# NIAGARA RIVER ICE CONTROL

By

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## INTRODUCTION

Ice jams varying in magnitude and location, have been common in this river for as many years as there are records, with perhaps the most famous of recent memory having taken place in 1938 when the Honeymoon Bridge, spanning the Maid of the Mist Pool below the Falls was wrecked. On the other hand, Hydro-Electric development has continued more or less steadily since 1900 in spite of the many known difficulties. The power installations of Ontario Hydro and the Power Authority of the State of New York in the Niagara area have a combined capacity of the order of 4 1/2 million kilowatts which ranks this site among the largest of the developed power sites in the world. It is no exaggeration to say that the ice problems would be of similar rank if such statistics were available.

In 1950 a treaty was signed between Canada and the United States which specified certain minimum flows over the Falls for scenic purposes, and allocated the remaining flow of the river to the two countries for power purposes. All works affecting the scenic spectacle or ice carrying ability of the river are subject to the approval of the International Niagara River Board of Control and its parent body the International Joint Commission which has jurisdiction over all boundary waters. The cost of building, operating and maintaining these works has been shared by the two power entities, but their design has been primarily the responsibility of Ontario Hydro.

Many changes have been made to improve the ice carrying capacity of the river and many unusual features are included in the water diverting intakes and the ice handling equipment. During the winter of 1964 - 65, the most significant change of all came about when an ice boom was installed at the outlet of Lake Erie. This paper describes the ice problems, ice control organization and emergency equipment, and the operating experience before and after the installation of the Lake Erie ice boom.

## Description of Problems

The climate in winter behaves rather like a pendulum swinging backwards and forwards between extremes of cold and those of warmth. The river itself is too shallow to form an ice cover and the peculiarities of the Lake Erie ice make this otherwise logical step exceedingly unsuitable.

Lake Erie and the upper Niagara River produce vast quantities of ice every winter, and virtually all that enters the river, or is made therein, must pass over the falls and downriver to Lake Ontario. There are inevitably some areas which are very shallow, others where downstream currents are inadequate or non-existent, and finally areas where adverse winds tend to restrict ice movements. The problem areas have been identified and operating techniques developed to prevent the formation of an ice cover everywhere except the Maid of the Mist Pool where an ice bridge forms almost every year. The various problems which occur are directly related to the types of ice which come down the river, and these are described in the paragraphs which follow.

Lake Ice

The relationship of the Niagara River to Lake Erie and the other Great Lakes is shown on Plate I. In a normal winter the entire surface area of Lake Erie, (10,000 square miles) tends to become completely ice covered. Until the winter of 1964 - 65 it was customary for a considerable quantity of ice from the lake to come down the Niagara River in the early winter until the pieces became large enough to form a natural ice bridge between Buffalo on the United States shore and Fort Erie on the Canadian shore. An appreciation of the volume of ice leaving the lake may be obtained from Plate II. Under average wind conditions, this quantity could vary from a few square miles to perhaps 20 square miles in one day,

Until there was sufficient cold weather to consolidate the ice bridge, an uneasy period existed during which a severe storm could break the arch and force up to 40 square miles of ice per day into the river. Its composition was an amalgam of slush, black ice and white ice, piled together by the wind and waves. A typical piece is shown on Plate III A where it was stranded by the receding water after the storm. The point "X" is 10 feet in height. Also shown on Plate III B is a typical pile of ice 100 yards from shore, and on Plate III C a similar pile one mile off shore. The difficulties in passing such material down a river which is less than 10 feet deep in many areas can well be imagined.

River Ice

There are about 40 square miles of river between Lakes Erie and Ontario (Plate IV) with the falls located approximately half way between the two lakes. The 20 square miles upstream of the Falls is actually a giant refrigerator creating a number of types of ice problems. Between Fort Erie and the upstream end of Grand Island the fall is sufficient to create velocities in excess of 10 feet per second. Water leaves Lake Erie at a temperature very close to freezing, becomes super-cooled in the fast flowing rapids, and immense' quantities of frazil are generated. The velocities in the channels around Grand Island are much slower, of the order of 3 to 4 feet per second, and as a result the frazil comes to the surface, and joins together into huge flocks. This area at the head of the river is also famous for its snow storms being adjacent to a large body of water, and on the downwind side of the principal storm direction, therefore it should not be surprising to learn that vast quantities of slush ice are also produced. The frazil and slush combines during its seven hour trip downstream to the area where the power intakes divert their water, and the surface layer freezes into a hard pan, (Plate V) which may be up to two inches in thickness, and may be hundreds of feet in diameter. Under normal circumstances, one to two feet of the softer material adheres to the underside of the pan, but because of shore friction assisted by on-shore winds the pans and soft material may be compressed into layers up to 8 feet or more in thickness. The effects of variations in temperature are illustrated by the pictures on Plate V where the result of a 17°F previous night is shown as Case "A", and the result of a 7°F previous night as Case "B". Wind-chill is, of course, an additional factor.

On Plate V "B" most of the ice is moving towards the viewer with the exception of that which is aground on the shoal. The locations of the intakes to the Power Tunnels on both sides of the river are shown together with the Control Structure and the two falls. The area between the Control Structure and the Power Authority of the State of New York intakes is referred to as the Grass Island Pool. The Control Structure has 18 sluices with gates 100 feet wide which open downwards to allow the ice to pass over the top. The maximum depth over the sills is about 10 feet, and over the bottom beyond the end of the Control Structure the maximum depth is about 8 feet. All of the ice leaving Lake Erie, or created by the river, must pass over these outlets.

Anchor Ice

Conditions are also favourable for the formation of large quantities of anchor ice when the nights are cold and clear, because the entire upstream reach of the river is less than 30 feet in depth and in most areas depths are less than 15 feet. The effects of this type of ice on dison discharge from the lake are illustrated by Plate VI where it can be seen that a reduction of 27,000 cfs occurred in a period of 10 hours. In this case the reduction amounted to 21% of the flow available for power. On days when the sun provides sufficient radiation, quantities of this ice rise to the surface over a short period of time bringing stones, mud, and other debris lifted from the bottom. Some of this material is deposited as the ice passes through the Grass Island Pool particularly after passing through the Control Structure and leads to a number of maintenance problems with the gates.

River Bank Ice

Due to a seiche on Lake Erie, the outflow may increase by as much as 100,000 cfs in as little as four hours, causing a rise in river levels of several feet. This phenomenon creates yet another problem by breaking off huge pieces of ice from the shores of the upper river. (Plate VII) The river itself is 2,500 feet wide where the picture was taken, and the large pieces are estimated to be over 1,000 feet in length, compared to a sluice width of 100 feet.

Summary of Quantities of River Ice

A conservative estimate of the volume of frazil and/or slush ice created by the river each day in $0^{\circ}F$ weather is 3 million cubic yards. Anchor ice and river bank ice are in addition to this amount.

Lower River

An ice bridge forms in the Maid of the Mist Pool each year due to a combination of circumstances involving the vast quantities of ice coming from upstream, low velocities, and the narrow width of the gorge. There are large eddies in this pool which further reduce its ability to pass ice downstream. The product of the 20 square miles of refrigerator surface in the upper river leaves the Grass Island Pool via an exit width of one mile and becomes crammed into a width of only several hundred feet with the results shown on Plate VIII. This ice bridge is about two miles in length and all the ice from the lake or upper river must pass underneath on its way to Lake Ontario. When the volume of ice is too large, or the type of ice is too hard, the water level rises on the upstream side of this ice bridge. Fortunately, a rise of 60 feet can take place without serious difficulty. The rise which took place in 1938 when the Honeymoon Bridge was wrecked, was not actually measured but has been estimated to be approximately 10 feet greater. In this case the whole ice bridge moved downstream and demolished the abutments to the Honeymoon Bridge, which incidentally were again covered when these pictures were taken.

No further problems are encountered until the ice passes the high head plants which are located about 8 miles from Lake Ontario. Here the river leaves the gorge and the velocity is substantially reduced. During the 7 hour trip to the lake the effects of wind-chill may combine with low velocity to re-freeze the ice passed down from upstream into large pans. In addition north and east winds over Lake Ontario may prevent the exit of the ice into the lake. Once ice cover has formed over this reach it tends to thicken rapidly in cold weather and on occasion the water level at the plants has been known to rise as much as 40 feet.

<u>Summary of Ice Problems</u>

Each type of ice by itself can cause some problems, however there are two combinations of weather conditions which require the greatest amount of attention, as follows:

1. High winds and river flows which force up to 40 square miles of Lake Erie ice per day into the river, particularly if the storm lasts for more than one day.

2. An extended period of cold weather when the temperature averages $10^{\circ}F$ or less accompanied by strong winds and snow.

<u>Ice Control Organization</u>

The ice control organization must cover all the problem areas between the two lakes, and is of course a joint Power Authority - Ontario Hydro undertaking. The focal point is the River Control office located in the Canadian end of the Control Structure. On the upstream side, it overlooks the Grass Island Pool and the power intakes to the high head plants, and on the downstream side it overlooks the cascades above the falls (Plate V). It is the nerve centre and is staffed 24 hours a day with personnel who operate the gates so as to provide the minimum flow over the falls specified by the treaty, allocate the remaining portion of the river flow which is available for power diversions to the two power entities, collect all ice reports, direct ice breaking activities, and provide in effect continuous surveillance of the overall problem. They receive water level information by telemeter from Fort Erie (Plate IV) which provides an indication of the inflow to the river every hour, from Material Dock which is the controlling gauge for river levels, and from the Ashland Avenue gauge which is downstream of the falls and is used to compute flow over the falls every hour. Other telemetered water levels are also received for various special duties.

Because of the important influence of weather on ice movement and on power production, it is perhaps understandable that Ontario Hydro utilizes its meteorological staff to provide specialized forecasts of wind, temperature and snowfall. Whenever the forecast indicates the need for above-average care, a team of observers is put to work at critical locations to provide additional information to the River Control office, such as whenever the rate of ice movement along the shore reduces towards 1 ft/sec.

Because of the location of the intakes, (see Plate V "B") ice movements in the Grass Island Pool are of paramount importance. The Power Authority has an observation post at the downstream end of its intakes which is equipped with search light, two-way radio and telephone. In addition a mobile observer reports on ice conditions along the length of their ice channel. Ontario Hydro has observers at its intakes and on the control dam when heavy ice runs are in progress and all these areas are illuminated at night. In addition, reports are received from the Fort Erie area, the upper river around Grand Island and the lower river from the power houses to Niagara-on-the Lake. The upstream observers are particularly useful whenever ice is coming out of the lake as they provide early warnings so that preparations may be made in advance. These may take the form of altering the depths in the river to suit the type of ice expected, and alerting the ice breaker crews for duty.

A helicopter is available for on-the-site observations during critical periods and it has also been used regularly during the past four winters to land on the ice, particularly in Lake Erie, to obtain ice thickness measurements for determining ice cover stability under various wind and weather conditions.

Photographic surveys of conditions in the river and Lake Erie are made at frequent intervals, and particularly after any severe meteorological disturbance.

Considerable use is also made of the aerial surveys by the Department of Transport relating to the extent of the cover on the lake as this affects the reaction of the lake to wind conditions.

In winter there are very few day-light hours and even these may have periods of limited visibility due to blowing snow or to winter mist off the water. When visual observations become impossible, the differences in water levels between successive telemetered gauges provide a reliable means of locating troublesome areas, however these only indicate trouble after it has commenced, and wherever possible the rule is prevention rather than cure, because a jam may form in half an hour but last for half the winter.

Emergency Measures for Ice Clearing

While the cardinal rule for this river is to keep the ice moving downstream until it reaches Lake Ontario, and rules based on velocities and other criteria have been developed for the prevention of jams, it has nevertheless been found advisable to provide means for overcoming ice jams in recognition that some will occur.

Two 35-ton ice breakers were constructed in 1962 one for each Power Entity, for operation upstream of the Control Structure. These boats are very strongly constucted, are 40 feet long with a beam of 14 feet, draw less than 4 feet and are powered by twin engines totalling some 500 horsepower. Radio communication is provided to the River Control office so that gate movements can be coordinated with ice breaking activities. Both boats are equipped with radar for navigating in bad weather, and as a safety precaution they normally operate together.

During periods when the daily temperature averages 15°F or less, the boats are used almost constantly to break the river ice into pieces which will skim through the 100-foot width sluices with the gates lowered only just sufficiently to pass the amount of ice shown in Plate V "B". They are also used to break the river bank slabs (Plate VII) before they reach the dam.

If it becomes necessary to remove an ice jam in the upper river, the Control Structure can be most useful. Water levels may be raised several feet to float some of the ice which has become grounded, and then by opening gates, sufficient force may be created to start most of the mass moving towards the dam where it becomes broken by the piers and the hydraulic action combined. The remaining grounded pieces may be split by the boats until they float away by themselves. The water level raising procedure is rather lengthy as it requires a large quantity of water and about one day to arrange and complete.

The ice breaker in the lower river is being used on an experimental basis to prevent the formation of an ice cover over the portion of the river between the power houses and Lake Ontario. If an ice cover becomes established in this area it assumes massive proportions and therefore the ice breaker has been selected accordingly. The present vessel weights 400 tons, is 95 feet long with a beam of 30 feet, draws 12 feet and is powered with twin engines totalling some 3,000 horsepower.

Lake Erie Ice Boom

As indicated above, the factors causing the greatest difficulty in the past were strong winds over Lake Erie from the southwest to west after the lake had partially frozen, or during the period in which a natural ice bridge was forming between Buffalo and Fort Erie. In an average year approximately four weeks elapsed after ice started to form in Lake Erie before the ice bridge gained sufficient strength to hold the ice in the lake. An ice run of above-average proportions is shown on Plate II where "A" shows conditions at the exit from the lake, and "B" conditions in the upper river, after the high velocity stream has slowed down and the ice compacted.

From experience gained by observing the operating characteristics of ice booms installed by Ontario Hydro and the Power Authority of the State of New York in the International Rapids Section of the St. Lawrence River, it appeared that a similar boom would have a number of beneficial results in controlling the Lake Erie problem. Accordingly, in 1964 the two Power Entities requested and received permission from the International Joint Commission to install an ice boom, two miles in length, between Buffalo and Fort Erie. Its purpose is to accelerate the rate at which the ice arch forms between the shores and to stabilize the arch once it has formed. The boom is not designed to prevent all the ice from leaving Lake Erie but to vastly reduce the quantity of this ice. It is not feasible to prevent the ice cover in this lake from moving under the influence of a storm because the water level may rise as much as six feet which is more than sufficient to break any shore restraint. Under the influence of the wind most of the eastern portion of the lake ice surface, moves forward until it wedges once more against the shore at the new water level. In the process the ice surface may break into huge slabs and those touching the boom may be pushed over the top. After the storm subsides, the boom comes back to the surface as the result of its own buoyancy and cuts off the flow of loose pieces.

So far, the boom has reduced the number of days in which ice used to pour out of Lake Erie to the corresponding number of hours. There has not yet been a storm of equivalent intensity to those which produced the most massive ice runs of the past, however the boom has held back all but minor quantities of ice despite a rise in level of 5-1/2 feet and winds of 35 mph and there is reason to expect from its performance to date that it will continue to be successful.

Review of Recent Ice Problems

Events of the years 1962 and 1963 were reviewed in a previous paper by the author entitled "Niagara Power Versus the Ice Machine".[1] During those two winters construction work was in progress on the control dam, excavations to provide greater depths and widths were not completed and there were no ice breakers available. The difficulties which were encountered were expected to be greatly alleviated by the completed channel excavations and the ice breakers, so that the winter of 1964 was anticipated with a reasonable amount of confidence. It turned out to be a year in which the lowest flows in 30 years were experienced with weather conditions in Lake Erie not conducive to the early formation of the natural ice arch, but ideal for the formation of ice problems. Iceballs were created in Lake Erie of sufficient strength to survive the trip through the high velocity rapids section near the Peace Bridge and travel down the river to ground in the Grass Island Pool in 12 feet of water. (Plate IX) In order to remove the iceballs, it was necessary to split each of them in half with the ice breakers, and as there were several thousand iceballs and only two boats, it will be appreciated that this operation took some time, during which more ice was being fed into the Grass Island Pool from the lake. As a matter of interest it is necessary when splitting one of the iceballs to ensure that the ice breaker has enough momentum to ride right over otherwise the boat becomes marooned on top. In addition, the iceballs contained rocks, wood, and other debris which were a little hard on the propellers.

The stream of iceballs mixed with various other types of ice commenced leaving the lake on January 3 (illustrated by Plate II). After four days in which a succession of runs of this type occurred, the grounded ice provided enough resistance to the movement of the other types to cause an ice cover over the east channel around Grand Island. At this point in time the ice bridge formed by itself in Lake Erie but over a relatively narrow stretch of the lake, and an uneasy peace descended.

The volume of ice and adverse winds combined to cause an ice cover to form about one mile upstream of Niagara-on-the-Lake and extending some six miles upriver. (Plate X) When the picture was taken a chartered ice breaker was re-opening the channel which was fortunate in the light of the events which followed.

1. Presented at the January 1964 meeting of the Canadian Electrical Association.

On January 25th, 25 mile per hour southwest winds gusting to 50 miles per hour occurred and broke the Lake Erie ice bridge causing a massive run of lake ice throughout the 25th and the 26th. All this ice had to come down the west channel around Grand Island and through the Grass Island Pool and the Control Structure. Ice was observed to be rolling along the bottom upstream of the Control Structure where depths exceeded 12 feet. By January 26 the only available exit from the Grass Island Pool was a channel about 800 feet in width on the Canadian side of the river. (Plate XI A)

During this storm the water level at the base of the Canadian Falls rose 62 feet (Plate XI B), and ice conditions were similar to those which caused the Honeymoon Bridge to fall in 1938, however, in this case the amount of water passing under the ice bridge was considerably less due to the power diversions from the river above. For example, the flow through the Maid of the Mist Pool at the height of the ice jam in 1938 was approximately 170,000 cfs, whereas in 1964 it varied from 100,000 down to 80,000 cfs. It is believed that the power diversions saved the Maid of the Mist Pool installations from an epic jam on this occasion.

Winter of 1965

This was the first year of operating experience with the Lake Erie ice boom in place. Winter arrived very late, and the cover did not begin to form on Lake Erie until after the middle January. By January 21, the ice cover extended approximately 8 miles to the west and was measured as being 6 inches in thickness one mile upstream from the boom. The weather was not sufficiently cold to properly consolidate the cover and on January 23 all but 2-1/2 miles of the cover was shifted westward by the wind leaving a strip from shore to shore resting against the boom. Several days of mild weather followed, with air temperatures reaching 40° accompanied by rain over most of Lake Erie. On January 26 with temperatures still above freezing, a severe storm developed during the evening with winds of more than 35 miles an hour gusting to 70 miles per hour. During this storm the Fort Erie water level rose 5-1/2 feet in four hours and the flow out of the lake increased by more than 100,000 cfs with the result that some ice moved over the boom as expected. No difficulties were encountered in passing the ice which came out of the lake down the river to Lake Ontario, and the boom restricted the duration of the run to a few hours rather than several days.

Problems relating to river ice continued as in the past but the River Control Organization functioned effectively, on a number of occasions, to prevent the formation of serious jams.

Winter of 1966

This winter was in many respects similar to that of 1965, when the ice cover again did not begin to form on Lake Erie until after the middle of January. On January 27 a rise of three feet took place in the water level at Fort Erie under the influence of winds up to 34 miles per hour. Although the ice behind the boom was still relatively thin, no ice came over the boom on this occasion. The situation before and after this storm is illustrated by Plate XII.

Once again the river ice problems were handled effectively by the River Control Organization.

Conclusion

The ice boom has been successful in reducing the duration and the frequency of Lake Erie ice runs. This feature in combination with those already completed in the Grass Island Pool may be expected to reduce difficulties arising from severe storms, and in the future problems will be composed principally of anchor ice and river ice respectively accompanied by extended periods of cold weather. There is one further problem however in that the boom must be removed by the 1st of April in each year and the ice frequently does not entirely leave Lake Erie until the middle of May so that there remains a period about six weeks in which the massive ice runs of the past can still take place.

Acknowledgement

Many of the photographs included in this paper are taken by the Power Authority of the State of New York, whose willing permission for their use in this paper is an indication of the co-operative spirit which has made this joint operation a success.

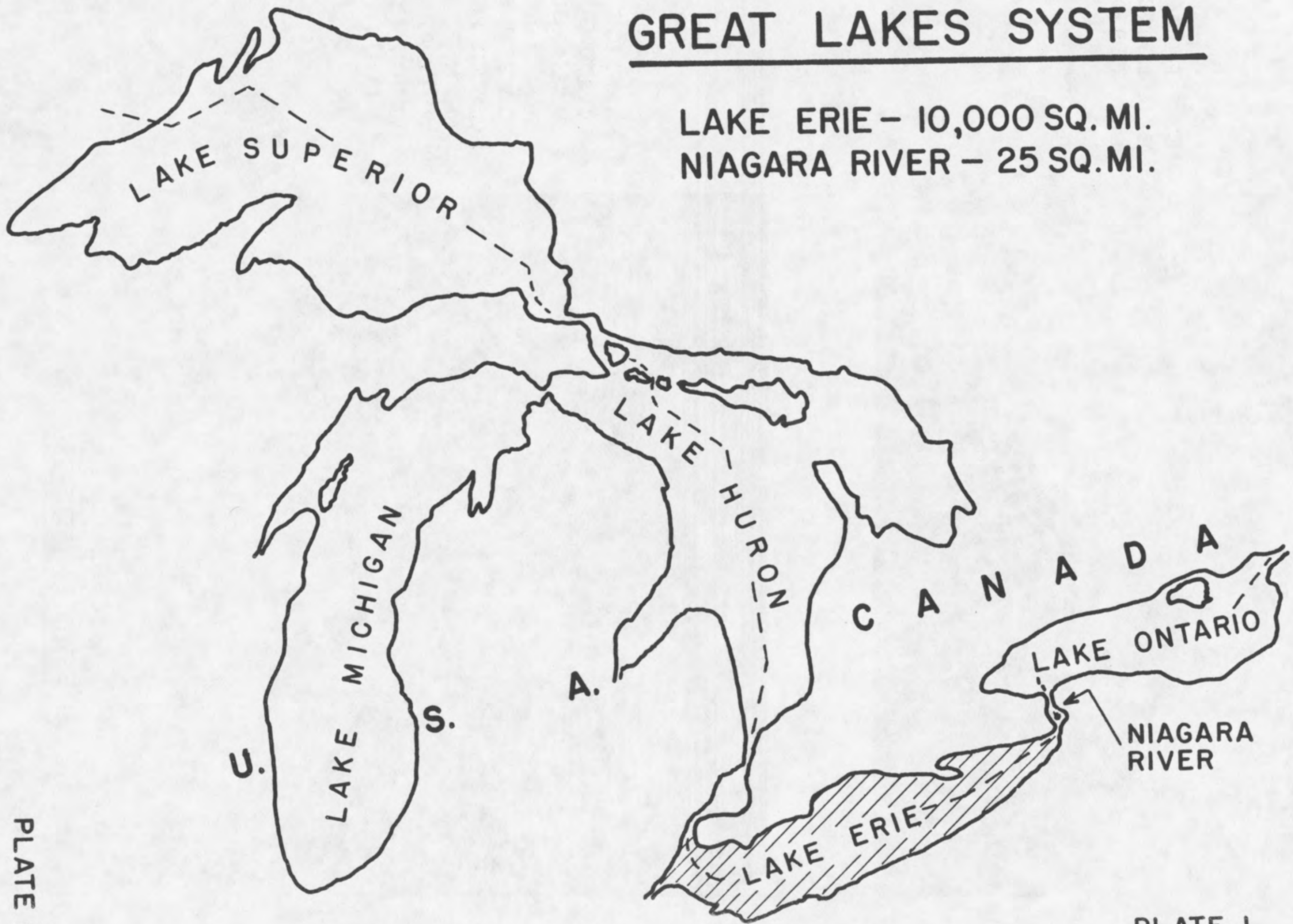



PLATE I.

PLATE I.

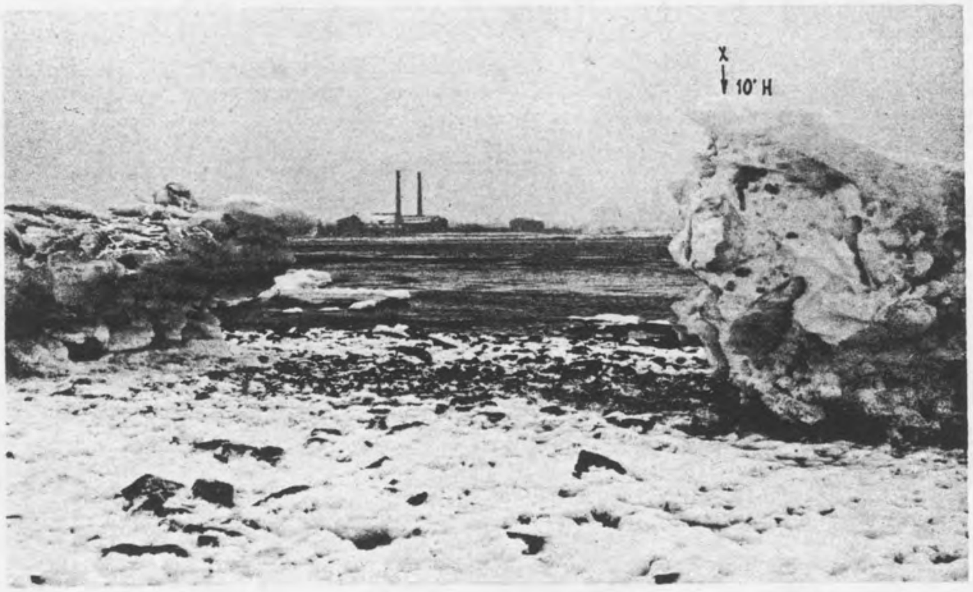
"A"

EXIT FROM LAKE ERIE LOOKING DOWNSTREAM. MASSIVE ICE RUN IN PROGRESS.
(3/1/64)

"B"

SAME ICE RUN DIVIDING TO PASS AROUND GRAND ISLAND. ICE TENDS TO COVER THE CHANNELS DUE TO LOWER VELOCITY.
(3/1/64)

LAKE ERIE ICE RUN
PRIOR TO ICE BOOM




"A"

LOOKING TOWARDS BUFFALO, SHOWING AMALGAMATION OF TYPES OF LAKE ICE (10/III/64)

"B"

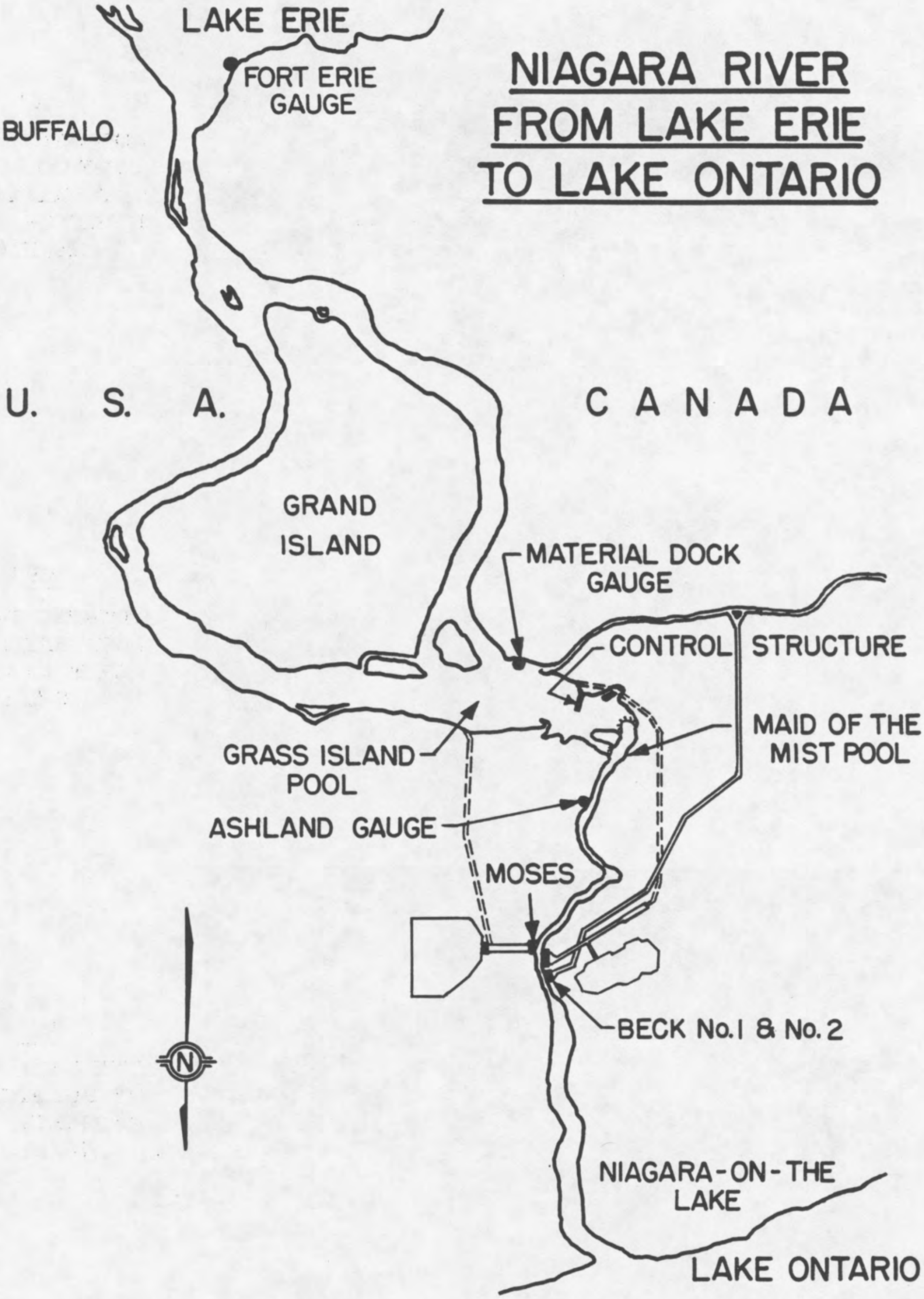
LOOKING TOWARDS FORT ERIE, 100 YARDS OFFSHORE (27/I/65)

"C"

ONE MILE WEST OF BUFFALO HARBOUR (6/III/64)

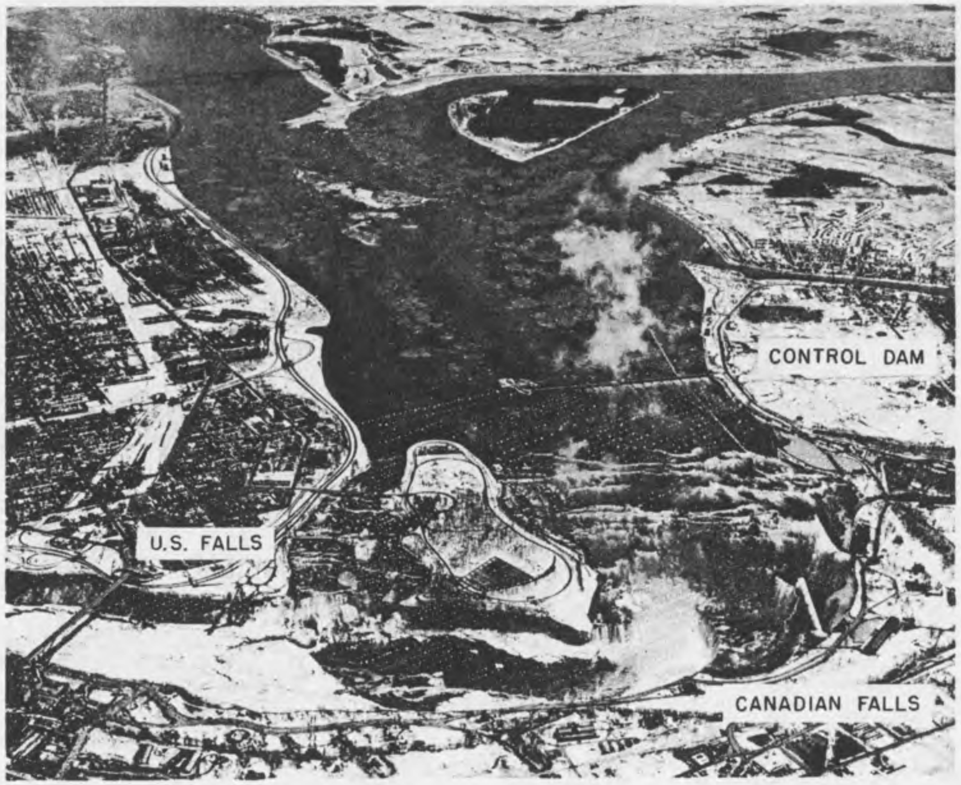
LAKE ERIE ICE PROBLEMS

PLATE III



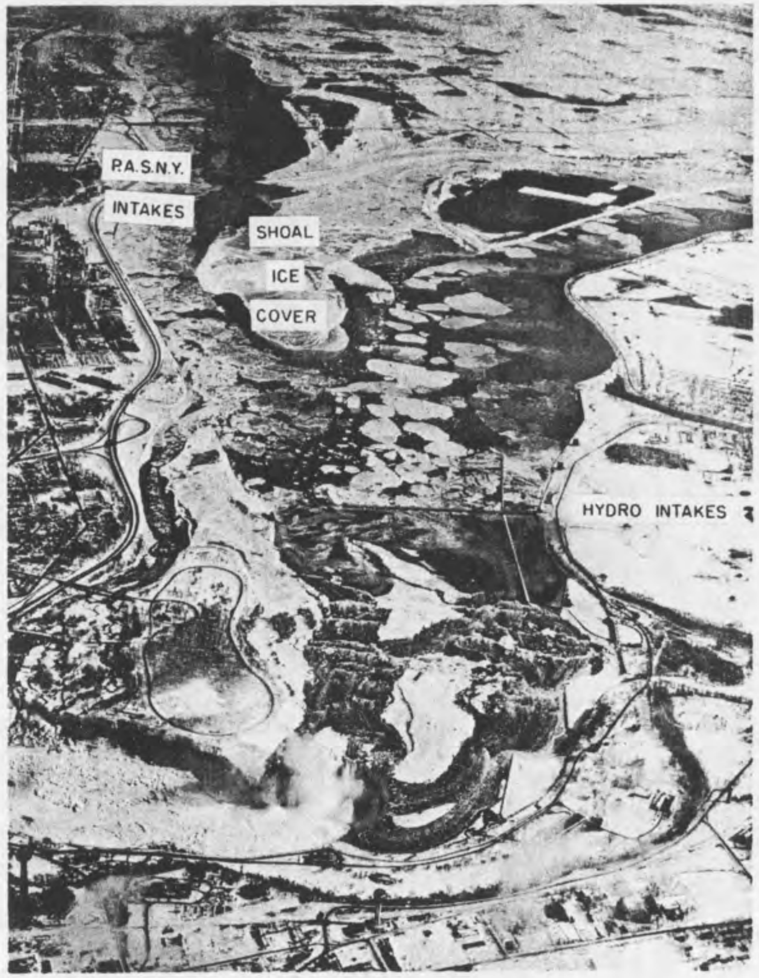
NIAGARA RIVER
FROM LAKE ERIE
TO LAKE ONTARIO
LAKE ERIE
FORT ERIE
GAUGE
BUFFALO
U. S. A.
CANADA
GRAND
ISLAND
MATERIAL DOCK
GAUGE
CONTROL STRUCTURE
MAID OF THE
MIST POOL
GRASS ISLAND
POOL
ASHLAND GAUGE
MOSES
BECK No.1 & No.2
N
NIAGARA-ON-THE
LAKE
LAKE ONTARIO


PLATE IV




"A"

AVERAGE AIR TEMPERATURE
0000 to 0800 17° F.
4/IV/64

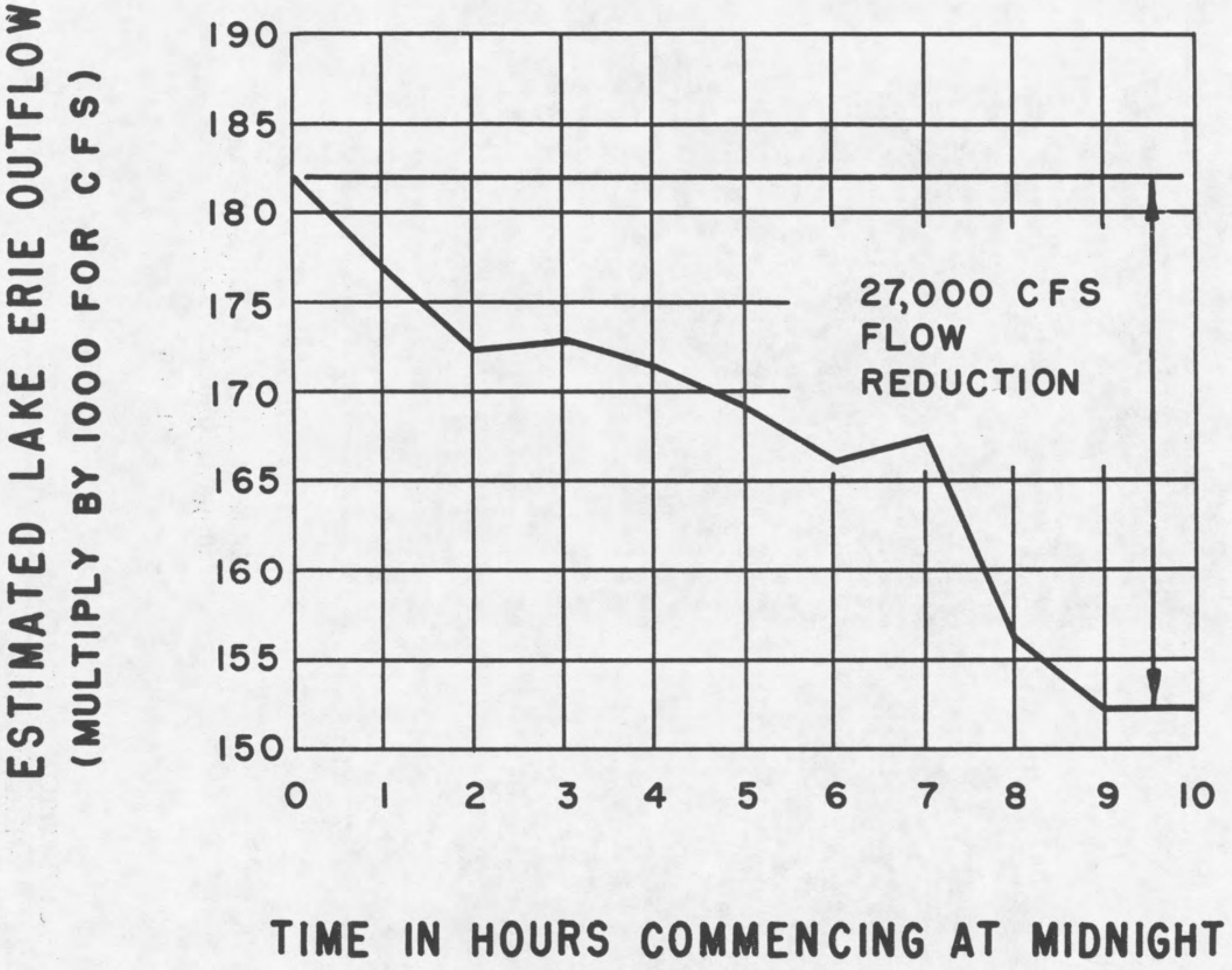



"B"

AVERAGE AIR TEMPERATURE
0000 to 0800 7° F.
4/II/65

COMPARISON OF ICE PRODUCTION IN RIVER DUE TO DIFFERENT AIR TEMPERATURES

PLATE V



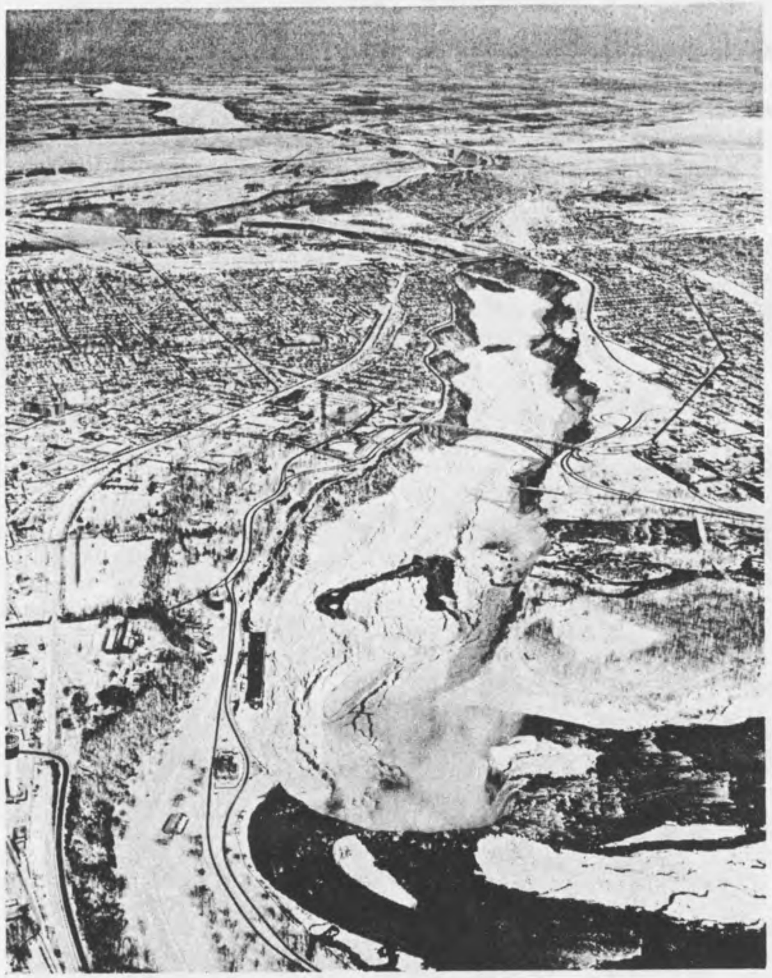

FLOW REDUCTION DUE TO ANCHOR ICE
NIAGARA RIVER JAN. 28, 1966.

PLATE VI

SLABS LEAVING RIVER BANK

ESTIMATED LENGTH - 1000 FT.
9/II/65

PLATE VII



"A"

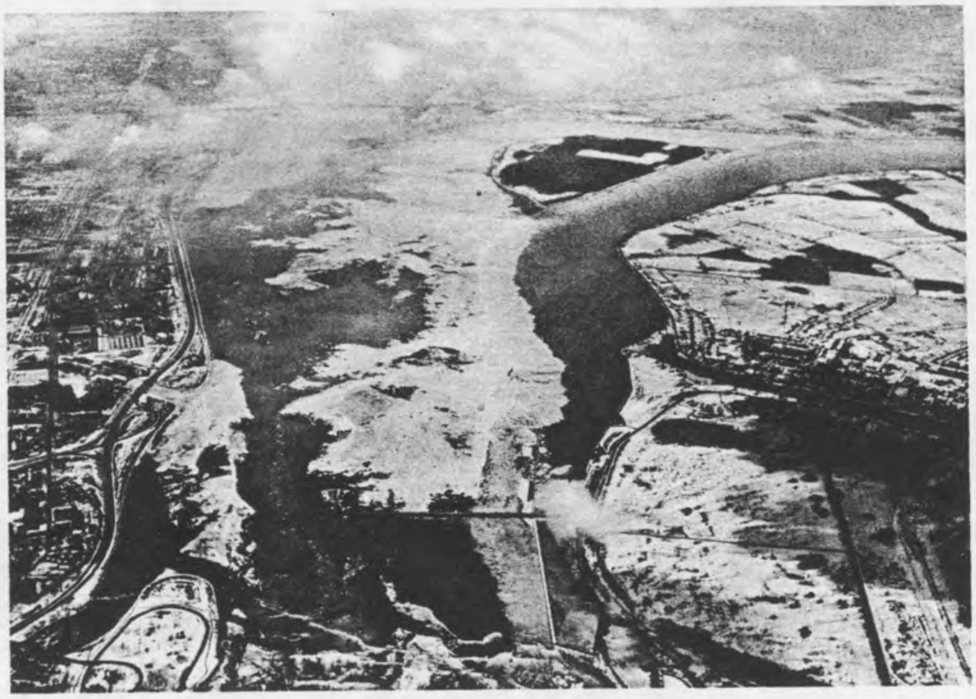
LOOKING DOWNSTREAM
TOWARDS LAKE ONTARIO
8/II/64

"B"

CLOSE UP
5/II/64

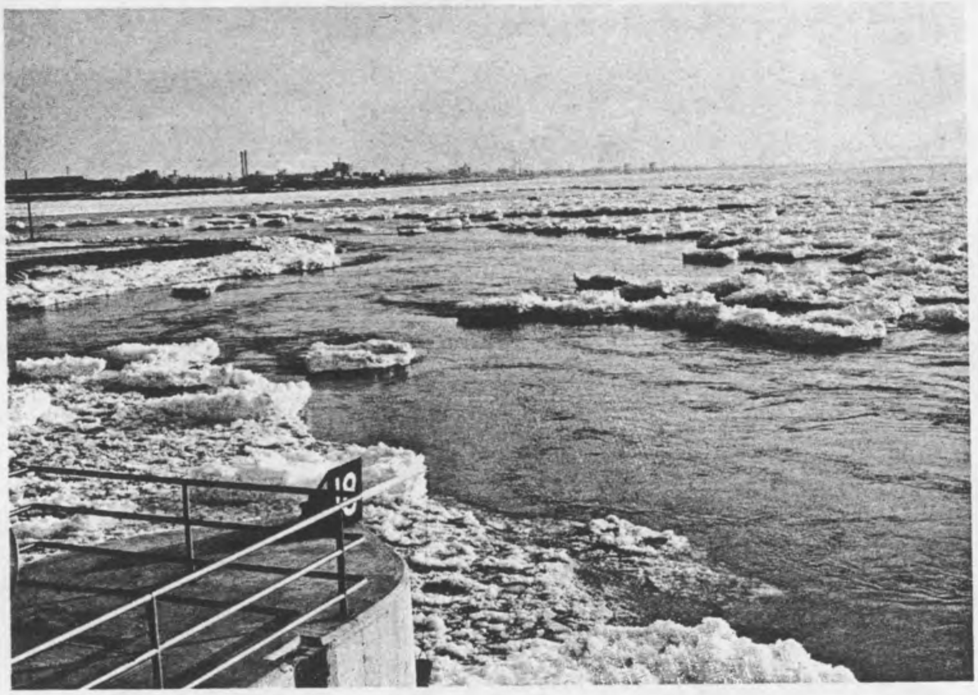
MAID OF MIST POOL ICE BRIDGE

PLATE VIII



"A"

END OF ICE RUN OF PLATE VIII, 4 DAYS LATER. LOOKING UPSTREAM OVER GRASS ISLAND POOL. TWO THIRDS OF RIVER BLOCKED BY "ICE BALLS".
(7/I/64)



"B"

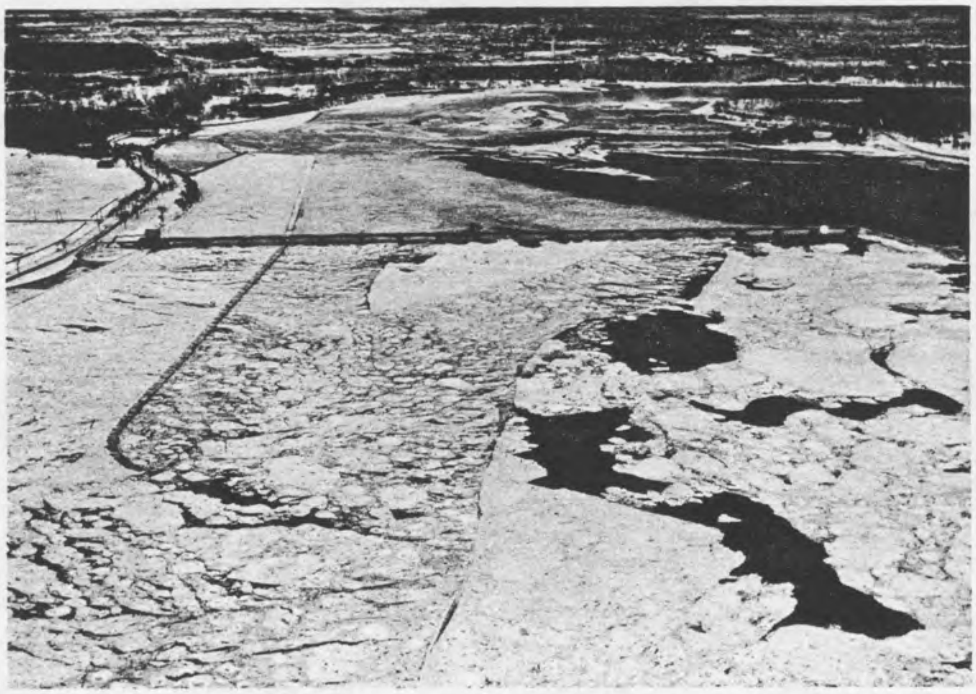
CLOSE UP OF ABOVE FROM CONTROL DAM. "ICE BALLS" AGROUND IN 12' OF WATER.
(5/I/64)

GRASS ISLAND POOL ICE JAM

LOWER RIVER ICE JAM LOOKING UPSTREAM

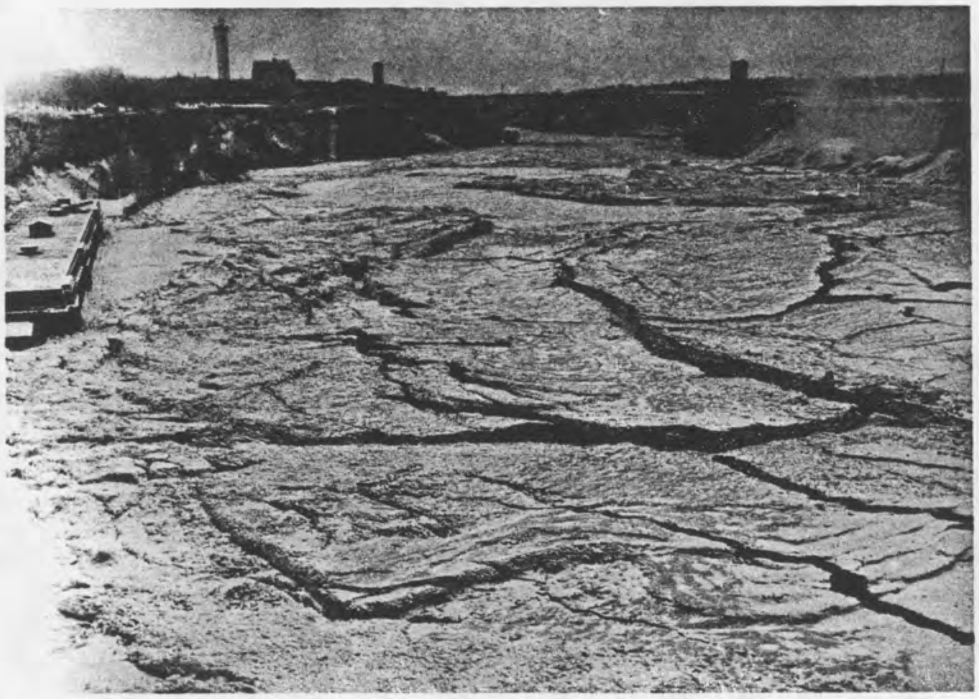
ICE COVER BEING REMOVED BY ICEBREAKER
(SEE ARROW) 14/I/64

PLATE X



"A"

LOOKING DOWN-STREAM TOWARDS CONTROL STRUCTURE OVER REMAINING "CLEAR" WIDTH OF RIVER, ESTIMATED TO BE 800'.



"B"

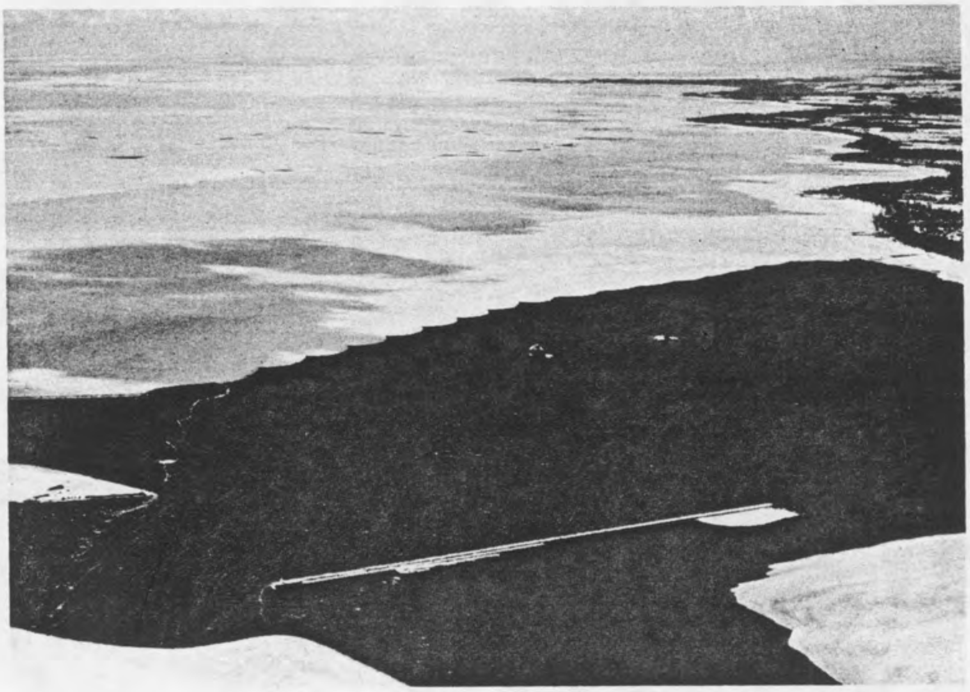
LOOKING DOWN-STREAM OVER MAID OF MIST ICE BRIDGE. WATER LEVEL 62' ABOVE NORMAL AT POWERHOUSE ON LEFT, ICE JUST BE-LOW WINDOW SILLS.

MASSIVE RUN OF LAKE ERIE ICE PASSING THROUGH GRASS ISLAND AND MAID OF MIST POOLS

26/I/64

"A"

ICE CONDITION
SIMILAR TO II "A",
BUT BOOM IN PLACE.
LOOKING DOWNRIVER.
(24/I/66)



"B"

ICE COVER 4 DAYS
AFTER ABOVE.
LOOKING WEST OVER
LAKE ERIE.
(28/I/66)

ICE BOOM IN PLACE