RIJKSWATERSTAAT COMMUNICATIONS

Nr 7

THE USE OF EXPLOSIVES FOR CLEARING ICE

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BOORLAAN 2 — THE HAGUE — NETHERLANDS

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Clearing ice barriers with dynamite. *Photograph by Nat. Foto Persbureau.*

1. Introduction

Broadly speaking, explosives are substances the chemical composition of which is capable of undergoing a sudden change under certain circumstances, for instance, when heat is applied or electricity is caused to flow through them or when they are subjected to considerable percussion. Then gases are formed that occupy a far greater space under normal atmospheric pressure and temperature than the original substance. They are released under tremendous pressure owing to the great quantity of heat liberated in the process.

Explosives such as gunpowder, which are not high explosives, are only combustible and turn relatively slowly into gases that have a disruptive effect if they are confined.

High explosives such as TNT, dynamite and guncotton are also combustible but they detonate or explode, which means that conversion into gas is practically instantaneous so that they have a shattering effect if confined. Detonation is brought about by the sudden application of a very high temperature or a very powerful blow that is capable of suddenly generating the necessary high temperature in the explosive.

It is known that attempts were made 200 years ago to use explosives for clearing ice. It was not so much for the benefit of shipping as to remove the ice obstructing the rivers, which formed barriers and caused extensive flooding. Although scientists had discovered how to express the effect of explosives on solids as formulae by the end of the nineteenth century, they had not yet succeeded in producing a formula for their effect on ice. Tables showing the results of experiments conducted in the previous seventy years were the only source of information on the subject. People had to use their own judgment and the results of prior tests, if any were extant. It was when the Delta project and its manifold problems came up for discussion that the need to examine the possibility of making effective use of explosives for clearing ice became apparent.

The programme of experiments drawn up for the purpose included:

a. fundamental tests on Lake IJssel to discover the effects of explosions on ice;

b. tests with explosives on ice in the main rivers under easy conditions for ice-breakers;

c. tests with explosives on ice in the main rivers under difficult conditions for ice-breakers.

A "Working Party for Ice" was set up in the Rijkswaterstaat, to conduct the experiments. Before carrying out any tests, the Working Party sought the advice of the Army Mine School at Soesterberg; the Army also did the placing of the explosives. It turned out to be possible to express the effect of the explosives on the ice in formulae by using the results of the fundamental tests referred to under *a*. The application of those formulae and their effectiveness was then tested.

2. History

As far as can be ascertained, the first attempts to clear ice by means of explosives were made in Germany in 1758. Bombs were affixed below the ice and exploded.

Experiments were conducted more or less regularly after that, although the explosives used above or below the ice altered as time went by. They used bombs or gunpowder in wooden boxes or in bags made of cartridge paper dipped in pitch or in well caulked barrels.

In 1771 a sub-lieutenant in the artillery raised the matter of adopting this method of clearing ice in Holland, too. He suggested to the States of Holland that the ice barriers that had formed in the rivers should be removed by means of mines. No action of that nature appears to have been taken, however, because the earliest known experiments on our rivers date from 1845. In that year there were a number of explosions near Bato's Erf (former hamlet and estate), at Wamel*) on the river Waal and at Dreumelen*). There wooden barrels were filled with gunpowder and let far enough down into the ice to allow the lid to remain just above the surface of the ice. The biggest charge of explosives used in these experiments weighed 350 Kgs (Kilogrammes) and was contained in two barrels lashed together.

Steamboats were used to break the ice in the river Waal when it started to thaw in 1871, but gunpowder was also used to crack the ice with. Opinions on the general results were not unfavourable, but nothing definite was said about the part played by the explosions.

In the winter of 1875/1876 the Sappers and Miners Battalion carried out experiments with dynamite, gunpowder and other explosives, including what is called "lithofracteur".

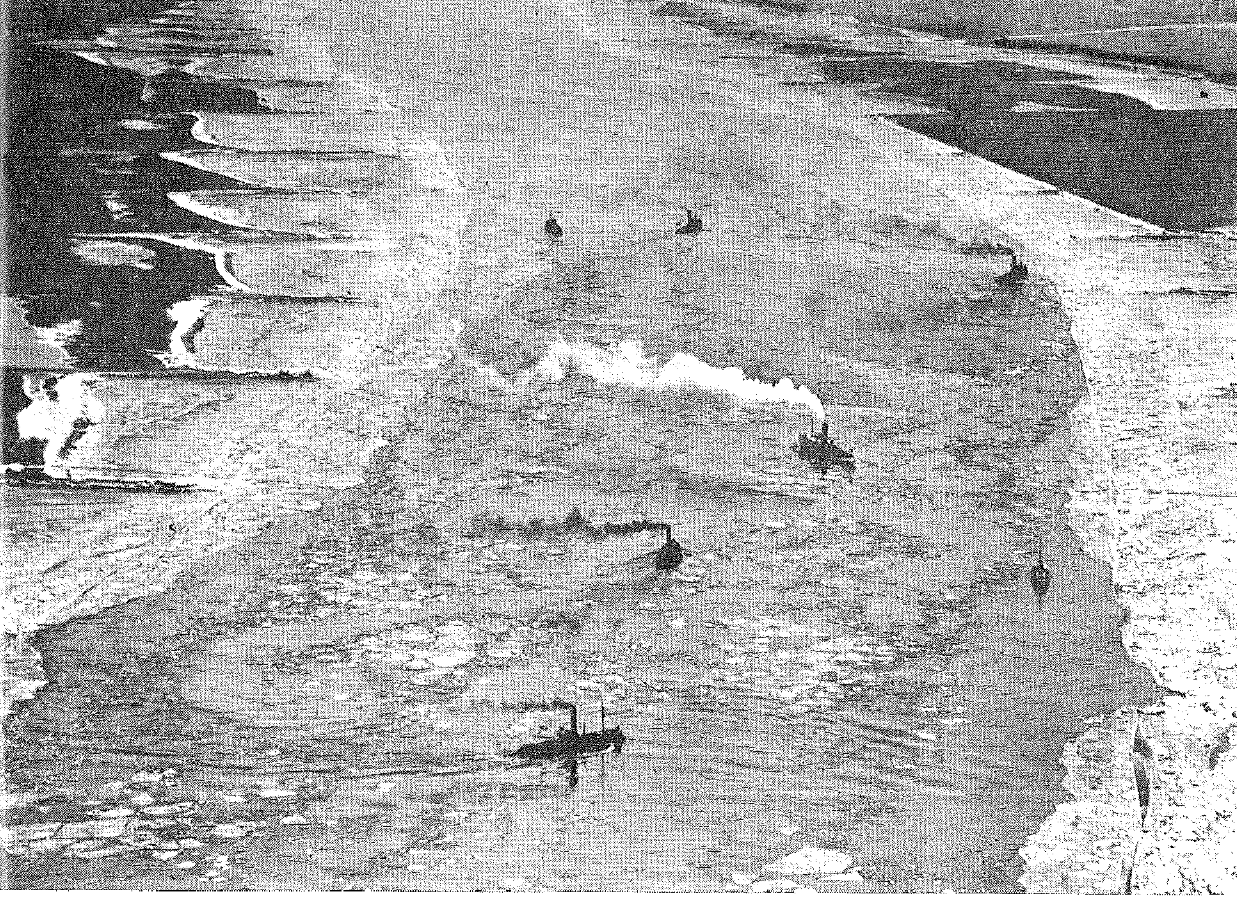
Gunpowder was used to good effect in January 1880 after it had started thawing and explosives were used in January and February 1881 after the cold spell to assist the steamboats. "Lithofracteur" was used as well as gunpowder.

Dynamite was used extensively in the winter of 1891. It became evident that this explosive produced fewer cracks than gunpowder. The main duty of the explosives squads was to clear the ice barriers that the steamboats could not reach.

Explosives were also used in 1895 to assist the ice-breakers. Gunpowder was the explosive generally employed, but occasionally it was dynamite. There is no record of the results obtained.

Both explosives were used once more in the winter of 1917, chiefly to crack the ice in front of the ice-breakers so as to make their work easier. The ice-breakers do not appear to have benefited; ice in which holes had been blown with dynamite or gunpowder seems to have been just as difficult to deal with as ice that had not been touched. Observers said that explosives were of little use.

*) Villages.



Breaking ice on the Waal near Ophemert, February 1954. *Photograph by Royal Dutch Airlines.*

The same method was adopted in 1929; once again explosives were used in advance of the ice-breakers. This time, however, TNT was employed and Thermit was tried a few times. The latter was not a success. Opinions now differed from those held in 1917; it was thought that cracking the ice with explosives ahead of the ice-breakers did make things somewhat easier for them.

TNT was used again in 1940, both to condition the ice ahead of the ice-breakers and to break up the ice in places the ice-breakers could not reach. It is recorded that although the explosions made craters there were no cracks around them.

Attempts were made in 1942 to remove an ice barrier near the village of Ewijk with explosives. Sixteen charges of TNT weighing 10 Kgs each were exploded simultaneously. The holes to receive them were drilled deep enough and the charges were only 8 metres apart. In spite of that, the results fell far below expectations.

In the winter of 1940/1941 the Germans tried bombarding ice from aircraft. One of the bombs struck the ice 80 metres below a bridge, luckily without exploding. Five other bombs also failed to explode. None of those duds were ever found.

Sawing holes with a chain saw.

Photograph by Rijkswaterstaat.

3. Fundamental tests on Lake IJssel

Ever since 1961 whenever there has been ice of adequate thickness, experiments have been carried out to test the effect of explosives. There were experiments on 27th January 1961, 11th January 1963, 31st January 1963, 7th February 1963 and 12th February 1963. They were conducted near Elburg on the stretch of Lake IJssel known as Veluwemeer; on the above dates the ice was about 11 cms (centimetres), 30 cms, 40 cms, 45 cms and 50 cms thick, respectively. The charges were placed on the ice and at various depths below it. Different sizes of charge were used. The diameter of each hole blown in the ice was measured and the thickness of the ice recorded.

The holes required to enable charges to be placed under the ice were either sawn in it or blown in it by detonating charges placed on it. A chain saw driven by a petrol engine was used for sawing the holes. Small, square apertures were made in this manner. The thickness of the ice was arrived at by measuring the block sawn out. The holes made by detonating charges on the ice were not well shaped as a rule and measuring the thickness of the ice was something of a problem. A block had to be sawn out nearby and measured or the edge of the hole had to be approached for the purpose. 125 grammes TNT were enough to blow a suitable hole in ice up to 30 cms thick. That size of charge did not weaken the ice around the aperture to any noticeable extent. Heavier charges had to be employed for ice thicker than 30 cms but then there was considerable weakening of the ice around the hole.

Most of the TNT used in the experiments was in blocks or tins. A few TNT mines weighing 9 Kgs were also used.

Electric detonators were used to explode the charges. The charges below the ice were suspended from slats placed across the apertures. Tests were also made to discover the effect of what are called percussion charges, i.e. two charges suspended one below the other underneath the ice and detonated simultaneously.

4. Tests with explosives on ice in the main rivers

On 5th February 1963 conditions were such as to make it possible to carry out a series of experiments near the village of Opijnen on the river Waal. At that time the ice was about 25 cms thick but of such a structure that one powerful ice-breaker assisted by two of medium power managed to break about 4 kilometres of river per day over its entire width of 250 metres. That gives a capacity of about 500 metres of river per effective breaking hour using three ice-breakers.

The effect of the detonation of charges on the solid sheet of ice was similar to that produced during the tests that had already been conducted in Veluwemeer.

The effect on the breaking capacity of the ice-breakers of the "softening up" of the solid sheets of ice in advance was checked by arranging the charges as shown in Figure 1.

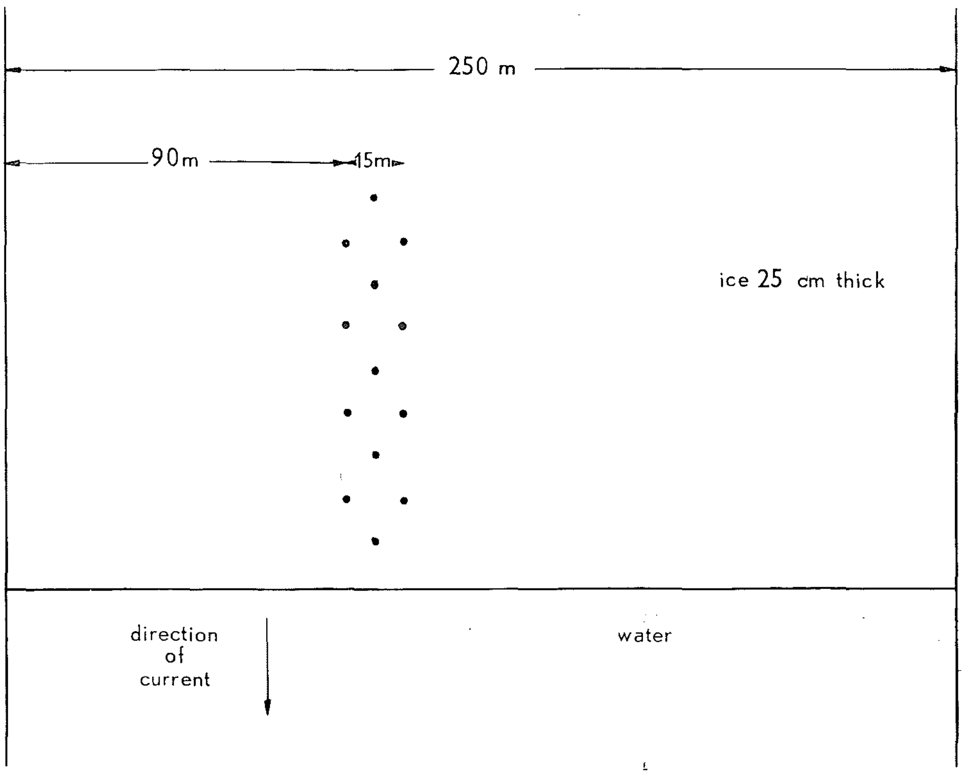


Figure 1. Position of charges underneath the solid ice in the Waal near Opijnen.

The charges were suspended 1 metre below the upper surface of the ice in holes made by detonating charges placed on the ice. The section "softened up" by exploding the charges underneath the ice was then broken up by the ice-breakers. Their breaking capacity did not increase noticeably, nor did the ice show any signs of becoming detached or floating away. The final experiment consisted in detonating four heavy percussion charges placed across the river at intervals of 75 metres and 75 metres away from the downstream edge of the solid sheet of ice. The main charges weighed 9 Kgs each and the percussion charges 3 Kgs.

Although the explosions made large holes in the ice, the rest of the solid mass was apparently still so strong that it did not become detached.

5. The charge formula

If an explosive charge is detonated in water at M (detonation point) which is at a certain depth (h) below the surface (see Figure 2), a sphere of gas of a certain volume is created. There is a certain pressure within the sphere, depending on the quantity of explosive used and its explosive power. The pressure propagates itself spherically from the detonation point through the water and the force exerted by the pressure wave thus set up mainly gives rise to a change in volume. Spherical stress has been set up. The radial stress set up in a sphere of radius r is

$$\frac{pR^2}{r^2},$$

in which p is the pressure in the sphere of gas with radius R.

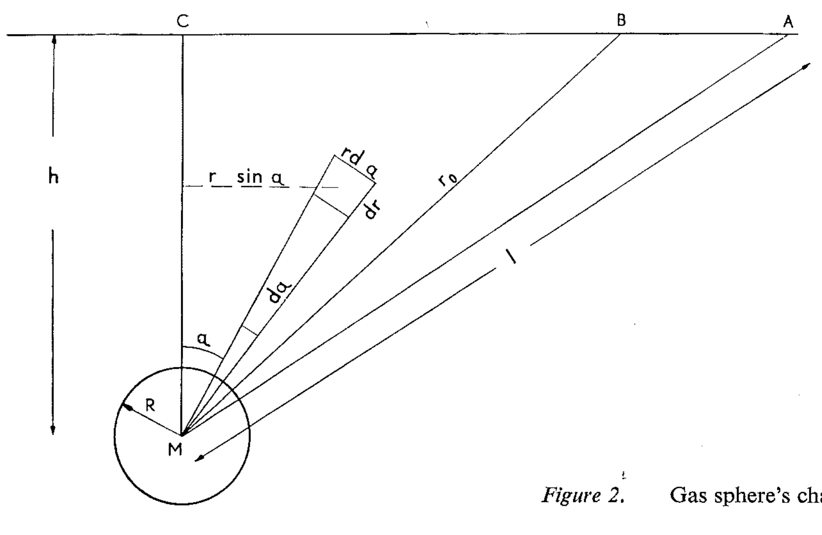


Figure 2. Gas sphere's change of shape.

Assume there is a plane surface r dα dr in area situated a distance of r away from M. The volume dV of the ring with radius r sin α will be $2\pi r^2 \sin\alpha\, d\alpha\, dr$.

The specific change in the volume of the water will be $\varepsilon = \mu\sigma$ in which

$$\mu = \frac{1}{K},$$

K being the compression modulus.

The deformation force dW is $\frac{1}{2}\varepsilon\sigma\, dV$, in which

$$\sigma = \frac{pR^2}{r^2},$$

dV is volume of ring and p is pressure in sphere of gas with radius R. We then see that

$$dW = \tfrac{1}{2}\mu\sigma\, dV = \frac{\pi\mu p^2 R^4}{r^2} dr \sin\alpha\, d\alpha .$$

Force is exerted until the diameter of the sphere is l, when atmospheric pressure is reached. Then we see that

$$W = \pi\mu p^2 R^4 \int_0^{\pi} \sin\alpha\, d\alpha \int_R^{l} \frac{dr}{r^2} = -\pi\mu p^2 R^4 \int_0^{\pi} \sin\alpha\, d\alpha \left| \frac{1}{r} \right|_R^{l} =$$

$$= \pi\mu p^2 R^4 \left(\frac{l-R}{lR}\right) \int_0^{\pi} \sin\alpha\, d\alpha = -\pi\mu p^2 R^4 \left(\frac{l-R}{lR}\right) \Big| \cos\alpha \Big|_0^{\pi} =$$

$$= -\frac{\pi\mu p^2 R^4 (l-R)}{lR}(-2) = \frac{2\pi\mu p^2 R^4 (l-R)}{lR} . \qquad (1)$$

The stress in a sphere of radius l is $\frac{pR^2}{2}$.

This will balance atmospheric pressure, so

$$pR^2 = l^2 . \qquad (2)$$

If there is ice on top of the water (the underside of the ice is shown in Figure 2), the deformation energy will rupture it up to B.

The stress at B will be $\frac{pR^2}{r_0^2}$.

It will have to balance C^2, which is the resistance to pressure of the ice, so

$$\frac{pR^2}{r_0^2} = C^2 \quad \text{or} \quad pR^2 = C^2 r_0^2 . \qquad (3)$$

From (2) and (3) it follows that

$$l = Cr_0 . \quad (4)$$

According to the general law governing gases, the pressure p, the volume V, the mass m and the absolute temperature are related to one another in the following manner: $pV = mCT$ or $p\frac{4}{3}\pi R^3 = mCT = C^1W$ or $W = \varphi pR^3$. Since the weight of the charge L is proportionate to the energy W, we see that $L = \delta pR^3$, and since according to (3)

$$pR^2 = C^2 r_0^2 ,$$

we see that

$$L = \delta C^2 r_0^2 R \qquad \text{or} \qquad R = \frac{L}{\delta C^2 r_0^2} . \quad (5)$$

Since the weight of the charge L is proportionate to the energy $W (L = \lambda W)$, (3), (4) and (5) substituted in (1) gives us

$$L = \frac{2\pi\mu\lambda C^4 r_0^4 \left(Cr_0 - \dfrac{L}{\delta C^2 r_0^2} \right)}{\dfrac{Cr_0 L}{\delta C^2 r_0^2}}$$

or

$$L = \frac{2\pi\mu\lambda\delta C^6 r_0^6}{L} - 2\pi\mu\lambda C^3 r_0^3$$

or

$$L^2 + 2\pi\mu\lambda L C^3 r_0^3 - 2\pi\mu\lambda\delta C^6 r_0^6 = 0$$

$$L = \frac{-2\pi\mu\lambda C^3 r_0^3 \pm \sqrt{4\pi^2\mu^2\lambda^2 C^6 r_0^6 + 8\pi\mu\lambda\delta C^6 r_0^6}}{2} =$$

$$= \pi\mu\lambda C^3 r_0^3 \left[-1 + \sqrt{1 + \frac{2\delta}{\pi\mu\lambda}} \right] .$$

Only the positive root is operative. The term under the root symbol is constant and greater than unity, so we may write

$$L = A r_0^3 \quad (6)$$

If there is ice of thickness d, the spherical pressure wave will be deflected at A and will reach the surface at C, so that a hole with radius t will be blown in the ice (see Figure 3); consequently

$$\sin i_1 = n \sin i_2 , \quad (7)$$

in which n is a constant and the detonation point M seems to have moved to N. The stress along AB and AC remains unaltered.

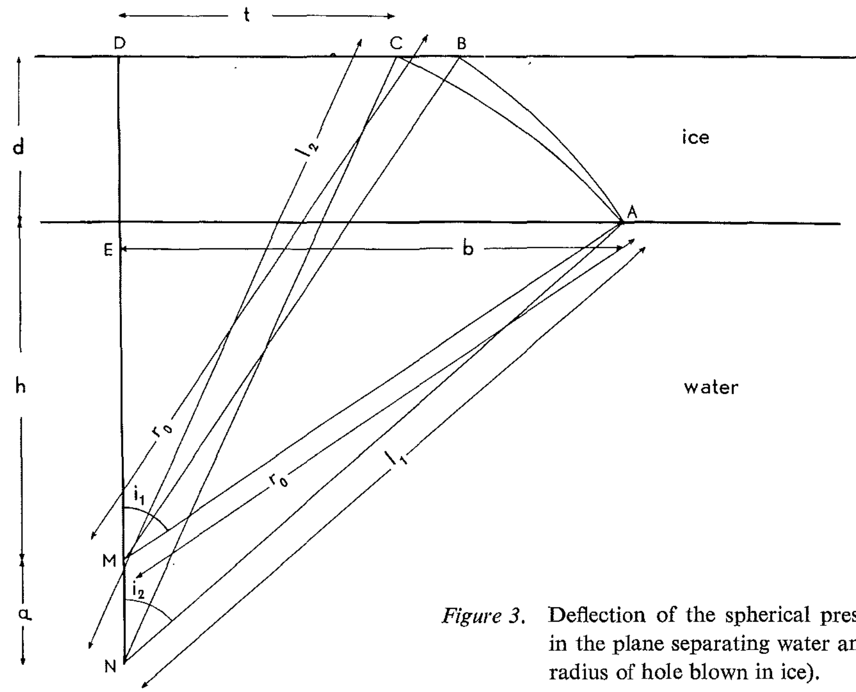


Figure 3. Deflection of the spherical pressure wave in the plane separating water and ice (t = radius of hole blown in ice).

From (7) we see that

$$\frac{b}{r_0} = \frac{nb}{l_1} \qquad \text{or} \qquad l_1 = l_2 = nr_0 \tag{8}$$

and that

$$t^2 = n^2 r_0^2 - (d + h + a)^2 . \tag{9}$$

In the latter

$$a = nr_0 \cos i_2 - r_0 \cos i_1 =$$

$$= nr_0 \sqrt{1 - \sin^2 i_2} - h = nr_0 \sqrt{1 - \frac{\sin^2 i_1}{n^2}} - h =$$

$$= r_0 \sqrt{n^2 - \sin^2 i_1} - h = r_0 \sqrt{n^2 - 1 + \cos^2 i_1} - h =$$

$$= r_0 \sqrt{n^2 - 1 + \frac{h^2}{r_0^2}} - h = \sqrt{r_0^2 (n^2 - 1) + h^2} - h .$$

This value for a substituted in (9) gives

$$t^2 = n^2 r_0^2 - \left[d + \sqrt{r_0^2 (n^2 - 1) + h^2} \right]^2 . \tag{10}$$

In the latter, r_0 is the term from (6) $L = Ar_0^3$.

6. Size of charge that will just break ice from below

To discover this, t (radius of hole blown) in (10) is made zero, so that

$$n^2 r_0^2 = \left[d + \sqrt{r_0^2(n^2 - 1) + h^2}\right]^2.$$

On working this out we see that

$$r_0^2 = h^2 + d^2(2n^2 - 1) + 2nd\sqrt{d^2(n^2 - 1) + h^2}.$$

Substituting

$$r_0 = \sqrt[3]{\frac{L}{A}}$$

(formula 6), we get the charge required (L)

$$\sqrt[3]{\left(\frac{L}{A}\right)^2} = h^2 + d^2(2n^2 - 1) + 2nd\sqrt{d^2(n^2 - 1) + h^2}. \qquad (11)$$

This formula can be used to calculate the minimum weights of charge for various h and d values required to rupture the ice.

7. Double charge, called percussion charge, underneath the ice (Figure 4)

r_1 must satisfy equation (10):

$$t^2 = n^2 r_1^2 - \left[d + \sqrt{r_1^2(n^2 - 1) + h_1^2}\right]^2$$

from this we see that r_1 can be deduced from

$$r_1^2 = (t^2 - d^2 + h_1^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_1^2n^2}, \qquad (12)$$

r_2 must satisfy

$$r_2^2 = (t^2 - d^2 + h_2^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_2^2n^2}. \qquad (13)$$

The stress at C due to the charge L_1 is $\dfrac{p_1 R_1^2}{r_1^2}$.

Charge L_2 also sets up a stress at the same point. It is $\dfrac{p_2 R_2^2}{r_2^2}$.

The two stresses must balance the resistance to pressure of the ice, i.e.

$$\frac{p_1 R_1^2}{r_1^2} + \frac{p_2 R_2^2}{r_2^2} = C^2. \qquad (14)$$

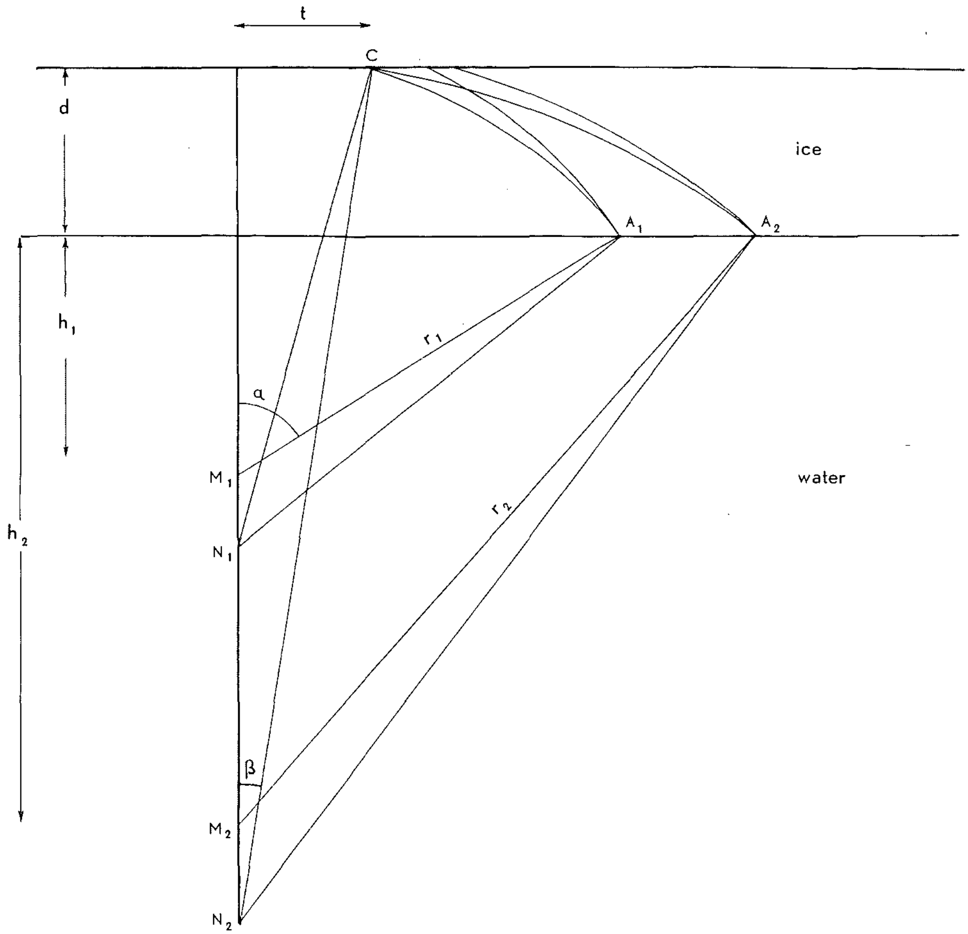


Figure 4. Deflection of pressure waves in the plane between water and ice when double charges (percussion charges) are used (t = radius of hole blown in ice).

The aberration due to the shock wave not reaching A_1 and A_2 simultaneously because of the difference in distance is ignored.
Formula (3) shows us that for L_1

$$p_1R_1^2 = C^2r_1^2$$

or

$$p_1R_1^2 = C^2\sqrt[3]{\left(\frac{L_1}{A}\right)^2}.$$

For L_2 we get

$$p_2R_2^2 = C^2\sqrt[3]{\left(\frac{L_2}{A}\right)^2}.$$

Fixing the firing-cable to the charge.

Photograph by Rijkswaterstaat.

Substituting these two terms in (14) we get

$$\frac{\sqrt[3]{\left(\frac{L_1}{A}\right)^2}}{r_1^2} + \frac{\sqrt[3]{\left(\frac{L_2}{A}\right)^2}}{r_2^2} = 1 \qquad \text{or} \qquad \frac{\sqrt[3]{L_1^2}}{r_1^2} + \frac{\sqrt[3]{L_2^2}}{r_2^2} = \left(\sqrt[3]{A}\right)^2.$$

Substituting the values of r_1 and r_2 obtained from formulas (12) and (13) gives us the charge formula for percussion charges, viz.

$$\frac{\sqrt[3]{L_1^2}}{r_1^2} + \frac{\sqrt[3]{L_2^2}}{r_2^2} = \left(\sqrt[3]{A}\right)^2 \qquad (15)$$

in which

$$r_1^2 = (t^2 - d^2 + h_1^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_1^2n^2},$$

$$r_2^2 = (t^2 - d^2 + h_2^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_2^2n^2}.$$

This formula can be used for calculating the diameter (t) of the hole blown in the ice.

8. Charge formula for charges placed on the ice

The spherical pressure wave is deflected in the air/ice plane (Figure 5), as is the case with charges placed underneath the ice. The detonation point M appears to move to N.

A formula analogous to (5) gives us for a charge underneath the ice

$$t^2 = n^2 r_0^2 - \left[d + \sqrt{r_0^2 (n^2 - 1)}\right]^2 \tag{16}$$

r_0 being the term from (6) $L = Ar_0^3$.

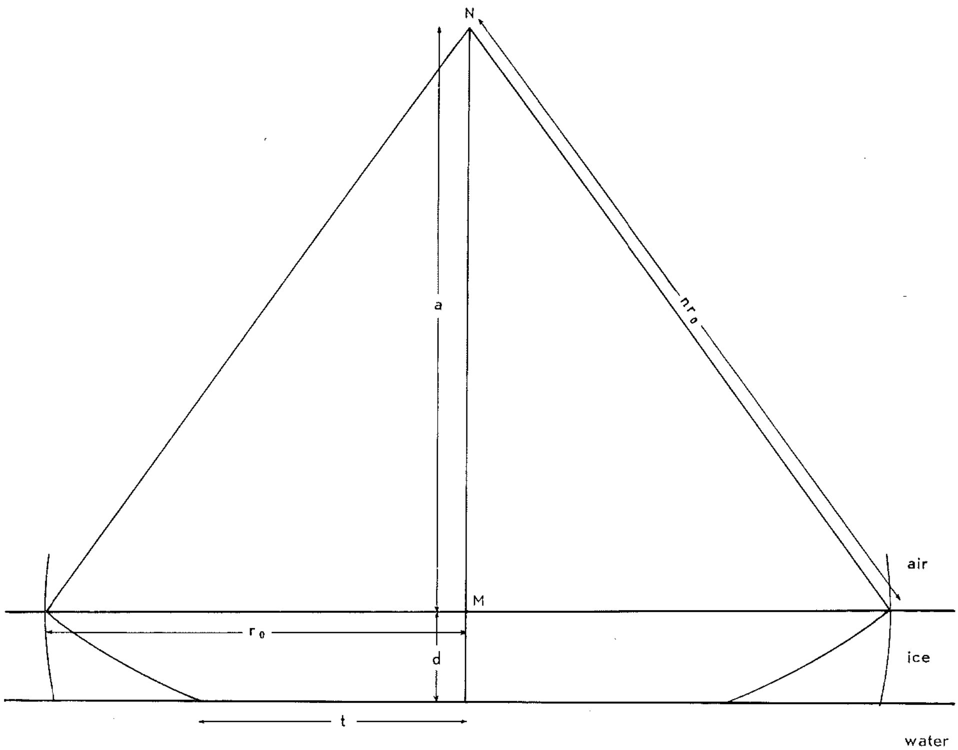


Figure 5. Deflection of spherical pressure wave in the air/ice plane (t = radius of hole blown in ice).

9. Weight of charge placed on the ice just powerful enough to break it

To arrive at this, t (radius of hole blown in ice) is made zero in (16), so that

$$n^2 r_0^2 = \left[d + \sqrt{r_0^2 (n^2 - 1)}\right]^2.$$

On working this out we get a formula analogous to (11)

$$\sqrt[3]{\left(\frac{L}{A}\right)^2} = d^2 (2n^2 - 1) + 2n\,d\sqrt{d^2 (n^2 - 1)}. \tag{17}$$

This formula can be used for calculating for various d values the minimum weights of charge just powerful enough to break the ice.

10. Determining the coefficients

The coefficients A and n can be determined by using the results of experiments reported on in

- Explosives regulation No. 427 of 1914, Engineers Corps;
- "Clearing ice with dynamite and guncotton" by G. J. Blaauw, from "Minutes of meeting on 14th November 1871", Royal Institute of Engineers Journal, Institute year 1871–1872;
- Reports on experiments conducted by the Rijkswaterstaat and the Army on Veluwemeer in 1961 and 1963 (for internal use only).

The following formulae were used for calculating the A coefficients:
(6) and (10) for single charges under the ice;
(6) and (15) for double charges under the ice;
(6) and (16) for charges on the ice.

The value at which the least spreading occurred in coefficient A was taken as the deflection coefficient n and after the elemination of the dependence on the measured quantities.

Firing the charge.

Photograph by Rijkswaterstaat.

Tables 1 to 8 give the results of tests with the values of A and n calculated therefrom for the various types of explosive.

L = weight of charge in Kgs
d = thickness of ice in metres
h = depth of charge below under-surface of ice in metres
t = radius of hole in metres

and for percussion charges

h_2 = depth of main charge below under-surface of ice in metres
h_1 = depth of percussion charge below under-surface of ice in metres
L_2 = weight of main charge in Kgs
L_1 = weight of percussion charge in Kgs.

Table 1. Calculation of coefficient A for single charges of gunpowder under the ice when n = 1.1

No. of tests	L	d	h	t	A
5	7.0	0.25	1.25	2.50	0.268
5	12.0	0.25	1.75	4.00	0.129
5	12.0	0.35	1.65	3.50	0.174
5	15.0	0.35	2.15	3.75	0.157
5	25.0	0.35	2.15	6.00	0.088
5	12.0	0.45	1.55	3.00	0.237
5	25.0	0.45	2.05	7.00	0.058
5	12.0	0.55	1.45	3.50	0.167
5	25.0	0.55	1.95	7.00	0.057
5	12.0	0.65	1.35	3.50	0.163
3	25.0	0.65	1.85	6.00	0.084
3	25.0	1.90	0.60	4.25	0.137
				average:	0.146

Table 2. Calculation of coefficient A for single charges of dynamite under the ice when n = 1.1

No. of tests	L	d	h	t	A
4	2.50	0.15	0.85	3.75	0.041
4	2.50	0.25	0.25	3.50	0.052
8	5.00	0.25	0.25	3.75	0.085
12	5.00	0.25	1.75	4.25	0.047
30	2.50	0.35	0.65	4.00	0.033
3	5.00	0.35	1.65	4.50	0.040
16	2.50	0.45	0.55	4.00	0.032
12	2.50	0.55	0.45	3.25	0.054
7	2.50	0.65	0.35	3.50	0.042
5	2.50	0.85	0.15	2.625	0.078
				average:	0.045

Effect of charge underneath the ice. Some tangential and radical cracks are visible around the hole.

Photograph by Rijkswaterstaat.

Table 3. Calculation of coefficient A for single charges of guncotton under the ice when n = 1.1

No. of tests	L	d	h	t	A
6	0.28	0.63	0.32	1.20	0.053
1	0.28	0.52	0.43	1.25	0.055
4	0.28	0.47	0.48	1.425	0.045
6	0.28	0.95	0.00	1.105	0.037
3	0.56	0.63	0.32	2.00	0.038
2	0.56	0.52	0.43	1.90	0.047
6	0.56	0.47	0.48	1.79	0.055
3	0.84	0.63	0.47	2.00	0.055
1	0.84	0.52	0.58	2.50	0.035
2	0.84	0.47	0.63	2.50	0.036
				average:	0.047

Table 4. Calculation of coefficient A for single charges of American TNT under the ice when n = 1.1

No. of tests	L	d	h	t	A
1	0.454	0.09	0.00	1.525	0.117
1	0.454	0.11	0.50	1.70	0.073
1	0.908	0.10	0.00	2.11	0.090
1	0.908	0.14	0.50	2.10	0.081
1	0.908	0.13	2.00	1.25	0.059
				average:	0.084

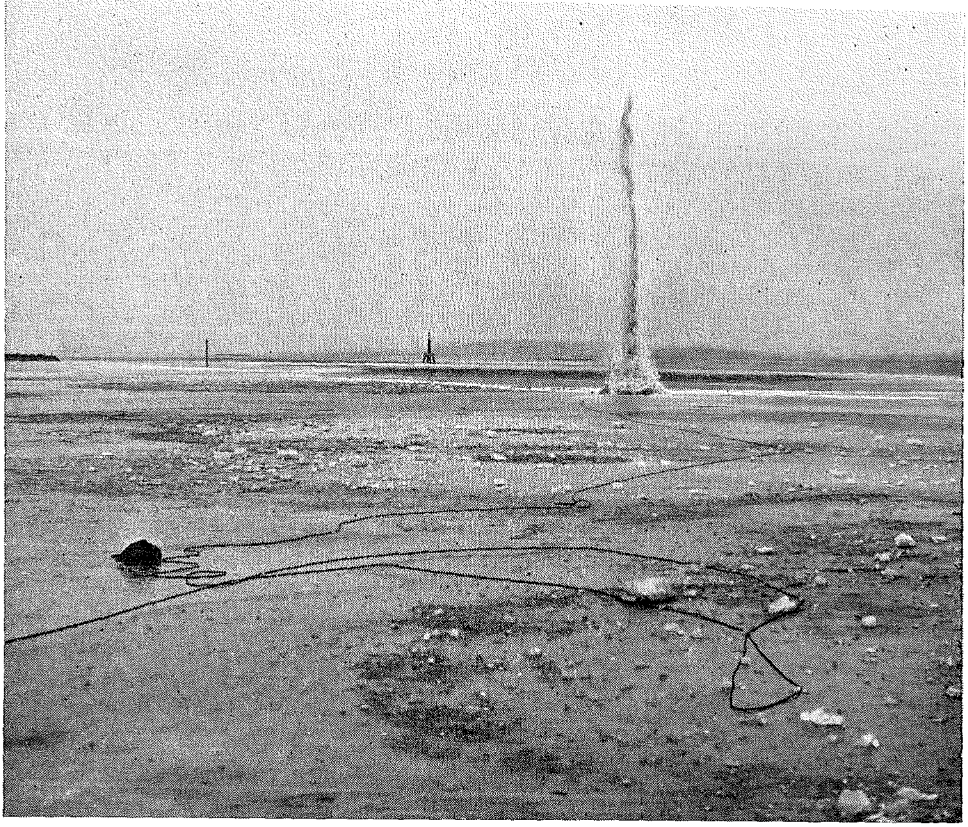
Table 5. Calculation of coefficient for single charges of Dutch TNT under the ice when n = 1.1

No. of tests	L	d	h	t	A	Average	Remarks
1	0.25	0.40	1.00	0.575	0.064	0.066	sawn
1	0.25	0.35	0.00	1.25	0.079		sawn
1	0.50	0.36	0.00	1.725	0.069		sawn
1	1.00	0.39	0.00	2.30	0.063		sawn
1	2.00	0.35	0.00	3.075	0.058		sawn
1	0.25	0.30	0.00	1.20	0.095		sawn
1	0.50	0.30	0.00	1.95	0.053		sawn
1	1.00	0.30	0.00	2.65	0.045		sawn
1	8.50[1])	0.40	2.70	4.75	0.045	0.043	500 g TNT
1	0.50	0.40	2.00	0.40	0.033		500 g TNT
1	1.00	0.40	2.00	0.50	0.064		500 g TNT
1	2.00	0.40	2.00	3.00	0.033		500 g TNT
1	3.00	0.40	2.00	3.50	0.037		500 g TNT
1	8.50[1])	0.30	1.50	5.25	0.048		500 g TNT
1	0.50	0.40	1.00	2.10	0.028	0.027	500 g TNT
1	1.00	0.40	1.00	3.15	0.022		500 g TNT
1	2.00	0.40	1.00	3.50	0.034		500 g TNT
1	3.00	0.40	1.00	4.625	0.025		500 g TNT
1	0.50	0.30	0.50	1.95	0.047	0.054	125 g TNT
1	1.00	0.30	0.50	2.45	0.052		125 g TNT
1	2.00	0.30	0.50	3.00	0.061		125 g TNT

[1]) mine M 26

As stated under the heading "Remarks" some of the holes made to admit the charges were sawn while others were blown with TNT.

Table 5 shows that the holes for the charges may be either sawn or blown in the ice by means of a small charge of TNT. If the charges used for making the holes weigh 125 grammes the ice will not be weakened any more than it would if the holes were sawn. If charges of TNT weighing 500 grammes TNT were used, the ice will be weakened more than it would if the holes were sawn, which is reflected in a smaller value for A. There is less weakening the deeper the main charge is set.



Detonating percussion charge underneath the ice. *Photograph by Rijkswaterstaat.*

Table 6. Calculation of coefficient A for double charges of Dutch TNT under the ice when n = 1.1

No. of tests	h_2	h_1	L_2	L_1	d	t	A
1	1.22	0.22	2	1	0.28	3.825	0.060
1	1.50	0.50	8.5[1])	3	0.40	6.00	0.061
1	2.00	1.30	8.5[1])	3	0.40	6.50	0.046
1	2.00	0.60	3	1	0.50	4.60	0.039
1	1.97	1.27	3	1	0.53	3.50	0.069
1	2.00	2.00	3	0.50[2])	0.40	3.875	0.045
1	1.60	1.50	3	1	0.40	3.75	0.068
1	1.55	1.45	3	1	0.45	4.425	0.044
1	0.45	0.15	3	1	0.55	3.50	0.096
1	1.45	1.15	8.5[1])	3	0.55	6.00	0.058
1	1.45	1.15	8.5[1])	1	0.55	5.25	0.062
1	1.45	1.45	8.5[1])	0.125[3])	0.55	4.50	0.066
1	2.30	2.00	8.5[1])	1	0.50	5.375	0.051
1	2.45	2.15	8.5[1])	3	0.45	5.625	0.060
						average:	0.059

[1]) mine M 26 [2]) block on its side [3]) plastic explosive

Table 7. Calculation of coefficient A for double charges of ammonal in tins under the ice when n = 1.1

No. of tests	h_2	h_1	L_2	L_1	d	t	A
1	1.50	0.50	3	1	0.50	3.25	0.098
1	0.95	0.20	3	1	0.45	4.125	0.061
1	1.50	0.50	6	2	0.50	5.00	0.067
1	0.95	0.45	3	3	0.50	4.50	0.075
						average:	0.075

Table 8. Calculation of coefficient A for charges of TNT and plastic explosive on the ice when n = 1.7

No. of tests	Type of explosive	L	d	t	A	Average
1	Am TNT	0.454	0.12	0.965	0.298	
1	Am TNT	0.908	0.12	1.325	0.266	0.343
1	Am TNT	1.362	0.12	1.25	0.464	
1	Mine M 26	8.500	0.28	3.25	0.172	
1	Dutch TNT	0.250	0.28	0.30	0.294	
1	Dutch TNT	0.500	0.28	0.375	0.514	
1	Dutch TNT	1.000	0.28	0.65	0.593	0.352
1	Dutch TNT	0.250	0.41	0.25	0.113	[1]
1	Dutch TNT	0.500	0.41	0.35	0.206	
1	Dutch TNT	1.000	0.41	0.40	0.391	
1	Dutch TNT	1.000	0.21	0.20	1.093	drilling cartridge
1	plastic explosive	0.0625	0.28	0.20	0.085	
1	plastic explosive	0.125	0.28	0.25	0.159	0.135
1	plastic explosive	0.125	0.28	0.25	0.159	

[1]) charge did not go through ice

11. Summary of results

11.1. Single charge under the ice

$$t^2 = n^2 \sqrt[3]{\frac{L^2}{A^2}} - \left[d + \sqrt{\sqrt[3]{\frac{L^2}{A^2}}(n^2 - 1) + h^2}\right]^2$$

in which

- t = radius of hole blown in metres
- n = deflection coefficient (here taken as 1.1)
- L = weight of charge in Kgs
- A = constant
- d = thickness of ice in metres
- h = distance from charge to under-surface of ice in metres.

Value of A for

Dutch TNT	0.066
American TNT	0.084
Guncotton	0.047
Dynamite	0.045
Ammonal	0.075
Gunpowder	0.146.

The connection between the weight of charge L, the diameter of the hole blown and the thickness of the ice when Dutch TNT is used at various depths below the ice is shown in Figures 6 to 14. The data on which these figures are based are given in Tables 9 to 17.

11.2. Double charge under the ice

$$r_1^2 = (t^2 - d^2 + h_1^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_1^2n^2},$$

$$r_2^2 = (t^2 - d^2 + h_2^2 + 2d^2n^2) + 2d\sqrt{d^2n^4 - t^2 + t^2n^2 - d^2n^2 + h_2^2n^2},$$

$$\frac{\sqrt[3]{L_1^2}}{r_1^2} + \frac{\sqrt[3]{L_2^2}}{r_2^2} = \sqrt[3]{A^2}$$

in which

- t = diameter of hole blown in metres
- n = deflection coefficient (here taken as 1.1)
- d = thickness of ice in metres
- h_1 = distance from main charge to under-surface of ice
- h_2 = distance from percussion charge to under-surface of ice
- L_1 = weight of main charge in Kgs
- L_2 = weight of percussion charge in Kgs
- A = constant.

he values given in 11.1 can be taken for the constant A.

11.3. Charge on the ice

$$t^2 = n^2 \sqrt[3]{\frac{L^2}{A^2}} - \left[d + \sqrt{\sqrt[3]{\frac{L^2}{A^2}}(n^2 - 1)} \right]^2$$

in which

t = diameter of hole blown in metres
n = deflection coefficient (here taken as 1.7)
L = weight of charge in Kgs
A = constant
d = thickness of ice in metres.

Values for A

Dutch TNT	0.352
American TNT	0.343
Mine M 26	0.172
Plastic explosive	0.135
TNT (drilling cartridge)	1.093.

The connection between the weight of charge L, the diameter of the hole blown and the thickness of the ice is shown for Dutch TNT in Figure 15. The data on which this figure is based are given in Table 18.

11.4. Minimum charge needed to break through the ice

11.4.1. Charge under the ice

$$L = A\sqrt{[h^2 + d^2(2n^2 - 1) + 2nd\sqrt{d^2(n^2 - 1) + h^2}]^3}$$

in which

L = weight of charge that will just break through the ice, in Kgs
n = deflection coefficient (here taken as 1.1)
d = thickness of ice in metres
h = distance from charge to under-surface of ice in metres
A = constant.

The data given in 11.1 can be adopted for the constant A.

The connection between the minimum charge needed to break through the ice and the thickness of the ice with charges at various depths and using Dutch TNT is shown in Figure 16. The data on which this figure is based are given in Table 19.

11.4.2. Charge on the ice

$$L = Ad^3\left(n + \sqrt{n^2 - 1}\right)^3$$

in which

L = weight of charge that will just break through the ice, in Kgs
n = deflection coefficient (here taken as 1.7)
d = thickness of ice in metres
A = constant.

The data given in 11.3 can be adopted for the constant A.

Ice floes slid underneath each other at Hardinxveld on the Upper Merwede, February 1929. The ice-breaker (part of which is to be seen in the right lower corner) is steaming backwards. Ice floes shooting to the surface. *Photograph reproduced by kind permission of Mr. C. G. Krayenhoff van de Leur.*

The connection between the minimum charge needed to break through the ice and the thickness of the ice is given in Figure 17. The data on which this figure is based are given in Table 20.

12. How explosives can be used for removing ice

12.1. Cost of breaking solid sheet ice

The thickness of ice in the rivers varies roughly from 10 cms to 40 cms. Ice may pile up in places when ice floes slide underneath each other. Ice-breaking on the rivers is usually done first of all by attacking it with three heavy motor-driven ice-breakers (220–325 h.p.). The most powerful one is in the middle, the other two on either side of it. They are followed by a few smaller ice-breakers that reduce the floes and sheets of ice to smaller proportions. Ice-breakers can negotiate thin ice (i.e. up to about 10 cms) without difficulty. The waves they create break the ice. When dealing with thick ice (i.e. up to 40 cms or 50 cms) anchored to the banks, the ice-breakers have to retreat again and again to get up speed; their momentum will then take them anything from $\frac{1}{2}$ to $1\frac{1}{2}$ times their own length into the ice. Steam-driven ice-breakers will travel further than motor-propelled vessels. The area they can deal with in a certain time is about the same; steam-driven vessels are more difficult to manoeuvre than those driven by internal combustion engines.

Ice on the lower reaches of the rivers can only be broken at ebb tide, because the ice has to be got rid of. The work can go on all day on the upper reaches. The time may come when it will be desirable to break ice at night, too. A good system of beacons and proper lighting would be essential if that is to be done.

The daily "production" of an ice-breaker in normal river ice (30–40 cms thick) may be set at 900 metres of river 300 metres wide, i.e. an area of 27 hectares. The average cost may be set at 190 Dutch guilders per "breaking" hour. Assuming that breaking goes on for 9 hours daily, this works out at 70 guilders per hectare.

12.2. Cost of blowing up solid sheet ice

12.2.1. Charges placed on the ice

The simpliest employment is the M 26 mine. When placed on ice 40 cms thick it will blow a hole in it with a radius of 2.25 metres. The area of ice thus destroyed is $\pi(2.25)^2$ square metres. If the holes are located at the corners of a network of squares of such a size that the holes touch each other, the total area destroyed will be $4/\pi : \pi 2.25^2 = 20.25\ m^2$. Taking 45 guilders as the cost of a mine, this works out at 2.22 guilders per square metre. The mines are comparatively easy to lay. It may be assumed that one man can lay and detonate 12 mines per hour if the ice is smooth and easy to move about on. At a wage of 5 guilders per hour that means another 0.01 guilder per square metre.

About 125 men would be required to break the same area in one day as a single ice-breaker (i.e. 900×300 square metres), because

$$\frac{900 \times 300}{9 \times 20.25 \times 12} = \text{approx}.125.$$

The cost per hectare is 10.000×2.23 guilders $= 22.300$ guilders. That is 320 times as expensive as an ice-breaker.

The cost can be cut and the number of men required can be reduced considerably by blowing continuous swaths in the ice so that large floes can float away and be reduced by ice-breakers. The holes would have to overlap far enough to make the ice self-releasing and incapable of getting caught. This will be difficult to achieve in practice.

12.2.2. Charges underneath the ice

Explosives are most effective when charges are placed immediately below the ice. The relation between quantity of explosive, thickness of ice and diameter of hole for that position of the charge is shown in Figure 6. The quantity of explosive per square metre of ice blown out increases as the quantity of explosive rises. If the ice is 40 cms thick, 0.75 Kgs TNT must be detonated on it to make the hole through which the main charge must be lowered. This should be added to the main charge. It will then be seen that the total quantity of explosive required per square metre of ice blown up is at its lowest when a main charge of 2 Kgs TNT is used. The total quantity of explosive required is then 2.75 Kgs. With TNT at 4 guilders a Kg the cost of blowing up a square metre of ice works out at 0.33 guilders, the cost of labour being negligible. The cost of clearing one hectare would be 3.300 guilders, i.e. 47 times as much as it would cost to use ice-breakers for the same area. It may be assumed that one man would be able to set off 8 charges per hour on the ice or 6 charges under the ice if it is smooth and easy to move about on. By this method 260 men would be required to break the same area of ice in one 9-hour day as an ice-breaker could break, i.e. over 2 times as many as would be needed for detonating charges placed on the ice.

12.3. Clearing ice barriers

Ice barriers may form under certain circumstances in both the upper and the lower reaches of the rivers due to ice floes sliding under a sheet of ice that is anchored along the sides. The water level may rise, depending on the thickness of the ice-jam and the extent to which the water is prevented from running away. Sometimes the mass of ice is so loosely packed that huge quantities shoot to the surface as soon as breaking operations start. The operation consists largely in cracking the solid top layer to allow the ice below it to reach the surface and float away (see photograph page 26). Though it is sometimes slow work, it is not difficult. Breaking by means of ice-breakers is again the best and most economical method.

If the ice piles up so much that it prevents the water from getting away and the level is in danger of rising, the obstruction is called an ice dam. They may reach the bottom and may extend along a considerable stretch of the river. They may be as much as 6 metres thick and their downstream ends may project several metres above the water. The water level downstream is usually low, due to the obstruction, and the strong current flowing underneath the dam may cause sand to be moved and sand-banks to form. Breaking is accomplished by attacking the ice from the downstream end; large lumps are broken off until the ice starts moving. It may take as long as three days to do this. The work is not entirely lacking in hazards, because the downstream edge sticks several metres straight up out of the water. There is also the danger of the vessels running aground, owing to sandbanks that may have formed, reducing their manoeuvreability.

Recourse may be had to various expedients when attempting to clear ice dams with explosives. Charges can be placed on the ice. If they are to be at all effective, they should shatter the ice right to the bottom of the dam. But that requires very heavy charges; 700 Kgs TNT would be needed for a dam 4 metres thick. Very much less explosive is required when M 26 mines (8.5 Kgs TNT) are employed.

Another method is to detonate charges underneath the ice. According to Figure 6, an ice dam 4 metres thick would require a charge weighing anything between 10 and

Ice dam at Deest on the Waal, February 1940. *Photograph, property of Rijkswaterstaat.*

20 Kgs. The difficulty lies in making a hole big enough to take a charge of that size. A hole may be hacked in the ice with a chopper or small charges can be detonated on the ice, but the greatest depth attainable by such means is about 1 metre. A 300 Kg charge of TNT or 16 M 26 mines (13.5 Kgs TNT) would be needed to smash the remaining 3 metres. The foregoing explains why attempts to clear ice dams by means of explosives have so far not been very successful. The charges were too light to shatter the ice right down to the bottom of the dam, no matter whether they were placed on the ice or in holes in the ice.

There are serious objections to using explosives in the manner described above. The detonation of very heavy charges may damage buildings or structures in the vicinity. That may compel us to restrict the number of charges detonated simultaneously, even when using M 26 mines. After detonation, ice-breakers would have to go into action to reduce any pieces loosened and to break off large portions of the dam. It would undoubtedly have been weakened by such treatment, but then the difficulty would arise of deciding whether further charges should be set off and whether such a step would endanger the lives of those engaged in the work.

Consequently, it is advisable to set off as large a number of mines as possible simultaneously when they are being used in groups, because it may be dangerous to go on the dam after they have been detonated.

13. Conclusions

It is clear from the foregoing that it is theoretically possible to clear ice by means of explosives. Practical tests have shown, however, that placing the charges and detonating them is time-consuming and calls for a large labour force. Moreover, explosives are much more expensive than ice-breakers. The simplest method is to put explosive charges on the ice. But the quantity required per square metre of ice shattered in that manner is excessive. It can be reduced quite considerably by using M 26 mines.

Detonating very large charges may cause damage to buildings, installations, etc. in the vicinity. So in many cases the total quantity of explosive set off at a certain moment would have to be kept down.

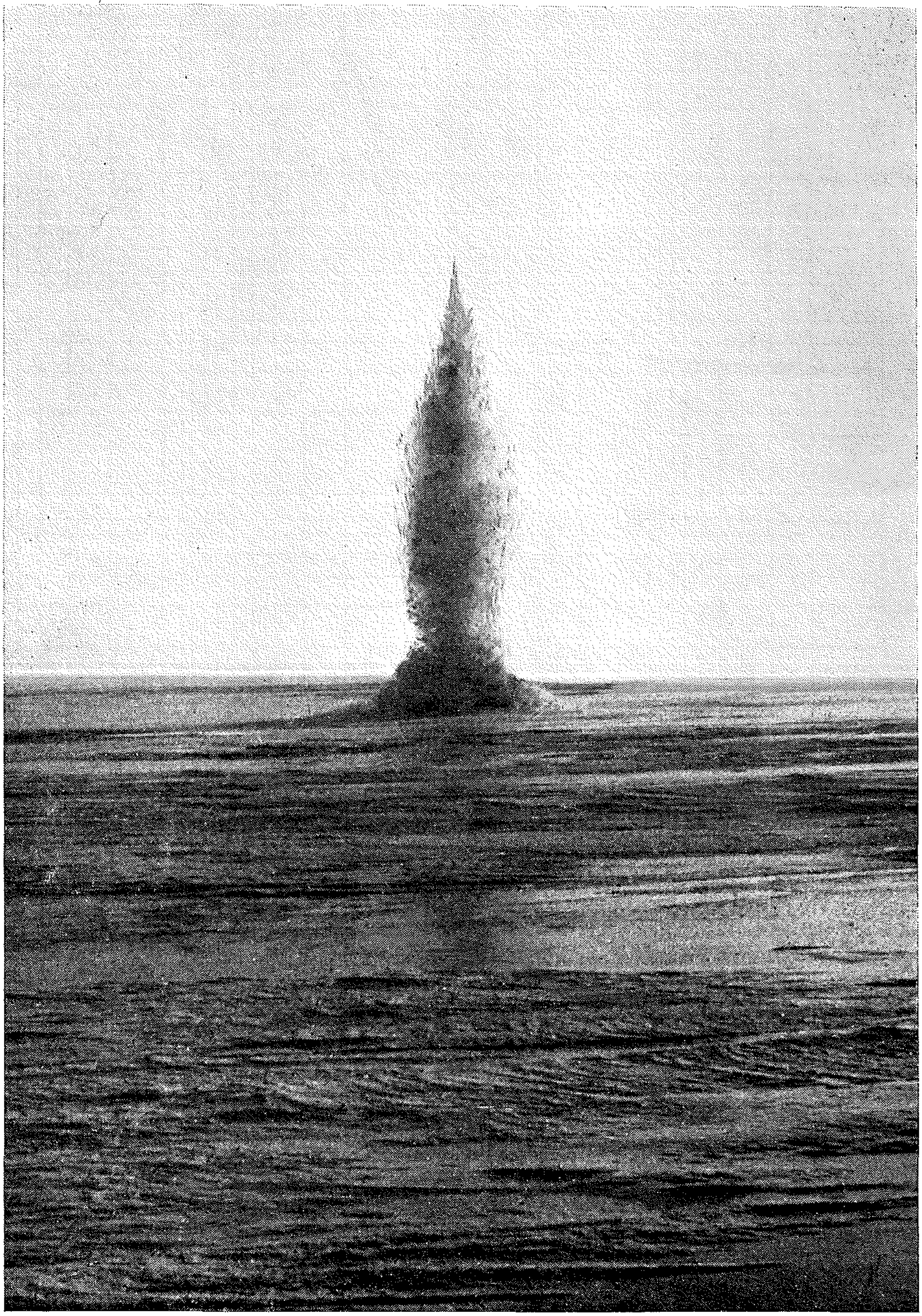
Explosives are most effective when placed right underneath the ice. But that cannot be done until holes have been made in the ice, which increases the quantity of explosive needed and the time required for the whole operation.

Another disadvantage of explosives is that they make craters or round holes in the ice with very few cracks. Consequently, the rest of the ice is not weakened as much as one would imagine, so it makes little difference to the work the ice-breakers have to do. Besides, extreme care must be taken when moving about on river ice, both before and after using explosives.

To sum up: Ice-breakers are always preferable to explosives, even when large ice dams have to be dealt with. The use of explosives is only justified if it has been found impossible to break an ice dam with ice-breakers or in case of emergency.

The calculations in this report and the results they produce give some idea of the size and optimum placing of charges.

Although the idea of bombarding ice and attacking it with rockets from the air would seem an attractive proposition because it can be done with greater safety to those employing the method, it is open to grave objections because it is difficult to control. The risk of projectiles not exploding when they hit ice is very great indeed, and as it is very difficult to find duds again, the method is condemned; it would constitute too great a hazard to shipping.



Photograph by G. Piket.

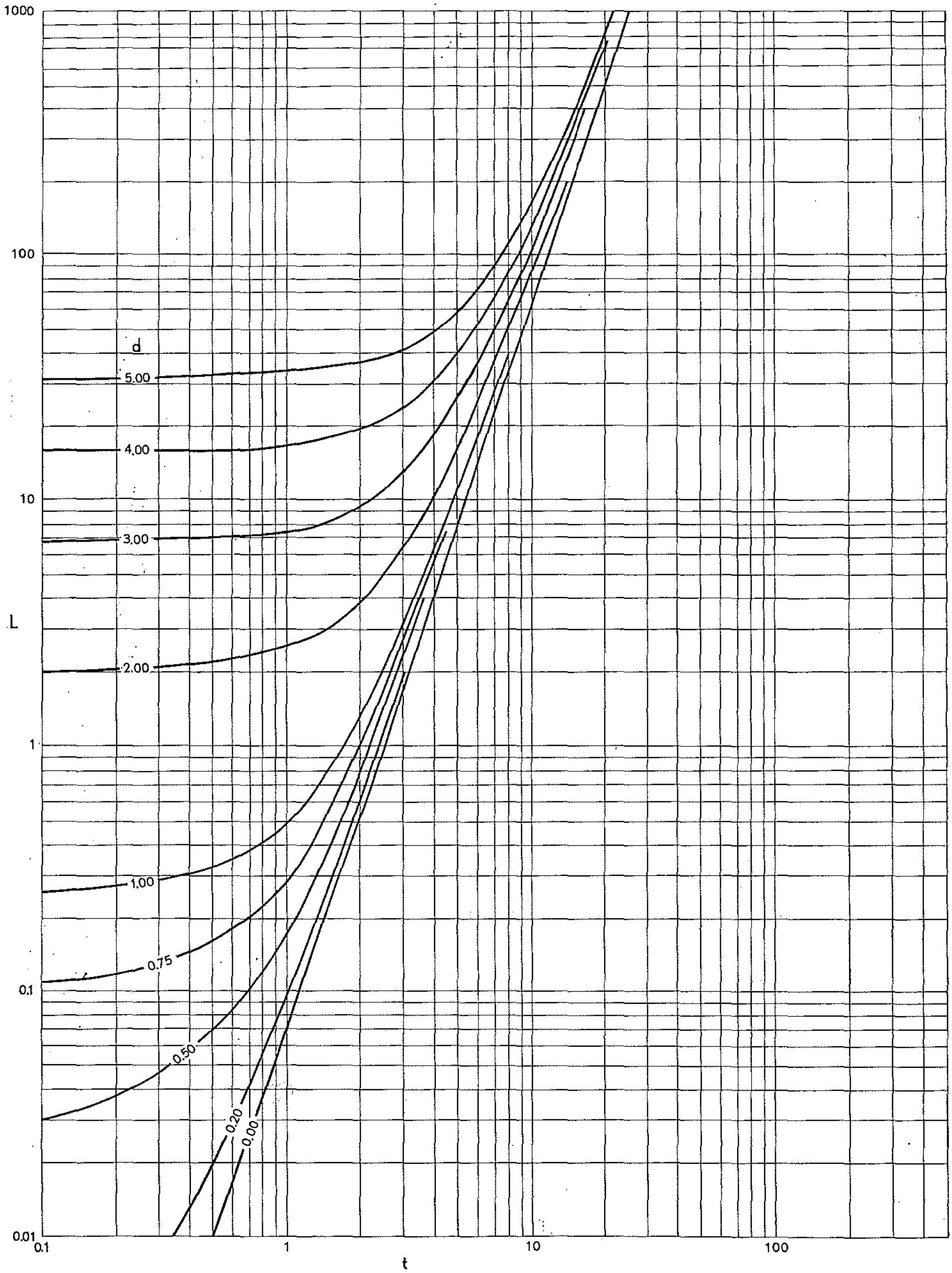


Figure 6. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius of hole blown in ice) for charges placed 0.00 metre below the under-surface of the ice.

Table 9. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 0.00 metre below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250	1.56	1.45	1.21	0.89	0.04				
0.500	1.96	1.86	1.64	1.40	1.03				
0.750	2.25	2.14	1.94	1.72	1.41				
1	2.47	2.37	2.18	1.96	1.69				
2	3.12	3.02	2.84	2.65	2.42	0.07			
3	3.57	3.47	3.29	3.12	2.91	1.48			
4	3.93	3.83	3.66	3.49	3.29	2.06			
5	4.23	4.13	3.96	3.80	3.61	2.48			
7.50	4.84	4.75	4.58	4.42	4.24	3.25	1.07		
10	5.33	5.24	5.07	4.92	4.75	3.83	2.18		
20	6.72	6.62	6.46	6.32	6.16	5.37	4.20	2.12	
30	7.69	7.59	7.44	7.30	7.15	6.40	5.38	3.86	
40	8.46	8.37	8.22	8.08	7.93	7.22	6.27	4.96	2.80
50	9.12	9.02	8.87	8.73	8.59	7.90	7.00	5.80	4.04
75	10.44	10.34	10.19	10.06	9.92	9.26	8.44	7.39	6.01
100	11.49	11.39	11.24	11.11	10.97	10.34	9.56	8.59	7.37
200	14.47	14.38	14.23	14.10	13.97	13.38	12.67	11.85	10.87
300	16.56	16.47	16.33	16.20	16.07	15.49	14.83	14.06	13.17
400	18.23	18.14	18.00	17.87	17.74	17.18	16.53	15.80	14.96
500	19.64	19.55	19.40	19.28	19.15	18.59	17.96	17.26	16.45
750	22.48	22.39	22.25	22.12	22.00	21.45	20.85	20.18	19.43
1 000	24.74	24.65	24.51	24.39	24.26	23.73	23.14	22.48	21.77
10 000	53.31	53.22	53.08	52.96	52.84	52.35	51.83	51.29	50.72

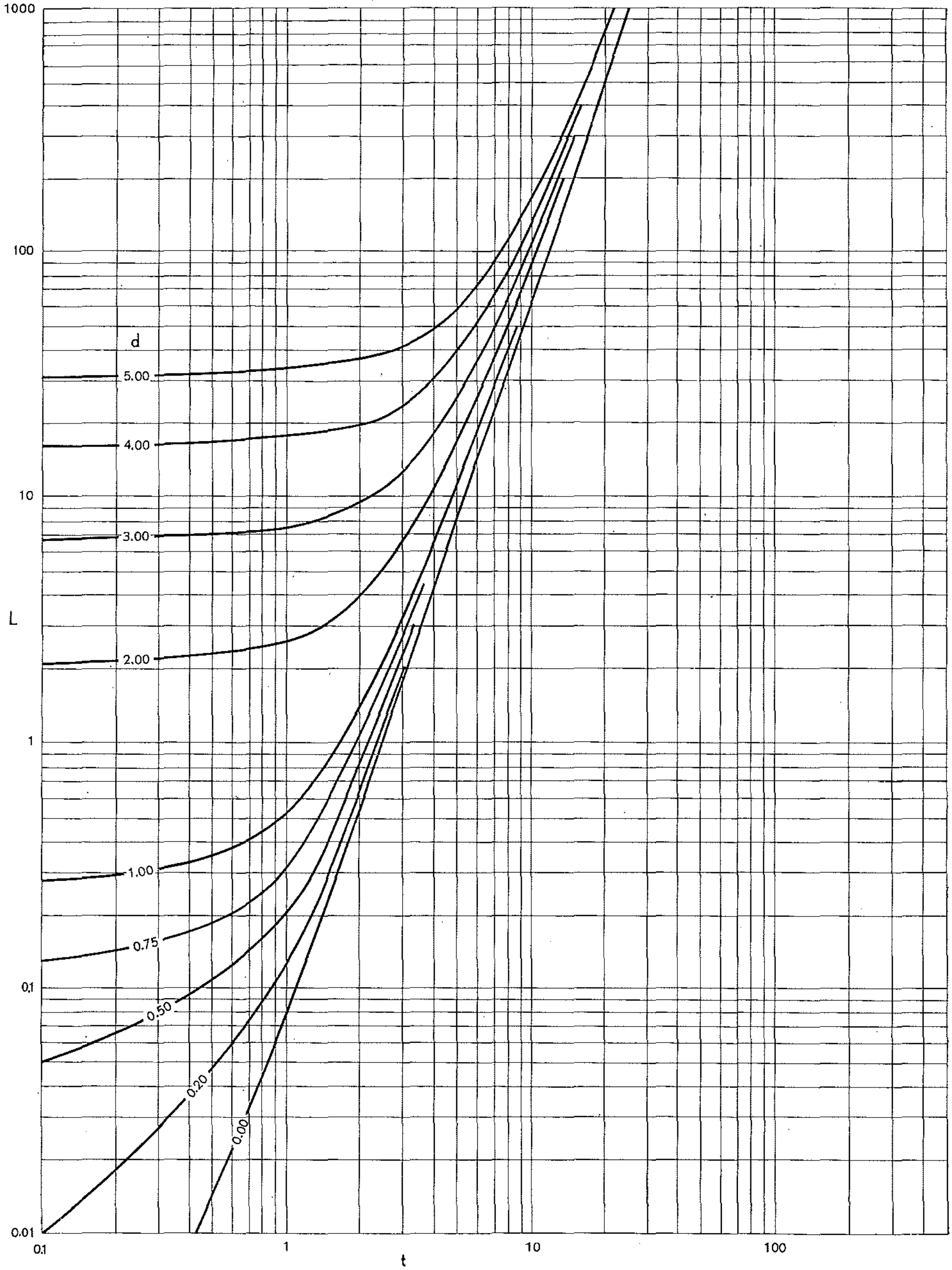


Figure 7. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius of hole blown in ice) for charges placed 0.25 metre below the under-surface of the ice.

Table 10. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 0.25 metre below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250	1.54	1.42	1.17	0.82					
0.500	1.95	1.84	1.62	1.35	0.96				
0.750	2.23	2.13	1.92	1.68	1.37				
1	2.46	2.36	2.16	1.94	1.66				
2	3.11	3.01	2.82	2.63	2.40				
3	3.56	3.46	3.28	3.10	2.89	1.43			
4	3.92	3.82	3.65	3.48	3.28	2.02			
5	4.22	4.12	3.95	3.79	3.60	2.45			
7.50	4.84	4.74	4.57	4.41	4.24	3.24	1.00		
10	5.32	5.23	5.06	4.91	4.74	3.81	2.15		
20	6.71	6.62	6.46	6.31	6.15	5.36	4.19	2.08	
30	7.68	7.59	7.44	7.29	7.14	6.40	5.37	3.85	
40	8.46	8.36	8.21	8.07	7.92	7.21	6.26	4.95	2.77
50	9.11	9.02	8.87	8.73	8.58	7.89	7.00	5.79	4.02
75	10.43	10.34	10.19	10.05	9.91	9.26	8.43	7.38	6.00
100	11.48	11.39	11.24	11.11	10.97	10.33	9.55	8.58	7.36
200	14.47	14.38	14.23	14.10	13.97	13.37	12.67	11.84	10.86
300	16.56	16.47	16.32	16.20	16.07	15.49	14.82	14.06	13.17
400	18.23	18.14	17.99	17.87	17.74	17.17	16.53	15.80	14.96
500	19.64	19.55	19.40	19.28	19.15	18.59	17.96	17.25	16.45
750	22.48	22.39	22.24	22.12	22.00	21.45	20.85	20.17	19.42
1 000	24.74	24.65	24.51	24.39	24.26	23.72	23.13	22.48	21.77
10 000	53.31	53.22	53.08	52.96	52.84	52.34	51.83	51.29	50.72

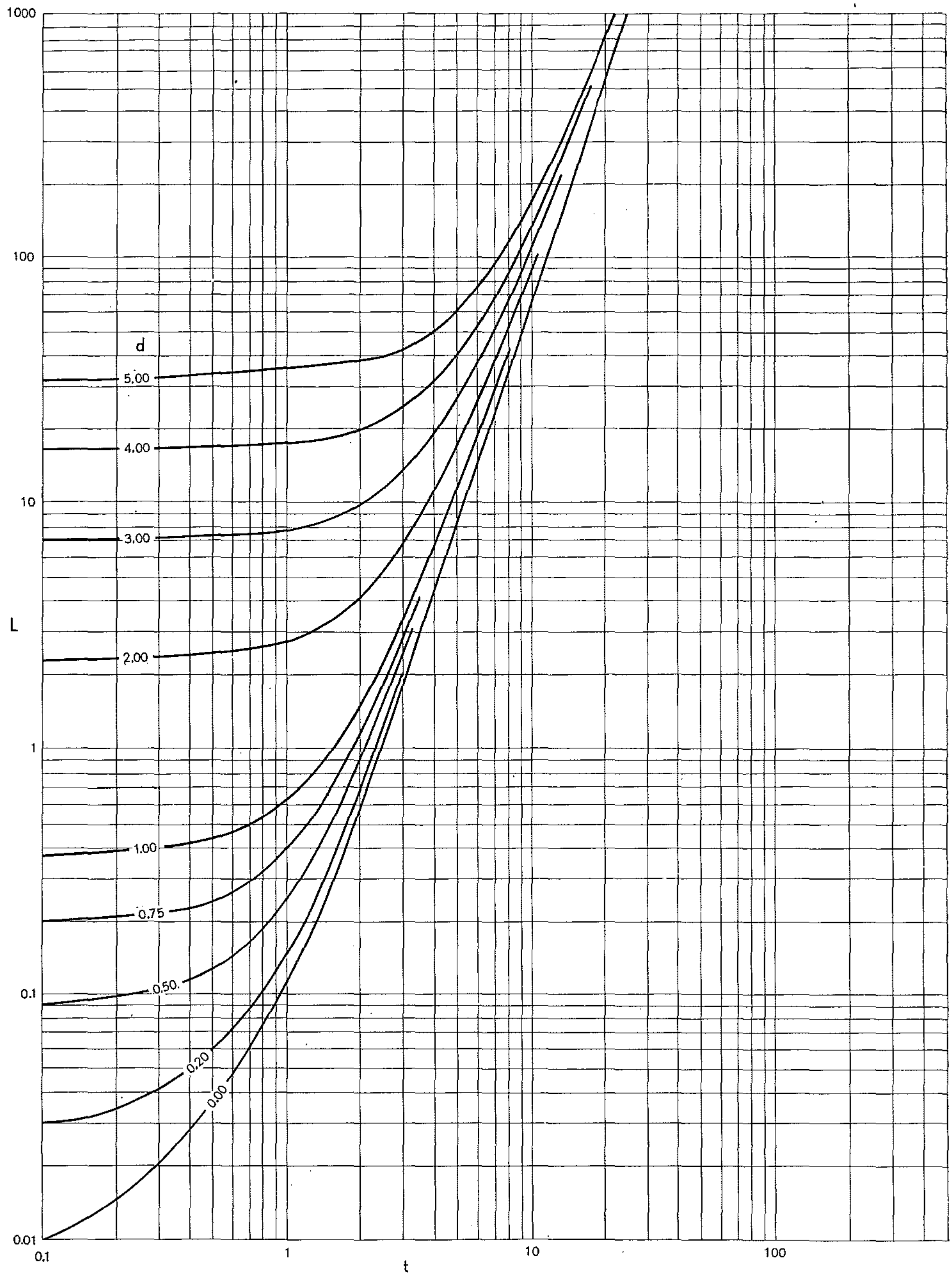


Figure 8. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius of hole blown in ice) for charges placed 0.50 metre below the under-surface of the ice.

Table 11. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 0.50 metre below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250	1.48	1.34	1.03	0.56					
0.500	1.90	1.78	1.53	1.22	0.74				
0.750	2.19	2.08	1.85	1.59	1.23				
1	2.42	2.31	2.09	1.86	1.55				
2	3.08	2.97	2.78	2.58	2.33				
3	3.53	3.43	3.24	3.06	2.84	1.28			
4	3.90	3.79	3.61	3.44	3.23	1.92			
5	4.20	4.10	3.92	3.75	3.56	2.38			
7.50	4.82	4.72	4.55	4.39	4.20	3.18	0.75		
10	5.31	5.21	5.04	4.88	4.71	3.77	2.05		
20	6.70	6.60	6.44	6.30	6.13	5.33	4.14	1.98	
30	7.67	7.58	7.42	7.28	7.12	6.37	5.34	3.79	
40	8.45	8.35	8.20	8.06	7.91	7.19	6.24	4.91	2.70
50	9.10	9.01	8.85	8.72	8.57	7.88	6.97	5.76	3.97
75	10.42	10.33	10.18	10.04	9.90	9.24	8.41	7.36	5.96
100	11.48	11.38	11.23	11.10	10.96	10.32	9.54	8.57	7.34
200	14.46	14.37	14.22	14.09	13.96	13.36	12.66	11.83	10.85
300	16.56	16.46	16.32	16.19	16.06	15.48	14.82	14.05	13.16
400	18.22	18.13	17.99	17.86	17.73	17.17	16.52	15.79	14.95
500	19.63	19.54	19.40	19.27	19.14	18.59	17.96	17.24	16.44
750	22.48	22.38	22.24	22.12	21.99	21.45	20.84	20.17	19.42
1 000	24.74	24.65	24.50	24.38	24.26	23.72	23.13	22.48	21.76
10 000	53.31	53.22	53.08	52.96	52.84	52.35	51.83	51.29	50.72

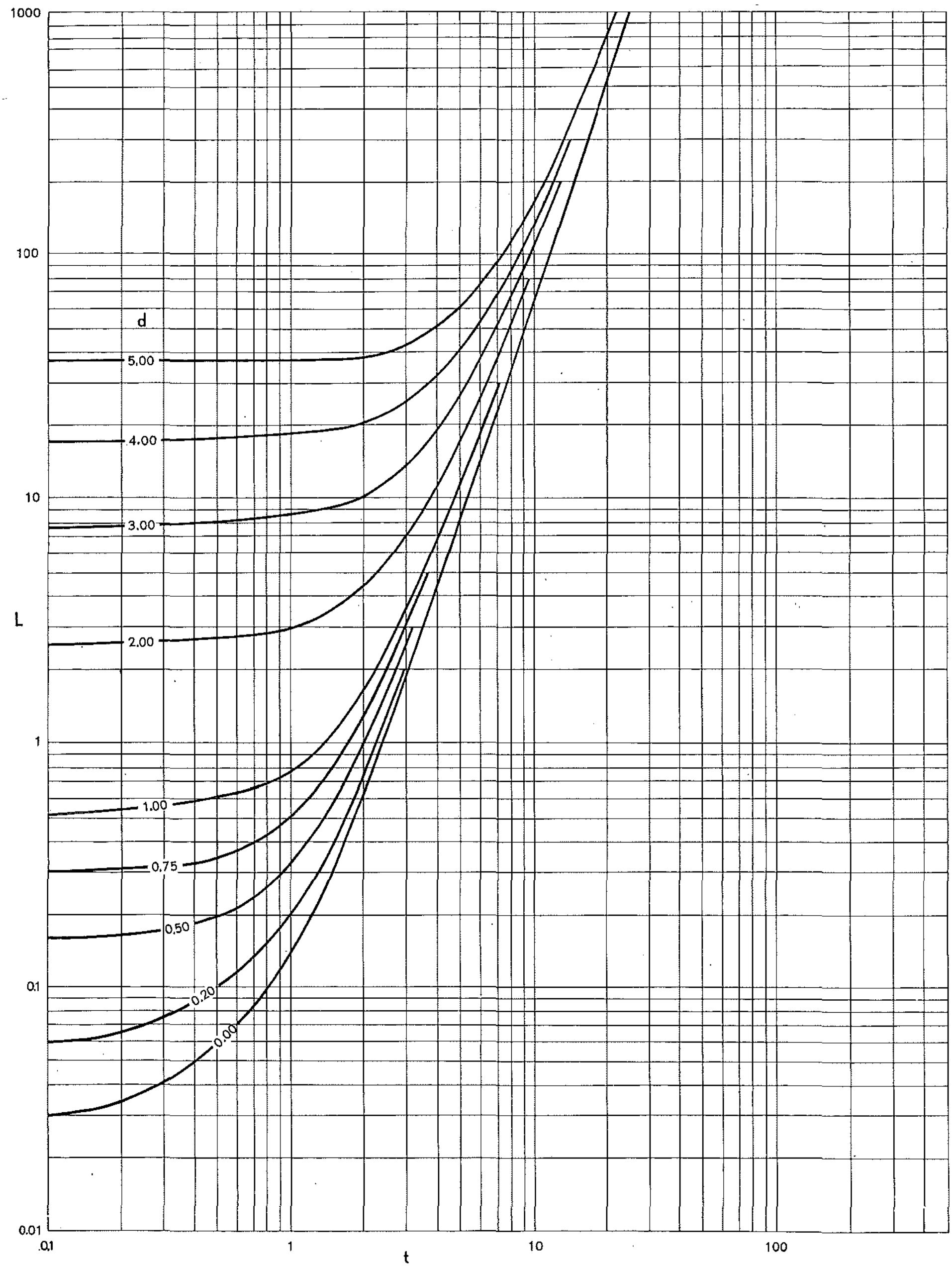


Figure 9. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius of hole blown in ice) for charges placed 0.75 metre below the under-surface of the ice.

Table 12. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 0.75 metre below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250	1.37	1.19	0.76						
0.500	1.82	1.67	1.37	0.99					
0.750	2.12	1.99	1.72	1.42	0.97				
1	2.36	2.23	1.99	1.72	1.36				
2	3.03	2.91	2.70	2.48	2.22				
3	3.49	3.38	3.18	2.98	2.75	0.99			
4	3.86	3.75	3.56	3.37	3.16	1.75			
5	4.16	4.06	3.88	3.70	3.49	2.24			
7.50	4.78	4.68	4.51	4.34	4.15	3.09			
10	5.28	5.18	5.00	4.84	4.66	3.69	1.88		
20	6.68	6.58	6.41	6.26	6.10	5.28	4.07	1.79	
30	7.65	7.56	7.40	7.25	7.10	6.34	5.29	3.71	
40	8.43	8.33	8.18	8.04	7.88	7.16	6.19	4.84	2.56
50	9.08	8.99	8.83	8.70	8.55	7.85	6.93	5.71	3.89
75	10.41	10.31	10.16	10.02	9.88	9.22	8.38	7.32	5.91
100	11.46	11.37	11.22	11.08	10.94	10.30	9.51	8.53	7.29
200	14.45	14.36	14.21	14.08	13.95	13.35	12.64	11.81	10.82
300	16.55	16.45	16.31	16.18	16.05	15.47	14.80	14.03	13.14
400	18.22	18.12	17.98	17.85	17.72	17.16	16.51	15.77	14.93
500	19.63	19.53	19.39	19.26	19.13	18.58	17.94	17.23	16.43
750	22.47	22.38	22.23	22.11	21.98	21.44	20.83	20.16	19.41
1 000	24.73	24.64	24.50	24.38	24.25	23.71	23.12	22.47	21.75
10 000	53.31	53.21	53.07	52.96	52.84	52.34	51.82	51.28	50.72

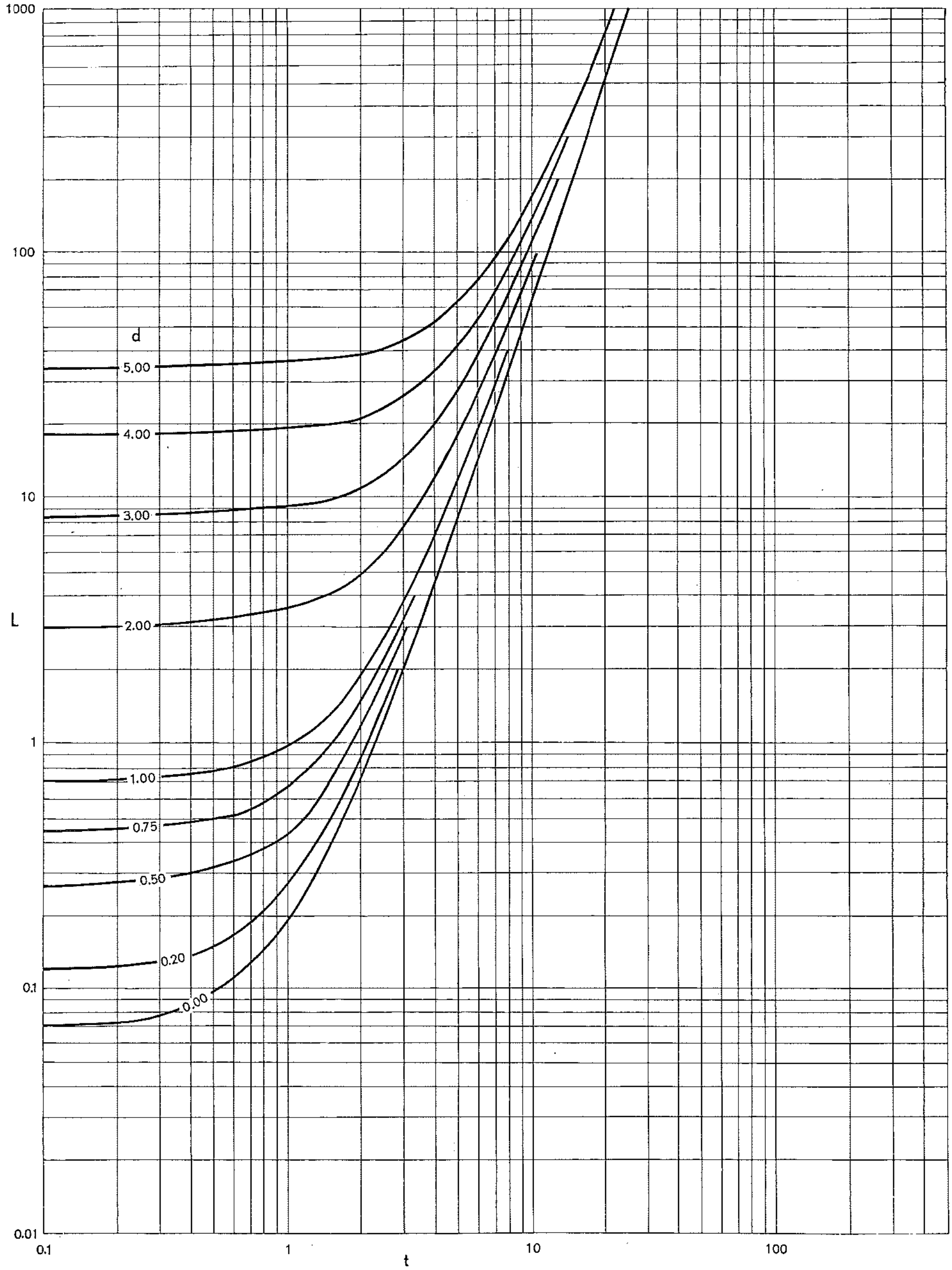


Figure 10. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius of hole blown in ice) for charges placed 1.00 metre below the under-surface of the ice.

Table 13. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 1.00 metre below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250	1.20	0.95							
0.500	1.69	1.51	1.12	0.53					
0.750	2.01	1.86	1.54	1.16	0.43				
1	2.26	2.12	1.83	1.51	1.05				
2	2.95	2.82	2.59	2.35	2.06				
3	3.43	3.31	3.09	2.88	2.63	0.26			
4	3.80	3.68	3.48	3.28	3.05	1.48			
5	4.11	4.00	3.80	3.62	3.40	2.04			
7.50	4.74	4.63	4.45	4.27	4.07	2.95			
10	5.24	5.13	4.95	4.78	4.60	3.59	1.61		
20	6.64	6.54	6.37	6.22	6.05	5.21	3.96	1.49	
30	7.62	7.52	7.36	7.22	7.06	6.28	5.21	3.58	
40	8.40	8.30	8.15	8.00	7.85	7.11	6.13	4.75	2.36
50	9.06	8.96	8.81	8.67	8.52	7.80	6.88	5.63	3.76
75	10.39	10.29	10.14	10.00	9.86	9.18	8.34	7.27	5.83
100	11.44	11.35	11.19	11.06	10.92	10.27	9.48	8.49	7.24
200	14.44	14.34	14.19	14.06	13.93	13.33	12.62	11.78	10.79
300	16.54	16.44	16.29	16.17	16.03	15.45	14.78	14.00	13.11
400	18.20	18.11	17.96	17.84	17.71	17.14	16.49	15.75	14.91
500	19.62	19.52	19.38	19.25	19.12	18.56	17.93	17.21	16.41
750	22.46	22.37	22.22	22.10	21.97	21.42	20.82	20.14	19.39
1 000	24.72	24.63	24.49	24.36	24.24	23.70	23.11	22.46	21.74
10 000	53.30	53.21	53.07	52.95	52.83	52.34	51.82	51.28	50.71

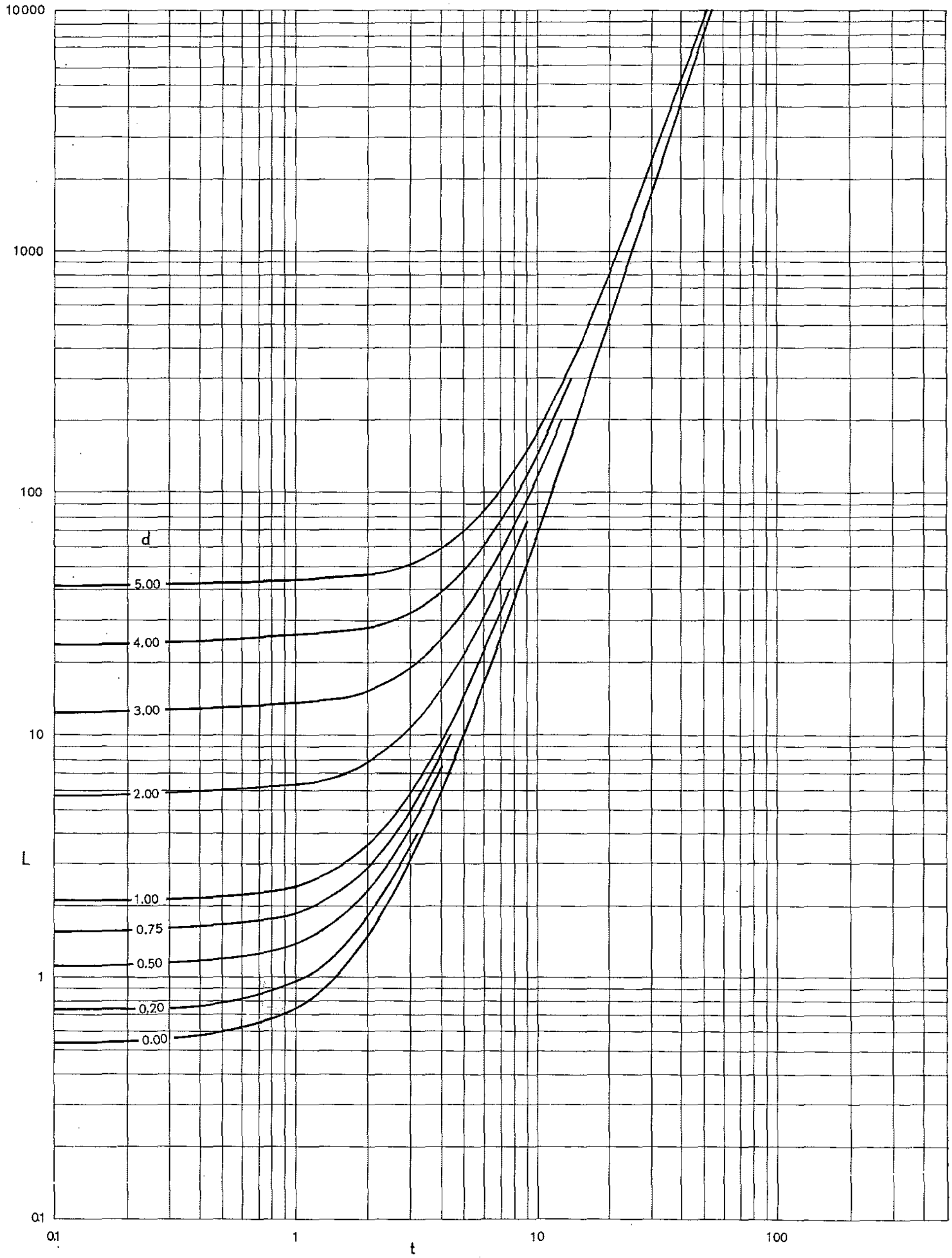


Figure 11. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius of hole blown in ice) for charges placed 2.00 metres below the under-surface of the ice.

Table 14. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 2.00 metres below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250									
0.500									
0.750	1.03	0.34							
1	1.46	1.08							
2	2.39	2.17	1.74	1.21					
3	2.96	2.77	2.43	2.07	1.60				
4	3.38	3.21	2.91	2.61	2.25				
5	3.73	3.57	3.30	3.03	2.71				
7.50	4.41	4.27	4.03	3.80	3.53	1.87			
10	4.94	4.81	4.58	4.37	4.14	2.79			
20	6.41	6.29	6.10	5.92	5.72	4.74	3.18		
30	7.42	7.31	7.13	6.96	6.78	5.91	4.67	2.59	
40	8.22	8.11	7.94	7.78	7.61	6.79	5.70	4.09	
50	8.89	8.79	8.62	8.46	8.30	7.52	6.50	5.10	2.79
75	10.24	10.14	9.97	9.83	9.67	8.95	8.05	6.89	5.30
100	11.31	11.21	11.05	10.90	10.75	10.07	9.23	8.18	6.83
200	14.33	14.23	14.08	13.94	13.80	13.18	12.44	11.58	10.54
300	16.44	16.35	16.20	16.06	15.93	15.33	14.64	13.84	12.92
400	18.12	18.03	17.88	17.75	17.61	17.03	16.37	15.61	14.75
500	19.54	19.44	19.29	19.17	19.03	18.46	17.82	17.09	16.26
750	22.39	22.30	22.15	22.03	21.90	21.34	20.72	20.04	19.27
1 000	24.66	24.57	24.42	24.30	24.17	23.63	23.03	22.36	21.64
10 000	53.27	53.18	53.04	52.92	52.80	52.31	51.79	51.24	50.68

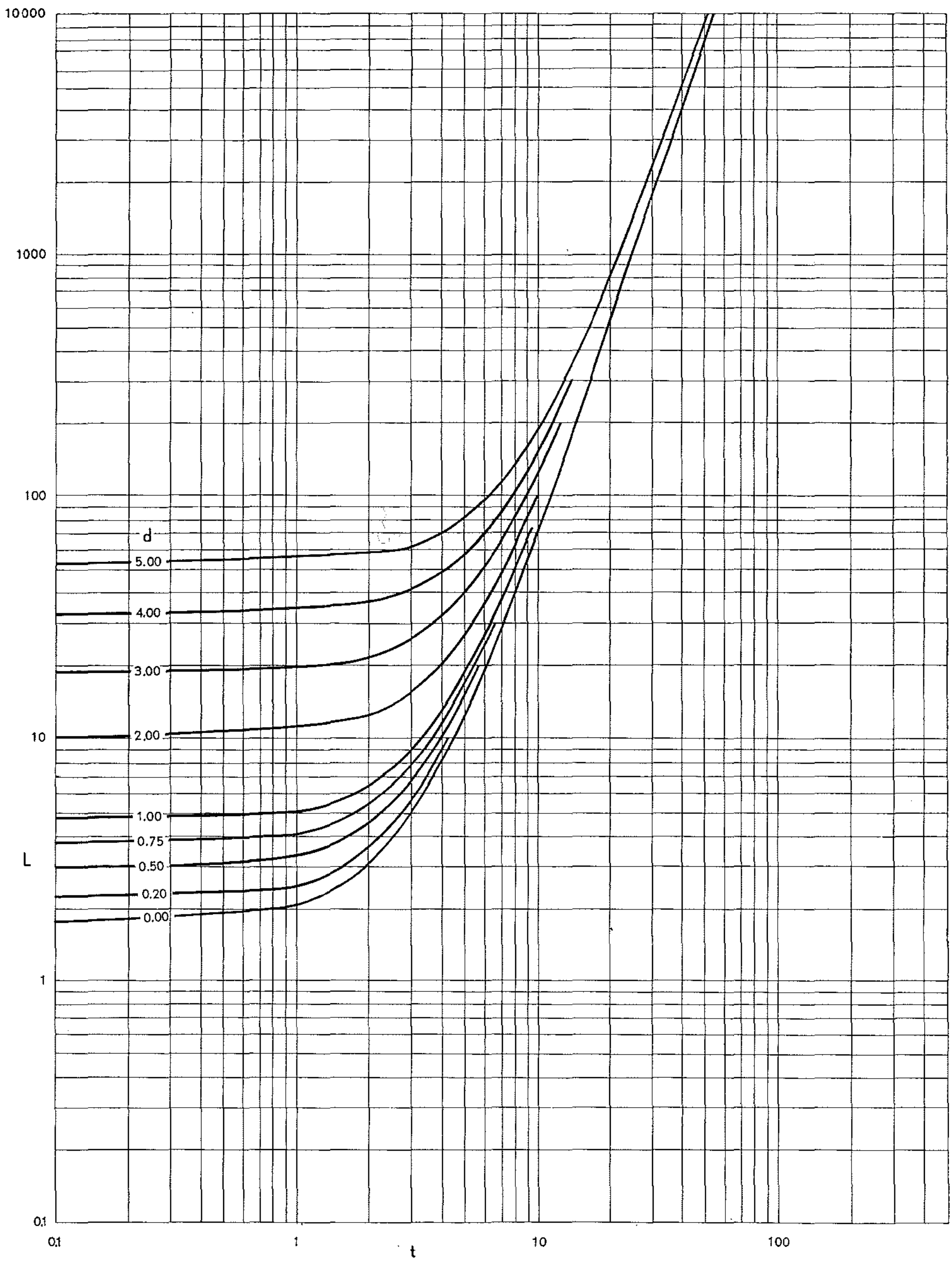


Figure 12. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius of hole blown in ice) for charges placed 3.00 metres below the under-surface of the ice.

Table 15. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 3.00 metres below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250									
0.500									
0.750									
1									
2	0.85								
3	1.93	1.53	0.26						
4	2.54	2.23	1.64	0.79					
5	2.98	2.73	2.25	1.73	0.87				
7.50	3.80	3.60	3.24	2.88	2.45				
10	4.41	4.22	3.91	3.61	3.27				
20	6.01	5.86	5.62	5.40	5.15	3.86	1.15		
30	7.08	6.94	6.73	6.53	6.31	5.25	3.65		
40	7.91	7.79	7.58	7.40	7.20	6.24	4.92	2.72	
50	8.61	8.49	8.29	8.11	7.93	7.04	5.85	4.12	
75	10.00	9.88	9.70	9.53	9.36	8.56	7.55	6.22	4.30
100	11.09	10.98	10.80	10.64	10.48	9.73	8.81	7.64	6.11
200	14.16	14.05	13.89	13.74	13.60	12.93	12.16	11.23	10.13
300	16.29	16.19	16.03	15.89	15.75	15.12	14.40	13.57	12.60
400	17.98	17.88	17.73	17.59	17.45	16.85	16.16	15.38	14.48
500	19.41	19.31	19.16	19.02	18.89	18.30	17.63	16.88	16.03
750	22.28	22.18	22.03	21.90	21.77	21.20	20.57	19.86	19.08
1 000	24.56	24.47	24.32	24.19	24.06	23.50	22.89	22.21	21.47
10 000	53.23	53.13	52.99	52.87	52.75	52.26	51.73	51.19	50.62

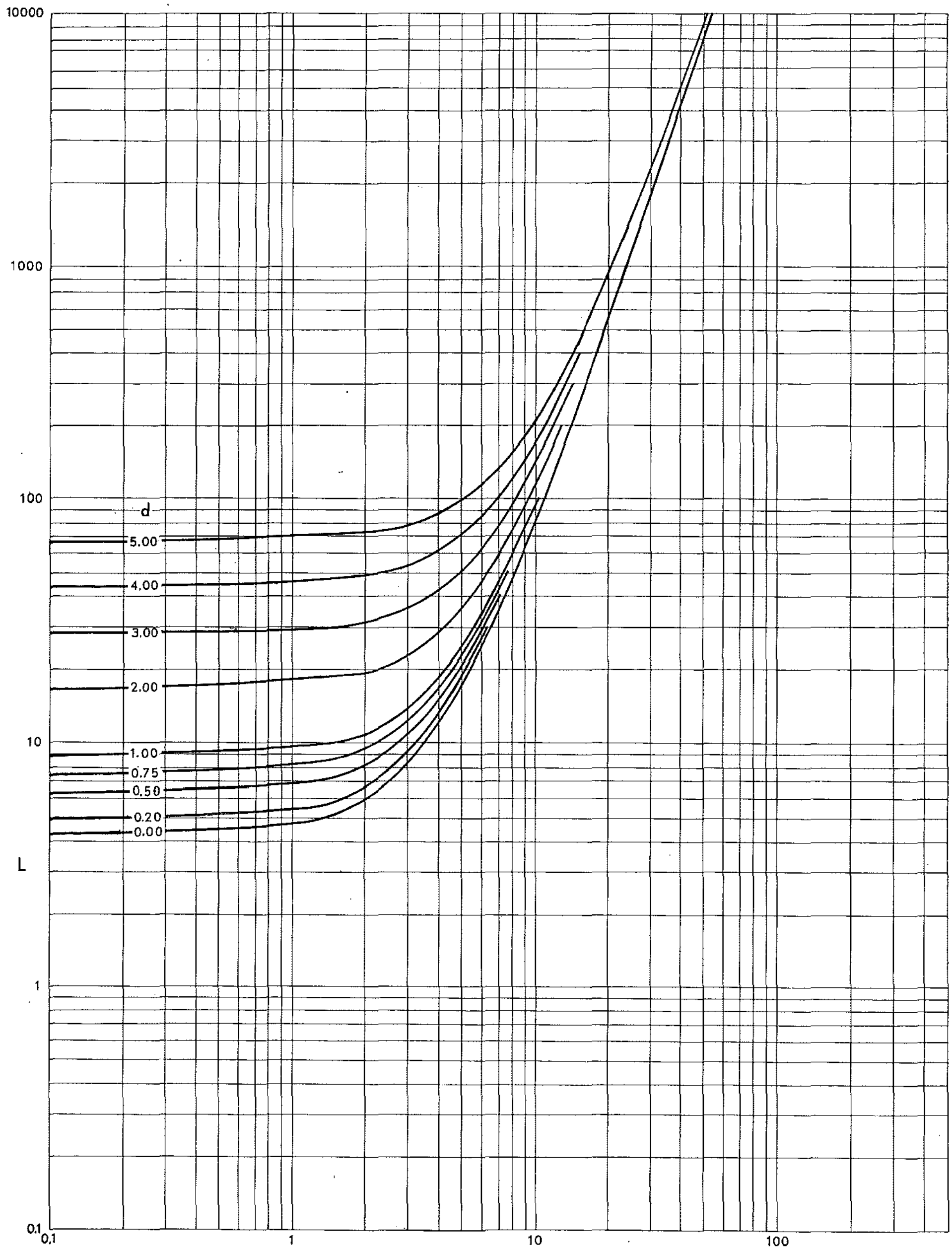


Figure 13. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius of hole blown in ice) for charges placed 4.00 metres below the under-surface of the ice.

Table 16. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 4.00 metres below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250									
0.500									
0.750									
1									
2									
3									
4									
5	1.38	0.29							
7.50	2.73	2.36	1.62	0.19					
10	3.52	3.24	2.74	2.20	1.43				
20	5.40	5.20	4.88	4.58	4.24	2.22			
30	6.57	6.40	6.13	5.88	5.61	4.22	1.46		
40	7.46	7.30	7.06	6.83	6.59	5.42	3.63		
50	8.19	8.05	7.82	7.61	7.38	6.32	4.84	2.20	
75	9.64	9.51	9.30	9.11	8.91	8.00	6.82	5.20	2.36
100	10.77	10.64	10.44	10.27	10.08	9.24	8.20	6.86	4.98
200	13.91	13.79	13.62	13.46	13.30	12.59	11.74	10.74	9.54
300	16.08	15.97	15.80	15.65	15.50	14.84	14.07	13.18	12.15
400	17.79	17.68	17.52	17.38	17.23	16.59	15.87	15.04	14.10
500	19.23	19.12	18.96	18.82	18.68	18.06	17.37	16.58	15.69
750	22.12	22.02	21.87	21.73	21.60	21.01	20.35	19.62	18.81
1 000	24.42	24.32	24.17	24.04	23.90	23.33	22.70	22.00	21.24
10 000	53.16	53.07	52.92	52.80	52.68	52.18	51.66	51.11	50.53

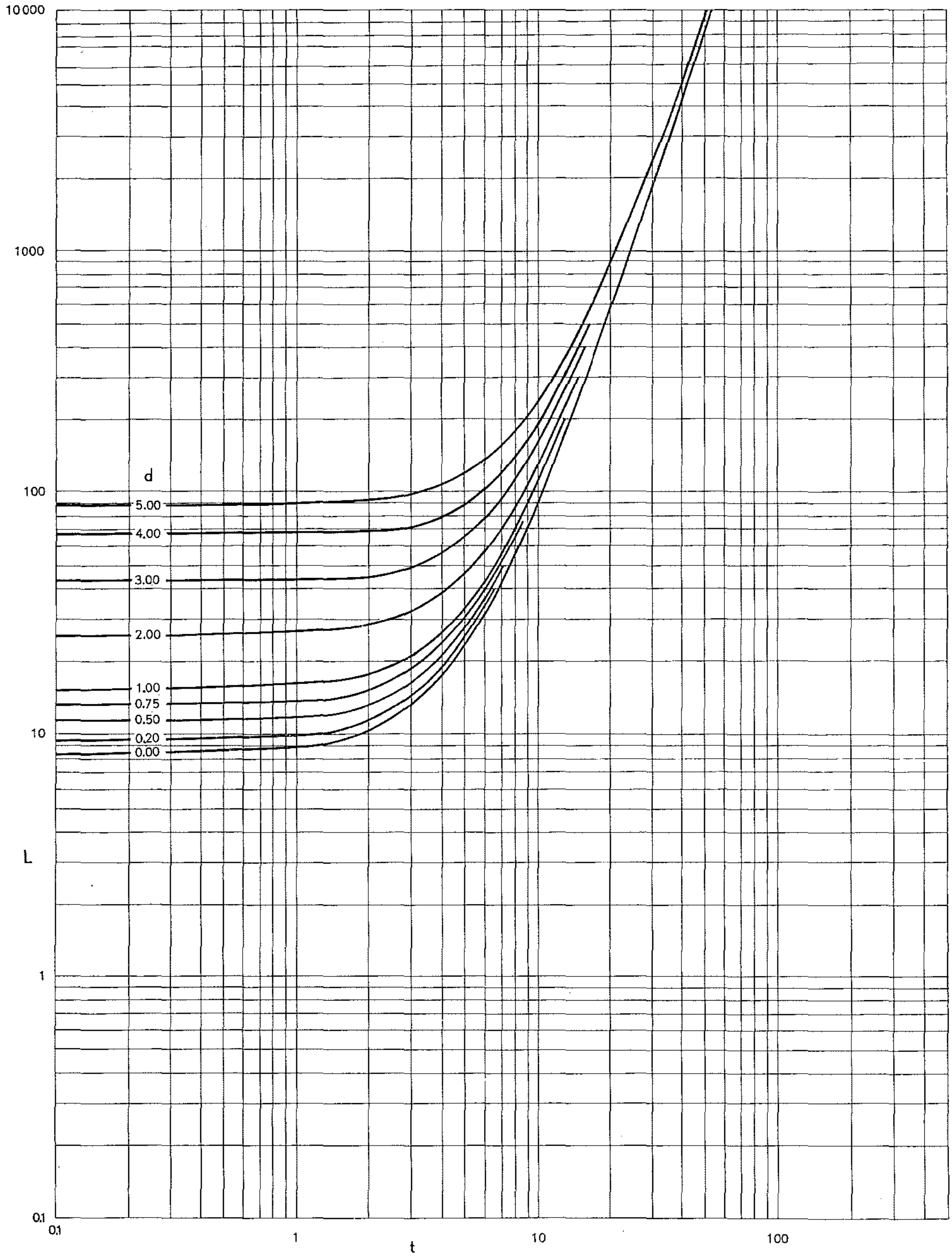


Figure 14. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius of hole blown in ice) for charges placed 5.00 metres below the under-surface of the ice.

Table 17. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed 5.00 metres below the under-surface of the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.250									
0.500									
0.750									
1									
2									
3									
4									
5									
7.50									
10	1.85	1.08							
20	4.48	4.21	3.74	3.28	2.72				
30	5.84	5.62	5.27	4.94	4.57	2.38			
40	6.83	6.64	6.33	6.05	5.74	4.16			
50	7.62	7.45	7.16	6.91	6.64	5.30	3.16		
75	9.16	9.00	8.76	8.54	8.31	7.23	5.78	3.54	
100	10.34	10.20	9.97	9.77	9.56	8.60	7.37	5.73	3.05
200	13.58	13.46	13.26	13.09	12.92	12.13	11.21	10.10	8.74
300	15.79	15.68	15.49	15.34	15.17	14.46	13.63	12.68	11.55
400	17.53	17.42	17.25	17.10	16.94	16.26	15.49	14.61	13.60
500	18.99	18.88	18.71	18.57	18.42	17.76	17.03	16.20	15.26
750	21.92	21.81	21.65	21.51	21.37	20.75	20.07	19.31	18.46
1 000	24.23	24.13	23.97	23.84	23.70	23.10	22.45	21.73	20.94
10 000	53.08	52.98	52.84	52.72	52.60	52.09	51.56	51.01	50.42

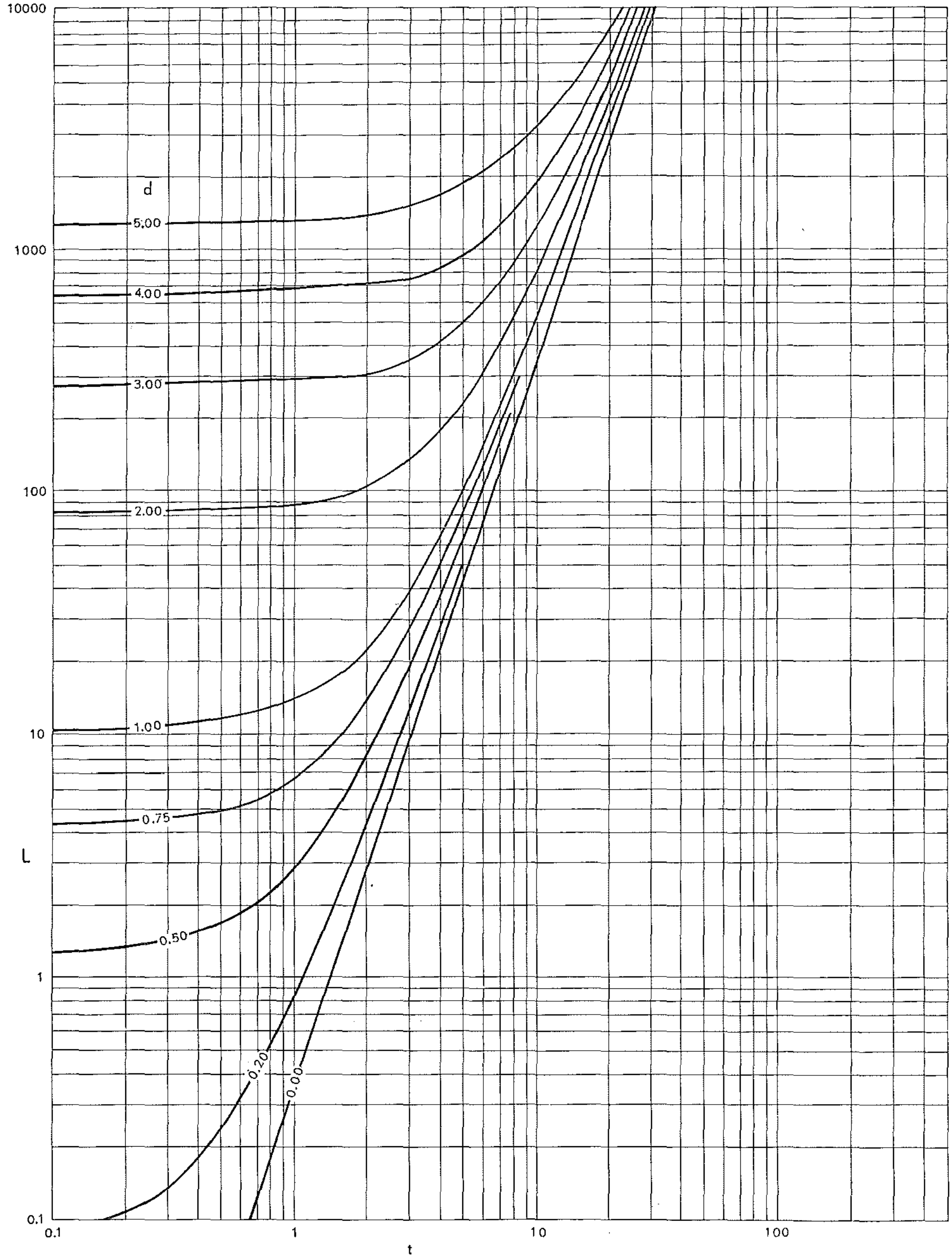


Figure 15. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius of hole blown in ice) for charges placed on the ice.

Table 18. Connection between L (Dutch TNT in Kgs), d (thickness of ice in metres) and t (radius in metres of hole blown in ice) for charges placed on the ice.

L	d = 0.00	d = 0.20	d = 0.50	d = 0.75	d = 1.00	d = 2.00	d = 3.00	d = 4.00	d = 5.00
0.125	0.71	0.27							
0.250	0.89	0.52							
0.500	1.12	0.78							
0.750	1.29	0.95							
1	1.42	1.09							
2	1.78	1.47	0.69						
3	2.04	1.74	1.06						
4	2.25	1.94	1.31						
5	2.42	2.12	1.51	0.56					
7.50	2.77	2.47	1.90	1.19					
10	3.05	2.76	2.21	1.57					
20	3.84	3.55	3.04	2.51	1.79				
30	4.40	4.11	3.62	3.12	2.50				
40	4.84	4.56	4.07	3.59	3.02				
50	5.22	4.93	4.45	3.99	3.45				
75	5.97	5.69	5.22	4.77	4.27				
100	6.57	6.29	5.82	5.39	4.91	1.75			
200	8.28	8.00	7.55	7.14	6.70	4.36			
300	9.48	9.20	8.75	8.35	7.93	5.81	1.64		
400	10.44	10.16	9.71	9.32	8.90	6.89	3.72		
500	11.24	10.96	10.52	10.13	9.72	7.78	4.96		
750	12.87	12.59	12.15	11.77	11.37	9.53	7.10	2.84	
1 000	14.16	13.88	13.45	13.07	12.68	10.90	8.65	5.37	
10 000	30.51	30.24	29.81	29.45	19.09	27.56	25.89	24.07	22.06

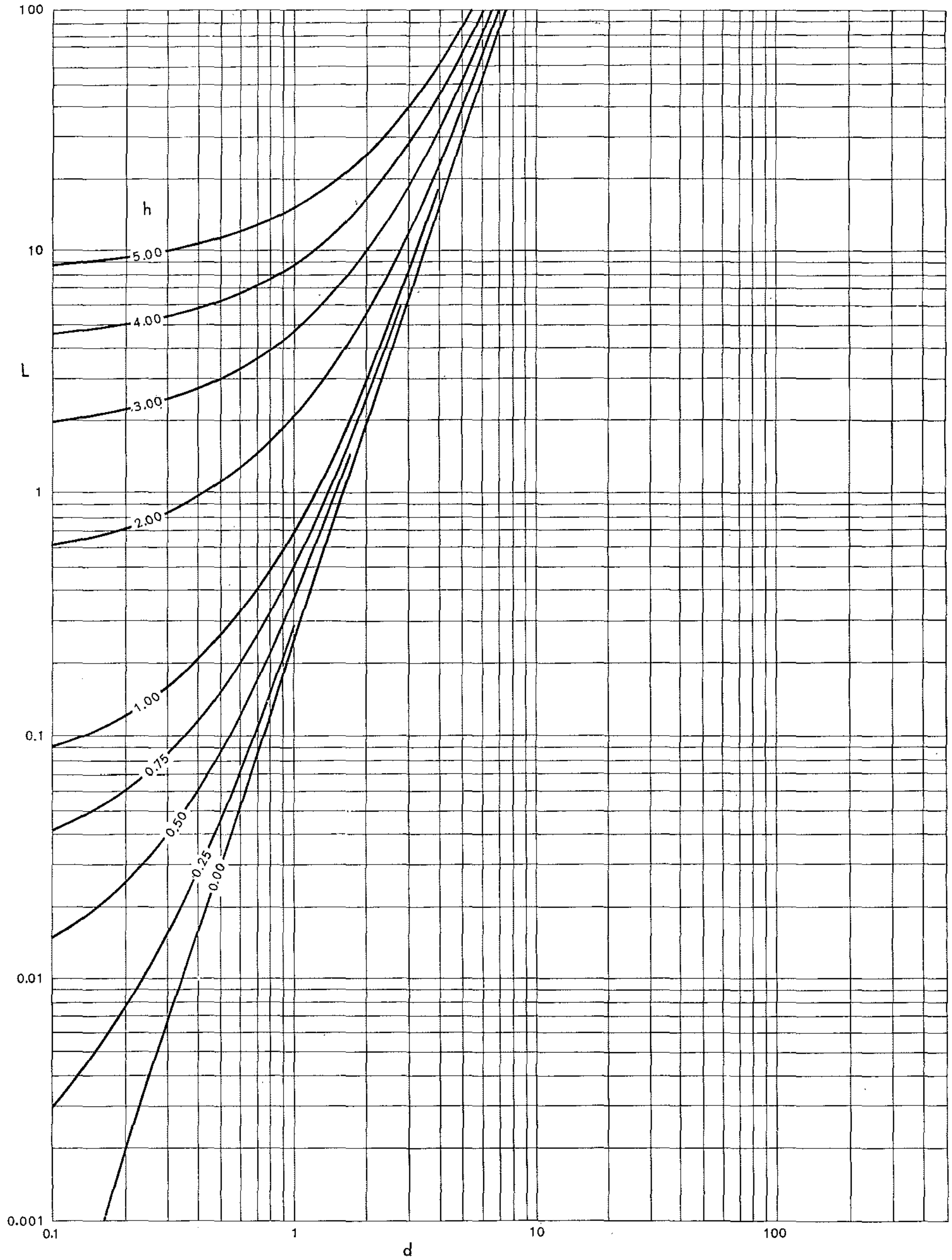


Figure 16. Quantity of L (Dutch TNT in Kgs), placed h metres below the under-surface of ice d metres thick that will just break through the ice.

Table 19. Quantity of L (Dutch TNT in Kgs), placed h metres below the under-surface of ice d metres thick that will just break through the ice.

d	h = 0.00	h = 0.25	h = 0.50	h = 0.75	h = 1.00	h = 2.00	h = 3.00	h = 4.00	h = 5.00
0.00	0.000	0.001	0.008	0.028	0.066	0.528	1.782	4.224	8.250
0.10	0.000	0.003	0.015	0.042	0.091	0.620	1.986	4.583	8.808
0.20	0.002	0.008	0.025	0.061	0.121	0.724	2.206	4.964	9.392
0.30	0.007	0.015	0.040	0.086	0.159	0.840	2.444	5.367	10.004
0.40	0.016	0.028	0.061	0.118	0.204	0.969	2.700	5.793	10.645
0.50	0.031	0.046	0.088	0.157	0.258	1.111	2.975	6.244	11.315
0.75	0.105	0.129	0.194	0.296	0.440	1.535	3.751	7.482	13.124
1.00	0.250	0.282	0.371	0.511	0.703	2.066	4.666	8.890	15.136
2.00	1.998	2.063	2.253	2.558	2.969	5.622	10.032	16.532	25.499
3.00	6.743	6.841	7.131	7.605	8.250	12.397	18.975	28.175	40.326
4.00	15.982	16.113	16.503	17.144	18.026	23.751	32.735	44.977	60.711
5.00	31.216	31.379	31.868	32.676	33.792	41.127	52.659	68.197	87.846

Measuring diameter of hole blown in ice. *Photograph by G. Piket.*

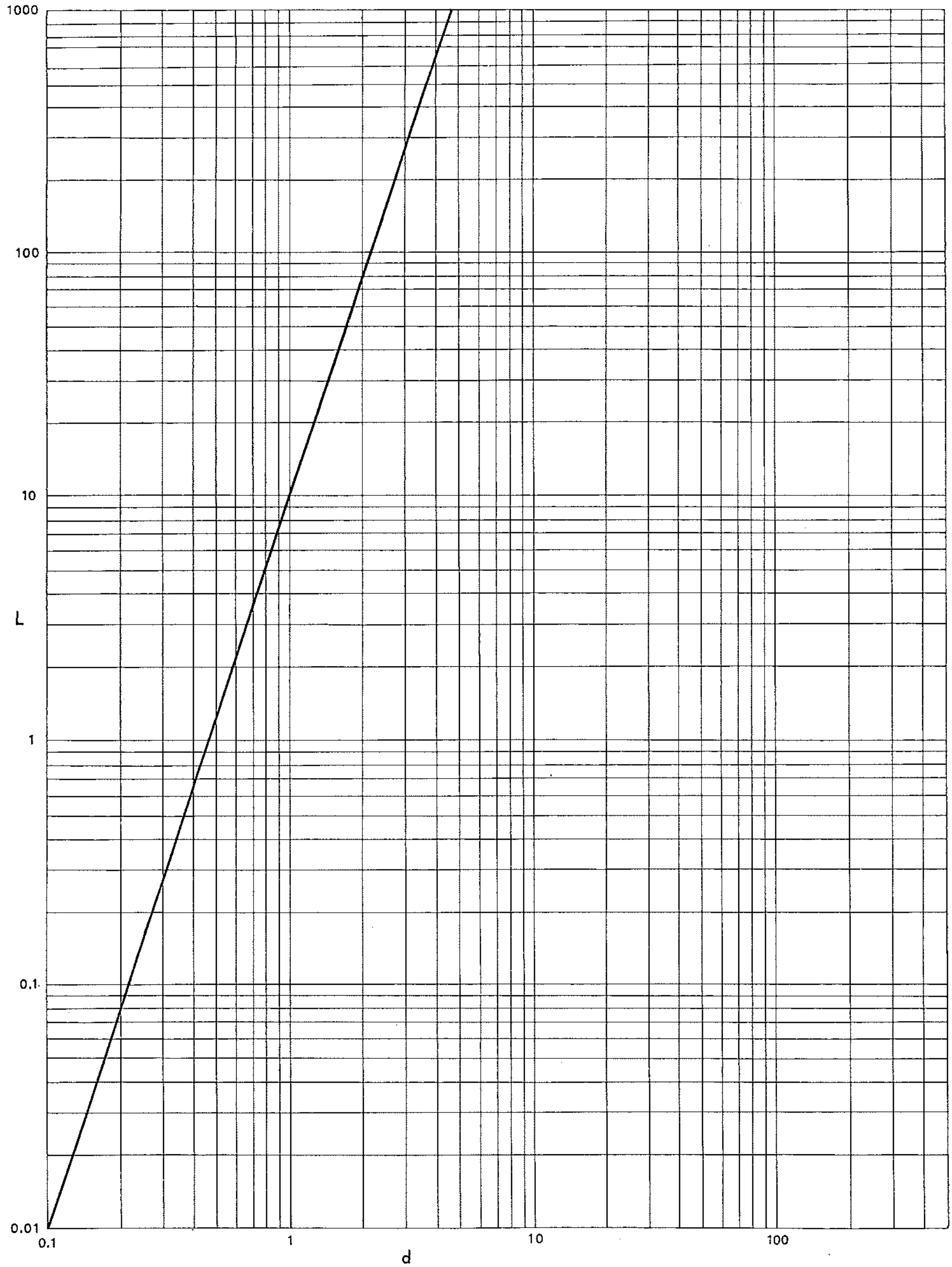
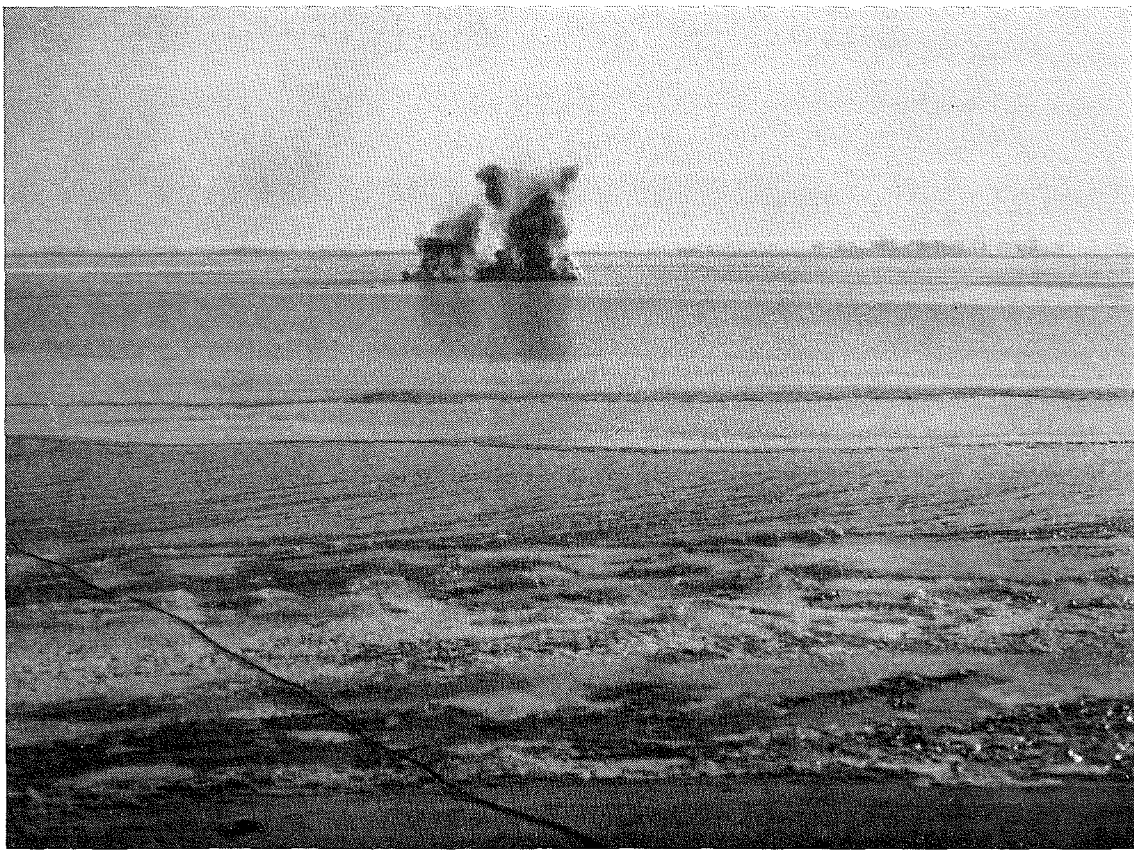


Figure 17. Quantity of L (Dutch TNT in Kgs), placed on ice d metres thick that will just break through the ice.

Table 20. Quantity of L (Dutch TNT in Kgs), placed on ice d metres thick that will just break through the ice.

d	L	d	L	d	L
0.00	0.000	0.40	0.655	2.00	81.860
0.10	0.010	0.50	1.279	3.00	276.28
0.20	0.082	0.75	4.317	4.00	654.88
0.30	0.276	1.00	10.232	5.00	1279.1



Blowing holes with charges on the ice. The cable used for firing the charge electrically is seen in the foreground. *Photograph by Rijkswaterstaat.*

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A. Waalewijn:
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Nr 4. Dr. L. F. Kamps†:
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