

II. *Researches on Explosives.—Fired Gunpowder.* By Captain NOBLE (late R.A.),
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A. INTRODUCTORY HISTORY.

THE investigations which form the subject of this memoir have occupied our attention for a considerable time, having been commenced in 1868. They have been made

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collaterally with a series of experiments carried on by a Committee appointed by the Secretary of State for War, with the view, among other objects, of determining the most suitable description of powder for use in heavy ordnance, which is still continually increasing in size; indeed our main object has been to endeavour to throw additional light upon the intricate and difficult subject under investigation by that Committee.

There are perhaps few questions upon which, till within quite a recent date, such discordant opinions have been entertained as upon the phenomena and results which attend the combustion of gunpowder. As regards the question alone of the pressure developed, the estimates are most discordant, varying from the 1000 atmospheres of ROBINS to the 100,000 atmospheres of RUMFORD; or even, discarding these extreme opinions in favour of views which have been accepted in modern text-books as more reliable, the difference between an estimate of 2200* and of 29,000† atmospheres is sufficiently startling as regards a physical fact of so much importance. The views regarding the decomposition of gunpowder are nearly as various; and we therefore think that a description and discussion of our own researches may be usefully preceded by a short account of the labours of the previous investigators of this subject and of the grounds upon which their conclusions were based.

In the year 1702, DE LA HIRE, who, according to ROBINS, was the first writer on the force of fired gunpowder, supposed that it was due to the increased elasticity of the air contained in and between the grains, the function of the powder itself being merely that of a heating agent. ROBINS (who, however, greatly underrated the temperature of explosion) pointed out that the elasticity so acquired would not exceed 5 atmospheres, and that such a pressure was not the two-hundredth part of the effort necessary to produce the observed effects.

ROBINS‡, in 1743, read before the Royal Society a paper in which he described experiments tending to show that gunpowder, when fired, generated permanent gases which, at ordinary temperatures and atmospheric pressure, occupied a volume 236 times greater than that of the unexploded powder. He made further experiments to show that, at the temperature which he conceived to be that of explosion, the elasticity of the permanent gases would be increased fourfold, and hence the maximum pressure due to fired gunpowder would be about 1000 atmospheres.

ROBINS considered that the whole of the powder (such as he employed) was fired before the bullet was sensibly moved from its seat. He argued that, were such not the case, a much greater effect would be realized from the powder when the weight of the bullet was doubled, trebled, &c.; but his experiments showed that in all these cases the work done by the powder was nearly the same.

* BLOXAM, C. L., 'Chemistry, Inorganic and Organic,' 1867, p. 427. OWEN, Lieut.-Col., R.A., 'Principles and Practice of Modern Artillery,' 1871, p. 155.

† PROBERT, G., 'Traité d'Artillerie Théorique et Expérimentale,' 1859, pp. 354-360.

‡ New Principles of Gunnery, 1805, pp. 59-74.

In 1778 Dr. HUTTON*, of Newcastle-on-Tyne, read before the Royal Society an account of his celebrated researches in Gunnery; and in his 37th tract are detailed the experiments from which he deduced the maximum pressure of gunpowder to be about twice that given by ROBINS, or a little more than 2000 atmospheres.

HUTTON, like ROBINS, saw that the moving force of gunpowder was due to the elasticity of the highly heated gases produced by explosion; and, upon the assumption that the powder was instantaneously ignited, he gave formulæ for deducing the pressure of the gas and velocity of the projectile at any point of the bore. These formulæ, the principles of thermodynamics being then unknown, are erroneous, no account being taken of the loss of temperature due to work performed; but we shall have occasion to point out that the error arising from this cause is not nearly so great as might be at first supposed †.

In 1797 Count RUMFORD‡ communicated to the Royal Society his experimental determinations of the pressure of fired gunpowder; his results, although conjecturally corrected by more than one writer, have retained up to the present time their position as the standard, if not the only, series of experiments in which the pressure has been obtained by direct observation.

In prosecuting his remarkable experiments Count RUMFORD had two objects in view: *first* to ascertain the force exerted by exploded powder when it completely filled the space in which it was exploded; *secondly*, to determine the relation between the density of the gases and the tension.

The apparatus used by RUMFORD consisted of a small strong wrought-iron vessel or chamber 0.25 inch (6.3 millims.) in diameter, and containing a volume of .0897 cubic inch (1.47 cub. centim.). It was terminated at one end by a small closed vent filled with powder, so arranged that the charge could be fired by the application of a red-hot ball; at the other end it was closed by a hemisphere upon which any required weight could be placed.

When an experiment was to be made, a given charge was placed in the vessel, and a weight, considered equivalent to the resulting gaseous pressure, was applied to the hemisphere. If, on firing, the weight was lifted, it was gradually increased until it was just sufficient to confine the products of explosion, and the gaseous pressure was calculated from the weight found necessary.

The powder experimented with was sporting, of very fine grain; and as it contained only 67 per cent. nitre, it differed considerably from ordinary powder. Its specific gravity (1.868) and gravimetric density (1.08) were also very high; but in his experiments Count RUMFORD appears to have arranged so that the weight of a given volume of gun-

* Mathematical Tracts, 1812, vol. iii. pp. 209–316.

† HUTTON, in a note to the new edition of ROBINS'S 'Gunnery,' published in 1805, mentions that the elastic force of gunpowder was considered by JOHN BERNOULLI to be that of 100 atmospheres, while DANIEL BERNOULLI considered it to be equal to about 10,000 atmospheres.—ROBINS, *loc. cit.* p. 57.

‡ Philosophical Transactions, 1797, p. 222.

powder was nearly exactly equal to that of the same volume of water,—that is to say, the gravimetric density was about equal to unity.

The curve drawn on Plate 13 exhibits the results of the first and most reliable series of Count RUMFORD'S observations. It shows the relation he believed to exist between the density of the gas and its pressure, and is expressed by the empirical formula $p=1.841x^{1+.0004x}$, p being the tension and x the density of the gas.

The charges with which RUMFORD experimented were very small; the largest, with one exception (by which his vessel was destroyed), was 18 grains (1.17 grm.). The total quantity of powder required to fill the vessel was about 28 grains (1.81 grm.). It will be observed that, if the curve (Plate 13) were supposed to be true up to the point when the chamber is completely filled, the pressure exhibited would be about 29,000 atmospheres. But, high as this result is, RUMFORD considered it much below the truth. In addition to the series the results of which are graphically represented, a second series was made, the results of which were very discordant.

From Plate 13 it will be observed that, with a charge of 12 grains (0.78 grm.) (equivalent to a mean density in the products of combustion of 0.428), the tension of the gas was in the first experiment about 2700 atmospheres; but in this second series the tension with the same charge was repeatedly found higher than 9000 atmospheres.

The discrepancies between the two series of experiments are not explained; but, relying upon the second series, and on the experiment by which the cylinder was destroyed, RUMFORD calculated that the tension of exploded gunpowder, such as that employed by him, when filling completely the space in which it is confined, is 101,021 atmospheres (662 tons on the square inch)*. He accounts for this enormous pressure by ascribing it to the elasticity of the steam contained in the gunpowder, the tension of which he estimates as being doubled by every addition of temperature equal to 30° F. He further considers the combustion of powder in artillery and small arms to be comparatively slow, and that hence the initial tension he assumes is, in their case, not realized.

In 1823 GAY-LUSSAC appears to have communicated to the "Comité des Poudres et Salpêtres" a report of his experiments upon the decomposition of gunpowder†. GAY-LUSSAC'S products were obtained by allowing small quantities of gunpowder to fall into a tube arranged to receive the gases, and heated to redness. The collected permanent gases, when analyzed, gave in 100 volumes 52.6 volumes of carbonic anhydride, 5 of carbonic oxide, and 42.4 of nitrogen. GAY-LUSSAC gave the volume of these gases, at a temperature of 0° C. and 760 millims. barometric pressure, as occupying 450 times the space filled by the powder, the gravimetric density of which was .9. PIOBERT, however, points out that GAY-LUSSAC'S results, thus stated, are not possible, and suggests that, by an error, the quantity of gas actually found has been doubled.

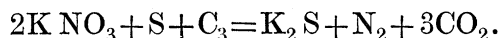
PIOBERT'S suggestion is, from various corroborative circumstances, exceedingly pro-

* RUMFORD, *loc. cit.* p. 280.

† We have been unable to obtain the original of this report; see, however, PIOBERT, *loc. cit.* p. 293.

bable, and is confirmed by the fact that GAY-LUSSAC himself estimated the permanent gases at about 250 volumes.

In 1825 CHEVREUL*, after drawing attention to the difference in the decomposition of gunpowder when occurring explosively, as in the bore of a gun, and when taking place slowly, as by ignition in open air, supposes the decomposition in the former case to be represented by the equation



He points out that the actual constituents of gunpowder are employed in proportions almost in exact accordance with this formula; and the same view appears to have been taken by GRAHAM†, who further supposes that the potassium sulphide is converted into sulphate on coming into contact with the air.

CHEVREUL gives potassium sulphide, sulphate, carbonate, cyanide, nitrate or hyp-nitrite, and carbon as composing the solid residue of gunpowder when burnt slowly; and gives further, as the result of some experiments of his own, for the gaseous products in 100 volumes:—

Carbonic anhydride	45·41 vols.
Nitrogen	37·53 „
Nitrous oxide	8·10 „
Sulph. hydrogen	0·59 „
Marsh-gas	3·50 „
Carbonic oxide	4·87 „

Between the years 1831–36 a great number of very important experiments, chiefly upon the combustion and inflammation of gunpowder, were made by General PIOBERT. The results of these experiments, together with PIOBERT's theoretical views, are contained in his work on the properties and effects of gunpowder‡.

PIOBERT considered that the velocity of inflammation of gunpowder, that is the transmission of the ignition from one grain to another, when the charge was contained in a close vessel or tube offering a high resistance, was very great; but he did not § consider that the influence of the high temperature and great tension of the gases exercised a sensible effect in increasing the rapidity of combustion of the individual grains.

It is somewhat difficult to collect his views upon the subject of the decomposition of gunpowder; and his work on this point must be taken more as a *résumé* of the views of chemists on the subject than as an expression of his own. He seems, however, to have ascribed a great influence to the mode of ignition, even on the quantity of permanent gases, and quotes results varying from 200 volumes to 650 volumes||, all taken at atmospheric temperatures and pressure.

* Dictionnaire des Sciences Naturelles, tom. xxxv. p. 58.

† Encyclopædia Britannica, Art. "Gunpowder."

‡ PIOBERT, G., 'Traité d'Artillerie, Propriétés et Effets de la Poudre,' 1859.

§ *Loc. cit.* pp. 158–162.

|| *Loc. cit.* p. 292.

He states that, from theory*, the quantity of gas should be comprised between 330 and 350 volumes, and should amount in weight to three fifths of that of the powder.

As regards the tension of the products at the moment of explosion, he accepts as tolerably correct the first series of RUMFORD'S experiments, and makes the pressure of gunpowder, when fired in its own space, about 23,000 atmospheres†.

He further considers it possible that the presence‡ of the vapour of water may add to the explosive force of gunpowder. He shares RUMFORD'S views as to the solid products being in the state of vapour at the moment of explosion; he ascribes the high tension he assumes to the difference in the behaviour of vapours and permanent gases when highly heated, and divides the phenomenon of explosion into two very distinct epochs:—the first when the solid products are in the state of elastic vapours, adding their tension to that of the permanent gases; the second epoch being when the permanent gases act alone, the vapours being condensed.

In 1843 General CAVALLI§ proposed to apply to an experimental gun, at various distances from the bottom of the bore, a series of small barrels of wrought iron, arranged to throw a spherical bullet which would be acted upon by the charge of the gun while giving motion to its projectile. By ascertaining the velocities of these bullets, CAVALLI considered that the tensions in the bore would be ascertained. This arrangement was carried out with a "canon de 16," under his own superintendence, in 1845; and from these experiments was deduced the theoretical thickness of the metal at various points along the bore.

General CAVALLI appears to have estimated at a very high rate the tensions realized in the bores of guns. He|| considered that, with the Belgian "brisante" powder of 1850, a tension of 24,000 atmospheres (158 tons per square inch) was actually realized, while in the less inflammable powders the tension was, he considered, under 4000 atmospheres.

In 1854 a Prussian Artillery Committee made a series of experiments¶ to determine the pressure exerted by the powder in the bores of the 6- and 12-pounder smooth-bored guns.

The plan adopted was a great improvement on that suggested by CAVALLI, and was as follows:—

In the powder-chamber a hole was drilled, and in this hole was fitted a small gun-barrel of a length of, say, 8 inches. Now, if the gun be loaded, and if in the small side barrel we place a cylinder whose longitudinal section is the same as that of the projectile, when the gun is fired, on the assumption that the pressure in the powder-chamber is uniform, the cylinder and the projectile will in equal times describe equal spaces, and

* PROBERT, *loc. cit.* p. 291.

† *Loc. cit.* p. 359.

‡ *Loc. cit.* p. 316.

§ *Revue de Technologie Militaire*, tom. ii. p. 147.

|| CAVALLI, Gen., 'Mémoire sur les Éclatements des Canons &c.,' 1867, p. 83.

¶ *Archiv für die Offiziere der Königlich Preussischen Artillerie- und Ingenieur-Corps*, tom. xxxiv. p. 2. *Revue de Technologie Militaire*, tom. i. p. 9, tom. ii. p. 152.

after the cylinder has travelled 8 inches it will be withdrawn from the action of the charge. If, then, we know the velocity of the cylinder, we know that of the projectile when it has travelled 8 inches. Again, if we make the section of the cylinder half that of the projectile, it will describe in the same time double the space and have acquired double the velocity, and so on; so that, for example, if the section of the cylinder be one eighth of that of the projectile, we shall, if we know the cylinder's velocity, know that of the projectile when it has travelled 1 inch.

The general results at which the Prussian Committee arrived were, that in the 6-pounders the maximum pressure realized was about 1100 atmospheres (7·2 tons per square inch), and in the 12-pounders about 1300 atmospheres (8·5 tons per square inch). They further found that, with every charge with which they experimented, two maxima of tension were distinctly perceptible.

These experiments were made the subject of an elaborate memoir by the distinguished Russian Artillerist General MAYEVSKI*, who confirmed generally the results arrived at by the Prussian Committee.

Between the years 1857 and 1859 Major RODMAN† made an extensive series of experiments on gunpowder for the United States Government.

The chief objects of RODMAN'S experiments were:—1st, to ascertain the pressure exerted on the bores of their then Service Guns; 2nd, to determine the pressures in guns of different calibres, the charges and projectiles in each calibre being so arranged that an equal column or weight of powder was behind an equal column or weight of shot; 3rd, to investigate the effect produced on the gaseous tension in the bore of a gun by an increment in the size of the grains of the powder; and 4th, to determine the ratio which the tension of fired gunpowder bore to its density.

In carrying out these experiments, RODMAN made use of an instrument devised by himself, and since extensively used on the Continent. It is represented in Plate 14. fig. 1, and consists of a cylinder, A, communicating by a passage, B, with the bore of the gun or interior of the vessel, the pressure existing in which it is desired to measure.

In the cylinder is fitted the indicating-apparatus, consisting of a piece of copper, C, against which is placed the knife D, shown in elevation and section. The pressure of the gas acting on the base of the piston E causes the indenting-tool to make a cut on the soft copper, and, by mechanical means, the pressure necessary to make a similar cut in the copper can be determined.

A small cup at F prevents any gas passing the indenting-tool, while the little channel G allows escape should any, by chance, pass.

RODMAN considered that his experiments showed that the velocities obtained in large guns with the service small-grained powder might be obtained, with a greatly diminished

* *Revue de Technologie Militaire*, tom. ii. p. 174.

† *Experiments on Metal for Cannon and qualities of Cannon Powder*. Boston, 1861.

strain on the gun, by the use of powder properly adapted in size of grain to the calibre and length of bore proposed to be used.

RODMAN'S conclusions on this head are extremely valuable, although, as has been elsewhere pointed out*, some of his experimental results are open to grave criticism. His experiments on the relation between the tension and density of powder (the powder being placed in a strong shell and fired through a small vent) were not carried far enough to be of much value; but on Plate 13. fig. 2 we have represented his results in comparison with those of RUMFORD.

RODMAN also made an attempt to determine the pressure that would be exerted when powder was exploded in its own space. He fired the charges, as before, through a vent in a strong shell, and considered that the maximum pressure would be realized before the shell burst. His results were very various, ranging from 4900 to 12,400 atmospheres, the highest tension being obtained with the smallest charge. These anomalous results were probably due to the distance from the charge at which his instrument was placed, the products of combustion doubtless attaining a very high velocity before acting on the piston.

In 1857 BUNSEN and SCHISCHKOFF published† their very important researches on gunpowder. Their experiments were directed, first, to determine the nature and proportions of the permanent gases generated by the explosion of gunpowder; secondly, to determine the amount of heat generated by the transformation. With the aid of these experimental data they deduced, from theoretical considerations, the temperature of explosion, the maximum pressure in a close chamber, and the total theoretical work which gunpowder is capable of performing on a projectile.

The powder in these experiments was not exploded, but deflagrated, by being allowed to fall in an attenuated stream into a heated bulb in which, and in the tubes connected with it, the products were collected.

The transformation, according to these experimenters, experienced by gunpowder in exploding, is shown in the following scheme. It will be observed that the permanent gases represented only about 31 per cent. of the weight of the powder, and occupied at 0° C. and 760 millims. only 193 cubic centims.—that is, approximately, 193 times the volume occupied by the unexploded powder.

* NOBLE, "Tension of Fired Gunpowder," Proc. Royal Institution, vol. vi. p. 282.

† POGGENDORFF'S 'Annalen,' vol. cii. p. 325. A translation of BUNSEN and SCHISCHKOFF'S memoir appeared in the occasional papers of the Royal Artillery Institution, vol. i. p. 297; see also, at p. 312 of the same volume, Mr. ABEL'S remarks on BUNSEN and SCHISCHKOFF'S results.

TABLE I.—Showing the transformation experienced by Gunpowder after BUNSEN and SCHISCHKOFF.

1. grm. powder	{	Nitre.....	·7899	}	gave when exploded:—	{	Residue 0·6806 grm.	{	K_2CO_3	grms. ·1264
		Sulphur	·0984				$K_2S_2O_8$		·0327	
		Charcoal {	C ·0769				Gases 0·3138 grm.		K_2SO_4	·4227
			H ·0041						K_2S	·0213
			O ·0307						KCNS	·0030
									KNO ₃	·0372
									(NH ₄) ₂ CO ₃ ..	·0286
									S	·0014
									C	·0073
										cub. centims.
									SH ₂	·0018 = 1·16
									O	·0014 = 1·00
									CO	·0094 = 7·49
									CO ₂	·2012 = 101·71
									H ₂	·0002 = 2·34
									N	·0998 = 79·40
							0·9944 ,,			193·10

In Table III. a comparative statement is given of the foregoing results with those of other recent experimenters and with those furnished by our investigations.

BUNSEN and SCHISCHKOFF determined the number of units of heat generated by combustion, by exploding a small charge of powder in a tube immersed in water. They found that the combustion of a gramme of powder gave rise to 620 gramme-units of heat; and hence they calculated that the temperature of explosion, in a close chamber impervious to heat, was 3340° C (5980° F.).

From the above data the pressure in a close vessel is deducible; and they computed that the maximum pressure which the gas can attain, which it may approximate to but can never reach, is about 4374 atmospheres, or 29 tons on the square inch.

BUNSEN and SCHISCHKOFF further computed the total theoretical work which a kilogramme of gunpowder is capable of producing on a projectile at 67,400 kilogrammetres.

In the course of our paper we shall have frequent occasion to refer to these very important researches.

In 1858 Dr. J. LINCK* repeated, with Würtemberg war-powder, BUNSEN and SCHISCHKOFF's analysis of the products of combustion, which were obtained by the same method. The composition of the powder used is given in Table II.

LINCK's results, which we have placed in the same Table as those of BUNSEN and SCHISCHKOFF, differed in several points from the results of the latter chemists, but chiefly in the much smaller quantity of potassium sulphate found. LINCK considered that 1 gramme of the powder used generated 218·3 cub. centims. of gas.

In 1863 M. VON KAROLYI† examined the products of combustion of Austrian musket- and ordnance-powder.

* Annalen der Chemie, vol. cix. p. 53.

† POGGENDORFF's 'Annalen,' April 1863. Philosophical Magazine, ser. 4, vol. xxvi. p. 266.

M. VON KAROLYI'S method of obtaining the products of combustion consisted in suspending in a spherical shell a small case containing a charge of the powder to be experimented with. Before firing the charge, the air contained in the shell was exhausted; the powder was fired by electricity.

The arrangement will readily be understood from the sketch shown in fig. 3, Plate 15.

After combustion, the gases were obtained for examination by means of the stop-cock, while the solid residue remaining in the shell was removed with water and filtered.

The composition of the powders used is given in Table II., and the results of analysis in Table III. VON KAROLYI computed that the gases resulting from 1 gramme of small-arm powder generated 226.6 cubic centims., and from 1 gramme of ordnance-powder 200.9 cub. centims.

The Astronomer Royal, Sir G. B. AIRY, in a paper* published in 1863, "On the Numerical Expression of the Destructive Energy in the Explosions of Steam-boilers, and on its comparison with the Destructive Energy of Gunpowder," considers that "the destructive energy of 1 cubic foot of water (62.23 lb.=28.23 kilos.) at the temperature which produces the pressure of 60 lb. to the square inch is equal to that of 1 pound of gunpowder, and that the destructive energy of 1 cubic foot of water at the temperature which produces the pressure of 60 lb. to the square inch, surrounded by hot iron, is precisely equal to the destructive energy of 2 lb. of gunpowder as fired in a cannon."

AIRY takes the energy of a kilogramme of powder as fired from a gun at 56,656 kilogrammetres=82.894 foot-tons per lb. of powder; so that the total energy of gunpowder would be somewhat less than double the above value. He states, however, that this estimate does not pretend to be very accurate.

In 1869 were published, in the 'Zeitschrift für Chemie' †, the results of some experiments made by Colonel FEDOROW to determine whether the products varied materially with the mode of combustion.

FEDOROW experimented (1) by firing a pistol with a blank charge into a glass tube 4 feet long, (2) and by firing a shotted 9-pounder bronze gun with 3 lb. of powder; the residues were in each case dissolved in water and analyzed.

The composition of the powder employed by FEDOROW is given in Table II., and his analytical results are shown in Table III.

From the experiments with the gun, FEDOROW calculated that the gaseous products were 82.6 cub. centims. N, 162.1 cub. centims. CO₂, and 14 cub. centims. SO₂ and O. He considers that several successive reactions take place during combustion, that potassium sulphate and carbonic anhydride are first formed, while the excess of carbon reduces the sulphate to carbonate, hyposulphite, and carbonic anhydride.

In 1871 Captain NOBLE ‡, one of the present writers, in detailing to the Royal Institution his earlier researches on the tension of fired gunpowder, stated that the conclusion at which he had arrived from the results of his experiments, where the

* Philosophical Magazine, ser. 4, vol. xxvi. p. 329.

† Vol. v. p. 12.

‡ Proceedings of Royal Institution, vol. vi. p. 282. Revue Scientifique, No. 48, p. 1125.

products of combustion were entirely or partially confined, was, that the maximum pressure of fired gunpowder, of the usual gravimetric density, when unrelieved by expansion, did not greatly exceed 6100 atmospheres (40 tons to the square inch). Upon the same occasion a curve was exhibited, showing the relation between the tension and the density of the exploded products. These results have been confirmed by our present more extensive and exact investigations.

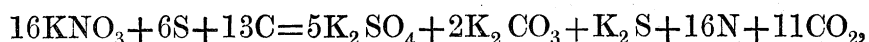
Captain NOBLE also stated that, by means of a special apparatus, which was fully described at the time, he had not only determined the tension of the gases at various densities, but had exploded considerable charges filling entirely the chambers of close vessels, and had altogether retained and at pleasure discharged the gaseous and other products of combustion*.

BERTHELOT† published, in 1872, a collection of theoretical papers upon the force of powder and other explosive substances.

BERTHELOT does not attempt to evaluate the force of fired gunpowder, but evidently accepts as tolerably correct‡ the tensions assigned by RUMFORD and PIOBERT, and accounts for the discrepancy between their conclusions and those of the modern chemists by assuming that the laws of MARIOTTE and GAY-LUSSAC lose all physical significance for pressures so enormous as those developed in the combustion of gunpowder.

BERTHELOT is disposed§ to think that dissociation plays a considerable role during the expansion of the products in the bore of a gun. He supposes that the phenomena of dissociation do not exercise their influence only during the period of maximum effect, but that, during the expansion of the gases, a cooling effect is produced, by which a more complete combination is effected and more heat disengaged.

Taking BUNSEN and SCHISCHKOFF'S experiments as a basis, BERTHELOT expresses the decomposition experienced by gunpowder by the equation||



which he considers represents their results with sufficient exactness.

In 1873 M. DE TROMENEC¶ communicated to the Academy of Sciences a short memoir on the means of comparing the absolute force of varieties of powder. His method was based upon the principle that, when a body is exploded without producing mechanical effect, the "force disponible" is converted into heat, and that it is only necessary to explode a given weight in a close vessel and determine the heat produced.

The apparatus used by DE TROMENEC was closed in much the same manner as was

* In the present paper, in Section K, the results of some of Capt. NOBLE'S earlier experiments are given. They accord, as will be seen, exceedingly well with the series we have discussed at length; but a few experiments made with a fine-grained powder are excluded, both because the powder, being sporting, was not comparable with the fine-grain used in the present researches, and because the differences in their composition are unknown, the sporting-powder not having been analyzed.

† Sur la Force de la Poudre. Paris, 1872.

‡ *Loc. cit.* p. 80.

§ *Loc. cit.* p. 83.

|| *Loc. cit.* p. 91.

¶ Comptes Rendus de l'Académie des Sciences, tom. lxxvii. p. 126.

that employed by Captain NOBLE in his earlier experiments already alluded to. The three kinds of powder experimented with gave results varying between 729 and 891 calories generated by the combustion of 1 kilogramme of powder.

In the same* number of the 'Comptes Rendus' in which DE TROMENEC's memoir is given, appears a note by MM. ROUX and SARRAU, in which, and in a subsequent note†, are determined, with small charges, some of the points to which our own investigations have been specially directed.

MM. ROUX and SARRAU have given, for five species of powder, the number of calories and volume of gas generated by a given weight of powder, and have from these data calculated the temperature of combustion and tension of the gas.

With one of the powders, representing closely the composition of those chiefly experimented with by us, the number of calories and volume of the gas agree nearly exactly with the numbers found by ourselves. There is, however, a considerable difference in our determinations (both theoretical and experimental) of the tension of the gas and also of the temperature of explosion, the temperature being estimated by ROUX and SARRAU at about 4200° C. and the tension at about 4700 atmospheres.

We shall return, however, to these points when discussing our own experiments.

B. OBJECTS OF EXPERIMENTS.

The chief objects which we had in view in making these investigations were:—

First. To ascertain the products of combustion of gunpowder fired under circumstances similar to those which exist when it is exploded in guns or mines.

Second. To ascertain the tension of the products of combustion at the moment of explosion, and to determine the law according to which the tension varies with the gravimetric density of the powder.

Third. To ascertain whether any, and, if so, what well-defined variation in the nature or proportions of the products accompanies a change in the density or size of grains of the powder.

Fourth. To determine whether any, and, if so, what influence is exerted on the nature of the metamorphosis by the pressure under which the gunpowder is fired.

Fifth. To determine the volume of permanent gases liberated by the explosion.

Sixth. To compare the explosion of gunpowder fired in a close vessel with that of similar gunpowder when fired in the bore of a gun.

Seventh. To determine the heat generated by the combustion of gunpowder, and thence to deduce the temperature at the instant of explosion.

Eighth. To determine the work which gunpowder is capable of performing on a shot in the bore of a gun, and thence to ascertain the total theoretical work, if the bore be supposed of indefinite length.

* Comptes Rendus, tom. lxxvii. p. 138.

† Ibid. p. 478.

C. METHODS OF EXPERIMENT.

1. *Explosion-apparatus.*

We propose, in the first place, to describe the principal apparatus used in these investigations, and shall commence with that portion which is of primary importance, viz. the vessel in which the explosions were produced. Two sizes of vessels were used, the larger being capable of holding about $2\frac{1}{4}$ lb. (1 kilogramme) of powder, the other being about half that capacity.

Both vessels were of the same general construction, and similar to that described in Captain NOBLE'S Lecture at the Royal Institution already referred to. A drawing of the apparatus is given in Plate 14. figs. 2 & 3.

A (see figs. 2 & 3) is a mild steel vessel of great strength, carefully tempered in oil, in the chamber of which (B) the charge to be exploded is placed.

The main orifice of the chamber is closed by a screwed plug (C), called the firing-plug, which is fitted and ground into its place with great exactness.

In the firing-plug itself is a conical hole, which is stopped by the plug D, also ground into its place with great accuracy. As the firing-plug is generally placed on the top of the cylinder, and as, before firing, the conical plug would drop into the chamber if not held, it is retained in position by means of the set-screw S, between which and the cylinder a small washer (W) of ebonite is placed. After firing, the cone is, of course, firmly held, and the only effect of internal pressure is more completely to seal the aperture. At E is the arrangement for letting the gases escape; the small hole F communicates with the chamber where the powder is fired, and perfect tightness is secured by means of the mitred surface (G). When it is wished to let the gases escape, the screw E is slightly withdrawn, and the gas passes into the passage H.

At K is placed the "crusher-apparatus" for determining the tension at the moment of explosion.

When it is desired to explode a charge, the crusher-apparatus, after due preparation, is first carefully screwed into its place, and the hole F closed. The cone in the firing-plug is covered with the finest tissue-paper, to act as an insulator.

The two wires LL, one in the insulated cone, the other in the cylinder, are connected by a very fine platinum wire passing through a small glass tube filled with mealed powder. Upon completing connexion with a DANIELL'S battery the charge is fired.

The only audible indication of the explosion is a slight click; but frequently, upon approaching the nose to the apparatus, a faint smell of sulphuretted hydrogen is perceptible.

The difficulties we have met with in using this apparatus are more serious than might at first sight appear.

In the first place, the dangerous nature of these experiments rendered the greatest caution necessary, while, as regards the retention of the products, the application of

contrivances of well-known efficacy for closing the joints, such as *papier-mâché* wads between disks of metal (a method which has been successfully employed with guns), are inadmissible, because the destruction of the closing or cementing material used, by the heat, would obviously affect the composition of the gas. Every operation connected with the preparation of the apparatus for an experiment has to be conducted with the most scrupulous care. Should any of the screws not be perfectly home, so that no appreciable amount of gas can escape, the gases, instantly upon their generation, will either cut a way out for themselves, escaping with the violence of an explosion, or will blow out the part improperly secured, in either case destroying the apparatus.

The effect produced upon the apparatus, when the gas has escaped by cutting a passage for itself, is very curious. If, for example, one of the plugs has not been sufficiently screwed home, so that the products of combustion escape between the male and female threads, the whole of these threads at the point of escape present the appearance of being washed away, the metal having been evidently in a state of fusion, and carried over the surface of the plug by the rush of the highly heated products.

Again, the difficulty of opening the vessel after explosion, when large charges have been used, is very great. This will be readily understood when the temperature and pressure of explosion are considered. The exploding-chamber being filled with products intensely heated and under an enormous pressure, there is an expansion of the interior surface of the cylinder. Hence small portions of the fluid products become forced in between the threads of the screws. These solidify into a substance of intense hardness, which cements together the metal surfaces, and, on cooling, the contraction of the cylinder puts such a pressure on the screw, that, in attempting to open it, seizure is very difficult to avoid. In one or two cases it was found impossible to open the cylinder until melted iron had been run round it, so as to cause it to expand.

This difficulty has been in a great measure avoided, in the more recent experiments, by making the screws conical, so that when once started clearance is rapidly given, and they are removed with comparative ease.

2. *Measurement of Pressure.*

The apparatus used for the measurement of the tension of the gas was precisely similar to that which has been used by the Committee on Explosives, and consists of a screw-plug of steel (Plate 14. figs. 4 & 5), which admits of a cylinder of copper or other material (A) being placed in the small chamber (B). The entrance to the chamber is closed by the movable piston (C), and the admission of the gas is prevented by the use of the gas-check, D. When the powder is fired, the gas acts upon the base of the piston and compresses the cylinder. The amount of compression of the cylinder serves as an index to the force exerted, the relation between the amount of crush and the pressure necessary to produce it being previously carefully determined.

3. *Measurement of the Volume of the Permanent Gases.*

The apparatus used for the measurement of the permanent gases is shown in Plate 15. figs. 1 & 2. A is a vessel the annular space (B) of which is filled with water; on the surface of this a thin film of oil is floated, to prevent any slight absorption of the gas which might otherwise take place.

Immediately after the explosion of a charge, the gas from which it is desired to measure, the cylinder (C) containing the products is placed on the table (D), and the gasometer (E) is placed over the cylinder; the height of the water on the glass scale (F) being then registered, the escape-screw (G) of the cylinder is turned, by means of a turncock passing through the stuffing-box (M).

When the gas has all escaped, the height indicated on the glass scale being again registered, the cubic contents are known, and the thermometer (H) and height of barometer being noted, the necessary data are available for reducing the volume of the gas to a temperature of 0°C . and a barometric pressure of 760 millims.

4. *Measurement of Heat.*

To determine the heat generated by explosion, a charge of powder was weighed and placed in one of the smaller cylinders described, which was kept for some hours in a room of very uniform temperature. When the apparatus was throughout of the same temperature, the thermometer was read, the cylinder closed, and the charge exploded.

Immediately after explosion the cylinder was placed in a calorimeter containing a given weight of water at a measured temperature, the vessel being carefully protected from radiation, and its calorific value in water having been previously determined.

The uniform transmission of heat through the entire volume of water was maintained by agitation of the liquid, and the thermometer was read every five minutes until the maximum was reached. The observations were then continued for an equal time to determine the loss of heat in the calorimeter due to radiation, &c.; the amount so determined was added to the maximum temperature.

In this method there is a possible source of error; the walls of the cylinder being of very considerable thickness, it is obvious that, although the outer surface of the cylinder must be of the same temperature as the water, it by no means follows that this is true of the internal surface; consequently the loss of heat due to radiation, &c. may be in some degree compensated by a flow of heat from the interior.

We had reason, from some experiments we made, to believe that the error due to this cause was very small; and our views were confirmed by finding no appreciable rise of temperature on placing some water from the calorimeter into the chamber of the cylinder immediately after an experiment.

5. *Collection of Gaseous Products.*

To collect the gases for analysis, a small pipe was screwed into the escape-passage (H) of the cylinder (Plate 14. figs. 2 & 3), and an india-rubber tube, terminating in a glass

nozzle, was led to a mercurial trough. Before the gas was taken, a sufficient quantity was allowed to escape to clear the tubes of air; the gas was then collected in tubes over mercury, and confined in the usual manner by sealing them with the blowpipe.

The gas was generally collected in from five to fifteen minutes from the time of explosion. Owing to the dangerous nature of the experiments, and the precautions necessary to be adopted in exploding such considerable charges of powder, it was not generally possible to collect the gases more rapidly; but a comparison of the analysis of different tubes taken from the same experiment has shown that, at all events within moderate limits, no change takes place in the composition of the gas by its continued contact with the solid products.

6. *Collection of Solid Products.*

The collection of the solid products presented much more difficulty than that of the gaseous products. On opening the cylinder, the whole of the solid products were found collected at the bottom, there being generally an exceedingly thin (in fact, with large charges, quite an inappreciable) deposit on the sides. Upon the firing-plug there was usually a button of deposit, which differed considerably both in appearance and in chemical composition from the rest. In the button a crystalline structure was quite apparent, some of the crystals being large and transparent. The surface of the deposit was generally perfectly smooth and of a very dark grey, almost black, colour. This colour, however, was only superficial, and through the black could be perceived what was probably the real colour of the surface, a dark olive-green. The surface of the deposit, and the sides of the cylinders, had a somewhat greasy appearance, and were indeed greasy to the touch. On the smooth surface were frequently observed very minute particles, in appearance like soot, but of the greasy texture to which we have alluded.

The removal of the deposit was generally attended with great difficulty, as it formed an exceedingly hard and compact mass, which always had to be cut out with steel chisels. Lumps would frequently break off, but a considerable portion flew off before the chisel in fine dust. In various experiments, on examining the fracture as exhibited by the lumps, the variation in physical appearance was very striking, there being marked differences in colour, and also, frequently, a marked absence of homogeneity, patches of different colours being interspersed with the more uniform shade of the fracture. There was no appearance of general crystalline structure in the deposit; but, on examination with a microscope and sometimes with the naked eye, shining crystals of metallic lustre (sulphide of iron) were observed. On the whole, the general appearance of the deposit was attended with such considerable variations, that, for minute details, we must refer to the account of the experiments themselves. The deposit always smelt powerfully of sulphuretted hydrogen, and frequently strongly of ammonia. It was always exceedingly deliquescent, and after a short exposure to the air became black on the surface, gradually passing over into an inky-looking pasty mass. As in

physical appearance, so in behaviour of the solid, when removed from the cylinder, there were considerable differences between the experiments. The deposit was transferred to thoroughly dried and warm bottles, and sealed up as rapidly as possible. In most cases, during the very short time that elapsed while the transference was being made, no apparent change took place; but in some a great tendency to development of heat was apparent; and in one instance, in which a portion of the deposit (exhibiting this tendency in a high degree) was kept exposed to the action of the air, the rise of temperature was so great that the paper on which it was placed became charred, and the deposit itself changed colour with great rapidity, becoming a bright orange-yellow on the surface.

This tendency to heating always disappeared when the deposit was confined in a bottle and fresh access of air excluded.

The portion of the residue which could not be removed from the cylinder in a dry state was dissolved out with water, the solution being reserved for examination in well-closed bottles.

D. ANALYSIS OF THE PRODUCTS OF EXPLOSION.

1. *Gaseous Products.*

The method pursued for the analysis of the gaseous products of explosion presented only one important point of difference from that pursued by BUNSEN and SCHISCHKOFF. The volume of gas at command being more considerable than was the case in the investigations of those chemists, it was found more convenient to have recourse to methods for determining the sulphuretted hydrogen differing from that which they adopted—namely, its estimation by oxidation of the sulphur in the ball of potassium hydrate employed for absorbing the carbonic anhydride and sulphuretted hydrogen together. In some instances the volume of this gas was ascertained by absorption with manganese balls, but generally the following indirect method was pursued. The combined volume of carbonic anhydride and sulphuretted hydrogen was determined in one portion of the gas by means of potassium hydrate; another portion of gas was then treated with a small quantity of cupric sulphate, and the volume of carbonic anhydride determined in the gas thus freed from sulphuretted hydrogen.

The following numerical data relating to the analysis of the gases obtained by the explosion of 190·5 grms. of R. L. G. gunpowder (of Waltham-Abbey manufacture) in five times its own space are given in illustration of the detailed result obtained:—

I.				
	Volume.	Tempe- rature.	Pressure.	Volume corrected for temperature and pressure.
1. Original volume of gas	144·4	13·3	0·7243	99·80
2. After absorption of CO ₂ and SH ₂ .	78·2	13·3	0·6727	50·16
3. After absorption of oxygen . . .	76·9	14·4	0·6795	49·64

II.

	Volume.	Tempe- rature. °	Pressure.	Volume corrected for temperature and pressure.
4. Volume of original gas after absorp- tion of sulphuretted hydrogen }	144·2	14·2	0·7293	99·97
5. After absorption of CO ₂	82·2	16·3	0·6672	51·76
6. After absorption of oxygen	80·6	18·8	0·6735	50·79

III.

7. Portion of 3 transferred to eu- diometer }	174·8	15·4	0·1983	32·81
8*. After addition of air	248·4	15·5	0·2712	63·75
9. After addition of oxygen	319·5	15·6	0·3427	103·58
10. After explosion with oxyhydrogen gas }	310·8	15·8	0·3302	97·02
11. After absorption of CO ₂	291·6	18·3	0·3271	89·39
12. Portion of 11 transferred to clean eudiometer. }	301·5	18·6	0·3141	88·66
13. After addition of hydrogen	550·8	18·9	0·5642	290·85
14. After explosion (dry)	416·0	18·8	0·4295	167·16

By calculation from the above data, the composition^o of this gas, in volumes per cent., was found to be as follows:—

Carbonic anhydride	46·17
Sulphuretted hydrogen	3·91
Oxygen	0·52
Carbonic oxide	11·46
Marsh-gas	0·03
Hydrogen	2·72
Nitrogen	35·18

The gas in each experiment was generally collected in three or four large tubes. The contents in one tube sufficed, in most instances, for the complete analysis; but the results obtained were always controlled by determinations of several, if not of the whole, of the constituents in the contents of another tube. Only in one instance were the contents of different tubes, collected from one and the same experiment, found to differ materially in composition; in this particular instance the proportion of sulphuretted hydrogen in the different tubes was discordant. The mean of the results furnished by the contents of the three tubes was taken to represent the composition of the gas.

* Air was added to dilute the gas in this and one or two subsequent explosion experiments; but this precaution was found to be unnecessary, and was therefore not continued.

2. Solid Residue.—Preparation of the Residue for Analysis.

The residue, as collected for analysis, consisted of one or more large masses, besides a quantity in a more or less fine state of division which had been detached from the sides of the vessel. The appearance presented by the large pieces themselves indicated that they were by no means homogeneous, and they evidently differed in some respects from the smaller particles just referred to; moreover the foreign matters (metal and glass) could not be expected to be uniformly distributed throughout the mass, and a chemical examination of the latter clearly indicated that certain constituents existed in different proportions in the upper and lower parts of the residue. For these reasons, in order to insure the attainment of results correctly representing the composition of the residue, it appeared indispensable to operate upon the entire quantity at one time, with the view of determining the total amount of matter insoluble in water, and of preparing a solution of uniform composition in which the several components of the residue could be estimated. As the investigation proceeded, much inconvenience and delay were experienced from the necessity of working with very large quantities (from 400 to 100 grms.), which rendered the filtrations and washings protracted operations, and necessitated dealing with very large volumes of liquid. It was therefore attempted to expedite the examination of the residues by so preparing them that only portions might be operated upon at one time in conducting the individual determinations of the constituents. The impossibility of pulverizing and mixing the residue by any ordinary mode of proceeding, on account of the rapidity with which oxygen and water were absorbed from the air, was demonstrated by two or three attempts. An arrangement was therefore devised for performing the operation in an atmosphere of pure nitrogen. The gas employed was prepared in the following manner:—

A gasometer filled with air was submitted to a gentle pressure, causing the air to flow very slowly through a delivery-pipe to a porcelain tube filled with copper turnings and raised to a red heat. To remove any traces of oxygen, the nitrogen passed from the tube through two WOLFE'S bottles containing pyrogallic acid dissolved in a solution of potassium hydrate; and, finally, to remove moisture, it passed through two U-tubes filled with pumicestone moistened with sulphuric acid. The nitrogen thus obtained was collected in india-rubber bags; the residue was placed in a closed mill, connected by an india-rubber tube with the gas-bag, which was subjected to a considerable pressure to establish a plenum in the mill. The substance was then ground, and allowed to fall into bottles, which were at once sealed. By this treatment a sufficient degree of uniformity in different samples of any particular residue was generally attained; in some cases, however, the state of division of the substance was not sufficiently fine to secure such intimacy of mixture as would preclude the occurrence of discrepancies in the analytical results furnished by different samples. It was therefore found necessary to return occasionally to the employment of the entire residue obtained in one experiment for determining its composition.

3. *Analysis of the Solid Residue.*

Qualitative analysis indicated that the proportions of the following substances had to be determined in the solid residue.

a. *Portion insoluble in water.*—This consisted of steel (unavoidably detached from the interior of the vessel during removal of the residue) and of small quantities of other metals, besides glass, which were used in the construction of the electric igniting arrangement. The weight of these substances was deducted from the residue, as foreign to the research.

In addition to these substances, the residue insoluble in water contained generally traces of charcoal, besides sulphur, which was combined with iron and portions of the other metals, and the amount of which is included in the statement of results as *free sulphur*, together with the proportion which was found, in combination with potassium, in excess of the amount required to form the monosulphide.

b. *Portion soluble in water.*—In this, the chief portion of the residue, there existed the potassium sulphide, sulphocyanate, hyposulphite, sulphate, carbonate, and nitrate, besides ammonium carbonate, and, in very exceptional cases, potassium hydrate. The estimation of the proportions in which these several constituents existed in the residue was conducted as follows:—

c. *Water contained in the residue.*—It is obvious that the highly hygroscopic nature of the powder-residue rendered it impossible to transfer the product of an explosion from the iron cylinder to suitable receptacles for its preservation out of contact with the atmosphere without some absorption of moisture, however expeditiously the operation was performed. Moreover any water produced during the explosion, or preexisting in the powder, would necessarily be retained by the solid residue after explosion, as the gas remained in contact with a large surface of this powerful desiccating agent for some time before it could be collected. In some instances the water was expelled from the residue by exposing it for some time to a slow current of hydrogen at 300° C., the gas and volatile matters being passed into solution of lead acetate, for the purpose of retaining sulphur, and the weight of the dried residue determined. The amount of residue, however, was generally too considerable for this operation to be satisfactorily performed; there was therefore no alternative in such cases but to assume that the difference between the total weight of the residue and the combined weights of its several solid constituents, ascertained in almost every instance by duplicate and check determinations, represented the amount of water present in the substance*.

d. *Separation of the portion insoluble in water, and determination of Sulphur in it.*—The separation was accomplished by thoroughly washing the entire residue, or about 7 grammes of the ground residue, with well-boiled water until no discoloration was produced in the washings by lead acetate. Boiled water was employed to avoid oxi-

* If discrepancies existed between the results of determination of the several constituents and the check-determinations, the water was estimated, as described, in a portion of the residue.

duction of any of the constituents. After drying and washing the residue, it was introduced, with its filter, into a small flask; a little potassium bichromate was added before addition of nitric acid, to guard against violent reaction and the possibility of minute quantities of sulphur escaping as sulphuretted hydrogen. The oxidation was completed by the addition of potassium chlorate; the liquid, after sufficient dilution, was filtered and evaporated, the residue redissolved in water, with addition of chlorhydric acid, and the sulphuric acid determined in the solution by the usual method.

The *proportion of charcoal* contained in the insoluble residue was, in most instances, so small that no importance could be attached to any attempt to determine the quantity. In a few cases its amount was determined by combustion.

e. *Potassium monosulphide*.—The method pursued differed but very slightly from that adopted by BUNSEN and SCHISCHKOFF. The aqueous solution, separated from the insoluble portion, was digested with pure ignited cupric oxide in a well-closed flask, with occasional agitation, until it became colourless. The oxide containing sulphide was then filtered off, thoroughly washed, and the sulphur was determined in it by oxidation according to the method just described (d).

f. *Potassium sulphate*.—The filtrate obtained after the treatment with cupric oxide just described (or a measured quantity of it, if the entire residue was operated upon at one time) was mixed with chlorhydric acid and boiled to expel the sulphurous acid resulting from the decomposition of hyposulphite; the liquid was then separated by filtration from liberated sulphur, and the sulphuric acid determined as barium sulphate.

g. *Potassium hyposulphite*.—The solution obtained by treatment, as above described, of about 4 grammes of the residue (or a sufficient volume prepared from the entire residue) was acidulated with acetic acid; 3 or 4 cub. centims. of starch solution were added, and the hyposulphurous acid determined by means of a standard iodine solution.

h. *Potassium sulphocyanate*.—A solution of the residue, after separation of the insoluble portion and the soluble sulphide, was carefully acidified with a measured quantity of dilute chlorhydric acid, so as to avoid separation of sulphur. The oxidation of the hyposulphite was then effected by the gradual addition of a very dilute solution of ferric chloride until the liquid exhibited a permanent pink tint. A measured quantity of the ferric solution was afterwards gradually added until the greatest attainable depth of colour was produced. To determine what was the amount of sulphocyanate thus arrived at, a volume of water corresponding to that of the original solution tested was mixed with equal volumes of the dilute chlorhydric acid and ferric chloride to those used in the previous experiments. A solution of potassium sulphocyanate of known strength was then gradually added until a depth of colour corresponding to that of the actual assay was produced.

i. *Potassium carbonate*.—After the usual treatment of a solution of the residue with cupric oxide, pure manganous sulphate or chloride was added to the liquid in excess; the resulting precipitate might generally be washed by decantation in the first instance; after complete washing it was transferred to a small flask suitably fitted for the libera-

tion of carbonic anhydride from it, by addition of sulphuric acid, and for the transmission of the gas through small weighed absorption-tubes containing respectively sulphuric acid, calcium chloride, and solution of potassium hydrate. The increase in weight of the latter corresponded to the proportion of carbonic anhydride in the solid residue.

j. *Potassium sulphide, potassium carbonate, and potassium hydrate.*—Pure manganous chloride or sulphate was added in excess to the aqueous solution of the residue, and the amount of manganese, in the thoroughly washed precipitate, determined as red oxide. If the amount obtained exceeded those which would be furnished by the potassium sulphide and carbonate (deduced from the previous determinations), the excess was taken to correspond to potassium hydrate existing in the residue. If it was less, the sulphur existing as monosulphide of potassium was calculated from the weight of the manganous oxide, and the difference between it and the sulphur found in the cupric oxide (in determination e) was taken to represent excess of sulphur, or *free sulphur*, and was added to the result of determination d, the necessary correction being made in the number furnished by determination e.

k. *Total amount of potassium.*—The solution of the residue, after treatment with cupric oxide, was evaporated with excess of sulphuric acid, and the residue repeatedly treated with ammonium carbonate and ignited, until the weight of potassium sulphate was constant. Or water and sulphuric acid were added to about 4 grms. of the residue, and after boiling to expel sulphurous acid, two or three drops of nitric acid were added to peroxidize the little iron in solution and excess of ammonia to precipitate the latter. The precipitate and insoluble matters (glass &c.) were then filtered off, and the solution evaporated, the weight of potassium sulphate being ascertained by treatment of the residue as already described. In this way the amount of potassium arrived at indirectly, by the determinations of the several substances with which it existed in combination, was controlled by direct estimation.

l. *Ammonium sesquicarbonate.*—The solution of about 12 grms. of the residue was diluted to one litre; the liquid was then carefully distilled until about 250 cub. centims. remained in the retort, the distillate being allowed to pass into dilute chlorhydric acid. As some minute quantities of potassium salt might have passed over, the distillate was returned to a retort, mixed with excess of sodium carbonate and again distilled, the product passing into dilute chlorhydric acid. This second distillate was evaporated, and the ammonium determined as platinum salt with the usual precautions, the weight of the latter being controlled by ignition and determination of the weight of the platinum.

m. *Potassium nitrate.*—The portion of solution remaining in the retort, after the first distillation above described, was acidified with sulphuric acid; a piece of thin sheet zinc was then placed in the liquid and allowed to remain for a week, a small quantity of sulphuric acid being occasionally added. After the lapse of that time the zinc was removed, and the ammonia produced from any nitrate existing in the liquid was determined exactly as at l.

E. COMPOSITION OF THE GUNPOWDERS EMPLOYED.

The method pursued in determining the proportions of proximate constituents in the samples of gunpowder present but very few points of difference from those ordinarily adopted, and need therefore not be detailed.

It may be mentioned, however, with reference to the determination of the proportion of saltpetre, that a very appreciable amount of the most finely divided particles of the charcoal generally passes through the filter during the final washings, however carefully the operation be conducted.

These last washings, which contain only a very small proportion of the saltpetre, were therefore evaporated separately, and the residue was carefully heated until the small quantity of charcoal was completely oxidized. The resulting carbonate was then converted into nitrate by careful treatment with dilute nitric acid, and the product added to the remainder of the saltpetre previously extracted.

The composition of the charcoal contained in the powders was determined by combustion, after as complete a separation of the other constituents as possible. There was, of course, no difficulty in completely extracting the saltpetre; but the sulphur cannot be entirely removed from the charcoal by digestion and repeated washings with pure carbon disulphide. The amount remaining was therefore always determined by oxidation of the charcoal, and estimation of sulphuric acid produced; the necessary correction thus arrived at was made in the amount of charcoal used for analysis. The latter was dried by exposing it for some time (in the platinum boat in which it was to be burned) to a temperature of about 170° in a current of pure dry hydrogen; it was allowed nearly to cool in this gas, and dry air was then passed over for some time, the boat being afterwards rapidly transferred to a well-stoppered tube for weighing. The dried charcoal was burned in a very slow current of pure dry oxygen, the resulting products being allowed to pass over the red-hot cupric oxide, and finally over a layer of about 8 inches of lead chromate, heated to incipient redness. The efficiency of this layer in retaining all sulphurous acid was fully established by preliminary test experiments.

The following tabular statement (Table II.) gives the percentage composition of the five samples* of gunpowder employed in these investigations as deduced from the analytical results.

In every instance at least two determinations were made of each constituent, the means of closely concordant results being given in the Table.

This Table also includes the results of analysis by BUNSEN and SCHISCHKOFF, KAROLYI, LINCK, and FEDEROW, of the gunpowders employed in their experiments.

* The authors are indebted to Colonel C. W. YOUNGHUSBAND, R.A., F.R.S., the Superintendent of the Waltham-Abbey Gunpowder Works, for having selected and furnished to them the samples of English gunpowder employed in their investigations.

TABLE II.—Results of Analysis of Gunpowders employed in these Investigations and of those used by other Investigators.

Components per cent.	Description of Gunpowders employed in experiments.								
	Pebble powder. Waltham Abbey.	Rifle Large-grain. Waltham Abbey.	Rifle Fine-grain. Waltham Abbey.	Fine-grain. Waltham Abbey.	Spanish Spherical Pebble powder.				
Saltpetre	74·67	74·95	75·04	73·55	75·30				
Potassium sulphate	0·09	0·15	0·14	0·36	0·27				
Potassium chloride					0·02				
Sulphur.....	10·07	10·27	9·93	10·02	12·42				
Charcoal ...	{ Carbon 12·12 Hydrogen ... 0·42 Oxygen 1·45 Ash 0·23	{ 10·86 0·42 1·99 0·25	{ 10·67 0·52 2·66 0·24	{ 11·36 0·49 2·57 0·17	{ 8·65 0·38 1·68 0·63				
						14·22	13·52	14·09	14·59
Water	0·95	1·11	0·80	1·48	0·65				
	Gunpowders employed by other Investigators.								
	Bunsen and Schischkoff. Sporting-powder.	Karolyi. Austrian cannon- powder.	Karolyi. Austrian small- arm powder.	Linck. Württemberg cannon-powder.	Federow*. Russian powder.				
Saltpetre	77·99	73·78	77·15	74·66	74·18				
Sulphur.....	9·84	12·80	8·63	12·49	9·89				
Charcoal ...	{ Carbon 7·69 Hydrogen ... 0·41 Oxygen 3·07 Ash traces	{ 10·88 0·38 1·82 0·31	{ 11·78 0·42 1·79 0·28	{ 12·31 0·54	{ 10·75 0·43 3·31 0·34				
						11·17	13·39	14·27	12·85
Water.....					1·10				

It will be seen that the several English service-powders of Waltham-Abbey manufacture did not differ from each other very importantly in composition; the most noteworthy points of difference are the somewhat low proportion of saltpetre in the F. G. powder and the slightly higher proportion of carbon in the pebble powder.

The charcoals contained in these powders presented some decided differences in composition, as is shown by the following comparative statement:—

	Pebble.	R. L. G.	R. F. G.	F. G.
Carbon . . .	85·26	80·32	75·72	77·88
Hydrogen . .	2·98	3·08	3·70	3·37
Oxygen . . .	10·16	14·75	18·84	17·60
Ash	1·60	1·85	1·74	1·15

The charcoal in the P. powder is somewhat more highly burned than that in the R. L. G., and decidedly more than the F. G. charcoal; that contained in the R. F. G. powder is prepared from a different wood to the others, which is known to furnish a comparatively quick-burning charcoal. Although, however, the charcoals themselves differ very decidedly from each other, it will be seen that the percentages of carbon in the gunpowders do not present great differences, the widest being between the P. and R. F. G. powders.

The Spanish spherical pebble powder was specially selected from various other foreign

* This is the only analysis of powder, by foreign investigators of the subject, in which the proportion of water, existing as a constituent of the powder experimented with, is given.

powders for purposes of experiment, on account of the comparatively wide difference presented in composition between it and the English powders, the proportion of sulphur being high, and that of carbon being low. The charcoal in this powder (made from hemp) had the following percentage composition:—

Carbon	76·29
Hydrogen	3·31
Oxygen	14·87
Ash	5·53

The proportions of carbon and hydrogen are therefore similar to those existing in the F. G. powder; but the amount of ash in the hemp-charcoal is very high compared to that contained in the charcoals from light woods used generally in the manufacture of gunpowder.

All the powders used by the recent foreign experimenters differed very decidedly both from each other and from the powders employed by us. The sporting-powder of BUNSEN and SCHISCHKOFF, and KAROLYI'S small-arm powder, were of very exceptional composition, while the Russian powder used by FEDEROW was the only one resembling our service-powders in composition.

F. EXAMINATION OF THE ANALYTICAL RESULTS.

Table III. gives the composition in volumes per cent. of the gases, and the percentage composition of the solid products furnished by a number of experiments with the different gunpowders, the charges exploded having occupied various spaces in the explosion-chambers. This Table also includes the results obtained by other recent experimenters in the analytical examination of the products of explosion of gunpowder.

Table IV. shows the composition by weights of the products of combustion furnished by 1 gramme of gunpowder under the different circumstances of our experiments. The complicated nature of the analysis of these products has rendered it impossible to complete the examination of the entire series furnished by our experiments; we trust, however, at a future time to fill up the blanks * remaining in this tabular statement.]

* The majority of these blanks have been now filled up.—February 1875.

TABLE IV.—Showing the composition by weight of the products of combustion of 1 gramme of fired Gunpowder.

No. of expt.	Nature of powder.	Mean density of products of combustion.	Pressure of explosion in tons per sq. inch.	Proportion by weight of solid products.	Proportion by weight of total gaseous products.	Proportions by weight of solid products.										Proportions by weight of gaseous products.						Volume of gas calculated from analysis.	
						K ₂ CO ₃ .	K ₂ S ₂ O ₈ .	K ₂ SO ₄ .	K ₂ S.	KCN.S.	KNO ₃ .	(NH ₄) ₂ CO ₃ .	C.	Free S.	Not estimated.	SH ₂ .	O.	CO.	CO ₂ .	CH ₄ .	H.		N.
8.	Pebble.	.10	1.3	.5612	.4388	K ₂ CO ₃ . -3115	K ₂ S ₂ O ₈ . -1163	K ₂ SO ₄ . -0843	K ₂ S. -0416	KCN.S. -0005	KNO ₃ . -0027	(NH ₄) ₂ CO ₃ . -0009	C. -0072	Free S. -0034	Not estimated.	SH ₂ . -0134	O.	CO. -0519	CO ₂ . -2577	CH ₄	H. -0007	N. -1151	281
1.	R. L. G.	.10	1.6	.5722	.4278	-3007	-1166	-1171	-0230	-0000	-0032	-0003	-0041	.....	.....	-0041	.....	-0303	-2597	-0006	-0005	-1201	269
7.	Pebble.	.20	2.9	.5596	.4404	-3216	-0208	-0768	-1011	-0003	.....	-0005	.....	-0385	.....	-0184	.....	-0575	-2517	.....	-0009	-1119	285
3.	R. L. G.	.20	2.7	.5723	.4277	-3128	-0329	-1378	-0547	-0003	-0007	-0004	.....	-0326	.....	-0149	.....	-0393	-2504	.....	-0006	-1202	272
17.	F. G.	.20	3.7	.5817	.4183	-3454	-0308	-1409	-0298	-0001	-0005	-0009	.....	-0333	.....	-0154	.....	-0416	-2512	.....	-0010	-1091	267
9.	Pebble.	.30	4.9	.5574	.4426	-3312	-0241	-0703	-0920	-0012	-0002	-0007	.....	-0375	.....	-0125	.....	-0550	-2620	.....	-0007	-1124	283
4.	R. L. G.	.30	6.4	.5758	.4242	3017	-0740	-1395	-0337	-0003	-0002	-0002	.....	-0262	.....	-0127	.....	-0390	-2610	.....	-0007	-1108	268
12.	P.	.40	9.1	.5698	.4302	-3146	-0802	-0752	-0553	-0014	-0005	-0004	.....	-0345	.....	-0070	.....	-0475	-2650	-0006	-0006	-1095	279
11.*	R. L. G.	.40	8.1	.5790	.4210	-2819	-1393	-1324	-0117	-0009	-0007	-0002	.....	-0119	.....	-0078	.....	-0360	-2624	-0005	-0006	-1137	265
19.*	F. G.	.40	9.9	.5824	.4176	-2615	-1666	-1268	-0196	-0004	-0005	-0002	.....	-0068	.....	-0080	.....	-0339	-2678	.....	-0008	-1071	262
14.	P.	.50	12.2	.5517	.4483	-3098	-0338	-0658	-1055	-0013	-0011	-0004	.....	-0340	.....	-0084	.....	-0473	-2770	-0012	-0005	-1139	282
70.*	R. L. G.	.50	10.7	.5804	.4196	-3520	-1470	-0269	-0206	-0017	-0029	-0006	.....	-0237	.....	-0066	.....	-0563	-2522	-0016	-0007	-1022	269
75.*	F. G.	.50	10.2	.5811	.4180	-3255	-0780	-1204	-0252	-0004	-0005	-0005	.....	-0306	.....	-0088	.....	-0343	-2650	-0005	-0007	-1096	263
37.*	P.	.60	14.8	.5638	.4362	-3245	-0561	-0759	-0647	-0019	-0017	-0003	.....	-0387	.....	-0094	.....	-0474	-2681	-0011	-0005	-1097	275
39.	R. L. G.	.60	14.4	.5695	.4305	-3635	-0369	-0625	-0565	-0015	.....	-0006	.....	-0480	.....	-0067	.....	-0472	-2677	-0007	-0005	-1077	270
40.*	F. G.	.60	14.1	.5800	.4200	-2429	-1851	-1288	-0009	-0009	-0010	-0186	.....	-0026	.....	-0090	.....	-0316	-2689	-0003	-0006	-1096	258
79.*	Spanish.	.70	17.0	.6219	.3781	-2175	-0473	-2962	-0197	-0003	-0058	-0002	.....	-0350	.....	-0097	.....	-0134	-2440	.....	-0003	-1100	232
38.*	P.	.70	18.6	.5735	.4265	-2879	-1845	-0733	-0128	-0022	-0014	-0003	.....	-0111	.....	-0129	.....	-0419	-2630	-0007	-0005	-1075	268
41.*	R. L. G.	.70	19.5	.5756	.4244	-3470	-1070	-0606	-0221	-0028	-0024	-0001	.....	-0332	.....	-0115	.....	-0446	-2604	-0011	-0004	-1064	267
42.	F. G.	.70	18.2	.5808	.4192	-2499	-1863	-1220	.....	-0013	-0011	-0002	.....	-0027	.....	-0081	.....	-0258	-2718	-0009	-0005	-1117	260
78.*	R. F. G.	.70	18.9	.5848	.4152	-3447	-0477	-1279	-0247	-0002	-0004	-0005	.....	-0389	.....	-0063	.....	-0287	-2673	-0002	-0006	-1120	259
43.*	P.	.80	28.6	.5700	.4300	-3354	-1179	-0589	-0222	-0026	-0018	-0005	.....	-0307	.....	-0080	.....	-0399	-2717	-0006	-0004	-1094	269
44.	R. L. G.	.80	24.4	.5741	.4259	-3818	-0177	-0506	-0519	-0014	-0010	-0006	.....	-0691	.....	-0063	.....	-0405	-2702	-0014	-0004	-1071	268
47.*	F. G.	.80	27.1	.5850	.4150	-2553	-2025	-1236	.....	-0014	-0015	-0002	.....	-0005	.....	-0102	.....	-0270	-2637	-0008	-0005	-1121	259
77.*	P.	.90	31.4	.5733	.4267	-3680	-0761	-0523	-0220	-0033	-0025	-0007	.....	-0484	.....	-0086	.....	-0362	-2710	-0013	-0005	-1090	266
68.	R. L. G.	.90	35.6	.5714	.4286	-3755	-0491	-0487	-0413	-0021	-0011	-0009	.....	-0527	.....	-0077	.....	-0356	-2750	-0015	-0003	-1085	268
69.*	F. G.	.90	27.2	.5780	.4220	-2927	-1495	-1061	-0154	-0014	-0015	-0002	.....	-0112	.....	-0017	.....	-0252	-2738	-0003	-0005	-1105	254
						K ₂ CO ₃ .	K ₂ S ₂ O ₈ .	K ₂ SO ₄ .	K ₂ S.	KCN.S.	KNO ₃ .	(NH ₄) ₂ CO ₃ .	C.	S.	.....	SH ₂ .	O.	CO.	CO ₂ .	CH ₄ .	H.	N.	

* The analyses marked with an asterisk were added to this Table in February 1875.

† In this experiment the powder was exploded by detonation.

A comparison of the analytical data furnished by our examination of the products of explosion of gunpowder with those obtained by BUNSEN and SCHISCHKOFF and other recent investigators of this subject, points to the following principal differences in the results arrived at:—

As regards the *gaseous* products: the proportion of carbonic oxide is considerably lower in BUNSEN and SCHISCHKOFF's analysis and in one of KAROLYI's than in the results obtained by us; this might, in the case of BUNSEN and SCHISCHKOFF's results, be ascribed to the fact that the proportion which the saltpetre bears to the carbon in the English powder is lower than in the powder used by them, and that the proportion of sulphur is also lower. The Austrian cannon-powder employed by KAROLYI, which is not widely different from the English cannon (R. L. G.) powder, as regards the proportion of saltpetre and carbon, though containing a higher proportion of sulphur, furnished amounts of carbonic anhydride and carbonic oxide more nearly approaching those obtained with the English powder at a low pressure. But the other (small-arms) powder used by him furnished almost as low an amount of carbonic oxide as obtained by BUNSEN and SCHISCHKOFF, although the proportion of saltpetre to the carbon in this powder was about the same as in the other used by him. This result may be ascribable to the smaller proportion of sulphur existing in the former. The Würtemberg powder used by LINCK, which was made apparently with a very highly burned charcoal, but contained a similar proportion of saltpetre to the English powder and a high proportion of sulphur, also furnished a comparatively very small quantity of carbonic oxide. The proportions of this gas and of carbonic anhydride which it yielded were very similar to those obtained by BUNSEN and SCHISCHKOFF with a gunpowder of widely different composition, though the method of experiment pursued in the two instances was the same. Although the proportion of hydrogen contained in the powder with which LINCK experimented was very low, the amount of sulphuretted hydrogen which it furnished was remarkably high; and in this respect again the analysis differs greatly from that of the products similarly obtained by BUNSEN and SCHISCHKOFF. The proportions of water existing in the gunpowders used by these several experimenters is not stated, but it must probably have been very considerable in LINCK's powder.

The *solid* products of explosion obtained by BUNSEN and SCHISCHKOFF, LINCK, and KAROLYI differ remarkably from those furnished by our experiments. The potassium sulphate obtained by them was in LINCK's analysis about double, and in those of the other chemists more than double the highest amount we found*. The potassium carbonate furnished in the German experiments was about half that produced in ours; and the proportion of potassium sulphide found in the greater number of powder-residues which we examined was very greatly in excess of the results obtained by the German experimenters. LINCK found a large proportion of potassium hyposulphite in the solid products obtained by him, while the other chemists found comparatively

* Excepting in the case of a Spanish powder, which differed widely in composition from the other experimented with by us.—February 1875.

small amounts of this constituent; in our results (which will presently be compared among themselves) the hyposulphite was also found to vary in amount very greatly. These fluctuations were found by us, in most cases, to bear definite relation to those of the sulphide; but this is not observed to be the case in the analyses of LINCK and BUNSEN and SCHISCHKOFF on comparing them with ours.

The method pursued by these chemists for obtaining the products of decomposition of powder was of a nature calculated to furnish very variable results, which can scarcely be accepted as corresponding to those produced when gunpowder is exploded in an absolutely closed space or in the bore of a gun.

By allowing the powder-grains to drop gradually into a heated open bulb, not only is their decomposition accomplished under very different conditions to those attending the explosion of a confined charge of powder, but the solid products are necessarily subjected to further changes during their continued exposure to a high temperature and to the action of fresh quantities of powder deflagrated in contact with them. An imperfect metamorphosis of the powder-grains themselves and further secondary changes in the composition of the residue deposited (which will vary in extent with the duration of the experiment), the amount of heat applied externally, and the rate at which the powder-grains are successively deflagrated appear to be inevitable results of this mode of operation. A comparison of BUNSEN and SCHISCHKOFF's results with those shortly afterwards obtained by LINCK in BUNSEN's laboratory, the same method being pursued for effecting the decomposition of the powder, appears to demonstrate this conclusively.

The differences in the composition of the powders operated upon in the two investigations would certainly not suffice to account for the important differences exhibited by the results of analysis of the residues. The comparatively large proportion of potassium sulphide, the much larger proportion of hyposulphite, and the considerably smaller proportion of sulphate found by LINCK appear to indicate that the operation of burning the powder was conducted much more rapidly by him, a view which is supported by the fact that, while he found a considerable proportion of ammonium carbonate in the residue, none existed in the product obtained by BUNSEN and SCHISCHKOFF, who, however, found this constituent in the so-called powder-smoke which they collected in a long tube through which the gas escaped.

Our experiments have demonstrated conclusively that, even when the conditions under which the explosion of powder is effected in distinct operations are as closely alike as possible, very exceptional results, as regards the composition of the solid residue, may be obtained, experiments 7 & 17, 9 & 4, 14 & 70 being illustrations of this. Yet in no instance, however apparently abnormal, did any considerable proportion of potassium *nitrate* escape decomposition, the highest amounts discovered in the residues being 0.48 and 0.56 per cent. (experiments 1 & 8). These percentages existed in the products of explosion of powder formed under the *lowest* pressure; in only two instances, at higher pressures, were similar proportions found. The existence of so large a proportion as 5 per cent. of potassium nitrate in the residue obtained by BUNSEN and SCHISCHKOFF, the coexistence of 7.5 per cent. of hyposulphite and small quantities of

other oxidizable substances, and the existence also of a comparatively high proportion of oxygen in the gaseous products appear to indicate the occurrence of reactions in the course of the preparation of gas and residue, by the gradual deflagration of the powder, which were distinct from those attending the ordinary explosion of powder in a confined space.

The very considerable differences between the results of our analyses and of the experiments of BUNSEN and SCHISCHKOFF and of LINCK appear therefore clearly ascribable to the fact that the deflagration of gunpowder, as carried out by them, cannot be expected to furnish results similar to those produced when a charge of powder is exploded in a confined space under considerable pressure and in one operation.

This conclusion receives support from the results of analysis of powder-residues published by FEDEROW. Those products which he collected from a cannon in which 3 lb. of powder were fired furnished analytical results much more nearly resembling those obtained by us than those of BUNSEN and SCHISCHKOFF; the proportion of sulphate was similar to that obtained in many of our experiments, and therefore very much below that of the German experimenters, while the proportion of sulphide was very considerably higher than the largest amount obtained by us—a result, we believe, not difficult of explanation. In the residue collected in a glass tube by firing small quantities of powder (blank charges) in a pistol, which therefore were not exploded under any considerable pressure, and were consequently subjected to more gradual change, the results were of very different nature, the proportion of sulphate being comparatively very high, and that of the sulphide very low.

That the mode of operation pursued by KAROLYI should have furnished results similar to those obtained by BUNSEN and SCHISCHKOFF'S method is at first sight somewhat surprising, inasmuch as, by the arrangement which he adopted, the powder-charge was exploded in an envelope (a small thin shell) offering some amount of initial resistance. But as this explosion was accomplished in a capacious *exhausted* chamber, the pressure developed upon the first ignition of the charge suffered a sudden reduction at the moment that the shell was fractured, and most probably, therefore, before the entire charge had exploded. Hence it might have been expected that some portions of the oxidizable constituents of powder would escape oxidation, either entirely or partly, and that, at any rate, the oxidation of the sulphur would not be effected to the complete extent observed in operating according to BUNSEN and SCHISCHKOFF'S plan. But it appears that in one instance not a trace, and in another only 0.15 per cent., of potassium sulphide was found in the solid products, the proportion of hyposulphite found being at the same time much smaller than that observed by BUNSEN and SCHISCHKOFF; so that the sulphur-compounds obtained consisted chiefly of the highest product of oxidation, and yet in each of the two experiments nearly 4 per cent. of charcoal and a large proportion of hydrogen escaped oxidation altogether. In one experiment nearly 7 per cent. of sulphur appears to have been left in an uncombined state.

In our experiments, in which the powder was exploded under more or less considerable and sustained pressure, the complete oxidation of the sulphur might certainly be

expected to have been favoured to a much greater extent than in KAROLYI'S experiments; yet in all but one experiment, made with a powder of exceptional composition, the proportion of sulphate formed was very greatly below that found by KAROLYI. The irreconcilable nature of KAROLYI'S analytical results, though probably in some measure ascribable to the exceptional conditions under which he obtained his products, does not appear satisfactorily accounted for thereby.

On examination and comparison with each other of the analytical results given in the foregoing Tables, the following points suggest themselves:—

Excluding the results of a few explosions of marked exceptional character as regards the *solid* products furnished, and those produced under the lowest pressure, which were naturally expected to yield variable and discordant results, there is considerable similarity, not only between the products furnished by pebble powder when exploded under different conditions as regards pressure, but also between the results obtained with this powder and with the sample of R. L. G. powder employed in the experiments, which did not differ greatly in composition from it. The proportion of carbon was slightly lower in the R. L. G. than in the pebble powder; and this fact is in harmony with the proportion by weight which the total gaseous constituents bear to the solid in the products obtained with the two powders, it being somewhat the highest, in most instances, in the case of the pebble powder. The proportion of carbonic oxide is often rather higher in the gas obtained from the pebble powder than in that furnished by the R. L. G. powder; and this is in accordance with the fact that the proportion of carbon is somewhat higher, while that of the saltpetre is a little lower, in the former than in the latter. Excluding the results furnished by the experiments in which the powder was exploded in the largest space (in which, therefore, the gases were developed at the lowest pressures) it will be observed that with the slowest-burning powder (the pebble) the proportion of carbonic oxide decreases steadily, while that of the anhydride increases, in proportion to the pressure developed at the time of explosion.

The proportion of carbonic anhydride is about the same in the gas from the two gunpowders specified; but that of the potassium carbonate is somewhat different, and appears regulated by circumstances other than the composition of the powder, being highest in the residues furnished by the R. L. G. powder at the higher pressures, and lowest in those of the same powder furnished at lower pressures. The amount of carbonate furnished by the pebble powder under different conditions as to pressure varies, on the other hand, comparatively little, except at the highest pressure*.

The occasional occurrence of a small quantity of marsh-gas, like that of oxygen, is evidently an accidental result, being observed in some instances in the products obtained at low pressures, and the reverse in other instances.

In the gaseous products from the F. G. powder formed at pressures up to 50 per

* In 90 per cent. space the amount of carbonate formed was nearly equal to the proportions found in the residues from R. L. G. produced at the higher pressures.—February 1875.

cent. space, the carbonic oxide existed in proportions similar to those furnished by the R. L. G. powder. If the relative proportions of potassium nitrate and carbon in the powders furnished an indication of the proportions in which this gas should be formed, this particular powder should have furnished a higher proportion of carbonic oxide than the R. L. G., as it contains 0·5 per cent. more carbon and 1·4 per cent. less saltpetre than the latter; but then the proportion of sulphur in it is lower by 0·25 per cent.; moreover the charcoal in the F. G. was less highly burned, and therefore more rapidly oxidizable, a circumstance which may have a decided influence upon the amount of carbonic oxide produced by the explosion of gunpowder, distinct from that exerted by the proportion in which the ingredients exist. The difference in the amounts of carbonic oxide produced from this powder at the lower and the higher pressures is more marked than in the case of the other powders, the quantity in this as in the pebble powder decreasing decidedly as the pressure increases. The amount of carbonic anhydride which it furnished at the highest pressure (the powder occupied 90 per cent. of the space) is the largest found in any of the gaseous products*; but that produced when the powder occupied 70 per cent. of the total space was very nearly as high, while the amount obtained in the intermediate experiment (80 per cent. space) was decidedly lower, and corresponded closely to the proportions produced at the same pressure from R. L. G. and pebble powder.

In the experiments with P. and R. L. G. (excluding the explosions in 10 p. c. space) the amount of sulphuretted hydrogen was highest at the lowest pressures; in the case of R. L. G. powder the proportion fell gradually with the increase of pressure, excepting at the highest pressure; with pebble a similar relation was indicated, though much less regularly; with F. G. it was still less apparent, and with all three powders the proportion of this gas rose somewhat again at the highest pressure. With pebble and F. G. the hydrogen exhibited a steady diminution with increase of pressure, and a similar though less regular result was observable with R. L. G. It need be scarcely stated that the proportions of sulphuretted hydrogen and of hydrogen are in no instance sufficiently high to enter into account in a consideration of what are the chief reactions which occur upon the explosion of powder †.

While the results, as regards *gaseous* products, furnished by the three gunpowders

* Except in the case of the Spanish powder, which furnished an equally high proportion.—February 1875.

† The additional analyses which we have made since this paper was presented to the Royal Society enable us to summarize the general results furnished by examination of the gaseous products as follows:—(a) with all the powders the proportion of carbonic anhydride produced increases steadily and decidedly with the pressure; (b) with the P. and F. G. powders the carbonic oxide decreases steadily as the pressure increases; and the same is generally true as regards the R. L. G. powder, although the series of analyses exhibits some violent fluctuations; (c) the proportions of sulphuretted hydrogen and of hydrogen furnished by all the powders fall somewhat as the pressures increase, though the diminution is not very decided or regular; (d) free oxygen was in no case found in the products from P. powder; in one instance it was found in those from R. L. G., and it occurred in four instances in those from F. G.—February 1875.

above referred to were on the whole remarkably uniform, the composition of the *solid* residues exhibited comparatively great variations. Certain general results appear, however, to be well established by a number of the analyses. Excluding again those experiments conducted at the lowest pressure, the proportion of potassium sulphate produced in the several experiments, with the comparatively slow-burning pebble powder, was remarkably uniform at various pressures, being, as already pointed out, not more than one fourth the amount found in powder-residue by BUNSEN and SCHISCHKOFF. The proportion of sulphur not actually entering into the principal reactions involved in the explosion of the powder was also, with two exceptions, very uniform, being about 35 per cent. of the total amount contained in the powder. The proportion of potassium carbonate obtained from pebble powder was somewhat less uniform, but did not differ greatly in the different experiments with the same powder exploded in different spaces, excepting at the highest pressure. With the more rapidly-exploding R. L. G. powder, the sulphate formed at the lower pressures was nearly double that obtained with pebble powder; while at the highest pressures the amounts furnished by the two powders did not differ greatly, the amount of sulphur excluded from the chief reaction at those pressures, with R. L. G., being, however, more considerable than was the case with pebble powder under similar conditions. With regard to this part of the sulphur contained in the powder, which corresponds to what BUNSEN and SCHISCHKOFF term *free* sulphur, some portion of it almost always exists, not in combination with potassium as polysulphide, but combined with iron, and is therefore discovered in the residue left undissolved, upon treatment with water, of the solid products removed from the chamber. This proportion of the sulphur is evidently at once fixed, at the instant of explosion, by union with parts of the metal surfaces presented by the interior of the vessel in which the operation is conducted. The extent to which sulphur is thus abstracted from the powder-constituents, and precluded from entering into the reactions which are established by the explosion, or follow immediately upon it, must depend in some degree upon accidental circumstances, such as variations in the mechanical condition (smoothness, brightness, &c.) of the metal surfaces, and also upon the temperature developed at the instant of the explosion. The circumstance that, in the statement of the results of Experiment 42, both potassium oxide and sulphur are separately included is therefore explained by the above fact. The larger proportion of the "sulphur" specified in the several analyses existed as potassium polysulphide, and may therefore be styled *free* sulphur, as it did not take part in the chief reactions.

The *carbonate*, like the sulphate, differed decidedly in amount in the residues furnished by the R. L. G. powder exploded in the smaller and the larger spaces: in the former it was equal to the lowest result furnished by the pebble powder; in the others its proportion was about 10 per cent. higher than in the pebble-residues, excepting in one of them produced at the highest pressure. In the products obtained by the explosion of the smallest-grain powder (F. G.) the variations in the proportions of

carbonate are somewhat considerable; the proportions of sulphate were, on the other hand, much alike, except at the highest and lowest pressures. The proportion of hyposulphite was generally high, and that of the sulphide low, as compared with the proportions of these constituents in the other powder-residues just discussed. In two of the residues from F. G., the proportion of sulphur which did not enter into the principal reactions is about the same as that found in the pebble-powder residues; while in three others only small quantities of free sulphur existed—in two of these there was free potassium oxide. Two of the residues (Nos. 42 & 47) contained not a trace of potassium sulphide discoverable by the most delicate test (sodium nitroprusside).

With respect to the proportions of potassium sulphide and potassium hyposulphite found in the several residues analyzed, the following points appear to be worthy of note.

1. In the residues obtained by exploding pebble, R. L. G., and F. G. under the lowest pressures (the charges only occupying 10 per cent. of the total space), the proportion of potassium hyposulphite is in all cases high, while that of the sulphide is correspondingly low.

2. In the comparatively slow-burning pebble powder, the products of explosion of which at different pressures exhibited great similarity in many respects, there is a marked fluctuation in the proportion of hyposulphite; and this corresponds to a fluctuation, in the opposite direction, in the amount of sulphide found, while the sulphate varies but little. A similar fluctuation and relation is observed, as regards these two constituents, in the solid products of the experiments made with R. L. G. powder at the *lowest* pressures, but not, or only to a slight extent, in the residues furnished by the powder at higher pressures.

3. In most of the residues from F. G., the hyposulphite is large in amount and the sulphide small: in two of these (Nos. 42 & 47), which did not contain a trace of potassium sulphide, the proportion of hyposulphite was considerably higher than in any of the other experiments*; and in these cases there was no free sulphur—that is to say, no sulphur in the form of *polysulphide*, the small proportion given under the head of “sulphur” in the tabulated results being found in combination with iron derived from the interior of the chamber.

The circumstance that the hyposulphite generally existed in large proportions when the sulphide was small in amount, appeared at first sight to afford grounds for the belief that its production might be ascribable to a secondary reaction resulting in the oxidation of sulphide by carbonic anhydride, a view which might appear to receive support from the following circumstance. The upper portion of the solidified mass in the cylinder was found to contain a considerably larger proportion of hyposulphite than the remainder, as is demonstrated by the following results of a separate examination of the top and the lower portion of the residues obtained by exploding a charge

* One residue furnished by P. powder (experiment 38) contained a similarly high amount and a very small quantity of sulphide.—February 1875.

of 6804 grains (440.9 grms.) of R. L. G. powder, which occupied 90 per cent. of total space in the chamber (Experiment 68):—

Residue.	Carbonate.	Sulphate.	Hyposulphite.	Sulphide.	Sulphur.
Top portion	52.15	7.69	17.14	6.03	4.88
Lower portion	67.75	7.44	4.34	7.30	10.09

Similar results were obtained by the separate examination of the top part of other residues. Again, one of the small drops or buttons of the fused solid products which have been mentioned as being generally found upon the firing-plug in the cylinder (the residue of this particular experiment contained a somewhat considerable proportion of sulphide) was found to be quite free from sulphide, but contained hyposulphite. Lastly, a mixture of potassium carbonate and sulphide, after exposure in a crucible for 30 minutes to a temperature of about 1700° C. in a SIEMENS furnace (in which the atmosphere consisted of carbonic anhydride, carbonic oxide, and nitrogen), was found to contain a small quantity of hyposulphite. The production of this substance, as the result of a secondary reaction, should, however, be rendered evident by a marked increase in the proportion of carbonic oxide in all instances in which a large amount of hyposulphite was found; and this was certainly not the case, as will be seen by a comparison of the results of Experiments 8 and 7, 3 and 11, 19 and 17.

Experiment.	Carbonic anhydride.	Carbonic oxide.	Potassium.			
			carbonate.	sulphate.	hyposulphite.	sulphide.
8. Pebble .	.2577	.0519	.3115	.0843	.1163	.0416
7. Pebble .	.2517	.0575	.3216	.0768	.0208	.1011
3. R. L. G. .	.2504	.0393	.3128	.1378	.0329	.0547
11. R. L. G. .	.2624	.0360	.2819	.1324	.1393	.0117
19. F. G. . .	.2678	.0339	.2615	.1268	.1666	.0196
17. F. G. . .	.2512	.0416	.3454	.1409	.0308	.0298

It appears, therefore, that the formation of hyposulphite cannot be regarded as due to the occurrence of a secondary reaction between carbonic anhydride or carbonate and sulphide produced upon the explosion of gunpowder, but that it must be formed either during the primary reaction of the powder-constituents on each other (in other words, by the direct oxidizing action of saltpetre), or by an oxidation of sulphide by liberated oxygen following immediately upon the first change (which results in the formation of a large quantity of sulphide), and being regulated in extent by the amount of oxygen liberated at the moment of explosion. The view that hyposulphite must be, at any rate in part, due to the oxidation of sulphide formed in the first instance, appears to be supported by the circumstance that the proportion of the latter in the powder-residues is as variable as that of the hyposulphite, and is generally low when the hyposulphite is high. Moreover in our experiments the proportion of *sulphate* is, except possibly in a few instances, apparently not affected by the amount of hyposulphite formed. On the other hand, the amount of sulphur which exists either in combination with iron

(and other metals derived from the exploding-apparatus) or as polysulphide of potassium, and which therefore has not entered into the chief reactions, is generally low where the hyposulphite is high, which appears to indicate that the latter is also formed (at any rate occasionally) by an oxidation of free sulphur following immediately upon the first reaction.

In the products of decomposition of the powder examined by BUNSEN and SCHISCHKOFF, which were obtained, at any rate to a considerable extent, by a continued process of oxidation, the conversion of sulphur into the highest product (sulphate) was effected to a very great extent, there being no free sulphur and only an exceedingly small quantity of sulphide; but when the deflagration and action of heat were arrested, there was still a considerable proportion (7·5 per cent.) of *hyposulphite* existing in the solid residue. The *smoke*, or portions of the solid products mechanically carried away by the gases evolved and afterwards deposited, was found by those chemists also to contain as much as 4·9 per cent. of hyposulphite, while neither sulphide nor free sulphur were discovered (the sulphate being, on the other hand, considerably higher in amount than in the residue itself); the gas which escaped contained a very appreciable amount of free oxygen, and there was 5 per cent. of nitrate left in the residue when the operation was arrested. Here, therefore, the view appears a very probable one that the hyposulphite constituted an intermediate product of a reaction following upon the production of sulphide in the first instance. In LINCK'S experiment, conducted in the same way, the process of deflagration being, however, apparently arrested at an earlier stage, more than twice the amount of hyposulphite found by BUNSEN and SCHISCHKOFF existed in the residue, while there were still nearly 6 per cent. of sulphide and 0·5 per cent. of sulphur unoxidized, and a considerably smaller amount of sulphate formed. This difference between the results of two experiments conducted on the same plan may certainly be partly ascribed to the difference in the composition of the two gunpowders experimented with, as that used by LINCK was nearly of normal composition, and contained nearly 3 per cent. more sulphur, and quite 3 per cent. less saltpetre, than BUNSEN and SCHISCHKOFF'S powder; yet this very circumstance appears to support the view that, at the first instant of explosion, sulphide is formed in considerable proportion, its immediate oxidation and the nature and extent of that oxidation being regulated by the proportion of oxygen which is liberated at the time that the sulphide is formed, the same also applying to the proportion of sulphur which at the moment of explosion does not combine with potassium to form sulphide.

Potassium hyposulphite is stated to decompose at about 200° C.; but it is evidently formed at very much higher temperatures; and the experiments of BUNSEN and SCHISCHKOFF and of LINCK demonstrated that it may remain undecomposed, or may continue to be produced, in powder-residue which is maintained at a high temperature.

We ourselves have exposed portions of powder-residue obtained in our experiments for lengthened periods to the heat of a SIEMENS furnace (1700° C.), and have still detected small quantities of hyposulphite in the material after such exposure.

It will be seen on comparing our analytical results with the pressures recorded in the several experiments as being developed by the explosions, that the latter are not affected by very great differences in the composition of the products, or by important variations in the extent to which particular reactions appear to predominate over others. The pressures developed by explosion of the pebble and R. L. G. powders, under corresponding conditions as regards the relation of charge to total space, were almost identical up to the highest density; and the same was the case with F. G. powder at the lower densities; yet there were in several instances very considerable differences between the products formed from the different powders under the same pressures (or accompanied by the development of corresponding pressures), differences which were certainly not to be accounted for by the respective constitution of those powders.

The composition of the gases and residues obtained in Experiments 3, 7, and 17, and 12, 11, and 19 (Tables III. & IV.) may be referred to in illustration of this.

A cursory inspection of the analytical results at once shows that the variations in composition of the *solid* products furnished by the different powders, and even by the same powder under different conditions, are much more considerable than in those of the gaseous products; and it is evident that the reactions which occur among the powder-constituents, in addition to those which result in the development of gas, of fairly uniform composition (and very uniform as regards the proportions which it bears to the solid), from powders not differing widely in constitution from each other, are susceptible of very considerable variations, regarding the causes of which it appears only possible to form conjectures. Any attempt to express, even in a comparatively complicated chemical equation, the nature of the metamorphosis which a gunpowder of average composition may be considered to undergo, when exploded in a confined space, would therefore only be calculated to convey an erroneous impression as to the simplicity, or the definite nature, of the chemical results and their uniformity under different conditions, while it would, in reality, possess no important bearing upon an elucidation of the theory of explosion of gunpowder.

The extensive experiments which the Committee on Explosive Substances has instituted, with English and foreign gunpowders of very various composition, have conclusively demonstrated that the influence exerted upon the action of fired gunpowder by comparatively very considerable variations in the *constitution* of the gunpowder (except in the case of *small* charges applied in firearms) is often very small as compared with (or even more than counterbalanced by) the modifying effects of variations in the mechanical* and physical properties of the powder (*i. e.* in its density, hardness, the

* The desirability of applying these means to effecting modifications in the action of fired gunpowder was pointed out by Colonel BOXER in a memorandum submitted to the War Office in 1859; and the first Government Committee on Gunpowder, soon afterwards appointed (of which Colonel BOXER and Mr. ABEL were members), obtained successful results, which were reported officially in 1864, by limiting the alterations in the manufacture of gunpowder intended for use in heavy guns to modifications in the form, size, density, and

size and form of the grains or individual masses, &c.). Hence it is not surprising to find that a fine-grain gunpowder, which differs much more in mechanical than in chemical points from the larger powder (R. L. G.) used in these experiments, should present decided differences, not only in regard to the pressures which it develops under similar conditions, but also as regards the proportions and uniformity of the products which its explosion furnishes. On the other hand, the differences in regard to size of individual masses and other mechanical peculiarities between the R. L. G. and pebble powders are, comparatively, not so considerable, and are in directions much less likely to affect the results obtained by explosions in perfectly closed spaces.

Again, the analysis of solid residues furnished by different kinds of gunpowder which presented marked differences in composition, did not establish points of difference which could be traced to any influence exerted by such variations; indeed the proportions of the several products composing residues which were furnished by one and the same powder, in distinct experiments made at different pressures, differed in several instances quite as greatly as those found in some of the residues of different powders which presented decided differences in composition. This will be seen on comparing with each other the analysis of certain residues of P. powder (*e. g.* experiments 7 and 12), of R. L. G. powder (*e. g.* experiments 4 and 39), and of F. G. powder (experiments 17 and 42), and on then comparing the composition of the residues of F. G. and R. F. G. obtained in experiments 17 and 18.

When, however, the deviation from the normal composition of cannon-powder is comparatively great, a decided influence is thereby exerted upon the proportions in which the products of explosion are formed. Thus, in the Spanish pebble powder specially selected by us for experiment on account of the considerable difference between its composition and that of the English powders, the proportion which the saltpetre bears to the carbon is comparatively high, while the amount of sulphur it contains is very high. An examination of the gaseous products which it furnished shows that the proportion of carbonic oxide is only one half the amount produced under precisely the same conditions, as regards pressure, by R. F. G. powder, and about one third the amount contained in the products furnished by pebble and R. L. G. powders under nearly similar conditions. With respect to the solid products of explosion obtained with the Spanish powder, they also present several points of great difference from the products furnished by the powders of English manufacture. The amount of potassium carbonate is very much lower than in any of the other residues examined, and the sulphate very much exceeds in amount the largest proportion furnished by the English powders. The proportion of sulphide is small, while that of hyposulphite is also not considerable.

Although, for the reasons given in the foregoing, we cannot attempt to offer any

hardness of the individual grains or masses, the composition of the powder remaining unaltered. The Committee on Explosive Substances have adhered to this system in producing gunpowder suitable for the largest ordnance of the present day.

thing approaching a precise expression of the chemical changes which gunpowder of average composition undergoes when exploded in a confined space, we feel warranted by the results of our experiments in stating, with confidence, that the chemical theory of the decomposition of gunpowder, as based upon the results of BUNSEN and SCHISCHKOFF, and accepted in recent text-books, is certainly as far from correctly representing the general metamorphosis of gunpowder as was the old and long-accepted theory, according to which the primary products were simply potassium sulphide, carbonic anhydride, and nitrogen.

Moreover the following broad facts regarding the products furnished by the explosion of gunpowder appear to us to have been established by the analytical results given in this paper.

1. The proportion of carbonic oxide produced in the explosion of a gunpowder in which the saltpetre and charcoal exist in proportions calculated, according to the old theory, to produce carbonic anhydride only, is much more considerable than hitherto accepted.

2. The amount of the potassium carbonate formed, under all conditions (as regards nature of the gunpowder and pressure under which it is exploded), is very much larger than has hitherto been considered to be produced, according to the results of BUNSEN and SCHISCHKOFF and more recent experimenters.

3. The potassium sulphate furnished by a powder of average normal composition is very much smaller in amount than found by BUNSEN and SCHISCHKOFF, LINCK, and KAROLYI.

4. Potassium sulphide is never present in very considerable amount, though generally in much larger proportion than found by BUNSEN and SCHISCHKOFF; and there appears to be strong reason for believing that in most instances it exists in large amount as a primary result of the explosion of gunpowder.

5. Potassium hyposulphite is an important product of the decomposition of gunpowder in closed spaces, though very variable in amount. It appears probable (as above pointed out) that its production is in some measure subservient to that of the sulphide; and it may perhaps be regarded as representing, at any rate to a considerable extent, that substance in powder-residue—*i. e.* as having resulted, partially and to a variable extent, from the oxidation, by liberated oxygen, of sulphide, which has been formed in the first instance.

6. The proportion of sulphur which does not enter into the primary reaction on the explosion of powder is very variable, being in some instances high, while, in apparently exceptional results, the whole amount of sulphur contained in the powder becomes involved in the metamorphosis. In the case of pebble powder, the mechanical condition (size and regularity of grain) of which is perhaps more favourable to uniformity of decomposition under varied conditions as regards pressure than that of the smaller powders, the amount of sulphur which remains as potassium polysulphide is very uniform, except in the products obtained at the lowest pressure; and it is noteworthy

that with R. L. G. powder, under the same conditions, comparatively little sulphur escapes; while in the case of F. G. powder, under corresponding circumstances, there is no free sulphur at all.

7. But little can be said with regard to those products, gaseous and solid, which, though almost always occurring in small quantities in the products, and though apparently, in some instances, obeying certain rules with respect to the proportion in which they are formed, as already pointed out, cannot be regarded as important results of the explosion of powder. It may, however, be remarked that the regular formation of such substances as potassium sulphocyanate and ammonium carbonate, the regular escape of hydrogen and sulphydric acid from oxidation, while oxygen is occasionally coexistent, and the frequent occurrence of appreciable proportions of potassium nitrate, indicate a complexity as well as an incompleteness in the metamorphosis. Such complexity and incompleteness are, on the one hand, a natural result of the great abruptness as well as the comparative difficulty with which the reactions between the ingredients of the mechanical mixture take place; on the other hand, they favour the view that, even during the exceedingly brief period within which chemical activity continues, other changes may occur (in addition to the most simple, which follow immediately upon the ignition of the powder) when explosions take place at pressures such as are developed under practical conditions.

The tendency to incompleteness of metamorphosis, and also to the development of secondary reactions under favourable conditions, appears to be fairly demonstrated by the results obtained in exploding the different powders in spaces ten times that which the charges occupied (experiments 8, 1, and 16). It appears, however, that, even under apparently the most favourable conditions to uniformity of metamorphosis (namely in explosions produced under high pressures), accidental circumstances may operate detrimentally to the simplicity and completeness of the reactions. But the fact, indisputably demonstrated in the course of these researches, that such accidental variations in the nature of the changes resulting from the explosion do not, even when very considerable, affect the force exerted by fired gunpowder, as demonstrated by the recorded pressures, &c., indicates that a minute examination into the nature of the products of explosion of powder does not necessarily contribute directly to a comprehension of the causes which may operate in modifying the action of fired gunpowder.

G. VOLUME OF THE PERMANENT GASES.

The results of the experiments made to determine the quantity of permanent gases generated by the explosion of the three service-powders which we have employed are given in Nos. 53 to 62 and 64.

From a discussion of these results it appears that, in the case of pebble powder, the combustion of 386.2 grammes gave rise respectively to 106,357.8, 105,716.2, and 107,335.8 cub. centims. of gas at a temperature of 0° C. and a barometric pressure of 760 millims.; or, stating the result per gramme of powder, the combustion of 1 gramme

pebble generated respectively 275·4, 273·7, and 277·9 cub. centims., or a mean of 275·68 cub. centims., at the above temperature and pressure.

From the combustion of a similar quantity of R. L. G. powder resulted 106,080·4, 103,676·5, and 104,606·7 cub. centims., or 274·7, 268·45, and 270·86 cub. centims. of gas (mean=271·34 cub. centims.) per gramme of powder; while 99,694·9, 101,372·3, 99,164·8, and 100,289·0, or 262·4, 258·1, 256·8, and 259·68 (mean 259·2) cub. centims. per gramme were yielded by the F. G. powder.

The difference in quantity of gas between the pebble and the R. L. G. is very slight; but there appears to be a decided difference in the quantity generated by F. G. powder, the defect being much greater than can be accounted for by any errors of observation.

The results of those experiments show that the quantity of permanent gases generated by 1 gramme of the service pebble or R. L. G. powders is about 276 cub. centims. at 0° C. and 760 millims.—that is, they occupy at this temperature and pressure about 276 times the volume of the unexploded powder.

The volume given off by F. G. is less, being about 260 volumes; and, if we may trust to the single measurement we have made of the permanent gases of R. F. G. (in experiment 80), the volume generated by this powder does not differ greatly from that given off by F. G.

With the view of ascertaining whether a powder of a marked difference in composition, such as the Spanish spherical pellet powder, gave the same quantity of permanent gases as our service-powders, a measurement of the volume generated by this powder was made (in experiment 81).

The quantity was found to be notably less, being only 232·7 volumes; but this measurement was the result of one determination only.

H. RESULTS OF EXPLOSION, DEDUCED BY CALCULATION FROM ANALYTICAL DATA.

We are now in a position to apply two important tests to the results at which we have arrived as regards composition of products and measurement of gases. From a consideration of the analysis of the solid products of explosion, we are able to deduce the total weight of the solid residue, and thence, by difference, the weight of the gaseous products. On the other hand, from a consideration of the measurement of the volume of the gaseous products, combined with their analysis, we can calculate the weight of the gaseous and, by difference, that of the solid products; and if these calculations accord, a valuable corroboration of the accuracy of our results will be obtained. We can also compare the amounts of the elementary substances in the powder before and after combustion, and so obtain a still further corroboration of accuracy.

We have applied these tests to all the analyses completed; and we proceed to give two illustrations of the method—one applied to pebble, the other to F. G. powder.

In experiment 12, 411·085 grms. pebble powder were fired, and the products of combustion collected and analyzed. The analysis of this powder has been already

given; but for our present purpose it is convenient to give the proportions of the components, as found by analysis, in their elementary form.

The pebble powder, then, consisted of:—

	Percentage composition.	Composition by weight. grammes.
K	·2886	118·639
C	·1212	49·824
S	·1007	41·396
H	·0052	2·138
O	·3742	153·828
N	·1078	44·315
Ash	·0023	·945
	<hr/>	<hr/>
	1·0000	411·085

while the composition of the solid products of combustion was found to be:—

K_2CO_3	·55220	KCNS	·00244
$K_2S_2O_3$	·14080	KNO_3	·00084
K_2SO_4	·13200	$(NH_4)_2CO_3$	·00067
K_2S	·09700	S	·06058
		Not estimated	·01347

Now almost any practical method of weighing the solid residue would give us inexact results, the weight of the vessel used for explosion being too great to allow of sufficient accuracy if weighed in the vessel, and the hygroscopic nature of the residue, as well as the difficulty of removing it, preventing its being weighed after removal. But we can arrive at the weight in the following manner:—We know that the whole of the potassium originally contained in the powder will be found in the solid residue; we further know that potassium enters into the composition of potassium carbonate, hyposulphite, sulphate, sulphide, and sulphocyanate in the proportions respectively of 565, 411, 448, 709, and 402 parts out of every thousand. Hence if x be the weight of the solid residue we have the following equation:—

$$\begin{aligned} & \{ \cdot 565 \times \cdot 55220 + \cdot 411 \times \cdot 14080 + \cdot 448 \times \cdot 13200 + \cdot 709 \times \cdot 09700 \\ & + \cdot 402 \times \cdot 00244 + \cdot 386 \times \cdot 00084 \} x = 118 \cdot 639, \end{aligned}$$

118·639 grms. being the amount of potassium originally in the powder.

Hence x = solid products = 237·717 grms. = ·5783, and by difference gaseous products = 173·368 grms. = ·4217.

We can now perform the inverse process, and, from the measurement of the gas and the gaseous analysis, arrive at the weight of the solid products. Since 1 gm. of pebble powder gave rise to 275·68 cub. centims. of permanent gases, 411·085 grms. will generate 113,797·9 cub. centims. But the analysis of the permanent gases, in this particular experiment, gave SH_2 ·0170 volume, CO ·1395, CO_2 ·4952, CH_4 ·0032, H ·0235, N ·3216 volumes, while a cubic centimetre of these gases weighs respectively ·001523, ·001254, ·001971, ·0000896, and ·001254 gm. Hence we have as follows:—

	vols.	cub. centims.	grms.	weight.
SH ₂	·0170=	1,934·6	2·946	·0163
CO	·1395=	15,874·8	19·907	·1104
CO ₂	·4952=	56,352·7	111·071	·6160
CH ₄	·0032=	364·2	·261	·0015
H	·0235=	2,674·3	·240	·0013
N	·3216=	36,597·4	45·893	·2545
	<u>1·0000</u>	<u>113,798·0</u>	<u>180·318</u>	<u>1·0000</u>

Hence, taking the gas-measurement and analysis combined as the basis of calculation, we have:—

Gaseous products = 180·318 grms. Solid products = 230·767 grms.

or, if we take the mean of the two determinations as more nearly representing the truth,

Solid products = 234·242 grms. = ·5698

Gaseous products = 176·843 grms. = ·4302

Resolving the solid products of combustion into their elements, we have the following scheme:—

	Grms.	K.	C.	S.	H.	O.	N.
K ₂ CO ₃	129·348	73·082	11·253	.....	.....	45·013	.....
K ₂ S ₂ O ₃	32·981	13·555	.....	11·115	.....	8·311	.....
K ₂ SO ₄	30·920	13·852	.....	5·689	.....	11·379	.....
K ₂ S	22·721	16·109	.....	6·612	.....	.....	.....
KCNS	·572	·230	·069	·083	.....	.....	·189
KNO ₃	·197	·077	.....	·095	.....	.....	·027
(NH ₄) ₂ CO ₃	·157	·078	·020	.....	·013	.....	·046
C .....	.....	.....	.....	.....	.....	.....	.....
S	14·190	.....	.....	14·190	.....	.....	.....
Not estimated	3·155	.....	.....	1·263	.....	.....	.....
Totals	234·241	116·983	11·342	39·047	·013	64·703	·262

Following the same plan with the gaseous products, and comparing the total weights of the elements found with those existing in the powder before combustion, we have:—

	Grms.	K.	C.	S.	H.	O.	N.
SH ₂	2·882	.....	.....	2·712	0·170	.....	.....
O .....	.....	.....	.....	.....	.....	.....	.....
CO	19·523	.....	8·375	.....	.....	11·148	.....
CO ₂	108·936	.....	29·740	.....	.....	79·196	.....
CH ₄	·265	.....	·199	.....	·066	.....	.....
H	·230	.....	.....	.....	·230	.....	.....
N	45·007	.....	.....	.....	.....	.....	45·007
Total gaseous	176·843	.....	38·314	2·712	·466	90·344	45·007
Total solid	234·241	116·983	11·342	39·047	·013	64·703	·262
Total found	411·084	116·983	49·656	41·759	·479	155·047	45·269
Total originally in powder	411·085	118·639	49·824	41·396	2·138	153·828	45·
Errors .....	.....	-1·656	-0·168	+·363	-1·659	+1·219	+·269

If we perform similar calculations in the case of experiment 17, when 205·542 grms. of F. G. were exploded, and the products found to be of the undermentioned composition:—

Solid Products.		Gaseous Products.	
K_2CO_3 . . .	·5939	$(NH_4)_2CO_3$. . .	·0015
$K_2S_2O_3$. . .	·0530	S	·0572
K_2SO_4 . . .	·2422		
K_2S	·0512		
KCNS	·0002		
KNO_3	·0008		
			vol.
		SH_2	·0376
		CO	·1235
		CO_2	·4741
		CH_4 . . . .	. . . .
		H	·0413
		N	·3235

we obtain:—

For solid products 119·554 grms. = ·5817

For gaseous products. . . . 85·987 grms. = ·4183

or, resolving these products as before into their elements:—

	Grms.	K.	C.	S.	H.	O.	N.
K_2CO_3	71·003	40·117	6·177	.....	.....	24·709	.....
$K_2S_2O_3$	6·336	2·604	.....	2·135	.....	1·597	.....
K_2SO_4	28·956	12·972	.....	5·328	.....	10·656	.....
K_2S	6·121	4·340	.....	1·781	.....	.....	.....
KCNS	·024	·010	·003	·008	.....	.....	·003
KNO_3	·096	·037	.....	.....	.....	·045	·013
$(NH_4)_2CO_3$	·179	.....	·022	.....	·015	·090	·052
C .....	.....	.....	.....	.....	.....	.....	.....
S	6·839	.....	.....	6·839	.....	.....	.....
Total solid	119·554	60·080	6·202	16·091	·015	37·097	0·068
SH_2	3·164	.....	.....	2·977	·187	.....	.....
CO	8·556	.....	3·671	.....	.....	4·885	.....
CO_2	51·644	.....	14·099	.....	.....	37·545	.....
CH_4 .....	.....	.....	.....	.....	.....	.....	.....
H	·206	.....	.....	.....	·206	.....	.....
N	22·417	.....	.....	.....	.....	.....	22·417
Gaseous	85·987	.....	17·770	2·977	·393	42·430	22·417
Solid	119·554	60·080	6·202	16·091	·015	37·097	0·068
Found originally in powder	205·541 205·542	60·080 58·662	23·972 23·349	19·068 20·760	·408 1·336	79·527 79·031	22·485 22·700
Errors .....	.....	+1·418	+0·623	-1·692	-·928	+·496	-·215

It will be seen from this comparison that the results, when the nature of the analysis is taken into consideration, accord with great exactness. The volume of the gaseous products, calculated from the weight of the gases given in the first column of the Table, would be about 279 cub. centims. at 0° C. and 760 millims. per gramme of powder in the case of the pebble, and 267 cub. centims. in the case of the F. G. powder. These volumes are slightly more than the measured volumes; but it must be remembered

that it is not difficult to conceive causes which might tend to make the mean measured quantity of gas somewhat less than reality, while it is hardly possible that the reverse can be the case.

For example, without doubt an appreciable quantity of gas is occluded, as indicated by the conditions of the residues (see account of experiments Nos. 10 and 38) and by the disengagement of gas generally observed upon addition of water to the residue. In some instances also there may be, under the high pressure of explosion, a trifling leakage from the apparatus.

One point we must not pass over without observation. The deficiency of hydrogen in the products of explosion, although absolutely small, is relatively very large. The question then arises as to whether the missing hydrogen may not be present in the form of aqueous vapour. None was detected in the analysis of the gases; but it is not difficult to explain this fact, as the extremely hygroscopic property of the residue would most effectually dry the gases—the absorption of the vapour by the residue being actually demonstrated by the greasiness observed on the surface of the deposit and on the sides of cylinder immediately on its being opened after explosion. The entire proportion of water formed or preexisting must therefore have existed in the solid residues, but its determination therein was obviously impracticable.

The amount of water present can, however, be calculated from the deficiency of hydrogen shown in our Tables.

I. CONDITION OF PRODUCTS AT THE INSTANT OF OR SHORTLY AFTER EXPLOSION.

A careful examination of the contents of the cylinders after they were opened showed that, at all events shortly after explosion, the solid products were in a fluid state. It was of course impossible to open the cylinder while the solid products were still fluid; but it occurred to us that we might yet obtain valuable information as to the state of the contents at different periods after the explosion. Accordingly, in experiment 40, the cylinder being about two thirds filled with F. G., thirty seconds after the explosion the vessel was tilted so as to make an angle of 45° . Two minutes later it was restored to its first position.

On subsequent examination the deposit was found to be lying at the angle of 45° , and the edges of the deposit were perfectly sharp and well defined.

In experiment 41, the cylinder, being about three fourths filled with R. L. G., was allowed to rest for one minute after explosion. It was then placed sharply at an angle of 45° , and forty-five seconds later it was returned to its first position.

Upon opening it was found that when the cylinder was tilted over the deposit had just commenced to congeal; for upon the surface there had been a thin crust which the more fluid deposit underneath had broken through. The deposit was lying at an angle of 45° , but the crust through which the fluid had run was left standing like a thin sheet of ice.

Hence in this experiment, one minute after explosion, the non-gaseous products had commenced to congeal, and forty-five seconds later they were solid.

In experiment 77, the cylinder, being completely full of pebble powder and fired, was placed at an angle of 45° one minute after explosion, and the position of the cylinder was altered every fifteen seconds. It was found that at sixty and seventy-five seconds after explosion the deposit was perfectly fluid, the evidence of each motion of the cylinder being given by a wave of deposit. At ninety seconds it was rather viscid; at one hundred and five seconds the deposit hardly moved.

Hence in this experiment it was rather more than a minute and three quarters before the non-gaseous products became solid; and the conclusion from the experiments is that, very shortly after explosion, the non-gaseous products are collected as a fluid at the bottom of the exploding-vessel, and that some time elapses before these products finally assume the solid form.

J. THE POSSIBILITY OF DISSOCIATION AMONG GASEOUS PRODUCTS CONSIDERED.

In the attempt to reconcile or account for the discordant estimates of the pressure exerted by fired gunpowder, some authorities have supposed that the phenomena connected with dissociation play an important part, and that, for example, the dissociation of carbonic anhydride into carbonic oxide and oxygen may give rise to a considerable increment of pressure.

BERTHELOT has enunciated the view that the tendency to dissociation at very high temperatures possessed by compound gases operates in preventing the formation, at the time of explosion, of certain of the constituents which exist in the ultimate gaseous products, and that during the expansion in the bore of the gun and the concomitant fall of temperature, the compound gases existing in those ultimate products are gradually formed. He*, indeed, points out that the effects of dissociation must not be exaggerated, and that the decomposing influence of high temperature in the case of an explosion may be altogether or in part compensated by the inverse influence of pressure. Having given this subject our careful consideration, we cannot even go so far as BERTHELOT does in accepting the view that the results of explosion of powder in a gun are at all affected by dissociation, the occurrence of which we cannot consider probable even when the pressure to which the gases are subjected in the bore of a gun is relieved to the maximum extent.

It is perhaps, however, worth while examining what would be the effect on the pressure if the particular case of dissociation to which we have alluded above actually occurred.

Among the products of combustion of 1 gramme of powder is .28 gm. of CO_2 occupying, at 0°C . and 760 millims. pressure, 142 cub. centims.; now if we suppose this CO_2 dissociated into CO and O , the 142 cub. centims. of CO_2 would become 213 cub.

* BERTHELOT, 'Force de la Poudre &c.,' 1872, p. 81.

centims. of the mixed gases, and the total quantity of gas generated by a gramme of powder (282 cub. centims.) would become 353 cub. centims.

On the other hand, the .28 gramme of CO_2 contains .0764 gm. C., which, burnt to CO_2 , gives rise to 611 gramme-units, or burnt to CO gives rise to 187 gramme-units.

Now if a given weight of carbonic oxide, in combining with another atom of oxygen and burning to carbonic anhydride, generates 424 units of heat, it is obvious that the reverse process, or dissociation of the carbonic anhydride into carbonic oxide and oxygen, must absorb precisely the same amount of heat.

Hence the dissociation we have supposed would absorb 424 gramme-units of heat, and the consequent loss of temperature would reduce the pressure in a degree that would far more than compensate for the increment due to the increase of volume by dissociation.

K. TENSION OF FIRED POWDER OBSERVED IN A CLOSE VESSEL.

As it was one of our principal objects to determine with as much accuracy as possible not only the tension of fired gunpowder when filling completely the space in which it was exploded, but also to determine the law according to which the tension varied with the density, it has been our endeavour to render both varied and complete the experiments instituted to ascertain these important points.

In the first experiments described in this paper, as well as in the earlier series which formed the basis of Captain NOBLE'S lecture delivered to the Royal Institution, the method adopted to determine the variation of pressure was as follows:—The space in which the powder was to be fired having been carefully established, the weight of the powder to be experimented with which would accurately fill the space was ascertained, and $\frac{1}{10}$, $\frac{2}{10}$, $\frac{3}{10}$, &c. of the vessel was successively filled with powder, which was then fired, and the resulting pressures determined.

Later on it was found that, as with each description of powder the gravimetric density varied, it was more convenient to refer the pressure not, as at first, to a density arrived at by taking the weight of powder which completely filled a given space as unity, but to the specific gravity of water as unity. The densities given hereafter must therefore be taken to represent the mean density of the powder inclusive of the interstitial spaces between the grains, or, what is the same thing, the mean density of the products of explosion referred to water as unity. The gravimetric density of the modern pebble powders closely approximates to 1*; that of the old class of cannon-powders, such as L. G., R. L. G., &c., varied generally between† .870 and .920; that of F. G. and sporting-powders was still lower.

* This statement applies only to the powder taken in considerable bulk. In our explosion-vessels, the gravimetric density, when they were completely filled, did not exceed, with pebble powder, .92 or .93. The statement, therefore, that the powder was fired in so many per cent. of space does not actually refer to the space occupied in the chamber, but to a chamber of a size that would hold powder of our standard density.

† BOXER, Gen., R.A., 'Treatise on Artillery,' 1859, p. 21. MORDECAI, Major, U.S.A., 'Report on Gunpowder,' Washington, 1845, p. 187.

The results of the whole of our experiments, as far as they relate to tension, arranged according to the three descriptions of the powder used and to the density of the products of explosion, are given in Table V. The experiments numbered with an asterisk are taken from the earlier series made by Captain NOBLE. They accord very well with the present experiments; but the powder used in the first series not having been analyzed, we are not prepared to say that it was of exactly the same constitution as the corresponding kind of powder used in the present experiments, although the difference could of course be but very trifling, it being gunpowder of Waltham-Abbey manufacture, which, as shown by the analyses given in Table II., varies very little in composition.

TABLE V.—Giving the pressures actually observed, in tons per square inch, with F. G., R. L. G., and Pebble powders for various densities of the products of Explosion.

Mean density of products of explosion.	Nature of Powder.			Mean density of products of explosion.	Nature of Powder.		
	F. G.	R. L. G.	Pebble.		F. G.	R. L. G.	Pebble.
	Pressure in tons per square inch.	Pressure in tons per square inch.	Pressure in tons per square inch.		Pressure in tons per square inch.	Pressure in tons per square inch.	Pressure in tons per square inch.
·0940	.....	1·6	.....	·5000	10·48	10·48	.....
·1064	1·66	.....	1·39	”	10·20	10·70	.....
”	1·35	.....	1·26	”	.....	11·10	.....
”	0·96	.....	1·28	*·5300	.....	*11·80	.....
·1973	.....	2·67	.....	·5322	11·48	.....	12·20
·2000	.....	.....	2·70	·6000	14·14	14·36	13·78
·2114	.....	.....	2·93	”	.....	.....	13·50
·2129	3·70	.....	.....	”	.....	.....	14·80
”	3·58	.....	.....	*·6100	.....	*15·6	.....
”	3·00	.....	.....	*·6200	.....	*16·8	.....
·2963	.....	6·40	.....	·7000	18·2	19·54	18·60
·3000	.....	.....	5·40	”	†18·9	.....	‡17·00
·3171	.....	.....	4·90	*·7500	.....	*21·90	.....
·3193	6·75	.....	.....	·8000	23·20	24·40	28·60
”	6·32	.....	.....	”	27·10	23·20	24·20
*·3800	.....	*8·5	.....	·9000	27·20	35·6	33·40
”	.....	*7·7	.....	”	.....	.....	31·60
·3860	7·68	.....	.....	”	.....	.....	31·40
·3947	.....	8·1	.....	*·9000	.....	*33·1	.....
·4258	9·34	.....	8·40	.....	.....	*30·7	.....
”	.....	.....	9·10	.....	.....	*31·9	.....
·4615	8·68	.....	.....	·9150	.....	34·5	.....
·4893	10·14	.....	.....	·9300	.....	36·2	.....
·4934	.....	11·50	.....	·9300	.....	*34·0	§35·0

† R. F. G. powder.

‡ Spanish spherical pellet.

§ Pellet.

We have laid down on Plate 16 the whole of these experiments. The pressures given by the pebble and the R. L. G. are nearly identical; we have therefore considered them so, and have drawn but one curve to represent their mean results. The curve representing the pressures given by the F. G., although nearly identical with the pebble and R. L. G. at the lower densities, does not coincide at the higher densities. A separate curve has therefore been drawn for this powder. The lower tension is perhaps accounted

for by the difference between the quantity of permanent gas yielded by it and by the other two powders.

The corrected values of the tension, in terms of the density of the different powders, as indicated by the curves Plate 16, are given in the following Table:—

TABLE VI.—Showing the pressure corresponding to a given density of the products of explosion of F. G., R. L. G., and Pebble powders, as deduced from actual observation, in a close vessel. The pressures are given in tons per square inch, atmospheres, and kilogrammes per square centimetre.

Mean density of products of explosion.	Corresponding pressures for Pebble and R. L. G. powders.			Corresponding pressures for F. G. powder.		
	In tons per square inch.	In atmospheres.	In kilos. per square centimetre.	In tons per square inch.	In atmospheres.	In kilos. per square centimetre.
·05	0·70	107	110·2	0·70	107	110·2
·10	1·47	224	231·5	1·47	224	231·5
·15	2·33	355	367·0	2·33	355	367·0
·20	3·26	496	513·4	3·26	497	513·4
·25	4·26	649	670·9	4·26	650	670·9
·30	5·33	812	839·4	5·33	812	839·4
·35	6·49	988	1028·1	6·49	988	1022·1
·40	7·75	1180	1220·5	7·74	1179	1219·0
·45	9·14	1392	1439·5	9·10	1387	1433·2
·50	10·69	1628	1683·6	10·59	1614	1667·8
·55	12·43	1893	1957·6	12·22	1863	1924·5
·60	14·39	2191	2266·3	14·02	2136	2208·0
·65	16·60	2528	2614·3	16·04	2445	2526·1
·70	19·09	2907	3006·5	18·31	2790	2883·6
·75	21·89	3333	3447·5	20·86	3179	3285·2
·80	25·03	3812	3942·0	23·71	3613	3734·1
·85	28·54	4346	4495·0	26·88	4096	4233·3
·90	32·46	4943	5112·1	30·39	4632	4786·1
·95	36·83	5608	5800·4	34·26	5190	5335·6
1·00	41·70	6350	6567·3	38·52	5870	6066·5

In considering the pressures indicated, the question naturally arises as to how their value would be affected if the charges were greatly increased; or, to put the question in another form, it may be inquired whether the tensions indicated by our experiments are materially affected by the cooling influence of the vessel in which the explosion is conducted.

We think there are very strong grounds for assuming that the pressure is not materially affected by the above circumstances, except in cases where the density of the products of explosion is low and the quantity of powder therefore very small as compared with the space in which it is fired.

Thus it will be observed that the pressures obtained in experiment 2 and in experiments 65, 66, and 68 compare very well (the density being about the same), although the quantity of powder fired in the first case is only half of that fired in the last three experiments.

Again, if there were any considerable decrement of pressure due to loss of heat, we should expect to find that the tension indicated would be higher when means are taken to insure rapidity of combustion. Such, however, is not the case; for if reference be made to experiments 70 and 71, in which the charges were detonated by means of mercuric fulminate, it will be observed that the tension realized in these experiments was not materially higher than when the powder was fired in the ordinary way.

We may cite also, in support of our view, some interesting observations made during some earlier experiments in which charges of 10,500 grains (680.4 grms.) R. L. G. and pellet powder were fired in chambers entirely closed with the exception of a vent .2 inch (5.08 millims.) in diameter.

With the former powder the pressure realized under these circumstances was 36.2 tons per square inch (5513 atmospheres), with the latter 17.3 tons (2634 atmospheres). This large difference was due to the slower combustion of the pellet powder, upon the ignition of which, therefore, a large part of the products of combustion escaped by the vent before the whole of the powder was fired. When, however, the same powders were fired in vessels absolutely closed, the pressure indicated by the pellet powder was more than doubled (being 35 tons per square inch, or 5330 atmospheres), while the pressure indicated by the R. L. G. was practically the same (being 34 tons per square inch, or 5178 atmospheres).

From the experiments made by the Committee on Explosives, we are able to name approximately the absolute time that would be consumed in burning a charge of R. L. G. and of pebble, assuming that the powder be confined. With R. L. G. the time would be approximately .00128 second, with pebble approximately .0052 second. Of course these figures must vary greatly with different powders, as they depend not only on the nature, size of grain, and density of the powder, but also on the mode of ignition. They are interesting, however, as indicating the minuteness of the times involved and the relatively much larger time required for the decomposition of the pebble powder. It follows from the accordance of the pressures in the experiments just referred to, when powders differing so considerably in rapidity of combustion are fired in close vessels, that there is no very appreciable difference in pressure due to the longer time taken by the pebble powder to consume under these conditions.

But the strongest, and at the same time an altogether independent, corroboration of our view is derived from the experiments upon the pressures exerted in the bores of guns by the action of the charge.

Not only do these pressures, as obtained by observation, agree with most remarkable accuracy with the theoretical pressures deduced from the experiments in a close vessel, but, when in large guns the tensions due to very different charges are compared, not with reference to the position of the shot in the bore, but with reference to the mean density of the products of explosion, a most striking accordance is found to exist. We may therefore conclude that, where powders such as those we have experimented with are employed, there is but a trifling correction to be made in the observed pressure when

the powder entirely fills the space in which it is fired, or, indeed, whenever it occupies a considerable percentage of that space. But though the pressure may not be seriously affected when the generated gases are of a high density, it is more than probable that some very appreciable correction should be made in the results we have observed when experimenting with gases of low density. In this latter case the cooling influence of the vessel would be greatly increased, not only from the higher ratio which the cooling surface bears to the charge, but also from the slowness of combustion due to the comparatively feeble pressure; and we think the effect of slow combustion is clearly traceable in the low tensions observed with pebble powder (see curve, Plate 16) at densities of $\cdot 1$, $\cdot 2$, and $\cdot 3$, as compared with those given at corresponding densities by F. G. powder, the combustion of which would be much more rapid. But we shall return to this point when we compare our results with those demanded by theory.

Upon the same Plate (Plate 13) on which we have given curves representing the experiments of RUMFORD and RODMAN, there is also laid down a curve representing our own experiments. The very high results obtained by RUMFORD are probably in great measure attributable to his method of experiment. The charges being placed at one end of his little vessel, while the weight to be lifted, so to speak, closed the muzzle, the products of combustion acquired a high *vis viva* before striking the weight, and thus indicated a much higher pressure than that due to the tension of the gas, just as in ROBINS'S well-known experiment a musket-barrel may be easily bulged or burst by a bullet placed at some distance from the charge. That RUMFORD'S and even PIOBERT'S corrected estimate of the tension of fired gunpowder was very excessive is of course indisputably proved by our experiments, as the vessels in which they were made were quite incapable of resisting pressures at all approaching those assigned by these eminent authorities.

RODMAN'S results are also too high, from a defect in the application of his system of measurement, which has elsewhere* been pointed out; and his experiments on the ratio of tension to density were not carried sufficiently far to admit of comparison in the more important portion of the curve.

L. DETERMINATION OF HEAT GENERATED BY THE COMBUSTION OF GUNPOWDER.

The amount (that is the number of units) of heat liberated by the combustion of gunpowder is determined from experiments Nos. 46, 47, 48, 49, and 63.

The powder used was the R. L. G. and F. G.; but as it was found that there was no material difference in the heat liberated, we have drawn no special distinction between the experiments made with the two brands.

In each of the experiments Nos. 46, 48, and 63, 3800 grains (246·286 grms.) were exploded; and when the necessary reductions were made to convert the alterations in temperature which were observed into their equivalents in water, it was found that in experiment 48 the explosion of 246·286 grms. F. G. was sufficient to raise 173,077·4

* NOBLE, *loc. cit.* p. 25; *Revue Scientifique*, No. 48, p. 1138.

grms. of water through 1°C . In experiment 48 the explosion of the same quantity of R. L. G. was equivalent to raising 172,569 grms. of water through 1°C ., and in experiment 63 to raising 171,500 grms. through 1°C .; or, expressing these results in a different form, it appears that the combustion of a gramme of powder gave rise to quantities of heat represented by raising a gramme of water through $702^{\circ}\cdot 80\text{C}$., $700^{\circ}\cdot 69\text{C}$., and $696^{\circ}\cdot 50\text{C}$. respectively.

In experiments 47 and 49 the charge used was 393·978 grms.; and it was found that in experiment 47 the heat generated by the explosion of the F. G. was sufficient to raise 277,994·1 grms. of water through 1°C .; and in experiment 49 the explosion of the same quantity of R. L. G. generated heat represented by the raising of 278,185·5 grms. through 1°C .,—or, in the two experiments, 1 gramme of powder gave rise respectively to 705·61 and 706·09 gramme-units.

The mean of the whole of these experiments gives 702·34 gramme-units of heat generated by the explosion of a gramme of powder, and we shall probably have a very close approximation to the truth in assuming it at 705 gramme-units.

From this datum the temperature of explosion may be deduced, if we know the mean specific heat of the products of combustion. We have only to divide 705 by the specific heat, and the result is the required temperature.

The specific heat of all the gaseous products of combustion are known; and they have also been determined for the principal solid products at low temperatures, when they are [of course] in the solid form.

BUNSEN and SCHISCHKOFF, from their experiments, deduced the temperature of explosion on the assumption that the specific heats of the solid products remain invariable over the great range of temperature through which they pass.

With every deference to those distinguished chemists we think their assumption is quite untenable. Without, we believe, any known exception, the specific heat is largely increased in passing from the solid to the liquid state. In the case of water the specific heat is doubled; the specific heats of bromine, phosphorus, sulphur, and lead are increased from 25 to 40 per cent., and those of the nitrates of potassium and sodium nearly 50 per cent., while it is more than probable that, even with liquids, the specific heat increases very considerably with the temperature.

We shall, however, deduce from our experiments the temperature of explosion on BUNSEN and SCHISCHKOFF'S hypothesis, both with the view of enabling our results to be compared with theirs, and for the purpose of fixing a high limit, to which it is certain the temperature of explosion cannot reach. We shall afterwards endeavour to estimate more accurately the true temperature.

The data necessary for computing the specific heat of a gramme of exploded powder are given in the subjoined Table.

TABLE VII.—Showing the specific heats and proportions of the products generated by the combustion of gunpowder.

1. Products of combustion.	2. Proportion in a gramme.	3. Specific heat.	4. Authority.	5. Products of columns 2 & 3.
<i>Solid</i> ·5684.				
Potassium carbonate	·3382	·206	Kopp.	·06967
„ hyposulphite	·0355	·197	Pape.	·00700
„ sulphate	·0882	·196	Kopp.	·01729
„ sulphide	·0630	·108	Bunsen.	·00680
„ sulphocyanate	·0009			
„ nitrate	·0006	·239	Kopp.	·00014
Ammonia carbonate	·0006			
Sulphur	·0414	·171	Bunsen.	·00708
Carbon	·0000	·242	Regnault.	
<i>Gaseous</i> ·4316.				
Sulphuretted hydrogen	·0113	At constant volume. ·184	Clausius.	·00208
Oxygen	·0000	·155	„	
Carbonic oxide	·0447	·174	„	·00778
Carbonic anhydride	·2628	·172	„	·04520
Marsh-gas	·0005	·468	„	·00024
Hydrogen	·0010	2·411	„	·00241
Nitrogen	·1113	·173	„	·01925
				·18494

Adding up the numbers in column 5, we obtain ·18494 as the mean specific heat of the products of explosion of a gramme of powder at ordinary temperatures; and since, as we have said, the temperature of explosion is obtained by dividing the gramme-units of heat by the specific heat, we have the temperature of explosion = $\frac{705}{\cdot18494} = 3812^{\circ}$ C.; and we may accept this figure as indicating a temperature which is certainly not attained by the explosion of gunpowder. We defer until further on the consideration of the actual temperature.

M. DETERMINATION OF VOLUME OF SOLID PRODUCTS AT ORDINARY TEMPERATURES.

The space occupied by the solid products of combustion at temperatures but little removed from 0° is deduced from experiments Nos. 46, 48, 49, 57, 58, 60, 61, and 62. From these experiments it appears that

246·29	grms.	R. L. G.	gave rise to	76·46	cub. centims.	solid residue.
„	„	F. G.	„	67·26	„	„
393·98	„	R. L. G.	„	123·12	„	„
386·21	„	F. G.	„	115·34	„	„
„	„	R. L. G.	„	110·81	„	„
„	„	P.	„	111·78	„	„
„	„	R. L. G.	„	105·30	„	„
„	„	F. G.	„	108·54	„	„

Or, stating the results per gramme of powder, it appears that in the several experiments the solid products arising from the combustion of a gramme of powder occupied respectively $\cdot 3105$, $\cdot 2731$, $\cdot 3125$, $\cdot 2987$, $\cdot 2869$, $\cdot 2894$, $\cdot 2726$, and $\cdot 2810$ cub. centim.

The mean of these figures is $\cdot 2906$; and we may thence conclude that at 0° C. the solid residue of 1 gramme of burned powder occupies a volume closely approximating to $\cdot 29$ cub. centim.; therefore, since the solid products represent 57 per cent. of the original weight of the powder, it follows that at 0° C. the specific gravity of the residue is about 1.4.

N. PRESSURE IN CLOSE VESSELS, DEDUCED FROM THEORETICAL CONSIDERATIONS.

From the investigations we have described, it appears that in a close vessel, at the moment of explosion, or at all events shortly afterwards, the results of the decomposition of a given charge (say 1 gramme) of powder such as we have experimented with are as follows:—

1. About 43 per cent. by weight of permanent gases, occupying, at 0° C. and under a pressure of 760 millims., a volume of about 280 cub. centims.
2. About 57 per cent. by weight of liquid product, occupying, when in the solid form and at 0° C., a volume of about $\cdot 3$ cub. centim.

Now, if we assume that the conditions known to exist shortly after explosion obtain also at the moment of explosion, we are able, with the aid of our experiments, to compute the pressure, temperature of explosion, and volume occupied by the permanent gases. We propose to make these calculations, and then, by comparison with the results obtained under the varied conditions adopted in our experiments, to form an estimate of the correctness of our assumption. And, first, to establish a relation between the tension and the mean density of the products of explosion at the moment of ignition,—

Let A B C D, Plate 15. fig. 4, represent the interior of the vessel, of volume v , in which the experiments were made. Let C D E F represent the volume of a given charge of powder placed in the vessel. Let δ be the ratio which the volume C D E F bears to A B C D, and let C D H G ($v\alpha\delta$ suppose) be the volume occupied by the liquid products at the moment and temperature of explosion.

It is obviously, for our present purpose, a matter of indifference whether we suppose the liquid products collected, as in the figure, at the bottom of the vessel or mixed with the permanent gases in a finely divided state.

Our conditions on explosion, then, are:—we have the space C D H G = $v\alpha\delta$ occupied by the fluid residue, and the space A B H G = $v(1 - \alpha\delta)$ by the permanent gases.

Hence, since the tension of the permanent gases will vary directly as their density, we have, if p represent the pressure and D the density,

$$p = RD, \dots \dots \dots (1)$$

where R is a constant.

Now suppose the charge exploded in the chamber to be increased. In this case, not only is the density of the permanent gases increased on account of a larger quantity being generated, but the density is still further added to, from the gases being confined in a smaller space; the liquid residue CDHG being increased in a like proportion with the charge (D, in fact, varying as $\frac{\delta}{1-\alpha\delta}$), we have

$$p = R \cdot \frac{\delta}{1-\alpha\delta}; \quad \dots \dots \dots (2)$$

or if p_0, δ_0 be corresponding known values of p and δ ,

$$p = \frac{p_0(1-\alpha\delta_0)}{\delta_0} \frac{\delta}{1-\alpha\delta}. \quad \dots \dots \dots (3)$$

In taking the tension of the permanent gases to vary directly as their density, we have of course assumed that the temperature, whatever be the value of δ , is the same.

In our experiments the charges exploded have varied in quantity from that necessary to fill entirely the chamber to a small fraction of that quantity; but whatever the charge it is obvious that if the vessel be considered impervious to heat (and we have already pointed out that only with the lower charges is there a material error due to this hypothesis), the temperature at the moment of explosion would be the same; for, as in the case of JOULE'S celebrated experiment, any heat converted into work by the expansion of the gases would again be restored to the form of heat by the impact of the particles against the sides of the vessel.

Returning to (3), the value of the constant α in this equation has yet to be found. If from Table VI. we take out a second pair of corresponding values p_1, δ_1 , α is determined and will be found = .65, very nearly. Taking $\alpha = .65$, and from Table VI. or the curve Plate 16 taking $\delta_0 = .6$, $p_0 = 14.4$ tons, equation (3) becomes

$$p = 14.63 \frac{\delta}{1-\alpha\delta}. \quad \dots \dots \dots (4)$$

Substituting in this equation successively values of δ .05, .1, .15, &c., we obtain computed values of p , which we compare with those derived directly from observation in Table VIII.

TABLE VIII.—Showing the comparison, in atmospheres and tons per square inch, between the pressures actually observed in a close vessel and those calculated from the

$$\text{formula } p = p_0 \frac{(1 - \alpha \delta_0)}{\delta_0} \cdot \frac{\delta}{1 - \alpha \delta}.$$

1. Density of products of combustion.	2. Value of p deduced from direct observation.	3. Value of p deduced from equation (3) when $\alpha = .65$.	4. Value of p deduced from equation (3) when $\alpha = .60$.	5. Value of p deduced from direct observation.	6. Value of p deduced from equation (3) when $\alpha = .65$.	7. Value of p deduced from equation (3) when $\alpha = .6$.
	Tons per square inch.	Tons per square inch.	Tons per square inch.	Atmospheres.	Atmospheres.	Atmospheres.
.05	0.70	.758	.855	107	115	130
.10	1.47	1.565	1.765	224	238	269
.15	2.33	2.432	2.734	355	370	416
.20	3.26	3.363	3.771	496	512	574
.25	4.26	4.367	4.879	649	665	743
.30	5.33	5.452	6.071	812	830	924
.35	6.49	6.628	7.350	988	1009	1119
.40	7.75	7.908	8.732	1180	1204	1330
.45	9.14	9.305	10.228	1392	1417	1557
.50	10.69	10.837	11.851	1628	1650	1805
.55	12.43	12.524	13.620	1893	1907	2074
.60	14.39	14.390	15.554	2191	2191	2369
.65	16.60	16.466	17.679	2528	2507	2692
.70	19.09	18.791	20.024	2907	2861	3049
.75	21.89	21.410	22.625	3333	3260	3445
.80	25.03	24.383	25.525	3812	3713	3887
.85	28.54	27.789	28.780	4346	4232	4383
.90	32.46	31.728	32.460	4943	4831	4943
.95	36.83	36.336	36.654	5608	5538	5582
1.00	41.70	41.698	41.477	6350	6350	6316

Now if the figures given in columns 2 and 5, being those derived from the observations themselves corrected by differencing, be compared with the values given in columns 3 and 6, computed on the value $\alpha = .65$ (that is, on the assumption that at the temperature of explosion the liquid residue of 1 gramme of powder occupies .65 cub. centim.), it will be found that the two columns are practically identical, thus affording a confirmation of the strongest nature of the correctness of our assumption. The closeness of agreement will be best seen by examining the graphical representations in Plate 17. We have already, however, had more than once occasion to remark that there is reason to suppose that the observed pressures are slightly in defect, at all events at low densities. Other considerations have led us to the conclusion that a value of α not far removed from .6 would more nearly represent the truth, were all disturbing influences removed. We have therefore added to the above Table the pressures computed on this hypothesis; and Plate 17 shows at a glance the comparison between the three curves.

O. DETERMINATION OF THE TEMPERATURE OF EXPLOSION OF GUNPOWDER.

We are now in a position to compute the temperature of explosion.

The coil of wire was not to be found, but portions of it were observed welded to the sides of the cylinder.

Now we know that platinum is readily volatilized when exposed to the hydrogen-blowpipe at a temperature of about 3200°C ., and therefore, if the temperature of explosion had approached this point, we should have expected the very fine wire to be volatilized; remembering the low specific heat of platinum, we should furthermore have been warranted in expecting more decided signs of fusion in the sheet metal.

Again, in experiments 84, 85, and 68, pieces of platinum wire $\cdot 03$ inch ($0\cdot 75$ millim.) in diameter and 4 inches (100 millims.) long were placed in the cylinder with considerable charges of R. L. G. and F. G. In none of these experiments did the platinum melt, although, as in the case of the sheet platinum, there were signs of fusion on the surfaces of the wires. In experiment 79, however, in which platinum wire was placed with a corresponding charge of the Spanish powder, the wire was fused, with the exception of a small portion. With this powder, indeed, which is of a very different composition from the English powders and decidedly more rapidly explosive in its nature, it is quite possible that a somewhat higher heat may have been attained. But, as in one case the platinum wire was nearly fused, and in others it only showed signs of fusion, the conclusion we draw from the whole of these experiments on the fusion of the platinum is that the temperature of explosion is higher than the melting-point of that metal, but not greatly so. Now, according to DEVILLE, the melting-point of platinum is nearly 2000°C .; and hence we have a strong corroboration of the approximate accuracy of the theoretical temperature of explosion at which we have arrived, viz. 2231°C .

P. MEAN SPECIFIC HEAT OF LIQUID PRODUCTS.

We have already given the specific heat of the liquid products when in the solid form. If we assume the temperature above specified to be correct, a mean specific heat of the liquid product of $\cdot 4090$, or a total mean specific heat of the entire products of $\cdot 3094$, would result, being an increment of about 67 per cent.; and this, judging from the analogy of the case we have cited, does not appear an improbable conclusion.

Q. PROBABLE EXPANSION OF NON-GASEOUS PRODUCTS BETWEEN ZERO AND TEMPERATURE OF EXPLOSION.

So far as we are aware there were, prior to our experiments, no data existing as to the behaviour of the non-gaseous products of combustion at the high temperature involved, except perhaps the experiment made by BUNSEN and SCHISCHKOFF, who exposed on platinum foil the solid residue in an oxyhydrogen jet, and concluded, from there being no ebullition, that at the temperature of 3300°C . the tension of the resulting vapour did not reach one atmosphere. Taking the circumstances into account, we may indeed doubt if the residue itself actually reached the temperature we have named; but the experiment would at all events prove that, at the temperature which we find to be that developed by explosion, the solid or liquid products are not in the state of vapour, or at least that the small portion volatilized had but an insignificant tension.

To test, however, the behaviour of the residue for ourselves, we placed in one of SIEMENS'S gas-furnaces, the temperature of which was estimated at about 1700° C., several crucibles containing powder-residue. The behaviour of the residue was in all cases the same; at first there was a little spirting (probably due to escape of water), which, however, soon diminished, and in time the contents of the crucibles became perfectly quiet, but up to the end of the experiment only a very slight volatilization could be observed. In the case of three of the crucibles, two of which contained powder-residue, the other a mixture of potassium carbonate and liver of sulphur, when removed from the furnace after being exposed to the full heat for about a quarter of an hour, the volumes of the contents in the highly heated state were observed without difficulty. The contraction in cooling was evidently very great, especially at first. The contents set at a temperature of between 700° and 800° C., and when cool the expansion was measured by calibration with mercury. The first crucible gave an expansion of 77.8 per cent. between 0° C. and 1700° C.; the second (potass. carb. and liver of sulphur) an expansion of 93.3 per cent. The third (powder-residue) gave a considerably higher rate of expansion, above 100 per cent.; but we have not included the result, as, owing to the presence of a piece of platinum put in to test the temperature of the furnace, we were unable to make a very accurate measurement.

Of course the expansions, under the conditions we have just named, cannot be strictly compared with those which would have place in a close vessel under the high tension we know to exist; but they tend to confirm the results arrived at by a perfectly independent method. The experiments also show that, at a temperature approaching that developed by explosion, and under atmospheric pressure, the liquid products are still in that condition; and our experiments so far confirm those of BUNSEN and SCHISCHKOFF to which we have alluded.

R. OBSERVED PRESSURES IN THE BORES OF GUNS.

The data which we shall use for the discussion of the phenomena attending the combustion of gunpowder in ordnance are nearly entirely derived from the experiments carried on by the Committee of Explosives under the presidency of Colonel YOUNGHUSBAND, F.R.S.

Two methods, of an entirely distinct nature, were employed by the Committee for the elucidation of the questions they had to consider.

One method consisted in determining the tension of the gas at various points in the bore, by direct measurement. The other mode consisted in measuring the time at which the projectile passed certain fixed points in the bore, thence deducing the velocities from the seat of the shot to the muzzle, and finally obtaining, by calculation, the gaseous pressure necessary to generate the observed velocities.

The apparatus used for determining the tension by direct measurement was the crusher-gauge, which we have already described; that for ascertaining the velocity was a chronoscope specially designed for measuring very minute intervals of time. As the

construction of this instrument has been fully explained elsewhere, we shall only here give a very general description of it.

Its most recent form is shown in plan and elevation in Plate 18. figs. 1 & 2. The mechanical part consists of a series of thin disks, A, A, &c., 36 inches in circumference, keyed on to a shaft, S, and made to rotate at a very high and uniform velocity through the train of wheels F, by means of a very heavy descending weight at B, arranged, to avoid an inconvenient length of chain, upon a plan originally proposed by HUYGHENS. This weight is continually wound up by means of the fly-wheel and handle at T. The stop-clock D, which can be connected or disconnected with the shaft E at pleasure, gives the precise speed of the circumference of the disks, which is usually arranged at about 1250 inches a second.

The recording arrangement is as follows:—Each disk is furnished with an induction-coil, G, the primary wire from which is conveyed to any point, K, in the gun where we may wish to record the instant at which the shot passes. There is at each such point a special contrivance by which the shot in passing severs the primary wire, thereby causing a discharge from the secondary, which is connected with the discharger, Y. The spark records itself on the disk by means of paper specially prepared to receive it. The instrument is capable of recording the millionth part of a second, and, when in good working order, the probable error of a single observation should not exceed 4 or 5 one millionths of a second.

The guns were arranged for the experiments as shown in fig. 3 in the same Plate. Holes were drilled in the powder-chamber in the positions marked A, B, C, and in the bore in the positions marked 1 to 18.

In A, B, and C crusher-gauges were always placed; the holes numbered 1 to 18 were fitted with crusher-gauges or the chronoscope-plugs at option.

It would be beside our object in this paper to enter into a discussion of the special experiments undertaken by the Committee of Explosives. The chief object of their investigations was to determine the nature of powder most suitable for use with heavy guns—that is to say, the powder which will allow of the highest effect being realized without unduly straining the structure within which the explosion is confined. A number of experiments were therefore made with powders of abnormal types, interesting and instructive only to artillerists; and these experiments will doubtless be fully reported on at a later date, by the proper authorities.

In our present paper we shall confine our attention chiefly, if not entirely, to the results obtained with the well-defined and well-known powders which have been admitted into the service for use with rifled guns, and which are known under the names of “Rifled Large Grain” and “Pebble.” These powders are, moreover, the same as were used by us in our experiments in closed vessels, and therefore allow of a strict comparison with the tensions so obtained. But before giving the details, we cannot pass without notice certain differences in the results obtained by means of the two modes of experimenting to which we have alluded.

With pebble and other powders, where a slow and tolerably regular combustion takes place, the maximum tension of the gas, obtained both by direct measurement and by the chronoscope, agrees remarkably closely. There is generally a very slight difference indeed between the indicated pressures; but the case is greatly different where the powder is of a highly explosive or quickly burning description. In such a case, not only are the pressures indicated by the crusher-gauge generally much above those indicated by the chronoscope, but they differ widely in various parts of the powder-chamber, in the same experiment, and even in different parts of the same section of the bore. They are also locally affected by the form of the powder-chamber, and frequently indicate pressures considerably above the normal tensions that would be attained were the powder confined in a close vessel.

It is not difficult to explain these anomalies. When the powder is ignited comparatively slowly and tolerably uniformly, the pressure in the powder-chamber is also uniform, and approximates to that due to the density of the products of combustion.

The crusher-gauges, then, give similar results throughout the powder-chamber, and they accord closely with the results deduced from the chronoscope observations. But when a rapidly lighting or "brisante" powder is used, the products of combustion of the portion first ignited are projected with a very high velocity through the interstices of the charge, or between the charge and the bore; and on meeting with any resistance their *vis viva* is reconverted into pressure, producing the anomalous local pressures to which we have drawn attention.

We have pretty clear proof that, when this intense local action is set up, the gases are in a state of violent disturbance, and that waves of pressure pass backwards and forwards from one end of the charge to the other, the action occasionally lasting the whole time that the shot is in the bore. In fact, with the rapidly burning, and in a less degree even with the slower burning powders, motion is communicated to the projectile not by a steady, gradually decreasing pressure like the expansive action of steam in a cylinder, but by a series of impulses more or less violent.

The time during which these intense local pressures act is of course very minute; but still the existence of the pressures is registered by the crusher-gauges. The chronoscopic records, on the other hand, which are, so to speak, an integration of the infinitesimal impulses communicated to the shot, afford little or no indication of the intensity of the local pressures, but give reliable information as to the *mean* gaseous pressure on the base of the shot.

The two modes of observation are, as we have elsewhere pointed out, complementary one to the other. The chronoscope gives no clue to the existence of the local pressures which the crusher-gauge shows to exist; while, on the other hand, where wave- or oscillatory action exists, the results of the crusher-gauge cannot be at all relied on as indicating the mean pressure in the powder-chamber.

An interesting illustration of this distinction was afforded by two consecutive rounds fired from a 10-inch gun, in one of which wave-action was set up, in the other not. In

both cases the projectile quitted the gun with the same velocity, and the mean pressure throughout the bore should of course have been the same. The chronoscopic records were, as they ought to be, nearly identical for the two rounds; but the pressures indicated by the crusher-gauge were in the one round at the points A, B, C, 1, 4 (fig. 3, Plate 18), respectively 63·4, 41·6, 37·0, 41·9, and 25·8 tons on the square inch; in the other, at the same points, respectively 28·0, 29·8, 30·0, 29·8, and 19·8 tons on the square inch.

Where no wave-action exists, the chronoscopic pressures are generally somewhat higher than those of the crusher-gauge. The difference is not generally greater than about 5 to 7 per cent., although, in the case of some exceptionally heavy shot, this variation was considerably exceeded. Among the causes tending to produce this difference may be cited:—1. Friction in the parts of the crusher-gauge. 2. Slight diminution of pressure due to windage*. 3. *Vis viva* of particles of the charge and products of combustion, a portion of which would be communicated to the shot, but would not take effect on the crusher-gauge. On the whole, however, the accordance of results derived from methods so essentially different was quite as close as could reasonably be expected, and entirely satisfactory.

We now pass to the consideration of the tensions actually found to exist in the bores of guns. Two series of experiments were made by the Committee on Explosives with the 10-inch 18-ton gun. The one series was with charges of 70 lb. (31·75 kilos.) of pebble powder. The weights of the shot were made to vary, the first rounds being fired with projectiles of 300 lb. (136·05 kilos.), and the weights being successively increased to 350 lb., 400 lb., 450 lb., 500 lb., 600 lb., 800 lb., 1000 lb., and concluding with projectiles of the weight of 1200 lb. (544·20 kilos.).

In the other series charges of 60 lb. (27·21 kilos.) R. L. G. were used. The projectiles were of increasing weights as above; but the experiments were not carried so far, the heaviest projectile in this series being of 600 lb. (272 kilos.) weight.

As we shall have occasion more than once to refer to these experiments, and as the powder used was carefully selected to represent as nearly as possible the normal service-powder of each description, it appears to us convenient, in order to illustrate the methods followed in determining the powder-pressures, to take an example from each series.

This plan will further enable us to compare the difference of behaviour of pebble and R. L. G. powder in the bore of a gun.

Commencing, then, with the charge of 70 lb. (31·75 kilos.) pebble powder and the projectile of 300 lb. (136·05 kilos.), the results given by the chronoscope, to which we shall turn our attention in the first instance, are given in Table IX.

* In the experiments with the 38-ton gun an opportunity occurred of determining the differences in pressure due to the escape of the gases by the windage, and it was found that a reduction of windage of ·07 inch (1·75 millim.), *i. e.* the difference between ·01 inch and ·08 inch windage, reduced the maximum pressure indicated by the crusher-gauge by about 1 ton per square inch. Of course the mean pressure on the base of the projectile was not reduced in any thing like the same proportion.

In this Table column 1 gives the distances of the various plugs from the seat of the shot in feet, see fig. 3, Plate 18 (the distance from the seat of the shot to the bottom of the bore being 2 feet = 0.610 metre). Column 2 gives the same distances in metres. Column 3 gives the observed time of passing each plug. Column 4 gives the corrected time from the commencement of motion, the time from the commencement of motion to the first plug being interpolated. Column 5 gives the differences of time—that is, the time taken by the projectile to traverse the distance between the plugs. Column 6 gives the mean velocity of the projectile over the space between the plugs, in feet; and column 7 gives the same velocities in metres.

TABLE IX.—Giving data obtained with chronoscope for calculating velocity and pressure in the bore of a 10-inch 18-ton gun. Charge 70 lb. (31.75 kilos.) pebble powder. Weight of projectile 300 lb. (136.05 kilos.). Muzzle-velocity 1527 ft. (465.4 metres).

1.		2.		3.	4.	5.	6.		7.
Distance from seat of shot.				Time observed at plugs.	Total time from seat of shot.	Time taken by shot to traverse distance between plugs.	Mean velocity over spaces between plugs.		
feet.	metres.			seconds.	seconds.	seconds.	feet per second.	metres per second.	
0.00	0.000	.....		.....	0.00000	.....		
0.06	0.018			0.00000	0.002683	0.002683	22	6.7	
0.26	0.079			0.001096	0.003779	0.001096	183	55.8	
0.46	0.140			0.001611	0.004294	0.000515	388	118.3	
0.66	0.201			0.001967	0.004650	0.000356	562	171.3	
0.86	0.262			0.002272	0.004955	0.000305	656	199.9	
1.06	0.323			0.002548	0.005231	0.000276	725	221.0	
1.46	0.445			0.003036	0.005719	0.000488	820	249.9	
1.86	0.567			0.003469	0.006152	0.000433	924	281.6	
2.26	0.689			0.003869	0.006552	0.000400	1000	304.8	
2.66	0.811			0.004244	0.006927	0.000375	1065	324.6	
3.46	1.055			0.004947	0.007630	0.000703	1138	346.9	
4.26	1.298			0.005605	0.008288	0.000658	1215	370.3	
5.06	1.542			0.006234	0.008917	0.000629	1273	388.0	
6.66	2.030			0.007426	0.010109	0.001192	1342	409.0	
8.26	2.518			0.008554	0.011237	0.001128	1418	432.2	

From these data are deduced, by correction and interpolation, the times given in Table X. From the differences of the times are calculated the velocities, and from the velocities the pressures necessary to produce them are obtained.

TABLE X.—Giving the total time from commencement of motion, velocity, and tension of products of explosion, in bore of a 10-inch 18-ton gun, deduced from Table IX.

Travel.		Time.		Velocity.		Pressure.	
		Total.	Over intervals.				
feet.	metres.	seconds.	seconds.	feet per second.	metres per second.	tons per square inch.	atmospheres.
0·00	·000	·0000000	·0000000				
0·02	·006	·0018182	·0018182	11·0	3·35	1·723	262
0·04	·012	·0023772	·0005590	35·8	10·91	3·843	585
0·06	·018	·0026330	·0003058	65·4	19·93	6·096	928
0·08	·024	·0028950	·0002120	94·3	28·74	8·270	1259
0·10	·030	·0030576	·0001626	123·0	37·49	9·873	1503
0·12	·037	·0031908	·0001332	150·0	45·72	11·198	1705
0·14	·043	·0033044	·0001136	176·1	53·68	12·192	1857
0·16	·049	·0034042	·0000998	200·6	61·14	13·120	1998
0·18	·055	·0034936	·0000894	223·9	68·24	13·915	2119
0·20	·061	·0035748	·0000812	246·2	75·04	14·578	2220
0·22	·067	·0036496	·0000748	267·6	81·56	15·174	2311
0·24	·073	·0037190	·0000694	288·2	87·84	15·638	2381
0·26	·079	·0037840	·0000650	308·0	93·88	16·036	2442
0·28	·085	·0038452	·0000612	327·1	99·70	16·407	2498
0·30	·091	·0039030	·0000578	345·5	105·3	16·698	2543
0·32	·098	·0039580	·0000550	363·3	110·7	16·963	2583
0·34	·104	·0040106	·0000526	380·5	116·0	17·228	2623
0·36	·110	·0040610	·0000504	397·2	121·1	17·414	2652
0·38	·116	·0041094	·0000484	413·4	126·0	17·599	2680
0·40	·122	·0041560	·0000466	429·1	130·8	17·745	2702
0·42	·128	·0042010	·0000450	444·5	135·5	17·864	2720
0·44	·134	·0042446	·0000436	459·4	140·0	17·944	2733
0·46	·140	·0042868	·0000422	473·9	144·4	17·957	2734
0·48	·146	·0043278	·0000410	488·0	148·7	17·997	2741
0·50	·152	·0043676	·0000398	501·7	152·9	18·023	2745
0·52	·158	·0044064	·0000388	515·1	157·0	17·997	2741
0·54	·165	·0044442	·0000378	528·1	161·0	17·904	2726
0·56	·171	·0044810	·0000368	540·8	164·8	17·800	2711
0·66	·201	·0046544	·0001734	576·7	175·78	16·910	2575
0·76	·232	·0048132	·0001588	629·6	191·90	15·637	2381
0·86	·262	·0049614	·0001482	674·8	205·68	14·710	2240
0·96	·293	·0051013	·0001399	714·7	217·84	13·716	2089
1·06	·323	·0052347	·0001334	750·0	228·60	13·093	1994
1·16	·353	·0053625	·0001278	782·3	238·45	12·590	1917
1·26	·384	·0054856	·0001231	812·1	247·53	12·192	1857
1·36	·414	·0056047	·0001191	839·9	256·00	11·755	1790
1·46	·445	·0057202	·0001155	865·9	263·93	11·331	1725
1·56	·475	·0058325	·0001123	890·2	271·33	10·920	1663
1·66	·506	·0059420	·0001095	913·1	278·31	10·575	1610
1·76	·536	·0060490	·0001070	934·7	284·90	10·231	1558
1·86	·567	·0061537	·0001047	955·1	291·11	9·873	1503
1·96	·597	·0062562	·0001026	974·4	297·00	9·568	1457
2·06	·628	·0063570	·0001007	992·8	302·61	9·250	1409
2·16	·658	·0064560	·0000990	1010	307·85	8·972	1366
2·26	·689	·0065534	·0000974	1027	313·03	8·706	1326
2·36	·719	·0066493	·0000959	1043	317·91	8·442	1286
2·46	·750	·0067438	·0000945	1058	322·48	8·190	1247
2·56	·780	·0068371	·0000933	1072	326·75	7·952	1211
2·66	·811	·0069292	·0000921	1086	331·01	7·739	1178
2·76	·841	·0070201	·0000909	1100	335·28	7·541	1148
2·86	·871	·0071100	·0000899	1112	338·94	7·355	1120
2·96	·902	·0071989	·0000889	1125	342·90	7·183	1094
3·06	·932	·0072869	·0000880	1137	346·56	6·874	1047
3·46	1·054	·0076337	·0003463	1154	351·74	6·402	975
3·86	1·176	·0079685	·0003348	1195	364·24	5·911	900
4·26	1·298	·0082933	·0003248	1232	375·51	5·487	836
4·66	1·420	·0086097	·0003164	1265	385·57	5·089	775
5·06	1·542	·0089185	·0003088	1295	394·72	4·745	723
5·46	1·664	·0092209	·0003024	1322	402·95	4·453	678
5·86	1·786	·0095177	·0002968	1347	410·57	4·175	636
6·26	1·907	·0098093	·0002916	1371	417·88	3·936	599
6·66	2·029	·0100965	·0002872	1392	424·28	3·711	565
7·06	2·151	·0103797	·0002832	1412	430·38	3·526	537
7·46	2·273	·0106593	·0002796	1431	436·17	3·340	509
7·86	2·395	·0109357	·0002764	1448	441·35	3·168	482
8·26	2·517	·0112089	·0002732	1465	446·53		

We have not space within the limits of our paper to enter upon a discussion of the methods of calculation and correction necessary to arrive at the results tabulated; they are attended with very great labour, and a full consideration of the question would necessitate a separate paper. As we shall hereafter show, it is not difficult, if we were to suppose the powder entirely converted into gas on the instant of explosion, to lay down the law according to which the pressure would vary in the bore of the gun; but the case under consideration is a much more complicated one. The charge of powder is not instantly exploded, but is generally ignited at a single point; the pressure (commencing at zero) goes on increasing at an extremely rapid rate until the maximum increment is reached. It still goes on increasing, but at a rate becoming gradually slower, until the maximum tension is reached, when the increase of density of the gas, aided by the combustion of the powder, is just counterbalanced by the decrease of density due to the motion of the projectile. After the maximum of tension is reached, the pressure decreases, at first rapidly, subsequently slower and slower.

If these variations in pressure be represented by a curve, it would commence at the origin convex to the axis of x , would then become concave, then again convex, and would finally be asymptotic to the axis of x .

In the same way, the curve representing the velocity would commence by being convex to the axis of abscissæ; it would then become concave, and, were the bore long enough, would be finally asymptotic to a line parallel to the axis of x .

The results of Table X. are graphically represented in black lines in Plate 19, the space described by the shot being taken as the equicrescent or independent variable, and the two curves giving respectively the velocity and pressure at any point of the bore.

From the Table (or curves) it will be seen that the maximum pressure attained by the powder is 18 tons per square inch (2745 atmospheres), and that this pressure is reached when the projectile has moved $\cdot 5$ feet ($\cdot 153$ metre) and at $\cdot 00437$ second from the commencement of motion.

The results given in the Table have, as we have said, been arrived at by special methods of correction and interpolation; and their general correctness can be tested by examining whether a material alteration of pressure or velocity at any point can be made without seriously disturbing the times actually observed. It will be found that they cannot. But another question here presents itself for consideration. We have, in the curves on Plate 19, taken s as the independent variable; but if t were taken as the independent variable, and the relation between s and t were capable of being expressed by the explicit function $s=f(t)$, the velocity corresponding to any value of t would be represented by the first derived function of $f(t)$, and the pressure by the second derived function. This, then, if a simple relation between s and t could be established, would be an easy method of treating the problem; but it has appeared to us practically impossible to obtain a single expression which shall represent the relation between s and t for the whole time occupied by the shot in its passage through the bore.

If, for example, we endeavoured to represent the relation between s and t by a linear equation of the form

$$s = at + bt^2 + ct^3 + dt^4 \text{ \&c.}, \dots \dots \dots (8)$$

we should have to determine the most probable values of the coefficients a, b, c, d , &c. from the eighteen to twenty direct observations connecting s and t . The equation would further have to be such that the first and second derived functions should represent curves of the general nature we have described. It is obvious that, setting all other considerations aside, the labour of such a series of calculations would be insurmountable.

But although it is impossible to obtain a single relation between s and t for the whole length of the bore, we have endeavoured, on account of the great importance of the question, to obtain such a relation for the commencement of motion, where the question of pressure is of vital importance.

To do this we have taken only the observed values of s and t so far that we could be certain the position where the maximum pressure was attained was included, but have made no assumption whatever as to the actual position of maximum pressure.

We then assumed that the relation between s and t was capable of being expressed by an equation of the form

$$s = at^{\alpha + \beta t + \gamma t^2}; \dots \dots \dots (9)$$

and from the observed values of s and t the probable values of a, α, β, γ were computed by the method of least squares.

Treating in this manner the experiment under discussion, and taking from Table IX. the first six values of s and t *, we have obtained for the most probable values of

$$\begin{aligned} a &= 3.31076, \\ \alpha &= 1.37851, \\ \beta &= .76600, \\ \gamma &= -.06932, \end{aligned}$$

and for the relation between s and t the equation

$$s = 3.31076t^{1.37851 + .76600t - .06932t^2} \dots \dots \dots (10)$$

By differentiation we obtain for the velocity

$$\frac{ds}{dt} = v = \frac{s}{t} \{ (\alpha + \beta t + \gamma t^2) \cdot (1 + \log_e t) - (\alpha - \gamma t^2) \cdot \log_e t \}; \dots \dots \dots (11)$$

and by a second differentiation,

$$\begin{aligned} \text{pressure } T &= \frac{w}{g} \frac{d^2s}{dt^2} \\ &= \frac{w}{g} \cdot \frac{v}{t} \{ (\alpha + \beta t + \gamma t^2)(1 + \log_e t) - (\alpha - \gamma t^2) \log_e t - 1 \} \\ &\quad + \frac{w}{g} \cdot \frac{s}{t} \{ \beta + (\beta - 4\gamma t) \cdot (1 + \log_e t) \} \dots \dots \dots (12) \end{aligned}$$

* For the convenience of calculation, the unit of time used is not a second but the thousandth part of a second. The unit of space is altered in like proportion.

Table XI. gives the results of the calculations necessary for obtaining the values of s , v , and T from equations (10), (11), and (12).

To avoid repetition, we have introduced in this Table the following abbreviations:—

$$\left. \begin{aligned} M &= \alpha + \beta t + \gamma t^2, \\ N &= \alpha - \gamma t^2, \\ P &= M(1 + \log_e t) - N \log_e t, \\ P' &= \beta + (\beta - 4\gamma t)(1 + \log_e t); \end{aligned} \right\} \dots \dots \dots (13)$$

and the values furnished in Table XI. can be compared with those given in Table X.

But the comparison, both as to velocity and pressure, can be more readily seen by a graphical representation; and we have accordingly laid down in Plate 20, in full black lines, the curves of velocity and pressure taken from Table X.

The results of Table X. have already been graphically represented in Plate 19; but in Plate 20, t instead of s is taken as the independent variable, with the view of enabling the accordance of the methods to be more easily compared. The curves in dotted lines indicate the velocity and pressure shown in Table XI., and deduced from formulæ (10), (11), and (12).

It will be observed that the two curves of velocity approximate exceedingly closely. The difference between the pressure-curves also is not greater than might be expected; and the difference, such as it is, is due to our not having succeeded in obtaining an equation which represents the corresponding observed values of s and t so closely as do the values given in Table X.

The pressures given by the crusher-gauges (which can be compared with those given in either of the Tables X. or XI.) at the points A, B, C, 1, 4, are respectively 17·2, 15·6, 15·6, 12·8, and 11·1 tons per square inch, or in atmospheres, 2169, 2376, 2376, 1949, and 1690.

We now pass to the consideration of the results furnished by R. L. G. powder. Taking, as in the case of pebble powder, the particular set of experiments where shot of 300 lb. (136·05 kilos.) were used, the data furnished by the chronoscope are given in Table XII. (p. 117).

TABLE XI.—Giving the results of the calculations necessary in order to obtain the values of s , v , and T from Equations (10), (11), and (12). Pebble powder.

t .	M.	s .	$\frac{s}{t}$.	N.	$1 + \log_e t$.	$M(1 + \log_e t) - N \log_e t$.	v .	$\frac{v}{t}$.	$(P-1)\frac{v}{t}$.	P'.	$P' \cdot \frac{s}{t}$.	$\frac{d^2 s}{dt^2}$.	Pressure (T).	
													Tons per square inch.	Atmospheres.
2.8	2.979805	71.183	25.422	1.922018	2.029619	4.068930	103.430	36.939	113.3533	.744811	18.9346	132.2879	7.036	1071
3.0	3.052588	94.706	31.568	2.002435	2.098612	4.206297	132.784	44.261	141.9139	.627702	19.8142	161.7281	8.601	1310
3.2	3.119825	124.712	38.972	2.088397	2.163151	4.319539	172.661	53.956	179.1090	.503480	19.6216	198.7306	10.569	1609
3.4	3.181516	162.495	47.792	2.179906	2.223775	4.409265	210.632	61.950	211.0801	.372791	17.8164	228.8965	12.174	1854
3.5	3.210283	184.734	52.781	2.227741	2.252763	4.441170	234.409	66.974	230.4589	.305200	16.1088	246.5677	13.113	1997
3.6	3.237662	209.423	58.175	2.276961	2.280934	4.468253	259.940	72.205	250.4252	.236186	13.7404	264.1656	14.049	2139
3.7	3.263655	236.775	63.993	2.327569	2.308333	4.488377	287.224	77.628	270.7957	.165811	10.6107	281.4064	14.966	2279
3.8	3.288261	266.929	70.245	2.379563	2.335001	4.501375	316.427	83.270	291.5595	.094127	6.6122	298.1717	15.857	2415
3.9	3.311482	300.064	76.940	2.432943	2.360977	4.507152	346.780	88.917	311.8354	.021182	1.6296	313.4650	16.671	2539
4.0	3.333314	336.344	84.086	2.487710	2.386294	4.505557	378.854	94.713	332.0218	.052975	4.4549	327.5669	17.421	2653
4.1	3.353701	375.876	91.678	2.543863	2.410987	4.496181	412.222	100.542	351.5469	.128309	11.7622	339.8027	18.071	2752
4.2	3.372821	418.730	99.698	2.601303	2.435085	4.479017	446.549	106.321	369.8926	.204773	20.4152	349.4774	18.586	2830
4.3	3.390496	465.270	108.225	2.660328	2.458615	4.455537	482.200	112.139	387.4905	.282331	30.5532	356.9353	18.933	2891
4.4	3.406752	515.254	117.105	2.720641	2.481605	4.423368	517.999	117.727	403.0228	.360949	42.2690	360.7538	19.186	2922
4.5	3.421684	568.847	126.411	2.782341	2.504077	4.383297	554.097	123.133	416.5855	.440591	55.6953	360.8902	19.193	2923
4.6	3.435198	626.093	136.104	2.845426	2.526056	4.335222	590.041	128.270	427.8089	.521230	70.9415	356.8674	18.978	2890
4.7	3.447326	686.871	146.142	2.909898	2.547563	4.279937	625.347	133.052	436.2824	.602829	88.0988	348.1836	18.517	2820
4.8	3.458067	751.087	156.477	2.975758	2.568616	4.214629	659.492	137.394	441.6707	.685373	107.2436	334.4271	17.786	2709
4.9	3.467422	818.733	167.087	3.043003	2.589535	4.142050	692.082	141.241	443.7863	.769002	128.4899	315.2964	16.769	2554
5.0	3.475390	889.447	177.890	3.111635	2.609438	4.060323	722.380	144.476	442.2155	.853158	151.7686	290.4469	15.447	2352
5.1	3.481972	963.090	188.841	3.181653	2.629241	3.971264	749.937							
5.2	3.487167	1039.290	199.865	3.253058	2.648659	3.873138	774.104							

TABLE XII.—Giving data obtained with chronoscope for calculating the velocity and pressure in the bore of a 10-inch 18-ton gun. Charge 60 lb. (27·2 kilos.) R. L. G. Weight of projectile 300 lb. (136·05 kilos.).

Distance from base of shot.		Time observed at plugs.	Total time from seat of shot.	Time taken by shot to traverse distance between plugs.	Mean velocity over spaces between plugs.	
feet.	metres.	seconds.	seconds.	seconds.	feet per second.	metres per second.
0·00	0·000		·000000			
0·06	0·018	·000000	·000767	·000767	78·2	23·8
0·26	0·079	·000596	·001363	·000596	336	102·4
0·46	0·140	·001007	·001774	·000411	488	148·7
0·66	0·201	·001323	·002090	·000316	633	192·9
0·86	0·262	·001601	·002368	·000278	719	219·1
1·06	0·323	·001856	·002623	·000255	781	238·0
1·46	0·445	·002325	·003092	·000469	855	260·6
1·86	0·567	·002755	·003522	·000430	935	285·0

From these data, in the same manner as in the case of pebble powder, are calculated the velocities and pressures exhibited in Table XIII. (p. 118).

The velocity and pressure obtained with the R. L. G. powder are graphically represented by the dotted curves in Plate 19; and by comparing these with the similar curves furnished by pebble powder, the advantages obtained by the use of the slow-burning pebble powder are clearly seen.

Thus it will be observed that the muzzle-velocity obtained with the pebble powder is 1530 feet (466·3 metres), while the maximum pressure in the bore is 18 tons per square inch (2745 atmospheres). The velocity given by the R. L. G. powder is, on the other hand, only 1480 feet (451·1 metres), while the maximum pressure is 22·07 tons per square inch (3360 atmospheres).

If, as in the case of pebble powder, we express for the first instants of motion the relation between s and t by an equation of the form of that given in (9), we obtain

$$s = \cdot 57837t^3 - \cdot 42802t^2 + \cdot 02336t + \cdot 000245t^2, \dots \dots \dots (14)^*$$

and the values of s , v , T corresponding to those of t are given in the scheme shown in Table XIV.

* In this equation and Table XIV. the unit of time is, for convenience, the one ten-thousandth part of a second.

TABLE XIII.—Giving the total time from commencement of motion, velocity, and tension of products of explosion in bore of 10-inch 18-ton gun, deduced from Table XII.

Travel.		Time.		Velocity.		Pressure.	
		Total.	Over intervals.				
feet.	metres.	seconds.	seconds.	feet per second.	metres per second.	tons per square inch.	atmospheres.
0 00	•000	•0000000	•0005164	38·7	11·80	7·950	1211
0·02	•006	•0005164	•0001451	137·8	42·00	21·204	3229
0·04	•012	•0006615	•0001059	188·8	57·55	22·065	3360
0·06	•018	•0007674	•0000874	228·7	69·71	22·039	3356
0·08	•024	•0008548	•0000762	262·5	80·01	21·999	3350
0·10	•030	•0009310	•0000684	292·2	89·06	21·840	3326
0·12	•037	•0009994	•0000627	318·9	97·20	21·623	3292
0·14	•043	•0010621	•0000583	343·3	104·64	21·403	3259
0·16	•049	•0011204	•0000546	365·7	111·46	21·138	3219
0·18	•055	•0011750	•0000517	386·6	117·83	20·767	3162
0·20	•061	•0012267	•0000493	405·9	123·72	20·276	3088
0·22	•067	•0012760	•0000471	423·9	129·20	19·746	3007
0·24	•073	•0013231	•0000454	440·6	134·29	19·216	2926
0·26	•079	•0013685	•0000438	456·4	139·11	18·713	2850
0·28	•085	•0014123	•0000424	471·2	143·62	18·249	2779
0·30	•091	•0014547	•0000412	485·3	147·92	17·851	2718
0·32	•098	•0014959	•0000401	498·7	152·00	17·440	2656
0·34	•104	•0015360	•0000391	511·4	155·87	17·096	2603
0·36	•110	•0015751	•0000381	523·7	159·62	16·778	2555
0·38	•116	•0016132	•0000373	535·4	163·19	16·499	2512
0·40	•122	•0016505	•0000365	546·8	166·66	16·261	2476
0·42	•128	•0016870	•0000359	557·7	169·99	16·036	2442
0·44	•134	•0017229	•0000351	568·4	173·25	15·863	2416
0·46	•140	•0017580	•0000345	578·7	176·39	15·691	2389
0·48	•146	•0017925	•0000339	588·8	179·46	15·558	2369
0·50	•152	•0018264	•0000334	598·5	182·42	15·439	2351
0·52	•158	•0018598	•0000329	608·1	185·35	15·320	2333
0·54	•165	•0018927	•0000323	617·5	188·21	15·201	2315
0·56	•171	•0019250	•0001552	644·3	196·38	14·700	2238
0·66	•201	•0020802	•0001460	684·9	208·76	14·286	2175
0·76	•232	•0022262	•0001387	721·0	219·76	13·451	2048
0·86	•262	•0023649	•0002327	753·5	229·66	12·722	1937
0·96	•293	•0024976	•0001277	783·1	238·69	12·060	1836
1·06	•323	•0026253	•0001234	810·1	246·92	11·384	1734
1·16	•353	•0027487	•0001198	834·8	254·44	10·774	1641
1·26	•384	•0028685	•0001166	857·6	261·39	10·204	1554
1·36	•415	•0029851	•0001138	878·7	267·83	9·701	1477
1·46	•445	•0030989	•0001113	898·2	273·77	9·210	1402
1·56	•475	•0032102	•0001091	916·3	279·29	8·720	1328
1·66	•506	•0033193	•0001071	933·2	284·44	8·296	1263
1·76	•536	•0034264	•0001054	949·1	289·28	7·885	1201
1·86	•567	•0035318					

TABLE XIV.—Giving the results of the calculations for determining the values of s , v , and T from Equations (14), (11) and (12). R. L. G. powder.

t .	M.	s .	$\frac{s}{\bar{v}}$.	N.	$1 + \log_e t$.	$\frac{M(1 + \log_e t)}{-N \log_e t}$.	v .	$\frac{v}{\bar{v}}$.	$(P-1)\frac{v}{\bar{v}}$.	P'.	$P' \cdot \frac{s}{\bar{v}}$.	$\frac{d^2s}{dt^2}$.	Pressure (T).	
													Tons per square inch.	Atmo-spheres.
2	3-38228	6-03	3-015	3-42704	1-69315	3-35125	10-104	5-052	11-8785	-0-5959	-1-797	11-699	6-22	947
4	3-38850	59-18	14-795	3-42410	2-38629	3-21983	47-637	11-909	26-4360	-0-6975	1-0320	25-404	13-51	2057
6	3-29667	212-57	35-430	3-41920	2-79176	3-07713	109-023	18-170	37-7415	-0-7216	2-5566	35-185	18-71	2849
8	3-25681	505-13	63-141	3-41234	3-07944	2-92339	184-586	23-073	44-3784	-0-7115	4-4925	39-886	21-21	3230
8-5	3-24715	602-79	70-918	3-41032	3-14007	2-89796	205-517	24-178	45-8889	-0-7055	5-0036	40-885	21-74	3311
9	3-23762	710-70	78-965	3-40818	3-19722	2-86286	226-066	25-118	46-7913	-0-6985	5-5157	41-276	21-95	3342
9-5	3-22820	828-89	87-251	3-40591	3-25129	2-82812	246-756	25-974	47-4836	-0-6904	6-0238	41-460	22-04	3356
10	3-21891	957-45	95-745	3-40352	3-30258	2-79383	267-495	26-750	47-9850	-0-6814	6-5241	41-461	22-04	3356
11	3-20069	1245-60	113-200	3-39838	3-39790	2-72665	308-657	28-060	48-4498	-0-6611	7-4837	40-966	21-79	3318
12	3-18297	1574-70	131-23	3-39274	3-48491	2-66171	349-296	29-191	48-5070	-0-6378	8-3712	40-136	21-35	3251
13	3-16573	1943-80	149-52	3-38662	3-56495	2-59916	388-626	29-894	47-8053	-0-6122	9-1536	38-652	20-56	3131
14	3-14899	2351-53	167-97	3-38000	3-63906	2-53934	426-533	30-466	46-8988	-0-5844	9-8160	37-082	19-72	3003
15	3-13273	2796-30	186-42	3-37290	3-70805	2-48234	462-758	30-851	45-7312	-0-5547	10-3406	35-391	18-82	2866
16	3-11696	3276-45	204-78	3-36530	3-77259	2-42841	497-290	31-081	44-3964	-0-5233	10-7161	33-680	17-91	2727
17	3-10169	3790-33	222-96	3-35722	3-83321	2-37772	530-136	31-184	42-9638	-0-4904	10-9341	32-029	17-03	2593
19	3-07263	4913-00	258-57	3-33958	3-94444	2-28661	591-249	31-118	40-0375	-0-4206	10-8759	29-161	15-51	2362
21	3-04551	6152-37	292-97	3-31998	4-04452	2-20988	647-429	30-830	37-3006	-0-3460	10-1368	27-164	14-44	2199
23	3-02035	7500-70	326-12	3-29842	4-13549	2-14846	700-656	30-463	34-9857	-0-2675	8-7336	26-262	13-97	2127
25	2-99715	8954-50	358-18	3-27490	4-21888	2-10311	753-292							
27	2-97591	10515-00	389-45	3-24942	4-29584	2-07446	807-898							

The results of Table XIV., in comparison with those of the other mode of calculation (Table XIII.), are graphically compared in Plate 21. It will be observed that, as in the case of pebble powder, the two methods give values closely accordant; and if Plate 21 be compared with Plate 20, the differences in velocity and pressure at the commencement of motion between the two natures of powder are very strikingly shown. Thus it will be observed that with pebble powder the maximum pressure, 2745 atmospheres, is reached when the projectile has moved $\cdot 5$ foot ($\cdot 152$ metre), and at about $\cdot 00437$ second after the commencement of motion. With R. L. G. powder the maximum pressure, 3365 atmospheres, is reached when the projectile has moved only $\cdot 05$ foot ($\cdot 015$ metre), and at about $\cdot 00070$ second from the commencement of motion. The first foot of motion is, with the one powder, traversed in about $\cdot 0025$ second, with the other in about $\cdot 0051$ second.

The pressure given by the crusher-gauges in the experiments with R. L. G. under discussion (and these pressures should be compared both with those given in Table XIII. and with the crusher-gauge pressures furnished at the same points by pebble powder) were, at A, B, C, I, and 4 respectively, 44·2, 30·3, 22·5, 13·5, 12 tons per square inch, or, in atmospheres, 6731, 4614, 3426, 2056, and 1827.

In deducing the pressure from the velocity, we of course assumed that the gaseous products of combustion acted on the projectile in the manner in which gases are generally assumed to act.

With the slower-burning powders this hypothesis appears to be not far from the truth; but with the more explosive powders the crusher-gauges show that the powder acts on the shot, as we have already observed, by a succession of impulses; and in this case the curve of pressures derived from the chronoscopic observations must be taken to represent the mean pressures acting on the projectile throughout the bore.

With the various powders experimented on by the Committee on Explosives, there have of course been very great variations in the pressures indicated.

The highest mean pressure indicated by the chronoscope was 30·6 tons, 4660 atmospheres; and this pressure was attained with a charge of 60 lb. R. L. G., and a projectile weighing 400 lb. In the same series, the highest local or wave-pressure exhibited by the crusher-gauges was 57·8 tons, 8802 atmospheres; but this excessive pressure was exhibited only in the crusher marked A in Plate 18. fig. 3, and was probably confined to that particular point. The pressures exhibited by the same powder in the same round, at the points B and C in the powder-chamber, were respectively 37 tons, 5634 atmospheres, and 29·6 tons, 4507 atmospheres.

But although, in the various guns and with the various charges and special powders experimented with, the pressures at different points of the bore exhibit, as might be expected, marked differences, these differences almost altogether disappeared when powders of normal types and uniform make were experimented with, and when the pressure was referred, not to fixed positions in the bore of the gun, but to the density of the products of combustion.

We have already referred to the experiments made with cylinders gradually increasing in weight in the 10-inch gun. A similar series was made in the 11-inch gun with charges of powder of 85 lb. (38·56 kilos.); and as the series in both guns were made with great care and under as nearly as possible the same conditions, we selected, in the first instance, the experiments with pebble powder, in these guns to test the accordance or otherwise of the tensions, under the varied conditions of experiment, when taken simply as functions of the density.

The results of these calculations are graphically represented in curves 1 and 2, Plate 22; and it will be observed that with these different calibres and charges the tensions developed are as nearly as possible identical.

Curves 3 and 4 on the same Plate exhibit the results of similar calculations for 60 lb. R. L. G. fired in the 10-inch gun, and 30 lb. R. L. G. fired in the 8-inch gun. In this case also, although there are differences between the curves representing the pebble and R. L. G. powders, to which we shall allude further on, the accordance between the same description of powder fired from the different guns is almost perfect.

S. EFFECT OF INCREMENTS IN THE WEIGHT OF THE SHOT ON THE COMBUSTION AND TENSION OF POWDER IN THE BORE OF A GUN.

In our preliminary sketch of the labours of previous investigators, we alluded to the views held by ROBINS and RUMFORD upon the rapidity of combustion within the bore. The latter, relying chiefly upon the fact that powder, especially when in very large grains, was frequently blown unburned from the muzzle, concluded that the combustion was very slow. ROBINS, on the other hand, considered that, with the powder he employed, combustion was practically completed before the shot was materially displaced; and it is not easy to see why the unanswerable (if correct) and easily verified fact of which he makes use has received so little attention from artillerists.

ROBINS, it will be remembered, argues that if, as some assert, a considerable time is consumed in the combustion of the charge, a much greater effect would be realized from the powder where heavier projectiles were used, but that such is not the case.

The Committee on Explosives have completely verified the correctness of ROBINS'S views.

In the 10-inch gun, with a charge of 60 lb. (27·2 kilos.) R. L. G. powder, the work realized from the powder is only increased by about 5 per cent. when the weight of shot is doubled.

In the slower-burning pebble powder, with a charge of 70 lb. (31·75 kilos.), with a similar increase in the shot, the greater effect realized was about $8\frac{1}{2}$ per cent.; but when the weight was again doubled (that is, increased to four times the original weight), the additional effect was barely 1 per cent.

PIOBERT'S views, moreover, that the pressure exercises but a trifling influence upon the rate of combustion, appears to us entirely untenable. With a particular sample of service pebble powder, we found the time required for burning a single pebble in the

open air to be about 2 seconds. The same sample was entirely consumed in the bore of a 10-inch gun, and must therefore have been burned, in less than .009 second.

T. EFFECT OF MOISTURE UPON THE COMBUSTION AND TENSION OF POWDER.

It is perhaps unnecessary to say that we do not share the views of those who consider that the presence of water in powder may increase the tension of the products of explosion. We have made no experiments upon this head in closed vessels; but the following Table exhibits the effect of moisture in gunpowder upon the velocity of the projectile and the tension of the gas when the powder is fired in a gun, the proportions of moisture varying from 0.7 to 1.55 per cent. The powder from which these results were obtained, was pebble, carefully prepared by Colonel YOUNGHUSBAND, and was the same in all respects, except as regards the quantity of moisture.

TABLE XV.—Showing the effect of moisture in the powder upon the velocity of the projectile and pressure of the gas.

Percentage of moisture.	Velocity.		Maximum Pressures.	
	feet.	metres.	tons per square inch.	atmospheres.
0.70	1545	470.92	22.02	3353
0.75	1541	474.50	21.70	3304
0.80	1537	468.47	21.38	3256
0.85	1533.5	467.41	21.07	3208
0.90	1530	466.34	20.77	3163
0.95	1526.5	465.30	20.47	3117
1.00	1523.5	464.40	20.18	3073
1.05	1520.5	463.44	19.90	3030
1.10	1517.5	462.53	19.63	2989
1.15	1514.5	461.61	19.37	2949
1.20	1512	460.85	19.12	2911
1.25	1509.5	460.10	18.87	2873
1.30	1507	459.33	18.63	2837
1.35	1504.5	458.60	18.40	2802
1.40	1502	457.80	18.18	2768
1.45	1499.5	457.04	17.97	2736
1.50	1497.5	456.43	17.76	2704
1.55	1495.5	455.82	17.55	2672

From this Table it will be seen that by the addition of considerably less than 1 per cent. of moisture, the muzzle-velocity is reduced by about 60 feet, and the maximum pressure by about 20 per cent., pointing obviously to a much more rapid combustion in the case of the drier powder.

U. LOSS OF HEAT BY COMMUNICATION TO THE ENVELOPE IN WHICH THE CHARGE IS EXPLODED.

We have now given a hasty sketch of the means that have been adopted to determine the pressures actually existing in the bores of guns, and of the general results we have

arrived at; and before proceeding to the theoretical consideration of the relation which should then exist between the tension and the density of the gases, we must direct attention to an important point—and that is, “ what loss of heat do the gases suffer? or, in other words, what proportion of energy in the powder is wasted by communication to the envelope in which the powder is fired, that is, to the barrel of the gun?”

Every one is aware that if a common rifled musket be very rapidly fired, as may easily now be done by the use of breech-loading arms, the barrel becomes so hot that it cannot be touched with the naked hand with impunity, and, even with a field-gun, the increment of heat due to a few rounds is very considerable.

As far as we know, the Count de SAINT-ROBERT* made the first attempt to determine the amount of heat actually communicated to a small arm.

De SAINT-ROBERT made three series of experiments with service rifled muskets, firing the ordinary charge of 4·5 grms. In the first series the muskets were loaded in the usual manner, in the second series the ball was placed near the muzzle, in the third the muskets were loaded with powder alone. The results at which De SAINT-ROBERT arrived, and which are not difficult to explain, were, that the greatest quantity of heat was communicated to the musket when the ball was placed near the muzzle, that the quantity communicated, when no projectile at all was used, stood next in order, and that least heat was communicated when the musket was loaded in the usual manner.

He further found that the quantity of heat communicated in this last case, with the powder and arm used, was about 250 gramme-units per gramme of powder fired.

We found ourselves unable, however, to adopt Count de SAINT-ROBERT'S important results for the guns and charges we have been considering, because conclusions derived from small arms could hardly be applied to large ordnance without modification.

We therefore instituted the experiments described under Nos. 72 and 73. The gun, used was a 12-pr. B. L., and in the first experiment (No. 72) nine rounds were fired with $1\frac{3}{4}$ lb. (794 grms.) and a projectile weighing nearly 12 lb. (5330 grms.).

Prior to the rounds being fired, arrangements were made for placing the gun, whenever the series should be concluded, in a vessel containing a given weight of water; and before the experiment was commenced the gun and water were brought to the same temperature, and that temperature carefully determined.

After the firing the gun was placed in the water, and the rise of temperature due to the nine rounds determined. This rise was found to be equivalent to 236,834 grms. of water raised through 2°·305 C., or the heat communicated to the gun by the combustion of 1 gramme of the charge was equal to 76·4 gramme-units.

Of course an addition has to be made to this number on account both of some loss of heat in the determination and of the unavoidable loss of heat between the rounds.

The second experiment (No. 73) was made with 5 rounds of $1\frac{1}{2}$ lb. (680·4 grms.) of the same powder with the same weight of projectile. The heat communicated to the gun by the five rounds was, when expressed in water, sufficient to raise 112,867 grms.

* *Traité de Thermodynamique* (Turin, 1865), p 120.

through $2^{\circ}694$ C., or 1 gramme of the charge, in burning, communicated to the gun 89.4 gramme-units of heat.

Considering the difficulty, in an experiment of this nature, of avoiding a considerable loss from radiation, conduction, and other causes, we do not think we shall be far wrong in assuming that in the case of the 12 pr.-B. L. gun, fired under the conditions named, the heat communicated to the gun is about 100 gramme-units for each gramme of powder exploded.

To arrive at the amount of heat communicated to the gun when still larger guns are employed, there are two principal points to be considered—1st, the ratio which the amount of the surface bears to the weight of the charge exploded; and 2nd, the time during which the cooling effect of the bore operates upon the products of explosion. The first of these data is of course exactly known, and from our experiments the second is also known with very considerable exactness. Computing, therefore, from the data given by the 12-pr., the loss of heat suffered by the gases in the 10-inch gun, we find that loss to be represented by about 25 gramme-units; and hence we find that the quantity of work in the form of heat communicated to the gun varies approximately from 250 gramme-units per gramme of powder in the case of a rifled musket, to 25 gramme-units in the case of a 10-inch gun.

Similar considerations lead us to the conclusion that in a close vessel such as we employed for explosion, *when filled with powder*, the loss of pressure due to the communication of heat to the envelope would not amount to 1 per cent. of the total pressure developed.

V. PRESSURE IN THE BORES OF GUNS, DERIVED FROM THEORETICAL CONSIDERATIONS.

We now pass to the theoretical consideration of the question. Suppose the powder to be fired, as is the case in the chamber of a gun, and suppose, further, that the products of combustion are allowed to expand, what will be the relation between the tension of the gases and the volume they occupy throughout the bore?

For the sake of simplicity, we shall, in the first instance, assume that the gravimetric density of the powder is unity, that the powder fills completely the space in which it is placed, that the whole charge is exploded before the projectile is sensibly moved from its initial position, and that the expansion takes place in a vessel impervious to heat.

In our preliminary sketch we alluded to the results of HUTTON'S investigations as to the relations existing between the density and tension of the gases and the velocity of the projectile at any point of the bore. HUTTON, however, assumed that the tension of the inflamed gases was directly proportional to their density, and inversely as the space occupied by them. In other words, he supposed that the expansion of the gases, while doing work both on the projectile and on the products themselves, was effected without loss of heat.

Recent research, which has demonstrated that no work can be effected by the expansion of gases without a corresponding expenditure of heat, has enabled modern artillerymen

to correct HUTTON's assumption; and the question of the pressure exercised and work performed by gunpowder in the bore of a gun has been examined both by BUNSEN and SCHISCHKOFF, and by the Count de SAINT-ROBERT*.

De SAINT-ROBERT, like HUTTON, supposed that the whole of the products of explosion were, on ignition, in a gaseous state, and that hence the relation between the pressure and the volume of the products followed from the well-known law connecting the tension and volume of permanent gases.

BUNSEN and SCHISCHKOFF, on the other hand, who, like ourselves, have arrived at the conclusion that at the moment of explosion a large part of the products is not in the gaseous state, have deduced the total work which gunpowder is capable of performing, on the assumption that the work on the projectile is effected by the expansion of the permanent gases alone, without addition or subtraction of heat, and that, in fact, the non-gaseous products play no part in the expansion.

Sufficient data were not at the command of either of the authorities we have named to enable them adequately to test their theories; and we propose in the first place, with the data at our disposal, to compare their hypotheses with actual facts, by computing the tensions for different volumes and comparing the calculated results both with the tensions in a close vessel and with those derived from actual experiments in the bores of guns.

Assuming, in the first place, with De SAINT-ROBERT, that the whole of the products are in the gaseous form,—

Let p be the value of the elastic pressure of the permanent gases generated by the combustion of the powder corresponding to any volume v , and let p_0 , v_0 be the known initial values of p and v . Let also C_p be the specific heat of these gases at constant pressure, and C_v be the specific heat at constant volume. Then, from the well-known relation existing between p and v , where a permanent gas is permitted to expand in a vessel impervious to heat, we have

$$p = p_0 \left(\frac{v_0}{v} \right)^{\frac{C_p}{C_v}}; \dots \dots \dots (15)$$

and this equation, upon De SAINT-ROBERT's hypothesis, expresses the relation between the tension of the gases and the volume occupied by them in the bore of a gun.

Taking p_0 from Table VIII. at 41.477 tons per square inch, and assuming at unity the space v_0 occupied by the charge when at a gravimetric density of 1, taking, further, the value of $\frac{C_p}{C_v} = 1.41$ as computed by De SAINT-ROBERT, equation (15) becomes

$$p = 41.477 \left(\frac{1}{v} \right)^{1.41} \dots \dots \dots (16)$$

If we now take BUNSEN and SCHISCHKOFF's view, that a portion only of the products is in the form of permanent gases, and that they expand without addition or subtraction

* *Traité de Thermodynamique*, p. 154.

of heat, we are able, from equation (15), to deduce the law connecting the tension and the pressure. For if we call v' and v'_0 the volume at any instant and the initial volume of the permanent gases, we have from (15)

$$p = p_0 \left(\frac{v'_0}{v'} \right)^{\frac{C_p}{C_v}}; \dots \dots \dots (17)$$

but if α be the ratio which the volume of the non-gaseous products at the moment of explosion bears to that of the unexploded powder, we have

$$v'_0 = v_0(1 - \alpha), \quad v' = v - \alpha v_0, \dots \dots \dots (18)$$

and equation (17) becomes

$$p = p_0 \left(\frac{v_0(1 - \alpha)}{v - \alpha v_0} \right)^{\frac{C_p}{C_v}}; \dots \dots \dots (19)$$

and this is the relation between p and v on BUNSEN and SCHISCHKOFF'S hypothesis.

Taking, as before, $p_0 = 41.477$, $v_0 = 1$, and remembering that we have found the value of α to be $.6$, we have

$$p = 41.477 \left(\frac{.4}{v - .6} \right)^{\frac{C_p}{C_v}} \dots \dots \dots (20)$$

The value of the exponent $\frac{C_p}{C_v}$ can be deduced from the data given in Table XVI.

TABLE XVI.—Showing the percentage weights, specific heats at constant volume, and the specific heats at constant pressure of the permanent gases produced by the explosion of powder.

Nature of gas.	Percentage weight of gas.	Specific heat at constant pressure.	Specific heat at constant volume.
Sulphuretted hydrogen.....	.0262	.2432	.1840
Carbonic oxide .....	.1036	.2450	.1736
Carbonic anhydride .....	.6089	.2169	.1720
Marsh-gas .....	.0012	.5929	.4680
Hydrogen .....	.0023	3.4090	2.4110
Nitrogen .....	.2579	.2438	.1727

From the data in this Table the value of C_p is found to be $=.23528$, of $C_v = .1782$, and that of the fraction $\frac{C_p}{C_v} = 1.3203$; and equation (20) becomes

$$p = 41.477 \left(\frac{.4}{v - .6} \right)^{1.3203} \dots \dots \dots (21)$$

The results of (16) and (21) are given in Table XVII.; and in the same Table are given the values of p , both as deduced from actual experiment in the bore of the 10-inch and 11-inch guns (see Plate 22), and also as deduced from our experiments in a close vessel. The results of the experiments upon the tension of different densities in a close vessel represent of course the elastic force which would exist were the gas allowed to expand in a vessel impervious to heat, without production of work.

TABLE XVII.—Showing in terms of the density (1) the tension actually found to exist in the bores of guns, (2) the tension which would exist were the gases suffered to expand without production of work, (3) the tension calculated upon De SAINT-ROBERT'S hypothesis, (4) the tension calculated on BUNSEN and SCHISCHKOFF'S hypothesis.

Mean density of products of combustion.	Tension observed in bore of 18-ton gun (pebble powder).		Tension observed where the gases expand without production of work.		Tension calculated upon Count De St.-Robert's hypothesis.		Tension calculated upon Bunsen and Schischkoff's hypothesis.	
	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.
1·00	.....	.....	41·48	6320	41·48	6320	41·48	6320
·90	20·35	3101	32·46	4946	35·75	5448	30·00	4572
·80	17·01	2590	25·52	3889	30·14	4593	21·85	3330
·70	14·03	2133	20·02	3051	25·08	3822	15·85	2416
·60	11·33	1722	15·55	2370	20·18	3076	11·62	1771
·50	8·87	1352	11·85	1806	15·61	2378	7·93	1209
·40	6·65	1019	8·73	1330	11·40	1736	5·30	808
·30	4·67	722	6·07	925	7·60	1157	3·23	500
·20	2·93	459	3·77	574	4·29	653	1·75	267
·10	.....	.....	1·77	270	1·61	246	·64	98

The graphical representation of this Table is given in Plate 23; and by examination either of the Table or of the Curves, it is obvious that neither formula (16) nor (21) gives results which can be taken as at all representing the truth. The values of the elastic force, calculated on the assumption that the whole of the products of combustion are in the gaseous state, and that the effect on the projectile is produced by such expansion, are largely in excess of the pressures observed in the gun, and very greatly in excess even of the pressures observed when the gases were expanded without production of work. On the other hand, the pressures calculated on the assumption that the work is caused by the expansion of the permanent gases *alone*, without addition or subtraction of heat, are considerably in defect of those actually observed, and this too, although, no allowance is made for the absorption of heat by the gun.

At an early stage in our researches, when we found, contrary to our expectation, that the elastic pressures deduced from experiments in close vessels did not differ greatly (where the powder might be considered entirely consumed, or nearly so) from those deduced from experiments in the bores of guns themselves, we came to the conclusion that this departure from our expectation was probably due to the heat stored up in the liquid residue. In fact, instead of the expansion of the permanent gases taking place without addition of heat, the residue, in the finely divided state in which it must be on the ignition of the charge, may be considered a source of heat of the most perfect character, and available for compensating the cooling effect due to the expansion of the gases on production of work.

The question, then, that we now have to consider is—What will be the conditions of expansion of the permanent gases when dilating in the bore of a gun and drawing

heat, during their expansion, from the non-gaseous portions in a very finely divided state?

To solve this question we must have recourse to certain well-known principles of thermodynamics.

Let dH be the quantity of heat added to, or drawn from, the non-gaseous portion of the charge by the permanent gases, while the latter pass from the volume v' and temperature t to the volume $v' + dv'$ and temperature $t + dt$, we then have*

$$dH = t \cdot d\phi, \quad \dots \dots \dots (22)$$

ϕ being RANKINE'S thermodynamic function.

But if λ be the specific heat of the non-gaseous portion of the charge, and if β be the ratio between the weights of the gaseous and non-gaseous portions of the charge, and if we assume further, as we can do without material error, that λ is constant, we shall have

$$dH = -\beta\lambda dt; \quad \dots \dots \dots (23)$$

$$\therefore d\phi = -\beta\lambda \frac{dt}{t}, \quad \dots \dots \dots (24)$$

and by integration

$$\phi - \phi_0 = \log_e \left(\frac{t}{t_0} \right)^{-\beta\lambda}, \quad \dots \dots \dots (25)$$

But the value of $\phi - \phi_0$ for permanent gases is well known, being readily deduced from the general expression for the thermodynamic function.

This expression being†

$$\phi = C \log_e t + \frac{1}{J} \int \frac{dp}{dt} \cdot dv' \quad \dots \dots \dots (26)$$

(J being JOULE'S equivalent), and $\frac{dp}{dt}$ being readily obtained from the equation of elasticity and dilatibility of perfect gases,

$$pv' = R t,$$

we deduce from (26), by integration,

$$\begin{aligned} \phi - \phi_0 &= \log_e \left(\frac{t}{t_0} \right)^{C_v} \cdot \left(\frac{v'}{v'_0} \right)^{\frac{R}{J}} \\ &= \log_e \left(\frac{t}{t_0} \right)^{C_v} \cdot \left(\frac{v'}{v'_0} \right)^{C_p - C_v}, \quad \dots \dots \dots (27) \end{aligned}$$

since‡ $\frac{R}{J} = C_p - C_v$.

Hence, equating (25) and (27),

$$1 = \left(\frac{t}{t_0} \right)^{C_v + \beta\lambda} \cdot \left(\frac{v'}{v'_0} \right)^{C_p - C_v}.$$

* RANKINE, 'Steam-Engine,' p. 310. De SAINT-ROBERT, *loc. cit.* p. 68.
 † RANKINE, *loc. cit.* p. 311. De SAINT-ROBERT, *loc. cit.* p. 72.
 ‡ RANKINE, *loc. cit.* p. 318. CLAUSIUS, *loc. cit.* p. 39. De SAINT-ROBERT, *loc. cit.* p. 93.

Therefore

$$\frac{t}{t_0} = \left(\frac{v_0'}{v'}\right)^{\frac{C_p - C_v}{C_v + \beta\lambda}}, \dots \dots \dots (28)$$

and

$$\frac{p}{p_0} = \left(\frac{v_0'}{v'}\right)^{\frac{C_p + \beta\lambda}{C_v + \beta\lambda}}; \dots \dots \dots (29)$$

or, since $v_0' = v_0(1 - \alpha)$, $v' = v - \alpha v_0$,

$$\frac{p}{p_0} = \left\{ \frac{v_0(1 - \alpha)}{v - \alpha v_0} \right\}^{\frac{C_p + \beta\lambda}{C_v + \beta\lambda}}; \dots \dots \dots (30)$$

and equation (30) gives the true relation connecting p and v when the gaseous products expand in the bore of a gun with production of work.

The values of the constants in this equation we have already determined; they are as follow:— $C_v = 1782$, $C_p = 2353$, $p_0 = 41.477$, $\lambda = 4090$, $\beta = 1.3148$.

The results of equation (30) are given in Table XVIII.; and, as before, for comparison we give similar values of p both as derived from experiments with heavy ordnance and on the supposition of expansion without performance of work.

TABLE XVIII.—Giving, in terms of the density, the tensions actually found to exist in the bores of guns with pebble and R. L. G. powders; giving, further, (1) the tensions calculated from equation (30), (2) the tensions which would exist were the gases suffered to expand without production of work.

Mean density of products of combustion.	Tension observed in bores of guns. Pebble powder.		Tension observed in bores of guns. R. L. G. powder.		Tension calculated from formula (30).		Tension observed when the gases expand without production of work.	
	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.	Tons per sq. inch.	Atmospheres.
1.00	.....	.....	.....	.....	41.48	6316	41.48	6316
.95	.....	.....	.....	.....	36.30	5528	36.65	5581
.90	20.35	3099	27.33	4162	31.84	4848	32.46	4943
.85	18.63	2837	24.63	3751	27.95	4256	28.78	4383
.80	17.01	2590	22.01	3352	24.56	3740	25.53	3888
.75	15.48	2357	19.50	2969	21.56	3283	22.63	3446
.70	14.03	2136	17.16	2613	18.89	2877	20.02	3049
.65	12.65	1926	15.05	2292	16.51	2514	17.68	2692
.60	11.33	1725	13.21	2011	14.38	2190	15.55	2368
.55	10.07	1533	11.61	1768	12.46	1897	13.62	2074
.50	8.87	1351	10.18	1550	10.72	1632	11.85	1804
.45	7.73	1177	8.87	1351	9.15	1393	10.23	1558
.40	6.65	1013	7.65	1165	7.71	1174	8.73	1329
.35	5.63	857	6.49	988	6.40	975	7.35	1119
.30	4.67	711	5.39	821	5.21	793	6.07	924
.25	3.77	574	4.34	661	4.11	626	4.88	743
.20	2.93	446	3.33	507	3.11	474	3.77	574
.15	2.15	327	2.35	358	2.20	335	2.73	416
.10	.....	.....	.....	.....	1.37	209	1.76	268

The results of Table XVIII. are graphically represented in Plate 24; and on the axis of abscissæ are figured, for convenience, both the density of the products and the volume they occupy.

The curve marked A represents the tensions deduced (with a slight correction for loss of heat) from actual observation in a close vessel, and may, as we have already said, be taken to represent the pressures that would exist were the products of combustion allowed to expand in a vessel impervious to heat and without production of work.

The curve marked B, derived from equation (30), denotes the tensions that would exist in the bore of a gun, if we suppose the powder, of a gravimetric density=1 and filling entirely the chamber, to be completely consumed before the projectile is moved from its place, and to expand in a gun impervious to heat. By comparison with the Curve A will be seen the difference in tension arising from the loss of heat due to the work expended. The great importance of the heat contained in the non-gaseous portion of the charge is rendered apparent by comparison of Curve B with Curve 4, Plate 23, or Table XVII., where, on BUNSEN and SCHISCHKOFF's hypothesis, the permanent gases are supposed to expand without deriving any heat from the non-gaseous portion of the charge.

The area comprised between Curve B and the axis of abscissæ represents the maximum work that it is possible to obtain from powder.

Curve C represents the mean results obtained with R. L. G. powder from the 8-inch and 10-inch guns, and Curve D represents the mean results obtained with pebble powder from the 10-inch and 11-inch guns.

It is interesting to study the differences exhibited by these curves B, C, and D. The Curve C, representing the pressures obtained with R. L. G., denotes tensions not far removed from the theoretic curve, while the densities are still very high; before the volume is much increased, the two curves slide into one another and become almost coincident.

The Curve D, on the other hand, is at first very considerably below both the R. L. G. and the theoretic curve. It is still considerably lower even when the R. L. G. curve is practically coincident with the theoretic curve, and it retains a measurable though slight inferiority of pressure even up to the muzzle of the gun.

These differences are without doubt due to the fact that with the R. L. G. powder, at least under ordinary circumstances, the whole or a large proportion of the charge is consumed before the projectile is greatly removed from the seat of the shot. With the slower-burning pebble powder, on the other hand, a considerable quantity of powder remains unconsumed until the projectile approaches the muzzle; and the curve indicates in a very striking way the gradual consumption of the powder, and the portion of the bore in which the slow-burning powder may be considered practically burned.

It might perhaps be expected that the difference between the theoretic Curve B and the observed Curves C and D near the muzzle would be greater than is shown, since the Curve B has been obtained on the supposition that the expansion has taken place in a vessel impervious to heat.

We have pointed out, however, that although in muskets and small arms the loss of heat arising from communication to the bore is very considerable, it is comparatively unimportant in very large guns. In our calculations also we have taken λ , the specific heat of the non-gaseous portion of the charge, at its mean value. It should, however, be taken at a higher value, since the specific heat must increase rapidly with the temperature; and this difference no doubt more than compensates for the loss of heat to which we have referred as not being taken into account.

Our hypothesis as to a portion of the charge remaining unconsumed until the projectile approaches the muzzle, is confirmed by the well-known fact that in short guns, or where powder of high density or very large size is employed, considerable quantities sometimes escape combustion altogether.

The appearance of pellet or pebble powder which has been ignited and afterwards extinguished in passing through the atmosphere is well known to artillerists.

The general appearance (and in this appearance there is wonderful uniformity) is represented in Plate 15. fig. 5, and gives the idea of the combustion having proceeded from centres of ignition.

If we imagine a grain, or rather (taking into account the size of the grains of the present day) a pebble, of powder arriving unconsumed at a point a little in advance of that of maximum pressure, it is not difficult to conceive that such pebble will traverse the rest of the bore without being entirely consumed, when the great influence of diminished pressure, combined with the shortness of time due to the increasing velocity of the projectile, is considered.

Thus by reference to Table X. it will be found that the time taken by the projectile to describe the first foot ($\cdot 305$ metre) of motion is about $\cdot 005$ second, while the time taken to describe the remaining length of the bore, $7\cdot 25$ feet ($2\cdot 21$ metres), is only about $\cdot 011$ second.

The mean powder-pressure over the first foot, again, is about 15 tons per inch (2300 atmospheres), and over the remainder of the bore is only $5\cdot 25$ tons (800 atmospheres).

W. TEMPERATURE OF PRODUCTS OF COMBUSTION IN BORES OF GUNS.

The temperature in the bore of the gun during the expansion of the products is given by equation (28), or, restoring the values of v' and v'_0 ,

$$t = t_0 \left\{ \frac{v_0(1-\alpha)}{v-\alpha v_0} \right\}^{\frac{c_p-c_v}{c_v+\beta\lambda}} \dots \dots \dots (31)$$

The temperatures calculated from this formula are given in Table XIX. It is hardly necessary to point out that the values given in this Table are only strictly accurate when the charge is ignited before the projectile is sensibly moved; but in practice the correction due to this cause will not be great.

TABLE XIX.—Giving the temperature, in degrees Centigrade, and in terms of the density, of the products when expanded, with production of work, in the bore of a gun supposed impervious to heat.

Mean density of products of combustion.	Number of volumes of expansion.	Temperature. Degrees Centigrade.	Mean density of products of combustion.	Number of volumes of expansion.	Temperature. Degrees Centigrade.
1·00	1·0000	2231 ^o	·50	2·0000	2019 ^o
·95	1·0526	2209	·45	2·2222	1996
·90	1·1111	2188	·40	2·5000	1971
·85	1·1765	2167	·35	2·8571	1943
·80	1·2500	2146	·30	3·3333	1914
·75	1·3333	2126	·25	4·0000	1881
·70	1·4286	2105	·20	5·0000	1843
·65	1·5385	2084	·15	6·6667	1796
·60	1·6667	2063	·10	10·0000	1734
·55	1·8182	2041	·05	20·0000	1637

X. WORK EFFECTED BY GUNPOWDER.

The theoretic work which a charge of gunpowder is capable of effecting during the expansion to any volume v is, as we have said, represented by the area between the curve B, Plate 24, the ordinates corresponding to v and v_0 , and the axis of abscissæ. In mathematical language it is expressed by the definite integral

$$\int_{v_0}^v p \cdot dv. \dots \dots \dots (32)$$

Replacing in this equation the value of p derived from equation (30), we have for the work done by the powder in expanding from v_0 to v ,

$$W = p_0 \int_{v_0}^v \left\{ \frac{v_0(1-\alpha)}{v-\alpha v_0} \right\}^{\frac{C_p+\beta\lambda}{C_v+\beta\lambda}} \cdot dv \dots \dots \dots (33)$$

$$= \frac{p_0 v_0 (1-\alpha) (C_v + \beta\lambda)}{C_p - C_v} \left\{ 1 - \left(\frac{v_0(1-\alpha)}{v-\alpha v_0} \right)^{\frac{C_p - C_v}{C_v + \beta\lambda}} \right\} \dots \dots \dots (34)$$

The values of all the constants in this equation have already been given; but for our present purpose it is convenient to determine the work which 1 gramme of powder is capable of performing for different degrees of expansion. Assuming, then, that a gramme of powder is of the gravimetric density of unity (that is, that it occupies a volume of 1 cub. centim.), we have $v_0=1$; and expressing the initial pressures 41·5 tons (6320 atmospheres) in grammes per square centimetre, we have $p_0=6,532,450$ grammes per square centimetre.

We have calculated W from (34) for various values of v up to and inclusive of $v=20$. The results are embodied in the following Table, and are expressed both in kilogramme-metres per kilogramme and foot-tons per lb. of powder.

TABLE XX.—Giving the total work that gunpowder is capable of performing in the bore of a gun, in kilogrammetres per kilogramme and foot-tons per lb. of powder burned, in terms of the density of the products of explosion.

Density of products of combustion.	Number of volumes of expansion.	Total work that the gunpowder is capable of realizing.	
		Per kilogramme burned in kilogrammetres.	Per lb. burned in foot-tons.
·95	1·0526	3210·8	4·70
·90	1·1111	6339·6	9·29
·85	1·1768	9412·8	13·79
·80	1·2500	12443·3	18·23
·75	1·3333	15460·8	22·65
·70	1·4286	18488·1	27·08
·65	1·5385	21544·9	31·56
·60	1·6667	24650·8	36·11
·55	1·8182	27841·9	40·78
·50	2·0000	31153·7	45·62
·45	2·2222	34614·0	50·70
·40	2·5000	38290·0	56·08
·35	2·8571	42234·7	61·86
·30	3·3333	46565·9	68·21
·25	4·0000	51414·8	75·31
·20	5·0000	57031·7	83·53
·17	5·8824	60952·1	89·35
·16	6·2500	62368·1	91·45
·15	6·6667	63884·4	93·64
·14	7·1429	65470·1	95·94
·13	7·6923	67138·4	98·39
·12	8·3333	68940·1	101·00
·11	9·0909	70855·4	103·82
·10	10·0000	72903·7	106·87
·9	11·1111	75214·5	110·18
·8	12·5000	77679·9	113·81
·7	14·2857	80462·1	117·85
·6	16·6667	83582·1	122·42
·5	20·0000	87244·4	127·79

The results embodied in this Table are of very considerable importance. They enable us to say by simple inspection what is the maximum work that can be obtained from powder such as is employed by the British Government in any given length of gun. To make use of the Table, we have only to find the volume occupied by the charge (gravimetric density=1) and the number of times this volume is contained in the bore of the gun. The maximum work* per kilogramme or pound which the powder is capable of

* It is hardly necessary to point out that the velocity of the projectile at any point of the bore is directly deducible from equation (134). For the velocity being connected with the work by the equation

$$\text{velocity} = \sqrt{\frac{2g}{w} \cdot W},$$

w being the weight of the shot, we have only to take out from equation (34) or Table XX. the value of W for any given expansion, multiply it by the "factor of effect" (see p. 134) for the particular gun, charge, &c., and use in the above equation the value of W so found.

As an illustration, if it be required to determine the velocity at the muzzle of the 10-inch gun under the

performing during the given expansion is then taken out from the Table; and this work being multiplied by the number of kilogrammes or pounds in the charge gives the total maximum work. Thus, for example, in an 18-ton 10-inch gun, a charge of 70 lb. (31.75 kilos.) pebble powder is fired, and we wish to know what is the maximum work that the charge is capable of performing. We readily find that the length of the gun is such that $v=5.867$ vols.; and from the Table we find that 89.4 foot-tons or 61,000 kilogrammetres is the maximum work per lb. or per kilog.; multiplying by the number of pounds or kilos., we find that 6258 foot-tons or 1,936,750 kilogrammetres is the maximum work which the whole charge is capable of performing.

As a matter of course, this maximum effect is only approximated to, not attained; and for actual use it would be necessary to multiply the work so calculated by a factor dependent upon the nature of the powder, the mode of firing it, the weight of the shot, &c.; but in service-powders fired under the same circumstances the factor will not vary much. In the experimental powders used by the Committee on Explosives there were, it is true, very considerable differences, the work realized in the same gun varying from 56 foot-tons to 86 foot-tons per lb. of powder; but with service-powders fired under like conditions this great difference does not exist.

We have prepared at once, in illustration of the principles we have just laid down, as a test of the general correctness of our views and as likely to prove of considerable utility, a Table in which we have calculated, from the data given, first, the total work realized per lb. of powder burned for every gun, charge, and description of powder in the English service; second, the maximum theoretic work per lb. of powder it would be possible to realize with each gun and charge; and third, the factor of effect with each gun and charge—that is, the percentage of the maximum effect actually realized.

If the factors of effect be examined, it will be observed how, in spite of the use of slow-burning and therefore uneconomical powders in the large guns, the percentages realized gradually increase as we pass from the smallest to the largest gun in our Table—the highest factor being 93 per cent. in the case of the 38-ton gun, the lowest being 50.5 per cent. in the case of the little Abyssinian gun.

This difference in effect is of course in great measure due to the communication of heat to the bore of the gun, to which we have so frequently referred.

Y. DETERMINATION OF TOTAL THEORETIC WORK OF POWDER WHEN INDEFINITELY EXPANDED.

To determine the total work which powder is capable of performing if allowed to expand indefinitely, the integral in equation (33) must be taken between ∞ and v_0 . If

circumstances discussed at p. 111, the total work, as shown in the text, which the charge is capable of effecting is 6258 foot-tons; multiplying this by the factor for the gunpowder and weight of shot, we have $W=4880$ foot-tons; substituting this value of W in the above equation, we obtain $v=1532$ feet, or nearly identical with the observed velocity.—February 1875.

TABLE XXI.—Giving, with the data necessary for calculation, the work per lb. of powder realized, the total maximum theoretic work, and the factor of effect for every gun and charge in the British Service.

Nature of gun.	Bore.		Charge.		Projectile.		Gas.		Energy of powder.			
	Dia- meter.	Length.	Nature.	Weight.	Weight.	Velocity.	Total volumes in bore.	Final density.	Total.	Realized per lb. of powder.	Calcu- lated maxi- mum.	Per- centage realized.
	inches.	calibres.		lb. oz.	lb.	ft. per sec.			foot-tons.	foot-tons.	foot-tons.	
38 tons	12	16.5	P.	110 0	700	1430	7.342	.1362	9932	90.3	97.0	93.1
35 tons	12	13.5	P.	110 0	700	1300	6.007	.1665	8209	74.6	90.2	82.7
25 tons	12	12.0	P.	85 0	600	1300	6.910	.1447	7036	82.8	94.9	87.3
			P.	85 0	495	1358	6.910	.1447	6334	74.5	94.9	78.6
			P.	55 0	495	1142	10.679	.0936	4479	81.4	108.9	74.8
			R. L. G.	67 0	600	1180	8.765	.1141	5797	86.4	102.8	84.1
			R. L. G.	67 0	495	1271	8.765	.1141	5549	82.8	102.8	80.6
			R. L. G.	50 0	495	1140	11.750	.0851	4464	89.3	111.8	80.0
25 tons	11	13.2	P.	85 0	535	1315	5.585	.1708	6419	75.5	89.2	84.7
			P.	85 0	535	1315	5.855	.1700	6419	75.5	89.2	84.7
			R. L. G.	70 0	535	1217	7.109	.1407	5498	78.6	95.8	82.1
			R. L. G.	70 0	535	1217	7.109	.1407	5498	78.6	95.8	82.1
18 tons	10	14.5	P.	70 0	400	1364	5.867	.1704	5164	73.8	89.4	82.6
			P.	70 0	400	1340	5.867	.1704	4984	71.2	89.4	79.7
			P.	44 0	400	1125	9.334	.1071	3513	79.8	104.7	76.3
			R. L. G.	60 0	400	1298	6.844	.1461	4676	77.9	94.5	82.4
			R. L. G.	40 0	400	1117	10.269	.0974	3463	86.6	107.9	80.3
12½ tons.....	9	13.9	P.	50 0	250	1420	5.742	.1742	3498	70.0	88.6	79.1
			P.	50 0	250	1420	5.742	.1742	3498	70.0	88.6	79.1
			R. L. G.	43 0	250	1336	6.683	.1496	3096	72.0	93.6	77.1
			R. L. G.	43 0	250	1336	6.683	.1496	3096	72.0	93.6	77.1
			R. L. G.	30 0	250	1192	9.566	.1045	2465	82.2	105.2	78.2
9 tons.....	8	14.8	P.	35 0	180	1413	6.136	.1630	2493	71.3	90.9	78.4
			P.	35 0	180	1413	6.136	.1630	2493	71.3	90.9	78.4
			R. L. G.	30 0	180	1330	7.154	.1398	2209	73.7	96.0	76.8
			R. L. G.	30 0	180	1330	7.154	.1398	2209	73.7	96.0	76.8
			R. L. G.	20 0	180	1163	10.724	.0932	1689	84.5	109.1	77.6
7 tons.....	7	18.0	P.	30 0	115	1561	5.827	.1716	1945	64.8	89.0	72.9
			P.	30 0	115	1561	5.827	.1716	1945	64.8	89.0	72.9
			R. L. G.	22 0	115	1458	7.948	.1258	1696	77.1	99.4	77.6
			R. L. G.	22 0	115	1458	7.948	.1258	1696	77.1	99.4	77.6
			R. L. G.	14 0	115	1258	12.495	.0800	1263	90.2	113.3	79.7
6½ tons	7	15.9	P.	30 0	115	1525	5.148	.1943	1856	61.9	84.6	73.2
			P.	30 0	115	1525	5.148	.1943	1856	61.9	84.6	73.2
			R. L. G.	22 0	115	1430	7.021	.1424	1632	74.2	95.5	77.7
			R. L. G.	22 0	115	1430	7.021	.1424	1632	74.2	95.5	77.7
			R. L. G.	14 0	115	1230	11.039	.0906	1207	86.2	110.0	78.4
80-pr. of 101 cwt.	6.3	18.0	L. G.	10 0	80	1240	12.748	.0784	835.5	85.4	114.1	74.9
64-pr. of 64 cwt. wrt. iron	6.3	15.5	R. L. G.	8 0	64	1252	13.715	.0729	696.1	87.0	116.0	75.1
			L. G.	8 0	64	1229	13.715	.0729	670.8	83.8	116.0	72.3
64-pr. of 58 cwt.	6.3	17.2	R. L. G.	8 0	64	1245	15.234	.0656	688.3	86.0	118.7	72.5
64-pr. of 71 cwt.	6.3	16.4	R. L. G.	8 0	64	1230	14.518	.0689	671.9	84.0	117.3	71.6
40-pr. of 35 cwt.	4.75	18.0	R. L. G.	8 0	40	1357	6.830	.1464	511.1	63.9	94.6	67.6
			R. L. G.	7 0	40	1336	7.805	.1281	495.4	70.8	99.1	71.5
			R. L. G.	6 0	40	1305	9.105	.1098	472.7	78.8	103.8	76.0
25-pr. of 21 cwt.	4.0	18.0	R. L. G.	5 0	25	1355	6.518	.1534	318.5	63.7	92.8	68.7
			R. L. G.	4 8	25	1320	7.244	.1380	302.3	67.2	96.4	69.8
			R. L. G.	4 0	25	1278	8.151	.1227	283.3	70.8	100.4	70.5
16-pr. of 12 cwt.	3.6	19.0	R. L. G.	3 0	16	1352	8.365	.1195	202.9	67.6	101.0	67.9
			R. L. G.	2 8	16	1273	10.043	.0996	179.9	72.0	106.8	67.5
			R. L. G.	2 0	16	1167	12.541	.0797	151.2	75.6	113.4	66.6
9-pr. of 8 cwt.	3.0	21.3	R. L. G.	1 12	9	1381	9.320	.1073	119.1	68.0	104.6	65.1
			R. L. G.	1 8	9	1325	10.865	.0920	109.6	73.1	109.5	66.9
			R. L. G.	1 4	9	1203	13.026	.0768	90.38	72.3	114.5	63.2
9-pr. of 6 cwt.	3.0	17.5	R. L. G.	1 12	9	1262	7.649	.1307	99.46	56.8	98.1	57.9
			R. L. G.	1 8	9	1234	8.918	.1121	95.10	63.4	103.5	61.3
7-pr. of 220 lb. (bronze) ...	3.0	11.3	F. G.	0 12	7.25	955	11.538	.0867	45.88	61.2	111.0	55.2
			F. G.	0 10	7.25	854	13.873	.0721	36.69	58.7	116.0	50.6
7-pr. of 150 lb. (steel)	3.0	8.0	F. G.	0 6	7.25	673	16.346	.0612	22.79	60.8	121.0	50.5
7-inch B.L. of 82 cwt.	7.0	14.2	R. L. G.	10 0	110	1013	13.794	.0725	783.2	78.3	116.0	67.5
			R. L. G.	11 0	90	1165	12.541	.0797	847.6	77.1	113.0	68.0
64-pr. B.L. of 61 cwt.	6.4	10.9	R. L. G.	9 0	64	1200	8.982	.1113	639.5	71.1	103.5	68.8
40-pr. B.L. of 35 cwt.	4.75	22.4	R. L. G.	5 0	41	1180	13.590	.0736	396.1	79.2	115.6	68.6
20-pr. B.L. of 16 cwt. L. S.	3.75	22.4	R. L. G.	2 8	21	1130	13.377	.0748	186.1	74.4	115.3	64.0
20-pr. B.L. of 13 cwt. S. S.	3.75	14.5	R. L. G.	2 8	21	1000	8.672	.1153	145.7	58.3	102.4	57.5
12-pr. B.L. of 8 cwt.	3.0	20.5	R. L. G.	1 8	11.75	1150	10.457	.0956	107.8	71.9	108.0	67.9
9-pr. B.L. of 6 cwt.	3.0	17.7	R. L. G.	1 2	9.25	1057	12.019	.0832	71.71	63.7	112.1	56.9
6-pr. B.L. of 3 cwt.	2.5	21.2	R. L. G.	0 12	6.6	1046	12.500	.8000	50.11	66.8	113.4	59.0

so taken, we have

$$\begin{aligned} \text{Total work} &= \frac{p_0 v_0 (1 - \alpha) (C_v + \beta \lambda)}{C_p - C_v} \dots \dots \dots (35) \\ &= 332,128 \text{ gramme-metres per gramme of powder} \end{aligned}$$

(486 foot-tons per lb. of powder).

BUNSEN and SCHISCHKOFF'S estimate of the work which powder is capable of performing on a projectile, if indefinitely expanded, we have already given; but their estimate (being only the fifth part of that at which we have arrived) is altogether erroneous, as these eminent chemists appear to have overlooked the important part which the non-gaseous portion of the charge plays in expansion.

It is interesting to compare the above work of gunpowder with the total theoretic work of 1 gramme of coal, which is about 3,400,000 gramme-units. The work stored up in one gramme of coal is therefore more than ten times as great as that stored up in 1 gramme of powder.

The powder, it is true, contains all the oxygen necessary for its own combustion, while the coal draws nearly 3 grammes of oxygen from the air. Even allowing, however, for this, there is a considerable inferiority in the work done by gunpowder, which is doubtless in part due to the fact that the coal finds its oxygen already in the form of gas, while a considerable amount of work is expended by the gunpowder in placing its oxygen in a similar condition.

In an economic point of view also the oxygen stored up in the gunpowder is of no importance, as that consumed by coal costs nothing, while the oxygen in the powder is in a most expensive form. The fact is perhaps worth noting as demonstrating the impracticability of making economic engines deriving their motive power from the force of gunpowder.

Z. SUMMARY OF RESULTS.

It only now remains to summarize the principal results at which we have arrived in the course of our researches (*a*) when gunpowder is fired in a space entirely confined; (*b*) when it is suffered to expand in the bore of a gun.

(*a*) The results when powder is fired in a close space are as follow, and for convenience are computed upon 1 gramme of powder occupying a volume of 1 cub. centim. :—

1. On explosion, the products of combustion consist of about 57 per cent. by weight of matter, which ultimately assumes the solid form, and 43 per cent. by weight of permanent gases.

2. At the moment of explosion, the fluid products of combustion, doubtless in a very finely divided state, occupy a volume of about .6 cub. centim.

3. At the same instant the permanent gases occupy a volume of .4 cub. centim., so that both the fluid and gaseous matter are of approximately the same specific gravity.

4. The permanent gases generated by the explosion of a gramme of powder are such that, at 0° C. and 760 millims. barometric pressure, they occupy about 280 cub. centims., and therefore about 280 times the volume of the original powder.

5. The chemical constituents of the solid products are exhibited in Tables III. & VI.

6. The composition of the permanent gases is shown in the same Tables.

7. The tension of the products of combustion, when the powder fills entirely the space in which it is fired, is about 6400 atmospheres, or about 42 tons per square inch.

8. The tension varies with the mean density of the products of combustion according to the law given in equation (3).

9. About 705 gramme-units of heat are developed by the decomposition of 1 gramme of powder such as we have used in our experiments.

10. The temperature of explosion is about 2200° C. (about 4000° F.).

(b) When powder is fired in the bore of a gun, the results at which we have arrived are as follow:—

1. The products of explosion, at all events as far as regards the proportions of the solid and gaseous products, are the same as in the case of powder fired in a close vessel.

2. The work on the projectile is effected by the elastic force due to the permanent gases.

3. The reduction of temperature due to the expansion of the permanent gases is in a great measure compensated by the heat stored up in the liquid residue.

4. The law connecting the tension of the products of explosion with the volume they occupy is stated in equation (30).

5. The work that gunpowder is capable of performing in expanding in a vessel impervious to heat is given by equation (34), and the temperature during expansion is given by equation (31).

6. The total theoretic work of gunpowder when indefinitely expanded is about 332,000 gramme-metres per gramme of powder, or 486 foot-tons per lb. of powder.

With regard to one or two other points to which we specially directed our attention in these investigations, we consider that our results warrant us in stating that:—

1. Very small-grain powder, such as F. G. and R. F. G., furnish decidedly smaller proportions of gaseous products than a large-grain powder (R. L. G.), while the latter again furnishes somewhat smaller proportions than a still larger powder (pebble), though the difference between the gaseous products of these two powders is comparatively inconsiderable.

2. The variations in the composition of the products of explosion furnished in close chambers by one and the same powder under different conditions as regards pressure, and by two powders of similar composition under the same conditions as regards pressure, are so considerable that no value whatever can be attached to any attempt to give a general chemical expression to the metamorphosis of a gunpowder of normal composition.

3. The proportions in which the several constituents of solid powder-residue are formed are quite as much affected by slight accidental variations in the conditions which attend the explosion of one and the same powder in different experiments as by decided differences in the composition as well as in the size of grain of different powders.

4. In all but very exceptional results the solid residue furnished by the explosion of gunpowder contains, as important constituents, potassium carbonate, sulphate, hypsulphite, and sulphide, the proportion of carbonate being very much higher, and that of sulphate very much lower than stated by recent investigators.

ABSTRACT OF EXPERIMENTS.

In this abstract the following abbreviations are used:—

δ to represent the mean density of the products of explosion; A the area of the piston of the crusher-gauge; a , the sectional area of the crushing-cylinder.

Experiment 1, April 20, 1871.—The cylinder (fig. 2, Plate 14) having been prepared for the experiments, was calibrated and found to contain 14,000 grs. (907·20 grms). A charge of 1400 grs. (90·72 grms.) R. L. G. powder was then placed in the cylinder and fired.

The gaseous products of combustion were collected in tubes and sealed.

On opening the cylinder the solid products of combustion were found adhering to the sides pretty uniformly, but thicker at the bottom; they had to be scraped off for collection.

δ .	A.	a .	Crush, copper cylinder.	Pressure per square inch.
·0940	·1667	·0417	·009	1·6 ton.

Experiment 2, April 4, 1871.—Fired 3500 grs. (226·80 grms.) R. L. G. powder as above, in a similar cylinder, the powder exactly filling the space in which it was confined.

The gas was retained in the cylinder for about a second, and then, owing to a want of accurate fit in the collecting-screw, made its escape with a considerable explosion, completely, so to speak, washing away every trace both of the male and female screw along the channel it cut out for itself.

On opening the cylinder but little solid residue was found, and that uniformly distributed over the surface, and about ·07 inch thick.

Its colour was of a very bright vermilion red, rapidly changing to black on the surface, and was similar in all respects to the deposit so often seen in the powder-chambers of heavy guns.

Residue collected and sealed up in a test-tube.

δ .	A.	a .	Crush, copper cylinder.	Pressure per square inch.
·915	·1667	·0833	·293	34·5 tons.

Experiment 3, April 29, 1871.—Cylinder No. 6 calibrated and found to contain 14,702 grs. (952·68 grms.). 2940 grs. R. L. G. (190·54 grms.) were fired and the gases collected within fifteen minutes after firing.

On opening the cylinder the solid products were found to be collected at the bottom, only a very thin light-coloured deposit being on the sides.

The appearance of the deposit was very different from any yet obtained, being grey on the smooth surface and very bright yellow in fracture. It was exceedingly hard and very deliquescent.

The interior surface of the cylinder appeared quite bright when the deposit was removed.

A portion of the deposit, whitish on the surface, dark grey next the cylinder, was collected and sealed in separate test-tubes.

A tin cylinder was substituted for copper, to measure the crush in this experiment.

δ .	A.	a .	Crush, tin cylinder.	Pressure per square inch.
·1973	·1667	·0833	·165	2·67 tons.

Experiment 4, May 10, 1871.—4411 grs. (285·5 grms.) of R. L. G. powder were fired in cylinder No. 7. Gases were collected, commencing seven minutes after explosion.

On opening the cylinder the solid products were found in a mass at the bottom; and the sides of the cylinder were also as noted in the last experiment.

The residue, however, was of intense hardness, and the difficulty of removing it was very great. Hardly any could be got off in lumps, but it flew off like sand before the chisel.

Copper firing-wire fused off and dropped in the form of a button.

δ .	A.	a .	Crush, copper cylinder.	Pressure per square inch.
·2963	·1677	·0833	·033	6·4 tons.

Experiment 5, June 22, 1871.—Cylinder No. 6 calibrated and found to contain 15,859 grs. P. powder. Fired 1586 grs. (102·77 grms.) P; but, owing to the low pressure, the cylinder did not become closed up very tightly and most of the gas slowly escaped.

Solid products at the bottom and easily removed. Colour light grey on surface, dark grey next steel, shading into light grey near the surface.

δ .	A.	a .	Crush, tin cylinder.	Pressure per square inch.
·1064	·1667	·0833	·042	1·39 ton.

Experiment 6, June 28, 1871.—Fired 1586 grs. (102·77 grms.) pebble in same cylinder (No. 6) as that used in the last experiment. Nearly all the gas escaped from the same cause (defect of pressure). Products of combustion not collected.

δ .	A.	a .	Crush, tin cylinder.	Pressure in tons.
·1064	·1667	·0833	·032	1·26

Experiment 7, June 28, 1871.—Fired 3150 grs. (204·12 grms.) pebble powder in cylinder No. 6. Gas collected immediately. Solid products at bottom as usual, and tolerably easily detached. Colour whitish grey on the smooth surface, almost black next steel. Fracture yellowish green with splotches of grey.

δ .	A.	a .	Crush, tin cylinder.	Pressure in tons.
·2114	·1667	·0833	·188	2·93

Experiment 8, June 29, 1871.—Fired 1586 grs. (102·77 grms.) pebble powder in cylinder No. 6. There was a slight escape of gas at first, but the plug soon tightened. Gas collected and sealed immediately.

On opening the cylinder the deposit was found principally at the bottom. It adhered very firmly, and was removed with great difficulty.

The colour of the smooth surface was light grey and green, buff in one or two places. Fracture yellowish green.

The portions of the residue that could not be removed with a chisel were dissolved out.

The firing copper wires ·07 in diameter were melted and had formed a button, having, however, rather long stumps.

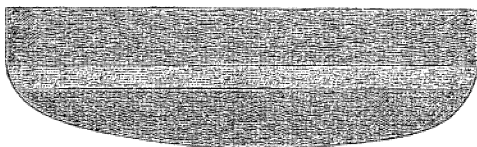
δ .	A.	a .	Crush, tin.	Pressure in tons.
·1064	·1667	·0833	·033	1·28

Experiment 9, June 29, 1871.—Fired 4725 grs. (306·18 grms.) pebble in cylinder No. 4.

On firing there was a slight escape of gas past the crusher-gauge.

The gases were collected within five minutes of the explosion; and after the tubes were sealed a rough measurement was made of the remaining quantity of gas, which amounted to 59,000 cub. centims.

The residue was very easily detached from the cylinder. It was darker grey on the surface than in the last experiment. The fracture was a deep olive-green with a stratum of light grey in the middle, thus (see figure).



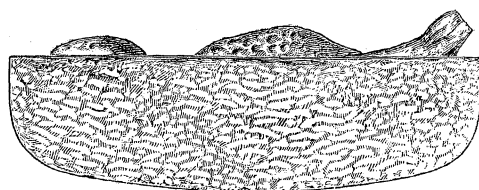
The deposit was all on the bottom, excepting a very thin coating on the sides. Firing-wires fused level with the plug.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·3171	·1667	·0833	·018	4·90

Experiment 10, July 5, 1871.—Fired 6344 grs. (411·09 grms.) P. powder in cylinder No. 6. Most of the gas escaped before enough could be collected.

Residue was found, when the cylinder was opened, at the bottom, not in the usual hard compact mass, but much looser in texture.

On the surface there were three large spongy projections, presenting an appearance as if the surface had been broken by the escape of occluded gas, thus (see figure).



Colour of surface grey in parts, also light

yellow shading into dark yellow. Colour of fracture grey, shading off into dirty yellow and occasionally into gamboge. Powerful odour of sulphuretted hydrogen.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·4258	·1667	·0833	·054	8·4

Experiment 11, July 5, 1871.—Fired 5881 grs. (381·09 grms.) R. L. G. in cylinder No. 4. Some little escape of gas past crusher-plug. Residue very hard and adhering strongly to the side; a portion obtained in solid lumps. Colour grey on surface, black next steel. Fracture olive-green.

A good deal of the deposit was chiselled off in the form of fine dust, and this, when it had lain for a minute or two, heated very much, say to about 80° or 90° C., agglomerating into loose lumps and changing from a light greenish-grey colour to a bright yellow. A portion of this last deposit was collected in a separate bottle.

When the crusher-gauge was taken out, the plug at the end was found to be broken right through transversely.

The fracture was perfectly clean and bright; it was therefore concluded that it must have broken after the great heat had subsided.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·3947	·1667	·0833	·051	8·10

Experiment 12, July 8, 1871.—Fired 6344 grs. (411·09 grms.) P. powder in cylinder No. 6. A good deal of leakage past the crusher-plug. Gas collected. Residue very hard, but it split off tolerably easily. The colour was grey throughout; fracture much the colour and appearance of slate. The difference in physical appearance between this residue and that in the last experiment was very great, the colour of the fine dust being grey, while in the last experiment it was a light yellow.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·4258	·1667	·0833	·063	9·1

Experiment 13, July 12, 1871.—Fired 7351 grs. (476·34 grms.) R. L. G. in cylinder No. 6. The products cut away the screw of the pressure-gauge and escaped.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·4934	·1667	·0833	·091	11·5

Experiment 14, July 12, 1871.—Fired 7930 grs. (513·86 grms.) P. in cylinder No. 4. Gas and residue collected as usual. Cylinder tight.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·5322	·1667	·0833	·100	12·2

Experiment 15, July 22, 1872.—Fired, in cylinder No. 6, 1586 grs. (102·77 grms.) of F. G. Cylinder perfectly tight. Gas and residue collected.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·1064	·1667	·0467	·003	1·66

Experiment 16, July 22, 1872.—Experiment 15 repeated with tin cylinder.

δ .	A.	a .	Crush, tin.	Pressure in tons.
·1064	1667	·0467	·148	1·25

Experiment 17, July 24, 1872.—Fired, in cylinder No. 6, 3172 grs. (205·55 grms.) F. G. Collected gas and residue. Residue very hard, but not so dark in colour as that in experiment No. 16. Surface dark grey, but of a lighter colour when fractured. A very thin coating on the sides of the cylinder.

Small bright yellow crystals pretty uniformly distributed through the residue.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·2129	·1667	·0417	·0475	3·70

Second experiment.

·2129	·1667	·0417	·0435	3·58
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Experiment 18.—Fired 4758 grs. (308·32 grms.) F. G. in cylinder No. 6. Cylinder perfectly tight. Collected gas and residue.

On opening the cylinder the residue was found all collected at the bottom; and it had evidently run down the sides in a very fluid state, the deposit on the side being very thin. Colour on surface dark grey. Fracture more uniform than usual, there being no patches of yellow and but few of a lighter colour.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·3193	·1667	·0467	·132	6·75

Experiment 19, August 26, 1872.—Fired, in cylinder No. 6, 6344 grs. (411·09 grms.) F. G. Cylinder perfectly tight. Colour and fracture dark grey, nearly black; but in places both surface and fracture light grey. No appearance of yellow anywhere in this deposit. All the residues, so far, of F. G. differ very considerably in appearance both from pebble and R. L. G.

The deposit on the sides was exceedingly thin, not more than ·01 inch in thickness.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·4258	·1667	·0417	·222	9·98

(This pressure rejected.)

Experiment 20, August 28, 1872.—Fired, in cylinder No. 6, 7930 grs. (513·86 grms.) F. G. Cylinder was absolutely tight. Gas collected in the usual manner. On opening the cylinder and removing the firing-plug, observed that the little button of residue adhering to the firing-plug, when cut into, had a large well-defined crystalline structure, the crystals being transparent although the surface of the button was dark grey. Sealed a portion in a tube for examination.

Residue in mass at bottom of cylinder as usual; next to nothing on sides. Colour and fracture much the same as in the last experiment, but the centre much lighter grey.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·5322	·1667	·0834	·145	15·8

(This pressure rejected.)

Experiments 21 to 24.—These experiments discarded.

N.B. From Experiment 16 inclusive, the crusher-gauge was put loose in the charge of powder to be fired; but it having been found that the crusher-gauge was heated to such an extent as to soften the copper cylinder and thereby affect the observations, these experiments were repeated, as far as regards the pressure determinations, in experiments 25 to 32.

Experiment 25, October 1, 1872.—Fired 2974 grs. (192·72 grms.) F. G. in cylinder No. 7.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·3860	·0834	·0417	·051	7·68

Experiment 26, October 17, 1872.—Fired 1586 grs. (102·77 grms.) F. G. in cylinder No. 6.

δ .	A.	a .	Crush, tin cylinder.	Pressure in tons.
·1064	·0834	·0417	·016	0·96

Experiment 27, October 18, 1872.—Fired 3172 grs. (205·55 grms.) F. G. in cylinder No. 6.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·2129	·0834	·0417	·008	3·0

Experiment 28, October 18, 1872.—Fired 4758 grs. (308·32 grms.) F. G. in cylinder No. 6.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·3193	·0834	·0417	·032	6·32

Experiment 29, October 19, 1872.—Fired 6344 grs. (411·09 grms.) F. G. in cylinder No. 6.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·4258	·0834	·0417	·074	9·34

Experiment 30, October 21, 1872.—Fired 7930 grs. (513·86 grms.) F. G. in cylinder No. 6.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·5322	·0834	·0417	·104	11·48

Experiment 31, October 29, 1872.—Fired 3507·5 grs. (227·286 grms.) F. G. in cylinder No. 7.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·4615	·0833	·0417	·065	8·68

Experiment 32, October 31, 1872.—Fired 3719 grs. (240·991 grms.) F. G. in cylinder No. 7.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·4593	·0833	·0417	·085	10·14

Experiment 33 (repetition).—Fired 2980 grs. (193·104 grms.) P. in cylinder No. 6.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·200	·0833	·0417	·006	2·70

Experiment 34 (repetition).—Fired 4470 grs. (289·656 grms.) P. in cylinder No. 6.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·300	·0833	·0417	·020	5·40

Experiment 35.—Fired 4560 grs. (295·488 grms.) P. in cylinder No. 7.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·600	·0833	·0417	·136	13·78

Experiment 36.—Fired 4560 grs. (295·488 grms.) P. in cylinder No. 7. Gas escaped.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·600	·0833	·0417	·132	13·50

Experiment 37, November 26, 1872.—Fired 4560 grs. (295·488 grms.) P. in cylinder No. 7.

On firing, a slight quantity of gas escaped with a puff. Gas collected. Surface of the deposit was rough and dark-looking. Fracture grey, with greenish-yellow patches in places; hardly any deposit on sides.

δ .	A.	α .	Crush, copper cylinder.	Pressure in tons.
·600	·0833	·0417	·150	14·80

Experiment 38, November 28, 1872.—Fired 5320 grs. (344·736 grms.) P. in cylinder No. 7.

A good deal of gas escaped through the gas-hole. Gas collected as usual. On opening, all the residue was found at the bottom; but in cooling the residue had contracted very much, separating on one side from the cylinder and leaving a considerable crack. The surface had a frothy appearance, as if occluded gas had been given off while still fluid. Colour dark grey on surface. Texture much more open than usual. Very much less yellow than in last experiment, and darker in colour than in experiment 36, from which the gas escaped. Examined the colour carefully next day, and found it had become more yellow, although not so yellow as the residue in experiment 37.

δ .	A.	α .	Crush, copper cylinder.	Pressure in tons.
·7000	·0833	·0417	·203	18·60

Experiment 39, November 29, 1872.—Fired 4560 grs. (295·488 grms.) R. L. G. in cylinder No. 7. Cylinder was perfectly tight. Residue all at bottom and firmly attached to sides. Surface level, but little dark roughnesses all over it. Colour and fracture much the same as in last experiment, but a little more grey.

δ .	A.	α .	Crush, copper cylinder.	Pressure in tons.
·6000	·0833	·0417	·144	14·36.

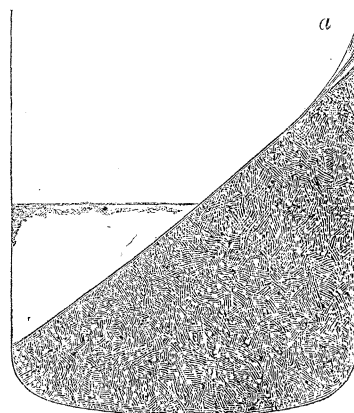
Experiment 40, December 2, 1872.—Fired 4560 grs. (295·488 grms.) F. G. in cylinder No. 7.

Cylinder tight, but a slight smell of sulphuretted hydrogen perceptible. Thirty seconds after explosion the cylinder was placed at an angle of 45°, and retained there for two minutes. When cylinder was opened the deposit was found lying at this angle, the surface being smooth and the edges sharply defined. Hence the deposit must have been perfectly fluid half a minute after explosion, and perfectly set two minutes later. Surface of deposit dark greenish grey; fracture much the same colour, and considerably darker either than that of R. L. G. or P. The bottled deposit had a powerful smell of ammonia.

δ .	A.	α .	Crush, copper cylinder.	Pressure in tons.
·6000	·0833	·0417	·141	14·14

Experiment 41, December 3, 1872.—Fired 5320 grs. (344·736 grms.) R. L. G. in cylinder No. 7.

One minute after firing, the cylinder was placed at an angle of 45° . Forty-five seconds later the position of the cylinder was reversed. Cylinder quite tight. On opening, it was found that one minute after explosion the deposit had just commenced to congeal on the top, a thin crust having been formed, which was broken through when the cylinder was returned to its original position; but a considerable portion of the crust was left. The sharpness with which the cylinder had struck its rest had made the deposit run up the side, as at *a*. Hence, a minute after explosion, the deposit was in a very fluid state, but had just begun to set. It could not, as evidenced by the mark at *a*, have been viscid. Forty-five seconds later the deposit was perfectly set. Colour dark grey with a dark olive-green hue. A few cavities in the deposit.



δ .	A.	<i>a</i> .	Crush, copper cylinder.	Pressure in tons.
·7000	·0833	·0417	·216	19·54

Experiment 42, December 4, 1872.—Fired 5320 grs. (344·736 grms.) F. G. in cylinder No. 7.

Cylinder tight, but slight smell of SH_2 . On opening the cylinder, the nose of the crusher-plug was found to have broken off, and it lay loose on the top of the deposit, showing that it must have fallen off after the deposit was solid. Crusher covered with slight deposit and numerous small crystals, apparently sulphide of iron. Deposit more like that of P. and R. L. G. than formerly. The bottled residue smelt most powerfully of ammonia, too powerfully to hold to the nose.

δ .	A.	<i>a</i> .	Crush, copper cylinder.	Pressure in tons.
·7000	·0833	·0417	·197	18·2

Experiment 43, December 5, 1872.—Fired 6080 grs. (393·984 grms.) pebble powder in No. 7 cylinder.

Cylinder perfectly tight.

δ .	A.	<i>a</i> .	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	0833	·126	28·6

Experiment 44, December 6, 1872.—Fired 6080 grs. (393·984 grms.) R. L. G. in cylinder No. 7.

A small quantity of gas leaked shortly after explosion. Deposit had a great many bright crystals (sulphide of iron) diffused through it.

δ .	A.	<i>a</i> .	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0833	·100	24·4

Experiment 45, December 17, 1872.—Fired 6080 grs. (393·984 grms.) F. G. in cylinder No. 7.

Gas escaped past cone.

δ .	A.	α .	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0833	·092	23·2

Experiment 46, December 24, 1872.—Fired 3800 grs. (246·286 grms.) R. L. G. in cylinder No. 7.

The weight of the mild steel cylinder was 72,688 grms. After firing, the cylinder being perfectly tight, 9,912 grms. water were added.

The temperature of the cylinder before firing was . 54°·15 F. (12°·28 C.).

The temperature of the water before firing was . 55°·75 F. (13°·20 C.).

After firing, the following observations of temperature were made, that of the room in which the observations were made being 56° F. (13°·35 C.) :—

Temperature of water before explosion	55°·75 F. (13°·20 C.)
" " 5 minutes after explosion	67·0 (19·4 C.)
" " 10 " "	70·8 (21·5 C.)
" " 15 " "	71·1 (21·66 C.)
" " 20 " "	71·2 (21·71 C.)
" " 25 " "	71·0 (21·6 C.)
" " 30 " "	70·8 (21·5 C.)
" " 35 " "	70·5 (21·35 C.)
" " 40 " "	70·5 (21·35 C.)
" " 45 " "	70·4 (21·30 C.)
" " 50 " "	70·3 (21·25 C.)

Since in twenty minutes the mass cooled by 0°·7, this amount should be added to the maximum temperature of the water.

At fifty-five minutes after the explosion the gases were suffered to escape, and water taken from the calorimeter was placed in the cylinder. The temperature of the water was found to be 69°·4 F. (20°·72 C.). N.B. Volume of deposit = 1180 grs. (76·464 cub. centims.).

δ .	A.	α .	Crush, copper cylinder.	Pressure in tons.
·5000	·0833	·0417	·090	10·48

Experiment 47, December 28, 1872.—Fired 6080 grs. (393·978 grms.) F. G. in same cylinder as was used in last experiment. After firing, the cylinder was at once placed in a vessel prepared for it filled with water. There was a slight crackling sound, but no escape of gas, except a few minute bubbles, which, however, soon ceased.

Weight of cylinder	72,688·0	grms.
„ water	15,340·0	„
Temperature of cylinder before experiment	57°·5	F.
„ water „	60°·45	F.;

and the heat generated by the explosion raised the common temperature of the cylinder and water to 80°·45 F. (26°·87 C.). Hence the steel was raised through 22°·95 F.=12°·75 C.; water through 20°·00 F.=11°·11 C.

Residue and gas collected from this experiment.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0833	·117	27·1

Experiment 48.—Fired 3800 grs. (246·286 grms.) F. G. in same cylinder as before, and with the same arrangements. On placing the cylinder in the water a few very small bubbles escaped from the firing-plug, and this slight escape continued during the experiment.

Weight of cylinder	72,688·0	grms.
„ water	14,158	„
Temperature of cylinder before experiment	56°·5	F.
„ water „	59°·15	F.;

and the heat generated by the explosion raised the common temperature to 71°·9 F. (22°·15 C.). Hence the steel was raised through 15°·4 F.=8°·555 C.; water through 12°·75 F.=7°·083 C.

Amount of deposit=1038 grs. (67·262 cub. centims.). The deposit seemed to have contracted, since solidification, from ·2 to ·25 inch.

δ.	A.	α.	Crush, copper cylinder.	Pressure in tons.
·5000	·0833	·0417	·090	10·48

Experiment 49.—Fired 6080 grs. (393·978 grms.) R. L. G. in same cylinder Cylinder perfectly tight, but before placing in water crackling sound noticed.

Cylinder weighed	72,688	grms.
Water „	14,845	„
Temperature of cylinder before explosion	46°·2	F.
„ water „	51°·85	F.
„ room	61°	F.;

and the heat generated raised the common temperature of cylinder and water to 71°·32 F. Hence steel raised through 25°·12 F.=13°·95 C.; water through 19°·47 F.=10°·82 C.

Amount of deposit=1900 grs. (123·120 cub. centims.).

δ .	A.	a.	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0417	·265	23·2

Experiments 50 to 52.—These experiments were undertaken to measure the volume of gas produced by the explosion of a given weight of powder. The gas was allowed to escape into a gasometer charged with a saturated saline solution; but as it was found that a considerable quantity of gas was absorbed by the water, this apparatus was replaced by the more perfect one described in the body of the paper.

Experiment 53, February 6, 1873.—Fired 5960 grs. (386·2 grms.) P. powder in cylinder No. 6; measured the quantity of gas produced.

Quantity of gas produced	112,455·5 cub. centims.
Temperature of gas when measured	18°·3 C.
Barometric pressure	767 millims.

Experiment 54, February 7, 1873.—Fired 5960 grs. (386·2 grms.) P. powder with same arrangements as in last experiment.

Quantity of gas measured	110,633·4 cub. centims.
Temperature of gas when measured	17°·2 C.
Barometric pressure	770 millims.

Experiment 55, February 8, 1873.—Fired 5960 grs. (386·2 grms.) R. L. G. with same arrangements.

Quantity of gas measured	110,269·6 cub. centims.
Temperature of gas when measured	16°·0 C.
Barometric pressure	774 millims.

Experiment 56, February 10, 1873.—Fired 5960 grs. (386·2 grms.) F. G. under same conditions.

Quantity of gas measured	104,875·3 cub. centims.
Temperature of gas	15°·0 C.
Barometric pressure	775 millims.

Experiment 57, February 11, 1873.—Fired 5960 grs. (386·2 grms.) F. G. under same arrangements.

Quantity of gas measured	103,345·2 cub. centims.
Temperature of gas	13°·3 C.
Barometric pressure	768 millims.

Amount of deposit measured, and found to occupy a space of 115·34 cub. centims. The deposit appeared not to have contracted much after solidification; but it had parted from the side, leaving a crack about 0·04 in. (1 millim.) wide.

Experiment 58, February 12, 1873.—Fired 5960 grs. (386·2 grms.) R. L. G. Same arrangements.

Quantity of gas measured	107,354·5 cub. centims.
Temperature of gas	14°·5 C.
Barometric pressure	772 millims.
Deposit occupied a space of.	110·8 cub. centims.

Experiment 59.—Experiment on mode of closing firing-plug.

Experiment 60, March 5, 1873.—Fired 5960 grs. (386·2 grms.) P.

Quantity of gas.	114,059·7 cub. centims.
Temperature of gas	19° C.
Barometric pressure	765 millims.
Deposit occupied a space of.	111·78 cub. centims.

Experiment 61, March 6, 1873.—Fired 5960 grs. (386·2 grms.) R. L. G.

Quantity of gas.	111,367·5 cub. centims.
Temperature of gas	15°·94 C.
Barometric pressure	755·6 millims.
Deposit occupied a space of.	105·30 cub. centims.

Experiment 62.—Fired 5960 grs. (386·2 grms.) F. G.

Quantity of gas.	108,881·8 cub. centims.
Temperature of gas	19°·61 C.
Barometric pressure	739·4 millims.
Deposit occupied a space of.	108·5 cub. centims.

Experiment 63.—Fired 3800 grs. (246·286 grms.) R. L. G. to determine heat. Cylinder quite tight.

Cylinder weighed	72,688 grms.
Water „	15,655·4 „
Temperature of cylinder before explosion	51°·4 F. (10°·72 C.)
„ water „	51·65 F.
„ room	52·5 F.

The heat generated raised the temperature of water and cylinder to 64°·25 F.

Hence steel raised through 12°·25 F.=7°·139 C.; water through 12°·6 F.=7°·0 C.

Experiment 64.—Fired 5960 grs. (386·2 grms.).

Quantity of gas	106,625·0	cub. centims.
Temperature of gas.	16°·55	C.
Barometric pressure	758·2	millims.

Experiment 65.—Fired 6840 grs. (443·23 grms.) P. in cylinder No. 7. This charge filled the cylinder nearly quite full. Cylinder, on firing, cracked between the firing- and crusher-plugs. Crack about ·5 millim. wide. Report very loud.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·900	·0833	·1833	·156	33·4

Experiment 66.—Fired 6840 grs. (443·23 grms.) P. In about a second after firing the gas made a fizzing sound, and in about another second escaped by blowing out the gauge-plug with a loud report. Lower threads of the screw on the crusher-plug washed away by the escape of the gas.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·900	·0833	·0833	·145	31·6

Experiment 67.—Experiment on mode of detonating a charge.

Experiment 68.—Fired 6840 grs. (443·23 grms.) R. L. G. Cylinder and all parts perfectly tight. Residue and gas collected. Observed that the deposit had apparently not contracted much.

On the firing-plug were several congealed drops of deposit like icicles, and on the surface below spots, which had apparently dropped from above, were visible.

Surface of deposit dark grey, almost black.

Fracture olive-green, with frequent spots of brilliant yellow of the size of a pin's head.

Top part of deposit put in separate bottle from bottom part, each sample being ground and mixed carefully in an atmosphere of dry nitrogen.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·900	·0833	·0833	·168	35·6

Experiment 69, May 29, 1873.—Fired 6840 grs. (443·23 grms.) F. G. Cylinder &c. perfectly tight. On opening the cylinder, found white crystals deposited on firing-plug. Deposit very dark and more greasy than usual.

Fracture dark grey, with only few spots of yellow.

Deposit first taken did not heat; but there was great difficulty in getting it to grind in an atmosphere of dry nitrogen.

The portion we succeeded in grinding was sealed in test-tube marked experiment 69*a*. Unground portion sealed in test-tube marked B. Bottom portions of the deposit, when exposed to the air, changed with great rapidity to a bright yellow on the surface,

with development of heat. It was got as rapidly as possible into the mill and was easily ground in dry nitrogen. This was sealed in bottle marked C, while some unground lumps were marked D.

A mixture of the top and bottom was ground in nitrogen and was marked E.

Transparent crystals (on firing-plug) also preserved in small tube.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·900	·0833	·0833	·118	27·2

Experiment 70, October 20, 1873.—Fired 3800 grs. (246·286 grms.) R. L. G. by means of a detonator containing 2 grms. of fulminate of mercury. Cylinder perfectly tight. Residue full of lustrous scales, otherwise of usual appearance; considerable lump of metal found in bottom (firing-wire and detonator-case).

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·500	·1667	·0833	·081	10·7

Experiment 71, October 22, 1873.—Last experiment repeated with similar results.

δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·500	·1667	·0833	·086	11·10

Experiment 72, October 24, 1873.—Fired, with a view to determine the amount of heat absorbed by a gun when fired, nine rounds of 1 lb. 12 oz. (793·788 grms.) R. L. G. in a 12-pr. B. L. gun; weight of shot 11 lbs. 12 oz. (5,329·72 grms.). Temperature of air 46°·2 F.

Time of firing six minutes. After firing, the gun was at once placed in a vessel of water and the changes of temperature observed. The following are the data:—

Weight of gun	387,141·6 grms.
Weight of water	192,777·0 „

Temperature of gun and water before firing 47°·0 F.; the heat communicated to the gun by nine rounds raised the common temperature of the gun and water to 51°·15 F.

Hence the heat raised the water and gun through 4°·15 F.=2°·305 C.

Experiment 73.—Fired five rounds 1·5 lb. (680·39 grms.) R. L. G. in a 12-pr. B. L. gun.

Weight of shot	532·75 grms.
Temperature of air	46°·5 F.
Time of firing	2 $\frac{1}{4}$ minutes.
Weight of gun	387,141·6 grms.
Weight of water	68,810·1 grms.
Temperature of gun and water before firing . . .	45°·7 F.
„ „ „ after „ . . .	50°·55 F.

Hence the heat communicated to the gun raised gun and }
 water through } $4^{\circ}\cdot85\text{ F.} = 2^{\circ}\cdot694\text{ C.}$

Experiment 74.—Exposed four crucibles filled with deposit from experiment 36 to most intense heat of one of SIEMENS'S gas-furnaces; one crucible uncovered, the rest covered. Temperature estimated at 1700° C. A portion of the residue spirted immediately and then became quiet. On removal from the furnace half an hour afterwards, a little vapour was observed coming from the crucibles. Their contents were perfectly liquid, setting at about 700° or 800° C.

The colour of the contents when cool was a bright sealing-wax red, similar to the deposit found in the chambers of guns, turning black on the surface on exposure to the air: sealed for examination.

Experiment 75, November 1, 1873.—Experiment 20 repeated, 3800 grs. (246·286 grms.) F. G., analysis of 20 being unsatisfactory. When exploded, cylinder perfectly tight; had to put a drop of water in gas-hole before gas would come away, the hole being sealed by the deposit.

Residue when got out very dark in colour; no yellow or green apparent when put in bottle; after grinding in nitrogen, a little heat appeared to be developed and a tinge of yellow appeared.

δ .	A.	a.	Crush, copper cylinder.	Pressure in tons.
·5000	·1667	·0833	·076	10·2

Experiment 76, November 3, 1873.—Experiment 43 repeated, results of analysis of previous experiment being irreconcilable; 6080 grs. (393·986 grms.) P.

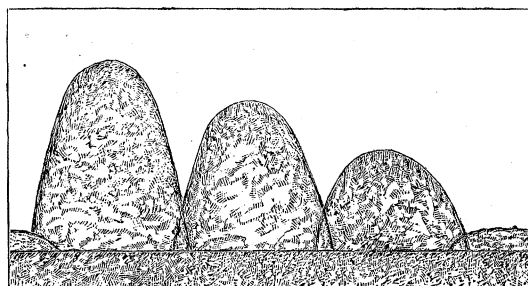
On opening the cylinder observed that the contraction was greater than usual; nothing else remarkable.

δ .	A.	a.	Crush, copper cylinder.	Pressure in tons.
·8000	·0833	·0833	·098	24·2

Experiment 77, November 13, 1873.—Fired 6840 grs. (417·312 grms.) P. After firing, the cylinder was allowed to stand for 60 seconds, then tilted over to an angle of 45° and replaced. At 75 seconds after firing it was again tilted on a different place, and so on up to 2 minutes.

On opening the cylinder it was found that at 60 and 75 seconds after explosion the deposit was perfectly fluid; at 90 seconds it was rather thick, and at 105 seconds it hardly moved.

The development of the interior surface of the cylinder appeared thus (see figure).



δ .	A.	a .	Crush, copper cylinder.	Pressure in tons.
·9000	·0833	·0833	1·44	31·4

Experiment 78, January 12, 1874.—Fired 5320 grs. (344·74 grms.) in same cylinder. On opening, the colour of the deposit was a lighter grey than usual. The contraction after setting appeared to be considerable, apparently ·2 inch.

In this experiment, before firing, a piece of the finest platinum wire*, also a piece of sheet platinum about 1 inch (26 millims.) square and ·03 inch (·76 millim.) thick were placed among the powder. After the explosion the thin platinum wire had disappeared, but small globules of the metal were found in many places welded to the surface of the cylinder.

The sheet platinum was not melted, but was doubled up; there were appearances, however, of fusion on its surface, and in places the platinum wire had been welded to the sheet. The weight of the sheet platinum was about 0·25 oz. (about 6 grms.).

δ .	A.	a .	Crush.	Pressure in tons.
·7	·0833	·0833	·067	18·9

Experiment 79, January 14, 1874.—Fired 5320 grs. (344·74 grms.) Spanish pebble powder; put in a coil of platinum wire ·06 inch (1·52 millim.) in diameter, weighing about 15 grms.

The platinum after the explosion was found in a lump at the bottom of the deposit thoroughly fused, with the exception of a small portion. Colour and appearance of residue rather different from the ordinary. There were a good many light-coloured splotches. The surface of the deposit was broken and rough, as if by the escape of gas.

δ .	A.	a .	Crush.	Pressure in tons.
·700	·0833	·0833	·056	17

Experiment 80, January 16, 1874.—Fired 5960 grs. (386·21 grms.) R. F. G.

Quantity of gas measured	109·540 cub. centims.
Temperature of gas	18°·33 C.
Barometric pressure	729 millims.

Experiment 81.—Fired 5960 grs. (386·21 grms.) pebble (Spanish).

Quantity of gas measured	98,607·7 cub. centims.
Temperature of gas	16°·67 C.
Barometric pressure	735 millims.

Experiment 82.—Placed in a SIEMENS furnace, at a temperature of about 1700° C., two crucibles, one containing powder-residue, the other equal weights of potassium carbonate and liver of sulphur. On first placing them in the furnace a little ebullition took place, apparently in both crucibles, but with some violence in the crucible with powder-residue. This ebullition, however, soon subsided and a slow volatilization

* Wound round the sheet platinum.

appeared to proceed. On taking the crucibles from the furnace, the height of the contents (which left marks on the crucibles) was noted, and the volume of the deposit and the amount of contraction were measured by means of mercury, with the following results:—

Powder-residue.

Volume at 1700° C.	=	17·859	cub. centims.
Volume at 0° C.	=	10·044	„ „
		7·815	„ „

Expansion between 0° and 1700° = 7·815 cub. centims., = 77·8 per cent.

Potassium carbonate and liver of sulphur.

Volume at 1700° C.	=	28·188	cub. centims.
Volume at 0° C.	=	14·580	„ „
		13·608	„ „

∴ expansion between 0° C. and 1700° C. = 13·608, = 93·3 per cent.

With the above two crucibles there was also a third, containing powder-residue, and in this crucible a piece of platinum was placed. The expansion measured was over 100 per cent., but could not be depended on, on account of the platinum. The metal was not appreciably altered by the heat.

Experiment 83.—Experiment 79 repeated.

Experiment 84.—Fired 5320 grs. (344·74 grms.) F. G. in small cylinder. Put a piece of platinum wire 4 inches long (100 millims.), 16 W. G. (1·5 millim. in diameter), with the powder. This wire showed signs of fusion on the surface, but was not at all melted.

Experiment 85, February 18, 1874.—Fired 5320 grs. (344·736 grms.) R. L. G. in cylinder. Placed in cylinder a piece of platinum wire 4 inches (100 millims.) long and 0·04 inch (1 millim.) in diameter. The wire was superficially fused, but otherwise little altered. No crusher used, the gauge having been destroyed in experiment 83.

Experiment 86, February 19, 1874.—Fired 5320 grs. (344·736 grms.) R. L. G. in same cylinder. Placed in the cylinder a piece of platinum wire of same dimensions as in last experiment, also the same length of copper wire, 0·13 inch (3·2 millims.) in diameter. The copper was completely fused and firmly attached to the cylinder, it being found necessary to remove it with a chisel. The platinum wire was superficially fused, as in the last experiment.

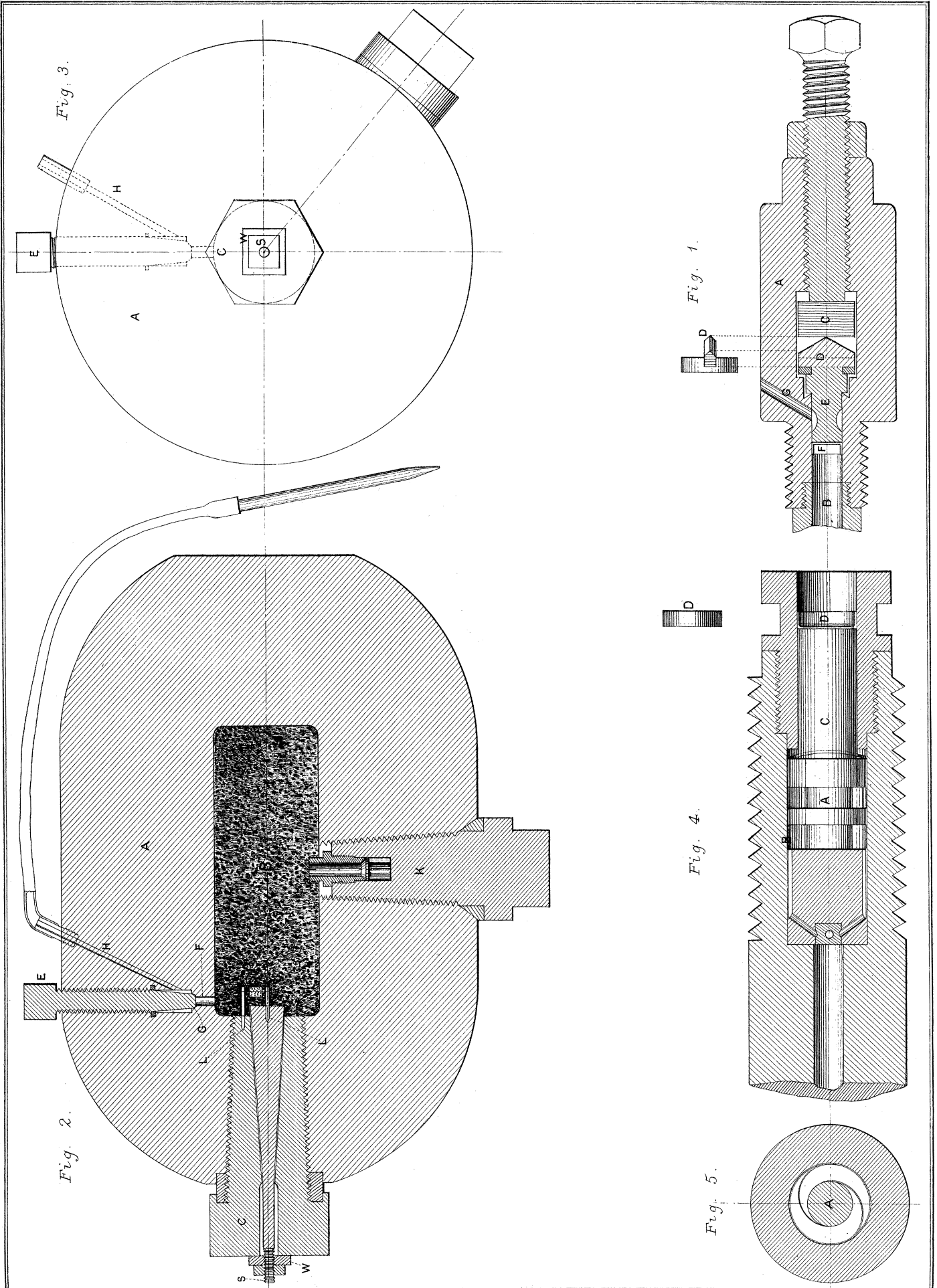


Fig. 3.

Fig. 2.

Fig. 1.

Fig. 4.

Fig. 5.

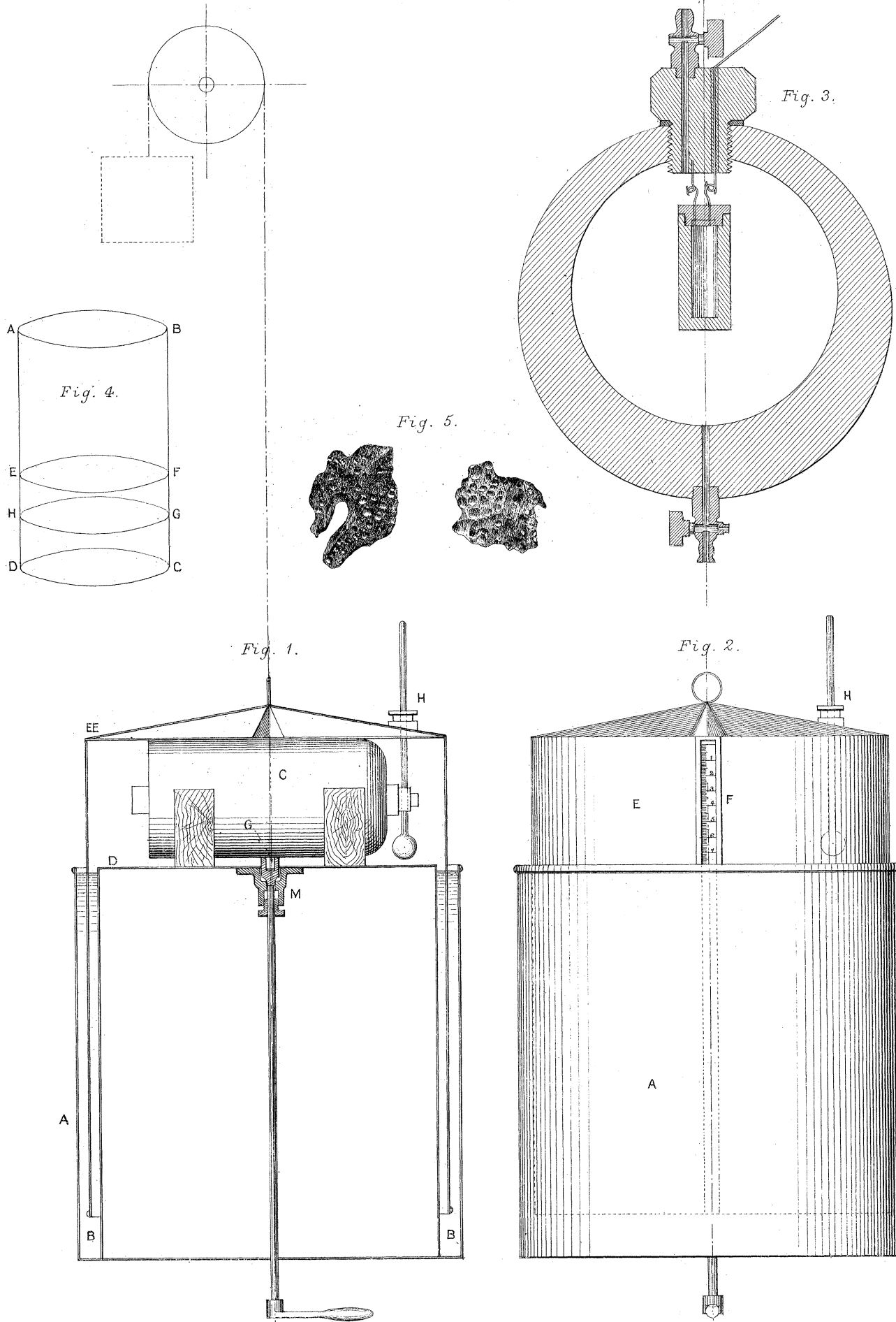


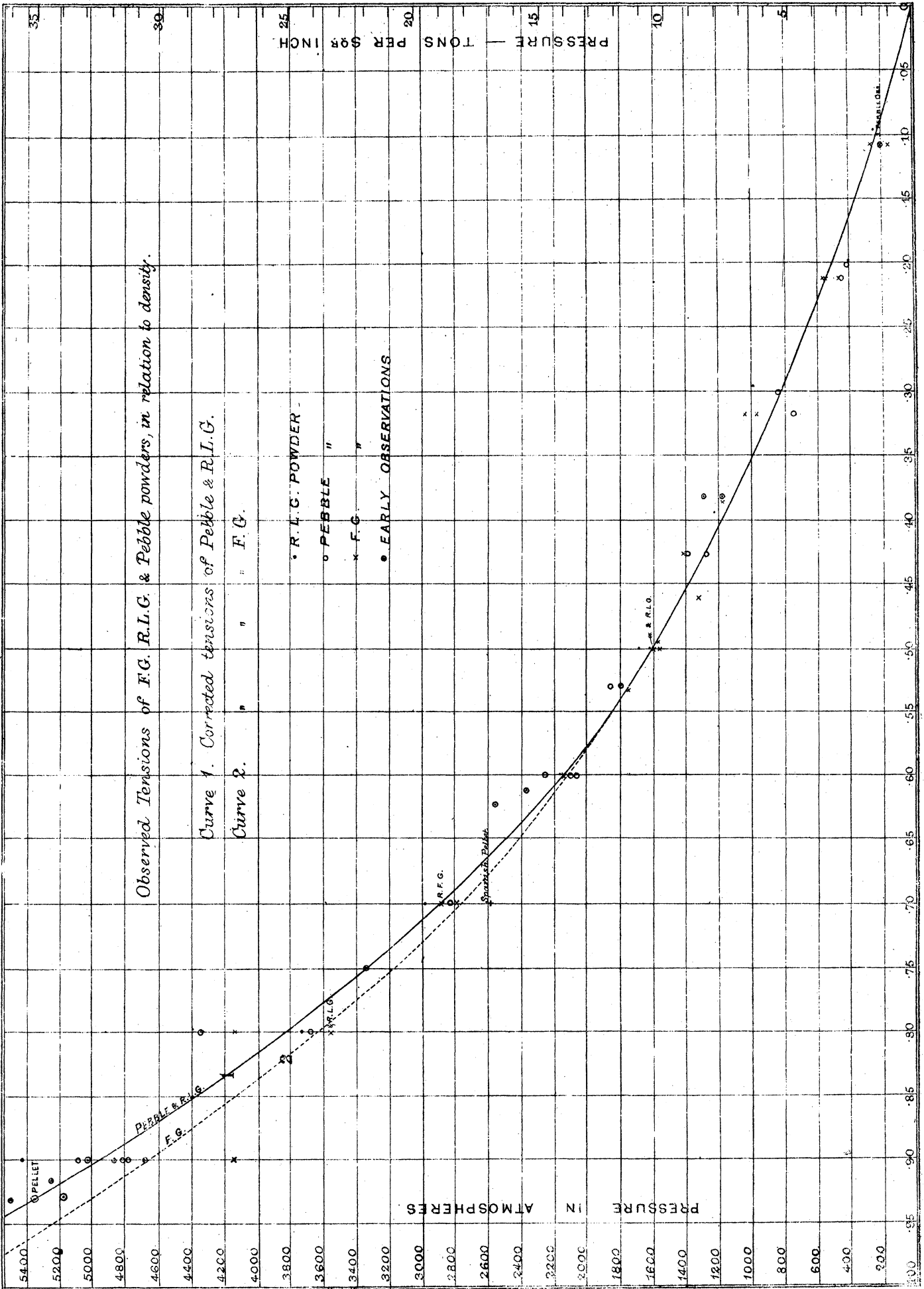
Fig. 3.

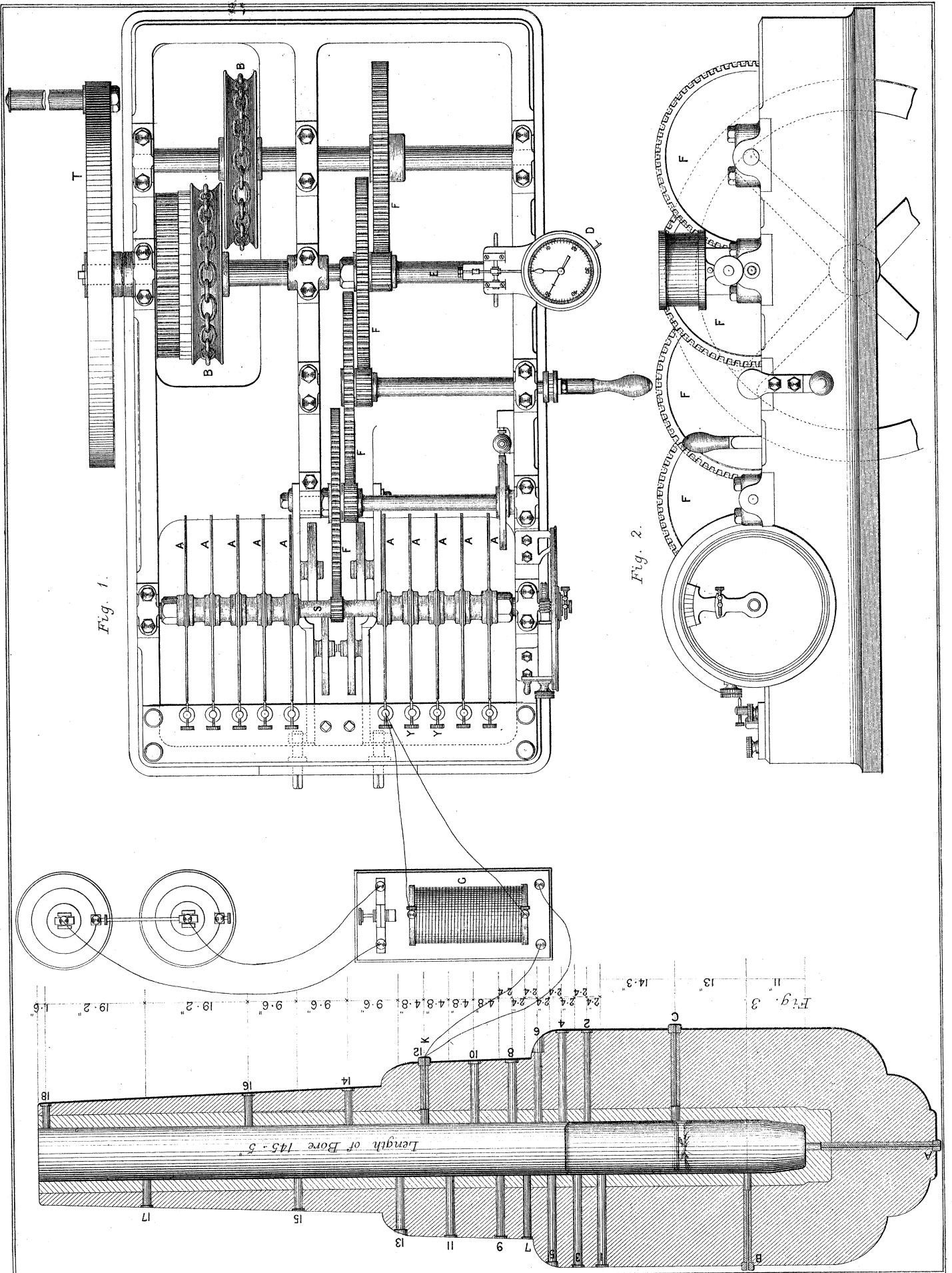
Fig. 4.

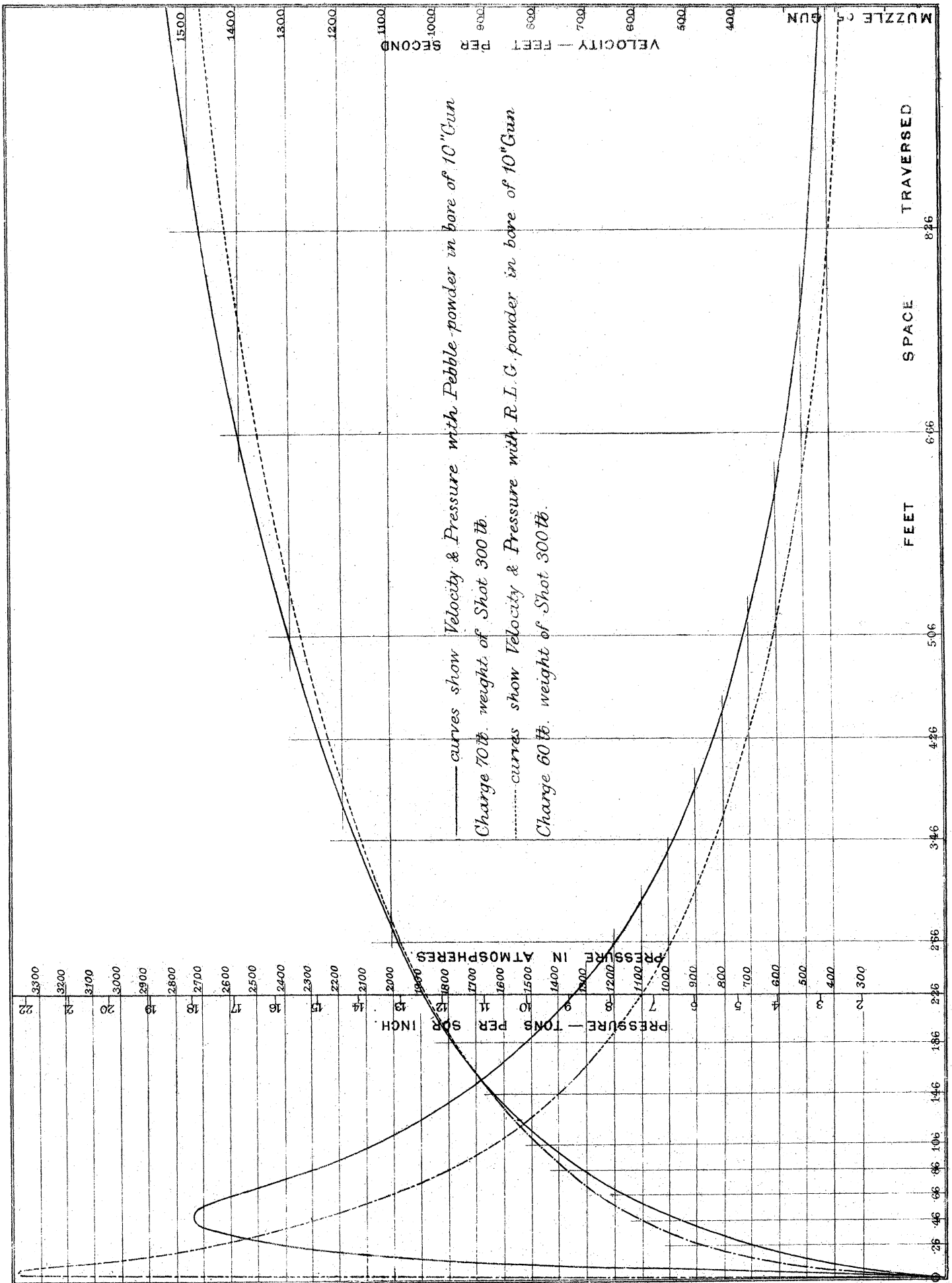
Fig. 5.

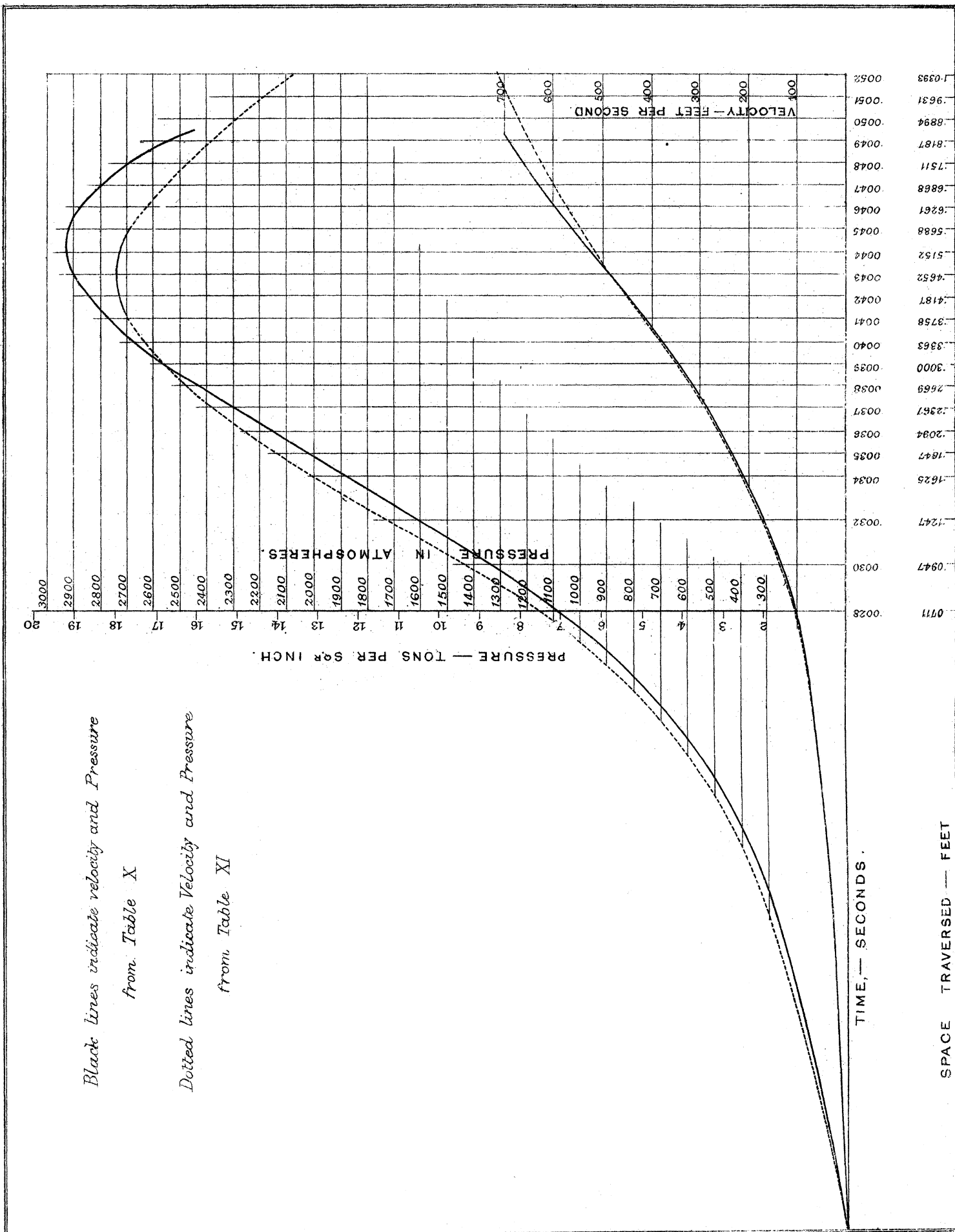
Fig. 1.

Fig. 2.

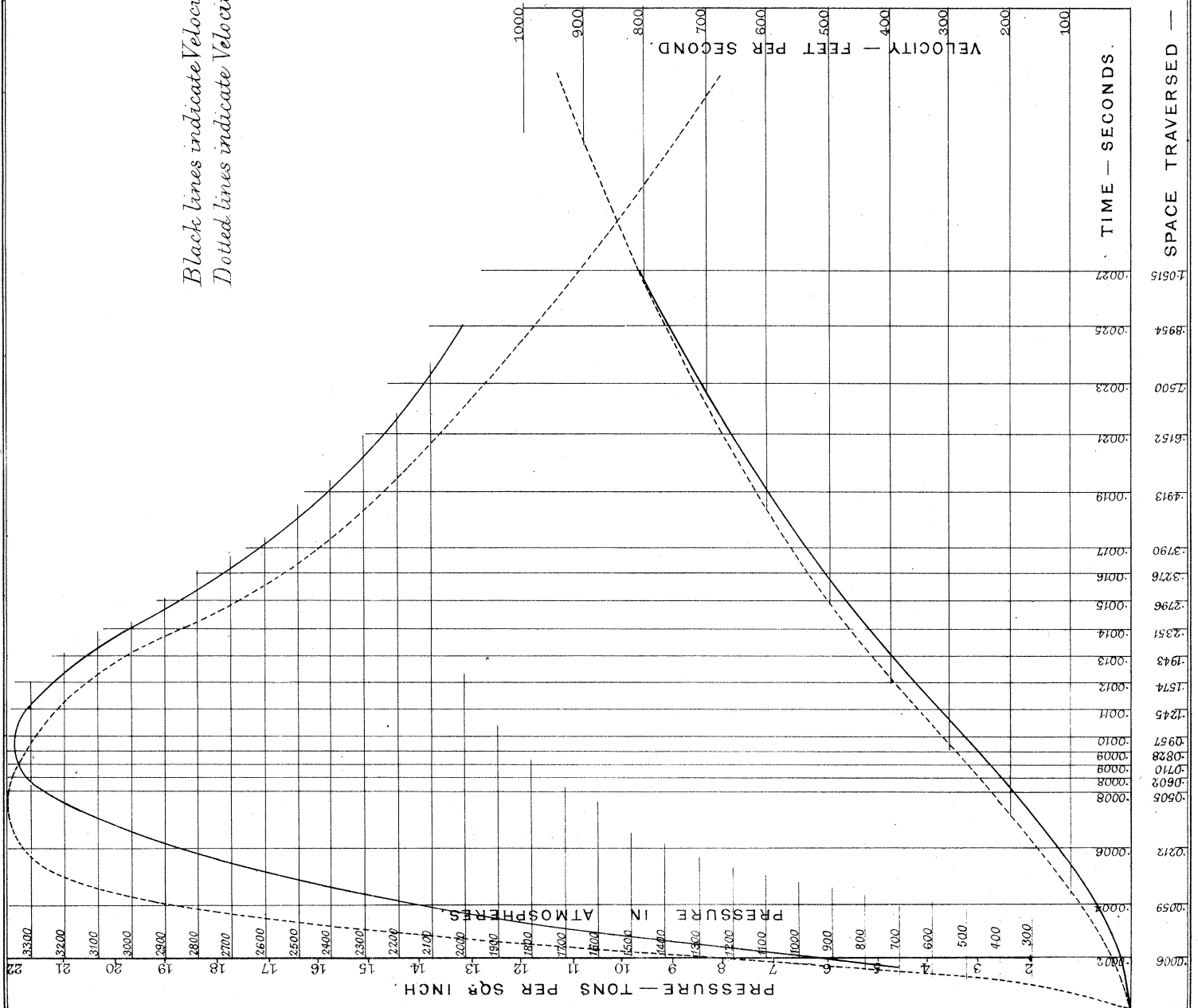


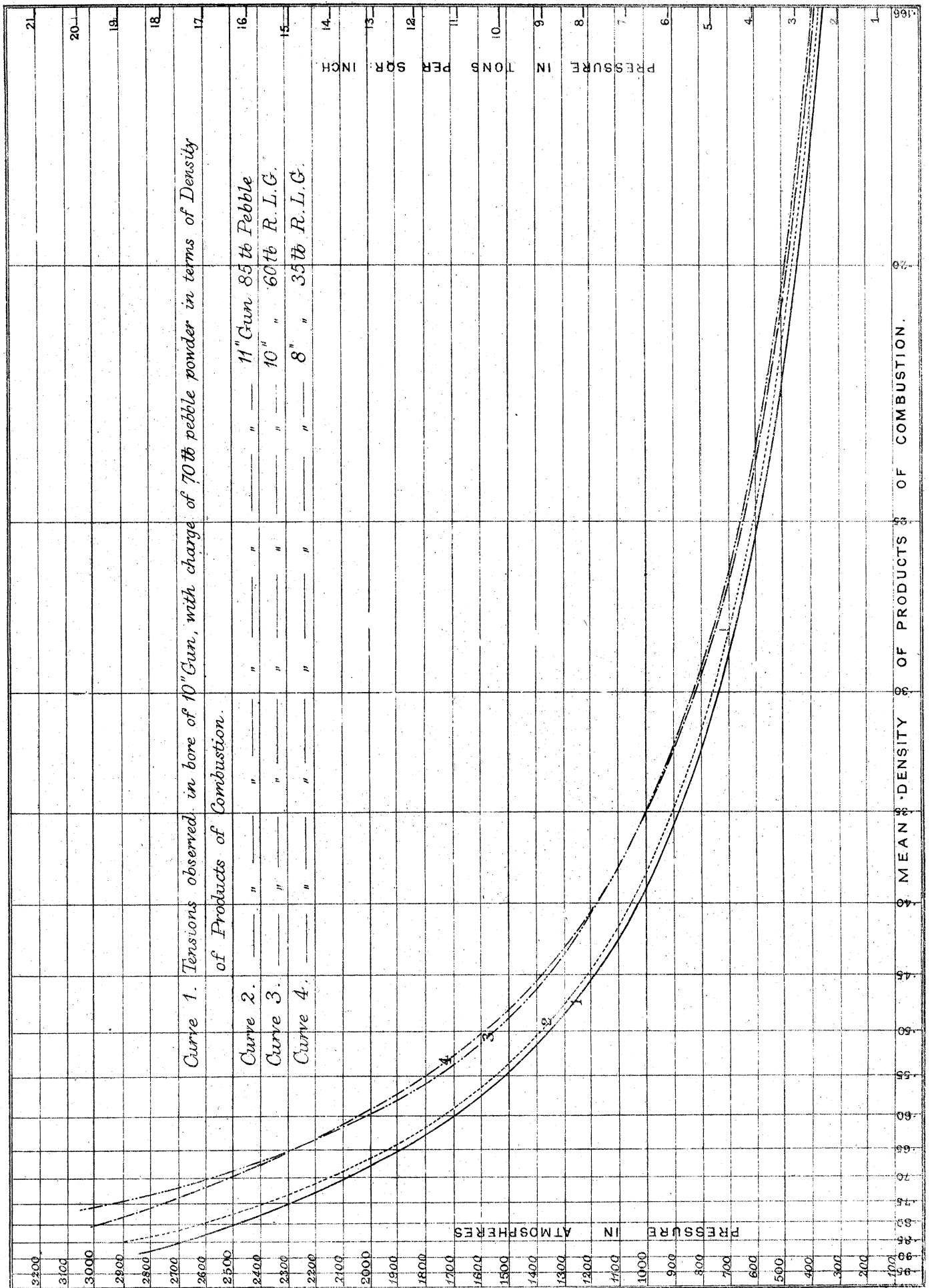


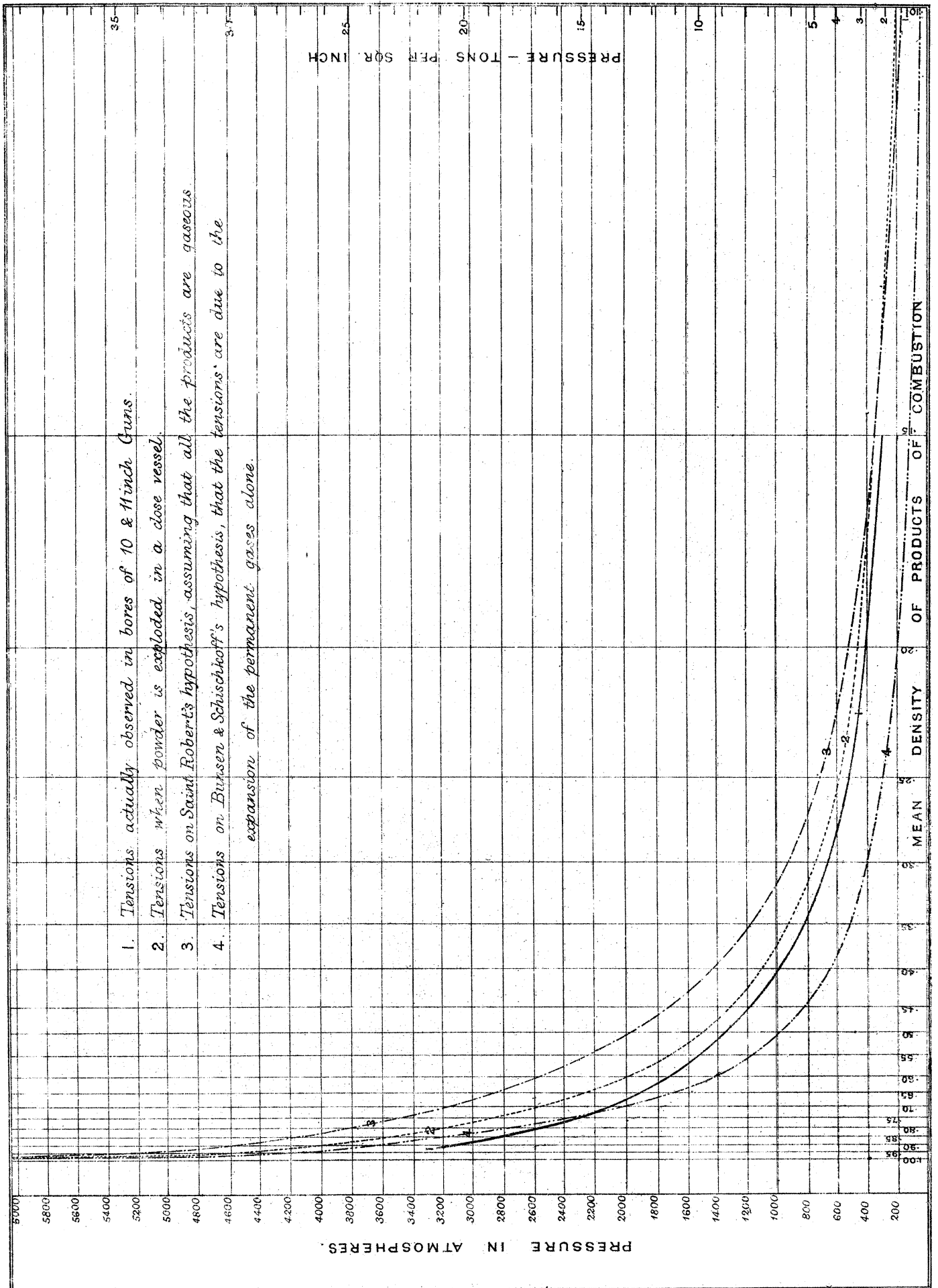




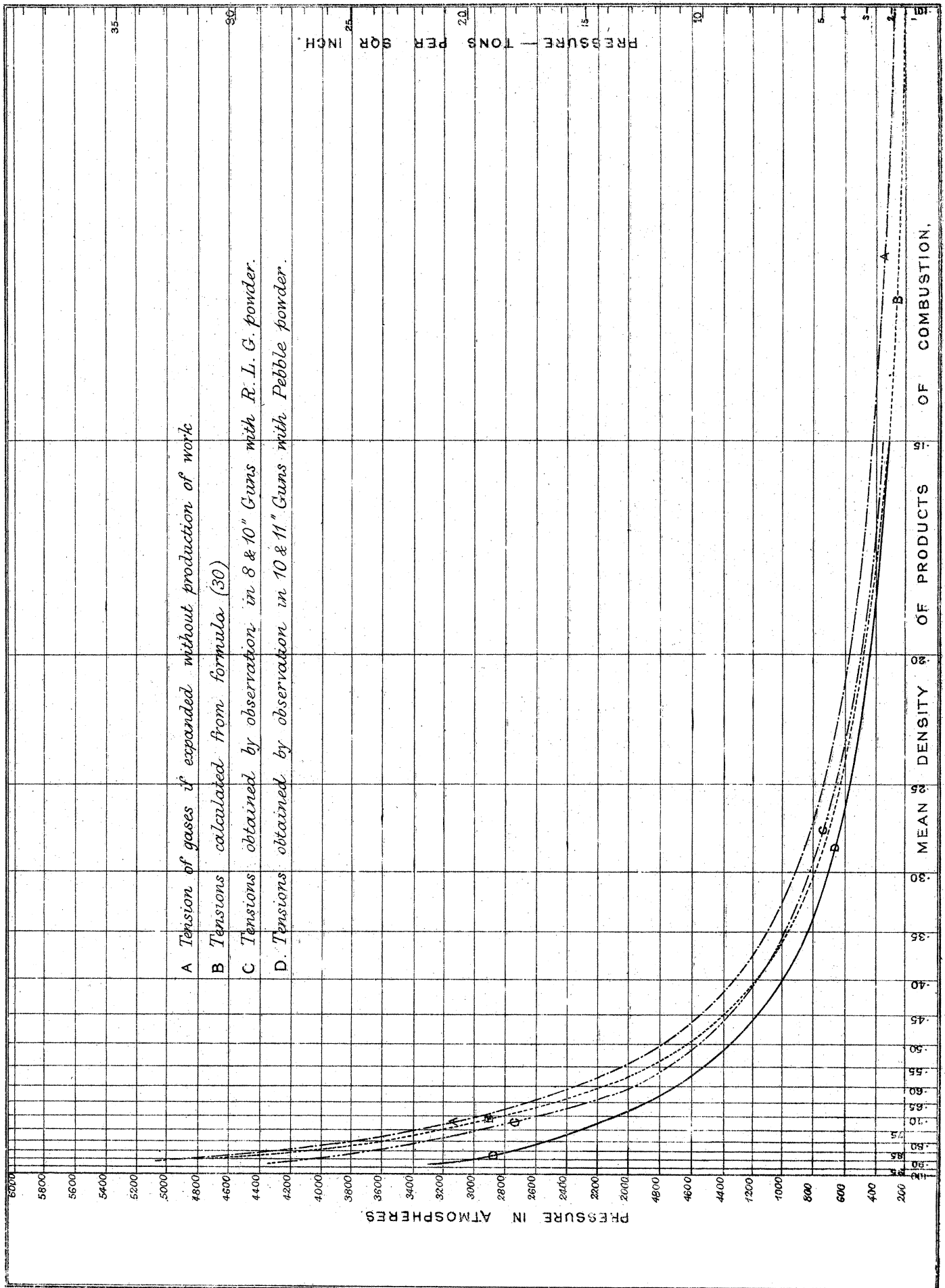
*Black lines indicate Velocity & Pressure from Table XIII.
Dotted lines indicate Velocity & Pressure from Table XIV.*







1. Tensions actually observed in bores of 10 & 11 inch Guns.
2. Tensions when powder is exploded in a close vessel.
3. Tensions on Saint Robert's hypothesis, assuming that all the products are gaseous.
4. Tensions on Bunsen & Schischkoff's hypothesis, that the tensions are due to the expansion of the permanent gases alone.



A Tension of gases if expanded without production of work
 B Tensions calculated from formula (30)
 C Tensions obtained by observation in 8 & 10" Guns with R. L. G. powder.
 D. Tensions obtained by observation in 10 & 11" Guns with Pebble powder.