IX. *Researches on Explosives.—Part IV.**

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[PLATES 10–19.]

IN Part III. of my 'Researches on Explosives' I gave the results of a very extensive series of experiments, the completion of which necessarily occupied a very long time, and the particular explosives with which I experimented were those with which artillerists in this country were familiar, and with which a considerable number of experiments had been made.

These explosives were (1) the cordite of the service known as Mark I; (2) the modified cordite known as M.D.; and (3) the nitrocellulose known as Rottweil R. R.

The experiments made by myself extended, for all the above explosives, from densities of 0·05 to 0·45 or 0·50, and pressures of from 2·75 tons per sq. inch (419 atmospheres) to pressures of 60 tons per sq. inch (9145 atmospheres), and although the transformation on ignition varied both with regard to the particular explosive employed and for each explosive as regards the density at which it was fired, yet when the observations were represented by curves drawn through or near the observed points there was a pretty close resemblance in the form of the curves, not only in respect to the variations in the quantities of the gases generated at the varied densities, but also with regard to the units of heat developed and the volumes of gas produced.

Certain anomalies, chiefly with reference to the temperature of explosion at different densities, having appeared, I was anxious to make experiments with other

* Small alterations are required in some of the figures given at the higher densities, owing to experiments which have been carried out at a density of 0·50 since the paper was prepared. The curves, however, have all been corrected to the later results.

explosives, and I have accordingly completed a similar examination of three other explosives, and the composition of the six explosives was approximately as follows :—

I.		II.	
Mark I cordite.	Percentage.	M.D. cordite.	Percentage.
Nitroglycerine	58·0	Nitroglycerine	30·0
Nitrocellulose	37·0	Nitrocellulose	65·0
Mineral jelly	5·0	Mineral jelly	5·0
III.		**IV.**	
Norwegian 165.	Percentage.	Norwegian 167.	Percentage.
Nitroglycerine	36·0	Nitroglycerine	40·0
Nitrocellulose	52·0	Nitrocellulose	50·0
Nitronaphthalene	6·0	Nitronaphthalene	5·0
Secret ingredient	6·0	Secret ingredient	5·0
V.		**VI.**	
Italian.	Percentage.	Nitrocellulose.	Percentage.
Nitroglycerine	47·1	Nitrocellulose (sol.)	85·5
Nitrocellulose (sol.)	52·3	Nitrocellulose (insol.)	14·5
Nitrocellulose (insol.)	0·6		

The results of my experiments with Explosives I., II. and VI. have been given in my 'Researches on Explosives,' Part III.,* and if reference be made to Plates 8, 9 and 10 in that paper, it will be seen how well, on the whole, the curves, showing the variation in the percentages of the gases, represent the observations. Similar curves, representing very accurately the observations, are now given for Explosives III., IV. and V. Some doubt might, however, be felt as to whether the transformation of the same explosive at the same density might be relied upon as being practically identical, and to test this point the following experiments were made :—

In Experiment 1586, a charge of Explosive III. at a density of 0·4 and pressure

* 'Phil. Trans.,' A, vol. 205, pp. 221, 222 and 223.

of 37·92 tons per sq. inch (5780 atmospheres) was fired, and analysis gave the percentage volumes of the permanent gases as follows :—

	Experiment 1586.	Experiment 1593.
	per cent.	per cent.
CO_2	33·10	33·00
CO	28·70	28·75
H	12·40	13·10
CH_4	10·85	10·55
N	14·95	14·60

The same experiment was repeated in Experiment 1593, the density being also 0·4, and the pressure 38·30 tons per sq. inch (5838 atmospheres), the results being for the sake of comparison placed alongside those of Experiment 1586.

These results I consider quite satisfactory, but the comparison with Explosive IV. was even closer.

In Experiment 1598 a charge of Explosive IV. was fired under a density of 0·4 and a pressure of 43·2 tons per sq. inch (6585 atmospheres), the percentage volumes of the permanent gases being :—

	Experiment 1598.	Experiment 1599.
	per cent.	per cent.
CO_2	34·40	34·40
CO	27·65	27·75
H	13·10	13·15
CH_4	8·98	8·95
N	15·87	15·75

In Experiment 1599 the same explosive was fired at the same density, the pressure being 40·76 tons per sq. inch (6213 atmospheres), and the percentage volumes are placed alongside those of the previous experiment. The two analyses are practically identical.*

When explosives are fired in a gun, the chamber in which the charge is placed is, of course, full of air, and in my experiments the charges were similarly treated.

With the view, however, of testing the difference due to the presence of air, I fired three charges of cordite all at a density of 0·05 (this density of course including the largest percentage of air), the three experiments being, first, with air; second, air exhausted; third, with an atmosphere of nitrogen.

The analysis gave the following results :—

* These results have been further confirmed by several other duplicate experiments.

	Experiment 1380.	Experiment 1520.	Experiment 1521.	
	Atmosphere of air.	Vessel exhausted.	Atmosphere of nitrogen.	Constituents other than nitrogen.
	per cent.	per cent.	per cent.	per cent.
CO_2	27·15	26·35	25·90	26·45
CO	34·35	35·05	34·90	35·70
H	17·50	19·50	18·45	18·85
CH_4	0·30	0·60	0·50	0·50
	79·30	81·50	79·75	81·50
N	20·70	18·50	20·25	—
	100·00	100·00	100·00	—
H_2O	2·65 grammes	2·51 grammes	2·52 grammes	—

The percentage of nitrogen is, of course, higher in Experiment 1521 than in 1520. After correcting in the former the other constituents for this difference, it will be noted from the last column that the experiment in nitrogen yielded slightly more carbon monoxide and slightly less hydrogen than did the charge fired in the exhausted vessel. The CO_2 and CH_4 are practically identical in the two experiments.

It may be interesting to compare the foregoing results with the analysis of the gases taken from the chamber of a 9·2-inch gun fired with a charge of 103 lbs. (46·71 kilos), giving a muzzle velocity of 2,600 f/s. (792·5 m/s.), and a pressure of 16·1 tons per sq. inch (2453 atmospheres).

As soon as possible after firing the muzzle of the gun was closed and the breech opened. An exhausted gas tube held in a special holder was introduced to the far end of the chamber, and one of its stop-cocks momentarily opened.

The analysis gave the following composition of the gases after deducting air : —

	Round 1.	Round 2.	Round 3. *	Round 4.
CO_2	25·7	25·4	26·0	26·5
CO	35·4	36·25	38·5	34·75
H	19·4	18·65	20·0	16·95
CH_4	0·7	0·3	0·5	0·3
N	18·8	19·4	15·0	21·5

* Results probably not very accurate owing to great dilution with air.

The samples for the first two rounds were taken so soon as the breech was opened, the last two after a dummy shot was rammed home. The composition of the gas after deducting the air is similar to that obtained by firing cordite at low densities in a closed vessel. It follows that atmospheric combustion had not taken place to any extent.

Although for the elucidation of the laws which govern the transformation of the explosives when fired I have taken the densities named, I must point out that the requirements of the artillerist are confined to much narrower limits, the density, of course, varying considerably with the particular explosive used.

In modern guns, for example, the chamber density varies from about 0·310 to nearly 0·500, a good deal of the variation being due to the nature of the explosive used. It is hardly necessary to point out to artillerists that the chamber density is not the density which is responsible for the pressure developed in the gun.

The difference, which is frequently very considerable, is due to the time taken by the explosive to burn, and this depends upon the nature, form, and dimensions of the explosive, the expansion suffered by the nascent gases and the heat lost, due to work done upon the projectile and by communication of heat to the gun, and under these circumstances the pressure developed would, with full charges if compared with close vessel pressures, represent densities approximately between 0·17 and 0·23.

The tables which are given in my late communication* to the Royal Society gave, for each particular density, the actual result observed. In the present paper the observations have been corrected by drawing curves to represent as nearly as possible the whole of the results, the actual observations, which are also given, showing in each case the departure from the curve. See Plates 10, 11, and 12.

If reference be made to the tables, or to the plates just mentioned, it will be observed how wide are the differences, not only in the absolute volumes of the several gases, but in the variations with reference to the densities at which they were fired.

Thus, for example, comparing Explosives III. and V. (Norwegian 165 and Italian ballistites, see Plate 10), while in the former the carbon monoxide commences at the density 0·05 with a percentage volume of 38·5, falling at a density of 0·45 to 22 per cent., the carbon dioxide commences with 13·3 per cent., rising rapidly to 31 per cent. In the latter explosive the CO commences at 20·5 per cent. and falls slowly to 15 per cent., while the CO_2 commences a little over 26 per cent., rising also comparatively slowly to nearly 34 per cent.

I may remark in passing that the Italian ballistite is the only explosive with which I have experimented, where, at low densities, the volume of CO_2 is greater than that of CO.

But there are in these two explosives other remarkable differences. Thus, in the Italian ballistite, at a density of 0·05, the volume of methane, CH_4, is a mere trace, about 0·02 per cent., but it remains very much lower than is the case with any other explosive, being only 1·9 per cent. at the density of 0·45. With the Norwegian, on the other hand, the CH_4, although the volume at commencement is only 0·4 per cent., is, at 0·45 density, 11 per cent.

Again, as might be expected from the large quantity of CH_4 found, in the case of

* 'Phil. Trans.,' A, vol. 205, pp. 221 to 223.

the Norwegian ballistite, the volume of hydrogen falls from over 20 per cent. to about 9 per cent., in the Italian the H rises from about 8 per cent. to about 10 per cent., falling slightly at higher densities.

In both explosives the N is practically constant at about 12 per cent. and 16 per cent. respectively, but there is a very great difference as regards the H_2O. In the Norwegian the H_2O is constant at 14 per cent., there being no greater difference than might be expected from errors of observation, while in the Italian the H_2O, which commences at density 0·05 with a volume of 29 per cent., falls at a density of 0·45 to about 24·5 per cent. No other explosive approaches the Italian ballistite in respect to the large volume of aqueous vapour formed, especially at low densities.

As regards the other explosives, the differences, although not so pronounced as those I have just quoted, are still remarkable. Thus, comparing Cordite Mark I and Norwegian 167 (see Plate 11), in the cordite the volume of CO_2 commences at 21 per cent., rising to $31\frac{1}{2}$ per cent. at $d = 0{\cdot}45$, while CO, commencing at $26\frac{1}{2}$ per cent., falls to $16\frac{1}{2}$ per cent., the two gases being of equal volume at a density of 0·19. In the case of Norwegian 167, the CO_2 commences at $15\frac{1}{2}$ per cent., rising to 31 per cent., while the CO, commencing at $35\frac{1}{2}$ per cent., rapidly falls to 21 per cent., the two gases being equal in volume at a density of about 0·34.

H_2O and N may, in both explosives, be regarded as nearly constant, H_2O being with the first at a volume of about 21 per cent., with the latter at a volume of about $15\frac{1}{2}$ per cent., N at volumes of approximately 15·3 per cent. and 13 per cent.

CH_4 rises from a trace in I. and IV. explosives to 5·5 per cent. in the case of cordite and to 9 per cent. in the case of the Norwegian, while the H falls from nearly 16 per cent. to 10·5 per cent. in I. and from 19 per cent. to 9·5 per cent. in the case of IV.

With respect, however, to Explosives II. and VI. (M.D. and nitrocellulose) there is, in the transformation, a remarkable similarity. In both explosives (see Plate 12) the CO_2 rises from about 15 per cent. to about $29\frac{1}{2}$ per cent., while the CO falls from about 35 per cent. to between 21 and 22 per cent., equal volumes being at the densities of about 0·32 and 0·36 respectively.

In both the marsh gas rises from a trace to about 9 per cent., while the hydrogen falls from about 20 per cent. to about 11 per cent. In both the H_2O and N are nearly constant, the H_2O being about 17 per cent. in each, while the N is about $12\frac{1}{2}$ per cent. with M.D., and about $11\frac{1}{2}$ with nitrocellulose.

In the tables are given the cubic centimetres per gramme of the permanent and total gases, and in Plate 13 are drawn curves representing for the six explosives the observations of these total volumes. It will be noted that in the case of the nitrocellulose and Norwegian ballistite 165 there is, with increasing density, a very considerable decrease in volume, but with the Italian ballistite throughout the range of the experiments there is hardly any change. The curves in this plate, it will be observed, are concave to the axis of abscissæ.

In the tables are shown the units of heat both for the water fluid and the water gaseous, and in Plate 14 are drawn curves of the units of heat, water gaseous, for the whole of the six explosives.

The Italian ballistite develops more heat than any of the other explosives, being a little higher than Mark I cordite. This is, of course, objectionable as regards erosion, but recently, when in Italy, I was informed that this heat had been greatly reduced by the incorporation of $12\frac{1}{2}$ per cent. of carbon.

I had already made some experiments with percentages of carbon, introduced as suggested by Lord RAYLEIGH.

The curves in this instance are all convex to the axis of abscissæ, and it is interesting to note that where the volume of gas per gramme is large the units of heat are low, and that where the volumes of gas are rapidly decreasing the curves representing the amount of heat developed show a rapid increase.

Thus, with the new explosives, the point to which I so often drew attention in the case of the great variety of the old gunpowders with which I experimented is confirmed, namely that, with an explosive, if ever a large volume of gas is formed the heat developed will be low, if a small volume be generated the heat developed will be high.

Coming now to the relation existing between the density of the charge and the pressure developed by the explosion, I have had some difficulty in regard to the abnormal pressures obtained with some explosives at high densities, but it must be remembered that the pressures to which I refer are very far above those with which artillerists are concerned, and do not materially affect the conditions of service of the propellants used in this or other countries.

If reference be made to the tables, or preferably Plate 19, it will be observed that, up to densities of 0·45, the Explosives I., II., and VI. are perfectly regular; there are no abnormal pressures in any of the three, and the curves fairly represent the observations. In the case of cordite, which has a considerably higher potential energy than the other two, I have, without any abnormal pressure, gone to densities of 0·5 and 0·55, representing pressures of 53 and 60 tons per sq. inch (8078 and 9145 atmospheres), but when M.D. and nitrocellulose were fired at the density of 0·5, the pressure of M.D. rose to 57 tons per sq. inch (8688 atmospheres) instead of the normal pressure, which should be about 49 tons per sq. inch (7469 atmospheres), and the pressure of the nitrocellulose rose to 56 tons per sq. inch (8535 atmospheres) instead of to what should have been the normal, about 47 tons per sq. inch (7164 atmospheres).

Referring again to the same plate, on which are also drawn curves representing the relation of pressure to density of Explosives III., IV., and V., it will be seen that, while the Italian ballistite follows approximately, up to a density of 0·45, the same law as rules in Explosives I., II., and VI., the two Norwegian ballistites show an abnormal, though small, increase in pressure when the density exceeds 0·3.

Norwegian 167, for example, gradually approaches the cordite pressure, and at the density of 0·45 apparently equals it.

The point now to be considered is: Are these slight increments of pressure in the Norwegian ballistites, and the much more abnormal increments in Explosives II. and VI. at densities of 0·5, real, or are they due either to partial detonation or to wave action on the crusher gauge during explosion?

Supposing there to be no detonation or violent motion of the gases, the pressure on the walls of the explosive cylinder should be dependent, in a vessel impervious to heat, solely on the quantity of gas produced and on the amount of heat generated by the explosion.

I have, therefore, calculated for the whole of the explosives the value of the products (volume of gas multiplied by units of heat water gaseous) and the results are shown in Plate 15.

It will be observed that the curves, which are very nearly straight lines, practically confirm the pressure curves of Explosives I., II., V. and VI., and they equally show that the abnormal pressures of II. and VI. at densities of 0·5 are not confirmed.

To test this latter point further, I repeated the experiments with M.D. and R.R. at the density of 0·5, so arranging the lighting of the charge that the rush of the nascent gases should not impinge directly on the crusher gauge. At the same time, to be certain that the transformation was the same, the usual course of analysing the products of explosion was followed. I give the results of R.R. as an illustration. It will be seen that the pressure indicated by the gauge was in this experiment normal, and, the transformation being the same, it follows that the high pressure obtained in the first experiment was due to wave action.

Experiment 1513.		Experiment 1607.	
Density	0·5	Density	0·5
	Tons per sq. inch.		Tons per sq. inch.
Pressure	56·00	Pressure	46·48
Atmospheres	8535	Atmospheres	7084
Permanent gases.	Percentage.	Permanent gases.	Percentage.
CO_2	38·75	CO_2	38·10
CO	24·75	CO	25·00
H	10·20	H	10·70
CH_4	12·00	CH_4	11·85
N	14·30	N	14·35

The repetition of the same density, 0·5, with M.D. was not so successful, the pressure not being considerably reduced.

I may point out also that the curves appear to show that the pressures determined at the very low densities are too small, although it is true this might have been

predicted. At low densities the small charge burns much more slowly, has a large percentage of air to heat up, and, from the slow burning, parts with a much greater percentage of heat to the walls of the explosion vessel.

The extraordinary rapidity with which the gases part with their heat may be appreciated if I mention that a charge of 32 grammes, giving rise to a pressure of close upon 8 tons (1219 atmospheres), parts with half of its heat to the walls of the explosion vessel in little more than half a second.

Since, with the Norwegian ballistites, there is a slight departure from previous experience, and from the pressures indicated by multiplying the volume of gas by the heat generated for densities higher than 0·3, I have shown for these explosives both the curves derived from the actual observations and that which would result if the pressure were determined from the data to which I have referred.

The next point we have to consider is: The data being as is shown in the tables and graphically in the plates, what temperature are we to assign to that generated by the explosion? With the view of studying the question I resorted to two methods: (i.) Knowing with very considerable accuracy the units of heat (water gaseous) generated by the explosion, and having determined approximately the specific heat of the gases, the temperature of explosion should be given by the equation

$$t = \frac{\text{gramme units of heat}}{\text{specific heat}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

(ii.) Knowing also with considerable accuracy the pressure at any given density, and knowing the pressure p_0 when the volume of gas generated is reduced to the temperature of 0° C. and a pressure of 760 millims. of mercury, the temperature is given by the equation

$$t = \frac{p - p_0}{0{\cdot}00367 \times p_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2).$$

With reference to equation (1), the specific heat of CO_2 is a very important factor in this determination, and the recent researches of Messrs. HOLBORN and AUSTIN upon the specific heat of gases at constant pressure at high temperatures having apparently shown that the specific heats given by MALLARD and LE CHATELIER for temperatures above 100° C. are considerably too high, I have taken the figures given by these physicists, which, I may observe, up to temperatures of 800° C. are confirmed by LANGEN.

The equation given by HOLBORN and AUSTIN for the specific heat of CO_2 at constant pressure is

$$\text{Specific heat} = 0{\cdot}2028 + 0{\cdot}000{,}128{,}4\theta - 0{\cdot}000{,}000{,}05\theta^2,$$

θ being the temperature.

The correctness of this equation for temperatures up to 800° C. has been proved, and assuming that the same equation holds up to 1300° C., the specific heats for each 100 degrees are given below.

θ, temperature.	Specific heat, constant pressure.	Δ_1.	Δ_2.
° C.			
0	0·2028		
		0·0134	
100	0·2162		0·0010
		0·0124	
200	0·2286		0·0010
		0·0114	
300	0·2400		0·0010
		0·0104	
400	0·2504		0·0011
		0·0093	
500	0·2597		0·0010
		0·0083	
600	0·2680		0·0010
		0·0073	
700	0·2753		0·0010
		0·0063	
800	0·2816		0·0010
		0·0053	
900	0·2869		0·0010
		0·0043	
1000	0·2912		0·0010
		0·0033	
1100	0·2945		0·0010
		0·0023	
1200	0·2968		0·0010
		0·0013	
1300	0·2981		0·0010
		0·0003	
1400	0·2984		

It will be observed from this table that, although between 0° C. and 1400° C. there is a large increase in the value of the specific heat, yet the increments per 100 degrees are rapidly decreasing, vanishing altogether at about 1400° C., at which temperature* there would be partial dissociation at atmospheric pressure. The temperature would, however, probably require to be considerably higher at the pressures we are considering.

The specific heats given are, as I have said, those for constant pressure, and to obtain those at constant volume it is necessary to divide by the constant k connecting the specific heats of gases and vapours at constant pressure and constant volume.

I give below the values I have used (1) of the specific heats at constant pressure—these are taken either from HOLBORN and AUSTIN'S paper, or from LANDOLT-

* MENDELEEF, 'Principles of Chemistry,' vol. 1, p. 381; also DEVILLE, 'Comptes Rendus,' vol. 56, p. 729; and BERTHELOT, 'Comptes Rendus,' vol. 68, p. 1035.

Börnstein, 'Physikalisch-chemische Tabellen,' 1905; (2) of the constant k—these are all taken from Landolt, pp. 407–8; (3) of the specific heats at constant volume.

Gases, &c.	Specific heat, constant pressure.	Value of k.	Specific heat, constant volume.
CO_2	0·2986	1·282	0·232
CO	0·2425	1·401	0·173
H	3·4100	1·408	2·422
CH_4	0·5922	1·316	0·450
N	0·2497	1·410	0·177
H_2O	0·4210	1·330	0·361

The specific heats calculated from the above data of the gases generated by the explosion of the six propellants are given in the tables, embodying the results of the whole of the experiments for each propellant, and in the tables are also given the temperatures of explosion deduced from equations (1) and (2), and here again it must be remembered that the temperatures with which artillerists are chiefly concerned are those due to densities varying approximately between 0·17 and 0·23.

For the sake of clearness, the temperatures obtained from equations (1) and (2) are graphically shown on Plates 16, 17, and 18.

Beginning with equation (1)—the Italian ballistite, which shows the highest temperature, commences at the density of 0·05 with 4943° C., this temperature hardly varying at all till the density of 0·25 is reached, when it slowly but regularly increases to about 5000° C. at $d = 0·45$. Cordite Mark I, commencing at 4742° C. with a very slight fall, is practically constant up to $d = 0·30$, after which it rises somewhat rapidly to a temperature of 4921° C. at $d = 0·45$ and to 5060° C. at $d = 0·50$.

M.D., commencing with 3814° C. with a slight fall, reaches the same temperature at $d = 0·22$, after which it rises rapidly to about 4455° C. at $d = 0·45$.

Norwegian ballistite 167 begins about 3748° C., and, with a very slight fall, regains the same temperature at $d = 0·2$, after which it reaches 4298° C. at $d = 0·45$ and 4437° C. at $d = 0·50$.

Norwegian ballistite 165 has a temperature 350° C. lower between densities 0·05 and 0·15, and, after the latter density, rises rapidly to 4177° C. at $d = 0·45$ and to 4325° C. at $d = 0·5$.

The nitrocellulose R.R., commencing at 3213° C., rises steadily, but not very rapidly, to 3861° C. at $d = 0·45$ and to 3977° C. at 0·5.

When, however, we come to the temperatures given by equation (2), we are met with some very remarkable differences, which are shown by the tables, but which are more readily appreciated if reference be made to Plates 16, 17, and 18, in which the explosives are arranged in descending order of the temperatures developed.

It will be observed that at the higher densities and pressures there is generally a very tolerable accordance in the temperatures obtained from the two formulæ, but as the density and pressure diminish the divergence becomes, in all cases, considerable, but very greatly more with the explosives which develop very high temperatures and which give rise to large percentages of carbonic anhydride.

The only construction I am able to put upon the tolerably close approximation of temperature given by the two formulæ at high densities and pressures, and the wide differences which exist in some of the explosives at low densities, is that, as I think it reasonable to expect, at high densities dissociation of the carbonic anhydride is prevented by the very high pressure, and that the great difference between, for instance, Italian ballistite and nitrocellulose R.R. at, say, the density of 0·1, is due, firstly, to the difference of the temperature at which the nascent gases are generated, and, secondly, to the proportion of CO_2 which is subject to dissociation.

Formula (1) gives for Italian ballistite at $d = 0{\cdot}1$ a temperature of nearly 5000° C., and for this explosive the temperature given by units of heat/by specific heat is nearly constant, while the percentage of CO_2 is 38·2. The same formula gives for the nitrocellulose at the same density a temperature of formation of 3200° C., while the percentage of CO_2 is only 19·45.

I have pointed out that, under atmospheric pressure, the dissociation of CO_2 commences at about 1300° C., and the very much higher temperatures of formation of the gases of the Italian ballistite, combined with its double percentage of CO_2, appear to me to be sufficient to explain the results obtained with this explosive.

If reference be made to Plate 16, it will be seen that while at the density of 0·1 there is, with Italian ballistite, a difference of about 1800° C. between the two formulæ, there is with the nitrocellulose a difference only of under 800° C.

The theory I venture to submit is as follows :—

The nascent gases are generated at temperatures approximately as given by equation (1) and by the red curves in Plates 16, 17, and 18.

Under the low densities and pressures at the very high temperatures with which we are concerned, the CO_2 and possibly some H_2O are partially dissociated, giving rise to the fall in temperature exhibited by the results obtained from equation (2) at low densities. At high densities, as already pointed out, the two equations give, in some cases, accordant results, in all cases tolerable agreement; it therefore appears to me to be reasonable to suppose that the facts I have recorded are due to partial dissociation at low densities and pressures, which dissociation is prevented by the very high pressures ruling at densities of 0·40, 0·45, and 0·50.

As no free oxygen is ever found in the analysis, in cooling down any free oxygen due to dissociation must have combined and the heat lost by dissociation regained. The re-combination must, however, be very gradual, as no discontinuity is observed in the cooling curves.

A certain amount of confirmation is given to the view I have taken by the fact

that if the explosives be arranged according to the amount of heat generated, derived from equation (1), regard being also had to the amount of CO_2 found, it will be found that the differences between the two formulæ decrease approximately as the factors to which I have referred decrease, as is shown in the following table :—

(1) Explosives.	(2) Temperature of formation derived from equation (1). Density = 0·05.	(3) Percentage of CO_2.	(4) Temperature reduced by dissociation derived from equation (2). Density = 0·05.	(5) Difference of temperature.
	° C.		° C.	° C.
Italian ballistite . . .	4943	37·05	2745	2198
Cordite Mark I . . .	4742	27·20	2800	1942
M.D.	3814	18·40	2345	1469
Norwegian 167 . . .	3748	18·45	2200	1548
Norwegian 165 . . .	3410	15·60	2000	1410
Nitrocellulose	3213	17·95	2260	953

The differences given in column (5) of the above table represent, for the very low density of 0·05, the differences which I suppose to be due chiefly to dissociation, but partly to the communication of heat to the explosion vessel—but these differences are very considerably less if the mean density giving rise to the maximum pressure in the bores of guns is taken. Thus with Italian ballistite the difference between the two formulæ is approximately 1210° C.; with cordite Mark I, 860° C.; with M.D., 560° C.; with Norwegian 167, 600° C.; with Norwegian 165, 510° C.; and with nitrocellulose R.R., 480°.

At the density of 0·45 the differences between the two formulæ are as follows :—

		° C.
Italian ballistite	difference	150,
Cordite Mark I	,,	200,
M.D.	,,	320,
Norwegian ballistite 167	,,	250,
Norwegian ballistite 165	,,	130,
Nitrocellulose	,,	180.

It will be observed, both from the above figures and the curves, that with the Italian ballistite alone at the density 0·45 is the temperature derived from equation (2) lower than that derived from equation (1). With all the other explosives the temperatures derived from equation (2) are the higher. The differences, however, are not great, being generally under 5 per cent., that is about 200° C.

In the case of experiments carried on, both at pressures and temperatures very greatly above the limits at which physicists ordinarily experiment, I can hardly hope

that the methods I have employed, and the conclusions at which I have arrived, will escape criticism.

The results of the experiments given in the tables and plates may, however, be taken as very approximately correct, and the repeat experiments I have made show that there is great constancy in the transformation which takes place on explosion at any given density.

I conclude by expressing my obligation to Dr. SODEAU and Mr. HUTCHINSON for their assistance in carrying out the various experiments, in the analysis, and in the laborious, but necessary calculations.

NOTE.—In the case of the Norwegian ballistites, the pressures at densities above 0·3 have been corrected to accord with the values obtained from the volume of the gas generated, multiplied by the units of heat determined.

APPENDIX.

Abstract of Experiments Referred to in Paper.

ITALIAN BALLISTITE.

Experiment 1528.—Fired in explosion vessel R, 15 grammes of Italian ballistite. Density of charge 0·05.
Pressure 3·22 tons per sq. inch (490·8 atmospheres).
Permanent gases 9186·4 cub. centims. at 0° C. and 760 millims.
Aqueous vapour 3843·9 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	3·256	9·515	0·442	2·604
Originally in ballistite . . .	3·444	9·588	0·422	2·359
Differences	−0·188	−0·073	+0·020	+0·245

Experiment 1527.—Fired in explosion vessel R, 30 grammes of Italian ballistite. Density of charge 0·10.
Pressure 6·42 tons per sq. inch (978·5 atmospheres).
Permanent gases 18,565·1 cub. centims. at 0° C. and 760 millims.
Aqueous vapour 6599·4 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	6·585	18·506	0·806	4·984
Originally in ballistite . . .	6·717	18·698	0·823	4·602
Differences	−0·132	− 0·192	−0·017	+0·382

Experiment 1523.—Fired in explosion vessel R, 45 grammes of Italian ballistite. Density of charge 0·15. Pressure 11·67 tons per sq. inch (1778·7 atmospheres).
Permanent gases 27,251·0 cub. centims. at 0° C. and 760 millims.
Aqueous vapour 9421·0 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	9·607	27·126	1·182	7·265
Originally in ballistite . . .	9·840	27·393	1·206	6·741
Differences	−0·233	−0·267	−0·024	+0·524

Experiment 1525.—Fired in explosion vessel R, 60 grammes of Italian ballistite. Density of charge 0·20. Pressure 15·45 tons per sq. inch (2354·9 atmospheres).
Permanent gases 36,559·0 cub. centims. at 0° C. and 760 millims.
Aqueous vapour 12,654·0 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	12·847	36·643	1·609	9·607
Originally in ballistite . . .	13·220	36·802	1·621	9·057
Differences	−0·373	−0·159	−0·012	+0·550

Experiment 1526.—Fired in explosion vessel R, 75 grammes of Italian ballistite. Density of charge 0·25. Pressure 20·65 tons per sq. inch (3147·4 atmospheres).
Permanent gases 46,276·5 cub. centims. at 0° C. and 760 millims.
Aqueous vapour 15,102·0 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	16·270	45·666	1·971	12·016
Originally in ballistite . . .	16·535	46·030	2·027	11·327
Differences	−0·265	−0·364	−0·056	+0·689

Experiment 1530.—Fired in explosion vessel R, 90 grammes of Italian ballistite. Density of charge 0·30.

Pressure 26·35 tons per sq. inch (4016·3 atmospheres).

Permanent gases 55,293·0 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 17,801·6 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	19·490	54·558	2·361	14·427
Originally in ballistite . . .	19·789	55·088	2·426	13·551
Differences	− 0·299	− 0·530	−0·065	+ 0·876

Experiment 1531.—Fired in explosion vessel R, 120 grammes of Italian ballistite. Density of charge 0·40.

Pressure 40·29 tons per sq. inch (6141·0 atmospheres).

Permanent gases 73,046·5 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 22,902·0 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	25·990	72·788	3·152	18·922
Originally in ballistite . . .	26·320	73·280	3·230	18·030
Differences	− 0·330	− 0·492	−0·078	+ 0·892

Experiment 1605.—Fired in explosion vessel Q, 126·9 grammes of Italian ballistite. Density of charge 0·45.

Pressure 45·57 tons per sq. inch (6945·8 atmospheres).

Permanent gases 76,776·7 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 24,569·0 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	27·637	77·436	3·436	20·035
Originally in ballistite . . .	28·000	77·946	3·433	19·181
Differences	− 0·363	− 0·510	+0·003	+ 0·854

NORWEGIAN 165.

Experiment 1577.—Fired in explosion vessel R, 15 grammes of Norwegian ballistite. Density of charge 0·05.

Pressure 2·49 tons per sq. inch (379·5 atmospheres).

Permanent gases 12,778·1 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 2139·7 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	4·212	8·533	0·476	2·404
Originally in ballistite . . .	4·375	8·664	0·500	2·086
Differences	−0·163	−0·131	−0·024	+0·318

Experiment 1576.—Fired in explosion vessel Q, 31 grammes of Norwegian ballistite. Density of charge 0·10.

Pressure 6·30 tons per sq. inch (960·2 atmospheres).

Permanent gases 26,017·1 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 4242·0 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	8·611	17·502	0·991	4·601
Originally in ballistite . . .	8·878	17·582	1·015	4·233
Differences	−0·267	− 0·080	−0·024	+0·368

Experiment 1534.—Fired in explosion vessel Q, 46·5 grammes of Norwegian ballistite. Density of charge 0·15.

Pressure 10·19 tons per sq. inch (1553·2 atmospheres).

Permanent gases 37,894·3 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 6120·5 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	12·969	26·211	1·503	6·583
Originally in ballistite . . .	13·233	26·206	1·512	6·309
Differences	− 0·264	+ 0·005	−0·009	+0·274

Experiment 1536.—Fired in explosion vessel Q, 62 grammes of Norwegian ballistite. Density of charge 0·20.

Pressure 14·62 tons per sq. inch (2228·4 atmospheres).

Permanent gases 49,158·5 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 8036·2 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	17·143	34·967	2·056	8·787
Originally in ballistite . . .	17·600	34·856	2·012	8·392
Differences	− 0·457	+ 0·111	+0·044	+0·395

Experiment 1539.—Fired in explosion vessel Q, 77·5 grammes of Norwegian ballistite. Density of charge 0·25.

Pressure 18·77 tons per sq. inch (2860·9 atmospheres).

Permanent gases 60,392·5 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 9685·8 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	21·622	44·029	2·478	10·865
Originally in ballistite . . .	22·117	43·800	2·528	10·545
Differences	− 0·495	+ 0·229	− 0·050	+ 0·320

Experiment 1540.—Fired in explosion vessel Q, 93 grammes of Norwegian ballistite. Density of charge 0·30.

Pressure 23·60 tons per sq. inch (3597·1 atmospheres).

Permanent gases 70,096·7 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 11,623·9 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	25·889	53·121	2·988	12·706
Originally in ballistite . . .	26·517	52·513	3·031	12·643
Differences	− 0·628	+ 0·608	− 0·043	+ 0·063

Experiment 1593.—Fired in explosion vessel Q, 124 grammes of Norwegian ballistite. Density of charge 0·40.

Pressure 38·30 tons per sq. inch (5837·6 atmospheres).

Permanent gases 88,638·0 cub centims. at 0° C. and 760 millims.

Aqueous vapour 14,733·9 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	34·452	70·736	4·032	16·233
Originally in ballistite . . .	35·130	69·570	4·015	16·750
Differences	− 0·678	+ 1·166	+0·017	− 0·517

Experiment 1600.—Fired in explosion vessel R, 135 grammes of Norwegian ballistite. Density of charge 0·45.

Pressure 46·96 tons per sq. inch (7157·5 atmospheres).

Permanent gases 93,232·7 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 15,226·5 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	37·292	76·242	4·367	17·777
Originally in ballistite . . .	37·996	75·246	4·342	18·116
Differences	− 0·704	+ 0·996	+0·025	− 0·339

NORWEGIAN 167.

Experiment 1581.—Fired in explosion vessel Q, 15·5 grammes of Norwegian 167. Density of charge 0·05.

Pressure 2·61 tons per sq. inch (397·8 atmospheres).

Permanent gases 12,539·9 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 2,639·8 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	4·172	9·080	0·490	2·541
Originally in ballistite . . .	4·347	9·182	0·505	2·247
Differences	−0·175	−0·102	−0·015	+0·294

Experiment 1580.—Fired in explosion vessel R, 30 grammes of Norwegian 167. Density of charge 0·10.

Pressure 6·71 tons per sq. inch (1022·7 atmospheres).

Permanent gases 24,036·6 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 4274·4 cub. centims.

RECONCILIATION.

	C.	O.	H.	N
	grammes	grammes	grammes	grammes
Found by analysis	8·047	17·167	0·900	4·584
Originally in ballistite . . .	8·196	17·313	0·952	4·236
Differences	−0·149	− 0·146	−0·052	+0·348

Experiment 1570.—Fired in explosion vessel Q, 46·5 grammes of Norwegian 167. Density of charge 0·15.

Pressure 10·04 tons per sq. inch (1530·3 atmospheres).

Permanent gases 37,070·7 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 6924·1 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	12·531	26·956	1·440	7·092
Originally in ballistite . . .	12·821	27·083	1·489	6·627
Differences	− 0·290	− 0·127	−0·049	+0·465

Experiment 1535.—Fired in explosion vessel Q, 62 grammes of Norwegian 167. Density of charge 0·20.

Pressure 14·83 tons per sq. inch (2260·4 atmospheres).

Permanent gases 48,402·3 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 8770·2 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	16·671	35·897	1·941	9·138
Originally in ballistite . . .	17·000	35·910	1·974	8·786
Differences	−0·329	− 0·013	−0·033	+0·352

Experiment 1538.—Fired in explosion vessel Q, 77·5 grammes of Norwegian 167. Density of charge 0·25.

Pressure 19·43 tons per sq. inch (2961·5 atmospheres).

Permanent gases 58,686·9 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 10,890·0 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	20·587	44·534	2·403	11·074
Originally in ballistite . . .	21·050	44·466	2·444	10·880
Differences	− 0·463	+ 0·068	−0·041	+ 0·194

Experiment 1537.—Fired in explosion vessel R, 90 grammes of Norwegian 167. Density of charge 0·30.

Pressure 25·62 tons per sq. inch (3905·0 atmospheres).

Permanent gases 66,328·5 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 12,634·0 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	24·045	52·133	2·816	12·730
Originally in ballistite . . .	24·499	51·750	2·844	12·662
Differences	− 0·454	+ 0·383	−0·028	+ 0·068

Experiment 1599.—Fired in explosion vessel R, 120 grammes of Norwegian 167. Density of charge 0·40.

Pressure 40·66 tons per sq. inch (6197·4 atmospheres).

Permanent gases 82,640·9 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 15,793·8 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	31·590	68·493	3·710	16·328
Originally in ballistite . . .	32·072	67·748	3·724	16·577
Differences	− 0·482	+ 0·745	−0·014	− 0·249

Experiment 1601.—Fired in explosion vessel R, 135 grammes of Norwegian 167. Density of charge 0·45.

Pressure 47·46 tons per sq. inch (7233·9 atmospheres).

Permanent gases 92,430·5 cub. centims. at 0° C. and 760 millims.

Aqueous vapour 17,785·5 cub. centims.

RECONCILIATION.

	C.	O.	H.	N.
	grammes	grammes	grammes	grammes
Found by analysis	35·911	77·970	4·284	18·899
Originally in ballistite . . .	36·600	77·312	4·249	18·917
Differences	− 0·689	+ 0·658	+0·035	− 0·018

Italian Ballistite.

Density of charge exploded		0·05	0·10	0·15	0·20	0·25	0·30	0·35	0·40	0·45	0·50
Volumes of permanent gases per gramme		583·0	600·0	604·5	605·5	606·0	604·5	603·0	602·0	600·0	597·0
Volumes of total gases per gramme		824·2	816·0	811·7	810·5	808·1	804·5	800·0	793·9	788·3	780·0
Percentage volumes of permanent gases	CO_2	37·05	38·20	39·15	39·95	40·50	41·10	42·15	43·40	44·70	46·20
	CO	28·85	27·40	26·15	25·00	24·10	23·35	22·20	20·95	19·30	17·55
	H	11·55	12·65	13·25	13·60	13·90	13·75	13·60	13·00	12·40	11·70
	CH_4	0·12	0·15	0·35	0·50	0·60	1·00	1·35	2·00	2·85	3·75
	N	22·43	21·60	21·10	20·95	20·90	20·80	20·70	20·65	20·75	20·80
Percentage volumes of total gases	CO_2	26·20	27·90	29·05	30·20	31·00	31·68	32·45	33·15	33·85	34·50
	CO	20·54	20·04	19·48	18·73	18·10	17·40	16·65	15·70	14·80	13·90
	H	8·18	9·23	9·78	10·10	10·31	10·30	10·05	9·90	9·60	9·20
	CH_4	0·10	0·18	0·24	0·32	0·49	0·72	1·00	1·50	2·00	2·60
	N	15·93	15·85	15·70	15·50	15·50	15·50	15·55	15·65	15·75	15·90
	H_2O	29·05	26·80	25·75	25·15	24·60	24·40	24·30	24·10	24·00	23·90
Percentage weights of total gases	CO_2	42·50	44·73	46·30	47·50	48·63	49·60	50·80	51·80	52·68	53·50
	CO	21·20	20·72	19·95	19·20	18·40	17·60	16·55	15·60	14·65	13·65
	H	0·60	0·66	0·70	0·74	0·75	0·75	0·73	0·70	0·66	0·62
	CH_4	0·06	0·09	0·15	0·19	0·28	0·40	0·60	0·90	1·16	1·53
	N	16·50	16·14	16·00	15·92	15·88	15·85	15·80	15·70	15·65	15·55
	H_2O	19·14	17·66	16·90	16·45	16·06	15·80	15·52	15·30	15·20	15·15
Pressure in tons per sq. inch		3·00	6·50	10·85	15·45	20·65	26·30	32·60	39·10	45·57	52·20
Pressure in atmospheres		457·3	990·7	1653·7	2354·9	3147·5	4008·7	4968·9	5959·6	6945·8	7956·3
Units of heat, water fluid		1330·3	1308·5	1302·5	1305·0	1309·0	1312·0	1319·5	1327·4	1335·3	1345·5
Units of heat, water gaseous		1227·7	1213·9	1211·9	1216·8	1222·9	1227·3	1236·3	1245·4	1253·8	1264·3
Specific heat		0·2484	0·2483	0·2489	0·2497	0·2502	0·2506	0·2510	0·2512	0·2515	0·2518
Temperatures of explosion (I.)		4943°	4889°	4869°	4873°	4888°	4897°	4926°	4955°	4980°	5025°
Temperatures of explosion (II.)		2745°	3060°	3380°	3686°	3972°	4235°	4466°	4655°	4805°	4930°

Cordite Mark I.

Density of charge exploded		0·05	0·10	0·15	0·20	0·25	0·30	0·35	0·40	0·45	0·50
Volumes of permanent gases per gramme		670·0	692·5	699·0	697·0	688·0	671·5	658·0	644·9	634·0	623·6
Volumes of total gases per gramme		870·0	878·5	880·0	875·5	865·0	848·0	832·5	820·0	809·5	798·8
Percentage volumes of permanent gases	CO_2	27·20	28·10	29·00	30·85	32·60	34·70	36·60	38·50	40·20	41·90
	CO	34·35	33·25	31·80	29·95	27·90	25·85	24·15	22·55	20·90	19·40
	H	17·52	19·05	19·65	19·40	18·85	17·65	16·35	14·90	13·50	12·00
	CH_4	0·23	0·45	0·80	1·35	2·10	3·00	3·95	4·95	6·00	7·00
	N	20·70	19·15	18·75	18·45	18·55	18·80	18·95	19·10	19·40	19·70
Percentage volumes of total gases	CO_2	21·07	21·98	23·13	24·37	25·87	27·64	29·30	30·56	31·60	32·48
	CO	26·46	26·13	25·20	23·91	22·31	20·44	18·75	17·46	16·35	15·43
	H	13·53	15·12	15·60	15·53	14·96	13·93	12·70	11·73	10·60	9·47
	CH_4	0·23	0·32	0·54	1·00	1·65	2·45	3·21	3·98	4·75	5·54
	N	15·97	15·08	14·93	14·86	14·90	14·95	15·04	15·11	15·35	15·60
	H_2O	22·74	21·37	20·60	20·33	20·31	20·59	21·00	21·16	21·35	21·48
Percentage weights of total gases	CO_2	36·10	38·15	40·20	42·15	44·25	46·10	47·65	49·10	50·35	51·65
	CO	29·00	28·55	27·50	25·82	23·79	21·80	19·82	18·05	16·45	15·20
	H	1·14	1·16	1·21	1·25	1·16	1·04	0·90	0·85	0·75	0·67
	CH_4	0·18	0·21	0·38	0·68	0·90	1·50	2·10	2·34	2·90	3·18
	N	17·63	16·93	16·40	16·10	15·95	15·76	15·68	15·66	15·60	15·50
	H_2O	15·95	15·00	14·31	14·00	13·95	13·80	13·85	14·00	13·95	13·80
Pressure in tons per sq. inch		3·25	7·00	11·70	17·00	22·75	28·90	35·05	41·35	47·30	53·30
Pressure in atmospheres		495·4	1066·9	1783·3	2591·1	3467·6	4404·9	5342·3	6302·6	7209·5	8124·0
Units of heat, water fluid		1272·3	1253·5	1244·5	1246·0	1252·5	1265·0	1282·0	1304·5	1329·0	1355·0
Units of heat, water gaseous		1186·8	1174·0	1170·0	1170·5	1177·0	1186·5	1201·0	1223·4	1252·0	1287·0
Specific heat		0·2503	0·2521	0·2531	0·2540	0·2542	0·2544	0·2546	0·2546	0·2544	0·2541
Temperatures of explosion (I.)		4742°	4665°	4620°	4608°	4625°	4665°	4720°	4800°	4920°	5060°
Temperatures of explosion (II.)		2800°	3100°	3415°	3760°	4110°	4435°	4723°	4960°	5120°	5270°

M.D. Cordite.

Density of charge exploded		0·05	0·10	0·15	0·20	0·25	0·30	0·35	0·40	0·45	0·50
Volumes of permanent gases per gramme		781·8	790·0	786·5	773·0	754·0	733·5	714·0	693·5	673·5	653·5
Volumes of total gases per gramme		955·4	948·0	931·0	913·5	893·5	873·0	852·0	832·0	810·6	789·5
Percentage volumes of permanent gases	CO_2	18·40	19·90	21·65	23·95	26·55	29·05	31·45	33·90	36·30	38·45
	CO	42·50	40·75	38·65	36·35	33·80	31·25	29·15	27·00	25·00	23·15
	H	23·10	23·25	22·70	21·50	19·90	18·10	16·20	14·15	12·00	9·90
	CH_4	0·35	1·00	2·00	3·25	4·75	6·40	7·75	9·30	10·75	12·15
	N	15·65	15·10	15·00	14·95	15·00	15·20	15·45	15·65	15·95	16·35
Percentage volumes of total gases	CO_2	14·85	16·45	18·35	20·30	22·25	24·15	26·20	28·15	30·15	32·35
	CO	34·87	33·95	32·40	30·50	28·45	26·45	24·40	22·60	20·85	19·00
	H	18·95	19·20	19·00	18·00	16·65	15·00	13·45	11·80	10·15	8·45
	CH_4	0·29	0·83	1·60	2·70	3·95	5·40	6·60	7·80	8·94	9·95
	N	12·89	12·57	12·45	12·50	12·65	12·85	13·00	13·05	13·21	13·45
	H_2O	18·15	17·00	16·20	16·00	16·05	16·15	16·35	16·60	16·70	16·80
Percentage weights of total gases	CO_2	27·80	30·55	33·30	36·20	38·90	41·50	43·82	46·10	48·26	50·30
	CO	41·33	39·90	37·60	34·70	31·70	28·84	26·20	23·63	21·15	18·94
	H	1·62	1·70	1·65	1·50	1·30	1·16	1·02	0·88	0·77	0·66
	CH_4	0·18	0·55	1·05	1·80	2·60	3·35	4·04	4·64	5·22	5·70
	N	15·32	14·80	14·60	14·35	14·20	14·00	13·85	13·75	13·65	13·55
	H_2O	13·75	12·50	11·80	11·45	11·30	11·15	11·07	11·00	10·95	10·85
Pressure in tons per sq. inch		3·00	6·50	10·50	15·45	20·95	26·70	32·45	38·25	43·95	49·50
Pressure in atmospheres		457·3	990·7	1600·4	2354·9	3193·2	4069·6	4946·0	5830·1	6698·9	7544·8
Units of heat, water fluid		1035·9	1024·5	1023·5	1030·0	1044·5	1070·0	1105·0	1145·0	1194·0	1242·0
Units of heat, water gaseous		965·0	959·0	959·0	964·5	981·0	1008·0	1045·0	1090·0	1132·5	1178·0
Specific heat		0·2530	0·2544	0·2550	0·2550	0·2546	0·2544	0·2542	0·2541	0·2542	0·2544
Temperatures of explosion (I.)		3814°	3770°	3761°	3790°	3853°	3962°	4111°	4290°	4455°	4630°
Temperatures of explosion (II.)		2345°	2565°	2850°	3240°	3623°	3961°	4275°	4551°	4817°	5051°

Norwegian Ballistite, Lot 167.

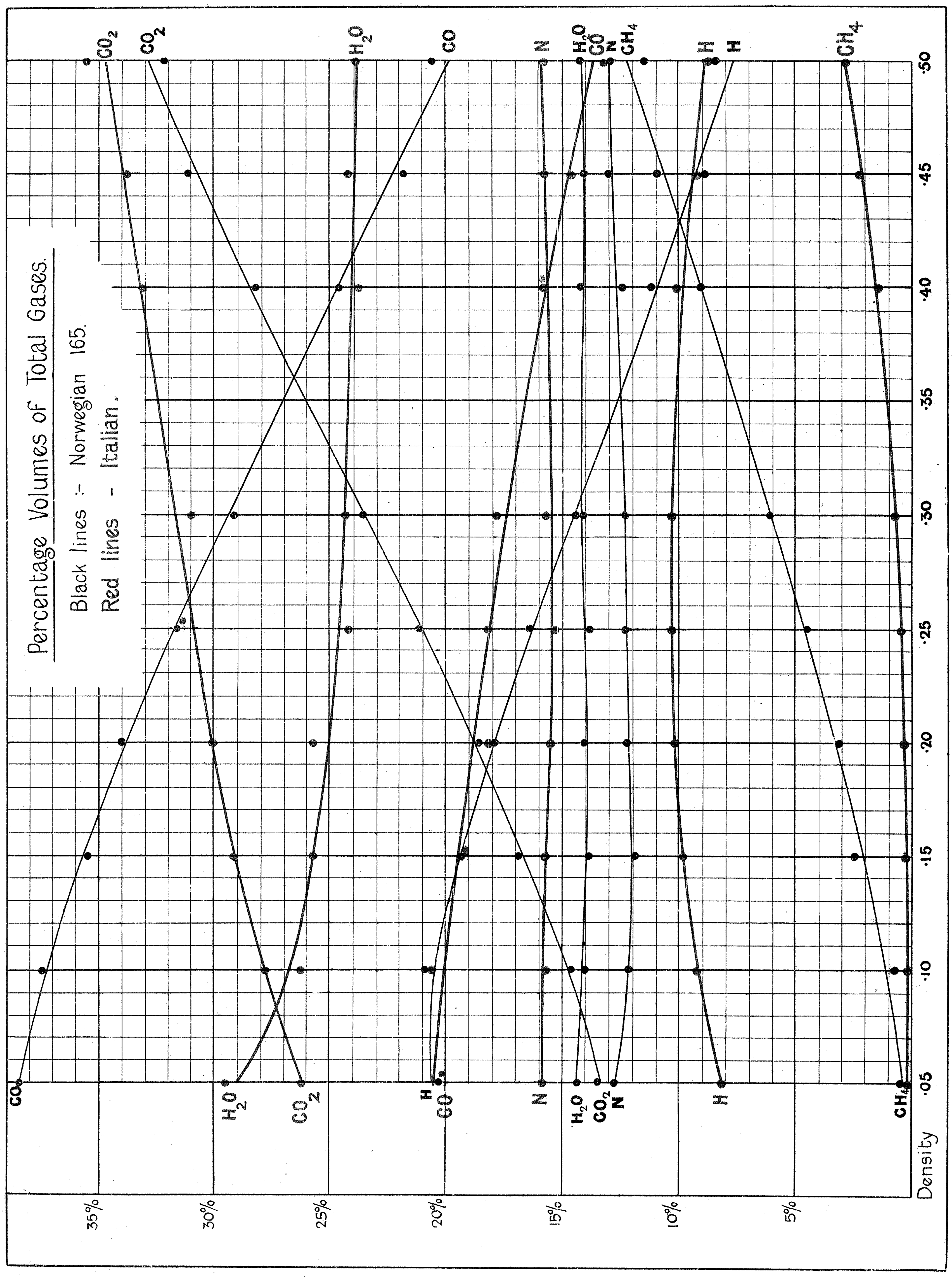
Density of charge exploded		0·05	0·10	0·15	0·20	0·25	0·30	0·35	0·40	0·45	0·50
Volumes of permanent gases per gramme		770·3	783·0	772·0	757·5	742·0	725·5	709·0	690·0	671·0	652·5
Volumes of total gases per gramme		932·4	924·0	914·0	899·0	880·5	861·0	841·0	820·0	803·5	782·0
Percentage volumes of permanent gases	CO_2	18·45	20·15	22·05	24·05	26·30	28·70	31·25	34·05	37·00	39·75
	CO	43·10	41·50	39·50	37·45	35·20	32·85	30·30	27·65	24·80	22·10
	H	22·00	22·30	21·85	20·90	19·40	17·55	15·50	13·45	11·40	9·40
	CH_4	0·30	0·65	1·50	2·60	4·00	5·55	7·30	8·95	10·60	12·20
	N	16·15	15·40	15·10	15·00	15·10	15·35	15·65	15·90	16·20	16·55
Percentage volumes of total gases	CO_2	15·40	16·70	18·35	20·15	22·11	24·35	26·53	28·76	30·97	33·50
	CO	35·57	34·95	33·50	31·60	29·66	27·65	25·47	23·20	20·88	18·60
	H	18·17	19·00	18·60	17·70	16·40	14·60	12·95	11·24	9·50	7·60
	CH_4	0·25	0·65	1·30	2·30	3·35	4·65	5·95	7·50	8·90	10·25
	N	13·28	12·90	12·85	12·73	12·80	12·90	13·05	13·25	13·65	13·95
	H_2O	17·33	15·80	15·40	15·52	15·68	15·85	16·05	16·05	16·10	16·10
Percentage weights of total gases	CO_2	28·51	30·85	33·10	35·60	38·29	41·05	43·75	46·50	49·05	51·65
	CO	41·60	40·35	38·40	35·80	33·20	30·15	27·10	24·00	21·05	17·75
	H	1·52	1·58	1·50	1·43	1·30	1·15	1·05	0·95	0·75	0·65
	CH_4	0·17	0·42	0·90	1·55	2·11	2·90	3·60	4·35	5·10	5·85
	N	15·70	14·95	14·70	14·42	14·05	13·75	13·65	13·60	13·75	13·95
	H_2O	12·50	11·85	11·40	11·20	11·05	11·00	10·85	10·60	10·30	10·15
Pressure in tons per sq. inch		2·70	6·50	10·40	14·70	19·75	25·50	32·25	40·00	48·10	56·75
Pressure in atmospheres		411·5	990·7	1585·1	2240·5	3010·3	3886·7	4915·5	6096·7	7331·3	8649·8
Units of heat, water fluid		1001·0	992·0	994·0	1005·5	1025·3	1050·5	1080·0	1114·5	1146·5	1180·5
Units of heat, water gaseous		934·0	928·5	932·9	945·5	966·1	991·6	1021·9	1057·7	1091·3	1126·1
Specific heat		0·2492	0·2502	0·2510	0·2518	0·2524	0·2529	0·2533	0·2536	0·2539	0·2538
Temperatures of explosion (I.)		3748°	3711°	3717°	3755°	3825°	3921°	4034°	4165°	4298°	4437°
Temperatures of explosion (II.)		2200°	2560°	2875°	3170°	3465°	3760°	4045°	4310°	4540°	4752°

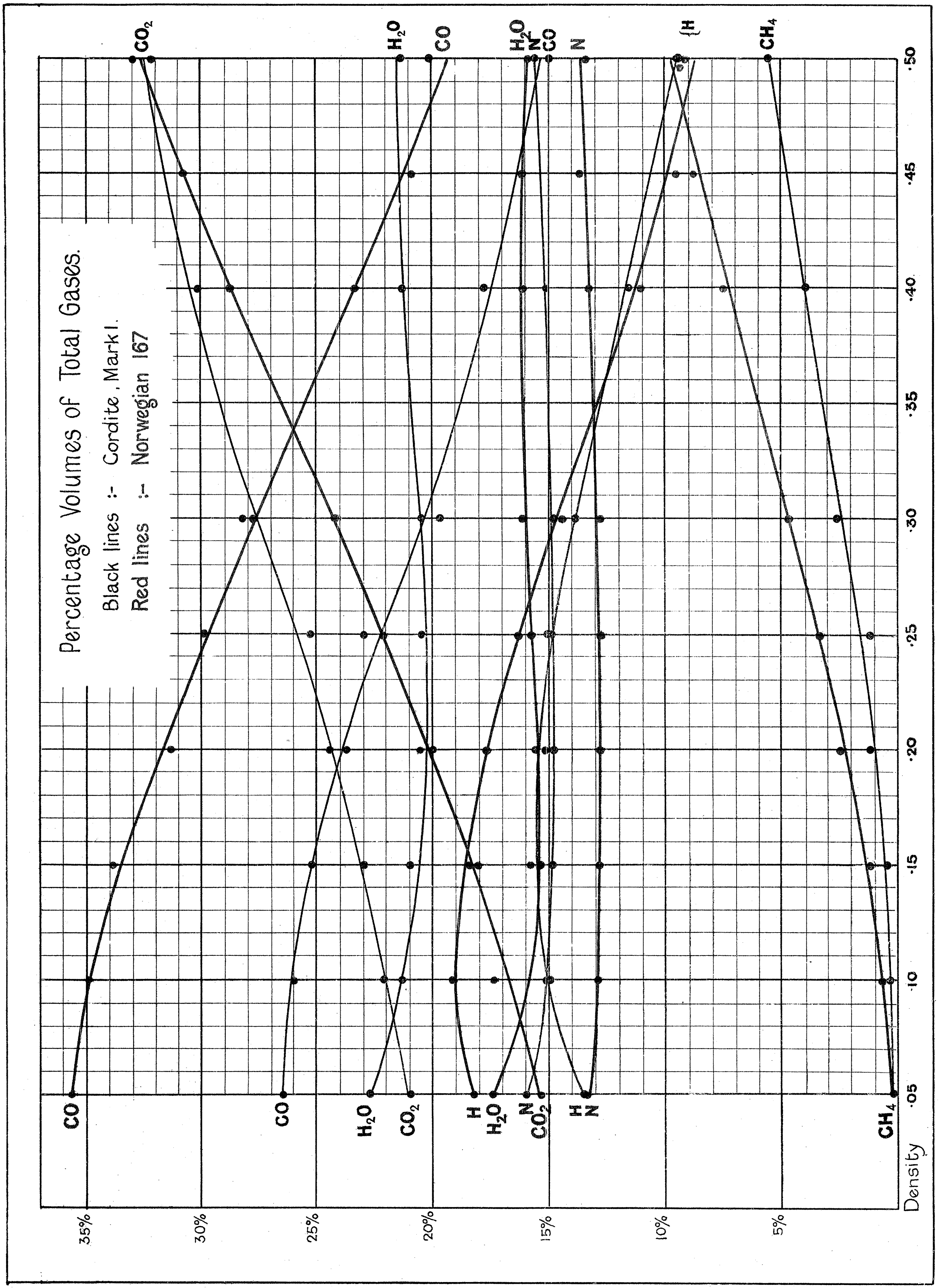
NORWEGIAN BALLISTITE, LOT 165.

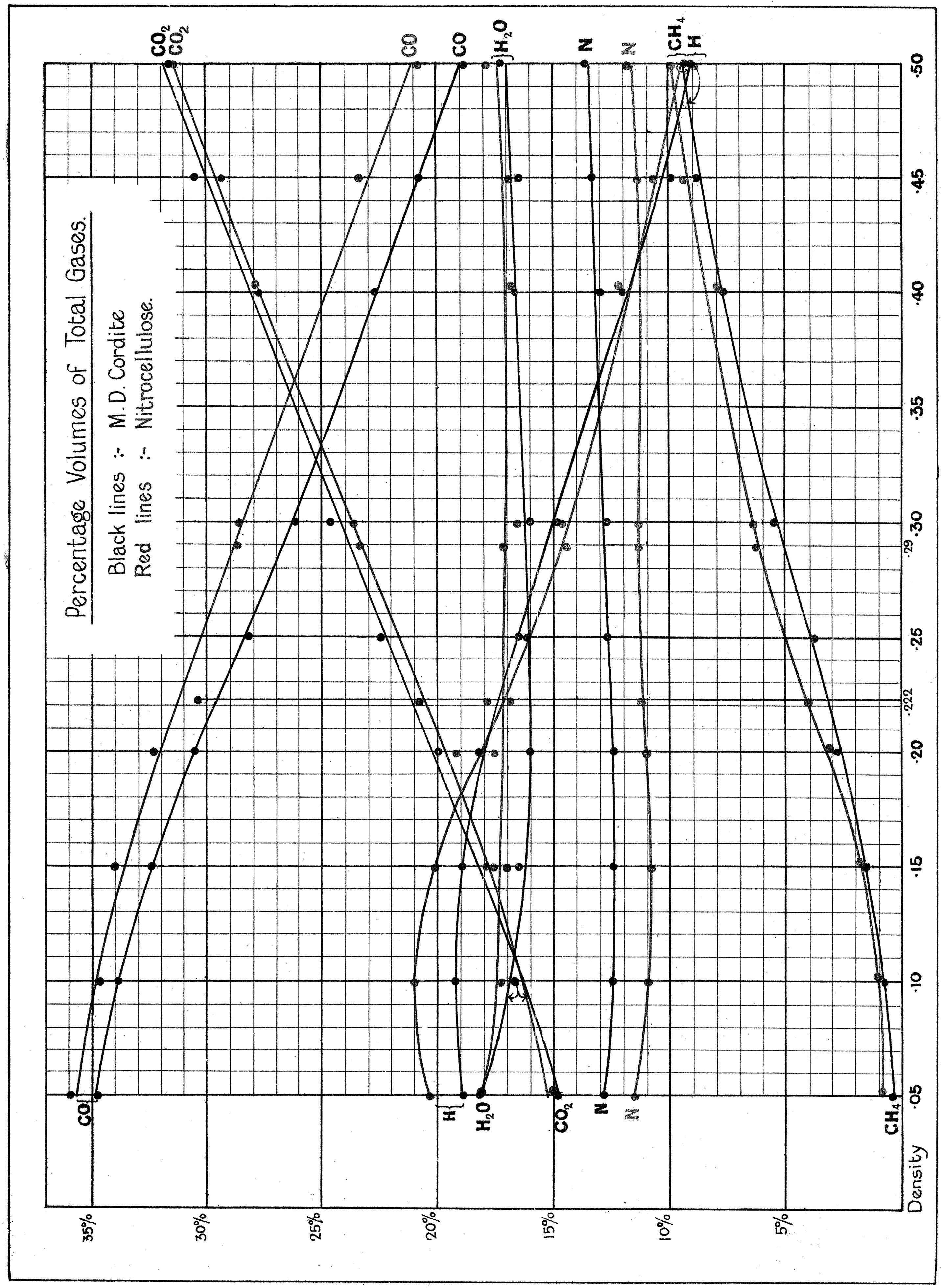
Density of charge exploded		0·05	0·10	0·15	0·20	0·25	0·30	0·35	0·40	0·45	0·50
Volumes of permanent gases per gramme		820·0	818·0	802·0	782·0	762·0	743·0	726·0	706·5	687·0	672·0
Volumes of total gases per gramme		959·0	950·0	931·3	909·9	887·0	864·0	844·5	821·0	801·0	780·0
Percentage volumes of permanent gases	CO_2	15·60	17·10	19·45	21·90	24·50	27·45	30·30	33·20	36·10	38·30
	CO	44·95	43·45	41·55	39·40	36·80	34·00	31·30	28·50	25·65	23·15
	H	23·75	24·15	22·75	20·95	19·00	16·95	14·85	12·70	10·65	9·00
	CH_4	0·65	1·20	2·25	3·70	5·40	7·05	8·90	10·80	12·60	14·30
	N	15·05	14·10	14·00	14·05	14·30	14·55	14·65	14·80	15·00	15·25
Percentage volumes of total gases	CO_2	13·40	14·80	16·75	18·70	21·07	23·55	26·10	28·50	30·95	33·40
	CO	38·50	37·22	35·60	33·87	31·64	29·40	26·80	24·55	21·95	19·50
	H	20·60	20·45	19·40	18·00	16·30	14·50	12·75	11·00	9·25	7·40
	CH_4	0·40	1·10	2·17	3·30	4·65	6·15	7·60	9·20	10·90	12·55
	N	12·70	12·18	12·05	12·15	12·34	12·37	12·50	12·65	12·90	13·00
	H_2O	14·40	14·25	14·03	13·98	14·00	14·03	14·25	14·10	14·05	14·15
Percentage weights of total gases	CO_2	25·25	27·75	30·77	33·80	37·10	40·25	43·50	46·24	48·95	51·40
	CO	46·12	44·25	41·75	38·65	35·15	31·78	28·35	25·15	22·00	18·85
	H	1·73	1·85	1·61	1·33	1·25	1·10	1·00	0·85	0·60	0·50
	CH_4	0·45	0·85	1·46	2·15	2·90	3·72	4·50	5·42	6·28	7·25
	N	15·42	14·45	14·00	13·89	13·70	13·40	13·10	12·97	13·00	13·00
	H_2O	11·03	10·85	10·41	10·18	9·90	9·75	9·55	9·37	9·17	9·00
Pressure in tons per sq. inch		2·55	6·15	10·10	14·40	19·00	24·00	30·45	38·30	46·96	56·00
Pressure in atmospheres		388·7	937·4	1539·4	2194·8	2895·9	3658·0	4641·2	5837·6	7157·5	8535·5
Units of heat, water fluid		918·9	911·5	919·5	935·5	964·0	998·5	1030·0	1065·0	1101·2	1140·0
Units of heat, water gaseous		859·8	853·4	863·7	881·0	911·0	945·7	978·8	1014·8	1052·1	1091·8
Specific heat		0·2520	0·2510	0·2504	0·2503	0·2502	0·2505	0·2510	0·2514	0·2519	0·2521
Temperatures of explosion (I.)		3412°	3400°	3449°	3530°	3635°	3770°	3905°	4040°	4177°	4325°
Temperatures of explosion (II.)		2000°	2365°	2715°	3010°	3305°	3573°	3850°	4103°	4325°	4530°

Nitrocellulose.

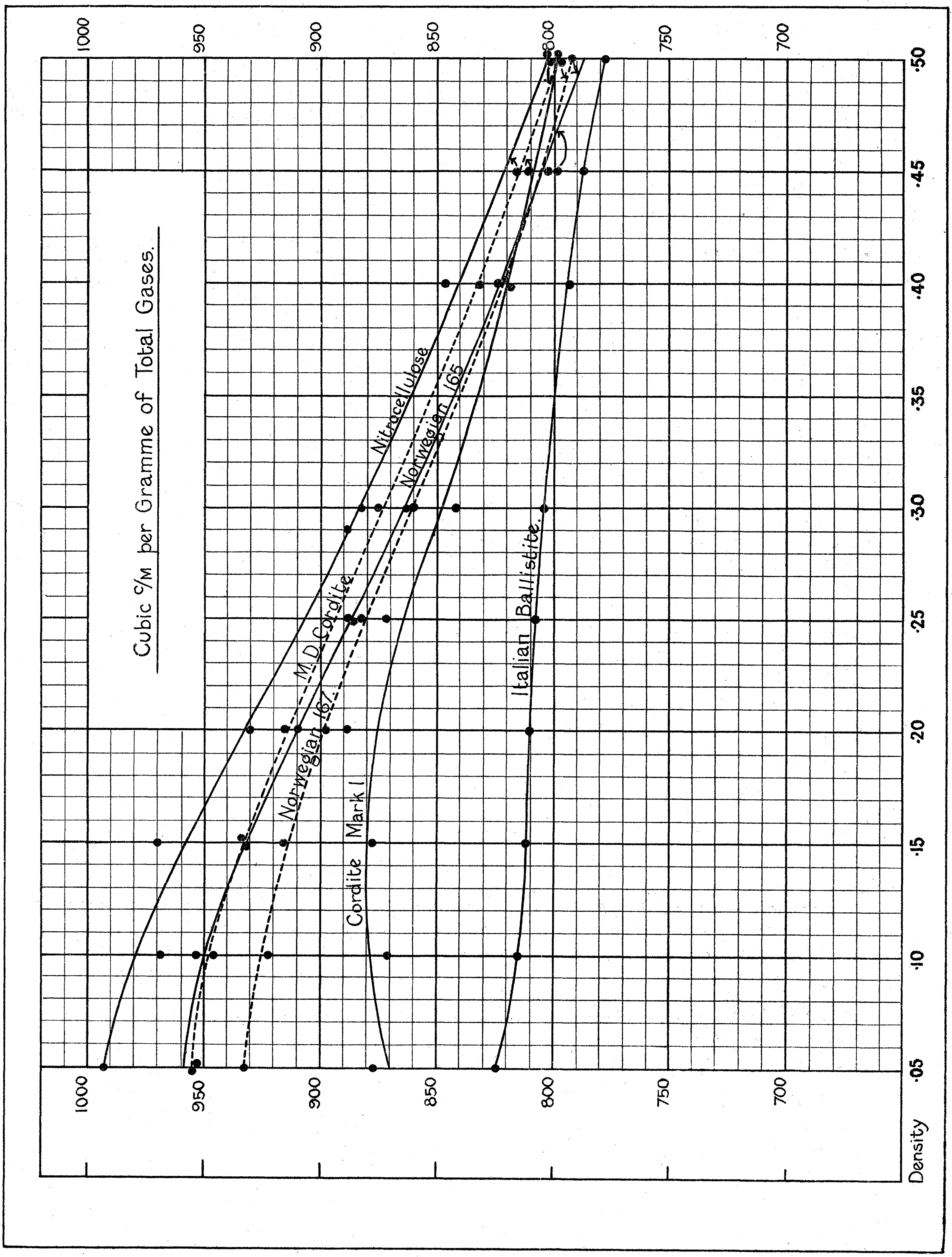
Density of charge exploded		0·05	0·10	0·15	0·20	0·25	0·30	0·35	0·40	0·45	0·50
Volumes of permanent gases per gramme		814·7	810·5	795·0	776·0	751·5	730·0	712·5	695·0	676·0	659·5
Volumes of total gases per gramme		993·1	980·0	958·5	934·0	906·5	883·0	862·0	841·0	821·0	802·0
Percentage volumes of permanent gases	CO_2	17·95	19·45	21·55	23·55	25·70	27·95	30·40	33·00	35·55	38·20
	CO	43·45	41·80	40·05	38·20	36·10	34·00	31·80	29·45	27·40	25·05
	H	24·45	24·80	23·70	21·65	19·15	17·10	15·36	14·10	12·75	11·80
	CH_4	0·50	1·00	1·90	3·55	5·75	7·50	9·00	10·02	10·90	11·60
	N	13·65	12·95	12·80	13·05	13·30	13·45	13·44	13·43	13·40	13·35
Percentage volumes of total gases	CO_2	14·95	16·19	17·50	19·40	21·50	23·50	25·50	27·60	29·60	31·60
	CO	35·36	34·60	33·35	31·90	29·95	28·25	26·50	24·65	22·85	20·96
	H	20·01	20·67	19·90	18·00	15·80	14·05	12·65	11·60	10·65	10·00
	CH_4	0·49	0·71	1·58	2·89	4·80	6·20	7·50	8·44	9·23	9·80
	N	11·19	10·75	10·62	10·83	11·04	11·16	11·08	11·00	11·00	11·00
	H_2O	18·00	17·08	17·05	16·98	16·91	16·84	16·77	16·71	16·67	16·64
Percentage weights of total gases	CO_2	28·25	30·45	32·70	35·15	37·40	39·95	42·55	45·27	47·70	50·20
	CO	43·51	41·70	39·37	36·58	33·60	30·83	28·30	25·60	23·14	20·60
	H	1·74	1·78	1·68	1·52	1·31	1·12	0·97	0·88	0·79	0·72
	CH_4	0·30	0·58	1·07	1·92	3·13	3·92	4·48	4·95	5·37	5·74
	N	13·71	12·92	12·58	12·48	12·41	12·29	12·10	11·80	11·60	11·44
	H_2O	12·49	12·57	12·60	12·35	12·15	11·89	11·60	11·50	11·40	11·30
Pressure in tons per sq. inch		3·00	6·40	9·95	13·80	18·30	22·95	28·40	34·30	40·45	46·80
Pressure in atmospheres		457·3	975·5	1516·6	2103·4	2789·3	3498·0	4328·7	5228·0	6165·4	7133·3
Units of heat, water fluid		874·0	884·5	900·5	924·0	945·5	968·5	993·0	1018·0	1041·0	1065·0
Units of heat, water gaseous		817·5	818·0	830·0	850·5	875·5	900·5	927·5	954·5	985·0	1015·0
Specific heat		0·2544	0·2560	0·2570	0·2568	0·2564	0·2558	0·2554	0·2551	0·2551	0·2552
Temperatures of explosion (I.)		3213°	3195°	3230°	3312°	3415°	3520°	3632°	3742°	3861°	3977°
Temperatures of explosion (II.)		2260°	2415°	2590°	2815°	3060°	3335°	3590°	3832°	4033°	4212°


Percentage Volumes of Total Gases.
Black lines :- Norwegian 165.
Red lines - Italian.
Density
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50
35%
30%
25%
20%
15%
10%
5%
CO
H_2O
CO_2
H
N
CH_4

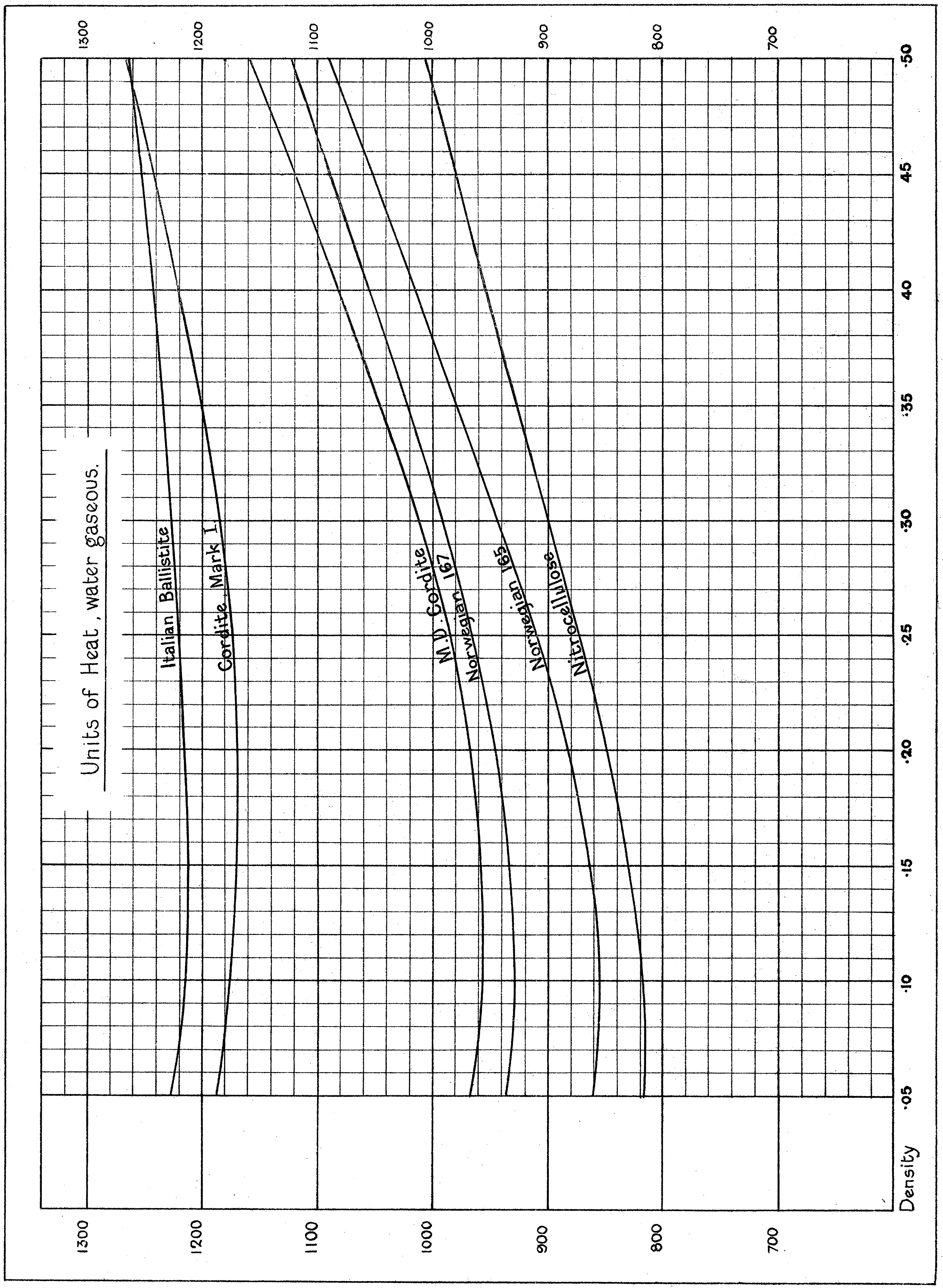

Percentage Volumes of Total Gases.
Black lines :- Cordite, Mark I.
Red lines :- Norwegian 167
CO
CO
H2O
CO2
H
H2O
N
CO2
H
N
CH4
CO2
H2O
CO
H2O
N2
CO
N
H
CH4
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50
Density
35%
30%
25%
20%
15%
10%
5%

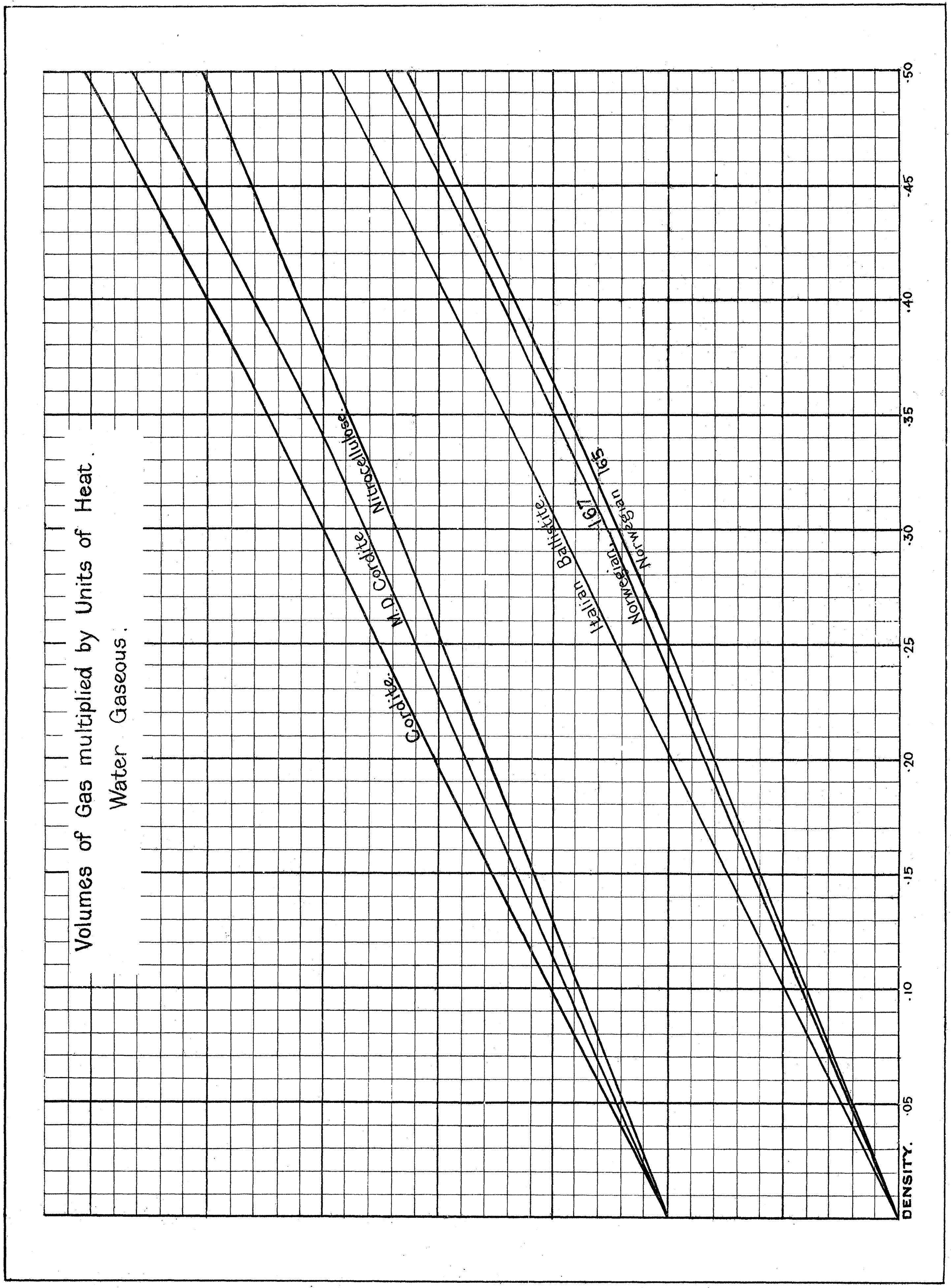


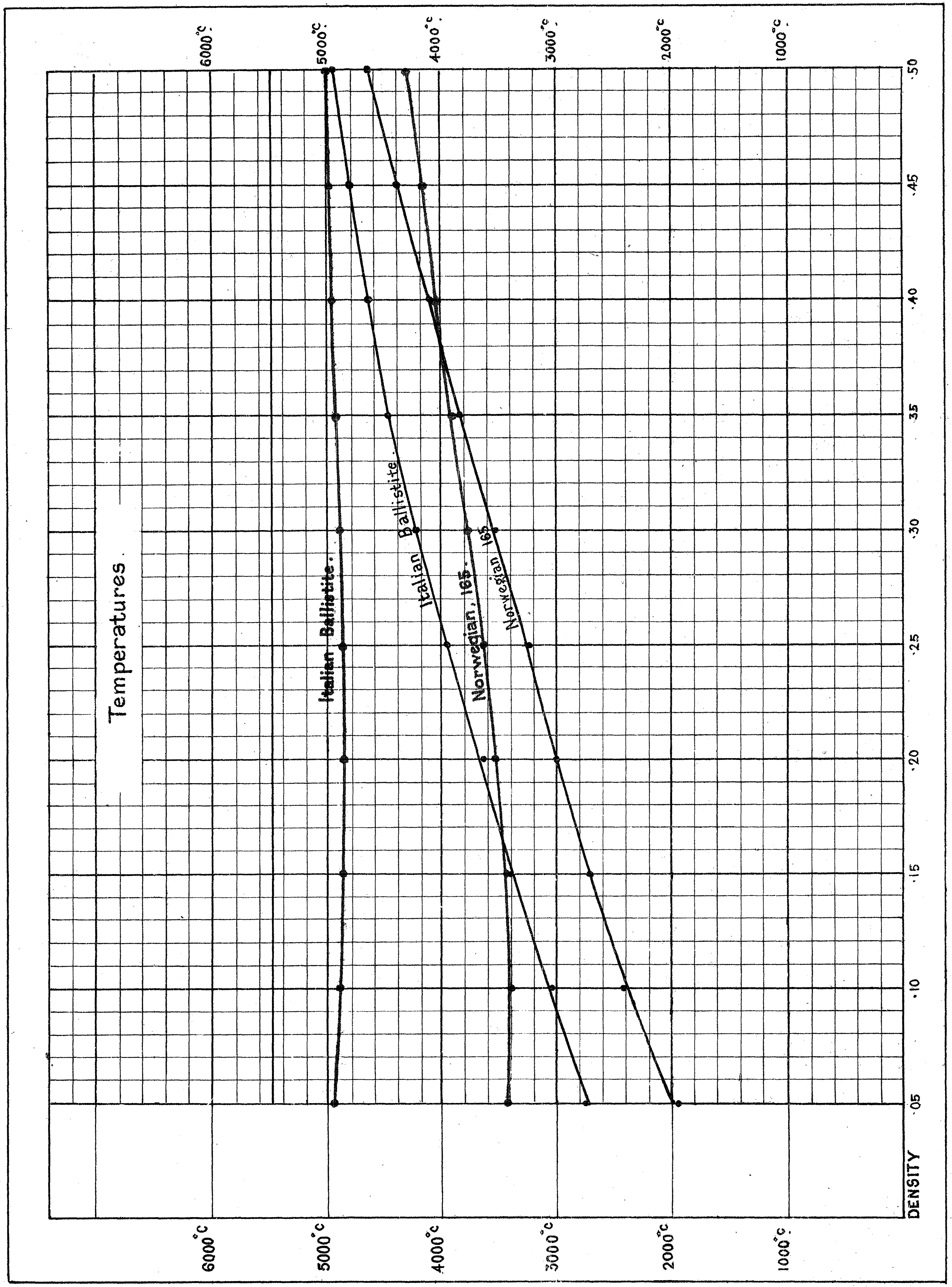
Percentage Volumes of Total Gases.
Black lines :- M. D. Cordite
Red lines :- Nitrocellulose.
CO₂
CO
H₂O
N
CH₄
H
35%
30%
25%
20%
15%
10%
5%
Density
·05
·10
·15
·20
·222
·25
·29
·30
·35
·40
·45
·50

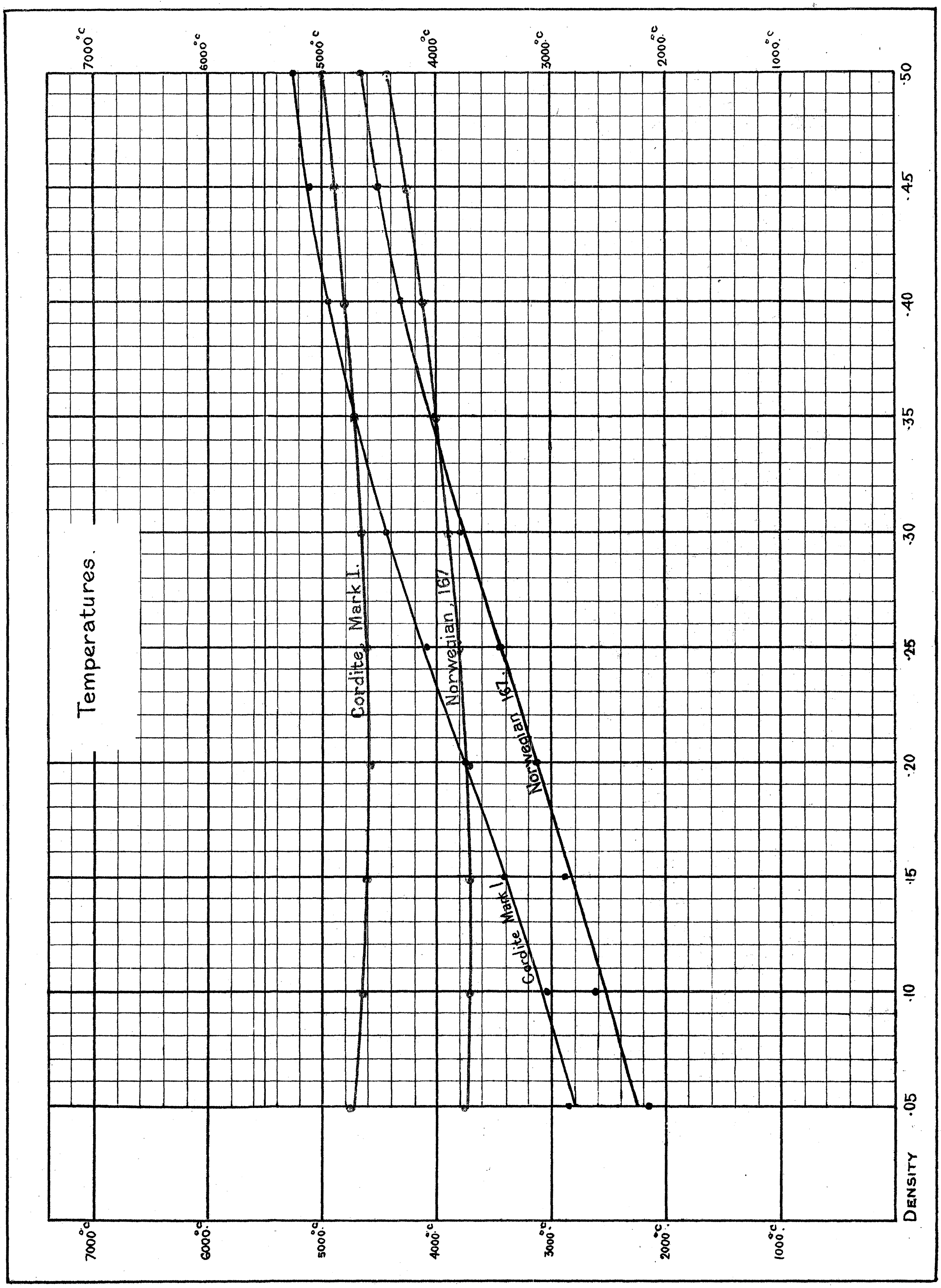


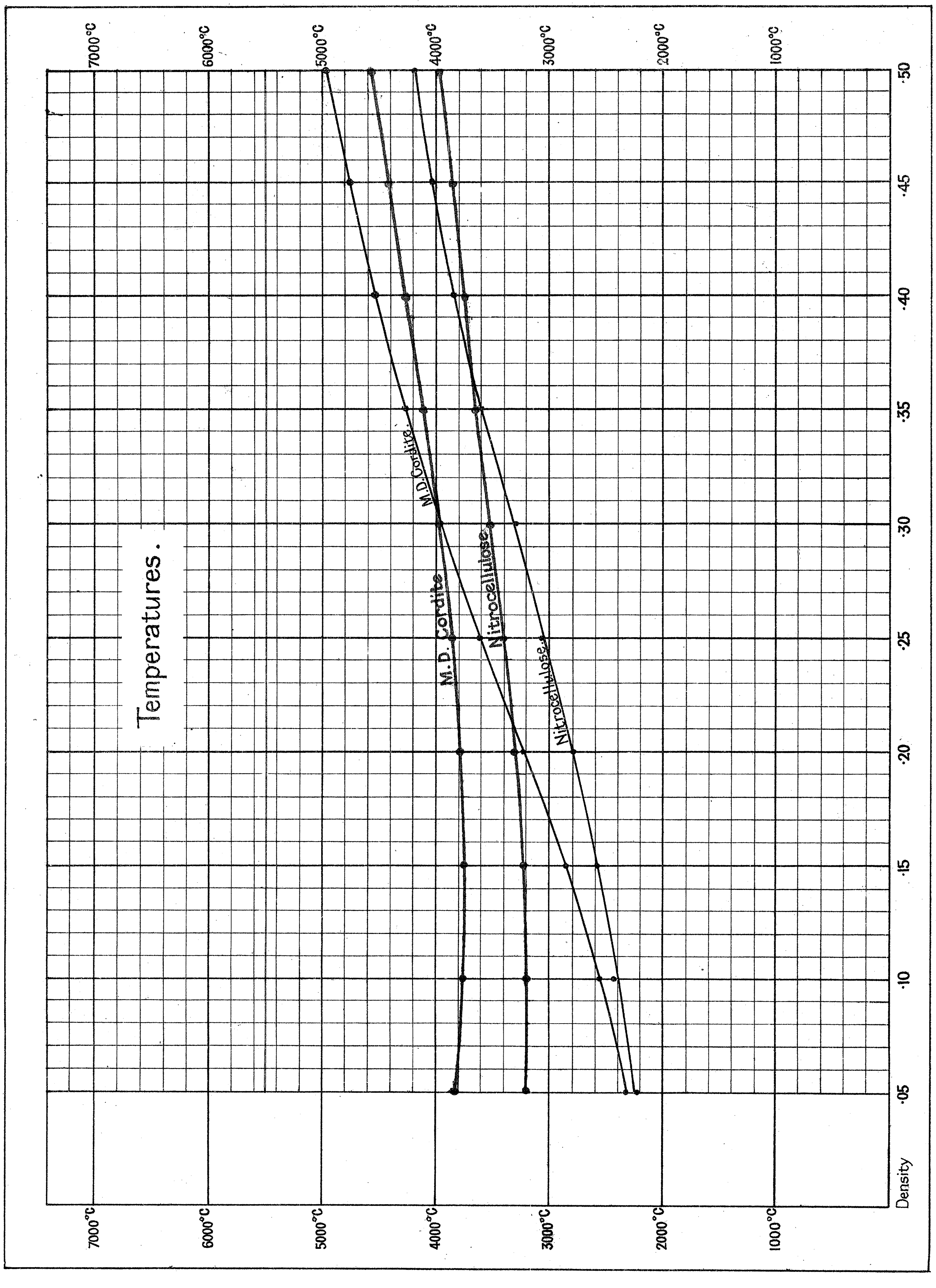
Cubic c/m per Gramme of Total Gases.
Nitrocellulose
Norwegian 165
M.D. Cordite
Norwegian 167
Cordite Mark I
Italian Ballistite.
Density
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50
1000
950
900
850
800
750
700

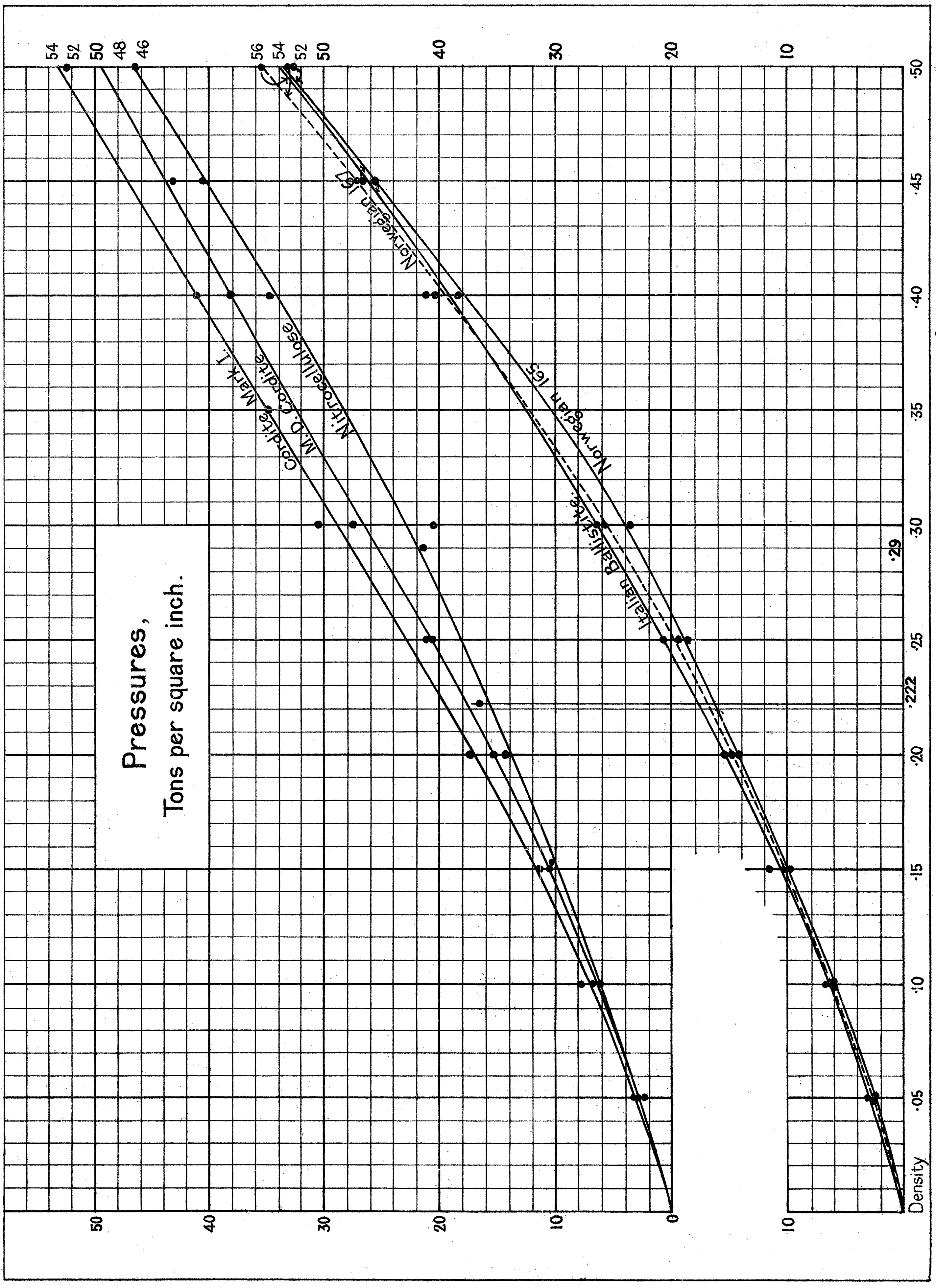

Units of Heat, water gaseous.
Italian Ballistite
Cordite, Mark I.
M.D. Cordite
Norwegian 167
Norwegian 165
Nitrocellulose
Density
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50
1300
1200
1100
1000
900
800
700


Volumes of Gas multiplied by Units of Heat.
Water Gaseous.
Cordite.
M.D. Cordite.
Nitrocellulose.
Ballistite.
Italian
1.67
Norwegian
1.65
Italian
Norwegian
DENSITY.
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50


Temperatures.
Italian Ballistite.
Italian Ballistite.
Norwegian, 165.
Norwegian 165
6000°C
5000°C
4000°C
3000°C
2000°C
1000°C
DENSITY
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50


Temperatures.
Cordite, Mark I.
Norwegian, 167
Norwegian 167.
Cordite Mark I
Density
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50
7000°c
6000°c
5000°c
4000°c
3000°c
2000°c
1000°c


Temperatures.
M.D. Cordite.
M.D. Cordite
Nitrocellulose.
Nitrocellulose.
Density
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50
7000°C
6000°C
5000°C
4000°C
3000°C
2000°C
1000°C


Pressures,
Tons per square inch.
Cordite Mark I.
M.D. Cordite
Nitrocellulose
Norwegian 165
Norwegian 167
Italian Ballistite
Density

Percentage Volumes of Total Gases.
Black lines :- Norwegian 165.
Red lines - Italian.
35%
30%
25%
20%
15%
10%
5%
Density
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50
CO
H2O
CO2
H
CO
N
H2O
CO2
N
H
CH4
CO2
CO2
H2O
CO
N
H2O
CO
N
CH4
H
H
CH4

Percentage Volumes of Total Gases.
Black lines :- Cordite, Mark I.
Red lines :- Norwegian 167
35%
30%
25%
20%
15%
10%
5%
Density
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50
CO
CO
H₂O
CO₂
H
H₂O
N
CO₂
H
N
CH₄
CO₂
H₂O
CO
H₂O
N
CO
N
{H
CH₄

Percentage Volumes of Total Gases.
Black lines :- M.D. Cordite
Red lines :- Nitrocellulose.
35%
30%
25%
20%
15%
10%
5%
CO
H
H_2O
CO_2
N
N
CH_4
CO_2
CO_2
CO
CO
H_2O
N
N
CH_4
H
Density
·05
·10
·15
·20
·222
·25
·29
·30
·35
·40
·45
·50

Temperatures.
6000°C
5000°C
4000°C
3000°C
2000°C
1000°C
Italian Ballistite.
Italian Ballistite.
Norwegian, 165.
Norwegian 165
DENSITY
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50

Temperatures.
7000°C
6000°C
5000°C
4000°C
3000°C
2000°C
1000°C
Cordite, Mark I.
Norwegian, 167
Cordite Mark I
Norwegian 167.
Density
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50


Temperatures.
7000°C
6000°C
5000°C
4000°C
3000°C
2000°C
1000°C
M.D. Cordite
Nitrocellulose
M.D. Cordite.
Nitrocellulose.
Density
·05
·10
·15
·20
·25
·30
·35
·40
·45
·50