis. These were for "non bumping" mines and represented reasonably good face conditions on wall faces supported by steel props.

Observations in the levels servicing such longwalls seek to determine the pattern of ground loading along these exposed edges of the coal blocks being mined. In conjunction with the observations

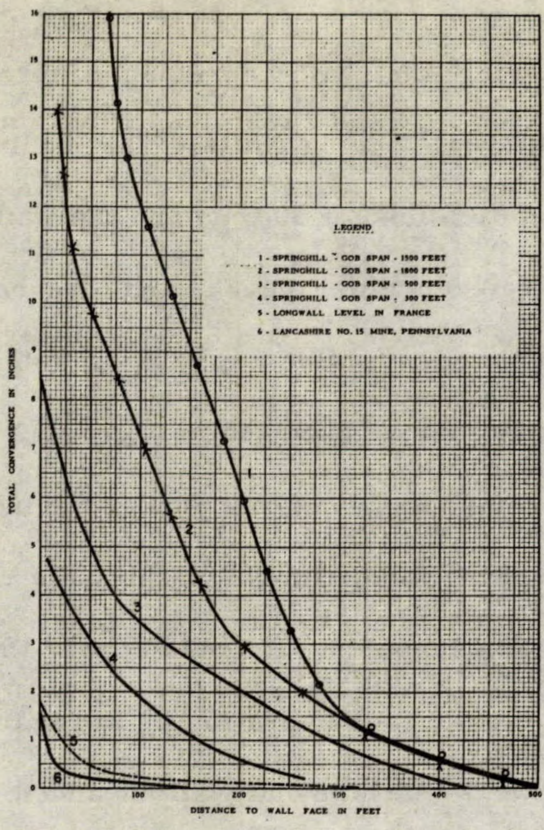


Fig. 7. - Closure on longwall roadways.

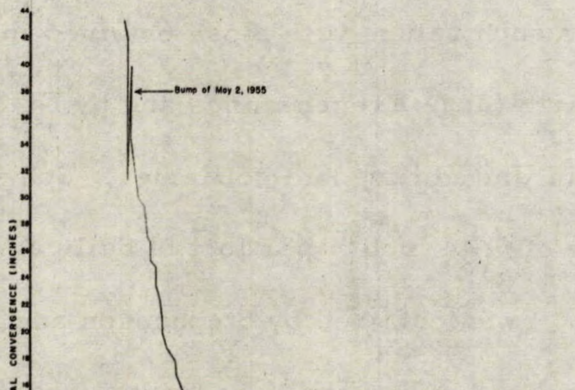


Fig. 8. - Closure during bump occurrences.

made at the extraction faces, it is hoped that such fringe studies in the "open" will help clarify and support information obtained with borehole instruments in the "solid". Elevation surveys were originally employed to differentiate between roof and floor movements but the results were not considered accurate enough to warrant continuing with this method. The principle shortcoming is the lack of a dependable base station within a reasonable distance of the observation points. In the case of the Springhill mines all evidence to date indicates that most of the convergence in roadways is due to floor lift.

Figure 7 illustrates the closure observed at typical roadway stations, plotted against distance to the wall face. For comparison, two samples are given of the convergence observed in a Pennsylvania mine (10) and of that observed in a longwall operation in France (11). These mines, particularly the Pennsylvania mine at 600 feet of cover, are substantially shallower than those at Springhill. The much greater amount and rate of convergences in the Springhill roadways are very apparent and such may be typical not only of coal mines operating under exceptionally deep cover but particularly of those possessing competent enclosing strata.

Reference to Figure 7 will also reveal that two of these typical Springhill stations were chosen from among those with relatively narrow spans of gob (300 and 500 feet), while the other two were selected from those with wider spans (1500 and 1800 feet). There is no great difference between the 500, 1500 and 1800 foot spans, indicating that at Springhill the rate of closure on the levels does not progressively increase with growth of gob span. Such studies are continuing and additional information might possibly reveal that, beginning at very short spans of 100 to 200 feet, there may be a pattern of increasing convergence with increasing span up to a certain maximum width of gob and that, thereafter, the relationship does not materially change.

Figure 8 illustrates the closure with time at a roadside station that was very close to two destructive bumps that occurred within 16 days of each other. Of interest is the decreased rate of convergence in the period preceding these bumps. This may have been indicative of a temporary decrease in ground stress at this point or, equally so, of the existence in this part of the roadway of strong pavement strata more resistant to yielding under increasing load and thereby able to store energy and release it violently. Because of the marked heterogeneity of rock beds it is conceivable that such stronger zones can exist in the roadways, perhaps at irregular intervals, and serve as potential loci for bumps. It is therefore considered that a more extensive study into the behaviour of floor rocks in roadways is well warranted.

In Western Canada, observations have been made in a number of mines in the Crowsnest Pass coal field but, for brevity, only two mines will be considered. One is the McGillivray Mine operating in a 9-foot seam of coal at a depth of approximately 2000 feet. The other is the adjacent International Mine, operating in the same seam, but in this mine the coal averages about 17 feet in thickness and the depth of the workings is approximately 2400 feet. An interesting contrast is that the McGillivray Mine is subject to severe bumps but there have never been any such occurrences in the International Mine. The strata enclosing both mines are, on the whole, massive and competent, but in International the rock beds in immediate contact with the seam are relatively weak shales whereas in McGillivray Mine the rocks in immediate contact are more competent sandy shales, sandstones and conglomerates. Although numerous faults intersect both workings the strata are more severely folded in the McGillivray area, resulting in discontinuities of the seam in some locations and causing variations in the dip of from thirty to sixty degrees. With some local changes, usually at faults, the pitch in the International Mine is fairly uniform at thirty degrees.

The extraction method in both mines is essentially the same, being pillar extraction on the retreat. The practice is to drive a two-place level entry from the main haulage slope, for several thousands of feet along the strike, to a predetermined boundary. Rooms are then driven up-pitch to an older level above to begin pillar development at the inside end. Pillar extraction follows closely upon pillar development and the two operations retreat toward the main slope. The panel of coal under such exploitation extends the full length of the level entry and measures about four hundred feet along the pitch. To the rise side of this panel the totally extracted area extends for several thousands of feet towards the outcrop. While there are some variations in size of pillars in each mine, those in International are approximately 85-foot-square blocks and in the McGillivray Mine they measure 85 feet on the strike and 50 feet on the pitch.

In the thicker seam of the International Mine all development work is done in the top seven feet of coal, with the full height of the seam subsequently mined at the pillar extraction line. In the McGillivray Mine the development work proceeds in the full thickness of the seam.

Bumps in the McGillivray Mine have occurred on the pillar extraction line and for distances up to 200 feet ahead. These latter are usually associated with pillar splitting operations. Although the International Mine has never been affected by bumps, there is a slow but heavy extrusion of the bottom ten feet of coal and immediate floor rock into the rooms and cross-cuts that frequently closes them completely and necessitates re-driving. This extrusion is observable for several hundred feet ahead of the pillar extraction line.

Figure 9 illustrates the closures observed in roadways servicing the extraction lines in these two collieries and, in order to complete the comparison, an equivalent record is included for a roadway leading to the retreating longwall in Number 2 Mine at Springhill. This figure shows the closure that occurred during a 500-foot advance of each of these three extraction faces. At the end of this advance, the extraction lines had arrived at the observation point. The horizontal axis of the graph indicates the length of time required to advance each extraction line the 500 feet. This method of comparing results over a long period, and for a large advance, was adopted

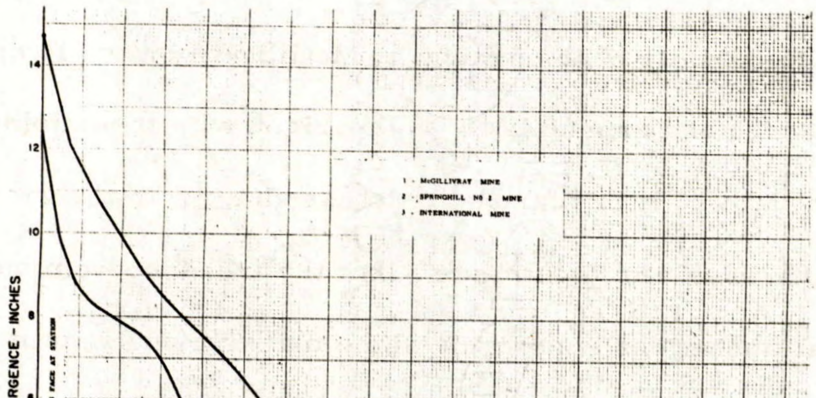
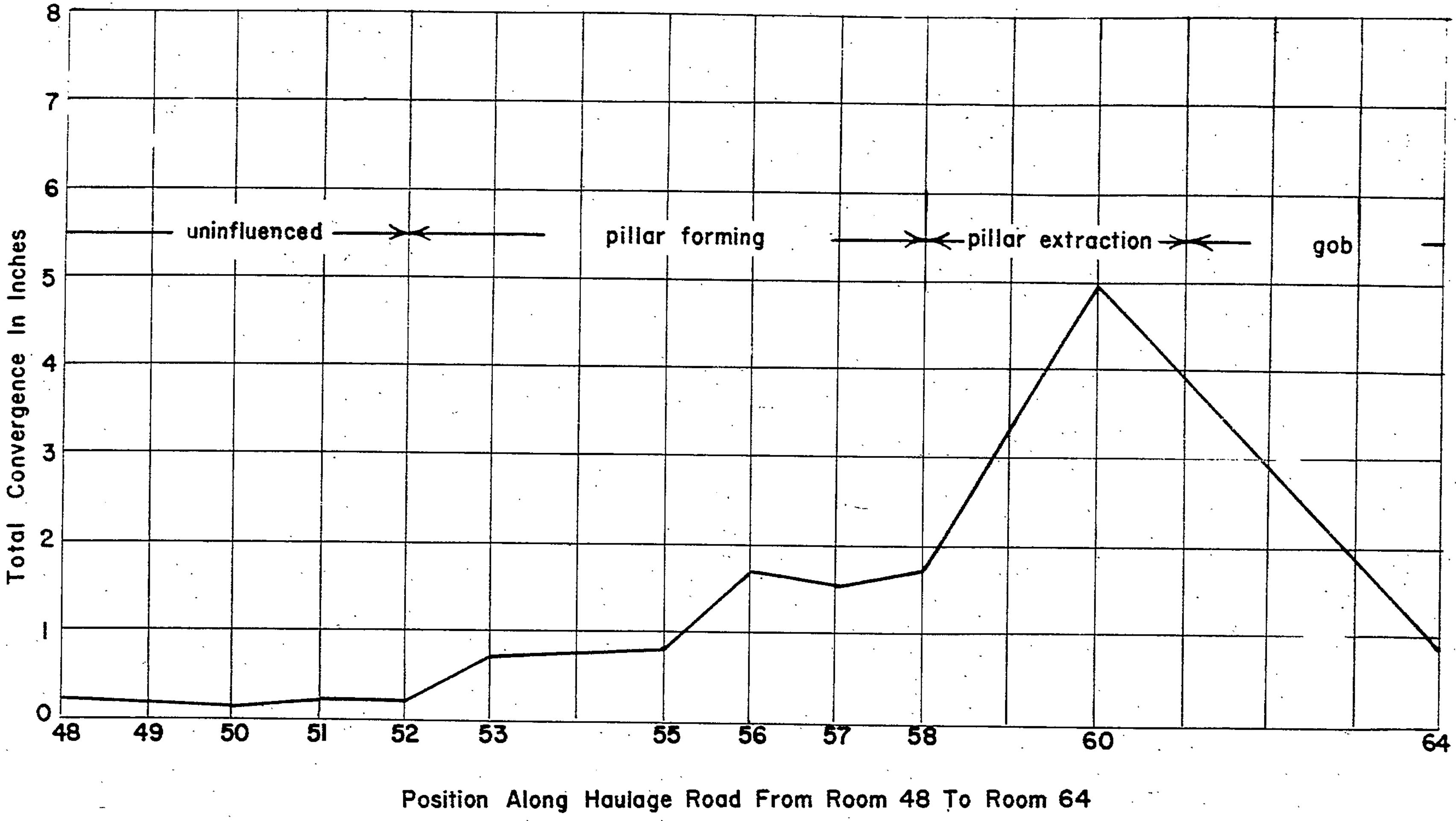


Fig. 9. - Closure associated with two pillar extraction operations.

because of the very irregular nature of the pillar extraction lines and the virtual impossibility of deciding, from pillar plans, just what were the true shape and successive positions of the pillar line during short intervals. All three operations progressed at normal speed during their selected periods, but the effect of an annual holiday period at Springhill is discernible by flattening of its graph about 50 days before the end of these observations.

The rigidity of the ground in McGillivray Mine is apparent from this record and especially in comparison with the adjoining International Mine. It is reasonable to assume, from the ground behaviour observable in both mines, that the freedom from bumps in International operations, under the same massive cover as its immediately adjacent neighbor, is due to the more yielding characteristics of the thicker seam and of its immediate roof and floor rocks. Such strata cannot, apparently, store up sufficient strain energy for violent release. However, it should not be understood by inference that the seam in the McGillivray is a strong coal, capable of large resistance to converging rock walls, for it is quite characteristic of the sheared and friable coals of the Rocky Mountain region. It is not, for instance, as strong a coal as that of Springhill. Nevertheless, it will be observed from Figure 9 that closure at McGillivray is markedly less than in Springhill. The reason for the rigidity of the ground in the McGillivray Mine must lie in the greater strength of all its rock beds, which are able to sustain long spans across yielding pillars and totally excavated areas. It is suggested, therefore, that in the pillar development area ahead of the McGillivray extraction line, the roof and floor strata may already be largely self-supporting but converging slowly enough, as indicated in Figure 9, to maintain the enclosed pillars in a high state of stress for appreciable periods before crushing. Experience at the mine indicates that pillars directly on,or adjacent to,the pillar extraction line are still highly stressed and generally can be mined safely only by taking successive slices off the destressed edges. An improved practice, based on this concept, would be to encourage greater yield in pillars by making them originally of reduced size and thus lower their capacity for storing strain energy. Similarly, large pillars already formed could be reduced in size by splitting them well in advance of the extraction line and before they come under the influence of the forward abutment pressure zone.

The observed effect of an abutment zone in the McGillivray Mine is illustrated in Figure 10. This shows the closure that was measured along a 1600-foot entry ahead of a pillar extraction line during a six-month period. The section between rooms 48 and 52 represents an outer section of entry, 400 feet long, that has not yet been affected by pillar development or pillar extraction operations. In this section the closure rate did not exceed 0.01 inch per day. Along the section between rooms 53 and 58, the coal was being cut up into pillars and the convergence rate was from 2 to 5 times greater than in the outer section. Near the pillar extraction zone, as indicated at room 60, the rate increases to a maximum and attains values up to 10 times the rate observed between rooms 48 and 52. This pattern



CONVERGENCE OBSERVED ON MAIN ROADWAY DURING 6 MONTH PERIOD

Fig. 10. - Closure in advance of a pillar extraction line.

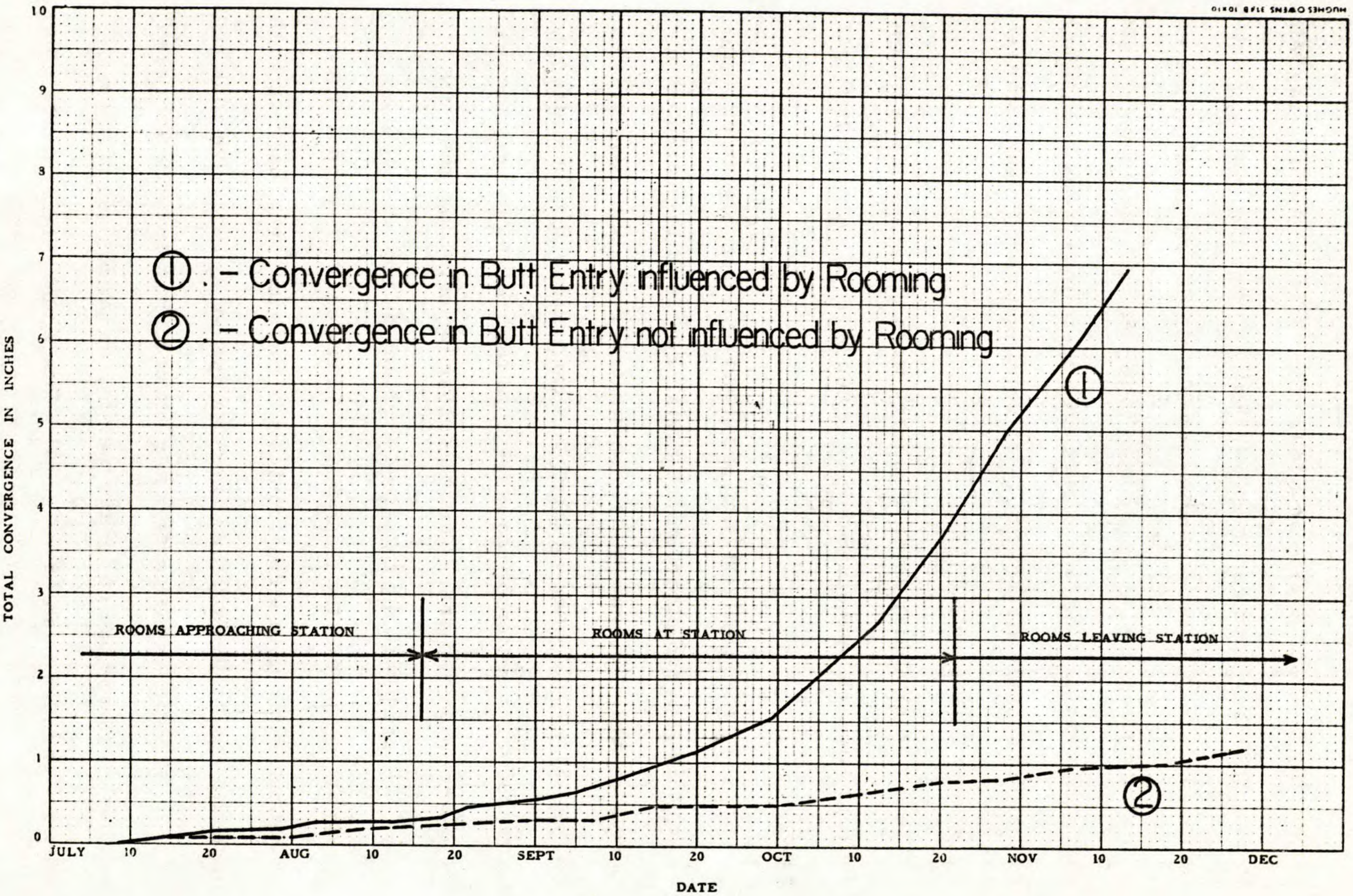


Fig. 11. - Closure associated with rooming in weak strata.

of rock closure ahead of an extraction line may be regarded as being reasonably normal for the conditions existing in the McGillivray Mine. However, this pattern can be substantially changed by mining practices, particularly in the zone extending for 200 or 300 feet ahead of the pillar extraction line. One practice is to conduct pillar development operations in this zone, for during such operations it has been observed that the already stressed coal is subjected to even higher stresses and bumps have resulted (12).

Much higher rates of closure were observed in the International Mine but space limitations forbid their illustration in this report.

For brief illustration of ground behaviour observed in the weak sediments at Lethbridge, Alberta, Figure 11 is presented to show a typical relationship between strata closure and extraction by rooms. It will be observed that seam extraction does not cause any increased deformation of roadways until the rooms are very close to the observation stations. This behaviour indicates that the weak strata fail readily in the extracted area and do not build up long unsupported spans in the gobs that could impose a forward abutment pressure. This is in strong contrast to the behaviour observed in the mountain coal fields with their very competent and massive rock beds.

While a considerable amount of information has also been obtained, with the use of dynamometers, on the loading of mine supports in these western mines, the data would require too lengthy a discussion for this report. The same limitation applies to the surface subsidence studies and roof bolting investigations conducted by the Mines Branch.

Observations in Solid Strata

As indicated earlier, it is considered that further significant advances in the understanding of the mechanics of ground failure depend on the employment of all available knowledge related to stress analysis, and to the degree that this knowledge can be utilized when dealing with such heterogeneous and aeolotropic materials as mine rocks that exhibit both elastic and plastic deformations under stress. In such studies, due consideration must be paid to the phenomena of time strain and to the influence of constraint upon the behaviour of rocks under stress. In this direction of continuing exploration into the largely unknown field of ground mechanics, encouragement is afforded by the very substantial progress made during the last quarter-century in the allied field of soil mechanics. As an outgrowth of current studies at the Mines Branch, and in the hope of gathering basic data related to stress conditions remote from the open workings of a mine, a beginning has been made in developing apparatus for observing stress changes "within the solid". To date, fairly extensive field tests have been conducted with a borehole load cell incorporating electric resistance strain gauges, an electrical resistivity device, and sonic apparatus. The load cell has been tested in coal and metal mines but the resistivity device was specifically designed for coal mines subject to outbursts of gas and coal. The sonic equipment has been employed in the iron ore mines at Wabana, Newfoundland.

Borehole Load Cells

With regard to borehole load cells in general, it was initially considered that preliminary information might be obtained by employing a simple hydraulic type as an exploring device pending the development of a more precise unit. Consequently, a number of hydraulic cells, molded from rubber, were installed inside boreholes drilled fifty feet deep into large coal blocks in the Coleman mines. Observations were continued for more than a year and until the pillar extraction line had reached the cells. Figure 12 is a graph of the pressures observed with one cell as the extraction line progressed more than 1100 feet to meet it. Although it would be inadvisable to interpret much from this record, it does indicate that the mining-induced stresses were detectable inside large coal pillars at appreciable distances ahead of an extraction line and that pressure on the embedded cell kept increasing as the extraction approached. Although this type of cell gives some indication of stress changes taking place within solid material, it has a number of disadvantages, the principal one being its inability to denote direction of stress within the enclosing medium. It is thus impossible to ascertain what stress phenomena are being observed and the readings could give rise to anomalous conclusions. Another disadvantage is its insensitivity to small borehole deformations, such as occur in competent rocks and minerals. As a borehole unit this simple type of hydraulic cell has a limited use in highly deformable materials such as the "mountain" coals of Western Canada and, possibly also, the soft clays of the "prairie" mines.

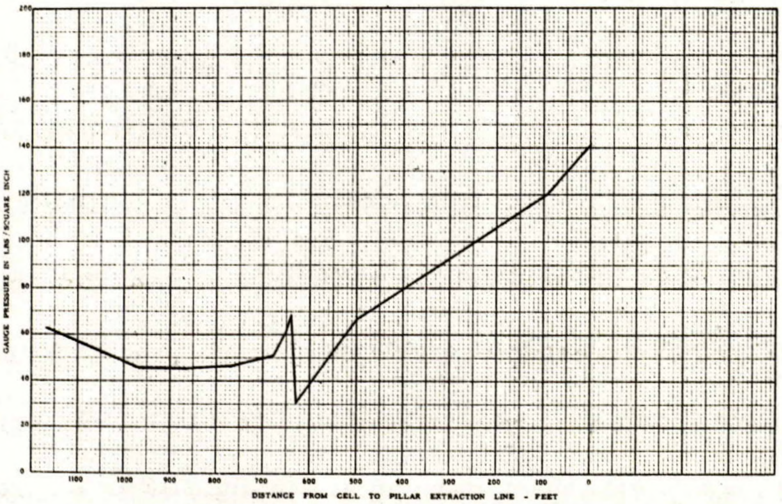


Fig. 12. - Record obtained with a hydraulic rubber cell.

When the development of more precise types of borehole load cells was initiated at the Mines Branch it was considered that, while the assessment of stress in a single direction would afford a welcome addition to current knowledge, an effort should be made to attempt observations of the two principal stresses and their orientation. It was also appreciated that, in view of their intended employment in underground mines, such units must retain a satisfactory degree of accuracy and reliability over extended periods of time.

Initial attempts along these lines have been directed toward the development of a strain-gauge load cell, incorporating electric resistance strain gauges bonded to a strain sensitive member of known elastic constants. Such efforts have been reported in earlier papers (13) (14) (15) and only the essentials will be repeated here. The main component is a metallic load-bearing disc which, as designed for anticipated ground stress conditions at Springhill, is 2 inches in diameter and 3/16 inches thick, with a rectangular rosette electric resistance strain gauge bonded to each face. This type of gauge has three separate strain measuring elements, mounted in horizontal, vertical and forty-five-degree positions. Originally, the load-bearing disc was made of magnesium in order to take advantage of its low modulus of elasticity and thus obtain a high strain sensitivity to change in applied stress. Later, because of a possible sparking hazard associated with light alloys, the disc was made of steel but sufficiently decreased in section to retain a desirable degree of sensitivity to changes in stress. In the earlier magnesium cell, the load-bearing disc was mounted inside a thin-walled cylindrical steel shell but the later steel models were machined out of solid stock,thus making the disc an integral part of the outer shell. The cylindrical shell is fitted with tightly fitted end caps to help exclude moisture and dust. Other essential components are, a dummy gauge for compensation of apparent strain due to temperature changes and a levelling device for proper orientation of the rosette grid at the back of bore holes. Ancillary apparatus includes special inserting rods and a plunger device for depositing the desired quantity of grouting material at the back of the borehole(and into which the cell is subsequently embedded). Readings may be taken with any satisfactory strain-gauge bridge but, because of the safety requirements in coal mines, a specially designed low current bridge, battery operated, was constructed at the Mines Branch. Laboratory tests with this type of cell embedded in blocks of concrete and coal gave a repeatable relationship between load applied to the unconfined blocks and the observed stress changes in the disc. It will be readily appreciated, however, that the observed stress in such an embedded body does not represent the magnitude of stress in the enclosing medium, but laboratory tests give some idea as to the ratio between the two under specific conditions. As an illustration of what has been observed at depth in the longwall workings at Springhill, Figure 13 is the record of a cell over a 3 to 4 month period as the wall face progressed from 380 to approximately 200 feet from the cell. This unit was installed in the coal 50 feet above the lower roadway in Figure 1. As may be noted,

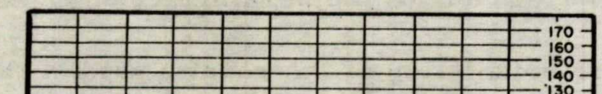


Fig. 13. - Record obtained with strain-gauge cell.

the increase in stress in the cell is fairly gradual but proceeds in a series of jogs, which is quite typical of what has also been observed in the open workings during current and earlier (16) investigations. The principal stress is dilational and the shear stress is of small magnitude.

The shortcomings of the strain-gauge load cell are, to some extent, by-products of the rugged underground conditions under which it must be applied and of the problem of making strain gauges stable over extended periods. Damage to cells has been experienced, ranging from crushing of the cell bodies and straining of the load-bearing disc beyond the elastic limit, under what must be abnormally high stresses in the coal, to rupture of the electric cable by great extrusions of the coal seam toward the mine openings as the extraction face nears the installed cells. Another serious difficulty is encountered when drilling the required boreholes in highly stressed areas of the seam. In such areas, holes have readily been drilled into the coal for distances of 15 to 20 feet, but immediately beyond such distances the holes collapse promptly. It is also considered that moisture plays a significant role in the breakdown of cells, in spite of very careful waterproofing precautions. It is appreciated, of course, that this type of unit is essentially a strain-sensitive strut which indicates the deformation of the borehole. As such, its behaviour is doubtful when the disc does not lie in the plane of applied stress. Despite such qualifying remarks it is considered that this type of borehole cell can provide useful data in underground observations (14).

From theoretical considerations it can be shown that, if the load cell has a modulus of elasticity at least 3 to 4 times greater than the surrounding media, it is thenpossible to relate the changes of stress in the cell to those in the media. This method has the advantage of not requiring an accurate knowledge of the modulus of the surrounding media (17). On the basis of this theory the Mines Branch is now also directing efforts towards development of an inclusion type of cell. Ideally, this cell should take the form of a solid cylindrical metal inclusion but, since it is necessary to measure the stresses inside this body, a compromise in the design is necessary. This requirement, and also that of observing stress in an arbitrary direction, is met by splitting the metal cylinder along the axis and sandwiching between these two halves a thin metal flat-jack, filled with oil. The stresses exerted on this oil are observed with a diaphragm-type recorder, using electrical resistance strain gauges. Work along much the same lines is being conducted in the United Kingdom. In this method it is essential to use the minimum volume of oil in order to maintain the effective elasticity of the load cell at a sufficiently high level. It may be possible to locate the recorder in the roadway so that if the electrical strain gauge fails it can be replaced and there is no loss of readings.

In conjunction with the development of this cell, another type of cell is being developed to measure the magnitude and direction of two principal stresses. For this, it is proposed to use a thick-walled steel tube and to measure the stresses in this tube by utilizing an air gauging technique. This particular technique has many interesting possibilities for use, particularly in coal mines where the use of electrical apparatus is restricted.

With both of these cells it is desirable, during installation, to pre-stress them as nearly as possible to the stress conditions of the enclosing media. An installation method for attaining the required stress level is being developed.

Electrical Resistivity Apparatus

The outburst phenomena in the mines at Canmore, Alberta, appears to be an interaction of stress change and the gas associated with the coal. Investigations are being directed toward clarifying the nature of this interaction by field methods, supplemented by laboratory studies referred to on page 6 of this report. The field investigations are concerned with studying the character of the coal and any changes that can be detected in connection with the outburst incidence. Initial investigations in this direction have employed apparatus to measure the variation in the electrical resistivity of the coal seam along boreholes drilled ahead of development faces. This method was regarded as an exploratory effort to determine whether a relationship could be established between the observed resistivity pattern of the coal and the occurrence of outbursts. Marked variations were found in the resistivity of the Canmore coal, with values ranging from 10^5 to 10^{11} ohm-cm over short distances along the borehole (6). The reason for such wide fluctuations have not yet been determined. Correlation of resistivity patterns with outburst phenomena has not been satisfactory, although a few results did suggest outbursts were associated with high resistivity values or abrupt changes in values.

Laboratory studies are being conducted at the Mines Branch into factors influencing the resistivity of coals. A report on this work is being prepared.

Sonic Apparatus

In the studies currently being made in the iron ore mines of Wabana, Newfoundland, it is of value to know the depth to which fissuring has weakened the pillars left to support the superincumbent strata and thereby gain insight into the continuing ability of such pillars as mine supports. This information is particularly valuable when investigating pillars of various dimensions, shapes and ages or when existing pillars are being reduced in size. For such observations, a method developed by the Hydro-Electric Power Commission of Ontario for measuring depth of cracks in massive concrete structures has been adapted for use in mines. As adapted, this method entails the measurement of sound velocity through ore and the enclosing rock strata. If voids are encountered, the sound wave must travel around them, thereby travelling a longer distance and giving rise to a lower apparent velocity of the wave.

In actual practice, two parallel holes, ten feet apart, are drilled horizontally into the ore pillars and a suitably designed transmitter and receiver traverse these holes. The holes are 2-1/4 inches in diameter and 10 feet long. The transmitter is energized to propagate a continuous wave which is picked up by the receiver and relayed back to a recording apparatus. This recording apparatus is a split-beam oscilloscope. On the upper trace of the oscilloscope is shown a positive blip, which indicates the time the wave left the transmitter, and a larger negative blip, which is the strobe marker. On the lower trace is shown the input from the receiver. A simple operation of moving the strobe marker, by means of a calibrated dial, from the blip indicating the initiation of the wave to the first appearance on the screen of the received wave, will allow the transit time to be read directly. In addition to these observations in ore pillars, a beginning has been made to observe the development of voids in the roof and floor strata.

Although it is theoretically possible to relate the velocity of a sound wave to changes in stress in a medium, no attempt has been made to measure stress in the ore pillars by the sonic method. It is considered that the amount of fracturing usually present in underground mine structures would disguise any change in transit time due to variation in stress.

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