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PREFACE

This report was prepared by Dr. Malcolm Mellor, Research Civil Engineer, of the Applied Research Branch and Mr. Austin Kovacs, Research Civil Engineer, of the Foundations and Materials Research Branch, both of the Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL). The study was conducted for the U.S. Coast Guard under MIPR No. Z-70099-1-12123.

Consultant services for the project were provided by Dr. Ivor Hawkes, USA CRREL Expert. Field assistance was provided by Mr. Bruce McKelvy and Mr. Gary Hogue. Photographs were taken by Mr. David Eaton, USA CRREL Photo Service. The Alaskan phase of the work was supported by the USA CRREL Alaska Field Station.

BREAKAGE OF FLOATING ICE BY COMPRESSED GAS BLASTING

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Introduction

Compressed gas appears to have a number of special advantages as a blasting agent for breaking floating ice. Existing systems utilizing compressed air or compressed carbon dioxide discharge at much lower pressures than typical chemical explosives, so that blasts can be made in close proximity to ship hulls or hydraulic structures without risk of damage. When the point of discharge is beneath the ice layer, the blasting action is such that the ice will tend to break by widespread heaving rather than by localized shattering. Furthermore, with compressed air systems repetitive blasting can be carried out without need for direct access to recharge the discharge ports. Finally, low pressure discharge minimizes the possibility of harming aquatic life, and there is no pollution from blast products.

To investigate the potential of compressed gas blasting as a means of breaking floating ice, tests were made on frozen lakes in New Hampshire and Alaska.

Blasting devices

Field tests were made with self-contained carbon dioxide shells, and with an airblasting system consisting of discharge shells and a high-pressure compressor. All the equipment was unmodified commercial equipment of the type used in the coal mining industry.

Carbon dioxide shells

The carbon dioxide shells were Cardox cartridges manufactured and serviced by the Long-Airdox Corporation. The Cardox shell blasts by discharging carbon dioxide at moderately high pressure; the sealing disk of the discharge head ruptures at pressures in the range 10,000 to 19,000 $\mathrm{lbf/in.}^2$, but pressure on exit from the discharge ports is appreciably lower (Davies and Hawkes 1964). The shell (Fig. 1) consists of a slender hollow cylinder filled with liquid carbon dioxide under a pressure of approximately 2000 $\mathrm{lbf/in.}^2$, a discharge head with angled blast ports, and a charging cap containing an electrically actuated chemical heater which is submerged in the liquid carbon dioxide. When the heater is fired electrically there is a sudden pressure increase, a shear disk at the discharge head ruptures, and carbon dioxide is released through the blast ports. The blast ports are angled so that the shell will tend to drive deeper into the shothole. However, if a shell is fired too deep inside impermeable material (i.e. with excessive burden) it can be ejected violently from the shothole as a projectile.

The shells used in this study were Cardox type 231-130, which have an outside diameter of $2^5/_{16}$ in. and a length of $59^5/_8$ in. The weight is nominally 29¾ lb empty and 33¾ lb when charged, i.e. the nominal charge weight is 4 lb.

Airblasting equipment

The airblasting equipment was an Airdox system manufactured by the Long-Airdox Corporation (see Hawkes et al. 1967). The system consists of a high pressure air compressor, a set of air receivers to store compressed air, and a blasting shell from which the compressed air is discharged explosively (Fig. 2). The compressor used in this study was a 6-stage air-cooled machine, with horizontally opposed cylinders, driven by a 50-hp, 3-phase, 440-volt electric motor. The capacity was 54 ft^3 of free air per minute, delivered at 12,000 lbf/in.^{2} Dimensions were 10 ft 7 in. × 4 ft 9½ in. × 3 ft 2½ in. high, and the weight of the compressor, motor and frame was 5400 lb. The air receiver consisted of a battery of six tubes, 2⅝ in. outside diameter by 7 ft long, coupled in parallel to give a total air capacity of approximately 1500 in.^{3} The majority of the tests were made with an automatic discharge shell (Fig. 3), which consists of a steel cylinder with an air capacity of 315 in.^{3} and a discharge head that has a special spring-loaded piston capable of releasing air rapidly when a preset pressure level is reached inside the cylinder. The automatic discharge shell has an outside diameter of 2⅝ in. and an overall length of 10 ft. A receiver shell (Fig. 3) was also available, but it was only used for two tests due to difficulties in reaching firing pressure because of a small pressure leak. The receiver shell has a 302-in.^{3} storage chamber (5½ in. ID), which on firing releases air to the blast ports via a discharge tube. This results in lower discharge pressure at the blast ports than is the case with the automatic discharge shell. The motor, compressor, air receivers, and associated lines, valves and gauges were mounted in an enclosed cabin on a Nodwell tracked vehicle (Fig. 4). Electrical power for the drive motor was supplied by a portable generator towed behind the Nodwell vehicle. High pressure air was carried from the receivers to the shell through reinforced flexible high pressure hose, 1 in. OD and 3/16 in. ID.

Test procedures

Two sets of Cardox tests were made on a lake in New Hampshire. During the first series the average ice thickness was 13 in. and the snow cover was from 3 to 9 in. During the second series the average ice thickness was 19 in. and the snow cover 0 to 3 in. Water depth was 30 to 40 ft. Each test position was cleared of snow, a 2⅜-in.-diameter shothole was drilled with a lightweight power auger, ice depth was measured, and a Cardox shell was inserted and wedged into place at the desired position. In most cases the blast ports of the shell were in water beneath the ice. A recovery line was attached to the shell, the other end of the line being secured to a timber deadman left free to drag in the snow. The shell was fired from a blasting machine. Each shot was photographed sequentially at 4 frames per second by a motorized camera, and after the shot the broken ice was photographed. Dimensions of the resulting hole and its surrounding fracture zone were measured.

After the second series of Cardox tests, comparative tests were made with 40% gelatin dynamite.

Airblasting tests were made at a lake on the Fort Wainwright military reservation near Fairbanks, Alaska. Ice thickness was 32.5 in. and the snow cover was 16 in. Water depth was 10 to 12 ft. Snow clearance was not attempted, as the necessary equipment and the resulting piles of snow would almost certainly have caused significant deflections and stresses in the ice. However, pilot blasting tests showed that cracks in the undisturbed snow cover always corresponded with cracks in the ice below. Because of failure of the 2½-in.-diameter auger, the airblast shell was inserted through 4½-in.-diameter boreholes, which were then stemmed with snow slush and allowed to partially refreeze. To avoid damage to the high pressure hose, the shell was fitted with a crossbar that prevented it from driving through the borehole on firing. A recovery cable was attached to the shell so that it could be retrieved after the ice had broken. Comparative tests were made with Cardox shells and with military dynamite (equivalent to commercial 60% dynamite).

Test results

The results of the first series of Cardox shots are summarized in Table I. Supplementary diagrammatic information is given in Figure 5. Photographs of blasts and blast damage are shown in Figures 6-13.

Results of the second series of Cardox tests are summarized in Table II. Photographs of test shots and their effects are given in Figures 14-19.

Table III gives results of tests made with 40% gelatin dynamite for comparison with the Cardox shells. Photographs of the dynamite shots and their effects are shown in Figures 20-23.

Table I. Results of Cardox shots under lake ice: first N.H. series.

Date 15 Jan 1971, snow cover 3-9 in., air temperature –5°C (+23°F), water depth 37 ft.

Shot no.	*Charged wt. of shell (lb - oz)*	*Depth of discharge* (ft)*	*Ice thickness (in.)*	*Mean hole diam† (ft)*	*Remarks*
1	30 - 0	0	14½	11.4	Low charge weight
2	34 - 0	0	14½	11.0	Close to shot 1
3	34 - 8	2	13	12.5	
4	34 - 12	4	11	6.0	Long radial cracks
5	34 - 8	6	13½	0	Ice shook and cracked 100 ft away
6	34 - 4	0	14	9.7	Close to shots 1 and 2

* Depth of blast ports below underside of ice.

† Mean of four measured diameters across completely broken area.

Table II. Results of Cardox shots against lake ice: second N.H. series.

Date 22 Feb 1971, snow cover 0-3 in., water depth 28 ft.

Shot no.	*Charged wt. of shell (lb - oz)*	*Depth of discharge* (ft)*	*Ice thickness (in.)*	*Mean diam of hole or cracked zone (ft)*	*Remarks*
1	33 - 0	0	19½	13.5	All broken blocks fell back in place. Good break.
2	34 - 8	1	18½	14.4	Blocks remained in place, leaving "dart-board" pattern.
3	34 - 8	2	19	17.8	Ice cracked in "dart-board" pattern, but no gross displacement of blocks.
4	33 - 8	3	19	8.1	Ice did not break; slight doming with radial cracks. Cardox shell split.
5	34 - 8				Misfire
6	34 - 0	0.7	19	11.1	45° shothole. Blocks fell back into hole. Good break.
7	34 - 0	–0.8	19	3.9	Ice highly fragmented, much flyrock.

Table III. Results of dynamite explosions under lake ice: N.H. tests.

Date 24 Feb 1971, mean snow cover approximately 7 in. All charges 1 lb of 40% gelatin dynamite fired electrically.

Shot no.	Charge depth* (ft)	Ice thickness (in.)	Mean diam of hole or cracked zone (ft)	Remarks
1	0	16	10.5/12.9	10.5 ft diam open hole with depressed rim of 12.0 ft diam.
2	1.5	19	14.5	No open hole. Ice thoroughly broken, but fragments fell back.
3	3	17	17.0	No open hole. Fragments fell back.
4	4.5	19	4.1/33	4.0 ft diam open hole with a 33 ft diam circumferential crack. Flyrock travel 50 ft. or more.

* Depth below bottom of ice.

Results of airblasting tests on lake ice in Alaska are given in Table IV. Results of comparison tests using Cardox shells are included in the same table, while results of comparison tests with dynamite are given in Table V.

Discussion

Blasting effectiveness. Probably the simplest way to assess the blasting effectiveness of compressed gas shells is to compare them with high explosive.

As far as can be ascertained, the Cardox 231-130 shell and the 300-in.^{3} Airdox shell (at 10,000 lbf/in.^{2}) are approximately equivalent to each other. Certainly in the limited Alaska lake ice tests the two types of shells gave very similar results, and comparison of results for blasts in frozen silt (McAnerney et al. 1969, Mellor and Kovacs 1971) suggest approximate equivalency. This being so, a comparison between explosive and one type of gas shell can usually be extended to include both Airdox and Cardox.

The lake ice tests indicate that in broad terms the 231-130 Cardox shell and, by extension, the 300-in.^{3} Airdox shell are equivalent to about 1 lb of dynamite. (The present results for dynamite are in broad agreement with numerous earlier results for a variety of high explosives fired under lake and river ice, e.g. Frankenstein and Smith 1970, Bolsenga 1968, Robert 1966.) This conclusion is supported by test data for airblasting in frozen silt (McAnerney et al. 1969, Hawkes and McAnerney 1968), which indicate that the maximum burden (perpendicular distance from free surface to shot point) for a 300-in.^{3} Airdox shell firing at 9000 lbf/in.^{2} is about 3 ft in uncracked material with no relief holes. Tests with the 231-130 Cardox shell in the same type of frozen silt also indicate that the critical depth for cratering (minimum depth for camouflet) is approximately 3 ft (Mellor and Kovacs 1971). Data for high explosives indicate that critical cratering depth for 1 lb of explosive in frozen silt is about 3.0 to 3.5 ft (Mellor and Sellmann 1970).

Another approach that can be used is to consider the relative amounts of potential energy released by explosives and compressed gas. A 300-in.^{3} compressed air shell has approximately 1×10^6 ft-lbf of energy when discharging adiabatically from 8000 lbf/in.^{2} to atmospheric pressure, and approximately 1.2×10^6 ft-lbf when discharging from 10,000 lbf/in.^{2} The potential energy of a

Table IV. Results of Airdox and Cardox shots on lake ice in Alaska.

Date 24-26 Mar 1971, snow cover 16½ in., ice thickness 2.71 ft, water depth 10-12 ft.

Shot no.	*Type of shell**	*Depth of discharge below bottom of ice (ft)*	*Discharge pressure ($lbf/in.^2$)*	*Effect of shot*
1	AAD	0	9,200	No ice breakage. Radial cracks, approximately 60° apart, extending out 3 ft from shothole.
2	AAD	0	10,000	No ice breakage. Radial cracks extending out 4 ft from shothole.
3	AAD	0	10,000	Repeat shot in shot no. 2 hole. No breakage or additional cracking.
4	AAD	−0.7	10,000	Ice broken through below 2-ft-deep shothole. Top surface of ice broken over 11 in. diam to depth of 4 in.
5	AAD	1.0	10,000	No ice breakage. Radial cracks, 60° apart, extending 3 ft from shothole.
6	AAD	2.0	10,000	No detectable effect.
7	AAD	−1.2	10,000	Shot at mid-depth of ice. Open hole 5.5 ft diam at surface, funneling down to 4 ft diam at shot depth. Radial cracks over diameter of 17.5 ft.
8	ARS	−1.35	10,000	Shothole angled at 35° from horizontal. Shot at mid-depth of ice. Oval hole 4 ft long by 2 ft wide. Negligible radial cracking.
9	ARS	0	11,000	No ice breakage. Radial cracking over diameter of 12 ft, with discontinuous circumferential crack 8 ft in diameter.
10	Cardox 231-130	1.0		No ice breakage. Some radial cracks extending 1 to 2 ft from shothole.
11	Cardox 231-130	0		No ice breakage. Some radial cracks extending 1 to 2 ft from shothole.

* AAD – Airdox automatic discharge shell.
ARS – Airdox receiver shell.

Cardox shell is not so easy to calculate, as the discharge involves combustion of the heater unit, with heat transfer and phase change processes in the shell, and there is a strong possibility that some carbon dioxide is discharged in the liquid state. The manufacturer is unable to furnish the required information. However, there is a presumption that the Airdox and Cardox tubes are roughly equivalent. Taking the heat of explosion for dynamite as 1 kcal/g, 1 lb of dynamite has approximately 1.4×10^6 ft-lbf of energy, which is very similar to the energy of a 300-$in.^3$ Airdox shell firing at 10,000 to 11,000 $lbf/in.^2$

Table V. Results of dynamite shots on lake ice in Alaska.

Date 24 Mar 1971, snow cover 16½ in., ice thickness 2.71 ft, water depth 10-12 ft, charges: military dynamite.

Shot no.	*Charge weight (lb)*	*Charge depth (ft)*	*Effect of shot*
1	2	2	Circumferential cracks to 21 ft diameter, slight depression inside this area. 10-ft-diam central area domed and fragmented.
2	4	2.5	Circumferential cracks to diameter of 34.5 ft. Slight depression 28 ft diam. Central hump to 9 ft diam. Open hole 5 ft diam.
3	3.5	0	Circumferential cracks and slight depression 25 ft diam. Hole completely choked with ice fragments 10 ft diam.

From the foregoing evidence it is concluded that the 231-130 Cardox shell and the 300-in.^{3} Airdox shell are approximately equivalent to 1 lb of dynamite in their blasting effectiveness.* They are, however, quite different from dynamite in their blasting action.

Blasting action. When a concentrated charge of high explosive is detonated under water the intense pressure generated by the explosion produces a shock wave that travels radially out, with a velocity that exceeds 16,000 ft/sec initially but soon decreases to the sonic velocity in water (about 4800 ft/sec). As the shock travels out its amplitude decays and its duration increases. The detonation also forms a gas bubble that expands, at a much lower rate than the shock, and imparts radial flow to the surrounding water. As the bubble expands, its internal pressure drops and kinetic energy is imparted to the water. This allows the bubble to continue expanding as its internal pressure drops below the local hydrostatic pressure, but eventually the underpressure in the bubble brings about flow reversal and contraction of the bubble. Thus in deep water the bubble pulsates, while at the same time migrating upward and deforming from the ideal spherical shape in response to the effects of the free surface.

While underwater discharge of compressed gas shells has not been studied in detail, a qualitative similarity to chemical explosive detonation may be expected, with the important difference that the discharge pressure at the ports of a shell is $\sim 10^4$ lbf/in.^{2}, whereas detonation pressures of typical chemical explosives are $\sim 10^6$ lbf/in.^{2} This means that initial amplitudes of any shock waves generated by gas shells will be smaller than those generated by explosives.

To obtain some idea of the relative characteristics of explosive and compressed gas, data for discharge in air can be considered. For convenience, pressure/distance data for explosives will be given for a 1-lb charge of high explosive.

Davies and Hawkes (1964) measured overpressure in air as a function of distance for C47 Cardox shells that were similar in weight to the type 231-130, but of somewhat smaller capacity. They found overpressures of 3500 lbf/in.^{2} at 1 in. and 310 lbf/in.^{2} at 10 in. from a shell bursting at 18,000 lbf/in.^{2} Detonation pressures of typical explosives are well over 10^6 lbf/in.^{2} (Dick 1968), and overpressure in air at 1 in. from a 1-lb charge is probably of the order of 10^5 lbf/in.^{2} Overpressure at 10 in. from a 1-lb charge is approximately 1000 lbf/in.^{2} (Mellor and Smith 1967). However, attenuation characteristics are such that 1 lb of explosive and a C47 Cardox shell give about the same overpressure in air at a range of 4 ft.

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* Earlier airblasting tests on frozen soils (Hawkes and McAnerney 1968, McAnerney et al. 1969) led to the conclusion that a 300-in.^{3} Airdox shell discharging from 8000 lbf/in.^{2} is equivalent to 5 lb of 60% dynamite. The 1969 paper suggests that 2 lb can be taken as a conservative figure.

When explosives are detonated under water, the shock pressure at a given distance is higher than it would be in air. According to relationships given by Cole (1948), shock pressures from a deep water explosion of 1 lb of TNT would be 26,000 lbf/in.^{2} at 10 in., and possibly 360,000 lbf/in.^{2} at 1 in. (the latter figure depends on uncertain extrapolation). No comparable data are available for compressed gas devices, but the shock pressures at close range must be much smaller, as the release pressures do not exceed 12,000 lbf/in.^{2} for Airdox and 19,000 lbf/in.^{2} for Cardox. Its attenuation is similar to that of underwater explosions over the same pressure range, and discharge pressure is approximately 10,000 lbf/in.^{2} at 1 in. from the ports. Shock pressure at 10 in. from the ports will be less than 1000 lbf/in.^{2}

As the gas bubble from an underwater explosion expands, almost adiabatically, internal pressure decays rapidly, approximately as the fourth power of the bubble radius. According to a relationship given by Johansson and Persson (1970), bubble pressure for a 1-lb underwater charge of high explosive is approximately 325 lbf/in.^{2} when the bubble has grown to a radius of 10 in., and 25 lbf/in.^{2} when the bubble has grown to 20 in. Pressures in the bubble from a compressed gas shell can be estimated by assuming adiabatic expansion: taking 10,000 lbf/in.^{2} as initial pressure, 300 in.^{3} as initial volume, and 1.4 as the adiabatic constant, pressure is about 250 lbf/in.^{2} with a 10-in. radius and about 14 lbf/in.^{2} (roughly atmospheric pressure) with a 20-in. radius.

The foregoing considerations make it appear highly likely that ice breakage will always be initiated by shock wave shattering when a high explosive charge is fired underwater. A 1-lb charge produces peak shock pressures in excess of 10,000 lbf/in.^{2} at ranges up to 2 ft, and this pressure level is about an order of magnitude higher than the uniaxial compressive strength of ice. Peak pressures do not drop below the uniaxial compressive strength of ice until the range is about 10 ft from a 1-lb charge. The gas bubble pressure experienced at a range of 2 ft from a 1-lb charge is only about one atmosphere.

By contrast, the shock pressure from a gas shell at an underwater range of 1 ft has probably dropped below the uniaxial compressive strength of ice, but the gas bubble pressure at this radius is still more than 10 atmospheres. This would almost certainly result in the ice cover being broken in flexure.

These speculations are consistent with the experimental data. In 19-in.-thick ice, where the Cardox shells were working close to their limit, underwater discharge produced breakage patterns that were clearly indicative of flexure (see Fig. 14, 15, 18). There may have been some shatter damage to the underside of the ice, but it did not penetrate through to the top surface. In the same ice, 1-lb charges of dynamite shattered the ice and threw high plumes of water and ice fragments into the air. The gas bubble and the moving water probably caused secondary breakage, but the breakage pattern was controlled primarily by the vent hole produced by shattering. In this connection it is interesting to study Figure 22, in which ice fragments and water have been discharged through a central hole while a surrounding annulus of ice appears to be pulled *down* relative to the undisturbed surface. If it is assumed that the gas bubble continued its first expansion until it reached the upper surface of the ice and vented (i.e. it grew to a radius of 3 ft before venting), then the bubble pressure curve given by Johansson and Persson (1970) indicates that the internal pressure at the instant of venting could have dropped to 2.6 lbf/in.^{2} absolute. This would result in a downward pressure differential of 12 lbf/in.^{2} through the ice, and it might cause the ice to deflect downward.

Possibilities for practical application. The flexural breaks given by compressed gas shells working under optimum conditions seem far preferable to the breaks given by comparable explosive charges. There is no significant plume or flyrock, and the ice fragments are clean equant chunks (in contrast to the shattered mush produced by a brisant explosive). Furthermore, the pressures a few inches away from a shell are insufficient to damage typical hydraulic structures, ship hulls, or associated equipment.

Existing compressed gas shells seem quite satisfactory for breaking ice up to about 20 in. thick, and they might find immediate application in certain static situations, such as the protection of hydraulic structures from ice thrust. However, a single gas shell of the size currently available is not sufficiently powerful to break the thick ice that immobilizes icebreaking ships.

To make simple estimates of the capacity requirements for blasting ice with compressed gas, scaling relationships established both theoretically and empirically for explosives can probably be adopted. These relationships state that, for geometrically similar situations, linear dimensions scale in proportion to the cube root of charge weight (or energy yield) for a given type of explosive. This means that complete geometric similitude is maintained for charge depth, ice thickness, crater radius, bubble size, and radii for specified pressure levels, with the cube root of charge weight as the scale factor. It also implies that energy effectiveness is invariant with scale.

If cube root scaling is assumed for gas shells releasing at a fixed absolute pressure, and potential energy of the shell is taken as proportional to gas volume, then there will be a third power relation between required shell volume and ice thickness. If a single gas shell (Cardox 231-130 or 300-in.^{3} Airdox) has optimum performance when blasting against ice that is 1.5 ft thick, then the equivalent of eight shells would be needed when the ice is 3 ft thick, and the equivalent of 64 shells would be needed when the ice is 6 ft thick. If a single shell capable of blasting 6-ft ice were to be built, its linear dimensions, including wall thickness, would be approximately four times as great as those of the existing gas shells. Using existing compressors, recharge time for an air-blast shell of this capacity would be inordinately long – about 2 hours or so.

It might be more practical to generate high volumes of compressed gas in other ways. For example, special cartridges of deflagrating explosive ("low" explosive) could be fired in a gun set into a ship's hull below the waterline, something like a submarine torpedo tube. Another possibility would be to develop the compressed gas by direct combustion of fuel oils or natural gas, as in the REDSOD type of system proposed by Wood (1970).

Whatever method is used to generate the gas, some care will be needed to apply its force to best advantage. This would probably mean breaking the ice in flexure and containing the gas bubble beneath the ice as long as possible. In the second series of Cardox tests the "dartboard" breakage patterns were similar to those produced by a radially symmetric concentrated static load, which first forms radial cracks, then breaks the resulting wedge-shaped segments in flexure and, if there is sufficient interlocking of the segments, goes on to extend the cracking pattern radially outward. To obtain this effect with a gas bubble, the initial impulse should probably be applied to only a small area of the ice, perhaps an area with a diameter no greater than the ice thickness. The bubble pressure should be sufficient to break the ice, accelerate it, and produce a maximum displacement that is at least equal to the ice thickness. As the bubble spreads across the bottom surface of the ice its pressure should remain high enough to continue flexural breakage of the radial segments up to the time at which the center of the bubble vents to the atmosphere. From the very limited information obtained in the present tests, it is estimated that bubble pressure at the time of initial contact with the ice should be at least $\sim$500 lbf/in.^{2} For another rough estimate, the static bearing capacity of an ice cover can be considered. The maximum load that an ice sheet can carry (P) is often related to ice thickness h by an expression of the form:

$$\frac{P}{h^2} = K$$

where K is a constant with the dimensions of stress. Empirical values of K vary widely, but the upper limit bounding a wide range of field data is $K \approx 1000$ lbf/in.^{2} If gas pressure is applied over an area $\approx h^2$, the required initial pressure is thus $\sim$1000 lbf/in.^{2} These pressures are a good deal higher than those considered necessary for an explosive icebreaker by Wood (1970).

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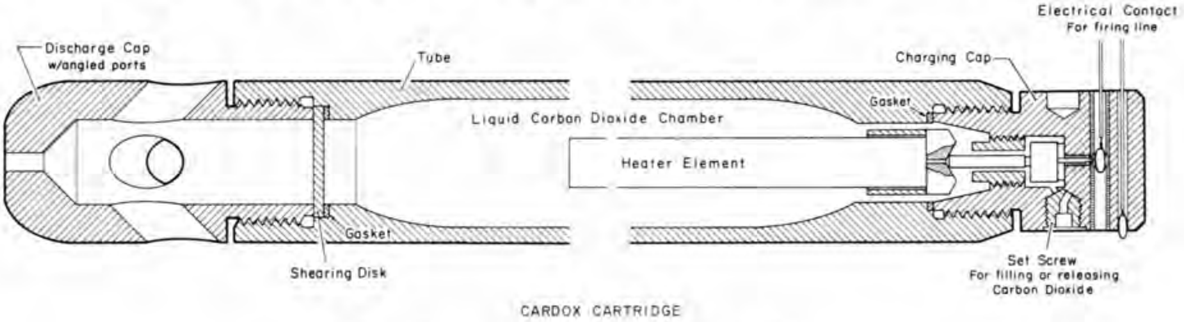


Figure 1. Diagram of the Cardox shell.

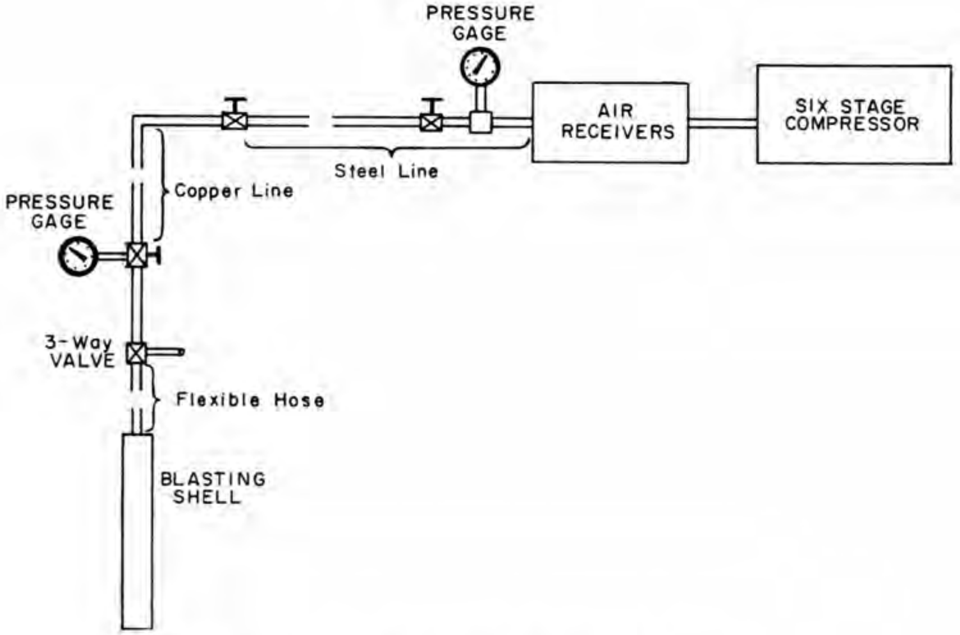
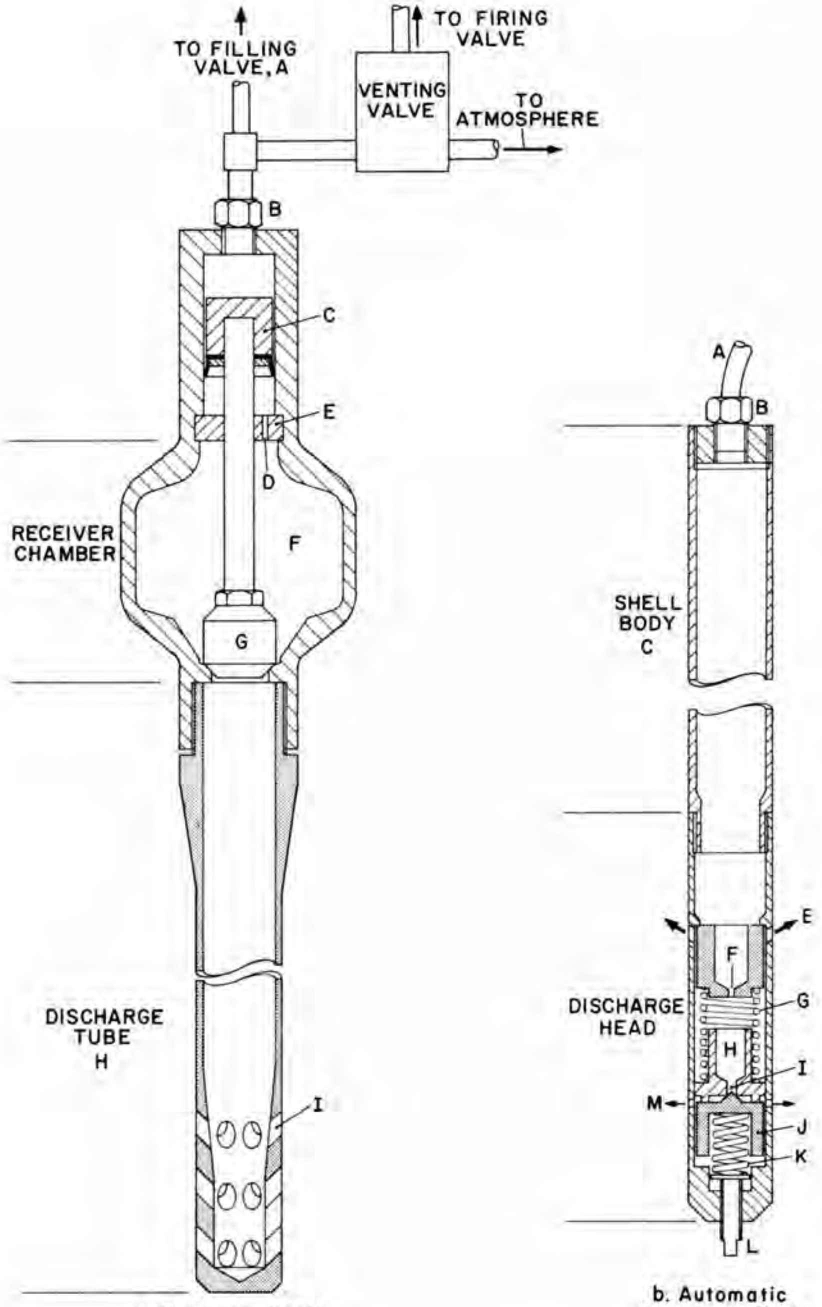


Figure 2. Schematic diagram of airblasting system.

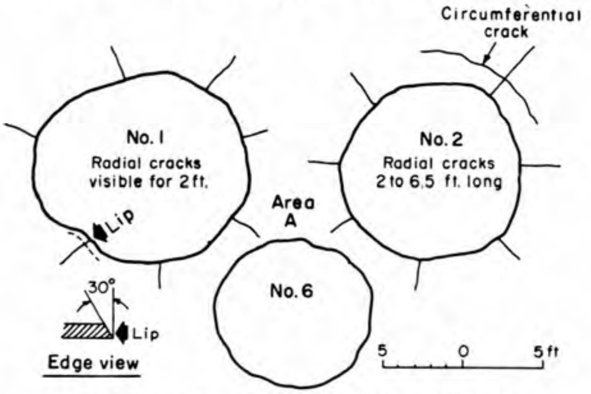


a. Receiver Shell

b. Automatic Discharge Shell

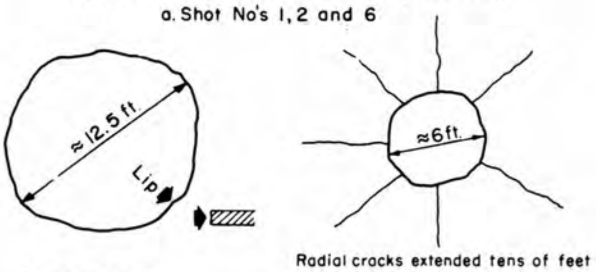
Figure 3. Details of two types of airblasting shell: (a) Receiver shell (C-piston for seating and releasing piston assembly, G-discharge value, I-discharge ports); (b) Automatic discharge shell (E-discharge ports, F-spring-loaded piston, H-spacer with axial hole I, J-piston loaded by spring K, M-vent ports).

Figure 4. Alaska test site. The six-stage airblást compressor is mounted on a tracked vehicle, and a cabin has been built around it for shelter. The vehicle is towing an electrical generator.



Area A cracked up but not overturned by Shot No. 6

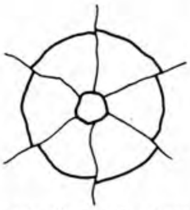
a. Shot No's 1, 2 and 6



Radial cracks extended tens of feet

b. Shot No. 3

c. Shot No. 4



Didn't vent. Widespread cracking

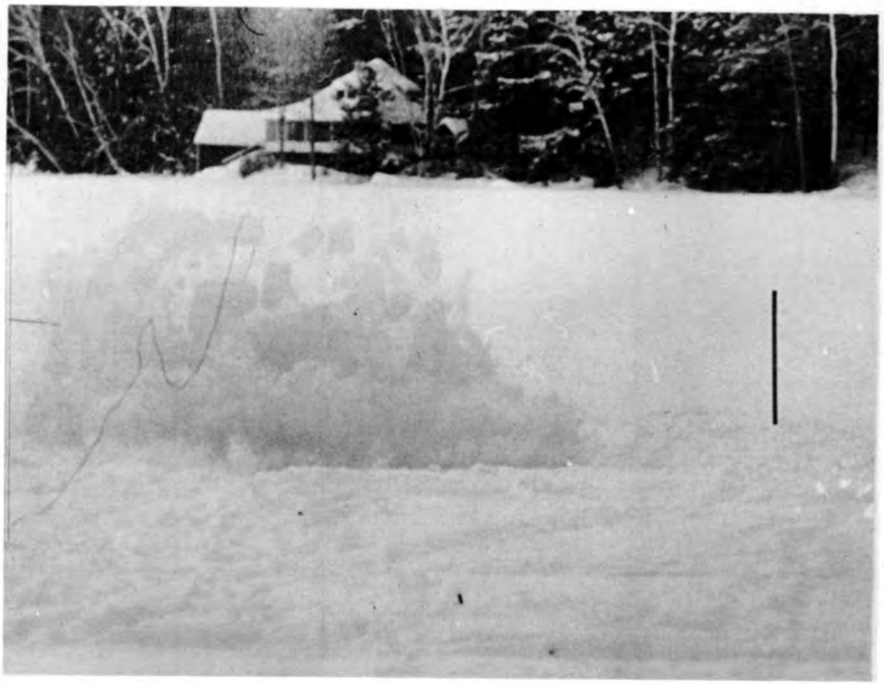
d. Shot No. 5

Figure 5. First N.H. series of Cardox tests – limits of ice breakage.

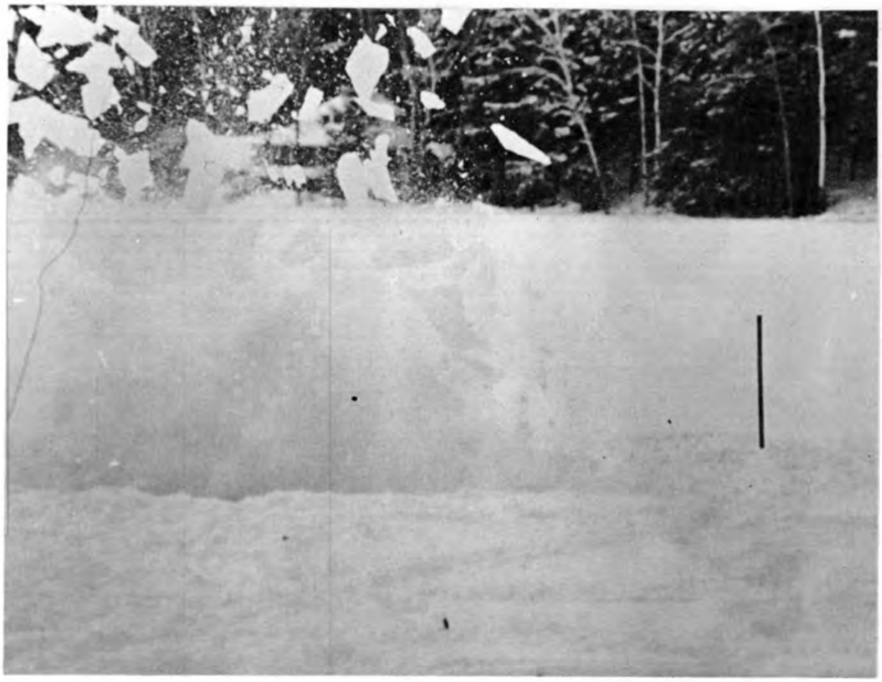
a.

b.

Figure 6. First N.H. test series. Cardox shell being placed for Shot #1.

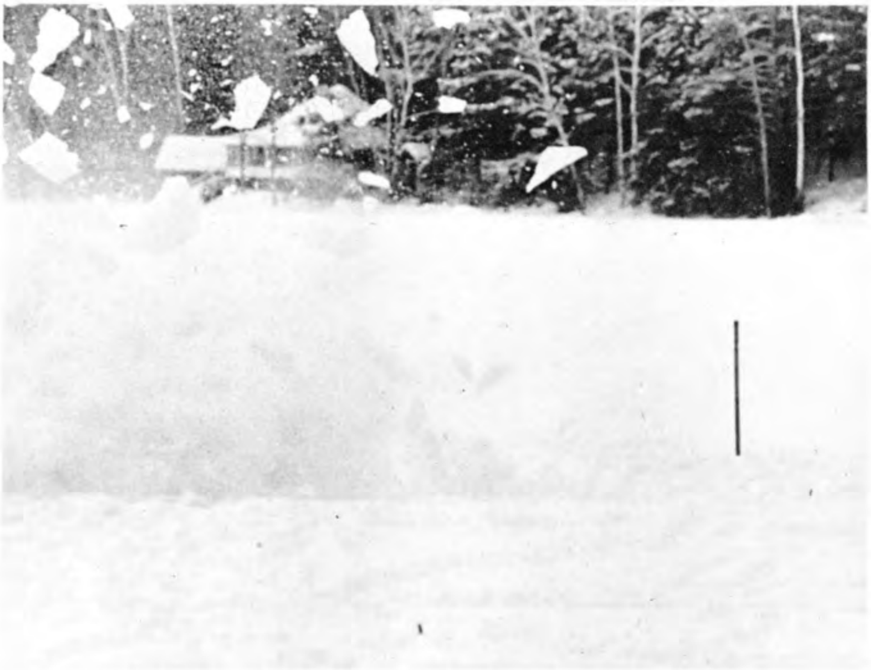


a.



b.

Figure 7. First N.H. test series. Ice breakage by Cardox shell no. 1.

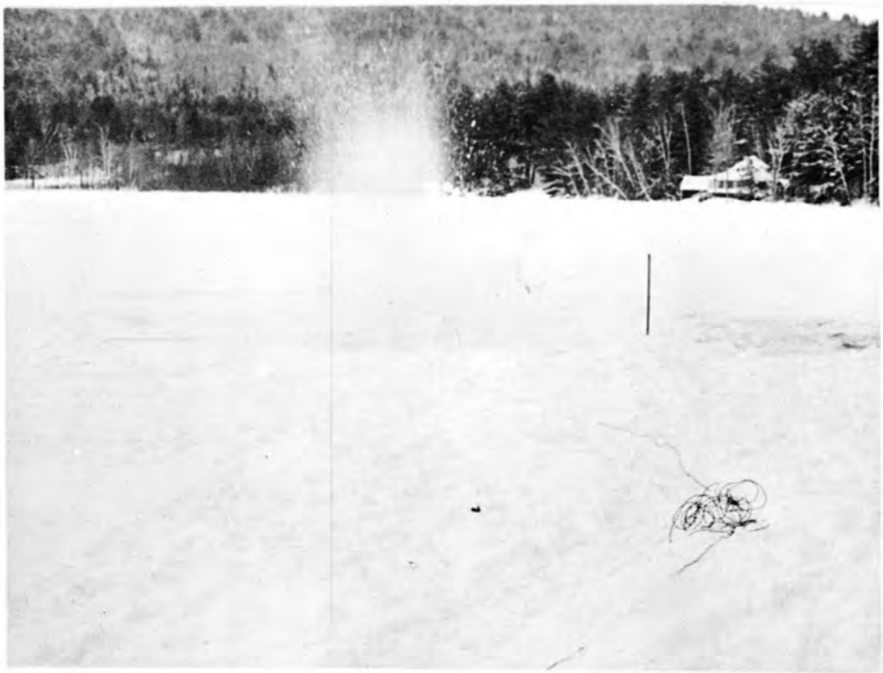


c.

d.

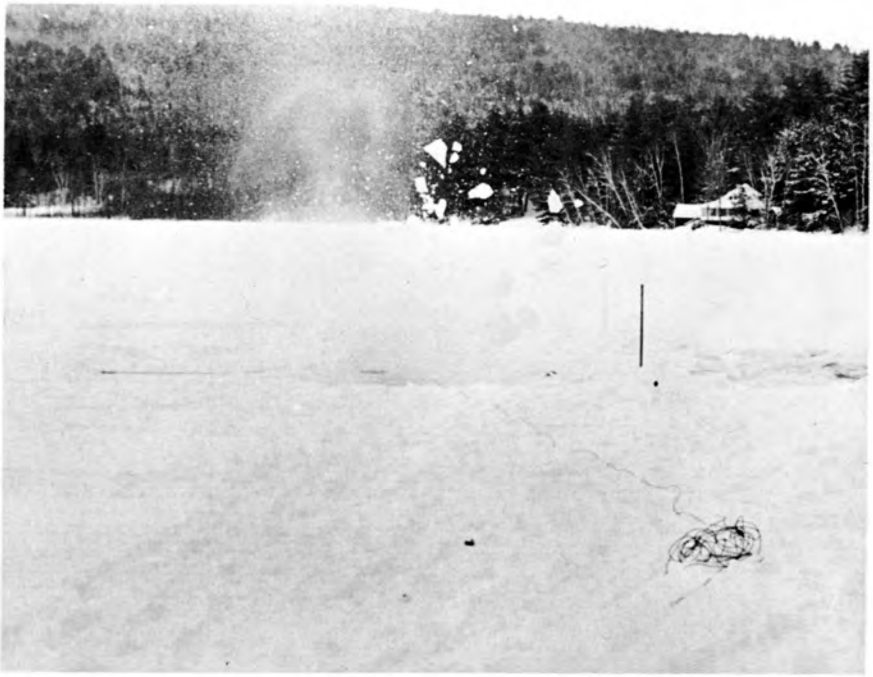
Figure 7 (Cont'd).

a.



b.

Figure 8. First N.H. test series. Discharge sequence for Cardox shell no. 2. Note size of debris in photo d.



c.

d.

Figure 8 (Cont'd).

Figure 9. First N.H. test series. Craters, or breakage areas, for Cardox shells no. 1 (foreground) and no. 2 (center).

a.

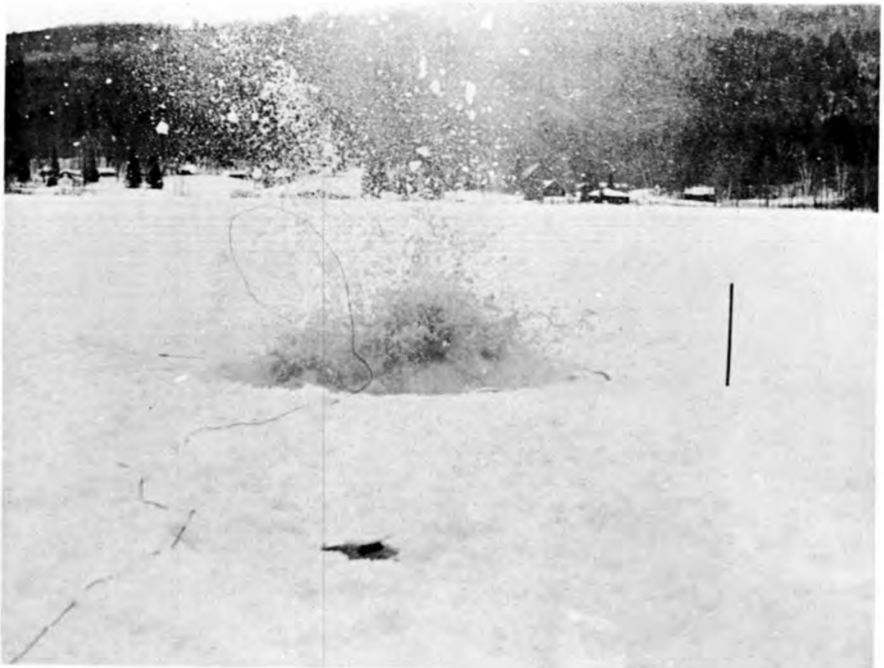
Figure 10. First N.H. test series. Installation of shell and discharge sequence for Cardox shot no. 3.

b.

c.

Figure 10 (Cont'd).

d.



e.

Figure 10 (Cont'd). First N.H. test series. Installation of shell and discharge sequence for Cardox shot no. 3.

a.

b.

Figure 11. First N.H. test series. Discharge sequence and debris for Cardox shell no. 4.

c.

d.

Figure 11 (Cont'd). First N.H. test series. Discharge sequence and debris for Cardox shell no. 4.

a.

b.

Figure 12. First N.H. test series. Discharge for Cardox shell no. 5.

Figure 13. First N.H. test series. Discharge for Cardox shell no. 5. (a) Connecting firing line to Cardox shell no. 6. (b) Ice broken by shell no. 6.

a.

b.

Figure 14. Second N.H. test series. Discharge sequence and pattern of ice breakage for Cardox shell no. 1.

c.

d.

Figure 14 (Cont'd). Second N.H. test series. Discharge sequence and pattern of ice breakage for Cardox shell no. 1.

e.

f.

Figure 14 (Cont'd).

a.

b.

Figure 15. Second N.H. test series. Discharge sequence and pattern of ice breakage for Cardox shell no. 2.

a.

b.

Figure 16. Second N.H. test series. Discharge sequence for Cardox shell no. 3.

c.

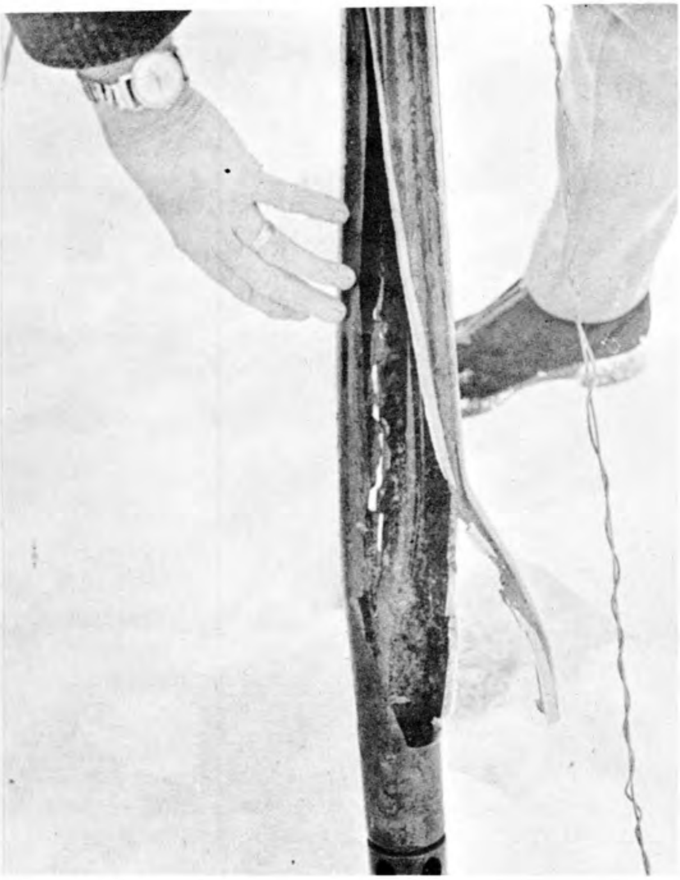
d.

Figure 16 (Cont'd). Second N.H. test series. Discharge sequence for Cardox shell no. 3.

a. *Discharge of Cardox shell no. 4.*

b. *Condition of shell after rupture.*

Figure 17. Second N.H. test series.



c. Condition of shell after rupture.

d. Effect of shot.

Figure 17 (Cont'd). Second N.H. test series.

a.

b.

Figure 18. Second N.H. test series. Discharge sequence and ice breakage pattern for Cardox shell no. 6.

c.

d.

Figure 18 (Cont'd). Second N.H. test series. Discharge sequence and ice breakage pattern for Cardox shell no. 6.

a.

b.

Figure 19. Second N.H. test series. Discharge sequence and shot effects for Cardox shell no. 7.

c.

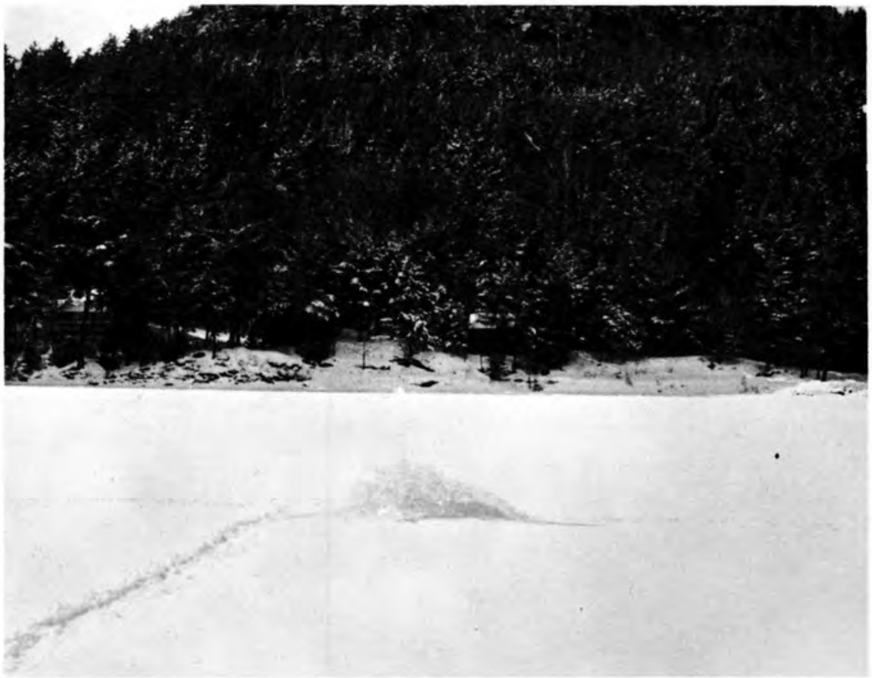
d.

Figure 19 (Cont'd). Second N.H. test series. Discharge sequence and shot effects for Cardox shell no. 7.

a.

b.

Figure 20. N.H. explosive tests. Discharge plume and crater for charge no. 1.



a.

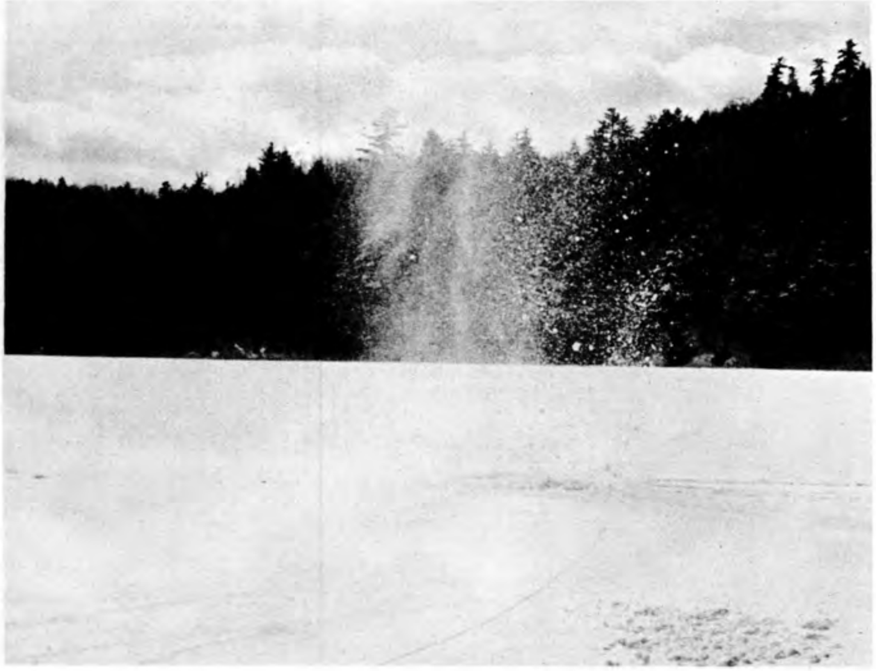
b.

Figure 21. N.H. explosive tests. Discharge and breakage pattern for charge no. 2.

a.

b.

Figure 22. N.H. explosive tests. Discharge sequence and final effects from charge no. 3. Note that in photo (b) the ice immediately surrounding the central vent is depressed relative to the undisturbed ice.



c.

d.

Figure 22 (Cont'd). N.H. explosive tests. Discharge sequence and final effects from charge no. 3.

a.

b.

Figure 23. N.H. explosive tests. Discharge and breakage for charge no. 4.

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13. ABSTRACT

Tests were made to determine the effectiveness of compressed-gas blasting devices for breaking floating ice sheets. Experiments were made on frozen lakes in New Hampshire and Alaska using the Cardox and Airdox blasting systems, and comparative tests were made with conventional chemical explosives. Gas blasting devices were found to be closely comparable to chemical explosives in terms of specific energy consumption, but absence of any significant shock wave in the gas blast results in a different mode of action. The gas devices fractured the ice largely by flexure, giving large fragments. Practical applications of gas blasting for ice breaking are discussed.

14. KEY WORDS

Blasting
Icebreakers
Ice control