ADSORPTION OF GASES AND WATER BY COAL:
THE CHANGE OF LINEAR DIMENSIONS DUE TO
ADSorption, AND THE CONDITION OF
ADSORBED GAS IN COAL SEAMS.

THESIS
submitted to the University of Edinburgh
for the
DEGREE OF Ph. D
by
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EDINBURGH
1934
and myself, read before the Royal Society of Edinburgh; and another portion dealing with the emission of gas at Cardowan Colliery, has been summarised in a recent paper (Trans. Inst. Min. Engrs., vol. lxxxvii, 1934, p. 190) read before the Institute of Mining Engineers. For the sake of convenience and uniformity, they are included for submission in the present form.

My grateful thanks for his invaluable aid are due to Professor H. Briggs, under whose direction and supervision the work herein described was carried out. The cost of the apparatus and materials was defrayed by grants from the Tait Fund for Mining Research, a fund administered by the Governors of the Heriot-Watt College.

Grateful acknowledgement is due to Mr. J. M. Williamson, Manager and Agent of Cardowan Colliery for affording every facility for pressure-measurement tests in the Meiklehill Main coal seam.

To the many others who so willingly helped me in carrying out these tests, I offer my very sincere thanks.

R. P. Sinha

Edinburgh,

November, 1934
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first investigator to obtain definite quantitative
evidence to show the immense capacity of dry coal to
adsorb gas.

The investigation carried out by Prof. Briggs,*
on adsorption of gases by coal under high pressure,
was of special interest in throwing important light
on the subject of the occurrence of sudden outbursts
in coal mines.

Although ample work has been done on coal as
to its adsorptive capacity, the elongation and
shrinkage of coal, respectively on sorption and dis-
charge of gas has, till now, been an unexplored
field of work, yielding wide ground for research.

The writer has not been able to find a book or an
article having any direct bearing on this subject,
which apart from being of great academic interest
is also of some practical significance.

That coal may shrink when gas is discharged,
was first suggested, by Prof. Briggs, and it is
interesting to note the following remarks made by
him**:

"We are all familiar with the fact that a coal-
face is full of small cracks, and it is natural
to attribute them to pressure or relief of
pressure; but it appears probable that those
cracks are due partly to shrinkage resulting
from gas-emission. These shrinkage cracks
must extend a great distance into the coal.
Being open channels, they facilitate the
drainage of gas, and by relieving the gas-
pressure they become the means of their own
extension. Once an opening is made in a
seam, there would appear to be no limit to
their/

** 'Trans. Inst. Min. Engrs., vol. lxxii., p. 323 (1926-
1927).
their development unless the seam is cut off by a fault or other disturbance."

The present work, therefore, is a result of the above suggestion and deals chiefly with the shrinkage of coal caused by the discharge of firedamp and the corresponding expansion due to adsorption of that gas. The shrinkage of coal on dissorption leads to the formation of shrinkage cracks and crevices; and as the emission of gas into mine-workings is governed by its pressure and by the permeability of the coal, a study of the increase in permeability due to shrinkage is important as a practical problem, and deserves attention.

Latterly, the enquiry was particularly directed towards arriving at an explanation of unusual discharges of gas, such as those preceding the explosions at Cardowan and Grassmore Collieries in 1932 and 1933 respectively.

This work also includes a section on the results of experiments to ascertain the pressure of firedamp in the Meiklehill Main coal seam at Cardowan Colliery by means of long boreholes drilled in the seam.
The barrel T, is a stout brass tube of 1'5 in. outside diam., and one eighth inch thick. Its two ends were threaded to receive two hexagonal screwed caps, E and F, Fig. 1. The end E, had a nut braised to it centrally, with a hole through it, to receive a calibrated pressure gauge A. The other end F, had a screwed gland L, fitted to it, which was one eighth inch bigger in diam. than the gauge glass G. A small cylindrical brass cap P, also one eighth inch bigger in diam. was made to fit the other end of the gauge glass. Two rubber rings as shown at, r₁ and r₂ provided the means for making this end of the apparatus gas tight. By means of the screw W, the gauge glass was held in position by forcing the cap P, horizontally and centrally, thus squeezing the rubber rings at the glass ends, to hold a pressure up to 400 lb. per sq. in.

A "Y" piece of iron B, fitted with the screw W, was firmly held in position by two adjustable lugs l₁ and l₂ as shown in plan, Fig. 1. Gas was introduced in to the apparatus through the inlet I, which was connected by a copper tube and nipple connection to a gas cylinder. A second cock D, allowed the pressure to be released, and facilitated the preliminary operation of flushing the apparatus to expel air. The whole apparatus and the reading Microscope M, were rigidly fixed to the table by means of suitable clamps.
Fig. 1.- Apparatus used for the measurement of expansion and contraction of coal.
The prism of coal $S$, held between the end $E$, and piston $K$, was maintained under longitudinal pressure by means of the spring $s$. Measurements of elongation and shrinkage of the coal were taken by the microscope $M$, sighted through the gauge tube $G$, on a very fine mark at $m$. After considerable trial, it was found that a piece of brass turned on a lathe by a very sharp cutting tool showed under the microscope, several sharp bright lines, crossing a dull yellow background.

A well defined mark is very essential for measuring small movements such as $0.005$ or $0.01$ m.m., because the error introduced in sighting the web of the microscope on to a thick and undefined line, would considerably decrease the value of such measurement.

Great difficulties were experienced at the gauge glass end of the apparatus, because unless the pressure applied by the screw $W$, was truly central, it would tilt and finally burst under pressure. Many a time, after a test had been in progress for a few days, it would be foiled one day by the gauge tube suddenly bursting into pieces. This necessitated the apparatus being detached from the bench every time on a burst, for test by immersion in water after fitting in a new gauge tube and washers.

The fibre washer, at the end $E$, had a tendency/
tendency to curl up inside against the coal prism S, thus causing it to be moved forward and a false elongation to be recorded. This was eliminated by a device shown in Fig. 2. A circular flat headed stud D, with a hole H, in the centre was screwed to the hexagonal cap E, from inside. The prism of coal S, was thus held between two metal surfaces, as shown in Fig. 1.

Blank experiments with dummy prisms of brass and iron were carried out to find out if there was any correction to be applied to the readings in consequence of:

(a) The mechanical stress imposed on the apparatus itself by raising the internal pressure to 300 lb. per sq. in.

(b) The slight variation in room-temperature during the tests.

The blank tests showed that no such correction was needed.

To test the accuracy of taking linear measurements, of exceedingly small movements, by the cathetometer, a series of 50 readings from both directions, i.e., left to right and right to left, were taken between two well defined marks. The average uncertainty of reading, affecting a single measurement (expansion or contraction) was thus ascertained to be ±0.0021 m.m.

As/
Fig. 2.- Device to eliminate error caused by the curling up of the fibre washer.

Fig. 3.- Method adopted to provide fixed marks inside the gauge glass.
As the time required for each test in some cases, extended as far as 200 - 300 hours or more, it was observed, that, even the faintest deposit of a microscopic film of dust ordinarily suspended in the air, on the fine screw threads of the micrometer wheel, affected the readings, despite of every care being taken to cover the measuring instrument.

The error was eliminated by a device fitted inside the gauge tube, as shown by the cross-section of this part of the apparatus, in Fig. 5. This was achieved by fixing a hollow brass tube t, in the neck of the cap F, which also allowed the free movement of a cylindrical piece of brass P, a continuation of the piston rod R, Fig. 1. About one quarter to half an inch of this hollow tube projected inside the gauge tube G, into the field of view of the reading microscope. The external diameter of P, whose end butted against the spring s, was one thirty-second to one sixty-fourth inch less than the internal diameter of the hollow tube t; so that when the microscope was focused on to the measuring mark, some well defined sharp lines were also observed on the fixed hollow tube, which had been previously turned on a lathe for this purpose. It will be observed that marks were obtained on the hollow tube t, which remained stationary during the test, no matter how long.
Four well defined sharp lines were thus selected such as, a, b, c, and d Fig. 3. Of these, a and b were the moving marks, because they responded by moving forwards or backwards due to elongation or shrinkage of the prism of coal, - the movement being imparted by means of the piston rod R. By suitable focussing and adjustments, all these four marks were made sharp enough for measuring the distances between them accurately, before the beginning of a test. The increase or decrease in distance, between a pair of the moving and fixed lines, gave the true amount of elongation or shrinkage respectively. Each time a measurement was taken, all these four marks were read. By deduction, the fixed distances between a and b on the moving brass, and between c and d on the fixed hollow tube, provided an excellent check on the accuracy of reading the distance between a and d or b and c. This distance was variable, as it increased or decreased according to the elongation or shrinkage of coal respectively. This method also eliminated the effect of any accidental error occurring from unsuspected movements of the measuring instrument or the apparatus itself. Although the time taken for a set of readings was increased four-fold, the accuracy and the safeguard against error attained, was ample justification for the method adopted. No correction for refraction had to be applied to these readings.
The marks as mentioned above, had a tendency to grow a little duller after a few tests. So, a device was introduced by which the cylindrical brass piece P and the hollow tube t, could be withdrawn by way of end E, re-brightened by turning on the lathe or substituting new ones, and put back into the apparatus again by the same end. This was to save dismantling the whole apparatus and interfering with the gauge glass end, which as explained before, was very difficult to make absolutely gas tight, unless with several attempts to do so at the expense of too much time. It was because of this, that when once the apparatus was fixed to the bench after immersion tests in water and other adjustments, every possible means was adopted to avoid the taking down of any permanently fixed part. As shown in Fig. 3, the small stud D, was soldered to the spring s. A small central projection from D, fitted into a similar central recess bored in the cylindrical piece P. By screwing in a threaded thin rod into a hole provided for this purpose in piston K, Fig. 1, from end E, the cylindrical brass piece P, could be taken out of the apparatus and the marks brightened. A small hook was used in pulling out the hollow tube t, for the same purpose.

Another improvement was introduced by making
the piston rod of adjustable length. Thus, prisms of different lengths could be used with great ease and facility. This also facilitated the maintaining of a standard longitudinal pressure by the spring s, on the coal prism.
atleast a year.

Highly developed cleavage planes and cleats in some coal, make it extremely difficult, if not impossible, to cut out suitable prisms of coal from it. It is often worthwhile spending a little time to examine each block very carefully on all sides to find the most suitable plane from which to cut. Skill in cutting, automatically, comes to one when its technique is finally acquired. One of the best methods of cutting a prism from an incoherent and brittle block of coal, is by means of a hack-saw, using blades about one-half inch wide and 12 inches long with 25 teeth to the inch. The cutting effect on the coal is produced during the forward stroke of the blade only. Special care should be taken to avoid undue strain on the block while cutting. The sides and more specially the ends of the prisms should be finally polished to obtain a smooth and even surface.

A specimen from freshly hewn coal is comparatively easier to cut than from older lumps wrought a while before. A clarain specimen is rather more difficult to cut than a durain, cannel or anthracite specimen. The last three, were compact and free from cracks, whereas, the clarains were intersected by cleavage planes.
In these tests, the term "clarain," is used for term indicating a finely-laminated intergrowth of bright and dull coal. The bright bands were mostly vitrain.

The prepared specimens were kept in test tubes of suitable size and corked when not in use. Extra pieces of coal of the same kind as the prism and from the same lump from which the prism was cut, were also corked with each specimen, for purpose of analysis when necessary.
PRELIMINARY TESTS BEFORE CONDUCTING FINAL EXPERIMENT

The prism of coal was inserted into the apparatus and the cap E, Fig. 1, was gently screwed in and out a few times, while the movement of the reading marks was observed by the microscope. This was done to ensure,

1. That the spring s, Fig. 1, was in perfect condition and maintained the prism of coal under correct longitudinal pressure.

2. That the cylindrical piece of brass P moved freely in the hollow tube t, Fig. 3.

3. That the marks c and d on tube t, as explained before, remained stationary as fixed data lines, while the marks a and b moved backwards and forwards inside the gauge glass.

The above three conditions being satisfied, the cap E, was finally screwed in tight. A series of 5 to 10 readings of the four marks as mentioned above, were then taken and the distances between a - b, c -d, and b -c, or a- d, were noted in m.m., to three places of decimals.

The/
The apparatus was flushed with gas (fire-damp or carbon dioxide, whichever was used for the experiment) to expel air. The pressure was then raised to the amount desired and it was maintained until elongation of the prism of coal due to gas adsorption had apparently ceased.

Measurements of linear elongation were taken by a number of readings as explained before. The pressure was then released to the atmosphere and the ensuing contraction ascertained in like manner.
THE GASES USED IN THE EXPERIMENT

The firedamp used in these tests was obtained from Messrs Insoles Ltd., proprietor of Cymmer colliery, Porth, Glamorganshire. The gas which comes out below the base of Pennent Series and practically on top of the Coal Measure, is led to the surface through a two inch pipe and has been a continuous feeder since 1879 at the rate of 800 cu. ft. of free gas per hour. The gas is conveyed to high pressure compressures and compressed to 700 - 800 lb. per sq. in., in cylinders for sale.

By means of a fine adjustment needle valve fitted to such a cylinder, the flow of gas to the apparatus was controlled with great ease and facility.

An average analysis of Cymmer firedamp as published in the Sixth Report of Explosions in Mines Committee,* is shown in Table I.

It may, however, be noted here that a recent (1933) analysis** showed its composition to be: methane, 97.5%; carbon dioxide, 0.74 - 0.76%.


** The analysis was made at the Laboratory of the Safety in Mines Research Board, Sheffield, from samples of gas sent by us.
The carbon dioxide with which some of the experiments were conducted was discharged through a thin copper tube connexion from "J" Sparklet bulbs.* A small steel bulb containing liquid carbon dioxide was set free by perforating the metal seal in its throat by a hand wheel containing a puncturing needle, which also functioned as a valve regulating the rate of discharge.

Table 1. - Average analysis of Gwynne firedamp.

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<th>Composition</th>
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<tbody>
<tr>
<td>Carbon dioxide</td>
<td>0.9</td>
</tr>
<tr>
<td>Ethylene hydrocarbons</td>
<td>0.2</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>0.2</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>nil</td>
</tr>
<tr>
<td>Methane</td>
<td>96.4</td>
</tr>
<tr>
<td>Ethane</td>
<td>nil</td>
</tr>
<tr>
<td>Nitrogen (by difference)</td>
<td>2.3</td>
</tr>
</tbody>
</table>

CHAPTER VI

EXPANSION OF CHARCOAL ON CH₄ ADSORPTION.
EXPANSION OF CHARCOAL ON CH₄ ADSORPTION

It was considered essential before conducting experiments on coal prisms, to test the efficient working of the apparatus itself. For this purpose a prism of ordinary wood charcoal, (parallel to the grain) 81 mm. long and 19 mm. square in cross-section, was put into the apparatus and CH₄, at a pressure of 200 lb. per sq. in., was introduced. The reason for selecting a piece of charcoal for this test was because it has now been definitely proved that charcoal expands on gas adsorption.

The result is shown by the time-elongation curve, in Fig. 4. The quick response of charcoal to methane is evident by the almost vertical line of the graph from the origin. However, the maximum elongation of 0.216% at apparent equilibrium seems to be very low compared to the values with carbon dioxide, obtained by Meehan and Bangham,* at atmospheric pressure.

The result of a second test on the same specimen at different pressures from 0 - 200 lb. per sq. in., is shown by the pressure-elongation curve, Fig. 5.

Fig. 4.- Time-elongation curve for wood charcoal on methane adsorption.

Fig. 5.- Pressure-elongation curve for wood charcoal.
Fig. 5. As the time interval in the latter test was only 20 minutes between each pressure, the elongation of 0.198 % at 200 lb. per sq. in. as compared to 0.216 % in the former test is comprehensible.

The path of the shrinkage curve as shown by the dotted line in Fig. 5, presents some evidence of hysteresis loop.

These tests, however, in the present work were carried out mainly to demonstrate the working of the apparatus to register elongation and shrinkage efficiently. As tests on the elongation of charcoal on methane adsorption has not been done before, it was considered worthwhile to put this result on record.
### Table 2: Characters and source of the specimens.

<table>
<thead>
<tr>
<th>Description</th>
<th>Source</th>
<th>Volatile matter per. cent</th>
<th>Ash per cent.</th>
<th>Moisture (expelled at 105°C) Per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clarain I R</td>
<td>Humph Coal, Lanarkshire.</td>
<td>33.3</td>
<td>1.6</td>
<td>8.5</td>
</tr>
<tr>
<td>Clarain I P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarain II P</td>
<td>Great Seam, Easthouses Colliery, Midlothian</td>
<td>33.8</td>
<td>3.3</td>
<td>9.7</td>
</tr>
<tr>
<td>Clarain III P</td>
<td>Niddrie &amp; Benhar Coal Co., Midlothian (seam uncertain).</td>
<td>42.5</td>
<td>1.0</td>
<td>7.4</td>
</tr>
<tr>
<td>Anthracite I P</td>
<td>Stanlyyd Vein, Blaina Colliery, Carmarthenshire.</td>
<td>6.1</td>
<td>1.5</td>
<td>3.2</td>
</tr>
<tr>
<td>Anthracite I (a) P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthracite II P</td>
<td>Polmaise Colliery, Stirlingshire.</td>
<td>6.5</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Durain I P</td>
<td>Peacock Splint Loanhead, Midlothian.</td>
<td>44.2</td>
<td>2.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Durain II P</td>
<td>Great Seam, Easthouses Colliery, Midlothian.</td>
<td>34.2</td>
<td>4.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Cannel, P</td>
<td>Kittlepurse Seam Roslin Colliery, Midlothian.</td>
<td>29.2</td>
<td>41.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Peacock Rough, P</td>
<td>Roslin Colliery, Midlothian.</td>
<td>34.1</td>
<td>6.6</td>
<td>6.6</td>
</tr>
<tr>
<td>Peacock Splint, P</td>
<td></td>
<td>34.4</td>
<td>5.3</td>
<td>6.9</td>
</tr>
<tr>
<td>Smithy Coal, P</td>
<td>Bridgeness Colliery.</td>
<td>20.3</td>
<td>1.4</td>
<td>0.9</td>
</tr>
</tbody>
</table>
both firedamp and carbon dioxide were studied as shown together in Fig. 6.

Clarain

A prism of Clarain IR responded quickly to firedamp, at a pressure of 200 lb. per sq. in. The maximum percentage elongation amounting to 0.0725, was reached after 18 minutes from the start, and although the specimen was left under the same gas pressure for another 15 hours, no further elongation was apparently observed to have taken place.

The same prism on a second test at different pressures from 0-200 lb. per sq. in., showed a maximum elongation of 0.0945 per cent. A time interval of 25 minutes was allowed between each subsequent reading; this interval being considered sufficient as shown by the previous test.

On a third test, with carbon dioxide at 200 lb. per sq. in., the elongation recorded after 15 minutes was 0.259 per cent., nearly three times as great as with firedamp. When the same specimen was experimented upon a fourth time with firedamp, at 300 lb. per sq. in., elongation increased to 0.303 per cent., the equilibrium having been reached 24 hours from the beginning, as shown in Fig. 6.

Another prism, Clarain IR, from the same lump of coal as Clarain IR, gave a maximum elongation of 0.129 per cent. only, after 23.5 hours. It will be/
Fig. 6.- Time-movement Chart for different coals, on methane adsorption at 300 lb. per sq. in.
be observed that in both the above examples, the prisms ceased to show further reactions after an elapse of approximately the same time i.e., 24 hours. But, when the pressure was released to the atmosphere, Clarain IR did not show any sign of shrinkage movement till after an elapse of 10 minutes, whereas, Clarain IP, began to shrink almost at once on release of pressure. The shrinkage movements of these two specimens as depicted in Fig. 6, also bring out a marked difference in their respective residual elongations. The last two experiments were brought to an end after approximately 140 hours when shrinkage movements had virtually ceased, although Clarain IR and Clarain IP were, at that time, 0.139 and 0.0064 per cent. respectively, greater than their original lengths. The results of tests on Clarain II P and III P are also shown in Fig. 6.

It will be observed that of all the clarain specimens, Clarain II P, showed the least elongation, i.e., 0.07 per cent., on gas adsorption. This was due to the high moisture percentage in that specimen as will be seen by referring to Table 2. The effect of moisture in coal on gas adsorption has been dealt with in a separate section. The behaviour of Clarain II and III P were very much similar to Clarain I P, except that in the first two examples the amount of residual elongations, (i.e., 0.019 and 0.026 per cent. respectively) were considerably higher, compared with 0.0064/
The results of tests on Anthracite I P, show a rather peculiar behaviour of this coal to firedamp. The prism showed no reaction whatsoever, when firedamp at a pressure of 120 lb. per sq. in. was introduced into the apparatus and maintained for fully 24 hours. Later, the pressure was increased to 200 lb. per sq. in., and even then, after 12 hours, no sign of elongation was observed.

Afterwards, the same prism, when tested with carbon dioxide at a pressure of 300 lb. per sq. in., showed the first sign of elongation after an interval of nearly 4 hours. The rate of elongation appreciably decreased after 46 hours, having attained an elongation of 0.477 per cent. at that time. Further movements virtually ceased after 93 hours, when a maximum elongation of 0.577 per cent. had been reached. When the gas was released to the atmosphere after 117.5 hours, the prism began to shrink at a rapid rate till after an elapse of 4 hours, the rate of shrinkage was appreciably diminished as shown in Fig. 6. The prism, at the end of the experiment, which was brought to a close after 190 hours had expired, was at that time 0.14 per cent. greater than its original length.

Seventeen/
after 6.5 hours was recorded. No further reaction was observed in the next 100 hours. It is to be noted that an analysis of this coal now gave its moisture content as 2.4 per cent., compared with 3.2 per cent. previously, showing the prism to be in a drier condition than before.

Upon a third test with carbon dioxide at a pressure of 300 lb. per sq. in., the prism responded very quickly, showing an elongation of 0.538 per cent. at the end of 80 hours. Afterwards, the specimen was once more tried with firedamp, when the maximum elongation recorded was 0.18 per cent. as shown in Fig. 7.

The behaviour of a prism of Scotch Anthracite i.e. Anthracite II P, as shown in Fig. 6, was not quite the same as that of Anthracite I P. It responded to firedamp on the very first trial, although the response was rather slow. Nevertheless, the specimen, at the end of 90 hours showed an elongation of 0.162 per cent.

**Durain**

Of all the coals tested, Durain I P showed the most rapid reaction, whether on carbon dioxide or on firedamp, as shown in Fig. 6. Almost 90 per cent. of the elongation took place within an hour of/
Fig. 7.- Time-movement Chart for Stanllyd Anthracite and other coals, on methane adsorption at 500 lb. per sq. in.
of the gas being admitted, the equilibrium having been reached after 4 hours, when an elongation of 0.156 per cent. was recorded. The shrinkage upon release of pressure was also very rapid. It will be observed that the curve showing the reaction with carbon dioxide is remarkably similar in shape to that obtained with firedamp, except that with the former, the movements are approximately three times as great.

Durain II P, was rather reluctant in taking up gas, consequently the movements were slow and small, as if composed of a series of periods of action and rest, alternately.

Cannel and some other specimens.

Although a prism of Kittlepurse Cannel, responded to firedamp in the beginning, showing an elongation of 0.048 per cent., there was no further movement till 21 hours after the first response. This specimen recorded the least elongation of all the coals tested, the amount being 0.061 per cent. only, after 25 hours had elapsed, as shown in Fig. 6.

The results of tests on Peacock Rough and Peacock Splint Coal from Roslin Colliery, Midlothian, are shown in Fig. 7. Particular interest attaches/
attaches to Smithy Coal from Bridgeness Colliery, having a remarkably small percentage of moisture i.e. 0.9 per cent. Yet the maximum elongation recorded was only 0.119 per cent, after 100 hours, shrinkage taking place at a very slow rate, equilibrium having been reached after 270.5 hours. But even then, the specimen was 0.044 per cent longer than its original length.

Discussion of results.

That elongation is a function both of time and pressure is quite evident from these results. Another point of interest brought about is that the elongation on gas adsorption does not appear to be a continuous phenomenon from the time the gas is admitted. This is evident by the steps in the time-elongation curves of some coals. It appears that at first the most easily accessible surfaces on the adsorbent are invaded and occupied by the gas molecules and a certain amount of elongation takes place.* A check in further invasion and occupation, results in a period of no movement, depicted by the short/

* The word 'invasion' has not been used in its proper sense, because the gas molecules are drawn to the surface. It is meant to express the two-dimensional bombardment by the anchored gas molecules at the sharp re-entrant angles on the surface.
short horizontal step in the curve. When a second barrier is broken, further occupation takes place as revealed by further elongation. This process of invasion and occupation continues till all the available internal surfaces are occupied by the gas molecules, revealing an apparent state of equilibrium. The rapid rate of elongation in some coal, such as Durain, shows that no great resistance is offered against the gas getting in, which means that the capillaries and interstices are more easily accessible. A sudden high rate of elongation after a step also shows that some such process of attack is going on inside the coal, as is evident in the case of Anthracite I. However, the phenomenon seems to be so varied that it is highly probable different mechanisms are operative in different cases, depending on the nature of the capillaries and the micro-structures of different coals.

The case of Stanllyd Anthracite is most interesting. It has been shown how quickly this coal responds to carbon dioxide, whereas, to firedamp it is utterly indifferent at first. But once the coal has taken in carbon dioxide and elongated, it then becomes an easy matter for firedamp to get in.

As a tentative hypothesis it is suggested here that the carbon dioxide molecule being of a linear/
between time and the percentage elongation on gas adsorption at 300 lb. per sq. in., at different moisture percentages, are shown by graphs in Figs. 9 - 14, and summarised in Table 3.

Table 3.- Percentage elongations at different moisture percentages.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Moisture per cent.</th>
<th>Elongation per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test No.1</td>
<td>Test No.2</td>
</tr>
<tr>
<td>Clarain II P</td>
<td>9.7</td>
<td>5.93</td>
</tr>
<tr>
<td>Durain II P</td>
<td>7.3</td>
<td>4.8</td>
</tr>
<tr>
<td>Clarain I P</td>
<td>8.5</td>
<td>4.9</td>
</tr>
<tr>
<td>Clarain III P</td>
<td>8/87.4</td>
<td>5.2</td>
</tr>
<tr>
<td>Durain I P</td>
<td>3.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Anthracite II P</td>
<td>3.5</td>
<td>2.1</td>
</tr>
</tbody>
</table>

It will be observed that on subsequent tests, the two specimens, Durain and Clarain II P, both belonging to the same coal seam showed without any doubt, an appreciable increase in linear elongation, consequent upon their loss of free moisture, as shown in Figs. 9 and 10 respectively.

The elongation for Clarain II P increased from 0.07 per cent., at a moisture content of 9.7 per cent.
Fig. 9.- Durain II P, Elongation on methane adsorption at different moisture content.

Fig. 10.- Clarain II P, Elongation on methane adsorption at different moisture content.
to 0.172 on a second test and to 0.274 on the third test, at their corresponding moisture percentages of 5.93 and 2.5 respectively. A somewhat similar result was obtained with Durain II P, whose recorded elongations were 0.0555, 0.1585, 0.208 per cent. respectively at their moisture contents of 7.3, 4.8 and 2.1 per cent.

Clarain I P, Fig. 11, showed very little increase in elongation on a second test inspite of a drop in moisture content from 8.5 to 4.9 per cent. Nevertheless, on a third test when the moisture had decreased to 5.5 per cent., an appreciable increase in elongation was recorded.

But with the other specimens, viz., Durain I P, Clarain III P, and Anthracite II P, a different state of affairs was revealed by the tests, in that, although the elongation on a second test increased with a corresponding decrease in moisture content, further loss of moisture in the specimens had a deleterious effect instead, as shown in Figs. 12, 13 and 14 respectively.

It would appear therefore, that there is also an optimum value for moisture in coals, at which the adsorption with its concomitant elongation, reaches a maximum value, after which further loss of moisture is deleterious. This view should be regarded more as a suggestion than a conclusion because/
Fig. 11.- Clarain I P, Elongation on methane adsorption at different moisture content.

Fig. 12.- Durain I P, Elongation on methane adsorption at different moisture content.
Fig. 13.- Clarain III P, Elongation on methane adsorption at different moisture content.

Fig. 14.- Anthracite II P, Elongation on methane adsorption at different moisture content.
because, unless all the circumstances accompanying these tests are taken into consideration, it is difficult to say anything definite. In the above examples, the effect of conducting more than one experiment on the same specimen, is not clearly understood. It is quite possible that subsequent tests may increase the adsorptive capacity of the coal, however small the effect may be. On the other hand, although the adsorptive capacity may be increased, the effect may be different on the concomitant elongation, due principally perhaps to the excessive strain set up in the coal on distention, each time it takes in gas.

Whatever other effects there may be, one fact in general can be deduced from these results, viz., that a decrease in the moisture content of coal does increase, to a certain extent, its capacity and rate of adsorption. Whether there is an optimum value for moisture at which the elongation is a maximum, can only be finally confirmed by further investigation in the subject.

It is generally supposed that the amount of gas a coal can adsorb at any pressure, stands in an inverse ratio to the amount of uncombined water the coal contains. But, an analysis of these tests does not agree with this view, for, it will be observed that in none of the above 6 examples, such an inverse ratio exists between elongation and moisture/
moisture content. Even the results of Clarain and Durain II P which showed a steady increase in elongation consequent upon loss of moisture, do not agree with the inverse-ratio relation. Taking into consideration the first and the second tests for Clarain II P, Fig. 10, it will be noted that the ratio between the two values of moisture percentages is 1.64, whereas the ratio between the two corresponding values for elongation is 2.46. Similar is the case with Durain II P, Fig. 9, with its ratios of 1.52 and 2.16 respectively, for moisture and elongation. Other values thus calculated are given in Table 4, which is only useful in so far as it demonstrates, that no such simple relation would appear to exist between the amount of elongation and the content of free moisture in coal, as was thought before.

Table 4.—Moisture and elongation ratios of different tests.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Moisture ratio</th>
<th>Elongation ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
<td>Test 2</td>
</tr>
<tr>
<td>Test 2</td>
<td>Test 3</td>
<td>Test 3</td>
</tr>
<tr>
<td>Clarain II P</td>
<td>1.64</td>
<td>3.88</td>
</tr>
<tr>
<td>Durain II P</td>
<td>1.52</td>
<td>3.48</td>
</tr>
<tr>
<td>Clarain I P</td>
<td>1.73</td>
<td>2.42</td>
</tr>
<tr>
<td>Clarain III P</td>
<td>1.42</td>
<td>2.64</td>
</tr>
<tr>
<td>Durain I P</td>
<td>1.13</td>
<td>1.32</td>
</tr>
<tr>
<td>Anthracite II P</td>
<td>1.66</td>
<td>2.32</td>
</tr>
</tbody>
</table>
A study of the rate of adsorption and elongation of a coal prism immediately on the introduction of gas, brings out other points of interest. Not only is the maximum elongation affected by the variation in moisture content, but the rate of elongation and shrinkage on introduction and release of gas respectively, is very markedly accelerated, quite out of proportion to the elongations at equilibria, as shown in Figs. 15 and 16, for Durain and Clarain II P, respectively. In these figures, both elongation and shrinkage have been plotted with their origins in opposite corners, to show at a glance their relative rates,-- the scale of movement and time being exactly the same. The curves representing second and third tests, marked by numbers, stand out in high relief compared to test No. 1. Here, if we take the values of elongations recorded after ten minutes from the time when gas was introduced, we obtain some surprising figures. As for example for Durain II P, for a decrease of 34 per cent. in moisture content, the elongation increased 650 per cent. in the second test after ten minutes, although the final value at equilibrium was only 110 per cent. greater than the value at equilibrium in the first test. Similarly, for a decrease of 39 per cent. in moisture content in Clarain II P, the increase on the/
Fig. 15. - Durain II P, Effect of moisture on the rate of elongation and shrinkage immediately on the introduction and release of gas-pressure. Moisture contents: - (1) 7.3%, (2) 4.8%, (3) 2.1%.

Fig. 16. - Clarain II P, Effect of moisture on the rate of elongation and shrinkage immediately on the introduction and release of gas-pressure. Moisture contents: - (1) 9.7%, (2) 5.9%, (3) 2.5%.
the previously recorded elongation of the first test after ten minutes, was as great as 725 per cent. The values for elongation and moisture used in the above calculation have been taken from the graphs, Figs. 15 and 16, and Table 3.

Such calculations are but of little value except that of demonstrating the perplexing state of affairs that are associated in gas adsorption, which require a good deal more investigation before a logically acceptable explanation can be put forward.

Nevertheless, among coals belonging to the same class, those having greater percentage of free moisture show as a general rule, a smaller percentage of elongation on gas adsorption. This is evident from the following Table 5, which includes all the coals so far tested.

Table 5.—Elongation and Moisture of different coals for comparison.

<table>
<thead>
<tr>
<th>Coal</th>
<th>Moisture per cent.</th>
<th>Elongation per cent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clarain II</td>
<td>9.7</td>
<td>0.07</td>
</tr>
<tr>
<td>Clarain I</td>
<td>8.5</td>
<td>0.129</td>
</tr>
<tr>
<td>Clarain III</td>
<td>7.4</td>
<td>0.133</td>
</tr>
<tr>
<td>Durain II</td>
<td>7.3</td>
<td>0.0755</td>
</tr>
<tr>
<td>Durain I</td>
<td>3.3</td>
<td>0.156</td>
</tr>
<tr>
<td>Anthracite II</td>
<td>3.5</td>
<td>0.162</td>
</tr>
<tr>
<td>Anthracite I</td>
<td>3.2</td>
<td>0.1946</td>
</tr>
<tr>
<td>Peacock Splint</td>
<td>6.9</td>
<td>0.071</td>
</tr>
<tr>
<td>Peacock Rough</td>
<td>6.6</td>
<td>0.0933</td>
</tr>
<tr>
<td>Bridgerness Smithy</td>
<td>0.9</td>
<td>0.119</td>
</tr>
</tbody>
</table>
The coals belonging to the same class have
been tabulated in order of merit as to their high
moisture content, so that the elongations in the third
column show a gradual increase in the values recorded;
it will be observed that these values are not proportion-
al to the decrease in moisture content.

Incidentally, a surprising example was a
specimen of Bridgeness Smithy coal, which in spite of
its remarkably low moisture content of 0.9 per cent.,
did not, however, exhibit a greater response to gas.
This fact would also go to prove that a low moisture
content in coal does not necessarily mean a high
adsorptive capacity, as has been discussed before.

It may be remarked here that the effect of
moisture on the adsorptive capacity of coal has
been investigated by Mr. J. I. Graham,* who found a
great difference in the volume adsorbed by dry and
moist coal dust (200-mesh) from the Barnsley Seam.

Although he has shown that moisture defini-
tely produces a marked inhibitory effect which is
especially pronounced at low gas pressures, we have
reason to believe that a stage is reached beyond
which any further loss of moisture is accompanied by
a corresponding loss in the adsorptive capacity.

That such is the case in colloidal silica has
been shown by Professor Briggs,** who found that any
further attempt to dispel the last portion of its
combined/

dissolution which was too quick for the above effect to be shown.

However, to gain some idea of the amount of contraction and elongation, respectively upon introduction and release of gas pressure, a method shown in Fig. 17, was adopted; so that the effect of gas adsorption may be entirely disregarded.

Two brass buttons, P₁ and P₂, were fixed by means of durofix, on to the polished ends of a durain coal prism, S. It was then coated all over to retard the access of gas to the coal, with durofix, layer upon layer, after subsequent drying, until it was completely enveloped as shown at D. After applying similarly a second coating of seccotine, the prism was then fitted into a glass tube G and filled with seccotine from both ends as shown in the figure. It was then tested in the apparatus under the same experimental conditions at a pressure of 300 lb. per sq. in. The results are given in Table 6.

Table 6.- Shrinkage due to elastic compression under gas pressure.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Pressure in lb. per sq.in.</th>
<th>Movement m.m.</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 to 300</td>
<td>0.005</td>
<td>shrinkage</td>
</tr>
<tr>
<td></td>
<td>300 to 0</td>
<td>0.005</td>
<td>elongation</td>
</tr>
<tr>
<td>2</td>
<td>0 to 300</td>
<td>0.0125</td>
<td>shrinkage</td>
</tr>
<tr>
<td></td>
<td>300 to 0</td>
<td>0.01</td>
<td>elongation</td>
</tr>
<tr>
<td>3</td>
<td>0 to 300</td>
<td>0</td>
<td>no movement,</td>
</tr>
<tr>
<td></td>
<td>300 to 0</td>
<td>0.005</td>
<td>trace of expansion</td>
</tr>
<tr>
<td>4</td>
<td>0 to 300</td>
<td>0.02</td>
<td>elongation</td>
</tr>
<tr>
<td></td>
<td>300 to 0</td>
<td>0.015</td>
<td>shrinkage</td>
</tr>
</tbody>
</table>
Fig. 17.- Device for the measurement of contraction due to elastic compression.

Fig. 18.- Stress-strain graph for Roslin Cannel.

Fig. 19.- Stress-strain graph for Lanarkshire Anthracite.
It will be observed that the shrinkage increased from 0.005 in the first test to 0.0125 mm. in the second test. It is difficult to account for this, unless we assume that some sort of resistance was offered by the colloidal covering against contraction in the first test. The gas must have begun to find access into the coal as is evident from the third test when instead of a contraction at 300 lb. per sq. in., a slight trace of elongation was noticed.

It must be remarked, however, that no high degree of accuracy is claimed for these measurements because we know neither the efficiency of the colloidal in retarding the access of gas into the coal, nor its effect on the coal prism itself. These measurements are only valuable in demonstrating that the contraction under gas pressure is small compared with the amount of elongation on adsorption.

Compression Tests on coal

These tests were carried out to determine the value of Young's Modulus for coal, with a view to further obtaining some idea of the amount of simple elastic compression under gas pressure.

Six specimens were sawn off from different blocks of coal which had been lying in the laboratory for a period varying from 6 to 10 months. Compression tests were carried out in a ten-ton testing/
testing machine. The load in all cases was applied parallel to the bedding plane. Measurements of shortenings under compression were registered by means of a dial indicator reading to two-thousandths of an inch, fixed between the anvils of the testing machine. The load was increased in stages of 0.05 of a ton and in three examples, i.e. Nos. 1, 2, 3, Table 7, the load was gradually decreased and the ensuing elongations were measured.

From the result of these tests, stresses in lb. per sq. in. were plotted against strains in inch to obtain stress-strain graphs for each prism of coal tested, as shown in Figs. 18 to 22. It would appear from these graphs that there is a definite bend in the curve somewhere between 300 to 400 lb. per sq. in., after which the contraction due to compression is almost uniform till very near the crushing point. This effect was also observed by Mr. C. T. Holland, of West Virginia, a previous experimenter in this subject, who carried out some compression tests on coal from Barbauchlaw Mine, Westlothian.

These results show that roughly speaking there are three stages during the compression of coal, i.e. -

1. The early part when strain set up by the load is erratic and invariably greater than/
**Fig. 20.** - Stress-strain graph for Cardowan Durain.

**Fig. 21.** - Stress-strain graph for Bridge ness Smithy coal.

**Fig. 22.** - Stress-strain graph for Durain from Easthouses and Cardowan.
than the latter part. This may be due to (a) the open spaces between the bedding and joint planes, and fissures and cracks, being closed by the load, (b) settling down of the prism ends until a firm contact is secured between the anvils of the testing machine.

2. Compression and contraction of the coal material itself; generally, uniform till very near the crushing point.

3. The last stage of compression, a little before the ultimate crushing strength, when the coal has a tendency to flow under pressure. Time effect is also noticed at this stage.

Table 7.- Young's Modulus for the coal tested.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Area square inch</th>
<th>Length inches</th>
<th>Ultimate crushing strength lb. per sq. in.</th>
<th>Young's Modulus lb. per sq. in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load in all examples were applied parallel to bedding.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Roslin Cannel</td>
<td>1.091</td>
<td>2.768</td>
<td>------</td>
<td>350,000</td>
</tr>
<tr>
<td>2. Lanarkshire Anthracite</td>
<td>0.911</td>
<td>2.325</td>
<td>1850</td>
<td>450,000</td>
</tr>
<tr>
<td>3. Durain from Cardowan</td>
<td>1.383</td>
<td>2.625</td>
<td>2100</td>
<td>370,000</td>
</tr>
<tr>
<td>4. Bridgeness</td>
<td>0.792</td>
<td>2.01</td>
<td>2550</td>
<td>350,000</td>
</tr>
<tr>
<td>5. Durain from Midlothian</td>
<td>0.749</td>
<td>3.003</td>
<td>2550</td>
<td>700,000</td>
</tr>
<tr>
<td>6. Durain from Midlothian</td>
<td>0.82</td>
<td>2.715</td>
<td>1900</td>
<td>260,000</td>
</tr>
</tbody>
</table>

The increase of strain due to increase in stress/
stress was fairly uniform right up to the crushing point in specimens Nos. 1, 3, and 4, but generally speaking, there is a tendency for the amount of strain to jump up in the region of the crushing point.

When the load was gradually decreased in specimens Nos. 1, 2, and 3, there was a definite evidence of hysteresis loop as shown in curves, Figs. 18, 19, and 20, respectively.

Values of Young's Modulus, computed from these tests are given in Table 7.

It will be observed that the value of Young's Modulus for coal computed from the results of tests at low pressures, say from 0 to about 400 lb. per sq. in., will fall shorter of the values given in Table 7. This is due to the closing of the cracks and joint planes before actual compression of the coal material itself begins. It may be remarked here that during preparation and grinding of the prisms, a further opening of the joints may occur which may also increase the amount of compression at low pressures.

When a specimen is under gas pressure, these cracks and joint planes will be filled with gas and any contraction that occurs is due to the compression of the coal material itself and not due to the closing of their cracks and joint planes. Therefore, we would be justified in using the values based on the above/
above results.

Analysis of strain when load is applied from all directions as is the case when a prism of coal is under gas pressure.*

Let \( E \) = Young's Modulus for the material and \( e_1, e_2, e_3 \), the strains along the directions of action of \( P_1, P_2, \) and \( P_3 \) respectively.

\[
1/m = \text{Poisson's Ratio.}
\]

Then, \[
E e_1 = P_1 - (P_2 + P_3) / m \quad (1)
\]
\[
E e_2 = P_2 - (P_1 + P_3) / m \quad (2)
\]
\[
E e_3 = P_3 - (P_1 + P_2) / m \quad (3)
\]

If the compression is equal in all directions, then

\[
P_1 = P_2 = P_3
\]

and \[
E e_1 = (P_1 - 2 P_1) / m = E e_2 = E e_3 \quad (4)
\]

Therefore, \[
e_1 = P_1(1 - 2/m) / E \quad (5)
\]

As the value of Poisson's Ratio \( (1/m) \) for coal has not been determined by any investigator up till now, we have to assume a value for it, based on our/

*"The properties of engineering materials," by W. C. Popplewell and E. Carrington, p. 11.
Grateful acknowledgment is also due to Mr. D. W. Phillips, Safety in Mines Research Board, Sheffield, for the above analysis.
equation, the contraction thus evaluated is 0.0177 mm. But in no case was such a big amount of contraction observed.

However, it may be remarked here that there is a considerable uncertainty in the value of Young's Modulus used in the above equations. There is a wide variation in this value for coals as shown by Müller,* who found that for bituminous coal, it ranged from 400,000 to 900,000 lb. per sq. in., depending on the coal and even on the method of test and size of test specimens. It is thus very unfortunate that no definite figure for contraction, free from any uncertainty, can be assessed from the data so far available.

These results, therefore, are not of great quantitative value, but only useful in showing that the contraction due to elastic compression is of a very small order compared to the effect of elongation due to gaseous absorption.

Undoubtedly, in a theoretical analysis, its true value would require to be taken into account, no matter how small it might be. But to show the effect in the experimental elongation curves, a very big scale for elongation (ordinate) must be adopted for such a correction to be effective.

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* Gluckauf, vol. lxvi, p. 1601, 1930
ADSORPTION OF WATER BY COAL AND THE CHANGE
OF LINEAR DIMENSIONS DUE TO ADSORPTION

The results of tests on anthracite, clarain
and durain specimens are shown by the time-elongation
curves in Fig. 23. The method employed for the tests
is shown diagrammatically by the sketch in Fig. 23 A,
which is self-explanatory. The apparatus containing
the coal specimen was connected to a vacuum pump, and
all the air and gas pumped out. This operation lasted
for about 18 to 24 hours until a vacuum of 20 to 25
inches could be fairly maintained. Air free distilled
water was then gradually introduced into the apparatus
and observations for elongations of the coal were
taken until equilibrium was apparently reached.

An expansion of 0.05 per cent. was recorded
for anthracite, at the end of 2 hours, no further ex-
pansion being observed in the next five hours. But,
after this, further expansion took place, until a
maximum of 0.155 per cent. was attained at 24.5 hours
from the beginning. Observations in the next 25 hours
did not show any increase in elongation. With a
view to finding if water under pressure would cause
further expansion of the coal, a pressure of 200 lb.
per sq. in. of methane was applied on the water
contained in the apparatus; but no further movements
were/
Fig. 23.- Elongation of coal on water sorption.

Fig. 23 A.- Apparatus for water adsorption test.
were observed. Incidentally, when the specimen was taken out, a very peculiar phenomenon was observed on its surface. In patches, here and there, a bright bluish tint was noticed and particularly one of its sides was tinted in a shiny peacock blue colour.

This fact is mentioned here, merely as a matter of interest. The effect seems to be of a physico-chemical nature, but without sufficient evidence for a feasible explanation, it is hard to understand this phenomenon. However, water seems to be one of the causes of this peculiar peacock blue colour in some coal seams, which has been noticed for a long time, as is evident by the term "peacock", being used, as a prefix to indicate certain coal seams in Scotland.

The clarain specimen, showed a comparatively rapid rate of elongation as is evident by its time-elongation curve in Fig. 24. Almost 94 per cent. of the maximum elongation recorded for this specimen, was reached after 5 hours, without any check in the movement unlike the anthracite as mentioned above. Although, an elongation of 0.232 per cent. was reached after 10 hours, a reading taken 25 hours from the beginning showed the elongation to be 0.2253 per cent., revealing a slight decrease from the former value attained. After this, however, no further movement was recorded.
The durain specimen showed a peculiar reaction in that the elongation increased uniformly until 0.0519 per cent was recorded at the end of half an hour, but a second measurement taken after another 20 minutes, showed a shrinkage of 0.0194 per cent. to have taken place. However, further elongations took place after this till, at apparent equilibrium the maximum elongation recorded was 0.195 per cent.

Although no tests in particular were carried out with water vapour, it is worth mentioning here that in connection with the elongation-shrinkage test with methane on a clarain specimen, the effect of water vapour was observed. This specimen showed a maximum elongation of 0.175 per cent. on methane adsorption at 300 lb. per sq. in. and after the release of pressure to atmospheric, it shrank 0.113 per cent. at the end of 12.5 hours. But at this stage, further shrinkage was checked and instead, the coal began to elongate, - a fact which appeared very curious at first sight. This elongation continued at a gradual rate till 0.07 per cent. was reached, thus the specimen at that time was 0.132 per cent. longer than its original length. The apparatus containing the coal was then connected to the vacuum pump. It was observed that provided the pump was kept going, a vacuum of 756 mm. of mercury, could be maintained, but as soon as the pump was stopped, the vacuum/
vacuum fell to 735 mm. in about 10 minutes and remained there for hours. Even after 18 hours no decrease in vacuum was observed.

This curious effect became comprehensible when we discovered that due to some residual water left inside the apparatus from a previous test, a certain amount of water vapour was present therein. Further evidence of the presence of water vapour was provided by the fine bubbles of condensed water, as seen, on the internal surface of the gauge glass. It was obvious from this that the elongation of coal was caused by the adsorption of water-vapour.

Later, when distilled water was introduced into the apparatus, a further elongation of only 0.035 per cent. was recorded, - a fact which goes to show that the coal must have had a good doze of water-vapour, with the result that very little room was available for adsorption of water.

In the experiments that followed, a drastic method of drying the apparatus was resorted to, as a result, the above effect disappeared, which also convinced us that water-vapour was the root cause of this elongation.

Discussion of results.

From the above few results, it is difficult to make a generalization as regards the nature and the/
of the seam. Two prisms of coal, averaging 80 mm. in length, and 20 mm. square in section, respectively at right angles to, and parallel with the bedding-planes, were carefully sawn from the same lump of coal from each of the layers. The positions of these layers are shown in Fig. 24 by the numbers. The prisms were numbered from 1 to 5 with suffixes 'P' and 'R', meaning parallel with and at right angles to the bedding, respectively, as mentioned before in the first section of this paper. The proximate analyses of the five specimens are given in Table 8.

The average temperature during these tests was 18.5°C. According to previous tests, the small variations in temperature that occurred did not affect the results. The firedamp used in the experiments was obtained from Cymer Colliery, Porth. Its Composition has already been given elsewhere.

Table 8.- Analyses of coal specimens.

<table>
<thead>
<tr>
<th>Description</th>
<th>Volatile matter %</th>
<th>Ash %</th>
<th>Moisture (expelled at 105°C) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardowan 1</td>
<td>28.7</td>
<td>3.38</td>
<td>4.3</td>
</tr>
<tr>
<td>&quot; 2</td>
<td>32.5</td>
<td>6.50</td>
<td>3.8</td>
</tr>
<tr>
<td>&quot; 3</td>
<td>34.4</td>
<td>5.50</td>
<td>3.5</td>
</tr>
<tr>
<td>&quot; 4</td>
<td>34.9</td>
<td>5.20</td>
<td>4.3</td>
</tr>
<tr>
<td>&quot; 5</td>
<td>31.9</td>
<td>4.10</td>
<td>3.7</td>
</tr>
</tbody>
</table>

The composition of the firedamp at Cardowan, as ascertained from two samples taken by us and analysed/
analysed at the Safety in Mines Research Laboratories, Sheffield, was as shown in Table 9, from which it will be seen that there was nothing unusual in the Cardowan firedamp.

Table 9.—Composition of firedamp from Cardowan.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>CO₂ %</th>
<th>O₂ %</th>
<th>CO %</th>
<th>CH₄ %</th>
<th>N₂ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ....</td>
<td>1-00</td>
<td>0-07</td>
<td>0</td>
<td>93-9</td>
<td>3-0</td>
</tr>
<tr>
<td>2 ....</td>
<td>0-45</td>
<td>0-41</td>
<td>0</td>
<td>92-9</td>
<td>6-2</td>
</tr>
</tbody>
</table>

Experimental.

The method employed for measuring linear elongation and shrinkage was precisely the same as described before, except that with Cardowan Coals the technique was modified to enable measurements to be made of the volume of gas discharged during the contraction period. First, gas at a pressure of 300 lb. per sq. in. was maintained in the apparatus for a uniform period of 100 hours, during which time the expansion was noted. The relief-cock was then opened for 8 seconds and then closed. The shrinkage due to gas dissorbed was kept under continuous observation, in some cases for 280 hours; at the same time the gas expelled was measured by means of a simple device, as shown in Fig. 25.

After closing the relief-cock, the needle-
Fig. 24—Section of Meiklehill Main Coal, Cardowan Colliery.

Fig. 25.—Apparatus for the measurement of dis sorbed gas.
References:—
1. Methane Cylinder.
2. Cathetometer.
3. Pressure Gauge.
5. Thermometer.
6. Apparatus for the measurement of elongation and shrinkage.
7. Coal specimen.
8. Gauge Glass.
9. Haldane Apparatus.
13. Connexion to Haldane Apparatus.
needle-valve 10, was opened to a graduated burette, 4, with a balancing tube. This enabled the dis sorbed gas to be collected over mercury and its volume to be measured in ccs. A note of temperature and barometric pressure was taken with each reading. A correction for water vapour was then applied to each measurement and the volume expressed in ccs. at N.T.P.

The purpose of opening the release-cock for 8 seconds was to allow of the escape of the free gas surrounding the prism of coal. Blank tests on metal pieces of the same size as the coal prisms indicated that that short period was sufficient for this purpose. The coal itself must have given up a little of its gas during the 8 seconds, and to that extent the volume measurements are a little on the low side.

Results.

The time-movement chart, Fig. 26, shows the percentage elongation of the Cardowan specimens on being subjected to firedamp at 300 lb. per sq. in. and their percentage shrinkage on release of that pressure. The samples 1, 4, and 5 responded quickly, elongating 0.006, 0.0125 and 0.0127 per cent. respectively, in the first two minutes after the gas was admitted. Elongation became slower as time went on, until apparent equilibrium was reached. The maximum/
maximum elongation for Cardowan 1 P was 0.098 per cent. after 26 hours; and for Cardowan 5 P, 0.1425 per cent. after 49 hours.

Cardowan 2 P and 3 P reacted differently, taking three hours and one hour respectively, before any sign of elongation was observed.

From the slow rate of elongation with long pauses at intervals in the cases 2 P and 3 P, it would appear that 100 hours' adsorption may not have been sufficient for these two specimens to elongate to their full extent. Similarly, 100 hours is probably too short a period for the complete saturation with gas of these compact prisms of coal. Be this as it may, the method provided a convenient means of studying the relative behaviour of the different layers.

The maximum percentage elongation for Cardowan 2 P was 0.063 after 100 hours, and for Cardowan 3 P, 0.0788 after 94.5 hours.

On the pressure being suddenly released to atmospheric after 100 hours, slight elastic elongations were observed to take place immediately in 2 P and 3 P as a preliminary to shrinkage; but specimens 1 P, 4 P, and 5 P at once began to shrink. Percentage shrinkages are also shown in Fig. 26. It will be observed that the amount of shrinkage on desorption of gas is not equal to the elongation on adsorption/
Fig. 26. Time-movement chart, Cardowan Specimens. Movement parallel with bedding. Firedamp at 300 lb. admitted at 0 hours; released at 100 hours.
adsorption; consequently, at the end of each test, a small amount of residual elongation remains. This is 0.018 per cent. for 1 P; 0.025 per cent. for 2 P; 0.0065 per cent. for 3 P; 0.003 per cent. for 4 P; and 0.012 per cent. for 5 P. Provided a sufficiently long period is allowed for dissorption, there is a tendency for these residual elongations to decrease.

The volumes of the expelled gas during the shrinkage period were measured and expressed in ccs. at N. T. P. per 100 grammes of coal. The values so obtained are plotted as ordinates against time in hours as abscissae in Fig. 27.

There seems to be a direct relationship between the volume of gas expelled and the amount of shrinkage caused in coal immediately the pressure is released, as shown by the volume and shrinkage curves in Figs. 28 and 29, respectively. The following Table 10 gives the rates of discharge of gas and shrinkage of the coals, immediately following the release of 300 lb. pressure after the coals had been subjected to that pressure for 100 hours.

The volume measurements of the expelled gas proceeded for more than 250 hours in cases of 5, 4, and 2, after which the experiment was discontinued, although the discharge of gas had not completely ceased.

To study the effect of adsorption and gas emission/
Fig. 27. Cardowan Specimens Cut Parallel with Bedding: Volume of Firedamp emitted on Release of Gas-pressure. Curves 1 to 5 refer to correspondingly numbered Specimens; Gas-pressure before Release, 300 lb. Curves 6 and 7 refer to Specimens 5 and 4 respectively; Gas-pressure before Release, 70 lb.
Fig. 28.- Time-volume curves for Cardowan specimens, immediately on release of pressure.

Fig. 29.- Time-shrinkage curves for Cardowan specimens, immediately on release of pressure.
Table 10. - Rates of discharge of gas and shrinkage of Cardowan specimens immediately upon release of gas-pressure.

<table>
<thead>
<tr>
<th>Specimen [No.]</th>
<th>Volume expelled in c.c. per min., per 100 grm. of coal.</th>
<th>Volume expelled, per min., in cu. ft. per ton.</th>
<th>Rate of shrinkage, mmg. per min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2  - P</td>
<td>1-25</td>
<td>0-4483</td>
<td>0-00075</td>
</tr>
<tr>
<td>3  -</td>
<td>15-70</td>
<td>5-637</td>
<td>0-005</td>
</tr>
<tr>
<td>4  -</td>
<td>19-50</td>
<td>7-00</td>
<td>0-008</td>
</tr>
<tr>
<td>5  -</td>
<td>52-60</td>
<td>18-90</td>
<td>0-018</td>
</tr>
<tr>
<td>6  -</td>
<td>50-50</td>
<td>18-13</td>
<td>0-012</td>
</tr>
</tbody>
</table>

Emission at low pressure, prisms 4 P and 5 P were tested at 70 lb. per sq. in. under the same experimental conditions. The volumes discharged subsequent to the release of pressure after the specimen had been 100 hours in gas, are shown by curves 7 and 6 in Fig. 2, relating respectively to specimens 4 P and 5 P. It will be observed that, of these two samples, 4 P expels the greater volume after the release of 70 lb. pressure, and 5 P after the release of 300 lb.

The following Table gives the maximum elongation and the rate of discharge on release of pressure for these specimens at 70 and 300 lb. per sq. in.

The quantity of firedamp dissorbed after 100 hours adsorption at 300 lb. pressure, by fusain, durain and a mixture of clarain and vitrain, from Cardowan Colliery, are shown in Figs. 30 and 31. These/
Fig. 30. - Time-volume curves for Fusain, Durain, and a mixture of Clarain and Vitrain from Cardowan Colliery, immediately on the release of pressure.

Fig. 31. - Time-volume curves for other coals.
Table 11.- Comparison of reactions of two Cardowan specimens subjected to firedamp at 300 and 70 lb. per sq. in., respectively.

<table>
<thead>
<tr>
<th></th>
<th>Specimen 5P</th>
<th>Specimen 4P</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 lb. Max. elongation %</td>
<td>0-1425</td>
<td>0-125</td>
</tr>
<tr>
<td>70 lb. Max. elongation %</td>
<td>0-032</td>
<td>0-087</td>
</tr>
<tr>
<td>Rate of discharge, immediately upon release of gas-pressure, in cu. ft. per ton per min.</td>
<td>18-13</td>
<td>18-90</td>
</tr>
<tr>
<td></td>
<td>3-59</td>
<td>6-48</td>
</tr>
</tbody>
</table>

These specimens were in the form of undried dust through 200-mesh. The moisture contents of fusain, durain and mixture of clarain and vitrain, were 8-7, 5-6 and 4-9 per cent., respectively.

The tests were extended to include also an examination of a few other coals, whose results are shown in Fig. 31. A summary of these results is tabulated in Table 12, which gives the maximum percentage elongation and the time at which this maximum was reached. The total volume dissorbed at the end of 50 hours after the release of pressure and the amount of residual elongation at that time, are also given in the same Table.

As tests on other specimens were only continued up to 50 to 80 hours, a time of 50 hours has been taken in the above Table, in order to show their relative order of the discharge of gas.
Table 12.—Summary of results of the Cardowan and other specimens, for comparison.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max. percentage, Elongation</th>
<th>Time at which this reached</th>
<th>Vol., (cc.N.T.P) dissolved at 50 hours from release of pressure</th>
<th>Residual elongation at the end of 50 hour pressure*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adsorption at 300 lb. per sq. in. for 100 hours</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardowan 1P</td>
<td>0.098</td>
<td>23</td>
<td>329.2</td>
<td>0.031</td>
</tr>
<tr>
<td>&quot; 2P</td>
<td>0.063</td>
<td>100</td>
<td>94</td>
<td>0.0253</td>
</tr>
<tr>
<td>&quot; 3P</td>
<td>0.0788</td>
<td>93.5</td>
<td>239</td>
<td>0.0065</td>
</tr>
<tr>
<td>&quot; 4P</td>
<td>0.125</td>
<td>28.25</td>
<td>336</td>
<td>0.00314</td>
</tr>
<tr>
<td>&quot; 5P</td>
<td>0.1425</td>
<td>49</td>
<td>515.8</td>
<td>0.0158</td>
</tr>
<tr>
<td>Peacock Rough, Roslin</td>
<td>0.0933</td>
<td>72</td>
<td>322</td>
<td>0.0186</td>
</tr>
<tr>
<td>Bridgeness Smithy Coal</td>
<td>0.119</td>
<td>100</td>
<td>280</td>
<td>0.063</td>
</tr>
<tr>
<td>Peacock Splinter, Roslin</td>
<td>0.071</td>
<td>27</td>
<td>251</td>
<td>0.00618</td>
</tr>
<tr>
<td>Anthracite</td>
<td>0.012</td>
<td>6.5</td>
<td>148</td>
<td>0</td>
</tr>
<tr>
<td>Cardowan Elas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powdered specimens (200-mesh) undried dust.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarain-vitrain mixture</td>
<td>-</td>
<td>-</td>
<td>575</td>
<td>-</td>
</tr>
<tr>
<td>Durain</td>
<td>-</td>
<td>-</td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td>Fusain</td>
<td>-</td>
<td>-</td>
<td>373</td>
<td>-</td>
</tr>
<tr>
<td>Adsorption at 70 lb. per sq. in. for 100 hours.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardowan 4P</td>
<td>0.087</td>
<td>72</td>
<td>247</td>
<td>0.0126</td>
</tr>
<tr>
<td>&quot; 5P</td>
<td>0.0317</td>
<td>69</td>
<td>165.5</td>
<td>0.00634</td>
</tr>
</tbody>
</table>

Discussion/
Discussion of results.

Stanhlyd Anthracite seems very peculiar compared with other coals. It is quite evident from Table 12, that 100 hours adsorption at 300 lb. per sq. in., is far from being sufficient time in which to allow firedamp to get into that coal. Its exceedingly impermeable nature to gas in its natural state, stands out in high relief compared with almost any other coal. Its great reluctance to part with its inherent gas is also well known. Yet it is generally supposed that molecularly speaking molecularly, anthracite is more porous and has better adsorptive capacity than bituminous coals. These tests, however, appear to throw some doubt on such a view, unless the coal be activated in some manner. A further study of this coal would be of great interest and value in clearing up these points.

The tests on powdered specimens of Cardowan Coals, show that the volume adsorbed by lump coal is 60 to 70 per cent. of that adsorbed by fine dust.

Of all the banded structure of coal, clarain (strictly speaking, a mixture of clarain and vitrain) appears to have the highest capacity for adsorbing gas, and furain the least, as is evident from Fig. 31; although a glance at Fig. 30, will show that the rate of discharge immediately on the release of pressure is higher for durain.

Some/
Some valuable tests on the gas content of coals from Cardowan Colliery were carried out by Mr. J. I. Graham, after the explosion at the above Colliery in 1932. His view fairly agrees with the results of the present tests, in so far as showing that the bottom part of the Meiklehill Main Coal seam has a higher capacity for gas than any other part in the seam.

His values for gas contents for the top, middle and bottom parts, respectively, are 682, 516, and 743 ccs. per 100 grms. of coal, compared to our corresponding values of 452, 360 and 592 ccs. per 100 grms., dis小姑娘ed by the coal over and above one atmosphere after 100 hours' adsorption, at 300 lb. per sq. in. At first sight, the latter values appear too low, but it must be remembered that Mr. Graham's tests, in which gas was pumped out from the coal, represent the absolute amount of gas contained in the coal; whereas our values represent the evolution of gas when the pressure over the coal is suddenly dropped from 300 lb. to atmospheric. In that light, these values are not comparable. Nevertheless, the relative order of gas content and gas dis小姑娘ed is the same in both tests.

It will be observed from the time-volume curves/

* Report on gas content and nature of coal taken from the vicinity of the explosion which occurred in the Main Seam, West Level, Cardowan No.1 Pit, on November 16th, 1932, by J. I. Graham

Grateful acknowledge is due to Mr. Graham for sending us a copy of the above report.
curves, Fig. 27, that the discharge is very rapid at release of pressure and that its rate rapidly decreases after a few hours, till after 100 hours it is extremely slow. This discharge of gas cannot continue indefinitely; and as the volume when completely expelled is an asymptotic value, it can be arrived at by extrapolation, by plotting volumes against a suitable inverse function of time selected to cause the curve to straighten out. The inverse function corresponding to infinite time is zero; hence the limiting value of volume is obtained by producing the straightened line to cut the 'Y' axis, as shown in Fig. 32.

Expressed in c.c. of firedamp per 100 grm. of coal, the ultimate values obtained in this way are 592 for 5P; 432 for 4P; 452 for 1P; 360 for 3P; and 200 for 2P. It will be observed that the values thus obtained must be considered as approximate, because the extrapolation is mainly based on rate of discharge of the latter period. Nevertheless, even based on such an assumption it will be found that the observed volumes agree, with not too great an error, over a large range, with the calculated volume from an equation of the following type:

\[ V = -C \left( \frac{1}{\sqrt{T}} \right) + V_\infty \]

where, \( V = \) Volume of gas expelled in c.c. at N. T. P. per 100 grm. of coal.

\( T = \) Time in hours.

\( C = \) /
An equation of the above type, however, would not be applicable to the early period of dissolution, immediately on the release of pressure. This is mainly because of the rapid evolution at the beginning, when the rate of discharge is different from the latter period. Plotting the log of time in minutes as abscissae and volume in cc. per 100 grm. at N. T. P., as ordinate immediately after the release of pressure, a straight line is obtained, whose equation for \( 5P \) works out to be:

\[
V = 140 \log t
\]

where, \( V \) = Volume in cc. at N. T. P. per 100 grm.

\( t \) = Time in minutes after release of pressure.

The volumes calculated according to the above equation, agrees fairly well with the observed volumes, for the early period of dissolution. Neither of the above two equations, however, can be applied over the entire range. Consequently, such equations are very unsatisfactory and have no definite physical meaning, except that they are useful in helping us to predict limited portions of the curve.

To test the validity of the above-mentioned method of extrapolation for deducing the ultimate asymptotic value, several other inverse functions of time, such as, \( 1/T \), \( 1/\sqrt{T} \), \( 1/\sqrt[3]{T} \), \( 1/\sqrt[4]{T} \), were plotted against volume.
It was observed that none of these inverse functions gave a continuous straight line over the whole range. Nevertheless, they all pointed, more or less, to the same direction of the probable value, showing that the ultimate volume of the expelled gas will be round about the region pointed out by them. However, this method provided a convenient means of assessing the relative ultimate capacities to hold gas by the different layers of the seam.

The relation between the volume of gas expelled and the amount of shrinkage caused in coal for the five specimens are depicted by the volume-shrinkage curves in Fig. 33. It would appear from these curves that the relation between shrinkage and volume is somewhat of a linear type (except for 5P), but all the experimental points do not lie on the curve so drawn and it is highly speculative to think that the deviation, slight though it may be, is due to experimental error. That this relation for 5P is not so simple as linear is quite evident from its curve. Any relation between shrinkage and volume, however, will not hold throughout the desorption period, because, even after the shrinkage of coal has completely ceased, the evolution of gas continues for a long time, although at a slow rate.

It may be noted here that in practice, as for example in a gassy seam, such as at Cardowan, the volume/
Fig. 32. - Extrapolation of ultimate volume disorbed on release of pressure.

Fig. 33. - Volume-shrinkage curves for Cardowan specimens.
volume of gas expelled may be higher than shown by the volume-shrinkage curves, in relation to the amount of shrinkage caused by it. This is because the seam 'in situ' will develop shrinkage cracks on gas evolution and enhance the rate of escape by the increased permeability thus created. Whereas in the laboratory experiments, the compact prisms of coal in the apparatus, had no opportunity to create cracks by shrinking which could have facilitated the evolution of gas.

However, it is evident from these experiments that there are considerable differences between the various layers of the Meiklehill Main Seam at Cardowan Colliery, in respect of their capacities to expel gas when pressure is released. The position of these layers in the seam and their relative responsiveness to gaseous discharge deserve some attention. The following comparative figures,* in which the reaction of the least responsive layer (No. 2) is taken as unity, clearly indicate the relative danger connected with these events.

When we consider that the undercut is done in layer No. 5, next to the floor and that No. 4, lies just over it, the greater riskiness of these two layers, in comparison to the rest, is beyond any doubt.

Table/

back in the wastes was considered untenable by the Chief Inspector of Mines, under such circumstances. There was substantial evidence, as was said during the enquiry, in support of the contention that there must have been a large volume of gas which by some way or means found its way into the place, and came in contact with the flame coming from the explosion.

But only now, in the light of these tests, the possibility, of a huge volume of gas being supplied from and above the under-cut, is comprehensible. Indeed, Mr. J. Masterton's view as to the cause of the explosion was not wide of the mark, when in the following excerpt from his written comment, he stated,*:-

"I think the explosion had its origin at shot hole 44 or 45 when either one or other was being fired.

The difficulty in the West Section on 16th November was to account for the presence of gas to carry on the ignition. That gas was, I think, under the holing and making there both below and above the place where 44 and 45 shots were and not getting away freely because of the holings."

Although the experimental evidence showing the possibility of the gas coming from and above the under-cut, is illuminating, it is necessary, if the occurrence is to be clearly understood, to look much deeper and in a more searching light into the subject to explain the abnormal and sudden discharge of gas. The information collected as regards the state of affairs/

* Report of the explosion at Cardowan Colliery,

Lanarkshire, by Sir H. Walker, 1933, p.16, cmd.4,309,
affairs that existed in the seam, before and after the explosion, throw some important light in this direc-
tion.

The seam was normally dry, except that in spots marked N and O, in plan, Fig. 34, water had collected on the road-sides. But the condition at the face; first began to change when the face line C D, had arrived at a position, 100 ft. back from the line G H, it reached on the 16th November, 1932,— the day of the explosion. There appeared a wet patch near the middle of the face and the flow of water was approxi-
mately estimated to be about 5 to 6 gallons per minute.

On the 10th of November, 1932, when the position of the face, was at E F, water began to discharge from the coal on the dip side. It was this part of the face where the explosion took place, on 16th November. After the explosion, the condition at the face as regards water began to get worse. The wet zone spread to other parts of the coal face. When the face line had reached the position J K, water was freely oozing from the entire section. This state of affairs existed till the face advanced to a position L M, when once more, the condition began to get drier. During the time of tests to ascertain gas pressure in the/
Fig. 34. - Plan of Meiklehill Main Coal workings, West Side, Cardowan Colliery.
CARDOWAN COLLIERY
Meiklehill Main Coal Workings, West Side

Scale of feet

- Distance from Pit Bottom to Face 3350 feet
- Depth from Surface 1300 feet

Average rate of Advance 245 feet per week

Virgin Ground:
2 miles to West, ½ mile to South, ½ mile to North

Section of Seam:
- Soft Bands 5' R
- Coal 2' 6"
- Harder Bands 6' 6"
- M. Main Coal 3' 4"
- Fract 2' 6"
- Bedrock

Note: The diagram shows the layout of the coal workings with various detail labels and coordinates, including the position of the main coal seam and other geological features.
the seam in question, the condition at the face, which by then had advanced a further 600 ft. from the position L M, was in outward appearance dry, although a hole dug in the pavement on the dip side would fill with water. In connection with gas pressure-measurement tests in the next section, it has been shown how water oozed from the open ends of some of the narrow copper tubes inserted in the bore-holes at the end of the face.

Judging from the above circumstances, it is evident then, that water possibly played an important part in causing the abnormal and sudden discharge of gas at that part of the face where ignition took place. It is a well-known fact that water is taken up more readily than firedamp by dry coal. Breaks in roof or floor induced by coal mining, may connect a gassy seam to a water-bearing strata, as a result of which a sudden discharge of gas may be expected. There are numerous practical instances on record in support of this contention. It has been pointed out by Prof. Knox, how water from a upper seam invading a gassy bed below through cracks in the floor may give rise to sudden out-bursts from the pavement.

In connection with the recent Grassmoor Colliery explosion, it has been suggested by Prof. Briggs:

Briggs, that a change at the face from a dry to a wet condition, may have been responsible for the sudden efflux of gas which became ignited. There is good evidence in support of the above suggestion, both in the report of the Grassmoor Colliery Explosion,* and in a reply by Mr. E. L. Ford, the Colliery Agent, to questions asked by Prof. Briggs, as a further elucidation of this point.

The evidence assembled above, is sufficient to indicate the danger of sudden efflux of gas when a wet patch is encountered in a seam that is normally dry and special precautions should be taken to guard against this danger.

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CHAPTER XII

UNDERGROUND TESTS FOR GAS PRESSURE.
UNDERGROUND TESTS FOR GAS-PRESSURE.

To determine the pressure of gas in the Meiklehill Main Coal at Cardovan Colliery three tests were carried out.

Test No. 1.

In the first test, which took place on November 18th, 1933, four bore-holes, two 10 ft. long and two 5 ft. long, and of 1·5 in. diam., were drilled at the face in the middle part of the seam. Their respective positions are shown on the plan, Fig. 34. The sketch in Fig. 35, shows the section of the bore-hole and the device used to measure gas pressure. Immediately the boring was completed and the hole cleaned out, a hollow copper barrel, C, with a thin flexible copper tube, T, attached to it, was pushed to the end. The hole was stemmed for the first 6 to 8 inches with plasticine, P, followed by clay, L. A fitting, consisting of a needle-valve, R, and pressure-gauge, G, was connected to the outer end of the copper tube.

Of these preliminary holes, Nos. 1 and 3, Fig. 34, each 5 ft. long, showed no pressure at all. While No. 1 was being drilled it seemed absolutely dry at first, but later when the copper barrel was inserted/
Fig. 35.—Device to ascertain the pressure of firedamp in the Meiklehill Main Coal Seam, Cardowan Colliery; Test No. 1.

Fig. 36.—Pressure-time chart for holes Nos. 2 and 4, Test No. 1.
inserted the stemming rod was found wet in certain parts. Later, after tamping, a rubber balloon was attached to the tube; some water collected in it, but no gas, although the balloon was left attached for more than two hours. The experience with bore-hole No. 3 was similar.

Bore-hole No. 2, 10 ft. long, opposite the road-head A, was wet. After stemming 20 in., a pressure of 17 lb. per sq. in. was registered. Tamping being inserted to the mouth of the hole, a maximum of 21 lb. per sq. in. was reached. The pressure kept steady for 25 hours, until the coal-cutting machine passed the place, making a 4.5 ft. undercut, after which the pressure fell to 15 lb. per sq. in. and continued to fall. Three hours after the undercut, the pressure had decreased to 10 lb. per sq. in.

Borehole No. 4, 10 ft. long, was also wet and a maximum pressure of 15 lb. per sq. in. for this hole was registered after full tamping. Twenty-four hours later the pressure had dropped to zero. Some water and gas were collected in a balloon attached to the tube. This part of the seam was crushed and broken.

The pressures recorded in holes Nos. 2 and 4, are plotted against time in Fig. 36.
In the second test, conducted on February 8th, 1934, a hole 41 ft. long was drilled opposite the bottom road B, Fig. 34, on the dip side of the face. The face had advanced about 230 ft. since the last test. With a view to finding the relation between gas-pressure and depth of hole, it was decided to measure the pressure at 3 points distributed along the hole. To achieve this, a device shown in Fig. 37, was adopted. The drawing is a section through an intermediate pocket in the bore-hole. C is stout copper barrel, open at one end, and provided with a false bottom F; it was partly filled with metal "scrubber," S, and glass wool, W, to prevent any dust or dirt getting into the flexible copper tube T. The latter was attached to C at K by means of a nipple connexion. The space between the closed end and the false bottom F was empty. A solid iron rod R was rigidly fixed in the centre of the barrel. This rod was twice the length of C, and was connected to a solid brass piston P at the inner end. The piston prevented C being choked by clay from the stemming in front; it also provided a clear gas space between P and C.

After a pocket had been pushed into position, the hole was stemmed with plasticine, D, for the first 6 or 8 inches, followed by clay. In the figure, the copper tube, t, is connected to another pocket situated/
the seam in question, the condition at the face, which by then had advanced a further 600 ft. from the position L M, was in outward appearance dry, although a hole dug in the pavement on the dip side would fill with water. In connection with gas pressure-measurement tests in the next section, it has been shown how water oozed from the open ends of some of the narrow copper tubes inserted in the bore-holes at the end of the face.

Judging from the above circumstances, it is evident then, that water possibly played an important part in causing the abnormal and sudden discharge of gas at that part of the face where ignition took place. It is a well-known fact that water is taken up more readily than firedamp by dry coal. Breaks in roof or floor induced by coal mining, may connect a gassy seam to a water-bearing strata, as a result of which a sudden discharge of gas may be expected. There are numerous practical instances on record in support of this contention. It has been pointed out by Prof. Knox,* how water from a upper seam invading a gassy bed below through cracks in the floor may give rise to sudden out-bursts from the pavement.

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Fig. 35.- Device to ascertain the pressure of firedamp in the Meiklehill Main Coal Seam, Cardowan Colliery; Test No. 1.

Fig. 36.- Pressure-time chart for holes Nos. 2 and 4, Test No. 1.
inserted the stemming rod was found wet in certain parts. Later, after tamping, a rubber balloon was attached to the tube; some water collected in it, but no gas, although the balloon was left attached for more than two hours. The experience with borehole No. 3 was similar.

Bore-hole No. 2, 10 ft. long, opposite the road-head A, was wet. After stemming 20 in., a pressure of 17 lb. per sq. in. was registered. Tamping being inserted to the mouth of the hole, a maximum of 21 lb. per sq. in. was reached. The pressure kept steady for 25 hours, until the coal-cutting machine passed the place, making a 4·5 ft. undercut, after which the pressure fell to 15 lb. per sq. in. and continued to fall. Three hours after the undercut, the pressure had decreased to 10 lb. per sq. in.

Borehole No. 4, 10 ft. long, was also wet and a maximum pressure of 15 lb. per sq. in. for this hole was registered after full tamping. Twenty-four hours later the pressure had dropped to zero. Some water and gas were collected in a balloon attached to the tube. This part of the seam was crushed and broken.

The pressures recorded in holes Nos. 2 and 4, are plotted against time in Fig. 36.

Test No. 2

In/
In the second test, conducted on February 8th, 1934, a hole 41 ft. long was drilled opposite the bottom road B, Fig. 34, on the dip side of the face. The face had advanced about 230 ft. since the last test. With a view to finding the relation between gas-pressure and depth of hole, it was decided to measure the pressure at 3 points distributed along the hole. To achieve this, a device shown in Fig. 37, was adopted. The drawing is a section through an intermediate pocket in the bore-hole. C is stout copper barrel, open at one end, and provided with a false bottom F; it was partly filled with metal "scrubber," S, and glass wool, W, to prevent any dust or dirt getting into the flexible copper tube T. The latter was attached to C at K by means of a nipple connexion. The space between the closed end and the false bottom F was empty. A solid iron rod R was rigidly fixed in the centre of the barrel. This rod was twice the length of C, and was connected to a solid brass piston P at the inner end. The piston prevented C being choked by clay from the stemming in front; it also provided a clear gas space between P and C.

After a pocket had been pushed into position, the hole was stemmed with plasticine, D, for the first 6 or 8 inches, followed by clay. In the figure, the copper tube, t, is connected to another pocket situated
situated farther in the hole. Each pocket thus having its tubular connexion, as many tubes pass out from the borehole as there are pockets in it.

The arrangement for boring the hole is shown by sectional elevation and plan in Fig. 38. A five-horsepower compressed air motor, M, was placed on two angle irons, A. The motor, in which the speed could be varied from 10 revs. per minute to anything upwards, was connected to the feed-screw of the Burnside borer, B, by means of a socket. The borer had to be placed, clear of the conveyor, C, as shown in the sectional elevation. The motive power for the motor was supplied from the compressed air pipe, P. An attempt was made to flush out the borings by means of the compressed air, but it proved very inefficient due to the hole being wet. So, latterly, water had to be used for flushing the borings. Some trouble was experienced with the pump of the Burnside borer which was then disconnected from the compressed air motor and the fault mended. The latter part of the drilling, however, was completed by hand labour.

In this test, there were three separate tubes leading to three pockets at distances of 41, 30, and 20 ft., respectively, from the mouth of the hole, as shown in Fig. 39. Each of these tubes was fitted at the outer end with a needle-valve having a screw attachment/
Fig. 37. - Sectional Elevation of Pocket in Borehole, Cardowan Colliery.

Fig. 38. - Arrangement for drilling, Test No. 2.
attachment for the pressure gauge.

The stemming rods were 3/4 inch gas tubings, in 3 ft. 6 in. lengths. A small brass piston, 1 3/4 in., diam., was screwed to the end of the stemming rod for tamping the clay. Before inserting the pocket, its tubular connexion was tied to the stemming rod at 8 ft. intervals. A chalk mark was put on the last rod to indicate the position of the pocket in the hole in relation to its tubular connexion. This was to ensure that during insertion, the tubular connexion lay evenly on the bottom of the borehole. The knots of strings were taken off, one by one as they came to the mouth of the borehole while the pocket was slowly pushed inwards.

The pressure in this hole are plotted against time in Fig. 40. Curves 1, 2, and 3 relate to the pockets at 41, 30, and 20 ft. respectively. The letter S shows in each case the first pressure measurement taken after the start of stemming. Time is reckoned from the completion of the respective boring distances.

A maximum of 69 lb. per sq. in. was reached in pocket No. 1 at 41 ft., but the pressure began to fall immediately until in 43 hours it was only 2 lb. per sq. in. Water was then flowing out of the hole, having been able to pass the stemming. Upon the valve/
Fig. 39: Positions of three pockets in borehole, Test No. 2.

Fig. 40: Pressure-Time Chart for Boreholes at Face, Cardowan Colliery.

- 41-ft. Borehole, Pocket No. 1 at extreme end.
- 2 at 30 ft. from mouth.
- 3 at 20 ft.
- 96-ft. Borehole, Pocket No. 1 at 80 ft.
- 2 at 50 ft.
- 3 at 25 ft.

First Pressure Measurement.
W Water oozed out of the tube.
valve being opened, water oozed out of the copper tube, as indicated by the letter W.

Pressure in pocket No. 2 at 30 ft. reached its maximum value of 25 lb. per sq. in. immediately after the first bit of stemming had been inserted, and then it began to fall gradually in spite of further stemming. It remained steady at 21 lb. for nearly 3 hours, after which there was a further fall of 2 lb. A reading taken 47 hours from the completion of drilling showed the pressure to be only 2 lb. Water oozed out of the copper tube when the valve was opened, as marked by the letter W.

Pocket No. 3, at 20 ft. registered a pressure of 14 lb. per sq. in. only, and it kept steady for a while. After 48 hours, the pressure had fallen to zero, and, like the other two pockets, water, at W, oozed out of the tube.

During the period of test, the coal had been undercut twice, once during the boring of the hole (although some space on both sides of the borehole was left without undercutting), and another 6 hours after the hole was completely stemmed. This hole which had begun 31 in. from the roof was only 9 in. from the roof at 41 ft., as found later when the face had advanced to that distance.

Test No. 3.

In the third test, carried out on March 18th, 1934/
1934, a hole 96 ft. long was bored in the coal. The arrangement for drilling is shown by plan in Fig. 41. A separate portable high pressure pump, $P$, was used to clear out the borings, instead of the pump attached to the Burnside borer, because, it had proved very inefficient in the previous test. The sump, $S$, at the bottom corner, provided an ample supply of water for the pump. A flexible copper tube, $T$, was connected from the portable pump to the pump block, $A$, of the Burnside borer, which was fixed upon two angle irons $E_1$ and $E_2$. It took 23 hours, including stoppages etc., to bore 96 ft. into the coal.

An unusual mishap was experienced after the completion of drilling. When the boring-rods were being drawn out, about 50 ft. of them were left behind in the borehole. This was due to a female part of the screw joint being bodily pulled out from the rod, as shown in Fig. 42. Fortunately, the rods were fished out without much difficulty.

A simple device, as shown in Fig. 43, was found to be both quick and efficient for preparing clay cartridges for stemming. An iron pipe, $A$, was held in a vertical position with a loosely fitted cap, $B$, at the bottom. Hand picked clay, sprinkled with little cement-water, was poured into the pipe and rammed hard with another tube, $C$, which had both ends plugged. The cap, $B$, was then taken out and/
Fig. 41.- Arrangement for drilling, Test No. 3.

Fig. 42.- Mishap in boring.

Fig. 43.- Device for making clay cartridges.
and the rammed clay was gradually forced out by C. Suitable lengths of clay cartridges were then put in packing cases, ready to be sent down the pit for use.

It was learnt from previous experience that there was a tendency for the gas-space of the pocket, to get choked by the clay stemming in front. As a precaution against this, wooden plugs were driven, into the clay stemming, immediately in front of a pocket, as shown in Fig. 44.

Three pockets were pushed home, one after the other, at 80, 50, and 25 ft. respectively, and stemmed in the way already described. The lack of sufficiently long stemming rods prevented the innermost pocket being thrust to the end of the hole.

Curves A, B, and C, Fig. 40, show the relation between pressure and time for these three pockets. A remarkable and puzzling variation of pressure in pocket A at 80 ft. was observed during stemming, as shown by the fluctuations in the curve. A maximum of 45 lb. per sq. in. for this hole was reached 32 hours from the time the drilling was completed. Pocket B, at 50 ft., showed a steady rise in pressure during stemming, until 30 lb. was attained. The maximum pressure recorded in this pocket was 35 lb./
Fig. 44. - Device to prevent choking of the gas-space in the pocket.

Fig. 45. - Extrapolation of ultimate pressure in the Meiklehill Main Coal Seam, Cardowan Colliery, from the results of Test No. 3.
lb., 39 hours from the completion of drilling. The pressure in the third pocket C at 25 ft. reached its maximum of 25 lb. after 46 hours from the completion of drilling.

At points marked W in curves A, B, and C samples of gas were collected, and upon the tubes being opened to the atmosphere water oozed from them; the pressure rose to its former value soon after the valves were closed again.

Discussion of results.

For causes not always avoidable, a lot of time elapsed in these tests between the moment the drilling was completed to the depth at which a pocket was inserted and the first measurement of pressure at that pocket. Nevertheless, an attempt was made, with the results from the longest hole, to extrapolate to infinite depth, and thus to arrive at the pressure in the virgin seam. The operation was carried out by plotting pressure of gas against an inverse function of the depth of hole, in a manner similar to that already described in connexion with the volume of gas adsorbed. As a result, a value of 70 lb. per sq. in. was deduced as a rough approximation to the initial pressure, as shown in Fig. 45.

The results of the boring tests, though showing that the pressure of firedamp in the Meikle-
hill/
hill Main Seam at Cardowan Colliery is probably not high -- being more of the order of the 70 lb. of some of the shrinkage experiments than of the 300 lb. used for the majority of those experiments -- are not of great quantitative value. They are chiefly useful in demonstrating the difficulty of obtaining satisfactory measurements of gas-pressure by means of boreholes, and in pointing the need for an improved technique. The readiness with which shrinkage cracks appear in the coal round about a borehole that is allowed to discharge gas, and the ease with which the pressure is relieved by these cracks are evident from the records. The appearance of water in the holes also complicated matters.

It is doubtful that pressures of high magnitude such as obtained by Wood * or by the early Belgian and French investigators, will be recorded again in coal seams that are being worked or developed.

Once a seam is opened, no direct record of its gas pressure can be obtained even by means of a long borehole. As soon as the "bleeding" of gas starts, shrinkage cracks begin to develop and may extend hundreds of yards in advance of the free surface in the coal from which the gas is exuding. A process such as this, would continue to carry on unless the seam is cut off by a fault or other disturbance and the bleeding of gas is completely checked.

similar P specimen, the rate of elongation for the former, immediately on the introduction of gas, is far greater than that of the latter.

The examples of Nos. 2 and 3 P, are very interesting. The former took 3 hours and the latter one hour, before any sign of elongation was observed; whereas, the R specimen of the same group were extremely quick in their response, as shown by their elongation curves in Fig. 47 and 48, respectively.

In a previous section, it has been shown how Clarain I R, showed a maximum elongation of 0.303 per cent, compared to 0.129 per cent, for Clarain I P. In fact, this phenomenon was first observed in the above specimen. It was with a view to confirming this phenomenon that these tests were carried out.

It may be of interest to note here that Meehan,* found that the expansion of charcoal on sorption of carbon dioxide is independent of the direction of the grain. So far as we are aware, no other tests have been carried out on any other rigid gels and none with gas under pressure. The variation in the elongation of coal (between an R and a P specimen) on gas adsorption has not been observed before, although it may be remarked here, that tests on the swelling of coal on wetting, carried out by Lea,** revealed the same thing.

As/

Fig. 46. - Cardowan I, Reaction of prisms at right angles (R) and parallel (P) to the bedding plane.

Fig. 47. - Cardowan II, Reaction of prisms at right angles (R) and parallel (P) to the Bedding plane.
As a suggestion it can be put forward here that the ash in the coal seems to bring about this appreciable difference between the elongations on gas adsorption of an R and a P specimen.

The P specimen may be compared to a pack of cards in a horizontal position and an R specimen to that in a vertical position, as is shown in Fig. 51.

In the figure, the small arrows indicate the direction of gas-pressure, and the thick arrows the direction of linear elongation. It will be observed that the ash in the P specimen will resist elongation parallel to the bedding and offer resistance against it, whereas, in the R specimen it does not materially interfere with the elongation in that direction.

This is evidenced by the quicker response and greater elongation observed in the R specimens than in the P ones. It can also be assumed, purely on a conjectural basis that the gas perhaps has a better facility for getting into the coal in a direction parallel to the stratification, as shown by the arrow A, than in a direction at right angles to it, as shown by the arrow B, in the above figure. Thus, taking an example of a prism of 100 mm. length and of 10 mm. square in section, the area exposed to the gas in a direction at right angles to the bedding for an R specimen, is 4000 sq. mm., whereas, for a P specimen, it is only 2200 sq. mm.
Fig. 48.- Cardowan III, Reaction of prisms at right angles (R) and parallel (P) to the bedding plane.

Fig. 49.- Cardowan IV, Reaction of prisms at right angles (R) and parallel (P) to the bedding plane.

Fig. 50.- Cardowan V, Reaction of prisms at right angles (R) and parallel (P) to the bedding plane.

Fig. 51.- Effect of ash on elongation & shrinkage.
Special interest attaches to the smaller amount of residual elongation (actually none at all in some cases) exhibited by the specimens taken normal to the bedding, as will be observed by referring to Table 15.

It may again be suggested that in a P specimen the elongation may cause some strain and perhaps also some damage to the internal structure of the ashy parts, with the result, that during the shrinkage period, a violent resistance is offered against the ensuing contraction; whereas, in an R specimen, a similar damage being parallel to the bedding, would not offer any great resistance.

From the above it can be inferred that the non-return of a specimen to its original length may depend to some extent, on the nature and amount of ash content in the coal. However, it must be admitted that any such suggestion is purely conjectural and without sufficient evidence, an explanation is of little value.

All the above ten specimens were examined under X-ray to find if there is any difference as to the ashy parts, but they all looked alike. An attempt was made to correlate the elongation with the ash content, but no such relation was found to exist. Further study is required to elucidate this phenomenon.
CHAPTER XIV

AN INVESTIGATION INTO THE RELATION BETWEEN LINEAR ELONGATION (DUE TO GAS ADSORPTION) AND GAS-PRESSURE.
AN INVESTIGATION INTO THE RELATION BETWEEN LINEAR ELONGATION (DUE TO GAS ADSORPTION) AND GAS-PRESSURE.

As the elongation due to gas adsorption varies with the pressure, an examination of this variation with respect to pressure was considered to be of some interest and hence the following experiments were carried out. The results of tests on seven specimens of coal of different varieties are shown by the pressure-elongation curves in Fig. 52 to 58. All the tests were carried out under the same experimental conditions and the same firedamp was used. During these tests, the temperature was fairly constant.

The curves with arrows pointing towards the origin indicate the shrinkage curves at release of pressure. In every case there was definite evidence of hysteresis being present on shrinkage. The clarain specimen, Fig. 52 with its long axis at right angles to the bedding is particularly interesting in that an inverted type of hysteresis loop was observed in this case. This was the only specimen at right angles to the bedding in these tests. Hence, it is very difficult to say if an inverted hysteresis loop is characteristic of such a specimen. But one fact/
Fig. 52.- Pressure-elongation curve for Clarain, Humph Coal, Lanarkshire.

Fig. 53.- Pressure-elongation curve for Durain, Peacock Splint, Loanhead.
fact seems certain that a right angle prism behaves differently to a prism parallel to the bedding. It has been noticed before, how the former showed greater elongation and less residual-elongation than the latter. However, further work is necessary in this direction to reveal the exact nature of this phenomenon.

No attempt, in general, has been made to join the experimental points by a sweeping curve, except in the case of a durain (Peacock Splint, Loanhead) Fig. 53; this was justified by the uniform nature of the recorded movements as is evident from the experimental points on the graph.

Several attempts have been made before by many investigators to evolve a law of relation between adsorption and pressure, mostly based upon the following exponential equation:

\[
x/m = kp^{1/n}
\]

where, \( x \) = The weight of gas adsorbed.
\( m \) = The weight of adsorbent.
\( p \) = The pressure of the gas.
\( k \) = Constant.
\( 1/n \) = An irrational fraction varying with circumstances.

Most of the works on adsorption of gases by solids, deal with the quantity adsorbed at different pressures. But as expansion is also due to gas adsorption/
adsorption, \(x/m\), in the above sorption Isotherm, may be replaced by percentage linear elongation (E) and expressed as, 

\[ E = kp \frac{1}{n} \]

Strictly speaking, the relation at constant temperature between E and p, should be, 

\[ E = kp - \frac{1}{B}p \]

where, \(1/B\) is the Bulk Modulus for the Material.

It has been shown previously that the last term is small enough to be negligible, especially, if the value for elongation is large.

Dr. Meehan,* made an attempt to correlate the elongation on carbon dioxide sorption by charcoal and pressure, using the above formula. He found, however, that that expression did not hold accurately with his observed results. He next tried a second expression, based on the adsorption equation due to A. M. Williams,** which is,

\[ \log \frac{E}{p} = G + HE \]

where, E and p are as before, and G and H are constants being functions of the temperature. According to his observation, the second equation fairly agreed with his experimental results. An examinations of his curves, however, shows that there is very little to choose/

* loc. cit., P. 127

choose between the above two equations for showing such an agreement.

An attempt was made here, with the elongations observed on firedamp adsorption by coal, at different pressures, to evolve a similar equation or an empirical formula showing the relation between $E$ and $p$.

It was found that in one instance, i.e., Durain, Peacock Splint, Fig. 53, the latter equation fairly agreed with the experimental results. In this case log $E/p$ when plotted against $p$, gave a straight line as shown in the above figure. It will be observed that two points, one at 6 and another at 18 atmospheres, are a little out of the way. If such deviation can be accepted within the limits of experimental error, then, the latter equation holds good in this case. The equation of this curve works out to be, $\log E/p = -0.0112 p - 1.3585$.

A similar attempt with Cardowan No. 4 P, Fig. 54, fails to agree with the above equation, as shown by the log $E/p$-against-$p$ curve in the above figure. In this case, log $E/p$ against log $P$, seems to be in better agreement than the former relation, although the straight line thus plotted can hardly be accepted as even tolerably straight, as evident by the dotted curve in Fig. 54.

Attempts on the results with other specimens utterly/
Fig. 54.- Pressure-elongation curve for Cardowan No. 4.

Fig. 55.- Pressure-elongation curve for Durain, Peacock Rough, Roslin.
utterly failed to show even the slightest possibility of a relation between $E$ and $p$ as, represented by the above equation.

Several other relations were tried with each specimen but all proved fruitless.

It may be remarked here that Dr. Meehan's test with charcoal was at pressures below one atmosphere only. Any other sorption isotherm that has been put forward is invariably based on experimental results mostly at low pressures. It is quite probable, that the relation between $E$ and $p$ is different at higher pressures. At any rate, as far as coal is concerned, it seems improbable that the latter equation will hold good at higher pressures.

The diversity in the experimental evidence of these coals, makes it difficult to correlate a satisfactory general relation between elongation and pressure. Different coal behaves differently and even two coals of the same kind, as for instance durains, Figs. 55 and 56, are not alike in their behaviour; and naturally so, when we consider that these substances can hardly be accepted as strictly homogeneous. There are so many other factors at work, such as moisture, volatile matter, ash etc., that unless we are further enlightened as to the individual nature of their effects, any attempt to find a general relation would prove fruitless. A good deal more work...
Fig. 56. - Pressure-elongation curve for Durain, Great Seam, Midlothian.

Fig. 57. - Pressure-elongation curve for Stanlyd Anthracite, Wales.

Fig. 58. - Pressure-elongation curve for Clarain, Great Seam, Midlothian.
work is necessary before we can proceed in that direction.

Several attempts have been made at such a correlation but they ultimately show the complexity of the mechanisms that are associated with gas adsorption by solids.

Dr. Bangham and Mr. Fakhoury,* have been able to correlate the expansion of charcoal and the volume adsorbed by it, but unless the assumptions made in the above correlation, are confirmed by definite experimental evidence, it remains merely as a tentative hypothesis. Any deviation of the experimental points, from the relation that is sought for, can be safely passed on as experimental error, although such deviation may actually be the result of the mechanism operative at different phases of sorption.

Mr. Graham* has shown that adsorption of nitrogen by moist coal up to a pressure of 50 atmos, approximates more nearly to Henry's Law, whereas, adsorption of firedamp, obeys a relation somewhat of the exponential equation. It may be remarked here, that the exponential equation does not fall in with the modern view of the process of adsorption.

It has been shown by Prof. Briggs,** that/

* loc. cit., p. 78
that with slight modification, Williams' equation also holds good at high pressure for gases above their critical temperature. His experimental evidence on the adsorption of hydrogen and nitrogen by coconut charcoal, at high pressures up to 100 atmos., was in close agreement with his view. The modification was needed to account for the unanchored gas in the pores which is merely compressed according to Boyle's Law. Our knowledge, however, of the size and extent of pores in the coal, is not enough to assess a value for the interstices in the coal. Most probably, such a space would be far too insignificant to be of any value for a modification to be applied in the above equation to test its validity for gas sorption by coal at high pressure. At any rate, the relation between elongation and pressure does not seem to be of the same type as between volume adsorbed and pressure.

An examination of the pressure-elongation curves of these specimens, (except Peacock Splint, Durain and Cardowan No. 4, Figs. 53 and 54, respectively) would appear to show that the elongation is approximately directly proportional to the pressure up to about 10 or 12 atmos. After this, however, there is a definite evidence of change in relation between E and p, as shown by a little flattening in the curves.
cent., which is even a little less than that recorded in the first test. The last 3 tests gave a constant value for elongation, which would seem to indicate that the internal state of the coal was in a somewhat settled condition. It will be noted that the residual elongation also varied in each test. An increase in linear elongation on a subsequent test showed an increase in residual elongation, although the amount was not in proportion to the increase on the former.

Tests were then continued on the same specimen at 300 lb. per sq. in., in the same manner, excepting that the time interval between elongation and shrinkage was one hour instead of half an hour of the previous experiment. The result is depicted by the upper graph in Fig. 59.

It will be observed that there is more uniformity of movement at 300 lb. pressure than at 200. Although there was an increase of 0.007 per cent. in elongation on a second test, the residual elongation, each test was remarkably uniform. Of particular interest is the smaller amount of the latter as observed in this case than at 200 lb. pressure. It may be remarked, here, that the coal had a better scope for shrinkage in this case, due to the longer time-interval. It is also evident that subsequent tests decrease the time taken up by the coal/
Fig. 59.- Effect on the elongation and shrinkage of coal by admitting and releasing gas, respectively, several times in succession, at 200 and 500 lb. per sq. in.

Fig. 60.- Effect on the elongation and shrinkage of coal at different pressures, on sorption and desorption of gas, respectively, by subsequent tests on the same specimen.
coal to reach its apparent equilibrium point for elongation on sorption, but they do not, however, seem to affect the rate of dissorption, as shown by the shrinkage curves which are almost of the same shape in each test.

It would thus appear that pumping gas in and out of the coal, several times, does not materially affect the elongation to any great extent. All it seems to do is to increase the rate of elongation at the beginning. That it does not effect the rate of dissorption, is also quite evident from these tests. No doubt, its effect at lower pressure (200 lb.) shows a somewhat erratic result, but more work is necessary for further elucidation of this point.

A second experiment was conducted on another durain specimen, but this time, observations were taken at different pressures, up to a maximum of 300 lb. per sq. in. Thus, elongations at different pressures from 0 to 300 lb. per sq. in. were measured; the pressure was then released and shrinkages at different pressures were similarly recorded. A time interval of 12 hours was allowed between each subsequent release of pressure. The result is depicted by the graph in Fig. 60. As the fourth test with carbon dioxide, gave a very high amount of elongation (0.515 per cent.), the ordinate (elongation) had to be altered/
altered, as shown on the right in the figure, to enable the CO\textsubscript{2}-curve to be shown along with the CH\textsubscript{4}-curves.

The values for elongation and shrinkage in different tests are tabulated for comparison in Table 16.

Table 16.- Effect on elongation and shrinkage by subsequent tests, at pressures from 0 to 300 lb. per sq. in.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Gas used</th>
<th>Percentage elongation at different pressures lb. per sq. in.</th>
<th>Percentage shrinkage at different pressures lb. per sq. in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>1</td>
<td>CH\textsubscript{4}</td>
<td>0.0435</td>
<td>0.0745</td>
</tr>
<tr>
<td>2</td>
<td>&quot;</td>
<td>0.038</td>
<td>0.0715</td>
</tr>
<tr>
<td>3</td>
<td>&quot;</td>
<td>0.029</td>
<td>0.0615</td>
</tr>
<tr>
<td>4</td>
<td>CO\textsubscript{2}</td>
<td>0.2</td>
<td>0.422</td>
</tr>
<tr>
<td>5</td>
<td>CH\textsubscript{4}</td>
<td>0.066</td>
<td>0.099</td>
</tr>
</tbody>
</table>

It will be observed that in this case a deleterious effect was brought about by subsequent tests. The effect of carbon dioxide is very marked in increasing the swelling properties of the coal on gas adsorption. It may be noted here that in the previous experiment (Fig. 59) the elongation first increased and then decreased to a certain degree on subsequent/
subsequent tests, until an apparently settled state or equilibrium was reached. After this, however, the coal elongated and shrank the same amount on subsequent tests. But the latter experiment (Fig. 60), shows a continual decrease in elongation on subsequent tests (the increase in elongation on the fifth test is obviously due to carbon dioxide).

It must be remembered, however, that in this test, a time-interval of 12 hours between each reading was allowed, compared to half an hour of the previous experiment (Fig. 59) at 200 and 300 lb. per sq. in., respectively. So that these two experiments represent two different effects and for that reason, are not comparable.

The net result, however, on subsequent tests seems decidedly to decrease the elongation, though small its amount may be.

May it be suggested here that some decrease in the attracting energy of the adsorbent is brought about by this continual attaching and detaching of the gas molecules on the surface of the polymers.

The slight drying effect caused each time on sorption may explain the little increase in elongation as observed in the first experiment, (Fig. 59), but then, it is difficult to account for the decrease in elongation in the tests that followed.

However/
However, a true picture of the mechanism going on inside is not possible with our limited knowledge and any attempt to explain these effects is like groping in the dark.
CHAPTER XVI

THE CONDITION OF ADSORBED GAS IN COAL SEAMS.
THE CONDITION OF ADSORBED GAS IN COAL SEAMS.

The generally held view that firedamp may exist in the coal in the liquid form is quite untenable in the light of modern researches on the liquefaction of gases. We cannot conceive of a temperature of \(-95.5^\circ\text{C}\), (the critical temperature of methane, according to Dewar), to exist in any coal seam and for that matter, in a seam of any kind below the surface of the earth. At the above temperature, a pressure of 50 atmospheres is required to liquefy methane; so that, any possibility of the gas being in a liquid state is very remote. But it is quite possible for carbon dioxide in the coal to exist in the liquid state, because its critical temperature is above \(15^\circ\text{C}\).

The cross-sectional area of the capillaries in the coal, are probably not many times greater than the dimension of a methane molecule. Indeed, it may be even smaller in some cases, such as Stanlyyd Anthracite, as has been shown before.

It is unfortunate that an estimate of the internal gaseous volume (volume of the capillaries and polymeral interstices), in the coal, is not possible. So that, a rough approximation as to the probable density of the adsorbed gas is beyond our reach/
reach at present. The fact that there is hardly any difference between the specific gravities of lump and fine coal, suggests that the internal gaseous volume must be exceedingly small. Consequently, the adsorbed film of gas must be in such a highly compressed state that its density may approach very nearly to that of the liquid itself or may be even greater.

It has been shown by Prof. Briggs,* that in colloidal silica and charcoal, the density of the adsorbed gas (nitrogen, at -196 °C) exceeds that of the liquid.

There is a great diversity of opinion as to the thickness of adsorbed films. The hypothesis of a thick stable film, as postulated by many early investigators, is now only accepted, if at all, with great reserve. In the light of modern researches on the theory and structure of molecules and atoms, the field of attraction does not extend through space to a distance greater than that of the order of a molecular diameter. Thus, as soon as a layer of gas molecules has formed on the surface of the polymers, the residual field of the latter will very nearly be satisfied. As a consequence, a second layer, even if formed will not be held at all firmly. Indeed, the sharing of the force of attachment by the second or subsequent layers, may seriously impair the anchorage of the first layer of molecules to the solid/

* loc. cit., p. 56
solid, to such an extent, as to upset true adsorption altogether. Thus, it seems probable, that the adsorbed film is only one molecule thick. The mono-molecular film theory of Langmuir is not clearly defined, in that it supposes the possibility of a second film on the first and a third on the second and so on, until the induced field of attraction is completely satisfied.

Unfortunately, however, no investigator has yet found a means by which he can obtain direct experimental evidence in support of his hypothesis, whether, it be the 'mono-molecular' or the 'multi-layer' or the 'classical thick' film.

In recent years, the supposition that the gas molecules adsorbed on solid surfaces may be in a state of translational motion parallel to the surface, is holding its ground with increasing favour.* The complex mechanism of expansion on gas adsorption has not yet been clearly understood. So that, the conception of a two-dimensional gas enables us to put forward a hypothesis in explanation of the swelling effect on sorption, which has not been possible hitherto. The gas which is firmly anchored on to the surface of the polymers, is able to move about in a directions only parallel to it, and violently bomb- and at the sharp re-entrant angles of the polymers.

The expansion of the solid, therefore, should be/

* loc. cit., p. 2
be directly proportional to the pressure of the gas. We have seen that that is so to a certain extent, after which the increase in elongation is not proportional to the pressure. This is probably due to the resistance offered by the molecules of the adsorbent against the further forcing of the particles apart. Naturally the bombardment does not meet with severe resistance at first. As a result the expansion takes place at a rapid rate as evidenced by experimental results; but when it comes to disturbing or straining the stable lattice built up in the interior of the adsorbent, an increase in the bombardment to maintain pressure becomes essential to the former rate of elongation. It is quite possible, that at a certain stage, the elongation may bring about the joining up of the neighbouring polymers (depending on the internal structure of the coal) which is evidenced by a sudden increase in elongation after an apparently slow rate.
CHAPTER XVII

SUMMARY OF RESULTS AND CONCLUSIONS.
SUMMARY OF RESULTS AND CONCLUSIONS.

1. A new type of apparatus for measuring linear elongation and shrinkage on gas adsorption and desorption, respectively, is described.

2. The expansion and contraction of different coals caused, respectively by the sorption and desorption of gas, are dealt with.

It has been shown that Stanllyd Anthracite is the least responsive of all the coals tested, to firedamp; although it responds quickly to carbon dioxide. It has been suggested that the CO$_2$ molecule being of a linear form, has better penetrating power than the CH$_4$ molecule, which is of a tetrahedron shape. It has been inferred from these tests that the cross-sectional area of the polymers in Stanllyd Anthracite may be smaller than that of a CH$_4$ molecule and bigger than that of a CO$_2$ molecule. The latter seems to bring about a depolymerisation effect due to strain set up on distention. As a consequence, CH$_4$, can then, get into this coal and cause elongation.
tion due to sorption

3. The loss of free moisture in coal seems to increase the elongation on gas adsorption to a certain extent, after which, however, further loss, proves deleterious. It is suggested that there is an optimum value for free moisture at which elongation is greatest on sorption.

4. Tests on shrinkage due to elastic compression are described. It has been shown that the contraction is of a very small order compared with the effect of elongation due to gaseous sorption. However, a definite value for contraction has not been found possible to assess.

5. Tests on the adsorption of water by coal are described. The elongation caused by water-adsorption is discussed. It is suggested that the adsorption of water is not due to capillary condensation.

6. It has been shown that the bottom part of the Meiklehill Main Coal Seam, Cardowan Colliery, has the highest capacity for gas emission.
The evidence assembled regarding the circumstances, both before and after the explosion at the above Colliery, in 1932, points to the conclusion, that, when a gassy seam is invaded by water from surrounding strata, a sudden efflux of gas is to be expected.

7. Underground test for gas-pressure in the above seam is described. It has been deduced that the gas-pressure in the seam in question is of the order of 70 lb. per. sq. in.

8. The elongation caused in coal on gas sorption, is not equal in all directions. It is greater in a direction at right angles to the bedding plane than in a direction parallel to it. It has been suggested that the non-return of a coal prism to its original length on dissorption, may be due to the ash in the coal.

9. Attempts have been made to correlate the elongation on sorption and pressure of gas. A mathematical analysis, however, has not been found successful due to the complex nature of the experimental evidence assembled. It is suggested/
suggested that the elongation is approximately directly proportional to the pressure to a certain extent.

10. It has been shown that admitting and releasing gas-pressure several times in succession, finally, brings about a deleterious effect on the elongation and shrinkage of coal respectively. It has been suggested that the continual attaching and detaching of the gas molecules on the surface of the polymers, may result in a loss of the attracting force in the adsorbent.

11. It has been suggested that the adsorbed firedamp exists in the capillaries and polymeral interstices of the coal, in the form of a highly compressed film of gas, which is, probably, as dense as the liquid itself. In the light of modern researches, the film is, probably, only one molecule thick, and not many molecules deep, as has been supposed before.

The elongation is caused by the bombardment of a two-dimensional gas on the surface of the polymers at the sharp re-entrant angles.