APPROXIMATE DETONATION PRESSURE OF INDUSTRIAL EXPLOSIVES

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(Received August 27, 1956)

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Summary

Detonation pressure p_D of industrial explosives is essential in the theoretical calculation and design of blasting rounds on the basis of shock wave theory of blasting. Calculation of p_D by use of thermodynamical-hydrodynamical theory of detonation is not only troublesome but also has many defects such as, that (1) different systems of theoretical formulas give different numerical results due to different equations of state and different thermochemical data (2) chemical compositions which are necessary for calculation are not always available in commercial explosives of practical importance.

Approximation formula for p_D in terms of detonation velocity D and loading density $\varDelta$, whose values are always available in commercial brochures on explosives, has been presented as follows:

$p_D = 0.000424 \ D^2 \ \varDelta \ (1 - 0.543\varDelta + 0.193\varDelta^2)$ gram, cm, sec.

§1. Introduction.

Detonation pressure p_D of industrial explosives plays an important role in the theory aud design of blasting of rock. To a first approximation peak pressure p_r at a distance r from a center of a spherical charge whose radius is "a" may be described as follows.: [1]

$$p_r = p_D \left(\frac{a}{r} \right)^n$$

On the basis of the equation (1) many practical formulas necessary to design blasting rounds may be derived. [2][3]

Detonation pressure of industrial explosives has never been measured so far chiefly because no material can withstand the crushing pressure realized by detonation of industrial explosives. In spite of tremendous efforts exerted to calculate detonation pressure on the basis of thermodynamics and hydrodynamics the res-

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1) Kumao Hino: Theory of blasting with concentrated charge : Journal of the Industrial Explosives Society, JapanVol. 15. No. 4. p. 236 (15).
2) Kumao Hino: Concentrated Type of No-cut Round of blasting; ibid. Vol. 16. No. 3. 1955 pp. 166~179.
3) Kumao Hino ; Theory and Practice of Coyote Blasting ibid. Vol. 17. No. 3, 1956 pp. 156 ~171

ults so far obtained are not so conclusive. One of the reasons for the difficulty of theoretical calculation of detonation pressure is lack of complete knowledge on equation of state of gases at extremely high pressure, high density and high temperature. One school of thoughts gives the result to the efiect that detonation temperature rises as loading density increases while another school of thoughts gives entirely opposite result to the effect that detonation temperature should decrease as loading density increases. This remarkable contradiction between two schools of thoughts is a proof that theoretical calculation of detonation pressure still remains a problem to be solved.

Moreover the results of calculation based on thermodynamics and hydrodynamics differ from author to author usually because people uses different thermo-chemical data such as specific heats in addition to difierent equations of state.

For theoretical calculations chemical compositions of industrial explosives must be known beforehand while this knowledge is not necessarilly available because commercial formulas are sometimes not disclosed. Fortunately detonation velocity and loading density of industrial explosives are all available in pamphlets describing commercial explosives. In the present paper an attempt has been made at finding approximate detonation pressure on the basis of detonation velocity and loading density alone of industrial explosives.

§2. **Relation between detonation pressure p_D, detonation velocity D and loading density $\varDelta$.**

2-1. Derivation of approximate formula.

Detonation pressure p_D [4] of solid explosive is described by the equation (1) as a function of loading density $\varDelta$, streaming velocity W and detonation velocity D.

$$p_D = \varDelta W D \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

The equation (1) is derived from the laws of conservation of mass and momentum and has no relation with equation of state.

If we assume the validity of Abel's equation for gaseous products of detonation, then we have:

$$p_D(v_1 - \alpha) = n_1 R T_1 \cdots\cdots\cdots\cdots (2)$$

$$D = \frac{k_1 + 1}{1 - \alpha \varDelta} \sqrt{\frac{n_1 R T_1}{k_1}} \cdots\cdots\cdots (3)$$

$$W = \sqrt{\frac{n_1 R T_1}{k_1}} \cdots\cdots\cdots\cdots\cdots (4)$$

where α = covolume

$$k_1 = 1 + \frac{n_1 R}{C_v}$$

n_1 = number of moles per unit mass.

R = Gas constant per mole

T_1 = detonation temperature

C_v = specific heat of gaseous products at constant volume

v_1 = specific volume of detonation product

From (3) and (4) we have:

$$W = D \frac{1 - \alpha \varDelta}{k_1 + 1} \cdots\cdots\cdots\cdots\cdots (5)$$

From (1) and (5) we have:

$$p_D = \frac{D^2 \varDelta}{k_1 + 1}(1 - \alpha \varDelta) \cdots\cdots\cdots (1)'$$

4) J. Taylor, Detonation in Condensed Explosives. (Oxford, at the Clarendon Press 1952) p. 67. (Ⅳ. 11)

At higher densities of practical interest the values of covolume α should not be assumed constant and α may be supposed to decrease as densities increase. To a first approximation let us assume that covolume α decreases linearly as density Δ increases.

$$\alpha = \alpha_0 - a\Delta \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

From equation (1)′ and (6) we have:

$$p_D = \frac{1}{k_1 + 1} D^2 \Delta (1 - \alpha_0\Delta + a\Delta^2) \cdots (7)$$

2-2. Previous suggestions.

C. Beyling and K. Drekopf [5] proposed the following approximation formula for detonation pressure of explosives.

$$p_D = \left(\frac{1}{6} \Delta D^2 \right) 1/g \quad\cdots\cdots\cdots\cdots\cdots\cdots (8)$$

where g=gravity constant. 980cm/sec^2 They assumed:

$$W = \frac{1}{6} D \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (9)$$

The relation (9) does not hold in general because D increases linearly as density Δ increases while actually the streaming velocity (Schwadengeschwindigkeit) W is almost independent of loading density Δ.

Yasushi Kumagai [6] has calculated detonation characteristics of industrial explosives according to hydro-thermodynamical method described by Paterson. [4] On the basis of calculated values of D and W he derived the following relation between D and W.

$$W = \frac{1}{1.9 + 2\Delta} D \quad\cdots\cdots\cdots\cdots\cdots (10)$$

Combination of the equations (1) and

(10) gives the following formula.

$$p_D = \left(\frac{1}{1.9 + 2\Delta} \right) \Delta D^2 / g$$

$$\text{(gram, cm, sec.)} \cdots\cdots\cdots\cdots (11)$$

He suggested another empirical formula:

$$p_D = \frac{1}{6} \Delta D^2 / g + 0.03D$$

$$\text{(gram, cm, sec.)} \cdots\cdots\cdots\cdots (12)$$

In the present paper an approximation formula (7) has been derived on the basis of hydro-thermodynamical theory.

§ 3. Calculation of detonation pressure.

3-1. Selection of coefficients.

An approximation formula (7) may be written in the following form:

$$p_D = \frac{C}{g} D^2 \Delta (1 - \alpha_0\Delta + a\Delta^2) \cdots\cdots (7)′$$

$$\text{or} \quad \frac{p_D g}{D^2 \Delta} = C (1 - \alpha_0\Delta + a\Delta^2) \cdots\cdots\cdots (13)$$

The values of $\frac{p_D g}{D^2 \Delta}$ have been plotted on y axis of Fig. 1, as function of Δ (x axis) using various values of p_D calculated by various authors, that is, (1) Drekopf (2) Roth, (3) Paterson (4) H. Jones and (5) Cook.

The coefficients of the equation (13) may be represented as follows.

(1) Drekopf [5] $\frac{p_D g}{\Delta D^2} = \frac{1}{6} = 0.1667$

gram-cm-second.

(2) Roth [7] $\frac{p_D g}{\Delta D^2} = 0.3177 \ (1 - 0.3813\Delta)$

(3) Paterson [8] $\frac{p_D g}{\Delta D^2} = 0.3846$

$$(1 - 0.3316\Delta + 0.0007\Delta^2)$$

5) C. Beyling and K. Drekopf; Sprengstoffe und Zündmittel, Berlin, Verlag von Julius Springer 1936 p. 56.

6) Yasushi Kumagai: Detonation Characteristics of Dynamites; Journal of Mining Institute of Kyushu, Vol. 23, No. 3, 1955. pp. 63~68.

7) J. F. Roth; Z. ges. Schiess-u. Sprengstoffw. 1940. 35, 243.

8) J. Taylor; Detonation in Condensed Explosives. loc. cit. pp. 121, 124, 127. (Nitroglycerine powder, Nitroglycerin semi-gelatin, Nitroglycerin gelatin, TNT powder).

(4) H. Jones [9] $\frac{p_Dg}{\Delta D^2}=0.4157$

$$(1-0.5430\Delta+0.1925\Delta^2)$$

(5) Cook Ⅱ [10] $\frac{p_Dg}{\Delta D^2}=0.3353$

$$(1-0.3016\Delta+0.0826\Delta^2)$$

Ⅲ [11] $\frac{p_Dg}{\Delta D^2}=0.3551$

$$(1-0.2640\Delta+0.0583\Delta^2)$$

Ⅳ [12] $\frac{p_Dg}{\Delta D^2}=0.3364$

$$(1-0.3447\Delta+0.0676\Delta^2)$$

le in the second group (4) Jones (5) (6) Cook decrease of $\frac{p_Dg}{\Delta D^2}$ with increasing Δ is rather mild. In group Ⅰ the calculated detonation temperature T_1 increases with loading density Δ while in group Ⅱ the temperature decreases with increasing loading density and this difference between two groups is of fundamental importance.

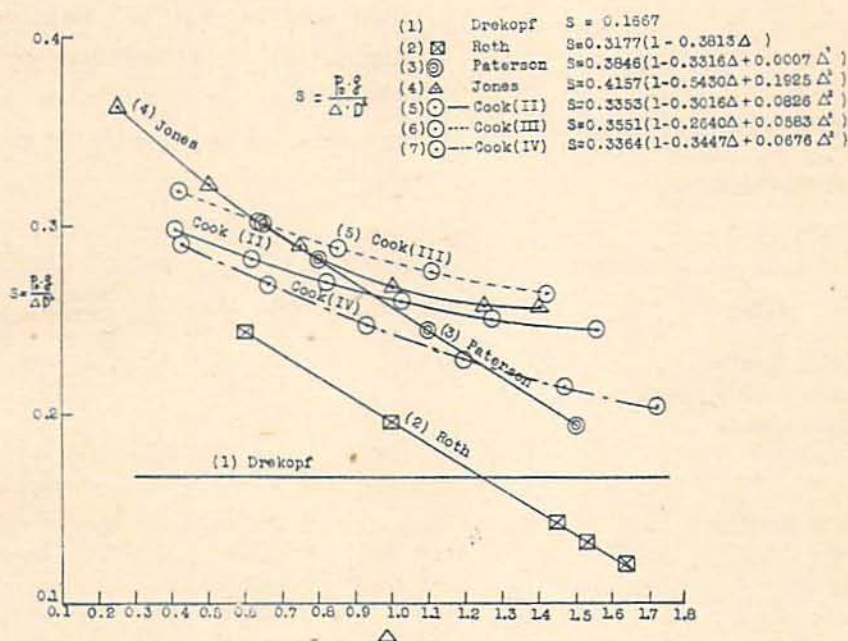In the present paper the equation (4) (H. Jones) has been utilized to calculate

Fig. 1. $\frac{p_D \cdot g}{\Delta \cdot D^2}$ and Δ for various authors.

In Fig.1. the relation (1) (Drekopf) may be considered quite inadequate while other relations may be divided into two groups. The first group (2) Roth, (3) Patterson (7) Cook shows sharp decrease of $\frac{p_Dg}{\Delta D^2}$ with increase of Δ whi-

approximate detonation pressure of industrial explosives whose chemical compositions are not always disclosed.

$p_Dg=0.4157D^2\Delta$

$$(1-0.5430\Delta+0.1925\Delta^2)\cdots\cdots(14)$$

or $p_D=0.000424D^2\Delta$

$$(1-0.543\Delta+0.193\Delta^2)\cdots\cdots\cdots(15)$$

where p_D in kg/cm², D in cm/sec. and Δ in g/cm³.

Fig. 2. is a nomogram for detonation pressure, detonation velocity and loading

9) ibid. p. 94 (PETN).

10) M. A. Cook; J. physical Chemistry 58, 1954, 1114. EDNA, $c=-0.25$, $D=5,650+3,860$ $(\Delta-1.0)$ m/sec.

11) ibid. $c=-0.25$, $D=5,960+3,275$ $(\Delta-1.0)$

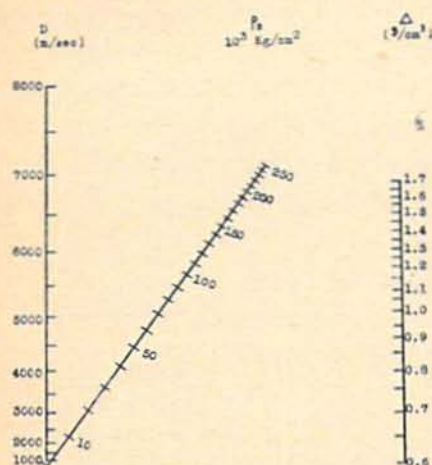12) ibid. $c=0$, $D=5,650+3,860$ $(\Delta-1.0)$

density.

Fig. 2. Nomogram for detonation pressure P_D, detonation velocity D and loading density Δ

3-2. Approximate detonation pressure of industrial explosives.

Detonation pressures of some industrial explosives have been calculated by use of the equation (15). The results have been summarized in Table 1, 2, 3, 4, 5, 6, 7. They should be taken as examples of calculated results and they are by no means inclusive, because there are too many kinds of commercial brands of explosives on the market and they change from year to year and their complete compilation may become too voluminous while calculation of detonation pressure by use of the equation (15) is quite simple.

Table 1. Great Britain *

Type	Density g/cm³	Velocity m/sec	Pressure 10³ atmosphere
Polar Blasting Gelatin	1.55	7,900	254
Polar Ammon Gelatin Dynamite	1.50	6,850	184
Polar Ammon Gelatin	1.45	6,400	155
Polar Rockite	1.0	4,250	49.6
Gelignol	1.2	5,150	84.2
Ammonal	1.10	4,960	71.0
TNT Powder	1.10	4,850	69.6
Polar Ajax	1.55	5,850	139
Polar Dynobel No. 2	1.12	4,450	59.3
Polar Viking	0.98	3,950	42.2
Polar Thames Powder	0.98	3,750	38.1
A 1 Rounkol	0.70	2,900	17.8
Douglas Powder	1.15	4,550	63.4
Gathurst Powder	1.10	4,350	56.0
Denaby Powder No. 2	0.98	3,750	38.0
Unibel	1.15	4,000	49.0
Unikol	0.75	2,750	16.1

* Manual on Blasting. 1953. 16 : 05~13, 15, 19, 21, 27.

Table 2. Canada. *

Type	Grade	Density g/cm²	Velocity m/sec	Pressure 10³ atmosphere
CIL Ditching Dynamite	50	1.35	5,300	98.9
Dynamex	40	1.35	3,540	44.1

Type	Grade	Density g/cm³	Velocity m/sec	Pressure 10³ atmosphere
Dynamex	60	1.32	3,870	51.7
	70	1.30	4,350	64.4
Ammonia Dynamite	20	1.25	2,080	14.2
	30	1.25	2,270	16.9
	40	1.18	2,400	18.0
	60	1.14	2,640	21.2
Stopeite	20	1.02	1,790	8.9
	30	1.02	2,150	12.9
	40	1.02	2,300	14.8
	50	1.02	2,450	16.7
Stumping Powder	20	1.09	1,755	9.0
Giant Gelatin	20	1.73	4,200	82.2
	25	1.70	4,260	82.9
	30	1.66	4,500	89.2
Giant Gelatin	35	1.58	4,530	85.3
	40	1.56	4,620	87.2
	60	1.50	5,340	112
	80	1.44	6,630	165
Forcite	30	1.66	3,630	58.0
	40	1.60	4,140	72.3
	60	1.50	4,620	83.7
	80	1.35	5,310	99.2
	90	1.35	5,670	113
Hi-Velocity Gelatin	60	1.34	5,910	122
Submagel	60	1.35	6,030	128
	75	1.30	6,420	140
Drifte Cilgel	70	1.30	3,600	44.1
	50	1.20	3,330	35.1
Brastol	60	0.95	3,315	29.1

* Canadian Industries Limited: Blasters' Handbook. 1951.

Table 3. France *

Type	Density	Volocity	Pressure
Explosif Nitraté No. 0	1.10	4,900	71.0
Explosif Nitraté No. 30	1.00	4,300	50.8
Stabilit	1.26	6,300	131
Nobelite	1.32	6,200	132
Gomme B. A. M.	1.65	7,000	215
Gomme A.	1.59	7,800	254

* Manual on Rock Blasting. Vol. Ⅱ. 1952, 16 : 03~13.

Table 4. Germany.*

Type	Density	Velocity	Pressure
Dynamit 1	1.54	6,350	163
Ammon-Gelit 1	1.47	6,800	174
Ammon-Gelit 2	1.50	6,350	158
Ammon-Gelit 3	1.53	6,150	152
Donarit 1	1.01	4,850	65.1
Wetter-Nobelit B	1.69	5,650	144
Wetter-Wasagit B	1.69	5,650	144
Wetter-Nobelit B	1.34	1,800	11.3
Wetter-Wasagit B	1.34	1,800	11.3
Wetter-Carbonit A	1.20	2,000	12.7
Wetter-Securit A	1.20	2,000	12.7
Wetter-Astralit A	1.20	1,600	8.1
Wetter-Bicarbit A	1.20	1,600	8.1

* Gerhard Fischer: Glückauf. 1954, 90, Nr. 37/38 p. 1111.

Table 5. Japan

Type	Density g/cm^3	Velocity m/sec	Pressure 10^3 atmosphere
Matsu Dynamite	1.60	7,500	237
Sakura Dynamite	1.55	6,500	171
Toku-Kiri Dynamite	1.45	7,000	185
Kiri Dynamite	1.45	6,500	160
Kashi Dynamite	1.48	6,500	163
Shin-Kashi Dynamite	1.48	6,000	139
Katsura Dynamite	0.9	5,000	63.6
Kaikon-explosive	0.9	3,000	22.9
Ushi-Ammonal	1.04	4,000	45.2
Kuro Carlit	1.05	4,600	60.3
Murasaki Carlit	1.11	4,600	62.8
Tokukaba Carlit	1.15	4,000	49.0
Tokuai Carlit	1.00	3,900	41.8
Shiraume Dynamite	1.55	6,000	146
Shoan Dynamite	0.95	3,000	23.8
S-Shoan Dynamite No. 1	1.0	3,000	24.7
S-Shoan Dynamite No. 2	1.05	2,500	17.8
S-Shoan Dyanmite No. 4	1.1	2,000	11.8
LD Shoan dynamite	0.7	2,200	10.2
Momiji Shoan dynamite	0.95	3,500	32.4
Toku-Shoan explosive	0.95	3,100	25.4
Shoan explosive No. 3	1.0	4,000	44.0
Kô-Shoan explosive	0.96	3,500	32.6
Shin-Midori Carlit	1.0	3,500	33.7

Table 6. Sweden *

Type	Density	Velocity	Pressure
Nitrolit	1.13	5,100	78.4
Extra dynamit LF B	1.40	6,300	145
Extra dynamit LF Ⅳ	1.41	6,700	165
Extra dynamit LF 60	1.45	6,800	175
Gummi dynamit	1.60	7,800	257

* Manual on Rock Blasting, Vol. Ⅱ. 1952. 16 : 03～21.

Table 7. United States of America. *

Type	Grade	Density g/cm^3	Velocity m/sec	Pressure 10^3 atmosphere
Du Pont Straight	15 to 35%	(102)*1.38	2,500	22.5
	40%	(102) 1.38	4,210	63.7
	50%	(104) 1.36	4,910	85.3
	60%	(105) 1.33	5,550	106.7
Red Cross Extra	20 ot 35%	(110) 1.28	2,440	19.9
	40 to 50%	(110) 1.28	3,110	32.3
	60%	(110) 1.28	3,720	46.2
Du Pont Extra	A	(115) 1.23	3,290	32.1
	B	(120) 1.18	3,200	30.0
	C	(125) 1.10	3,020	25.6
	D	(135) 1.04	–	–
	E	(142) 0.99	2,830	21.8
	F	(152) 0.93	2,740	19.5
	G	(162) 0.87	2,710	18.2
	H	(172) 0.82	2,680	17.1
Du Pont Extra	A-1	(115) 1.23	2,500	20.1
	B-1	(120) 1.18	2,410	18.2
	C-1	(125) 1.10	2,350	16.2
	D-1	(135) 1.04	2,290	14.8
	E-1	(142) 0.99	2,190	13.1
	F-1	(152) 0.93	2,100	11.5
	G-1	(162) 0.87	1,980	9.7
Red Cross Blasting FR	25%	(125) 1.13	1,160	4.1
	30%	(128) 1.10	1,220	4.4
	40%	(133) 1.06	1,340	5.1
	65%	(143) 0.99	1,550	6.6
Du Pont Gelatin	20%	(85) 1.66	3,200	45.1
	60%	(96) 1.47	6,000	138
	75%	(101) 1.40	6,280	144
	90%	(107) 1.33	6,800	160
Hi Velocity Gelatin	40%	(94) 31.5	5,090	102
	60%	(107) 51.3	6,000	125
	70%	(113) 81.2	6,190	126
	90%	(120) 81.1	6,700	139

Type	Grade	Density g/cm³	Velocity m/sec	Pressure 10³ atmosphere
Special Gelatin	30%	(89) 1.58	4,200	73.3
	80%	(107) 1.33	5,210	94.0
	90%	(109) 1.29	6,000	122
Gelex	No. 1	(110) 1.28	4,000	53.5
	No. 2	(122) 1.16	3,840	45.4
	No. 3	(130) 1.08	3,660	38.9
	No. 4	(140) 1.02	3,440	32.9
	No. 5	(150) 0.94	2,800	20.6
Duobel A		(135) 1.04	2,800	22.2
Duobel B		(150) 0.94	2,740	19.7
Duobel C		(165) 0.85	2,680	17.5
Duobel D		(185) 0.76	2,560	14.7
Duobel E		(205) 0.69	2,440	12.5
Monobel AA		(120) 1.18	2,410	18.2
Monobel A		(135) 1.04	2,130	12.8
Monobel B		(150) 0.94	1,950	10.0
Monobel C		(165) 0.85	1,890	8.7
Monobel D		(185) 0.76	1,860	7.6
Monobel E		(205) 0.69	1,830	7.0
Lump Coal C		(118) 0.62	1,520	4.5
Lump Coal CC		(165) 0.85	1,680	6.9
Gelobel AA		(102) 1.38	4,510	73.1
Gelobel B		(108) 1.31	3,510	42.1
Gelobel C		(120) 1.18	3,510	38.5

* Du Pont Blasters' Handbook 1952.

    1 feet=0.3048 meter, 1 pound=0.4536kg, 1 inch=0.0254meter, 1 in³=16.39cm³., density Δg/cm³ $=\frac{141}{n_s}$ where n represents cartridge count° (n cartridges $1\frac{1''}{4}\times 8''$ per 50 lbs)

要　　旨

産業用爆薬の爆轟圧力の近似計算式

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ショック波発破理論に於ける諸計算及びそれに基ずく発破の設計を行うに当つては使用するダイナマイトの爆轟圧力 p_D の数値が必要である。流体力学的熱力学的理論に基ずいて p_D を計算する方法は実用的には種々の難点があるがその主なものは（1）研究者に依つて使用されるガス状態方程式が皆異ると言つて良く又使用される熱化学的数値もそれぞれ異るのであつて又計算に使用する理論式の系列も必ずしも一定しない。従て異る出所の結果を集めて比較検討する事は全く意味がない。（2）発破設計に実用上重要な産業用爆薬の化学組成は原則として公表されていないがこの化学組成が判らぬと流体力学的熱力学的理論は使用出来ないので結局実用上重要な産業用爆薬の爆轟圧力の計算が出来ぬ事が多い。

　本報告に於ては爆薬の装填比重 Δg/cm³ と爆轟速度 Dcm/sec のみを用いて爆轟圧力 p_D g/cm² を算出する近似式に付て述べた。即ち

$$p_D=0.000424 D^2\Delta(1-0.543\Delta+0.193\Delta^2)\text{gram, cm,}$$

sec, 又 Δ と D より p_D を容易に求め得るノモグラムを報告し世界各国の主要なダイナマイト類の p_D の計算値を概括した。

(1956.8.23)