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Investigation of the Law of Burning of Modified Cordite

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VI. *Investigation of the Law of Burning of Modified Cordite.*

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CONTENTS.

SOME years ago the eminent French chemist VIEILLE first propounded the law of combustion by parallel surfaces for smokeless propellants. By a propellant we distinguish an explosive which explodes from one that detonates; and it is this combustion by parallel surfaces which is the distinguishing characteristic of the difference of the two phenomena.

Since VIEILLE first propounded his theory it has been generally accepted as correct. Investigators, however, have not, so far as I am aware, definitely determined what the law is. The general assumption has been that the law is of the form $S = aP^n$, where S is the skin burnt in a given time under the average pressure P, a and n being constants for the given explosive.

Now, the investigators who have dealt with this subject have all done so with the primary object of finding out what goes on inside a gun when the charge is fired. That has also been my primary object. In fact, it is the practical as distinguished from the purely scientific result of the law which has appealed to all investigators.

Now, the gun is a most complex gas-engine, and in the past has upset the most carefully conceived and elaborated theories. Previous investigators have therefore gone straight to the gun and endeavoured to solve the constants a and n in the general form of the above equation by a system of trial and error.* Some have concluded that n is unity, others that n is $\frac{1}{2}$ (INGALLS, America), $\frac{2}{3}$ (GOSSOT and LIOUVILLE, France), 0·9 (CENTERVALL, Sweden), &c. These are wide variations, and, as I shall show, are due in part to the form of the explosive that different investigators have experimented with and in part to the following causes.

The principle of calculation in the gun is that the space behind the projectile is treated as a closed vessel. Now, as the projectile moves down the bore the size of the vessel increases. The size of the vessel therefore directly depends on the distance the projectile will move in a given time under a given pressure. Here at once is the difficulty, and it entirely depends upon what friction or resistance to forward movement is assumed as to what values of a and n may be determined. This friction is made up of (1) the resistance to engraving of the driving band, (2) the resolved part of the rotational thrust due to the lands of the rifling, and (3) perhaps forcement of the projectile through the gun, which is possibly conical in form at any point where the projectile may be during its passage down the bore.

Now it is obvious that, however elaborate the theory, many large assumptions have to be made in determining the combined effect of (1), (2), and (3), and on these assumptions the whole resulting edifice must stand or fall.

In my investigations I tried to avoid the pit-fall of the practical application to the gun until I was entirely satisfied that I had determined the law of burning by parallel surfaces in a closed vessel of constant capacity. This paper, then, is a description of the methods I have used and the results I have arrived at in my investigations. A considerable amount of laborious arithmetical calculation has been involved, and I desire here to express my indebtedness to Captains A. R. IZAT and C. H. NEWCOMBE, Royal Artillery, who have rendered me valuable assistance in preparing the diagrams and in working out some of the calculations.

Description of the Apparatus used.

Fig. 1 shows a section of the type of closed vessel used. The pressure is registered by the compression of the copper A by the piston B. This piston carries a pen C which traces its movement on blackened paper carried on a revolving drum D (shown in fig. 2). E is a valve for releasing the gases from the vessel after firing. F shows the arrangements for electrically firing the charge. The internal capacity of the vessel I used was 28·18 cubic inches, and its internal length and diameter were nearly equal. The type of vessel shown in fig. 1 is unsatisfactory, because its great length as compared with its diameter is liable to set up wave actions.

* GOSSOT and LIOUVILLE (tome XIII., 'Mémorial des Poudres et Salpêtres') have recently compared closed-vessel time rises with those calculated when using their factors. The results are not very satisfactory, I think.

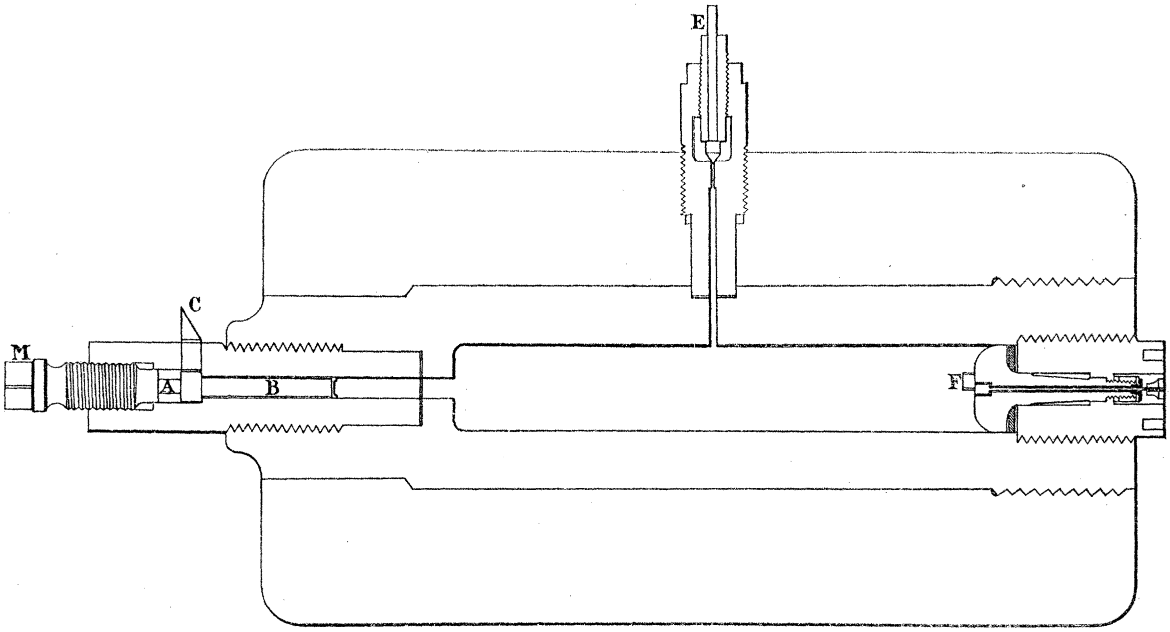


Fig. 1. Closed-vessel apparatus.

Fig. 2 shows the end view of the apparatus and the arrangement for recording the pressure and time.

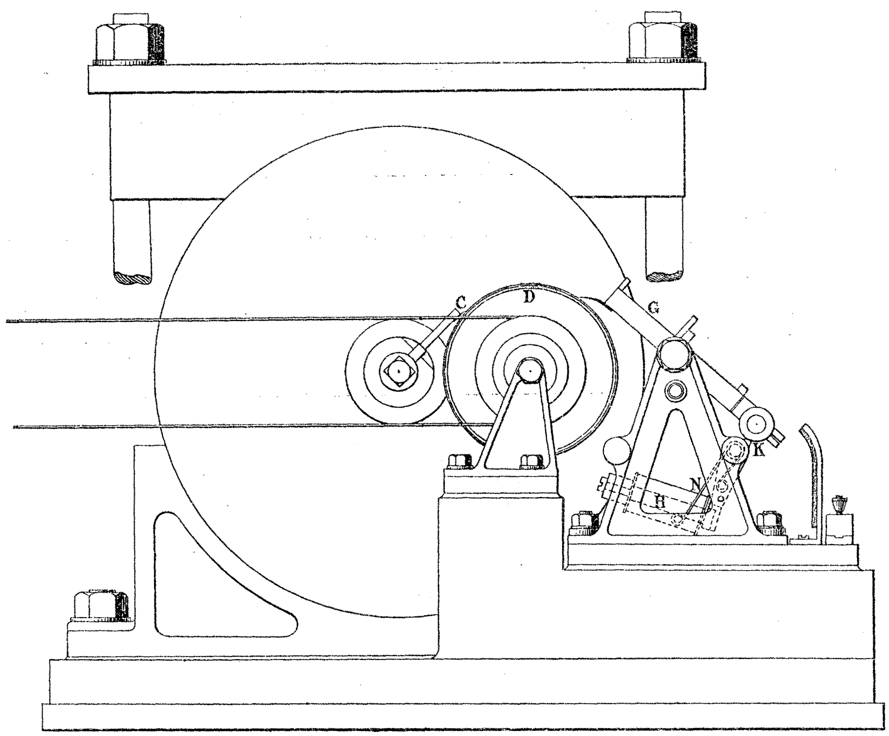
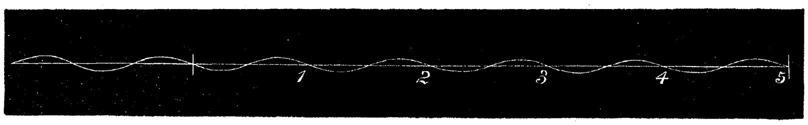


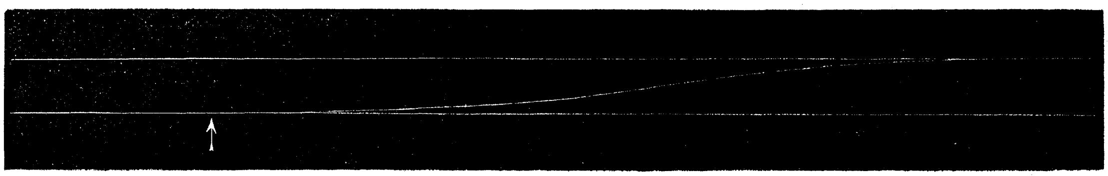
Fig. 2. End view of apparatus.

The drum D is driven by a motor and carries blackened paper on its periphery. G is an electrically sustained tuning-fork of the ordinary Sébert type. The one used in these experiments made 500 vibrations a second. The electro-magnet H and cam K are for the purpose of momentarily allowing the stylus on the end of the tuning-fork to trace a record on the drum and so give its speed—the spring N pulling the arm O (which carries the cam) away from the electro-magnet.

The use of the apparatus is as follows :—The charge having been placed in the vessel, the copper is placed in position and M is screwed home. The stylus on C is then adjusted on the drum, as is also the stylus on G in the position of release. The circuit of the electro-magnet H is carried by an adjustable joint to C in such a manner that the circuit is broken by the first movement of C as the copper compresses. The circuit being complete, the electro-magnet holds the arm O and lifts the stylus off the drum. When the circuit is broken the arm O is revolved by the spring N, and the cam K thus lowers the stylus G on to the drum and then lifts it off again. We thus obtain a record of the speed of the drum at the actual moment of firing. All being ready, the drum D is set in motion by the motor, whose speed can be regulated by a rheostat. The tuning-fork is started in the usual way, and the charge is then fired.

An example of an actual record is subjoined. These records are measured under a micrometer with a telescopic eye-piece carrying cross wires, the telescope being carried on a compound lathe rest. It measures centimetres to four places of decimals in both directions of movement.





Characteristics of the Explosive.

1. *Relation of Pressure and Density.*—The first step in the investigation of the burning of an explosive is to find the relation between the maximum pressure and the density at which the explosive is fired. The explosive I have experimented with is the latest British one, known as modified cordite. The Service abbreviation for this is M.D. cordite, and it will be so called throughout this paper, the original type of cordite being referred to as Mark I. In a closed vessel the maximum pressure is independent of the temperature of the cordite, but temperature has an influence on the time taken by the cordite to develop that pressure. The higher the temperature

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the quicker the time rise of pressure. In the gun, therefore, the temperature of the cordite has an influence on ballistics, since at a higher temperature, the pressure being raised more quickly, the projectile has less time in which to move forward; consequently there is a smaller space behind the projectile at times of equal developments of gas, and higher pressures are therefore realised. Temperature, therefore, is of no importance in determining the pressure-density relation, but is all-important in the investigation of time rises. I am not clear that other investigators have borne this in mind—their publications take no note of the fact.

The pressure-density relation of M.D. cordite is shown graphically on fig. 3, and is tabulated in Table A.

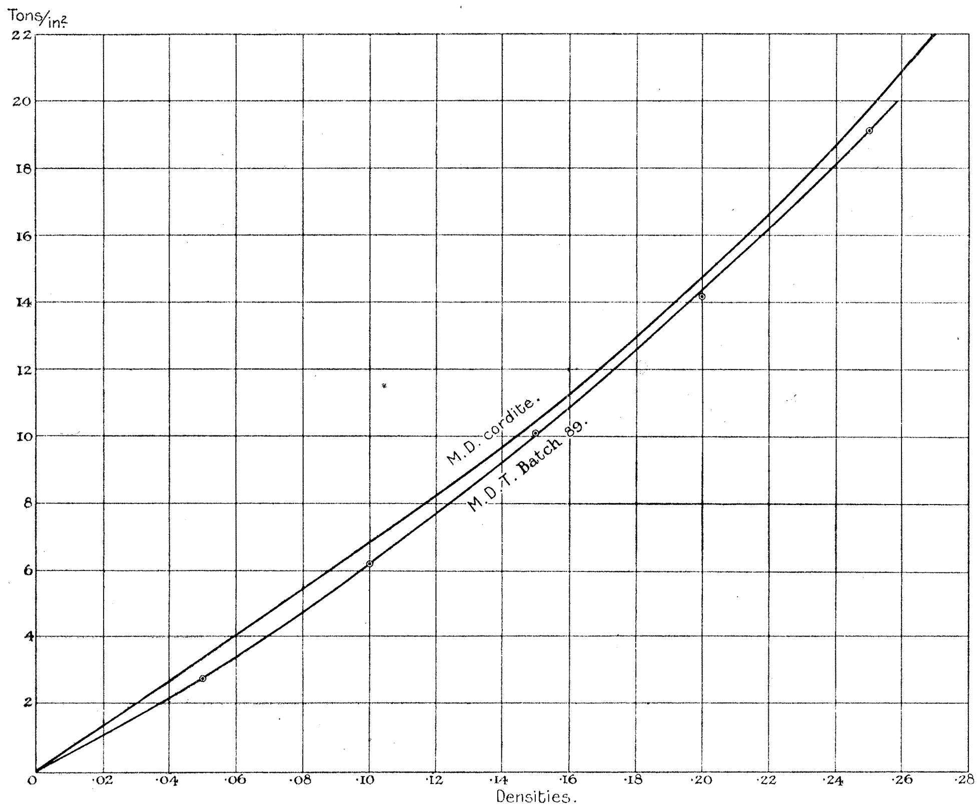

Fig. 3. Pressures and densities, M.D. cordite.

The equation connecting the two variables is

$$P = 360\Delta^3 - 54\Delta^2 + 69{\cdot}8\Delta,$$

where P is the pressure in tons on the square inch, and Δ is the gravimetric density of loading. Since artillerists work with the lb. as the unit of weight and the cubic inch as the unit of volume, and since 1 lb. of water occupies 27·73 cubic inches at 60° F., density is given by the formula 27·73 × weight of charge in lbs. ÷ capacity in cubic inches, and is then known as the gravimetric density.

The cubical form of this equation is of interest when one compares it with VAN DER WAALS' general equation

$$\left(p+\frac{a}{v^2}\right)(v-b) = \mathrm{RT},$$

which may be written

$$p\,(1-b\Delta) = ab\Delta^3-a\Delta^2+\mathrm{RT}\Delta.$$

It would appear, then, that in any general deduction of a pressure-density relation from VAN DER WAALS' equation omission of the term a/v^2 is not justified. PETAVEL neglected this term in his investigation of Mark I cordite.*

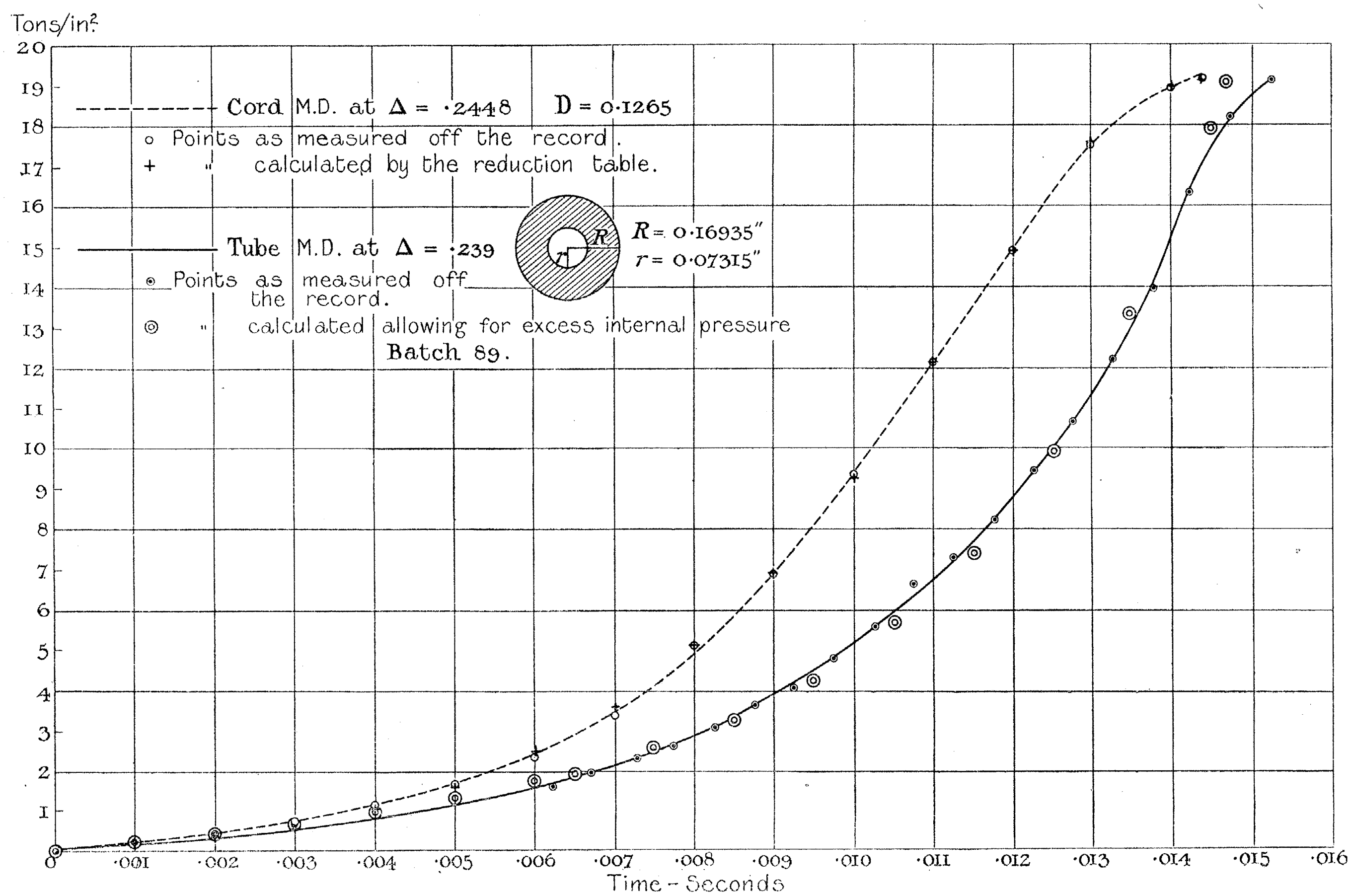

Fig. 4. Time rise of pressure, cord and tube M.D.

Cordite in manufacture is made in lots, and the above pressure-density relation is true of the general run of the cordite. In the earlier stages of the manufacture of some experimental forms of M.D. cordite the pressure-density relation was different. This may have been due to slightly different chemical constitution, to the presence of an excess quantity of volatile matter, or to minor variations in manufacture. The point is unimportant, because with experience in manufacture this variation disappears; but I mention it, as in one of the experiments I shall refer to later such an

* 'Phil. Trans.,' A, vol. 205, pp. 357–398.

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exceptional lot was used, and it will have to be referred to a special pressure-density curve.

2. *Investigation of the Time Rise of Pressure* (*Cord Form*).—M.D. cordite has been made in various forms, some of which are only experimental. As with Mark I cordite, the first form was cords; since that time tubes, strips, and double tubular forms have been made and experimented with.

The first time rises I investigated were, then, of M.D. cordite in the cord form. A time rise of such a cord, measuring 0·1265 inch in diameter, fired at 80° F. at a density of 0·2448, is shown on fig. 4. The close agreement of this beautiful curve with the points actually measured by the apparatus used in the experiment is an indication of the accuracy of the arrangements. Having obtained this time rise, the next step was the investigation of the law of combustion by parallel surfaces.

The method employed was the following:—Intervals of 0·001 second were worked to. From the curve the pressure at 0·001–0·002, &c. second was obtained. This pressure corresponds to a certain density of gas obtained from Table A. Now this gas is produced by a small reduction dr in the radius r of the cord, in other words, a skin or lamina is burnt off and converted into gas. The available capacity of the vessel for this quantity of gas is the total capacity less the volume occupied by the unburnt cordite. One has therefore only to solve for dr under these known conditions. This reduction dr then takes place in 0·001 second under an average pressure which is obtained from the time rise. The average pressures I have taken are those at half time in the interval. For instance, the average pressure during the first 0·001 second is the actual pressure shown on the curve at 0·0005 second. In actual practice, instead of working on the reduction of radius I have worked on the reduction of diameter.

Fig. 5 shows the results of this calculation for fig. 4 plotted in terms of reduction in diameter and pressure. This figure also shows the lines I have selected to represent the relation at temperatures of 60° F. and 80° F.

It appears quite clear that the relation is expressed by a straight line, and that therefore the power n is unity. The equation to the lines is of the form $S = aP + C$, a varying with the temperature of the cordite.

It is the existence of this constant C which has not been suspected before, and which, I think, shows the danger of assuming an equation of a theoretically perfect form and then trying to deduce constants by trial and error.

The meaning of the constant C can only be that below about 0·1 ton pressure the law of reduction in diameter does not hold. Obviously, when $P = 0$, S cannot equal C.

The cause of this change of law is, I suggest, that until some definite pressure is attained in the vessel true explosion does not commence. I advance the following explanation:—When the charge is first ignited, only the cordite in immediate contact with the igniter commences to burn. Cordite being a bad conductor of heat, this burning does not run along the cordite rapidly. This can easily be seen by burning cordite in the air, when it burns slowly along its length in the manner of slow-match and the flash is not rapidly transmitted as with gunpowder. Consequently, in the vessel the lighted ends of the cords burn non-explosively until such time as the vessel is completely filled with flame at a high temperature. At that moment there

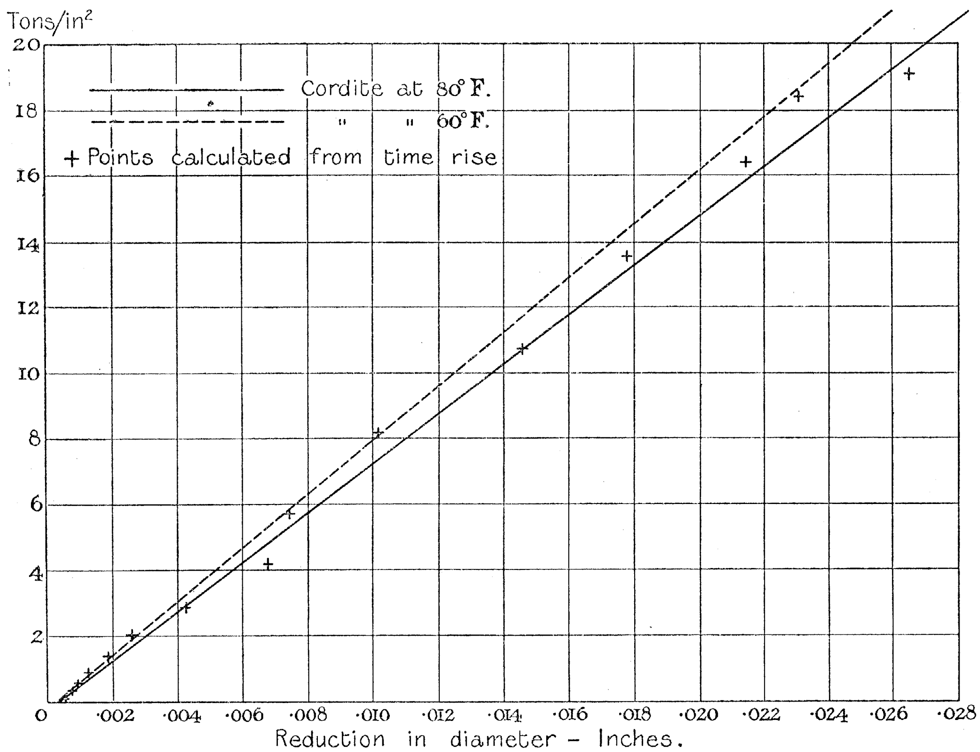

Fig. 5. M.D. cordite—reduction in diameter in 0·001 second when burning under a given average pressure.

is a definite pressure in the vessel which tends to separate the cords one from another. The cords now are lighted over their whole length and the true time of combustion by parallel surfaces commences. The constant C is thus due to the amount of gas produced by combustion of the ends of the sticks, when regarded as if produced by combustion over the whole length of the stick. The error introduced into the length of the sticks by this assumption is insignificant and can be neglected.

If this explanation is correct, one would expect the amount of cordite burnt previous to complete ignition of the charge to be independent of the temperature. That this is so was experimentally determined before the theoretical explanation of the constant suggested itself to me. Undoubtedly the time to complete ignition is different with change of temperature of the cordite, but this does not affect the ultimate time rise. Its sole effect is a small variation in the hang-fire of the charge. Theoretically the constant C must vary with the density of loading. It has been determined at a density of 0·25, and the small variation at lower densities does not affect the general accuracy of the calculation.

3. *Reconciliation of the Law of Reduction.*—Now the equation for reduction in diameter in 0·001 second at 80° F. has been determined as

$$\text{Redn.} = 0{\cdot}0013361 \times P + 0{\cdot}00028,$$

where P is the pressure in tons on the square inch.

At 60° F. the equation is

$$\text{Redn.} = 0{\cdot}001223 \times P + 0{\cdot}00028.$$

Both these results are tabulated in Tables B and C. In order to justify the selection of the lines shown on fig. 5 as representing the above relations, I have calculated the time rise of pressure of the charge of Cord M.D. shown in fig. 4, using Tables A and B. The calculated points are shown on fig. 4, and below I tabulate the results for comparison :—

Time, second.	Pressure in tons/inch².	
	As measured from the record.	As calculated.
0·001	Not definitely measurable	0·17
0·002	0·4	0·32
0·003	0·7	0·57
0·004	1·1	1·01
0·005	1·65	1·61
0·006	2·37	2·47
0·007	3·4	3·56
0·008	5·05	5·08
0·009	6·95	6·98
0·01	9·35	9·3
0·011	12·1	12·07
0·012	14·95	14·95
0·013	17·5	17·57
0·014	18·95	18·99
0·014345	—	19·1
0·0144	19·15	—

The variations in pressure are within the limits of experimental error, and the difference in total time of combustion is only 0·000055 of a second.

4. *Investigation of the Time Rise of Pressure* (*Tube Form*).—Fig. 6 shows the time rise of pressure of a certain sample of Tube M.D. Cordite (Batch 88). This class of cordite is known as M.D.T., and one of the governing factors of its rate of burning is the thickness of its annulus. On the same figure I show the calculated time rise of pressure of this sample, using the law I have established.

It is evident by inspection that the M.D.T. time rise does not directly follow the cord law of reduction in diameter. The rise of pressure at the beginning is much more rapid than when calculated as for cords. This difference presented a problem full of great difficulties and which I sought to solve for a long time at the expense of most laborious arithmetical calculations before I arrived at the solution which I now put forward.

Certain phenomena in connection with the burning of M.D.T. have always been apparent and indicated the lines on which I must work. If a stick of M.D.T. be

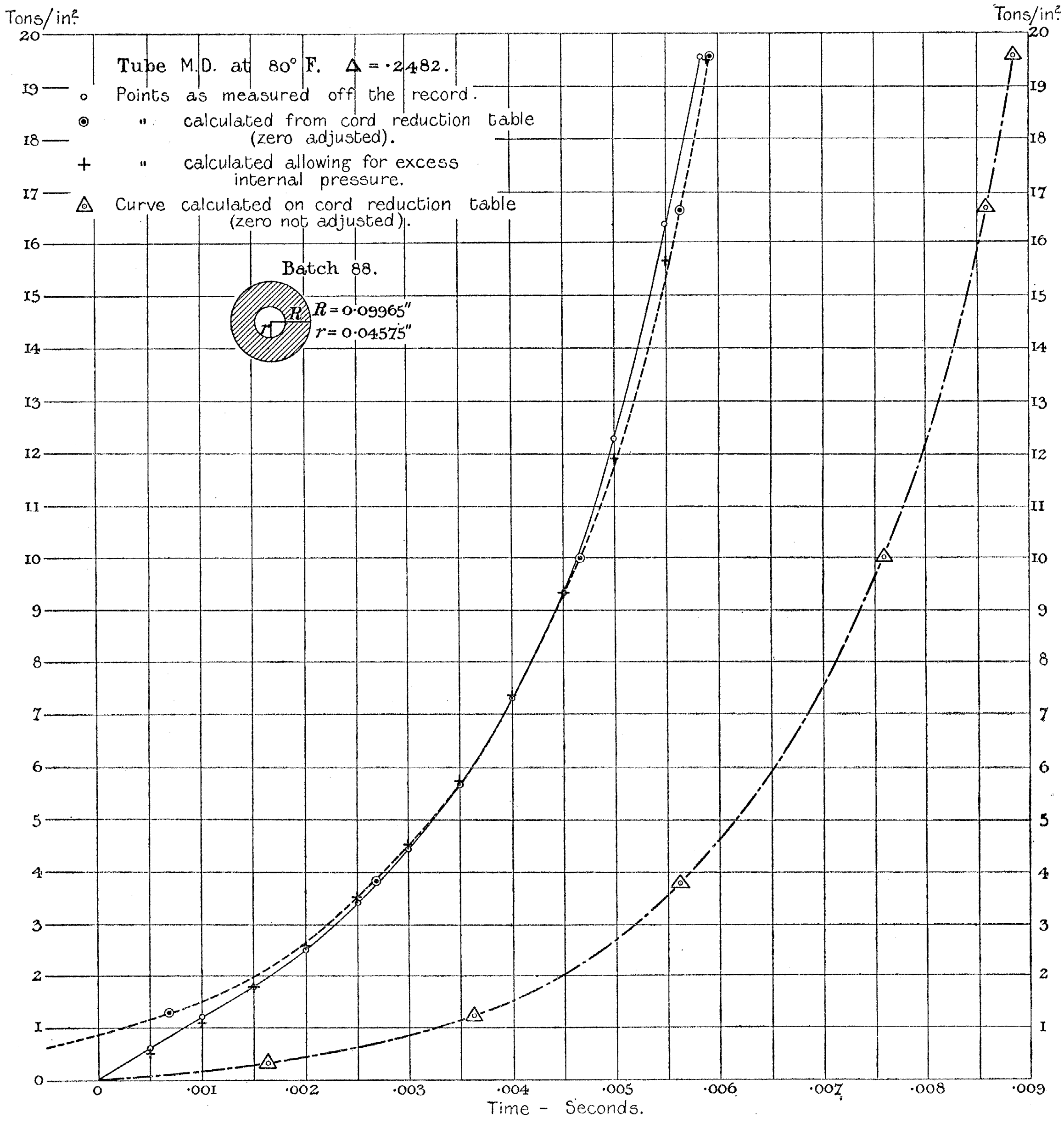

Fig. 6. Time rise of pressure—Tube M.D. at 80° F.

ignited in the open air the burning does not proceed regularly, but is accompanied by a succession of reports, the tube at the same time being projected about. The action, in fact, is very similar to that of the "cracker" firework.

Now these explosions and jumps are due to the formation of gas inside the tube at a quicker rate than it can get away at atmospheric pressure. The pressure inside the tube therefore rises to some point at which it bursts out explosively, the tube at the same time being projected in an opposite direction. This action goes on to such an extent that holes are often blown through the walls of the tube.

On firing M.D.T. in a gun, when any unconsumed is blown out I have often found tubes with these holes or splits in their walls. The distance between these holes is generally exceedingly regular. It is therefore clear that under certain conditions an excess pressure exists inside the tube, even when burning under pressure, *i.e.*, explosively.

Now, from the nature of my law of reduction, it follows that if an excess pressure exists inside the tube more cordite will be burnt in a given time. There is thus a reaction of cause and effect, and the internal excess pressure of itself tends to raise the inside pressure more rapidly. When the gas so formed escapes into the vessel it in turn raises the pressure existing in the vessel, and an increased rate of combustion is the consequence.

The time rise on fig. 6 very clearly shows this acceleration of the rate of burning. Since I saw no reason why there should be a departure from my fundamental law, my efforts were directed to determining what the excess internal pressure was and on what it depended. The principle adopted was as follows :—

The time rise gives the average and end pressure of any interval. The outsides of the tubes are burning under the cord law and produce a certain quantity of gas in the interval which can be calculated. The total amount of gas produced is known from the end pressure. The difference between these two amounts of gas has come from the inside of the tube, and hence the amount of cordite burnt from the inside can be calculated. Referring to Table B, we determine what pressure the inside of the tube must have been burning under to consume that amount of cordite in the time. From this the excess internal pressure is calculated.

The results of the calculation for Batch 88 are subjoined :—

Time, second.	During the 0·0005 second interval.		
	Average pressure in the vessel, tons/inch².	Excess pressure in the tube, tons/inch².	Total internal pressure in the tube, tons/inch².
0·0005	0·16	4·39	4·55
0·0010	0·83	5·58	6·41
0·0015	1·45	1·95	3·40
0·0020	2·09	− 1·34 (deficit)	0·75
0·0025	2·90	1·81	4·71
0·0030	3·87	1·28	5·15
0·0035	5·04	0·57	5·61
0·0040	6·41	− 0·53 (deficit)	5·88

Now the first results of this calculation are not at all obvious. But by adjusting the zero of the curve calculated on the cord law and comparing it with the actual record it seemed possible that at some point, to be determined, excess internal pressure disappeared and the tubes then burnt in strict accordance with the law in Table B. In adjusting the calculated curve so that its general lie was in closest agreement with the measured one, I found they crossed at about 5·7 tons. It then seemed that if internal excess pressure disappears at any point it must start at some maximum. A simple way of considering the decrease of excess internal pressure from a maximum to zero is to consider that the internal pressure in the tube is

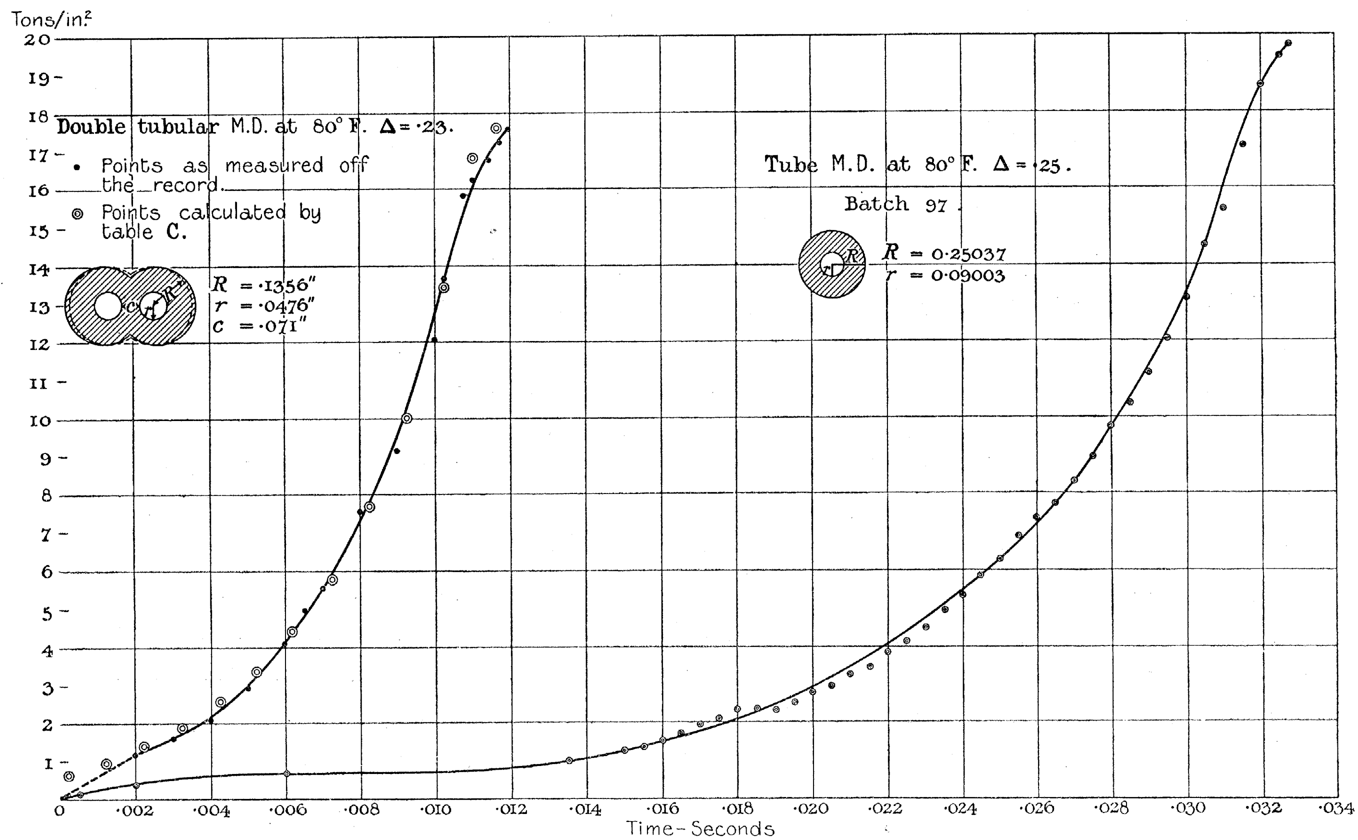

Fig. 7. Time rise of pressure.

a constant until the pressure in the vessel reaches that given pressure. From that moment internal and external pressures will be equal.

Referring to the tabulated results of total internal pressure, it will be seen that the average of the pressures given is 4·56 tons. This was the first pressure tried, but a better result was given assuming 4·85 tons.

The calculation, then, was made on the assumption that the internal pressure was 4·85 tons up to the moment at which the pressure in the vessel reached that figure. The external and internal diameters of the tubes at that moment are given by the calculation which then proceeds on the assumption that the internal and external pressures are equal.

The points obtained by this calculation are shown on fig. 6. Their general agreement with the measured curve is not so close as one would wish; but for a first attempt they appeared to support the idea that there are two phases in the combustion of a tubular propellant: (1) when excess pressure exists inside the tube, and (2) when this excess pressure disappears. Another batch, No. 97, was then tried. Its time rise is shown on fig. 7. The calculation gave:—

Time, second.	During the interval.		
	Average pressure in the vessel, tons/inch².	Excess pressure in the tube, tons/inch².	Total internal pressure in the tube, tons/inch².
0·0005	0·05	3·6	3·65
0·001	0·15	3·15	3·3
0·002	0·28	1·3	1·58
0·0025	0·38	0·56	0·94
0·003	0·43	−0·26 (deficit)	0·17
		Average internal P =	1·93 tons.

We now have two cases of calculated internal pressure, and the next point for consideration was: on what does this internal pressure depend? Looking at it from a theoretical point of view, it would seem to depend on the area of the hole and the length of the tube. The larger the hole the more readily can the gas get away. The longer the tube, for a given hole, the more difficult will be the escape of the gas.

In my closed-vessel experiments the cordite is cut to the internal length of the vessel to avoid the wave pressures which occur if the cordite is banked up at one end. The length variable does not therefore come in.

The internal radius and pressure of the two samples were:—

Batch.	Radius of hole.	Internal pressure.
88	0·04575	4·85
97	0·09003	1·93

Now, if internal pressure varies inversely as the area of the hole, the pressure of Batch 97 from Batch 88 would be given by $\frac{P}{4\cdot85} = \left(\frac{0\cdot04575}{0\cdot09003}\right)^2$; and, from this, P would be 1·25 tons against 1·93 tons found by the calculation. Having regard to the great variations which may be caused in my calculations by small experimental errors, this result was not as discouraging as it appears on the face of it.

On fig. 4 (lower curve) is shown the time rise and particulars of another batch of M.D.T., No. 89. This batch was one of the exceptional batches I have previously referred to, and did not show the same pressure density relation as the average run of M.D. cordite. The pressure density curve for this batch is shown on fig. 3 (lower curve).

Having obtained the time rise, I tested my theories by calculating a time rise under the two-phase condition I have explained.

The internal pressure, if proportional to the inverse ratio of the area of the holes, is 1·896 tons, using Batch 88 as the standard. The points of this calculated time rise are shown on fig. 4 (lower curve), and, except at the end of the rise, show a very close agreement with the actual condition of affairs.

The end of the rise shows disagreement. But if the actual rise of Batch 89 be compared with the others, it will be seen that the falling away of Batch 89 is a most exceptional condition of affairs for M.D.T. Whether the falling away was due to experimental errors or to some chance peculiarity of an exceptional sample I was not able to determine, as there was no more of the batch left.

The determination of the length influence on internal pressure requires a closed vessel of different dimensions, and I have not dealt with this aspect.

From the visible behaviour of M.D.T. when burning in air it is obvious that special actions are taking place. I venture to think that the calculations and experiments I here set forth support the theory that in the combustion of tubular propellants there are two distinct phases: the first when excess pressure exists inside the tube, and the second when internal excess pressure has ceased. With such a complicated problem it is clear that those investigators who have only had tubular forms of propellants to deal with would be faced with a most intractable problem in endeavouring to discover the true law of combustion by parallel surfaces. It is this difficulty which in part accounts for the various formulas which have been advanced.

Another somewhat important consideration is that, if you assume an equation of the form $S = \alpha P^n$ for a tubular propellant, all tubes that have the same annulus should give the same ballistics. It seems clear from experimental firings in guns that the size of hole for a given annulus has an influence on ballistics. There is no explanation of this fact in the simple equation formula, but it is at once explained by the system of calculation which I have here set forth. The system also explains the splits in the tubes and all the various phenomena connected with the combustion of tubular propellants.

At the same time it is possible to obtain also for tubes a reduction equation of the form Redn. $= \alpha P + C$. I originally obtained an equation of this form, which is set out in Table D. By this table I am able to calculate time rises very approximately with various tubes. But it is liable to break down, gives no explanation of the various phenomena, and is scientifically unsatisfactory in that there is no reason why the fundamental law of reduction should differ for tubes from cords.

Whilst admitting that Table D is merely an expedient, it offers the advantage of being quicker to work with, and the results are fairly consistent with the tubes as supplied.

5. *Investigation of the Time Rise of Double Tubular M.D. Cordite.*—It will be clear from a slight consideration that with the propellant in the cord form a decreasing surface is exposed as combustion proceeds. With the tube form an approximately constant surface is exposed. If it were not for excess internal pressure the surface would actually be constant. For if dr is the skin burnt at any time, and R and r the external and internal radii, the original surface is proportional to $2\pi(R+r)$; so when a skin dr is burnt the surface is proportional to $2\pi\{(R-dr)+(r+dr)\} = 2\pi(R+r)$.

Without going deeply into the science of internal ballistics it will be apparent that the longer maximum pressure can be sustained in the gun the greater will be the efficiency of that gun for a given length as regards muzzle velocity. Of course, there are limiting conditions as regards the capability of the gun to withstand this sustained maximum pressure, but such considerations are outside the scope of this paper. Speaking generally, however, there may be advantages in sustaining the maximum pressure in a gun. Now a double tubular form will present an increasing surface as combustion proceeds, and this will tend to sustain the maximum pressure in the gun.

The time rise of pressure of a sample of a double tube is shown on fig. 7 (left-hand curve). The dimensions of this double tube are given on the figure, the firm lines showing the actual shape which in manufacture had not come out as true arcs of circles. A mean circle was therefore determined for the purpose of calculation, and the adjusted double tube is shown by the dotted lines.

With the view of showing the results given by Table D, I have calculated the time rise of the double tube, using that table. The calculated points are shown on the figure. It will be seen that there is a very close agreement in the curves, except at the beginning. The error at the beginning is, of course, due to the excess internal pressure effect being greater with the double than with the single tube.

The American powder is a multitubular one, that is, short cylinders pierced with a number of holes. Excess internal pressure would have a very magnified effect on such a powder, and this, I think, accounts for the wide difference in value of the exponent of P as used by INGALLS.

Conclusion.

In the foregoing I have, after giving the reconciliation of my law for the cord form, confined myself to the cases where it apparently fails. I have endeavoured to show the cause of the failure and at the same time present the solution. I have not given examples of time rises of the strip form, for with them there is no disturbing cause so long as manufacture is not varied.

Undoubtedly it would be a great convenience in working if the integration of these curves were possible. Much thought has been given by different investigators in the past to this problem and much mathematical ingenuity has been displayed. But in these problems one does not obtain expressions which are directly integrable, and assumptions and approximations have necessarily to be made. Such approximations give exceedingly good results within limits, but when one comes to their application to the gun, and its many variables, the limits are so widened that a break-down under certain conditions is an ever-present danger.

I have, therefore, preferred to follow the system adopted by Mr. Bashforth in his calculations of extended trajectories, that is to say, I break up my time-rise curves into small arcs, and, assuming a mean pressure for the interval, find from the calculated end pressure if my assumption has been correct. If not, I have now a guide to the mean pressure to assume, and so on. In this manner each arc can generally be calculated in three trials, and with practice many arcs are obtained at the first attempt.

The application of this law to the practical case of the gun is outside the scope of this paper, and it is obviously undesirable to publish such investigations in connection with English ordnance.

For reasons which I have alluded to, the application to the gun presented more complications than the experiments which I have here outlined.

Having adopted certain frictional laws for the gun, based on the law of burning which I now put forward, I have found that the application holds over a very wide range of varying conditions of loading and calibre, when using cords which is the form with which we have most experience. There can be no higher test than this of the fundamental truth of the law.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

TABLE A.—Pressures and Densities, M.D. Cordite.

Density.	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.
0·00	0·00	0·06	0·13	0·20	0·27	0·34	0·41	0·48	0·55	0·62
0·01	0·69	0·76	0·83	0·90	0·97	1·04	1·11	1·18	1·25	1·32
0·02	1·38	1·45	1·52	1·59	1·66	1·73	1·80	1·87	1·94	2·00
0·03	2·06	2·13	2·20	2·27	2·34	2·41	2·48	2·55	2·61	2·67
0·04	2·73	2·80	2·87	2·94	3·01	3·08	3·15	3·22	3·28	3·34
0·05	3·40	3·47	3·54	3·61	3·68	3·75	3·82	3·89	3·95	4·01
0·06	4·07	4·14	4·21	4·28	4·35	4·42	4·49	4·56	4·62	4·68
0·07	4·74	4·80	4·86	4·93	5·00	5·07	5·14	5·21	5·28	5·35
0·08	5·42	5·48	5·55	5·62	5·69	5·76	5·83	5·90	5·97	6·03
0·09	6·11	6·17	6·24	6·31	6·38	6·45	6·52	6·59	6·66	6·73
0·10	6·80	6·87	6·94	7·01	7·08	7·15	7·22	7·29	7·36	7·43
0·11	7·50	7·57	7·64	7·71	7·78	7·85	7·92	7·99	8·06	8·14
0·12	8·22	8·29	8·36	8·43	8·50	8·57	8·64	8·71	8·79	8·87
0·13	8·95	9·02	9·09	9·16	9·23	9·30	9·38	9·46	9·54	9·62
0·14	9·70	9·77	9·84	9·91	9·99	10·07	10·15	10·23	10·31	10·39
0·15	10·47	10·54	10·62	10·70	10·78	10·86	10·94	11·02	11·10	11·18
0·16	11·26	11·34	11·42	11·50	11·58	11·66	11·74	11·82	11·90	11·98
0·17	12·07	12·15	12·23	12·31	12·39	12·47	12·55	12·64	12·73	12·82
0·18	12·91	12·99	13·07	13·15	13·24	13·33	13·42	13·51	13·60	13·69
0·19	13·78	13·87	13·96	14·05	14·14	14·23	14·32	14·41	14·50	14·59
0·20	14·68	14·77	14·86	14·95	15·04	15·13	15·22	15·31	15·41	15·51
0·21	15·61	15·70	15·79	15·88	15·97	16·07	16·17	16·27	16·37	16·47
0·22	16·57	16·67	16·77	16·87	16·97	17·07	17·17	17·27	17·37	17·47
0·23	17·58	17·68	17·78	17·88	17·98	18·08	18·18	18·29	18·40	18·51
0·24	18·62	18·72	18·82	18·93	19·04	19·15	19·26	19·37	19·48	19·59
0·25	19·70	19·81	19·92	20·03	20·14	20·25	20·36	20·47	20·58	20·70
0·26	20·82	—	—	—	—	—	—	—	—	—

TABLE B.—M.D. Cordite. Reduction in Diameter at 80° F. in 0·001 second.

Pressure.	0·0.	0·1.	0·2.	0·3.	0·4.	0·5.	0·6.	0·7.	0·8.	0·9.
tons										
0	—	0·00041	0·00055	0·00068	0·00082	0·00095	0·00109	0·00122	0·00136	0·00149
1	0·00162	0·00175	0·00188	0·00201	0·00214	0·00228	0·00241	0·00255	0·00268	0·00282
2	0·00295	0·00309	0·00322	0·00336	0·00349	0·00362	0·00376	0·00389	0·00402	0·00415
3	0·00428	0·00442	0·00455	0·00469	0·00482	0·00495	0·00509	0·00522	0·00536	0·00549
4	0·00562	0·00576	0·00589	0·00603	0·00616	0·00629	0·00643	0·00656	0·00670	0·00683
5	0·00696	0·00710	0·00723	0·00737	0·00750	0·00763	0·00777	0·00790	0·00804	0·00817
6	0·00830	0·00844	0·00857	0·00870	0·00883	0·00896	0·00910	0·00923	0·00937	0·00950
7	0·00963	0·00977	0·00990	0·01004	0·01017	0·01030	0·01044	0·01057	0·01071	0·01084
8	0·01097	0·01111	0·01124	0·01138	0·01151	0·01164	0·01178	0·01191	0·01204	0·01217
9	0·01230	0·01244	0·01257	0·01271	0·01284	0·01297	0·01311	0·01324	0·01338	0·01351
10	0·01364	0·01378	0·01391	0·01405	0·01418	0·01431	0·01445	0·01458	0·01472	0·01485
11	0·01498	0·01512	0·01525	0·01538	0·01551	0·01564	0·01578	0·01591	0·01605	0·01618
12	0·01631	0·01645	0·01658	0·01672	0·01685	0·01698	0·01712	0·01725	0·01739	0·01752
13	0·01765	0·01779	0·01792	0·01806	0·01819	0·01832	0·01846	0·01859	0·01873	0·01886
14	0·01899	0·01913	0·01926	0·01939	0·01952	0·01965	0·01979	0·01992	0·02006	0·02019
15	0·02032	0·02046	0·02059	0·02073	0·02086	0·02099	0·02113	0·02126	0·02140	0·02153
16	0·02166	0·02180	0·02193	0·02206	0·02219	0·02232	0·02246	0·02259	0·02273	0·02286
17	0·02299	0·02313	0·02326	0·02339	0·02353	0·02366	0·02380	0·02393	0·02407	0·02420
18	0·02433	0·02447	0·02460	0·02474	0·02487	0·02500	0·02514	0·02527	0·02541	0·02554
19	0·02567	0·02581	0·02594	0·02607	0·02620	0·02633	0·02647	0·02660	0·02674	0·02687
20	0·02700	—	—	—	—	—	—	—	—	—

TABLE C.—M.D. Cordite. Reduction in Diameter at 60° F. in 0·001 second.

Pressure.	0·0.	0·1.	0·2.	0·3.	0·4.	0·5.	0·6.	0·7.	0·8.	0·9.
tons										
0	—	0·00035	0·00048	0·00061	0·00074	0·00088	0·00101	0·00113	0·00126	0·00138
1	0·00150	0·00163	0·00175	0·00187	0·00199	0·00211	0·00224	0·00236	0·00249	0·00261
2	0·00273	0·00286	0·00298	0·00310	0·00322	0·00334	0·00347	0·00359	0·00371	0·00383
3	0·00395	0·00408	0·00420	0·00432	0·00444	0·00456	0·00469	0·00481	0·00493	0·00505
4	0·00517	0·00530	0·00542	0·00554	0·00566	0·00578	0·00591	0·00603	0·00615	0·00627
5	0·00639	0·00652	0·00664	0·00676	0·00688	0·00700	0·00713	0·00725	0·00738	0·00750
6	0·00762	0·00775	0·00787	0·00799	0·00811	0·00823	0·00836	0·00848	0·00860	0·00872
7	0·00884	0·00897	0·00909	0·00921	0·00933	0·00945	0·00958	0·00970	0·00982	0·00994
8	0·01006	0·01019	0·01031	0·01043	0·01055	0·01067	0·01080	0·01092	0·01105	0·01117
9	0·01129	0·01142	0·01154	0·01166	0·01178	0·01190	0·01203	0·01215	0·01227	0·01239
10	0·01251	0·01264	0·01276	0·01288	0·01300	0·01312	0·01325	0·01337	0·01349	0·01361
11	0·01373	0·01386	0·01398	0·01410	0·01422	0·01434	0·01447	0·01459	0·01472	0·01484
12	0·01496	0·01509	0·01521	0·01533	0·01545	0·01557	0·01570	0·01582	0·01594	0·01606
13	0·01618	0·01631	0·01643	0·01655	0·01667	0·01679	0·01692	0·01704	0·01716	0·01728
14	0·01740	0·01753	0·01765	0·01777	0·01789	0·01801	0·01814	0·01826	0·01838	0·01850
15	0·01862	0·01875	0·01887	0·01899	0·01911	0·01923	0·01936	0·01948	0·01961	0·01973
16	0·01985	0·01998	0·02010	0·02022	0·02034	0·02046	0·02059	0·02071	0·02083	0·02095
17	0·02107	0·02120	0·02132	0·02144	0·02156	0·02168	0·02181	0·02193	0·02205	0·02217
18	0·02229	0·02242	0·02254	0·02266	0·02278	0·02290	0·02303	0·02315	0·02328	0·02340
19	0·02352	0·02365	0·02377	0·02389	0·02401	0·02413	0·02426	0·02438	0·02450	0·02462
20	0·02474	—	—	—	—	—	—	—	—	—

TABLE D.—M.D. Tubular. Reduction in Annulus at 80° F. in 0·001 second.

Pressure.	0·0.	0·1.	0·2.	0·3.	0·4.	0·5.	0·6.	0·7.	0·8.	0·9.
tons										
0	—	0·00062	0·00076	0·00090	0·00104	0·00118	0·00132	0·00146	0·00160	0·00174
1	0·00188	0·00202	0·00216	0·00230	0·00244	0·00258	0·00272	0·00286	0·00300	0·00315
2	0·00329	0·00343	0·00357	0·00371	0·00385	0·00399	0·00413	0·00427	0·00441	0·00455
3	0·00469	0·00483	0·00497	0·00511	0·00525	0·00539	0·00553	0·00567	0·00582	0·00596
4	0·00610	0·00624	0·00638	0·00652	0·00666	0·00680	0·00694	0·00709	0·00723	0·00737
5	0·00751	0·00765	0·00779	0·00793	0·00807	0·00821	0·00836	0·00850	0·00864	0·00878
6	0·00892	0·00906	0·00920	0·00934	0·00948	0·00963	0·00977	0·00991	0·01005	0·01019
7	0·01033	0·01047	0·01061	0·01075	0·01090	0·01104	0·01118	0·01132	0·01146	0·01160
8	0·01174	0·01188	0·01202	0·01216	0·01230	0·01244	0·01258	0·01272	0·01286	0·01300
9	0·01314	0·01328	0·01342	0·01356	0·01370	0·01384	0·01398	0·01412	0·01426	0·01440
10	0·01454	0·01468	0·01482	0·01497	0·01511	0·01525	0·01539	0·01553	0·01567	0·01581
11	0·01595	0·01609	0·01624	0·01638	0·01652	0·01666	0·01680	0·01694	0·01708	0·01722
12	0·01736	0·01751	0·01765	0·01779	0·01793	0·01807	0·01821	0·01835	0·01849	0·01863
13	0·01878	0·01892	0·01906	0·01920	0·01934	0·01948	0·01962	0·01976	0·01990	0·02004
14	0·02018	0·02033	0·02047	0·02061	0·02075	0·02089	0·02103	0·02117	0·02131	0·02145
15	0·02159	0·02173	0·02188	0·02202	0·02216	0·02230	0·02244	0·02258	0·02272	0·02286
16	0·02300	0·02314	0·02328	0·02342	0·02356	0·02370	0·02384	0·02398	0·02412	0·02426
17	0·02440	0·02454	0·02468	0·02482	0·02496	0·02510	0·02524	0·02538	0·02552	0·02566
18	0·02580	0·02594	0·02608	0·02622	0·02636	0·02650	0·02664	0·02678	0·02692	0·02706
19	0·02720	0·02734	0·02748	0·02762	0·02776	0·02790	0·02804	0·02818	0·02832	0·02846
20	0·02860	—	—	—	—	—	—	—	—	—