LOCK WALL DEICING WITH WATER JETS:
FIELD TESTS AT
SHIP LOCKS IN MONTREAL, CANADA
AND SAULT STE. MARIE, MICHIGAN

W.H. Brierley, D.J. Calkins, S.L. DenHartog,
M. Mellor and H.T. Ueda

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Tests were made to evaluate a proposed technique for removing ice from lock walls during winter navigation. The technique involves use of a high-pressure water jet to slice through ice collars that adhere to vertical walls. The test equipment consisted of (1) a jet lance tipped with a nozzle designed to produce a long coherent jet, (2) a small tractor (hydraulically driven) to carry the lance, and (3) a high-pressure pump unit to supply water to the lance. Tests were made with operating pressures from 3,000 to 14,000 lbf/in.² and nozzle diameters from 0.063 to 0.152 in. Most of the work involved pressures around 9,000 lbf/in.² and nozzle diameters of approximately 0.09 in. Traverse speeds were in the range 3 to 17 ft/min. Jet penetrations of up to 4 ft were achieved in a single pass,
20. Abstract (cont’d)

and the equipment proved capable of cleaning the lock wall under the prevailing conditions. However, performance was somewhat less favorable than had been predicted, and a revised scheme involving changes in lock operating procedures was proposed.
PREFACE

This report was prepared by Dr. Malcolm Mellor, Research Physical Scientist, Darryl J. Calkins, Research Hydraulic Engineer, and Stephen L. DenHartog, Geologist, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL); Herbert T. Ueda, Mechanical Engineer, of the Technical Services Division, USA CRREL; and William H. Brierley, of the Gas Dynamics Laboratory, Division of Mechanical Engineering, National Research Council of Canada, Ottawa, Canada.

The study was performed under Work Unit CWIS 31334, Preventing and Removing Ice From Adhering to Lock Walls and Gates, in the Civil Works Program, Corps of Engineers.

This report was reviewed technically by Ben Hanamoto and Guenther Frankenstein of USA CRREL.

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LOCK WALL DEICING WITH WATER JETS  
Field Tests at Ship Locks in  
Montreal, Canada, and Sault Ste. Marie, Michigan  

W.H. Brierley, D.J. Calkins, S.L. DenHartog,  
M. Mellor and H.T. Ueda  

INTRODUCTION  

One of the problems encountered on the St. Lawrence Seaway and other navigable waterways is icing of lock walls at the onset of winter conditions. When a downbound vessel enters a lock, it carries with it a mass of floating ice, which may then be crushed against, and built up on, the lock wall by the vessel’s hull. With low air temperatures there may be further accretion by freezing of water during cycling of the lock, and during periods when no ships are using the lock. The situation is particularly serious with wide vessels (which may be only 5 ft narrower than the lock width), since the compaction of floating ice is great, and the resulting side friction on the hull may prevent the vessel from completely entering the lock.  

The possibility of using high-pressure water jets to remove the ice from these lock walls was investigated by Mellor (1974a) in a preliminary feasibility study. Based on favorable findings in this study, a high-pressure jet-cutting system was designed and built for testing the concept on lock walls. In view of previous fruitful collaboration between the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) and the National Research Council of Canada (NRC), participation by the Gas Dynamics Laboratory, Division of Mechanical Engineering, NRC, was requested and approved.  

The major purpose of this report is to present the field results obtained during the 1974-75 winter season for high-pressure water jet-cutting of ice.  

BACKGROUND INFORMATION  

For some years USACRREL has been investigating high-pressure water jets as a means of cutting materials such as rocks, frozen ground and ice. Most of the work on ice has been summarized by Mellor (1974a), while more recent results obtained at the National Research Council of Canada (NRC) have been given by Harris et al. (1974).  

A decision was made to mount a two-stage field investigation of lock wall deicing by hydraulic jets. The intention was to undertake initial trials at the close of the St. Lawrence Seaway shipping season in mid-December, working on a lock at Montreal. If justified by initial results, a further field venture with modified equipment and procedures was planned for the Poe Lock at Sault Ste. Marie, Michigan.  

The preliminary feasibility study (Mellor 1974b) produced a minimum specification for the required high-pressure pump. The specification called for a pressure capability of 10,000 lbf/in.² in continuous operation with a flow rate of approximately 30 gal/min, resulting in a hydraulic power of approximately 170 hp.
The jet lance was designed and fabricated in the Mechanical Engineering Division of the National Research Council, at Ottawa, Canada. The mounting bracket and frame were designed and built at USA CRREL, where they were fitted to a small four-wheel-drive rubber tire tractor which had a hydraulic drive system for low-speed operation. The aluminum mounting frame for the lance had the capability of telescoping horizontally to compensate for small changes in offset distance, as the small vehicle could not be expected to run exactly parallel to the lock wall. The lance was positioned and stabilized on the lock wall by Teflon-faced skis. It was designed to accommodate a slight inward angle of incidence (3° toe-in) toward the lock wall, as well as a forward incidence angle (≈ 15°). Figure 1 shows the unit rigged for traversing on the lock wall.

The high-pressure pumps were rented from industrial cleaning contractors, both using Peroni PTM-4542 plunger pumps. The Peroni pump is rated at 196 actual fluid horsepower
for continuous duty at 10,000 psig and 33.6 U.S. gal/min. Both contractors were unable to obtain the 196-hp output with their systems because the diesel engines had insufficient power. The firms that supplied the pumps were the 1) J.J. Gordon Company of Buffalo, New York, for the Montreal tests, and 2) James Fitzpatrick Industries Limited of Sault Ste. Marie, Ontario, for the Sault Ste. Marie tests. Figure 2 shows the pump unit mounted in a mobile truck.

The jet lance consisted of a 1/2-in.-ID stainless steel pressure pipe carried inside a 2-in. steel pipe. At the lower end was a nozzle block to which a range of nozzles could be attached. At the upper end was a modified tee-block, to which were attached a pressure gage and the feed hose swivel. Several nozzles were made for the lance; these had exit diameters of 0.086, 0.093, 0.101 and 0.152 in., with the length of each exit section twice the nozzle diameter. However, only two sizes, 0.086 and 0.093 in., were used extensively. The intake section had a diameter of 0.50 in. in all nozzles, with an entry cone of 20° (Fig. 3). Two additional nozzles with exit diameters of 0.093 and 0.101 in. were fabricated with 13° entry cones. Most of the nozzles used in the tests were made at NRC, Ottawa, by W.H. Brierley.

The delivery line from the pump to the lance was 1/2-in.-ID, flexible, high-pressure hose for the Sault Ste. Marie tests, but only 3/8-in.-ID type was available for the Montreal
tests. Feed water to the high pressure pump was supplied by a small gasoline-driven centrifugal pump, although any source with a 35-gal/min flow rate would have been sufficient.

TEST SITES

The first field test was carried out at the St. Lambert Lock near Montreal. This lock is the first in a series of locks on the St. Lawrence River maintained by the St. Lawrence Seaway Authority. It is the one that usually experiences the most severe lock wall icings near the end of the shipping season in mid to late December. Maximum vessel width permitted through the lock is 75 ft, leaving 2-1/2 ft on each side for clearance. Due to unusually mild weather conditions up to mid-December 1974, there was no ice on the walls and none was forecast. Consequently, a modified test plan involving manufactured ice blocks was put into operation.

The second field test was carried out at the Soo Locks, Sault Ste. Marie, Michigan, during February 1975. The Soo Locks provide ship passage between Lake Superior and Lake Huron; during winter they cater mainly to the newer bulk carriers moving iron ore. There are four parallel locks in the U.S. system operated by the Corps of Engineers, North Central Division, and there is also a Canadian lock. The lift is 21 ft, and the maximum draft of ships using the system is 25.5 ft. The MacArthur Lock is 800 ft long by 80 ft wide, and the Davis and Sabin Locks are each 1,350 ft long by 80 ft wide. The New Poe Lock, which is 1,200 ft long by 110 ft wide, gets most of the winter use, since the boats that operate in winter are the newer, wider ones. At the time of the jet-cutting tests, only the Poe Lock was operating. Except for the month of March, the 1974-75 winter was exceptionally warm and year-round navigation was possible.

The orientation of the Poe Lock is east-west. At the time of the tests the northerly-facing (shaded) wall carried a coating of dense ice that extended vertically for a distance of 7 ft or so, with an irregular thickness ranging from several inches to about 1-1/2 ft (Fig. 4). The upper part of this ice collar was securely bonded to the concrete wall, but adhesion appeared to be quite weak in the lower half. The southerly-facing wall, which happened to be the tie-up wall for ships, was essentially free of ice except when crushed ice debris was smeared on the wall by an entering vessel. Except for occasional brief periods of lock operation, water level in the lock was maintained at about 6 ft to 8 ft below high pool level; i.e. water level coincided with the base of the ice collar. The length of wall (one side) subject to icing was approximately 1,200 ft.

The Poe Lock is separated from the shore by the MacArthur Lock, and there is no access for highway vehicles or equipment. The small vehicle used to carry the jet lance had to be placed on the esplanade between the locks by the Coast Guard cutter Mackinaw, and high-pressure water had to be supplied through long hoses from pump vehicles parked on the shore.

MONTREAL TEST RESULTS

Tests were scheduled to begin on 10 December 1974, five days prior to the scheduled closing date for the Seaway (17 December was finally set as closing date for 1974). By 8 December it was clear that under the prevailing mild weather conditions there would be no icing on the lock walls during the planned test period, but it was decided to proceed with the work, since rescheduling was not feasible.
Figure 4. Lock wall icing.
All equipment was in position and operating by midday on 10 December. Ice blocks were purchased from a local supplier, and a bed of ice was formed by laying blocks on the pavement against the lock wall curbing, and hosing the ice mass to cement the blocks to the pavement and to each other (Fig. 5). Each block measured 11 in. high by 22 in. wide by 44 in. long, and 20 blocks were laid to give a bed that was approximately 11 in. high by 88 in. wide by 220 in. long.

The first step was a general test of all equipment. The lance was then mounted horizontally on the bracket, as shown in Figure 6, and the pump was run up to full pressure.
Table I. Traversing tests on ice blocks at Montreal.

<table>
<thead>
<tr>
<th>Nozzle diameter (in.)</th>
<th>Nozzle pressure (lbf/in.²)</th>
<th>Traverse speed (ft/min)</th>
<th>Standoff (in.)</th>
<th>Penetration (in.)</th>
<th>Approx spec energy* (lbf/in.²)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.086</td>
<td>8,500</td>
<td>15</td>
<td>5</td>
<td>12</td>
<td>$7.17 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>0.086</td>
<td>9,300</td>
<td>3</td>
<td>5</td>
<td>44</td>
<td>$1.12 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>0.086</td>
<td>9,200</td>
<td>3.1</td>
<td>2</td>
<td>44 max</td>
<td>$1.27 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>0.152</td>
<td>3,000</td>
<td>4.8</td>
<td>2</td>
<td>12.5</td>
<td>$7.97 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>0.063</td>
<td>13,000</td>
<td>2.87</td>
<td>3</td>
<td>26</td>
<td>$1.88 \times 10^5$</td>
<td>Pressure increase during run</td>
</tr>
<tr>
<td>0.063</td>
<td>14,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.086</td>
<td>9,500</td>
<td>4</td>
<td>2</td>
<td>34</td>
<td>$8.47 \times 10^4$</td>
<td>General penetration, breakage and deflection near end of block</td>
</tr>
<tr>
<td>0.086</td>
<td>9,500</td>
<td>4.1</td>
<td>4</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.086</td>
<td>9,600</td>
<td>9.0</td>
<td>4</td>
<td>13.5 avg</td>
<td>$1.27 \times 10^5$</td>
<td>Fresh &quot;cracking&quot; ice</td>
</tr>
<tr>
<td>0.086</td>
<td>9,600</td>
<td>16.8</td>
<td>2.5</td>
<td>8.5 avg</td>
<td>$1.08 \times 10^4$</td>
<td>Fresh &quot;cracking&quot; ice</td>
</tr>
<tr>
<td>0.086</td>
<td>9,600</td>
<td>16.0</td>
<td>1.5</td>
<td>8.5 avg</td>
<td>$1.14 \times 10^3$</td>
<td>Fresh &quot;cracking&quot; ice</td>
</tr>
<tr>
<td>0.086</td>
<td>9,300</td>
<td>11.8</td>
<td>3</td>
<td>22</td>
<td>$5.69 \times 10^4$</td>
<td>Old ice</td>
</tr>
</tbody>
</table>

* Taking a mean penetration and assuming a uniform initial slot width of 3 nozzle diameters.

The hydraulic system in the small tractor allowed it to be throttled to any travel speed from 2.5 ft/min to 25 ft/min.

On 11 December the cutting tests began, after overnight temperatures of approximately 15°F. Prior to starting work, however, the temperature was only a few degrees below freezing. Numerical results of the jet traversing tests are given in Table I. All nozzles used in these tests had entry cones of 20°. The jet traversed at about 4 in. above the pavement, and in many cases the ice overlying the cut became detached. When this happened, the ice tended to form a deflecting surface, and jet penetration deteriorated. It was therefore decided to try some traverses with the jet slicing the interface between the ice and the concrete.

After a preliminary trial indicated that the concrete pavement did not suffer any damage from the glancing incidence of the jet at a range of 3 ft, the nozzle was angled down at 3° from the horizontal and was set 1-1/4 in. above the pavement. With this arrangement the jet contacted the ice/concrete interface about 2 ft from the nozzle, or about 21 in. into the ice with a 3-in. standoff. The first interface cut was made at a traverse speed of 3.86 ft/min. The nozzle diameter was 0.086 in., the nozzle pressure was 9,700 lbf/in.², and the standoff was 3 in. There was complete penetration of the interface; i.e. ice was removed to a distance of 7.5 ft. The first 19 in. of the ice was cut internally, and a thin wedge of ice remained frozen to the concrete in this section.

A second interface cut was made at a traverse speed of 11.6 ft/min. The nozzle diameter was again 0.086 in., nozzle pressure was 9,500 lbf/in.², and the standoff was 3 in. This time there was continuous penetration to a depth of 3.7 ft.

The strength of the ice/concrete bond was questioned and the results obtained by cutting at the ice/concrete interface were taken with reservation. Subsequent tests at Sault Ste. Marie confirmed this suspicion that the ice was not securely bonded to the concrete.

By late afternoon on 11 December the available ice was more or less used up, and attention turned to determination of effective free-air jet length. Ice blocks were set up against a bridge pier, and the jet lance was swiveled on the tractor so that it could shoot...
directly ahead. The jet was directed at the ice block at extreme range, it was allowed to play for 20 sec, and the block was then examined for effect. The tractor was moved forward, and the process was repeated until some slight dishing of the face of the ice block occurred. The distance from the nozzle to the ice block was then measured to obtain the “maximum perceptible range.” Next, the distance was closed further until a definite cup was formed in the ice, and the distance was remeasured to give the “maximum effective distance.” Results are given in Table II.

Some qualitative aspects of the results need to be emphasized. In fresh new ice, cracks propagated ahead of the traversing jet, and the blocks tended to shatter under the action of the jet. By contrast, the jet tended to cut old ice blocks in a more orderly fashion, with less cracking and no shattering. Air temperature was well above freezing and light rain was falling, and since these new blocks had been exposed to these conditions for three hours or more, it seems unlikely that their internal temperature was much below 0°C. The most likely explanation of the difference between the two sets of blocks is that thermal strains had not had time to relax in the fresh ice, whereas the old ice would have had ample time for creep and recrystallization after remaining overnight.

### SAULT STE. MARIE TEST RESULTS

The equipment was set up on 16 February 1975 and the system was pressurized by late afternoon. Pressures developed at the jet nozzle were lower than expected, and results of traversing tests were disappointing. Tests were terminated at dusk, and subsequent calculations showed that the hydraulic power delivered at the nozzle was well below the rated capacity of the pump unit.

Testing resumed on 17 February, with the first part of the day devoted to troubleshooting. The delivery line was shortened as far as possible, and some 3/8-in.-ID hose that had been inadvertently coupled into the system on the previous day was replaced by 1/2-in.-ID hose. A tortuous bypass valve was also removed from the delivery line. With the approval of the equipment owners, the pump operators were induced to modify their somewhat conservative procedure and use a higher gear for the engine-pump transmission. The most heavily used nozzle, the 0.086, was found to have developed wear, and jet quality had deteriorated markedly. The exit section of the nozzle had developed grooves that looked like very fine concentric circles, probably by cavitation erosion. This nozzle, which has a 20° entry cone, was taken to the nearby Coast Guard station and rebored to 0.093-in. diameter, as was the corresponding 13° entry cone nozzle. These remedial measures brought the hydraulic power of the jet lance up to something approaching the rated power of the diesel unit. However, as it was clear that a single unit would not be capable of reaching

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**Table II. Free-air jet length (Montreal tests).**

<table>
<thead>
<tr>
<th>Nozzle diameter (in.)</th>
<th>Nozzle pressure (lb/in.²)</th>
<th>Maximum perceptible range (ft)*</th>
<th>Maximum effective distance (ft)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.086</td>
<td>9,000</td>
<td>13 (1,814)</td>
<td>11.9 (1,660)</td>
</tr>
<tr>
<td>0.101</td>
<td>7,000</td>
<td>14 (1,663)</td>
<td>12.0 (1,426)</td>
</tr>
<tr>
<td>0.152</td>
<td>3,000</td>
<td>20 (1,579)</td>
<td>18.7 (1,476)</td>
</tr>
</tbody>
</table>

* The figures in parentheses give the distance divided by the nozzle diameter.
the power level called for in the original design calculation (170 hp), arrangements were made for rental of a second unit to work in parallel on the following day.

The afternoon of 17 February began with traversing tests at various speeds and with various nozzle sizes. With the largest nozzle, 0.152 in. in diameter, the maximum pressure that could be developed was about 3,000 lbf/in.\(^2\), and at very low traverse speed (= 3 ft/min) this combination could not penetrate more than about 1 ft of ice. With a 0.101-in.-diam nozzle, the attainable pressure was about 7,000 lbf/in.\(^2\), and the penetration at low traverse speed increased to almost 2 ft. The smallest nozzles, 0.093 in. in diameter, could be driven at 8,000-8,500 lbf/in.\(^2\), and occasionally up to 9,000 lbf/in.\(^2\), and this gave penetrations of more than 3 ft at traverse speeds around 3 ft/min. As a result of these findings, most of the later work was carried out with 0.093-in.-diam nozzles.

One of the problems that showed up early in the tests was connected with breakoff of partially cut ice. As the traversing jet sliced through the ice, the partially detached material would crack off, leaving an arcuate surface. This curved surface would then tend to deflect the lower part of the jet in the manner of a turbine blade, causing the residual kinetic energy to dissipate without doing any useful work (Fig. 7). The severity of this problem was minimized by tipping the lance so that it had a "toe-in" towards the wall of approximately 3°, and a forward incidence angle of approximately 15°.

With a 0.093-in.-diam nozzle (20°), a pressure of approximately 8,500 lbf/in.\(^2\), and the attack angles just described, it was possible to make a complete cleaning cut at low traverse speed (3 ft/min or less). A section of ice that was about 7 ft in vertical extent was cut off the wall, as shown in Figure 8. However, this gives an exaggerated idea of cutting penetration, as the lower 3 ft of the ice collar was very weakly bonded.

Traverses were made at higher speeds, and at 15 ft/min the small jet was able to penetrate to about 16-in. depth in hard clear ice.

On 18 February two pumps were brought to the site. Parallel hoses were run out to the Poe Lock, where they were manifolded together into a single 1/2-in. hose that connected with the jet lance. The system was pressurized, the pumps began a 20-min run-in, but
before completion of the run-in period one of the pumps developed severe pressure pulsations. The same pump had experienced problems of drive shaft lubrication and poppet valve failure the previous day, but the new problem seemed to indicate serious damage to one of the cylinders, and the pump was therefore withdrawn from service. Since there was no other pump available, all idea of operating two pumps together had to be abandoned. The surviving pump was then used for additional cutting tests and for a cutting demonstration.

Results of the cutting tests are summarized in Table III. Whenever penetration exceeded about 4 ft, the jet went on to penetrate the remainder of the ice/concrete interface, where the ice was only weakly bonded. On the cold upper section of the wall, where the ice was securely bonded, there was no discernible difference between cutting at the interface and cutting in solid ice. This distinction between penetration in the upper and lower parts of the ice collar seemed to resolve the question raised during the St. Lambert tests, where it was found that penetration of the interface was more than twice as great as penetration in solid ice. Present indications are that the interface advantage applies only when the bond is weak or discontinuous.

Air temperatures were relatively high during the tests. On 17 February air temperature was in the upper twenties, and on 18 February air temperature rose above freezing. However, the weak ice bond in the lower part of the ice collar cannot be attributed solely to high air temperature. The lock wall above high pool elevation must cool appreciably during winter and suffer deep ‘‘frost penetration.’’ By contrast, the lock wall that lies below water level cannot drop below 0°C. Thus, there has to be a vertical temperature gradient, and a corresponding gradient of bond strength in the ice collar. The location of the 0°C isotherm inside the lock wall is obviously influenced by water level.
Table III. Jet-cutting tests at Soo Locks, February 1975.

<table>
<thead>
<tr>
<th>Nozzle diameter (in.)</th>
<th>Nozzle pressure (lbf/in.$^2$)</th>
<th>Traverse speed (ft/min)</th>
<th>Standoff (in.)</th>
<th>Penetration (in.)</th>
<th>Approx spec energy* (lbf/in.$^2$)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.152</td>
<td>3,000</td>
<td>3</td>
<td>3</td>
<td>10-12</td>
<td>$1.45 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>0.101</td>
<td>7,000</td>
<td>3</td>
<td>3</td>
<td>18-22</td>
<td>$1.89 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>0.093</td>
<td>8,500</td>
<td>3</td>
<td>3</td>
<td>42-48</td>
<td>$1.03 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>0.093</td>
<td>8,500</td>
<td>2</td>
<td>3</td>
<td>Complete</td>
<td>$1.45 \times 10^5$</td>
<td>Lower 3 ft weakly bonded</td>
</tr>
<tr>
<td>0.093</td>
<td>8,500</td>
<td>15</td>
<td>3</td>
<td>16</td>
<td>$5.82 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>0.093</td>
<td>8,500</td>
<td>3.55</td>
<td>3</td>
<td>36-40</td>
<td>$1.03 \times 10^5$</td>
<td>13° nozzle</td>
</tr>
<tr>
<td>0.093</td>
<td>8,500</td>
<td>4.45</td>
<td>3</td>
<td>32-36</td>
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* Taking a mean penetration and assuming uniform initial slot width of 3 nozzle diameters.

DISCUSSION

Montreal test results

The most obvious practical finding at Montreal was that the unit used in the tests did not come near meeting the original performance specification of 8-ft penetration at a traverse speed of 3 ft/min. To some extent this was expected, as the pump used at St. Lambert Lock did not meet the minimum specification of 170 hp that had previously been estimated. The rated hydraulic power of the St. Lambert unit was 140 hp, but in the main series of tests with the 0.086-in. nozzle it never delivered more than 121 hp at the lance. Thus, 40% more power than was available at St. Lambert was called for in the original estimate. The main question to be answered, therefore, was whether the theoretical estimate was in any way realistic.

The Montreal tests were too disjointed to be regarded as controlled experiments, but it seemed probable that they provided a good impression of general capability. The St. Lambert data were compared with results obtained with very similar equipment at Ottawa in February 1974. The main difference between the two sets of tests was in the ranges of traverse speeds that were investigated. The data ranges did not overlap, but in a plot of penetration against traverse speed for comparable pressures and nozzle sizes (Fig. 9) there did not seem to be any significant displacement or break of continuity.

In an attempt to revise the estimates of jet performance from the Montreal data, an analytical scheme used in earlier work (Mellor 1972, 1974a) was followed. When data were plotted in accordance with this approach, it became apparent that the relative performance of the large field rig was significantly less favorable than the performance of small laboratory units.

The other outcome of the St. Lambert tests that seemed to hold important implications was the indication that a cut along the ice/concrete interface might be achieved more easily than a cut in the ice itself. There were differences of opinion among the field crew concerning the integrity and continuity of the bond between the ice and the concrete, and weather
conditions were unsuited to a conclusive test. However, on the assumption that the interface advantage was real, revised theoretical estimates were made and it appeared that a unit of the size employed at Montreal would be capable of meeting the performance specification with various combinations of nozzle sizes and nozzle pressures.

Because of weather conditions at Montreal, it was impossible to determine directly whether or not a practical jet tool had the capability of cutting ice collars from lock walls at useful rates. The performance of the equipment in cutting solid ice was disappointing, but on the other hand, there seemed to be a possibility that cutting at an ice/concrete interface might be relatively easy. Under these circumstances, a decision was made to proceed with further testing at the Soo Locks, and a number of minor design changes were specified.

**Soo Locks results**

The test program at Sault Ste. Marie produced results that confirmed the Montreal data for penetration of solid ice, but there was no advantage to cutting at the ice/concrete interface when the collar was thoroughly bonded to the lock wall. In Figure 9 some results that can be compared directly with results from Montreal and Ottawa have been plotted.

The most valuable outcome of the Soo Locks tests was familiarization with the actual problem of lock wall icing. It soon became evident that the vertical extent of the bonded interface between the ice collar and the lock wall was controlled to a large extent by operating procedures. The part of the wall above high pool elevation is subject to cooling throughout the winter, but it is not systematically wetted. The part of the wall that remains more or less permanently submerged cannot easily be cooled below 0°C. Clear ice up to 6 ft thick has been observed on the lock walls from low pool elevation up to the top of the collar. This can be expected during cold weather and heavy traffic, but it does not cause the same problems as the collar. At the Poe Lock, water level is held at levels from 2 to 8 ft below high pool elevation in the intervals between ship transits, and therefore, a deep collar forms. If the water level were to be maintained closer to high pool elevation, the performance specification for a deicing system could be eased considerably.

![Figure 9. Penetration of water jet in ice as a function of the traversing velocity.](image-url)
The Soo Locks tests proved that a water jet is capable of cleaning ice from lock walls, although it seems likely that a unit capable of meeting the original performance specification would be prohibitively expensive to acquire and operate. However, if the vertical extent of the adhesion zone can be reduced from the 8 ft originally specified, then a jet tool might become attractive. Using the data from Montreal and Sault Ste. Marie to revise design calculations, it seems that a 150-hp pump operating at 13,000 lbf/in.² could cut to a depth of 3 ft at traverse speeds of about 7.5 ft/min.

**CONCLUSIONS AND RECOMMENDATIONS**

Water jets operating at pressures around 10,000 lbf/in.² are capable of cutting lock wall ice collars at useful rates without causing damage to the concrete of the lock wall itself. The power required to penetrate through 8 ft of ice in a single pass is likely to be unreasonably high, but it appears that the performance specification calling for 8-ft penetration may have been set unnecessarily high.

The economics of jet cutting relative to competing concepts should be examined. If jet cutting is then judged to be sufficiently attractive, further tests should be made with a 150-hp unit capable of reading pressures in excess of 10,000 lbf/in.². At the same time, lock operating procedures should be modified to limit the effective bonding depth for ice collars to approximately 3 ft.

**LITERATURE CITED**


