Draft Translation 395

BREAKING ICE WITH A JET OF GAS

G.N. IAkovlev

August 1973

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

DRAFT TRANSLATION 395

ENGLISH TITLE: BREAKING ICE WITH A JET OF GAS

FOREIGN TITLE: RAZRUSHENIE L'DA REAKTIVNOI GAZOVOI STRUEI

AUTHOR: G.N. IAkovlev

SOURCE: Trudy Arkticheskogo i Antarkticheskogo Nauchno-Issledovatel'skogo Instituta (Transactions of Arctic and Antarctic Scientific-Research Institute), No 300, Leningrad, 1971, pp 153-167

Translated by U.S. Joint Publications Research Service for U.S. Army Cold Regions Research and Engineering Laboratory, 1973, 16 p.

NOTICE

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The quest for new methods of breaking ice is one of the important practical problems. Among the various techniques which are being developed in the ice-research laboratory at the AASRI (Arctic and Antarctic Scientific-Research Institute), studies are also underway on the utilization of a thermodynamic method which currently is being applied successfully in industry for breaking rocks. Its introduction into production is being achieved along three lines. The first application area of the thermodynamic method is the drilling of boreholes for the placement of an explosive charge in the open-cut development of deposits of nonferrous and ferrous metal ores.

The mechanical boring technique is of low productivity and cannot assure the transmission of an adequate amount of force to the rock which is being broken up. Therefore, we have conducted extensive research activities in the development of basically new methods for breaking rocks. Among them the thermodynamic technique has become most popular.

The application of this method for drilling hard rocks has shown that the drilling rate is raised by 15-20 times, while the drilling cost is decreased by 8-10 times.

At the present time we have developed machine tools for the drilling of boreholes and blast holes for almost the entire range of measurements utilized in the mining industry, the construction material extraction and mineral raw material industry.

The second area of application of the thermodynamic technique has developed toward processing natural rock, concrete and ferroconcrete.

The mechanical processing has been solved relatively satisfactorily for rocks of low hardness, while the processing and cutting of hard rocks with the aid of hard alloy disks can in no way be regarded as economical. Currently, we have developed special thermal cutters for the cutting and processing of the strongest rocks. With the aid of such thermal cutters, we can cut channels, furrows, slots and even accomplish rough sketching on the surface of rock. With a thermal cutter of the proper design, we can perform core drilling and the cutting of variously shaped holes.

The output of the cutter and the processing of stone blocks with the aid of this method have increased by 16-20 times.

The gist of the reactive-thermal method is that the drilling or breaking of the material is accomplished with the aid of a high-temperature gas jet ejected at supersonic speed from the nozzle of a propelling jet. The burner includes a chamber in which there occurs fuel combustion and the formation of gases with high temperature and pressure. These gases have a large supply of heat and mechanical energy. Usually the working pressure in the thermal cutters' combustion chambers will vary from 5 to 9 atm, while temperature within the chamber reaches 3000-3300°. The hot gases from the chamber are ejected outward through a specially shaped nozzle (Laval nozzle) where passing through a critical section they acquire supersonic velocity.

As fuel we utilize kerosene or other types of fuel having a petroleum origin, while we use a gaseous oxygen as the oxidizer. The fuel mixture is injected into the combustion chamber with the aid of a centrifugal nozzle and an oxygen swirler. The nozzle is so designed that the kerosene entering it through the channels in the side walls is imparted a rotary motion and upon escape from the central orifice, it is atomized in the combustion chamber in the form of the finest sprays (mist).

For protecting the nozzle against fouling, a clean brass screen is installed in front of it. The oxygen swirler imparts a rotary motion to the oxygen flow and improves the displacement of the fuel and oxidizer. Cooling of the burner is provided for protection against the effect of high temperatures. On the chamber surface, there are screw-type channels along which water circulates, fed under a pressure of 5-8 atm, and removing the excess heat while passing through the housing walls and the combustion chamber. The cessation of water supply or a decrease in its pressure leads to an instantaneous combustion of the chamber.

The operating conditions of the burner depend on pressure and the quantity of fuel components which is being fed into it.

The outflow rate of gases in the nozzle section comprises around 2000 m/sec. Pressure of the working components is: oxygen 12-16 atm, kerosene 14-16 atm, and water 5-8 atm. The consumption of oxygen for the conventional burners equals approximately 8-10 kg/hour; of kerosene 8-10 kg/hour, and cooling water, 200-250 l/hr. The efficiency of jet burners reaches 60-70%.

Experiments in the breaking of rocks have shown that only a supersonic jet assures the intensive breakdown of the material since high temperature alone is inadequate for this purpose; within a minimal time, it is necessary to apply a large amount of heat to the object which is being broken down.

Only an incandescent jet escaping at supersonic velocity, having touched the materials' surface for a brief time (tenths of seconds) imparts a large amount of force to it. The conditions for the intensive breakdown of hard rocks include high temperature and jet velocity as the basis for instantaneous heat transmission and rapidly developing thermal stresses in them. In such a layer of rock, there develop high temperature gradients and, as a result, thermal stresses causing considerable deformations and shearing of the rock particles. The broken-off particles are ejected by the gas flows and the next layer then begins to disintegrate, etc. In this manner, the hard rocks are broken down by way of scaling. The aerodynamic impacts of the jet flow promote an intensive and purposeful breakdown.

We should particularly point out that by such a technique, we cannot cut all rocks but only those which have low heat conductivity, crystalline structure and are not eroded under the effect of high temperatures.

In this way, while the hard rocks having the indicated properties are broken down by means of scaling, the natural mineral materials (concretes and ferroconcretes) having a specific structure and porosity compensating the developing heat stresses in the material, melt under the effect of the jet.

We can speed up the breakdown process by introducing a thermal mixture into the jet (e.g. a mixture of aluminum and ferric oxide) accelerating the melting, increasing the fluidity and carrying out of the melt. At the present time, the Kazakh Polytechnical Institute using such a procedure has succeeded in cutting concrete by scaling, with the aid of a new design of jet burner.

Finally, the third area of utilizing the thermodynamic technique is the processing of frozen soils.

The tempestuous development of the open-cut mining of minerals and also the rapid construction rates of various enterprises, hydraulic stations, canals, highways, etc. have led to a significant growth in the scales of earth-processing operations.

It is necessary to point out that during the winter, these activities become greatly complicated by the development of frozen soils, which increase resistance to cutting by tens and hundreds of times vis-à-vis the conventional approaches.

The studies conducted by the Khar'kov Aviation Institute on the application of a thermodynamic method for the processing of frozen soils yielded positive results. However, the employment of oxygen-kerosene burners cooled by water revealed a number of significant shortcomings. The gas jets having a temperature above 2000° lead to the baking of salt and the formation of a tough rind on the surface, especially in the case of clay soils.

The application of costly and scarce oxygen as an oxidizer during large-scale operations is economically infeasible. Finally, the use of water for the cooling of burners involves appreciable difficulties during winter operations. Therefore, the Khar'kov Aviation Institute has developed new gasoline burners where compressed air is used as the oxidizer. The burners of the air-jet type have found broad application in the handling of frozen soil under various geologic and climatic conditions.

Tests Conducted on Breaking Ice with the Aid of Oxygen-Jet Burners

Experimental studies were conducted for clarifying the possibility of utilizing the thermodynamic method for breaking ice. For conducting the experiments, we utilized the test area for the fire treatment of granite at the Leningrad Stonecutting Plant.

The diagram for the thermodynamic facility has been shown in Fig. 1.

For preparing the ice samples, we utilized the small model basin at AASRI. The delivery of ice blocks to the plant facility was performed prior to the actual beginning of operations, since at that time the air temperature was +2°. We succeeded in conducting seven tests on the ice cutting.

The first experiment in cutting across a block proved unsuccessful since within 5 seconds, the burner melted. We replaced the cutter but the failure was repeated. The reason for this was a malfunction in the water cooling. Evidently, the water contained bits of ice which from time to time covered the inlet opening to the cutter, and the water supply was cut off. We were forced to blow out the entire line and to check its operation. We have shown in Fig. 2 a thermal cutter equipped with water cooling.

The operations then proceeded smoothly; we performed the ice cutting along and across the blocks, and also in a tank with water.

As the tests revealed, the breaking of ice by a thermodynamic technique took place in the form of a rapid melting in the influence area of a high-temperature flame of the burner. The breakdowns of ice in the form of flaking and scaling of the particles of materials with the carrying out of the disintegration products, as takes place during the breakdown of hard rocks, did not occur. In outward appearance, the breakdown of ice was reminiscent of the breakdown of such materials as concrete and ferroconcrete.

The cutting of ice was accompanied by a loud noise developing during escape of jet from the jet burner and its impacts along the surface of the ice block. During the operation, a gas cloud forms which has the strong odor of kerosene. Obviously, its vapors are intensively released during the incomplete combustion of the mixture and they escape into the air.

The high-temperature jet striking against the ice surface melts the ice; at this time, part of the melt water runs along the cut, while some of it is sprayed to the sides.

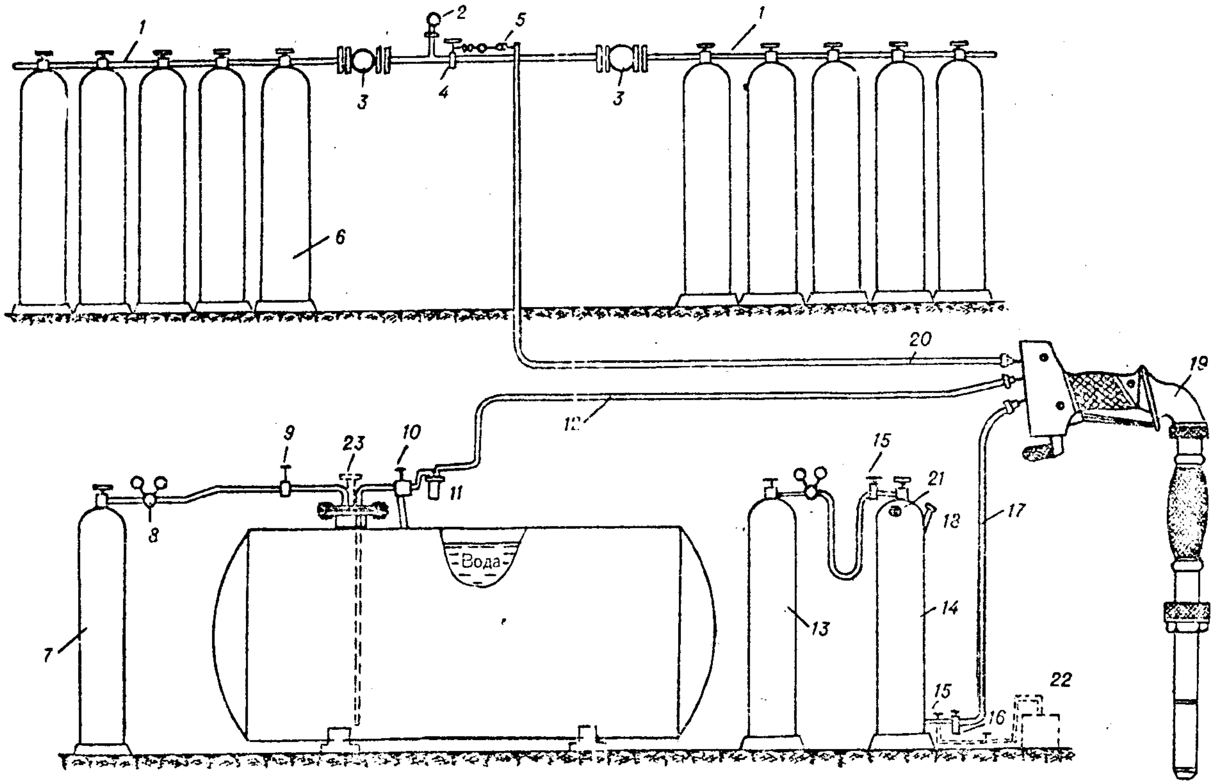

Fig. 1. Diagram of Thermodynamic Facility with Oxygen-Kerosene Burner and Water Cooling Device. 1 - collector; 2 - manometer; 3 - cut-off valve of collector; 4 - cut-off valve of oxygen bleeding; 5 - ramp-type reducing valve; 6 - oxygen tank; 7 - air tanks; 8 - pressure reducer; 9 - three-pass valve; 10 - cut-off valve; 11 - water sump; 12 - water hose; 13 - air tank; 14 - kerosene tank; 15 - three-pass valve; 16 - kerosene sump; 17 - kerosene hose; 18 - plug; 19 - thermal cutter; 20 - oxygen hose; 21 - nonreturn valve ($P_o = 10$ atm); 22 - vat for dumping kerosene; and 23 - nonreturn valve ($P_p = 10$ atm).

According to the appearance of the running water, we can theorize that some of it is brought to the boiling point, while the remaining part is even transformed to steam and participates in the formation of the gas cloud.

In the first test cutting across the block having lasted at total of 5 seconds, on its edge there formed a recess with a rib (with width of 4 cm, depth of 7 cm) in the form of a cavity with greatly melted walls.

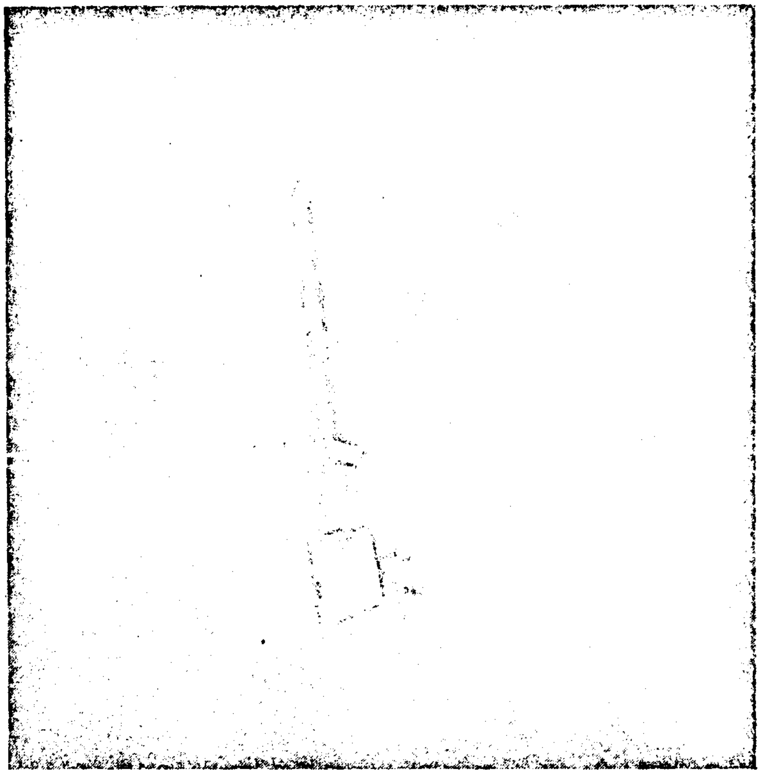

Fig. 2 Type of Thermal Cutter Equipped with Water Cooling

In the subsequent tests, the cut assumed the form of a wide slot over the entire width or length of the block. The width of cut from above was irregular and fluctuated within the limits from 7-12 cm. During the cutting along the block, i.e. at a considerable distance, the transverse profile of cut became distinctly outlined: narrower toward the top and wider toward the bottom, where the burner flame spread out.

Table 1

Cutting of Ice by Supersonic Gas Jet
(air temperature + 2°)

Number of tests and blocks	*Dimensions of blocks (cm)*	*Form and dimensions of cut*	*Duration of cutting (sec)*	*Area of cutting (cm^2/sec)*	*Rate of ice melting (cm^3/sec)*	*Remarks*
1	30×26×100	Cutting from rib, width of cut 4 cm, depth 7 cm	5	5	--	Oxygen pressure 16 atm, kerosene pressure 17.5 atm, trial cutting from rib along center of block; stopped owing to burning out of burner
2	30×26×100	Cutting from rib, width of cut 7-12 cm on cross-section of ice block	160	4.7	49	Oxygen pressure 16 atm, cut irregular with greatly melted walls
3	30×26×90	Cutting along ice block, width of cut 10 cm, length 90 cm, depth of cut 26 cm	180	13.0	130	Cutting conditions and fuel consumption the same; edges of cut uneven but smooth from melting; during cutting, watter boils under the flame and steam escapes
4	30×26×40	Cutting along ice block, width of cut 8 cm, depth of cut 15 cm, length of cut 40 cm	87	7.0	42	Cutting of ice block in tank containing water
5	30×26×40	Cutting along ice block, width of cut 8 cm, depth 18 cm, length 40 cm	110	6.6	40	Cutting of ice block in tank of water
6	30×26×100	Lengthwise cut, width 10 cm	265	9.8	98	Block of ice placed on two others; during lengthwise cutting, i e. at a considerable distance, the cut profile is clearly delineated: it is narrower at the nozzle and wider toward the bottom where the flame spreads out
7	30×26×100	Transverse cut, width about 10 cm (uneven)	90	8.7	87	Cutting regime as formerly
Average				7.8	74	

The entire surface of the cut was uneven but greatly melted, without sharp corners or bulges. During cutting in the dark, the ice block was effectively lighted from within by the cutter flame. When the cavity of the cut had already become of considerable size, an interesting acoustic phenomenon was detected. The gas jet penetrating the cut created a sound which, echoing in the cut cavity, changed its timbre and height.

The tests on the cutting of ice samples submerged in water proceeded similarly to the cutting of ice in air. A gas jet forced the water from the cut while from the sides, it (water) again penetrated the cavity and mixed intensively but we did not observe any appreciable atomizing of it.

At this time, the impression was created that in the first case, the cutting rate was faster but in a calculation of the cutting rate, it proved to be of about the same order. The area of cutting the ice in the individual tests, including the tests on cutting ice in water, varied from 4.7 to 13.0 cm^2/sec. The average reduced area of cutting ice by a jet gas flow from all tests comprised 7.8 cm^2/sec.

If we compare the amount of melted ice in the various experiments, as is evident from Table 1, it fluctuated in the limits from 40-130 cm^3/sec. The average rate of melting ice with the aid of the oxygen-kerosene thermal cutters comprises 74 cm^3/sec.

The tests performed indicated the basic difference in the processes involved in breaking down ice and rocks. The destruction of ice by a jet gas flow occurs by way of pure melting, while the processing of rocks occurs basically by means of mechanical breakdown.

Obviously, the reason for this is found in the specific properties of ice as a substance existing in nature at temperatures close to the temperature of its melting. Therefore, in the given case, a high-temperature gas jet cannot develop in the ice any appreciable temperature gradients or create any significant thermal stresses leading to the cracking or shearing of ice spicules. Therefore, ice simply melts, retaining the melted temperature unchanged.

On the other hand, in a thin layer of rock under the effect of a high-temperature jet, there originate high-temperature gradients and, as a result, significant deformations leading to the shearing and breakdown of the rock's particles. The aerodynamic impacts of a jet flow promote an intensive and directed disintegration. This summarizes the principal difference in the breakdown of ice and rocks.

Experiments on Breaking Ice with the Aid of Combustion Chambers of the Air-Breathing Type

For explaining the favorable outlook in the utilization of the second modification of the thermodynamic technique, i.e. with the aid of the air-breathing type of combustion chambers, for breaking down ice we performed experiments at Leningrad and Khar'kov.

In Leningrad for performing the tests we succeeded in utilizing the test facility for the fire treatment of granite at the Leningrad Stonecutting Plant where we accomplished experimental work on the adoption of air-breathing thermal cutters for the processing of granite. The studies indicated that although the productivity of these thermal cutters during the processing of granite is slightly less than in the case of the oxygen-jet burners, they do possess a number of advantages. The main one among them is the fact that we manage to do without the gaseous oxygen and water necessary for cooling the thermal instruments. This greatly simplifies the device and makes its operation more reliable under production conditions.

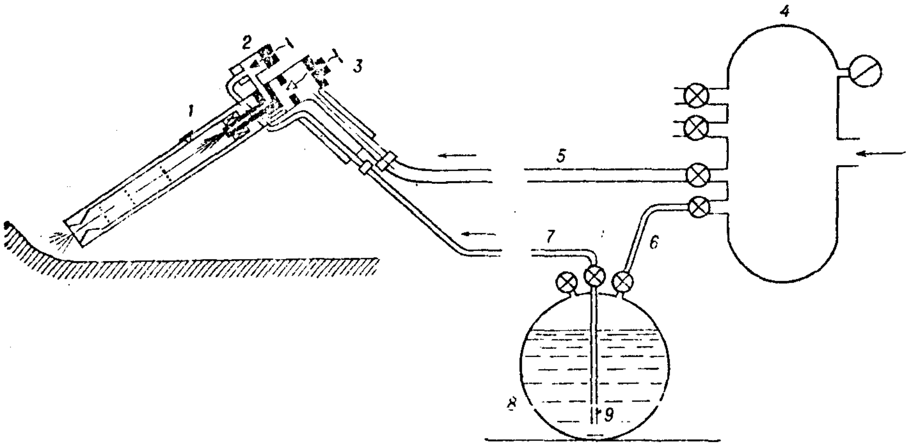

Fig. 3. Diagram Showing Air-Jet Device with Gasoline Burner. 1 - thermal cutter; 2 - fuel valve; 3 - air tap; 4 - compressor receiver for main air line; 5 - air hose; 6 - pressure hose; 7 - fuel hose; 8 - fuel tank; and 9 - intake tube.

The setup diagram for the air-jet thermal cutter which was utilized for cutting ice, has been shown in Fig. 3. The main units of this installation are: a compressor receiver for the supply of air, a fuel tank and a heat cutter. The temperature of the gas stream at the outlet from the heat cutter comprises 1000-1200°; the velocity of jet reaches 1200-1500 m/sec at an air flow rate of around 2.5-3 m^3/min.

The ice samples were prepared in the small model basin of the AASRI. The frozen ice was cut into pieces (blocks) in a basin and delivered to the test facility prior to the actual start of operations. The results from the tests on cutting ice have been shown in Table 2.

First Test. This included a lengthwise cutting of a block by the gas jet (Fig. 4). The cutting was accompanied by a loud sharp noise caused by the escape of the gas flow from the jet burner and by its impacts against the surface of the ice block. The noise was loudest when working under full power at the beginning of cutting; then it decreased somewhat as the cut became deeper.

The cutting of ice occurs by way of its rapid melting, i.e. similar to the breaking of ice with the aid of oxygen-kerosene combustion chambers. The edges and walls of the cut become greatly melted and uneven, wherein the form of these irregularities depends on the conditions of moving the heat cutter. The operator manipulates the cutter unevenly and where the cutter has stopped momentarily, one obtains a deeper cavity. This also is influenced by a variation in the angle of attack by the burner flame.

Duration of the test was 320 seconds, after which the block was cut completely through and broke into two parts.

Second Test. Lengthwise cutting of block over its entire length. The block was not cut to the end. The thin remaining arch served for taking measurements of the cut's parameters. The walls along the cut were greatly melted, with irregular edges; in the upper part, the cavity was slightly wider. During the cutting, the melt water was ejected to the sides together with the vapor and gases, and ran down the sides of the sample onto the ground and boiled.

Third Test. Drilling the ice. The gas jet quickly melted the ice; moreover, the hole's walls proved to be greatly melted from the surface and the hole's diameter turned out to be much larger than the diameter of the burner flame. During the drilling of the ice, water, steam and gas were spewed upward from the hole.

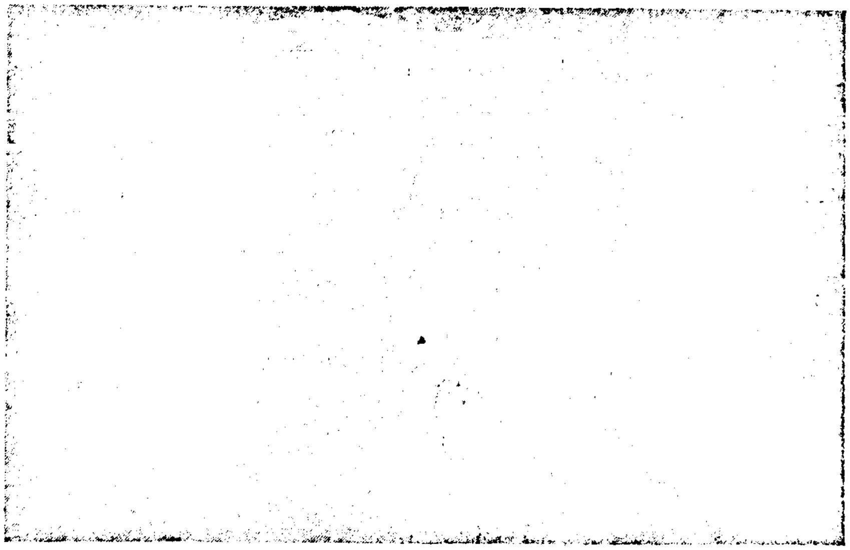

Fig. 4. Cutting Ice with Thermal Cutter.

Fourth Test. Cutting the ice across the block. The description of the cutting is similar to the foregoing. In all the tests the rates of cutting the ice proved to be similar. As is evident from Table 2, the cited cutting rate varied in the limits from 5.7 - 6.6 cm^2/sec.

The average normalized area of cut in all the tests comprised 6.2 cm^2/sec. As was expected, the rate of cutting ice with the aid of air-gasoline thermal cutters proved to be slightly less than in the utilization of oxygen-kerosene thermal cutters where it amounted to 7.8 cm^2/sec.

The quantity of melted ice per time unit in the experiments varied from 42 to 69 cm^3/sec and (other conditions being equal) obviously depended on the completeness of utilizing all the heat in the burner flame for thawing the ice. During ice cutting, it is inevitable to have unproductive heat losses expended for heating the air. Heat is used most fully on drilling the ice, where the rate of ice melting reaches 69 cm^3/sec. The average rate of ice melting with the aid of the air-gasoline thermal cutters amounted to 52 cm^3/sec.

Tests on the breakdown of ice in Khar'kov were conducted at the proving ground of the Jet Engine Department at the Aviation Institute, where this technique of breaking down frozen soils had been developed.

The pattern of the layout for the tests on the breakdown of ice was similar to that described above. Temperature of the gas jet in the combustion chamber reached 2000° and at the nozzle outlet, it was 1000-1200°. Diameter of the gas jet during the tests was 2 mm while its velocity ranged from 1200-1500 m/sec. Air supply was accomplished from a compressor and its flow rate reached 2.5 - 3 m^3/min.

Six cavities were made in the ice. On an average, in 1.5 minutes the ice melted for a depth of 10-12 cm. Owing to the high velocity of the jet, all the melted water was transported from the hole and a lot of steam formed at the beginning of the drilling. The block of ice was then cut by the gas jet. Five minutes were required for the cutting. During the cutting of the ice, much steam formed and the ice became greatly melted from the edges of the cut.

In general the experiments conducted in Khar'kov on ice cutting confirmed the results obtained in Leningrad.

Conclusions

Based on the tests conducted on breaking ice with the aid of the thermal jet method, we can form the following conclusions.

The destruction of ice by a gas jet both with the utilization of oxygen-kerosene and air-gasoline combustion chambers occurs only by melting the ice. The breakdown of the ice in the form of crushing, shearing and flaking of material particles (i.e. mechanical disintegration) with subsequent ejection of disintegration products does not occur.

In outward appearance, the process of cutting ice by a jet flow is similar to the breakdown of artificial mineral materials (concrete and ferroconcrete) having a specific structure and porosity which compensate for the developing thermal stresses. In these instances, the breakdown of the materials is also achieved by means of melting.

Apparently the chief difference in the cutting of ice by a high-temperature gas jet as compared with the breakdown of hard rocks is that in a thin rock layer under the effect of a high-temperature gas jet (up to 3000°), high temperature gradients develop and thermal stresses originate therefrom. The latter cause significant deformations and shearing of the rock's particles. The aerodynamic impacts of the jet stream promote an intensive and purposeful breakdown.

However during the cutting of ice, such a phenomenon does not occur. Obviously the reason for this is found in the specific nature of ice as a material existing in nature at temperatures close to its melting temperatures. Therefore a high-temperature gas jet is unable to create significant temperature gradients in the ice or to cause appreciable thermal stresses leading to the shearing of the ice particles. In this case the ice simply melts, preserving an unaltered melting temperature.

A comparison of the effectiveness of the oxygen-kerosene and air-gasoline combustion chambers has indicated that no significant difference occurs in the rate of cutting the ice. The oxygen-jet burners yield somewhat better results. For the oxygen-jet heat cutters, the standardized cutting area comprised 7.8 cm^2/sec and for the air-jet cutters, it was 6.2 cm^2/sec.

In a conversion to rate of ice melting, the first type of burners also has somewhat better parameters. Their rate of melting the ice constitutes 74 cm^3/sec, while that of the air-jet thermal cutters is 52 cm^3/sec. However, in spite of the slight advantages found in the ice cutting parameters of the oxygen-jet combustion chambers as compared with the air-jet ones, they do suffer from significant shortcomings. The principal among them is the necessity for utilizing water in the thermal instruments for cooling the combustion chamber, causing significant difficulties in their operation during winter operations. In addition, the utilization of expensive and scarce gaseous oxygen as an oxidizer during large-scale operations is economically infeasible.

Therefore the application of air-jet thermal tools for cutting ice is more promising, notwithstanding the fact that their parameters for rate of ice cutting are slightly lower than those obtainable with the oxygen-jet combustion chambers. The air-jet thermal cutting tools can function faultlessly at low air temperatures owing to the use of air for a coolant in place of water. The use of air also greatly simplifies the combustion chamber design, rendering its operation more reliable and more simple. Finally, the use of compressed air as an oxidizer instead of gaseous oxygen achieves a considerable economic gain.

Identifying the range of practical problems on cutting ice which can be solved with utilization of a pressurized gas jet, it is necessary to take into account that the breakdown of ice by means of melting is the most disadvantageous from an energy viewpoint since, as compared with other materials, ice has a high melting heat (80 cal/g).

From this standpoint, most promising are the methods of mechanical breakdown of ice (various cutting tools and installations, water jet, explosions etc.) particularly in those instances when the operations are tied in with the cutting of large ice volumes and the rapidity of accomplishing the tasks. It is evident that in these cases (e.g. as a cutting tool for an icebreaker path), the use of a jet does not appear promising. Therefore the range of practical problems on the breakdown of ice which can be solved by the use of a pressurized gas jet is limited only to the individual questions not associated with large-scale operations and rapidity of their completion.

1. Cutting ships free from ice when beset during winter. Usually in winter, an ice cushion forms around ships; prior to starting the navigational season, this cushion must be broken up. Freeing from such a cushion is usually done either by means of manual cutting of the ice with pickaxes or by explosions. The first method is quite laborious while the second can be used only with great caution owing to the danger of causing damage to the ship's hull. The employment of a pressurized gas jet for cutting the ships loose from the ice appears more effective.

2. Processing of frozen soils and solid rocks. It is necessary in making trenches during the installation of automatic radio-meteorological stations (ARMS) in the Arctic. For the digging of trenches in the assembly of these stations, manual operations are extremely laborious. Here one can employ successfully the method of processing frozen soils and solid rocks, based on the application of a reactive gas jet.

3. Cutting of blocks for obtainment of ice. Usually during the obtainment of ice, use is made of laborious hand cutting with the aid of axes and saws. The use of the method of ice cutting by a reactive gas jet greatly facilitates the work and raises the labor productivity.

4. Leveling the ice surface. In the construction of landing strips on the ice, the surface leveling tasks occupy a major role. The shearing of hummocks, breakdown of individual hummocks and pressure ridges are usually done by hand or by undercutting. In this case, the use of the reactive gas jet can provide much assistance.

5. Cutting structures free from ice. For safeguarding structures against ice pressure, use is made of various methods, beginning from manual cutting, heating ice with steam, electricity, breaking the ice with explosives, and so forth. For these purposes, the utilization of a reactive gas jet appears very promising.

6. Deep drilling of ice in the Antarctic. The cutting of deep holes in snow, firn and ice, as well as the drilling of boreholes with extraction of core samples from various depths have great scientific significance for studying the basic problems in contemporary glaciology. Currently for the cutting of boreholes, only mechanical drilling is utilized and a series of other drilling procedures (electric-heat etc.) is under development. The problem involved in drilling deep holes in the ice is still unsolved and the employment of the flame cutting technique can prove quite promising.

7. Cleaning of snow and ice from landing strips at airfields. The reactive gas jet technique is already in use for clearing the snow and ice from airfield landing strips.

In conclusion, it is necessary to point out that in future studies, it will be necessary to clarify the effectiveness of employing a reactive gas jet with the addition of a thermal mixture to it (e.g. aluminum and ferric oxide), implemented in the new design of a special thermal cutting tool.

The preliminary tests run on such a burner developed in the Kazakh Polytechnical Institute permitted us to increase the rate of cutting concrete and to perform its cutting by a mechanical procedure (flaking).

It should be indicated that in the quests for novel ways for counteracting ice, it is interesting to explore the possibility of breaking ice with the aid of optical-quantum generators (lasers) and also with the aid of a low-temperature plasma jet (ion generators).

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

BREAKING ICE WITH A JET OF GAS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Draft Translation

5. AUTHOR(S) *(First name, middle initial, last name)*

G.N. IAkovlev

6. REPORT DATE August 1973	7a. TOTAL NO. OF PAGES 16	7b. NO. OF REFS 4

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) Draft Translation 395
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

Thermodynamic methods are currently being applied successfully in industry for breaking rocks. These same methods have been examined for breaking ice. However, for large scale operations the use of a gas jet does not appear promising because of the large amount of energy required to melt ice.

14.KEY WORDS

Airports
Ice breaking
Ice cutting
Ice navigation
River ice
Sea ice
Ship icing
Thermal drills

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified
Security Classification