II. "On the Influence of Coal-dust in Colliery Explosions." No. 2. By W. Galloway. Communicated by Robert H. Scott, F.R.S., Secretary to the Council of the Meteorological Office. Received February 27, 1879.

In the former communication on this subject, which I had the honour of submitting to the Fellows ("Proc. Roy. Soc.," vol. xxiv, p. 354), some experiments were described which showed that a mixture of air and coal-dust of a certain known chemical composition was not inflammable at ordinary pressure and temperature; and that, when 0·892 per cent. of fire-damp (by volume), or a greater proportion, was added to the same mixture, it became inflammable and burned freely with a red smoky flame. The general conclusion to which the second result pointed was also stated in the same place to be, that, an explosion originated in any way whatever in a dry and dusty mine, may extend itself to remote parts of the workings, where the presence of fire-damp was quite unsuspected.

The wetness or dryness of the workings of a mine depends, other things being equal, on the temperature of the strata in which they are situated: for it is obvious that if, on the one hand, the temperature of the mine is lower than the dew-point of the air at the surface, the ventilating current will deposit moisture as it becomes cooled in passing through the workings; and if, on the other hand, the temperature of the mine is higher than the dew-point of the air at the surface, the ventilating current will absorb moisture and tend to produce a state of dryness. It is well known, however, that the temperature of the strata in the Coal Measures of this country increases at the rate of about 1° F. for every 60 feet of additional depth below the surface, and, therefore, from what precedes, it is evident *that the comparative wetness or dryness of a mine depends on its depth.*

As far as my own observations are concerned, I have found that coal mines, shallower than 400 feet, are damp or wet, and those deeper than 700 feet are dry and dusty: between these two points, also, there appears to be a kind of debateable ground in which wetness or dryness depends, for the time being, on the coldness or warmness of the air entering the mine at the surface.

In all dry coal mines the coal-dust lying on the floor of the roadways rises in clouds and fills the air when it is disturbed by the passage of men, horses, small waggons, &c.; a sudden puff of air, therefore, such as that produced by a local explosion of fire-damp, or by a shot blowing out its tamping, must necessarily produce the same effect in a greater or less degree according to its intensity. The mixture of coal-dust and air, formed by the action of either the fire-

damp explosion or the blown-out shot, will be inflammable if it contain any larger proportion of fire-damp than 0·892 per cent., and the flame of the original explosion will pass on through it, extending the area of the disturbance as far as the same conditions exist, or, it may be, to the utmost limits of the workings. If it contain more than 0·892 per cent. of fire-damp, it will be more and more explosive, according as the proportion of fire-damp is greater, until a maximum point is reached, beyond which its explosiveness will begin again to decline. If, lastly, it contain less than 0·892 per cent. of fire-damp, or even if it consist only of coal-dust and pure air, it will still be so nearly inflammable that it will probably become so when it undergoes the compression and consequent heating which the occurrence of an explosion in one part of a confined space must necessarily produce throughout the remainder of the same space. It is probable, moreover, that some kinds of coal-dust require less fire-damp than others to render their mixture with air inflammable; and it is conceivable that still other kinds may form inflammable mixtures with pure air.

I have partially investigated the relation between the proportions of air, coal-dust, and gas* required to insure inflammation or explosion on the application of a light; but as the series of experiments is not yet complete, I propose to reserve their description for some future opportunity. I may mention, however, that in the apparatus which I have hitherto employed, the proportion of coal-dust which gave the best results was much larger than might at first sight be thought necessary, namely, about one ounce of dust to a cubic foot of air for all mixtures of gas and air, ranging between one of gas and twenty of air, and one of gas and forty of air. Also, in one of the experiments with the return air of a mine, which I propose to describe in this place, the air requires to be literally *black with dust* before it will ignite. It is, therefore, obvious that the particles which are floating about in the air of a dry mine, in its normal state, cannot render it inflammable; and it is probable that only the sweeping action of a gust of wind, like a squall, passing along the galleries, can raise a sufficient quantity to do so.

Some of the colliery explosions which have occurred during the last two years are amongst the most disastrous on record, and the attempts that have been made to explain them are of the usual unsatisfactory character. The assumption, without a vestige of proof that fire-damp has suddenly burst from the strata, is still maintained even in cases in which the flame is seen to have ramified into the extremity of every *cul-de-sac* and extended to the opposite boundaries of the workings. The very token whereby the ubiquity of the flame is made manifest, is the so-called *charring* of the timber,

* As these experiments were only preliminary ones made chiefly for the purpose of testing the apparatus, common lighting gas was employed in them.

coal, and rubbish; and this, generally in the case of the timber, and always in the case of the coal and rubbish, consists of a coating of coked coal-dust adhering to them superficially, and testifying unmistakably by its presence that coal-dust has actually been playing the part which is claimed for it by myself and others.

Following are a few of the details that have become known regarding the most recent explosions of importance:—

Pemberton (11th October, 1877). 36 men killed. Depth 1,005 feet. At page 333 of the "Reports of the Inspectors of Mines," it is said:—"The Pemberton Colliery had been held up as a model of engineering, and seemed to be the last place at which a disaster of this kind was likely to happen." At page 332 of the same volume, the following gratuitous explanation of the explosion is given:—"The effect of a shot blowing out, and which appears to have occurred, would be to exhaust the face and sides of Rutter's place and Price's place, and this additional fire-damp rushing out into an atmosphere already heavily charged, would bring the air in this particular district up to the explosive point."

Blantyre (22nd October, 1877). 207 men killed. Depth of the workings from 800 to 900 feet. The seam is not very gaseous and the mine was supposed to be well ventilated. It was impossible to say where the explosion began. At page 7 of the official report it is said:—"The explosion extended throughout miles of the workings and was of the most violent kind. The gas in a large portion of the workings had apparently been mixed to a highly explosive state. The noise at the top of No. 2 shaft is described as having been like a shot in a sinking pit, and a great volume of smoke and dust came to the top. On the top of No. 3 shaft the noise was like the bursting of a steam pipe, or shot in a sinking pit, and was as quickly over, flame coming out of the shaft mouth. Flame seems to have extended through nearly all the working places." Again, at page 11:—"The mine being dry and dusty, and the dust being mixed with highly inflammable splint coal, would help to spread the flame and give force to the explosion." Lastly, at page 206 of the notes of evidence, a witness says:—"I desire to make a suggestion. On one occasion Mr. Watson (the manager) told me that the mine, being a dry one, like a desert, the coal-dust would aggravate an explosion."*

Unity Brook (12th March, 1878). 43 men killed. Depth of the workings 792 feet. The workings were examined, and found to be safe, half an hour before the explosion. The mine was dry and dusty.

* It is encouraging to observe that the agency of coal-dust has thus been recognized by some persons connected with mining, although it appears to have entirely escaped the notice of every one except Faraday and Lyell, and some of the French mining engineers, until after the appearance of my first paper on this subject in 1876.

Smoke and soot came up the upcast. The flame had travelled all through the mine and 100 yards up the shaft. Naked lights were used and shots were fired.

Apedale (27th March, 1878). 40 men killed. Depth (?). Smoke and flame came up the shaft. The workings were set on fire.

Haydock (7th June, 1878). 195* men killed. Depth of the workings 750 feet. Smoke and dust were ejected from the shafts. The mine was dry and dusty. It was not possible to say how or where the explosion had occurred. Locked safety lamps were used and no shots were fired in the district where the explosion happened.

Abercarne (11th September, 1878). 264 men killed. Depth (?). A flash of flame and a column of black smoke ascended high into the air above the mouth of the shaft. The workings were set on fire. This mine was well ventilated, and no accumulations of gas of any consequence were known to exist in it. The workings were unusually dry and contained much very fine coal-dust. Locked safety lamps were used and no shots were fired.

Dinas (13th January, 1879). 63 men killed. Depth of the shaft, 1,218 feet. The workings extended under high ground, where they were from 1,500 to 1,800 feet below the surface ; they were very dry and dusty. Small accumulations of explosive gas were sometimes formed in them, but not of sufficient magnitude to account for the disaster. The bottom of the principal shaft was filled up with rubbish in consequence of the timber which supported the entrance to the workings being blown away by the explosion. This obstruction has not yet been removed at the time I write, and the workings have not been entered, nor the bodies got out. I had visited this mine several times during the two or three years preceding the accident, and knew its general condition well. The return air coming from the working places, and therefore filling nearly one-half of the existing open space, *contained always more than 2 per cent. of fire-damp*. In this respect it did not materially differ from the return air of most of the steam coal collieries in the district, being better than some and worse than others. If there had been no coal-dust present I should have considered it to be comparatively safe. As it was, I strongly and repeatedly urged the manager to water the roadways so as to keep them always damp or moist, and he actually had two water-carts made for that purpose. On the occasion of my last visit before the explosion, however, I found they were not being employed, and I had no power to enforce my views. The result has been exactly what might have been anticipated, and what is liable to happen any day in every mine similarly circumstanced. It is quite plain that, with 2 per

* The official reports are not yet published, and in some cases the number of men killed may not be quite correct, as they are taken from the reports in the *Times*.

cent. of fire-damp in the return air, the slightest puff of a local fire-damp explosion, or of a blown-out shot, will raise sufficient dust to increase the amount of inflammable matter a hundredfold, and produce all the phenomena that have been observed in this and similar cases. Locked safety lamps were used, and shots were fired. The cause of this explosion, like that of the preceding ones, will in all probability never be ascertained.

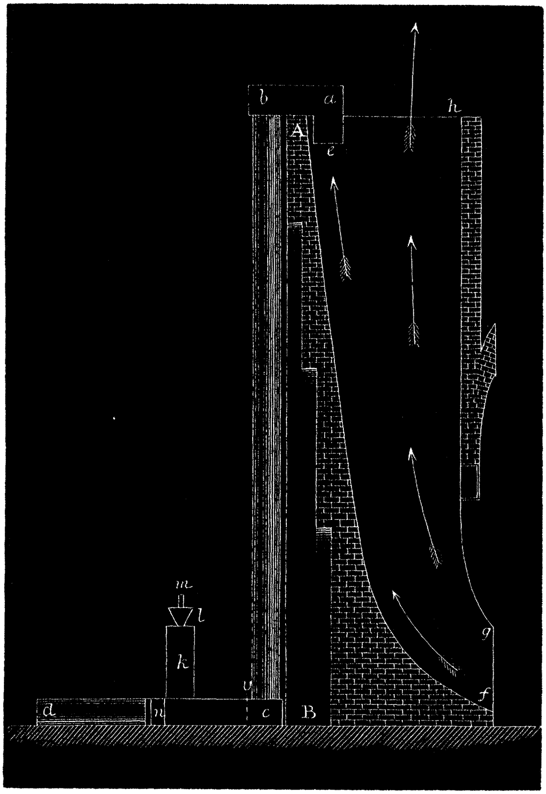
When smoke and soot are produced; or dust is ejected from the shafts; or the coal, stone, and timber have a charred appearance, due to a deposit of coked coal-dust on their surface; or, lastly, when large superficies of the sides of the galleries are found to be on fire immediately after the event, we may safely conclude that coal-dust has played an important, if not a predominant, part in the explosion. The manner in which coal-dust operates in setting fire to coal and timber is probably as follows:—The air is travelling rapidly in one direction along a gallery, throwing a continuous shower of dust, small pieces of coal, &c., against all surfaces that deflect it or obstruct its course; at the instant the flame traverses it, however, the coal-dust is melted; it then assumes the properties of flaming pitch, adheres to the surfaces against which it is thrown, and rapidly accumulates until it forms a crust of greater or less thickness, according to the length of time the air continues to travel in the same direction. If it is thick enough to retain its high temperature, and is supplied with fresh air immediately, it continues to burn, and the flame soon communicates itself to the body of the coal or timber; but if it is thin, or if the surrounding atmosphere cannot support combustion, it becomes extinguished. In the second case, the surface covered with the crust or layer of coke is vulgarly said to be *charred*.

During the course of the past year I have been enabled to make a considerable number of experiments with mixtures of coal-dust, air, and fire-damp; thanks to the liberality of the Lords of the Committee of Council on Education, who acted upon the recommendation of the Government Grant Committee in affording me pecuniary aid; and thanks also to the kind co-operation of Mr. Archibald Hood, managing director of Llwynypia Colliery, and his two sons, Messrs. Robert and William Hood, whose assistance has been quite invaluable to me. The two experiments I propose now to describe were made at Llwynypia Colliery with the coal-dust and fire-damp, whose analyses are given at pp. 357 and 358 of the "Proceedings," No. 168, 1876.

In order to test the truth of the hypothesis that the return air of a mine in which a considerable amount of fire-damp is emitted by the coal may be rendered inflammable by the addition of coal-dust, I had an apparatus constructed at Llwynypia Colliery, and placed close to the ventilating fan in such a position that a current of the return air from the upcast shaft could be made to pass through it at pleasure.

Referring to fig. 1, which represents the whole arrangement, *e*, *f*, *g*, *h* is the chimney of a Guibal fan, through which all the air from the

FIG. 1.



workings, amounting to about 80,000 cubic feet per minute, is ejected into the atmosphere. *a*, *b*, *c*, *d* is a bent pipe partly made up of square wooden boxes, partly of round sheet iron pipes; at the end, *a*, it overhangs, and partly dips into, the chimney of the fan; and at the other end the part *c*, *d*, runs along the surface of the ground. *k* is a branch of the same area in cross section as the other wooden parts of the apparatus; it is covered on the top, but is provided with a hopper *l*, having a wooden plug *m*, through which coal-dust can be introduced, *v* is a valve by means of which the velocity of the current can be regulated, and *n* is a door.

When the regulating valve is full open a strong current of return air, amounting to 1,251 cubic feet per minute, passes through the apparatus, and makes its escape at *d*. This air is not only saturated with

water, but it contains innumerable globules of water floating in it. On the 5th of October last its temperature was 69°·3 F. An oil lamp, having a good large flame, was placed inside the door *n*, so that the flame was in the centre of the current, and it was then found that the temperature of the air had increased to 74°·5. The temperature, quantity, and quality of the various currents of return air in this colliery were, on the 11th of April, 1878, as follows:—

Date upon which the observation was made.	Number of current.	Cubic feet of air per minute.	Temperature Fahr.	Height of cap on small flame.	Approximate percentage of fire-damp in the air.
1878.			Dry.	Inch.	
April 11	1	10,128	66°	$\frac{1}{8}$	2 per cent.
,, ,, ...	2	21,000	74°	$\frac{3}{16}$	$2\frac{1}{4}$,,
,, ,, ...	3	44,421	73°	$\frac{1}{4}$	$2\frac{1}{2}$,,
		75,549			

The elevation of temperature due to placing the lamp inside the apparatus is, therefore, not abnormal. The hopper having been filled with coal-dust the plug was raised somewhat and stirred about so as to determine the entry of dust into the chamber *k*. The immediate result was the appearance of a large and very hot red flame at the mouth of the pipe *d*. The length of the visible part of the flame varied from 6 to 8 feet, and its greatest diameter from 2 to $2\frac{1}{2}$ feet; and it was accompanied by large volumes of black smoke and dust. The pipe *d* soon became so hot that it could not be approached closely.

The second experiment is intended to illustrate the effects of an explosion of fire-damp in a dry mine containing coal-dust. One part of the apparatus represents a gallery with coal-dust lying on its floor as well as on the horizontal timbers, the buildings, and other rough surfaces at its top and sides; another part represents a cavity in the roof containing an explosive mixture of fire-damp and air. When the explosive gas is ignited the flame sweeps down into the gallery, the disturbance raises the coal-dust and the results are exactly those that have been foreseen. Figs. 2 to 6 show all that is necessary for under-

FIG. 2.

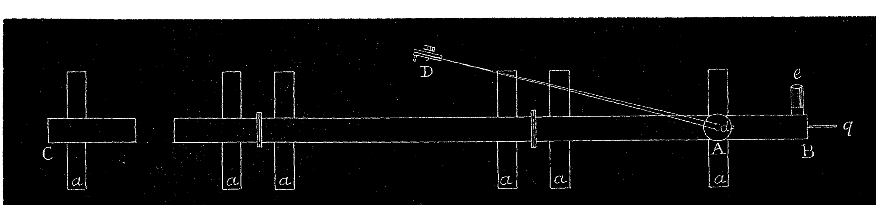


FIG. 3.

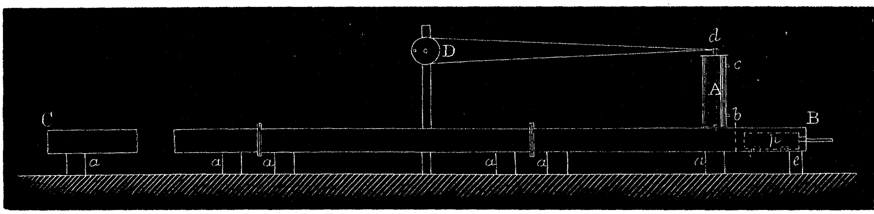


FIG. 4.

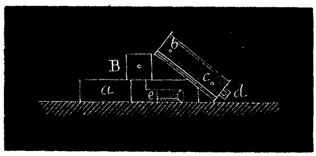


FIG. 5.

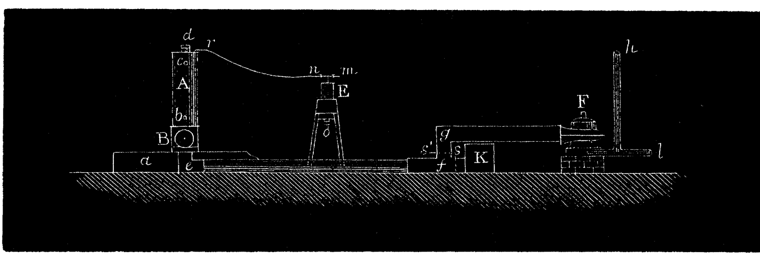
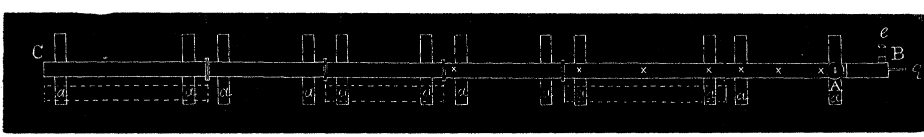


FIG. 6.



standing the apparatus and the experiment. In all the figures, A represents the cavity in the roof: it is a galvanized sheet-iron cylinder, 4 feet long by 15 inches in diameter, covered at the top and open at the bottom. There is a stuffing-box in its cover which allows a thin spindle to pass through it in an air-tight manner. At its lower end the spindle carries a fan which consists of a thin metallic disk 11 inches in diameter, having a hole 4 inches in diameter in its centre, and with radial blades $1\frac{1}{2}$ inches high on its upper surface. When the fan revolves, the blades, which are nearly touching the cover of the cylinder, throw out the air centrifugally and draw in new supplies through the hole in the disk. Immediately below the

hole in the disk, and concentric with it, there is a thin sheet-iron pipe 4 inches in diameter, whose upper end almost touches the disk while its lower end descends to within 4 or 5 inches of the bottom of the cylinder. When the fan is made to revolve rapidly, the air passes up through the central pipe with a velocity of 460 feet per minute. At its upper end the spindle carries a small grooved pulley, *d*, which is made to revolve by means of an endless cord passing round it and over another large grooved driving wheel D. The lower end of the cylinder rests on an iron ring screwed down to the top of the wooden gallery BC, in which there is an opening corresponding to the size of the cylinder. The cylinder is attached to one side of the iron ring by a hinge which allows it to be folded back into the position shown in fig. 4. At the other side it can be fastened by a screw in an upright position as shown in the other figures.

The gallery BC, consists of a range of wooden pipes 14 inches square inside, and, altogether, $79\frac{1}{2}$ feet long. The centre of the cylinder A is 5 feet from the end B, and there is a valve just below the point *b*, by means of which the part of the gallery towards B can be isolated from the remainder. The separate pipes have broad wooden flanges which are put close together when they are placed so as to form a gallery, but they are not fastened to each other in any way; they rest on wooden blocks *a a*, and any one of them can be drawn out from between the two on each side without disturbing the others. This is shown by the dotted lines in fig. 6. Near the end B there is a sheet-iron cylinder 3 feet long by 10 inches in diameter, closed at each end, and having an inlet pipe for steam at *q*, and an outlet pipe at *t* for condensed water and steam. At the same end also there is a branch *e*, *f*, *g*, leading to K, which is the horizontal part *d c*, of the apparatus represented in fig. 1. This branch is also connected with a blowing fan F, driven by a steam turbine of which *l* and *h* are the steam and exhaust pipes. The pipe bringing fire-damp from below ground, referred to in my former paper, can be made to deliver its fire-damp into the air inlets of the fan in the same way as in the former experiments. It will now be evident that currents of air of various qualities can be made to traverse the gallery B C from B towards C. Thus, if the valve *s* is open, while the valve *s′* is shut, the return air of the upcast shaft passes through the apparatus and escapes at C; but if *s′* is open and *s* is shut, the return air is cut off, and by setting the fan F in motion, we obtain either pure air, or air and fire-damp mixed, as we may desire. In every case, also, the air passes over, and is heated by, the steam cylinder *p*, so that, even when return air is used, the interior of the gallery CD can be kept dry.

The interior of the cylinder A is lined with wood about ·2 inch thick, and its capacity is about 4·648 cubic feet. For the purpose of obtaining the explosive mixture required, the cylinder E, 8 inches in diameter,

and 2 feet long, is filled with fire-damp, of which a certain measured proportion is afterwards transferred to the interior of the cylinder A through the india-rubber tube *r n*. This is done by admitting water through an india-rubber pipe attached at the point O. At the same time as the gas is flowing in at the top of the cylinder A, air is allowed to escape at the point *b* near its bottom by taking out a plug for that purpose. The plug is put in immediately after the operation is completed. The amount of fire-damp employed is as near as may be ·456 cubic foot. The cylinder E is refilled with fire-damp by shutting a stop-cock at *n*, opening another at *m*, which is connected with the fire-damp pipe by means of an india-rubber tube not shown in the drawing, and lowering the water bucket below the level of the bottom of the cylinder E. Before the fire-damp is admitted to the interior of the cylinder A, a paper diaphragm is inserted between its lower end and the ring to which it is hinged and screwed, so as to isolate it from the gallery BC. The explosive mixture in the cylinder A is ignited by the spark of a powerful magneto-electric machine which Messrs. Cross Brothers, of Cardiff, most kindly lent to me for the purposes of these experiments. The wires pass through the plug at *b*, and are brought together just inside the cylinder.

The method of forming an explosive mixture in the cylinder A, will now be sufficiently plain, but I will repeat the description of the operations in regular order. When the cylinder is in the position shown in fig. 4, several sheets of paper are laid over the opening in the top of the gallery; the cylinder is then raised to an upright position and fastened by means of the screw. The plug *b* is opened and fire-damp is made to flow through the pipe *r n*, displacing a corresponding volume of air which escapes at *b*. As soon as the requisite volume of gas has been obtained the cock *r* is shut and the plug *b* is replaced. The driving wheel D is next made to revolve at the rate of about eighty turns per minute; twenty-five or thirty turns being found quite sufficient to make a perfect mixture; and, thereafter, a spark from the magneto-electric machine causes the explosion.

When there is no coal-dust in the gallery BC, the flame of the fire-damp explosion does not extend further than from 7 to 9 feet from the bottom of the cylinder A. It should be understood that the valve at *b* is always closed just before the spark is passed.

When the gallery contains coal-dust, on the other hand, scattered along its floor, and lying on a few shelves, whose position will be given immediately, and when it is filled with the return air of the upcast shaft, the flame of the explosion traverses its whole length, and shoots out into the air at the end of C, to distances varying from from 4 to 15 feet beyond it. At first, it appeared to me that the wooden gallery might be prolonged indefinitely with the same result; but on adding another pipe at the end of C, I was surprised to find

that I could not, by any possibility, get the flame to travel more than one-half or two-thirds of the former distance, and I came to the conclusion that the initial impulse, which raises the coal-dust, is insufficient to overcome the resistance under the altered conditions. Again, I had 60 feet of nearly air-tight pipe prepared, thinking thereby to prevent the energy of the wave created by the fire-damp explosion from being dissipated; but here, once more, I found that it was impossible to get the flame to travel to a distance of more than 30 or 40 feet from the origin, and in this case I concluded that the expanded part of the wave extinguished the flame of the coal-dust. The best results were obtained when the wooden pipes had open seams along the junction of the boards of which they are formed.

At the beginning of the present month (March, 1879), Professor G. G. Stokes, F.R.S., communicated to me the suggestion that if a weak solution of chloride of calcium were used for watering the roadways of mines, instead of ordinary water, the deliquescent salt would tend to retard evaporation, and a smaller quantity of water would serve the purpose of keeping the workings damp. Accordingly, I have begun an experiment with such a solution in a dry mine, but it is not yet sufficiently advanced to enable me to state any results in the present paper.

The temperature of the air current passing along the gallery varied from 74° F. near the explosion-cylinder to 60° at the end C. The wooden shelves spoken of above were in sets of three (one above the other at equal distances) the shelves themselves being about 6 inches broad. One set was placed at each of the points ×, fig. 6; and a brick was placed so as to obstruct the passage below the lowest shelf of the first, third, and fourth sets for the purpose of causing the force of the explosion to exert itself more powerfully in sweeping the dust off the shelves and mixing it with the air.

The arrangements whereby pure air, or pure air and fire-damp, can be employed, were only completed before the weather became unsuitable for continuing the experiments, which, I need hardly say, are made in the open air. I obtained sufficient results, however, to show that the absence of even the small proportion of fire-damp contained in the return air of Llwynypia Colliery, makes a great difference in the force of the explosion and the distance to which the flame will travel along the gallery. I found, also, that when two per cent. of fire-damp was added to the current of pure air entering the fan F, even better results were obtained than with the return air of the mine.

Although this apparatus appears to be on too small a scale to solve the coal-dust question unequivocally, I think the results obtained with it are sufficiently conclusive to enable us to affirm, that a fire-damp explosion, occurring in a dry coal mine, is liable to be in-

definitely extended by the mixture of air and coal-dust produced by the disturbance which it initiates.

The dangers due to the presence of coal-dust in dry mines can be very easily avoided by sprinkling water plentifully on the principal roadways along which the air currents pass, in going to, and coming from, the working places. For example, Llwynypia Colliery, which was formerly one of the driest and most dusty of the mines in the South Wales basin, is now kept constantly damp or wet in this way with a daily expenditure of about 1,800 gallons of water. The amount of air passing through it at present is over 80,000 cubic feet per minute, and its out-put of coal is, on the average, about 800 tons per day.

III. "The Contact Theory of Voltaic Action." No. III. By Professors W. E. AYRTON and JOHN PERRY. Communicated by Dr. C. W. SIEMENS, F.R.S. Received February 19, 1879.

(Abstract.)

The authors commence by referring to the experiments that had been made prior to 1876, on the difference of potentials of a solid in contact with a liquid, and of two liquids in contact with one another, and they point out that:—

1. The earlier experiments were not carried out with apparatus susceptible of giving accurate results.

2. Owing to the incompleteness of the apparatus assumptions had to be made not justified by the experiments.

3. *No direct* experiments had been performed to determine the difference of potential of two liquids in contact, with the exception of a few by Kohlrausch, using a method which appeared to the authors quite inadmissible as regards accuracy of result.

In consequence of this great vagueness existed as to whether the contact difference of potentials between two substances, when one or both were liquids, was a constant depending only on the substances and the temperature, or whether it was a variable dependent upon what other substance was in contact with either. Some authorities regarded it as a variable. Gerland considered he had proved it to be a constant, but first, the agreement of the value of the electromotive force of each of his cells with the algebraical sum of the separate differences of potential at the various surfaces of separation, and which was the test of the accuracy of his theory, was so striking, and so much greater than polarisation, &c., usually allows one to obtain in experiments of such delicacy, that one could not help feeling doubtful regarding his

FIG. 1.

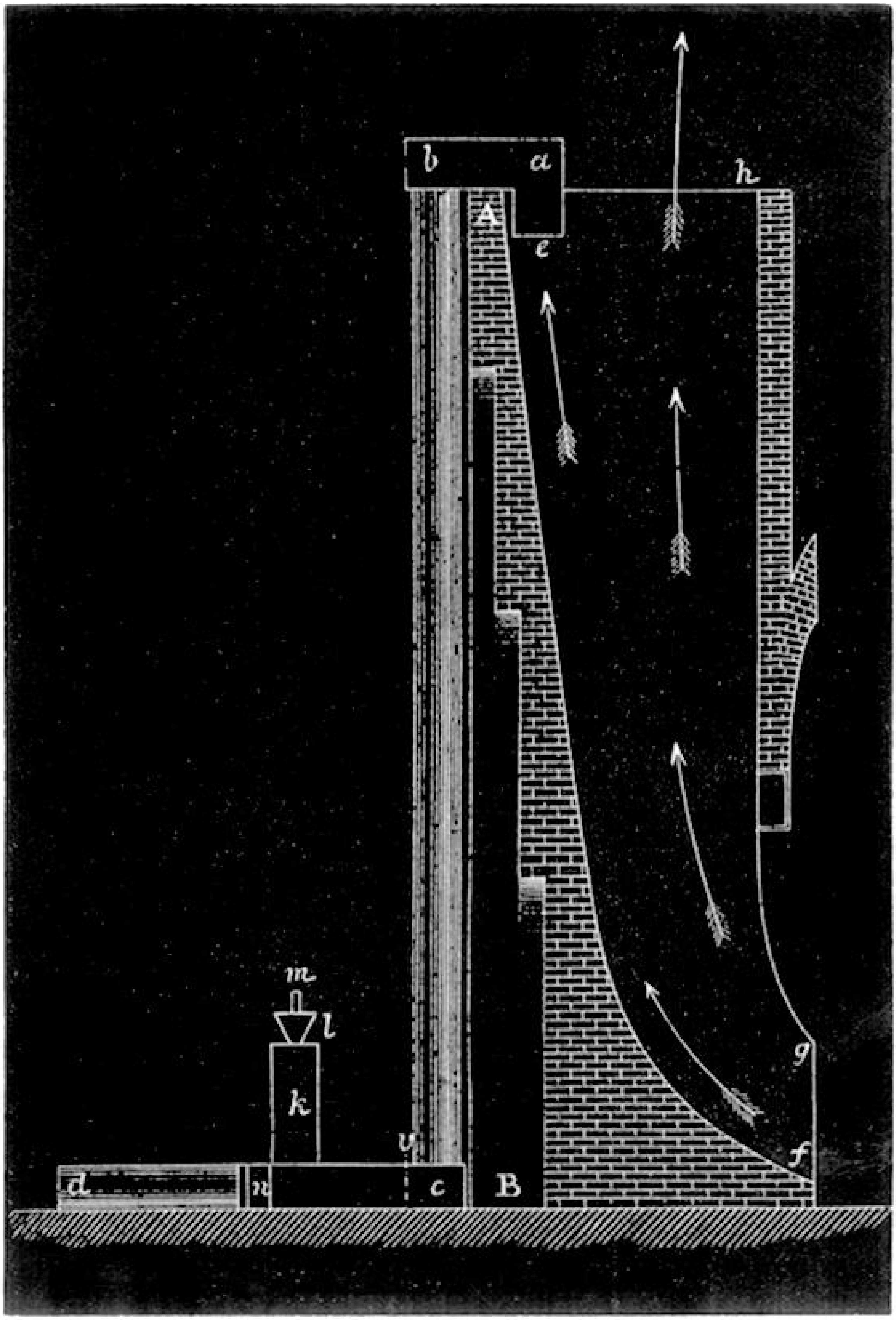


Fig. 2.

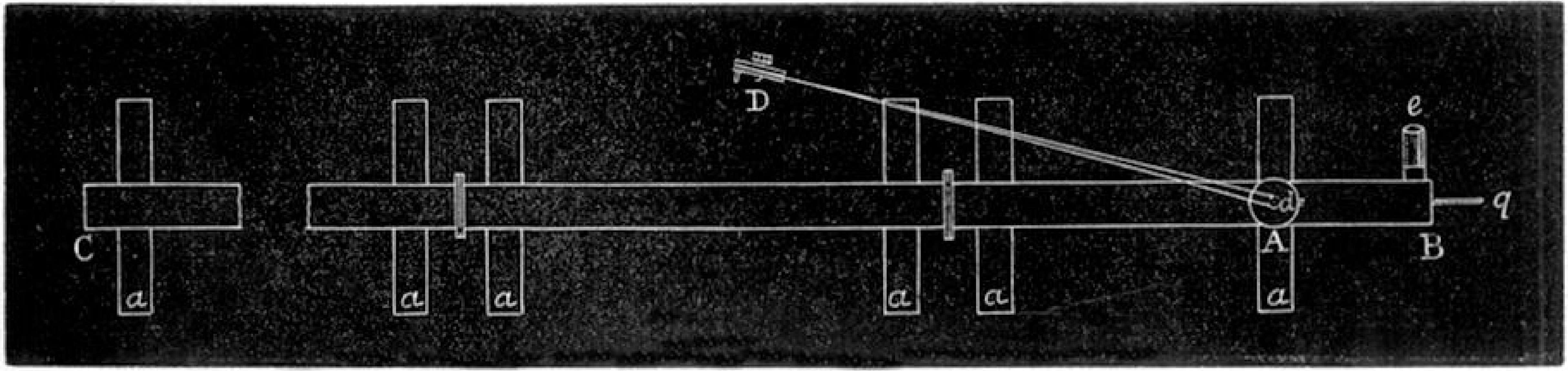


FIG. 3.

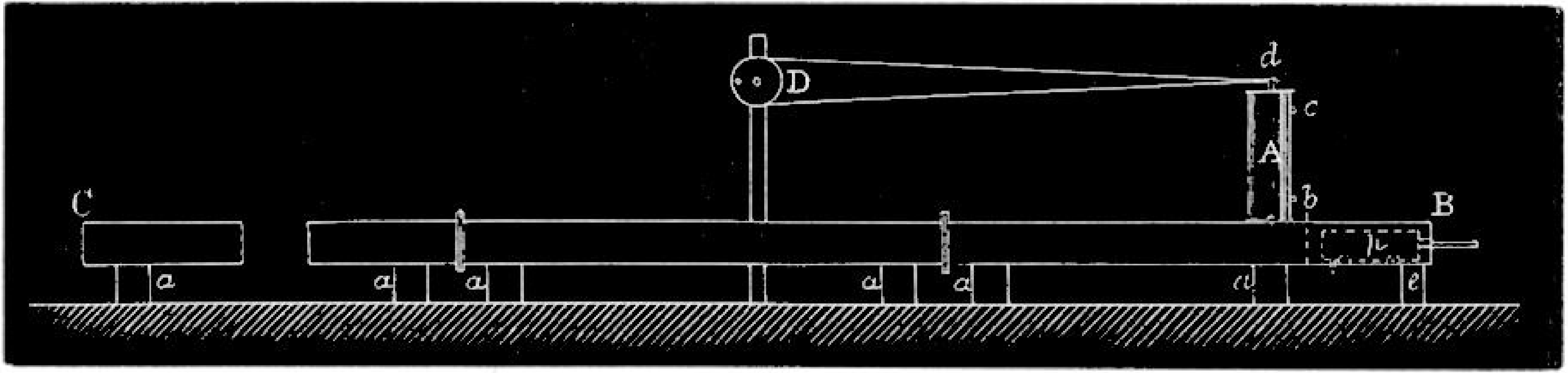


FIG. 4.

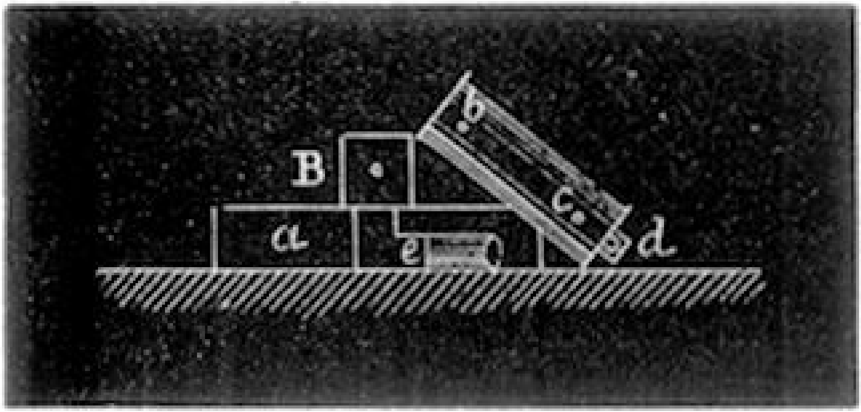


FIG. 5.

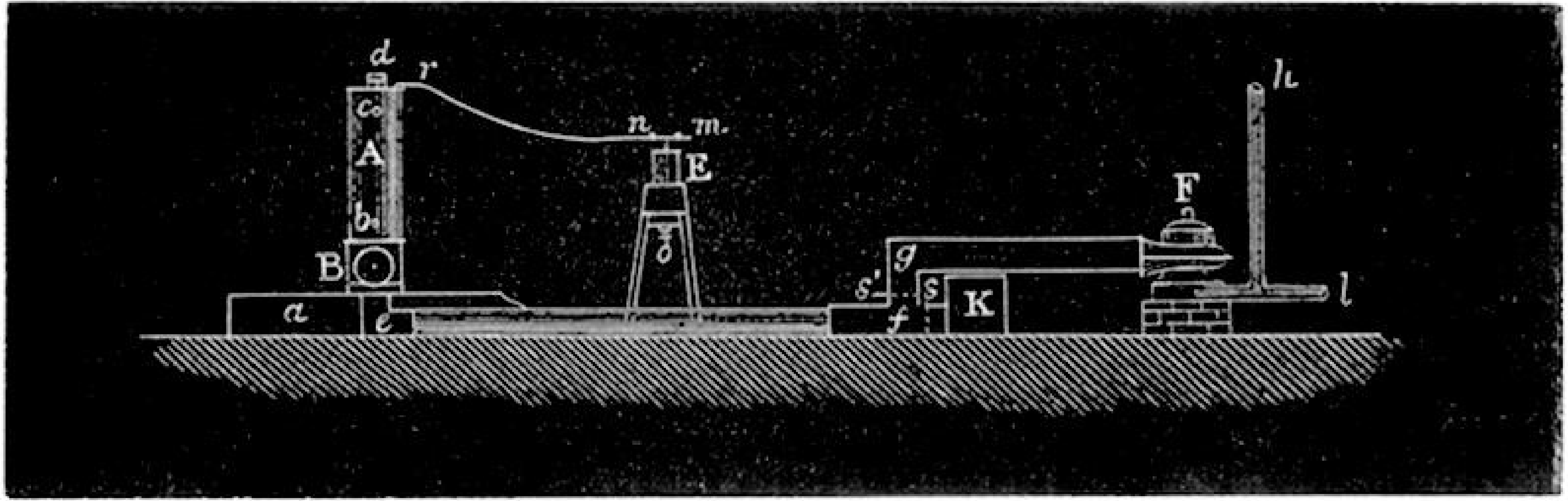


Fig. 6.