NRC Publications Archive Archives des publications du CNRC

Recovery of 2,3-butanediol from water by a solvent extraction and pervaporation separation scheme

Shao, Pinghai; Kumar, Ashwani

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version
acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien
DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1016/j.memsci.2008.12.033>

Journal of Membrane Science, 329, 1-2, pp. 160-168, 2009

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=f6cbc2f7-a877-41bf-917c-5c89c9a60951>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=f6cbc2f7-a877-41bf-917c-5c89c9a60951>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the
first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la
première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez
pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

NATIONAL RESEARCH COUNCIL

CANADA

ASSOCIATE COMMITTEE ON SOIL AND SNOW MECHANICS

PROCEEDINGS

OF THE

SYMPOSIUM ON AIR BUBBLING,

OTTAWA, 11 MAY 1961

Sponsored by the Subcommittee on Snow
and Ice, ACSSM and the Working Group
on Ice in Navigable Waters of the
Canadian Committee on Oceanography.

TECHNICAL MEMORANDUM NO. 70

OTTAWA

DECEMBER 1961

PREFACE

Snow and ice are major factors in many activities of economic importance to Canada. It is not surprising, therefore, to find at least four committees of the National Research Council directly concerned with these materials. These committees consider problems such as the prediction of run-off from melting snow covers, the prediction of winter ice conditions in the Gulf of St. Lawrence, the measurement of changes that occur in glaciers and how to keep highways and city streets clear of snow. By working together closely, they discharge their responsibilities with no needless duplication of effort.

One ice problem that has received considerable attention in recent years is that of maintaining water areas that would normally freeze over free of ice for part or all of a winter. The Working Group on Ice in Navigable Waters of the Canadian Committee on Oceanography and the Subcommittee on Snow and Ice of the Associate Committee on Soil and Snow Mechanics, two of the committees that are associated with the National Research Council, have given consideration to this problem. In response to demands for information, these committees sponsored jointly a conference on techniques for preventing ice formation on lakes, rivers and salt water areas. Invitations were extended to those actively engaged on this problem to present their experience and participate in the discussions. Through their contributions the conference successfully recorded and summarized what is now known in Canada on methods for preventing the formation of ice covers. The Associate Committee on Soil and Snow Mechanics is pleased to have the opportunity to publish in their Technical Memorandum series the Proceedings of this conference and thus to make available the information then presented.

The Associate Committee on Soil and Snow Mechanics and the Canadian Committee on Oceanography wish to express their appreciation to all who participated in the conference and contributed to its success. They wish, in particular, to acknowledge the kindness of the U.S. Navy Hydrographic Service for allowing a complete description of their air bubbling installation at Thule, Greenland, to be presented and discussed.

OTTAWA,
December 1961.

W. E. VAN STEENBURGH,
Chairman, Canadian Committee
on Oceanography.

R. F. LEGGET,
Chairman, Associate Committee
on Soil and Snow Mechanics.

CONTENTS

	<u>Page No.</u>
Conference summary by L. W. Gold	(iii)

MORNING SESSION

Chairman: L. W. Gold

Thermal regime of lakes and rivers with reference to air bubbling systems by G. P. Williams	1
The principles of operation of bubbling systems by W. D. Baines	12
Recent experimental observations on the use of air bubbling systems by S. Ince	23
Thermodynamic considerations on the use of air bubbling systems in salt water by E. R. Pounder	41

AFTERNOON SESSION

Chairman: T. A. Harwood

A model describing the physical processes of Project Polynya by Charles W. Senior	47
Operational details of Project Polynya by William A. Dotson	58
Description of air bubbling systems at Cambridge Bay and Tuktoyatuk, N.W.T. by T.M. Dick	70
Investigation of a compressed air bubbler system used for ice melting by W.D. Bonisteel and A. Bergs	78
Other contributions and general discussion	97

APPENDIX A: Summary of reports received on air bubbling installations

APPENDIX B: List of those attending meeting

CONFERENCE SUMMARY

L. W. Gold, Chairman, Snow and Ice Subcommittee of the NRC
Associate Committee on Soil and Snow Mechanics

The objective of the conference was to summarize the knowledge available in Canada on the use of air bubbling systems for melting or preventing the formation of ice covers on selected areas of lakes, rivers and oceans. It brought together engineers who have designed or constructed such systems and the men who are gathering the knowledge that is still required to determine if an area can be kept ice free and, to design the appropriate system if it can. The merging of their experience at this conference has greatly enlarged the knowledge of how bubbler systems work and their limitations.

Eight papers were presented. Five discussed various aspects of the design of bubbler systems, the nature of the circulation that they induce, and the thermal conditions required to ensure their successful operation. The remaining three presented details on the design of specific field installations and problems encountered in their operation. In addition, special reports on field installations were submitted, some of which were presented to the conference. All of these reports have been summarized and are included in the proceedings.

The papers by Williams, Baines and Senior bring out quite clearly that if an ice cover is to be melted, or its formation prevented, either heat must be supplied continuously to the water surface, or any ice that forms must be transported immediately out of the area to be kept ice free. During the winter, most fresh water lakes are thermally stratified, the warmer water, at a temperature between 32.0 and 39.2°F, being at the bottom. As illustrated by Williams, the warmer water is only slightly heavier than the water in contact with the ice and little work is required to raise it to the surface where the heat it contains can be used to melt ice or prevent its formation. Baines describes how air bubbles, emitted from pipes submerged in the water, will do this work very efficiently, putting into circulation by entrainment not only the water in the immediate vicinity of the rising bubbles, but also for some distance from them. Because of the large amount of heat that is usually available in the sub-surface water, air bubbling systems can be used in many lakes in Canada to keep sites ice free for appreciable periods of time and, in some cases, for the whole winter.

In most rivers the flow is turbulent, and for this case calculations by Baines show that the temperature of the water from

the surface to the river bottom can be assumed to be within $\frac{1}{4}^{\circ}\text{F}$ of 32°F at the time that the ice cover begins to form. Consequently, flowing water may not have the heat available for preventing ice formation as does a lake. The success of a bubbling system installed in flowing water will depend on the conditions at the site, such as the flow velocity and possible upstream sources of heat. Baines points out that for flow velocities in excess of 3 ft/sec, the turbulent mixing is great enough that an air bubbling installation would likely have little influence on the formation of surface ice, since this might be prevented by the flow itself. This opinion is supported by the field observation that ice covers form with difficulty when the flow is greater than about 2 ft per sec, and under such conditions the formation of frazil is common.

The use of bubbler systems for preventing ice formation in sea water requires special consideration. As pointed out by Pounder, the temperature at which the density of the water is a maximum decreases with increasing salt content from about 39°F for fresh water, to the equilibrium freezing temperature when the salinity is 24.7 parts per thousand. For salinities greater than 24.7 parts per thousand, as is the case for most sea water, the density does not have a maximum for temperature warmer than the equilibrium freezing temperature. In this case, the convective mixing due to the cooling of the surface water, and associated increase in density, will continue until ice begins to form. The measurements made at Thule and reported by Senior show that when ice begins to form, the water temperature will be almost constant and very close to the freezing temperature right to the bottom at most sites where bubblers might be used. As in the case of a river, there will be little heat available from the water under the ice cover, for melting ice or preventing its formation. Pounder does point out that if the salinity increases with depth, this could result in some ice melting by the action of a bubbler.

Although stationary sea water would not be expected to have the reserve of heat necessary for ice melting, it is possible that at some sites tidal or permanent currents carry sufficient warm or more saline water into the area to enable a bubbler system to perform satisfactorily. A possible example of this is the successful installation at Tuktoyaktuk, described by Dick.

The papers by Senior and Dotson show that in cases where the heat reserve has been depleted, the surface currents set up by the bubbler may be sufficient to remove the ice as it forms in the open area. This possibility has led them to consider other systems for establishing surface flow, such as the "outboard motor" technique which has been reported as successful in the Antarctic (Mc Murdo Sound).

The Conference showed that there is not yet a complete understanding of how air bubblers or surface flow developers prevent ice cover formation on sea water, and the conditions under which they can perform successfully. Further field observations should be undertaken to obtain the required information. When this knowledge is available, it should be possible to determine by adequate surveys if the ice cover can be prevented from forming at a particular ocean site, and what technique should be used. Failures, such as that at Cambridge Bay, described by Dick, might then be avoided.

It was apparent from the papers and discussion that for the many cases where bubbler systems have been used successfully, the design of such systems has been largely, if not completely, empirical. The material contained in the papers by Baines, Williams, Senior and Ince, and in a review by Williams (1) should now allow the design to be placed on a more rational basis. One of the first quantities that should be estimated at a possible site is the rate at which water must be brought to the surface to prevent ice from forming, or the surface flow velocity required to remove the ice that forms in the area to be kept clear. It should be possible to obtain a reasonable estimate of these quantities following the same procedure as used by Williams and by Pounder in the sample calculations presented in their papers.

Baines shows from theoretical reasoning, that the volume of water brought to the surface by a bubbler is likely proportional to $(Z)^{3/2}$ and $(Qa)^{2/3}$, where Z is the depth of the source of bubbles and Qa is the volume of air discharged from the orifice. There appears to be no suitable observations available that can be used to test the above theory. A field study by Kaitera (2) does indicate that the amount of water brought to the surface in a given time by one bubbler is proportional to the depth raised to the power of about $3/2$ and to the air discharge rate raised to a power less than 1. Although it is still not possible to calculate the volume flow that would be caused by a bubbler ejecting air at a given rate and given depth, the theory does allow one to appreciate the influence of depth and air discharge rate on this flow.

One conclusion that can be drawn from the foregoing is that if the volume of water brought to the surface in a given time by one bubbler is proportional to the rate of air discharge raised to a power less than one, then for a given total air discharge rate, the larger the number of orifices, the greater is the volume of water put into circulation. This conclusion is born out by the field observations of Kaitera (2). It is also a possible explanation for the observation by Hindes that the system with which he is familiar, which discharges

about the same amount of air per given length of pipe as the normal system, but through a greater number of orifices, induces better circulation. Bubble size might be a factor in producing this improved circulation, but, as pointed out by Baines, for the normal field installation this size probably does not depend on the diameter of the orifice, but may depend on the rate of discharge of the air.

The papers, reports and discussions contained in this Technical Memorandum of the Associate Committee on Soil and Snow Mechanics, record clearly the present state of our knowledge of the use of bubblers and flow developers for preventing the formation of an ice cover. They indicate also that further information is required on the dependence of the volume rate of induced flow on depth of bubbler, rate of air discharge and characteristics of the bubbler system, so that the design of such systems may be based more directly on the requirements of the site. The preliminary investigations described by Ince and Baines are an excellent beginning of the accumulation of this knowledge. It is hoped that this work will continue. The members of the Snow and Ice Sub-Committee and the Working Group on Ice in Navigable Waters hope also that the material presented in this publication will, in addition to being a useful contribution to engineering practice, act as a stimulus for further advances in our ability to combat ice.

REFERENCES

- (1) Williams, G.P. A Study of Winter Water Temperatures and Ice Prevention by Air Bubbling. Eng. Journal, 44, (3), March 1961, pp. 79-84.
- (2) Kaitera, P. Keeping Water from Freezing by Means of Compressed Air. Int. Union of Geod. and Geophy., Int. Assoc. of Sci. Hyd., Vol. 2, pp. 390-398, 1948.

THERMAL REGIME OF LAKES AND RIVERS
WITH REFERENCE TO AIR BUBBLING SYSTEMS

by

G. P. Williams

Air bubbling systems have been used successfully to melt ice or prevent its formation in lakes, rivers and ocean areas, but there are cases where they have been unsuccessful. If the action of a bubbler results in the melting of ice or the prevention of its formation, the bubbler must have brought, to the surface, water containing sufficient heat for this purpose. If the water does not contain the required heat it is unlikely that a bubbler will open a hole in an already established ice cover. These facts indicate that before a bubbler system is installed careful consideration should be given to the heat reserves available at a proposed site, and the heat losses to be expected, particularly in those cases where the temperature of the water is just at or slightly above the freezing point. The purpose of this paper is to discuss these thermal factors.

When a lake cools during the fall and early winter, convection currents continuously replace the surface water with the warmer, lighter water below. After the temperature of the water has dropped to 39.2°F, the density of the surface water decreases with further drop in temperature and will remain at the surface until cooled to the freezing point. An ice cover will then form. In a typical fresh-water lake of Central Canada the water temperature directly under the ice will be at 32°F, and will increase with depth to a maximum of between 35 to 39.2°F at the bottom. The change in water temperature with depth at a particular site will depend upon factors such as the water depth and the currents in the lake.

When a river cools, its water is kept at nearly the same temperature by mixing. Under these conditions, an ice cover will not start to form until the temperature of all the water in the river is close to 32.0°F. The average temperature of the water under the ice cover of rivers depends to a certain extent on the heat input from upstream sources, but it can never exceed 32.0°F by more than a fraction of a degree (1). In a typical river, the temperature at the water-ice interface will be 32°F and at the bottom of the river will be only slightly above 32°F.

In either fresh-water lakes or rivers there is only a slight difference in density between the water just under the ice cover, and the water at the bottom. Thirty-two cubic feet of water at 39.2°F resting on the bottom will weigh only about one quarter of a pound more than the same volume of water at 32°F just under the ice cover. The amount of work expended in raising this volume of water (2000 pounds) to the surface will be approximately the same as that used to raise one quarter of a pound the same distance in air. With these slight density differences any method which will induce mixing, such as a flow of air bubbles from the bottom to the surface, will result in a significant movement of warm water to the surface with very small energy input. The heat in this warmer water can then be used to melt surface ice or to prevent its formation. The rate at which ice can be melted in practice at successful bubbling installations indicates that the thermal exchange between water and ice under these conditions is quite good.

The heat available for melting or preventing ice formation is stored not only in the water under the ice cover, but also in the material underlying the lake or river. The ways by which this heat is used or lost at an air bubbling installation is in melting ice, through evaporation, convection and radiation from the open water surface and by conduction through the surrounding ice cover. Figure 1 shows the different sources of heat and heat losses which should be considered in the design of air bubbling systems is not included, as in most cases it is too small to be of significance.

HEAT SOURCES

Q_e and Q_a - Heat Available from the Water

The heat available at a temperature above 32°F in the water immediately under the opening created by the air bubbler is called Q_e in this paper. The heat in the water under the ice cover for some distance surrounding the open hole is called, in this paper, Q_a or advective heat. The magnitudes of Q_a and Q_e can be estimated if water temperatures are known, if the depth of the water body is known, and if the area of influence of the air bubbling unit can be defined. Water temperatures and depth can be measured readily to the accuracy required for a reasonable estimate of the heat available. The area of influence of the air bubbling jet and the resulting water temperature distribution is a question which is not so easily answered. The papers by Baines and Ince give further consideration to this factor.

If the temperature of one cubic foot of water is lowered 1°F, 62.5 Btu of heat are released. In the case of lakes, where the mean temperature of the water below the ice can be lowered 4 to 7°F by air bubbling, the heat released is from 250 to 440 Btu/cubic foot.

In river water where the average temperature of the water below an ice cover is only a fraction of a degree above 32°F, the amount of heat available is normally much less than for a lake. Because the amount of heat available from one cubic foot of water is small, the heat that can be brought to an air bubbling site from upstream sources is especially important in determining whether air bubbling installations will be successful at a particular site in a river.

Q_b - Heat Flow from Bottom Material

The heat that can be supplied from the bottom of a lake or river can be estimated if the thermal properties and density of the bottom material and the temperature gradient in the material are known. Field measurements of temperature gradients, density and thermal properties for a particular site are usually not available. Estimates can be made from a knowledge of the material and the size of the temperature gradients likely to be encountered.

For example, if the underlying material is granite, using an assumed thermal conductivity of 0.0045 Btu/ft² °F/in. sec (2), and an assumed temperature gradient of 0.1 to 0.15°F/in., the heat flow would be approximately 2.2 Btu/sq ft/hr. If the underlying material were silt loam with a thermal conductivity of less than half that of granite, under the same temperature gradient, the calculated heat flow would be 0.5 to 1.0 Btu/sq ft/hr. Nybrant (3) states that in latitude 50 to 60N, the heat flow from typical bottom material in October is approximately 1.8 Btu/sq ft/hr; in Dec. to Jan., 1 to 1.8 Btu/sq ft/hr, and almost negligible in April.

Compared to the heat available from the water under the ice cover, the heat supplied by the bottom material will probably be quite small. But where the reserves of heat are critical, such as for shallow water, or a flowing river, the heat supplied from the bottom material can be important particularly if this heat can be obtained from comparatively large areas.

As in the case of heat stored in the water, there is a limit to the amount of heat available from the bottom material. As already stated, under natural conditions the heat flow gradually diminishes from 1.8 Btu/sq ft/hr in October to an almost negligible flow in April. During the

early stages in the operation of an air bubbling system the temperature gradient in the bottom material will probably increase, resulting in greater heat flow. This may result, however, in the ground heat reserve being depleted sooner than is normal for the site.

HEAT LOSSES

Q_m - Heat Used to Melt Ice

To melt, ice requires 144 Btu/lb or 9000 Btu/cu ft. The amount of heat required to melt ice will be directly proportional to the thickness of the ice and the area to be kept open.

Q_o - Heat Loss to Atmosphere from Open Water

In the case of an open body of water under winter conditions, there can be large heat losses from the surface to the surrounding air. This heat loss can be estimated by calculating or measuring net radiative, evaporative and convective heat losses for the atmospheric conditions that prevail. This energy balance approach to estimating heat losses requires quite detailed meteorological records, which are normally not available for a specific site, and even when available, require so many assumptions for the calculations that the results are often not reliable.

For an estimate of surface heat losses under field conditions, the use of empirical formulae is usually more practical. Various empirical formulae have been given (3, 4) which relate heat losses to the air-water surface temperature difference. These formulae neglect many factors such as wind velocity and depth of water, but the fact that they give a reasonable estimate under most conditions and that only air temperature and water temperature records are needed, make them useful for practical application. The range of heat losses reported vary from approximately 3.5 to 5.0 Btu/sq ft/hr per degree Fahrenheit water-air temperature difference. For a 20°F air-water temperature difference, the heat loss would be from 70 to 100 Btu/sq ft /hr.

Q_c - Heat Conducted Through Ice Cover

The rate of heat loss through an ice cover is much less than the heat loss from an open water surface under the same atmospheric conditions. The heat loss would be further reduced if the ice were covered with snow.

The heat loss through 24 in. of ice for an average air temperature of about 10°F will probably not exceed 10 to 15 Btu/sq ft/hr. The heat loss with 12 in. of snow on top of the ice, under the same conditions, will probably not exceed 1.0 Btu/sq ft/hr. This compares to 70 to 100 Btu/sq ft/hr for an open water surface.

If the temperature gradient through the ice or snow cover is measured, and the thickness and density of the cover are known, values for heat flow through ice and snow can be calculated. If the water is not moving, most of this heat loss is associated with the forming of new ice, and comparatively little is from the water beneath the ice.

Because the amount of heat used in melting the ice and the amount of heat lost from open water surfaces are large in comparison with heat losses through the ice cover, the size of the open hole should be kept to a minimum to conserve the heat that is available in the water.

Q_P - Heat Used in Melting Snow Falling in the Open Water

If the air bubbling operation is in an area subject to heavy snowfall or drifting snow, heat will be used in melting any snow that falls into the open hole. Assuming that the temperature of the new snow is close to 32°F, it requires approximately the same energy to melt 10 in. of new snow as it does to melt 1 in. of ice. At sites where the amount of heat available is likely to be critical, the heat required to melt the snow that falls or drifts into the hole could be important.

SUMMARY OF HEAT SOURCES AND LOSSES

Table I presents a summary of the heat sources and heat losses and a comparison of their magnitude for various assumed conditions of operation. In this sample calculation the heat available from 30 ft of water over a 7-day period, when the area of influence of the bubbler equals the open area, would, under the most favourable conditions, just balance the expected heat losses. If the area of influence of the air bubbling unit is five times the open area, the heat available would enable the operation to be carried on for at least 21 days. If the depth was increased five times, the operation could be carried on for 3 to 4 months.

These calculations illustrate that if the water temperature under the ice cover is a few degrees above 32°F, the length of time a bubbler system can be operated successfully will depend mainly on the volume of

water influenced by the bubbler and the size of the open area. They show also that the relative importance of the heat losses from the open area increases with the length of time of operation. For example, in the case of the 100-day period, over 95 per cent of the total calculated heat loss is from the open water.

EXAMPLE OF AIR BUBBLING TRIAL

In the literature on air bubbling installations there are relatively few reports that give quantitative measurements on the heat available or the heat losses during a particular operation. In order to show the relative magnitude of heat losses and gains under actual field conditions the results for one bubbling trial are presented in this report.

The air bubbling trial was carried out from 26 January to 1 February 1960 under the auspices of the Hydraulics Laboratory, Division of Mechanical Engineering, National Research Council. The air bubbling equipment consisted of a single air-line installed on the bottom of a tank 200 by 400 ft. The water depth was about 7.3 ft. The total ice thickness at the beginning of the test varied from 16 to 17.5 in.; the ice was overlain by approximately 4 in. of snow. Continuous operation of the air bubbler at an air flow rate of 1 cfm over a 7-day period removed ice from a 1,500 sq ft area. Before the test, the measured water temperature profile was fairly typical for a shallow tank, being approximately 39°F from the bottom of the tank to about 3 ft under the ice cover, then decreasing to 32°F at the ice-water interface.

By measuring the water temperature at regular intervals it was possible to calculate Q_e and Q_a , the heat made available from the water. By measuring the amount of ice melted and the amount of new snow, the heat used in melting the ice, Q_m , and the heat required to melt the snow, Q_s , were calculated. Q_c , the heat loss to the atmosphere through the ice cover surrounding the open hole was neglected because both the upper and lower surfaces of the ice cover were at 0°C. During the period of test the average air temperature was 17.5°F as recorded at a nearby meteorological site. Using relationships previously developed (4, 5), the average heat loss from the open water surface was estimated. The only heat that was not measured and could not be calculated with reasonable accuracy was Q_b , that from the bottom of the tank.

For this example, when the weather conditions were not

particularly severe, about 60 per cent of the heat was utilized in melting the ice, about 39 per cent was lost to the atmosphere from the open water surface, and 1 per cent used to melt new snow. The significant feature of this trial was that over 95 per cent of the heat used to melt the ice and prevent ice formation came from the water under the ice cover surrounding the open hole. These results show that an air bubbling unit will put into circulation a volume of water much larger than that directly under the hole opened by the bubbling action. If this advective heat Q_a , had not been available, the heat, Q_2 , stored in the water under the opening would have been sufficient to melt only about 2 per cent of the ice which was melted.

It is interesting to note that if the thermal reserve is exhausted, and water in an open area is cooled down to 0°C , further cooling and mixing would probably result in frazil formation. Frazil consists of many small disc-like particles of ice which soon conglomerate into slush and floating ice globules. In this regard, a condition might arise where the formation of frazil could be used to advantage. If the ice particles and slush could be swept away either by natural currents or artificial means, it is possible that the heat released during freezing could balance the various heat losses and thus maintain an open hole in the ice. These conditions apply to open water areas in fast flowing rivers and to small openings observed at bridges, piers, etc., where natural river currents have sufficient velocity. For a small tank as in the example given, however, it is unlikely that frazil formation could be used to advantage.

CONCLUSION

The thermal reserve in lakes and rivers at a potential site for an air bubbling installation can be calculated with sufficient accuracy if water temperature profiles are measured, if the water depth is determined, and if the area of influence of the air bubbling unit is known. The heat losses to be expected can probably be estimated with sufficient accuracy if air temperature can be predicted and the thickness of the ice to be melted is known. In many cases where the thermal reserve is adequate, a detailed knowledge of the heat available and the heat losses to be expected is not necessary. Where the thermal reserve is likely to be critical at a particular site, calculation of the expected heat balance during the operation of an air bubbling system should be made to determine whether the system will be successful.

ACKNOWLEDGEMENTS

The author is indebted to Mr. L. Gold for most helpful discussions during the preparation of this paper. This is a contribution from the Division of Building Research, National Research Council, Ottawa, and is published with the approval of the Director of the Division.

REFERENCES

- (1) Baines D. W. On the Transfer of Heat from a River to an Ice Sheet. Presented at 1961 Hydraulics Conference, American Soc. of Mech. Eng. and the Eng. Inst. of Canada. Montreal, 8-11 May 1961.
- (2) Jen-Hu-Chang. Ground Temperature, Vol. I, 300 p. Harvard University, 21 June 1958.
- (3) Nybrant G. Water Temperature in Winter in a Pond and its Dependence upon Flow. Seminar, Ice Problems in Hydraulic Structures, 8th Congress Int. Assn. for Hydraulic Research, 1959.
- (4) Williams G. P. Winter Water Temperatures and Ice Prevention by Air Bubbling. Engineering Journal, Vol. 44, March 1961, p. 79-84.
- (5) Williams G.P. An Empirical Method of Estimating Total Heat Losses from Open Water Surfaces. Seminar, Ice Problems in Hydraulic Structures, 8th Congress Int. Assn. for Hydraulic Research 1959.

TABLE I

ESTIMATED HEAT SOURCES AND HEAT LOSSES
UNDER VARIOUS ASSUMED OPERATING CONDITIONS
FOR AIR BUBBLING SYSTEM IN FRESH WATER LAKES

HEAT VALUES UPON WHICH CALCULATIONS BASED	7 days	21 days	100 days
<u>HEAT SOURCES</u>	30' depth $\frac{\text{area influence}}{\text{open area}} = \frac{1}{1}$ Btu/sq ft of open water	30' depth $\frac{\text{area influence}}{\text{open area}} = \frac{5}{1}$ Btu/sq ft of open water	150' depth $\frac{\text{area influence}}{\text{open area}} = \frac{5}{1}$ Btu/sq ft of open water
Q_b 0 - 2.0 Btu/sq ft/hr	0 - 0.5×10^3	0 - 1×10^3	0 - 5×10^3
Q_e 250 - 440 Btu/cu ft of water	7 - 13×10^3	8 - 13×10^3	38 - 65×10^3
Q_a 250 - 440 Btu/cu ft of water	7 - 13×10^3	37 - 65×10^3	187 - 325×10^3
TOTAL	14 - 26.5×10^3	45 - 79×10^3	225 - 395×10^3
<u>HEAT LOSSES</u>			
Q_m 9000 Btu/cu ft of ice - 12 inches of ice	9 - 9×10^3	9 - 9×10^3	9 - 9×10^3
Q_a 70 - 100 Btu/sq ft/hr for 20°F air-water temp diff.	12 - 17×10^3	35 - 51×10^3	169 - 240×10^3
Q_s 900 Btu/cu ft of new snow/ week	1 - 1×10^3	3 - 3×10^3	13 - 13×10^3
Q_c Assume 0	0 -		
TOTAL	22 to 27×10^3	47 to 63×10^3	191 to 262×10^3

DISCUSSION

A. BREBNER inquired if the work done by the compressor was an important factor in melting ice or preventing its formation.

G. P. WILLIAMS replied that the horsepower of the compressor was very small compared with that required to keep the area ice-free.

J. N. HINDE pointed out that the contribution to the heat lost due to drifting snow may be underestimated. He inquired whether the rate of circulation figures applied to stagnant water; he also pointed out that the heat losses would be much greater if the top water were not stagnant.

G. P. WILLIAMS replied that the calculations used for the example in the paper did not make allowances for drifting snow. The values used for calculating heat losses generally applied to stagnant water. Values reported in the literature for heat losses from rivers, however, fall within the range of values presented in the paper.

WILLIAMS then asked why surface losses should be greater if the water had been in motion.

J. N. HINDE replied that the convective loss from a water surface depends upon the wind velocity. He suggested that the relative wind velocity would be greater between air and moving water than between air and stagnant water.

E. N. KING asked if the heat loss could be reduced by erection of a plastic house structure over the system.

J. N. HINDE reported that boards had been used successfully to prevent the open water in the hole from freezing by keeping out the snow.

G. P. WILLIAMS considered that a plastic cover would reduce the heat loss but the cost of such structures would make them impractical for many installations.

F. G. BARBER asked if there were any observations on the effect of the bubbler on temperature distribution within the lake.

L. W. GOLD replied that this would come out in discussion later in the day.

FIGURE I
HEAT AVAILABLE AND HEAT LOSSES
DURING AIR BUBBLING OPERATION

THE PRINCIPLES OF OPERATION OF BUBBLING SYSTEMS

by

W. Douglas Baines

The function of the air bubbler is to increase the transport of heat from a body of water to the ice cover or open upper surface. In this paper the rate at which this heat transport takes place will be discussed. It has been shown in the previous paper that there are many cases in which adequate heat exists in the body of water to maintain a steady flow through an open upper surface. Ideally, the air bubbler should be designed for the minimum rate of heat transport so that the heat in the lake or river will be available for the maximum length of time. This is not feasible because of several gaps in the theory which prevent the complete detailed analysis from being made. Nevertheless, sufficient is known of the heat flow so that the general principles of operation can be delineated. It is thus possible to avoid serious mistakes in the design of air bubblers.

The source of heat for the air bubbler lies in the excess temperature in the lower layers of the water. The bubbler induces a vertical current of water which carries this heat to the upper levels and against the under side of the ice sheet. Thus it is the flow pattern of the water current which is of primary interest to the engineer. From an experimental study of this flow pattern (1) and some field observations, the author has obtained a detailed picture of the general characteristics. These will be described in the following paragraphs.

FLOW PATTERN IN THE WATER

At very low air discharge rates, i. e. of the order of 0.01 cfm, the air issues from the air bubbler hole as individual bubbles of uniform size. These then proceed vertically upwards in a relatively straight line. For larger air discharges, however, the bubbles issue from the orifice in a heterogeneous mixture, the sizes varying from about 1/16 up to 1 inch in diameter. The bubbles rise at varying rates depending on their size and oscillate rapidly from side to side. The large bubbles induce turbulence which move the smaller bubbles laterally. Thus the size of the clouds of bubbles increases with vertical distance above the orifice. It appears that all bubbles are contained in a cone with a total included angle of 12° as shown in Fig. 1.

It might be expected that the size of the air bubbles depends on the size of the opening through which the air is forced and also the air discharge rate. However, measurements made by the author confirm the analysis of Silberman (2) that the size distribution is independent of the orifice size in the practical range. For orifices 0.04 in. diameter and larger the bubble characteristics depend only on the air discharge. Thus it is not feasible to vary the bubbler operation by varying the size of the holes. This influences only the pressure loss in the supply system.

The effect of the bubbles, however, extends beyond the cone containing them. Measurements show that there is a vertically induced velocity extending about twice the distance laterally. This water flow is induced by the rising air bubble column. Each bubble exerts a force on its surroundings proportional to its bouyancy. Thus the water around the bubble is accelerated and moves upward. This motion is transferred to the water beside the bubble column by viscosity and lateral turbulent fluctuations. The result is a jet of water moving upward with a maximum velocity immediately over the air source and decreasing along an s-curve radially outwards as shown on Figs. 1 and 3.

The force exerted by the air bubbles on the surrounding water is roughly constant during the period of ascent. If the installation is in very deep water the effect of compressibility is such that the bubble expands as it rises. In practical situations, however, this expansion need not be considered unless the depth is of the order of 100 feet or more. Thus it can be deduced that the momentum of the water jet must increase steadily as it proceeds upward. Measurements show that the peak velocity in the water jet is constant and thus the increase in momentum is accomplished by a steadily widening jet. The most significant practical conclusion of this analysis is that the volume of water transported and the total momentum of the vertical jet increases with the depth of submergence of the bubbles. Thus the deeper the body of water the more cheaply the bubbler can be operated.

Since the vertical jet is increasing in volume with distance above the source there must be a lateral flow to supply the fluid. This is commonly referred to as entrainment or entrained flow and is noted on Fig. 1. This steady inward flow to the jet which has a velocity of the order of a hundredth of a foot per second greatly increases the area influenced by the air bubbler. The heat convected to the vertical jet by entrainment is several orders greater than that which could be obtained by conduction.

The increase of momentum of the vertical jet with height is the major advantage of the air bubbler over the alternative systems of inducing a vertical flow. A jet of water injected at the bottom or a convection current from a heat source both have constant momentum with height. It can be shown that the energy of these jets decreases with height and thus the effectiveness for melting an ice sheet decreases with depth of submergence. The air bubbler has, of course, an additional advantage which greatly simplifies construction and that is that the orientation of the source is immaterial. The air bubbles and hence the water jet rise vertically regardless of the direction of issue of the air jet. Such is not true of the direct injection of water.

One measure of efficiency of the air bubbler is the ratio of flow of water induced to the flow of air. This is surprisingly large because of the momentum increase discussed above. Measurements made by the author in a water depth of 5.5 feet with an air discharge of 1 cfm indicated a discharge ratio of about 120. Thus the mass of water moved per unit mass of air injected is 800 times this value or about

100,000 and hence the practical benefit of the air bubbler as a mixing device. It has been reasoned that this flow ratio should be a function of the air discharge Q_a and the depth of submergence z . All available data leads to a relationship of the form

$$\frac{Q_w}{Q_a} \propto \frac{z^{3/2}}{Q_a^{1/3}}$$

but this has not been verified over a large range of operating conditions. Thus the characteristics of the vertical jet cannot be accurately predicted.

SURFACE JET

Upon reaching the water surface the air bubblers stop but the momentum of the water jet is converted into a radially spreading surface jet. This is relatively thin (6 inches or less) and hence of rather high velocity. The velocity distribution is a maximum at the free surface if it is open (note Fig. 4) and a maximum close to the surface if an ice cover exists. Measurements show that the surface jet is quite steady in spite of the unsteady oscillations of the vertical jet which forms it. Furthermore, the surface jet is radially symmetrical so that uniform ice melting effects can be expected.

The radial spread of the surface jet has the general characteristics of free turbulence. Kinetic energy is obtained entirely from the vertical jet and hence must decrease in the direction of flow. Analysis indicates that the maximum velocity should decrease inversely proportional to the radial distance and measurements confirm this trend. The decrease of maximum velocity is accompanied by thickening of the jet and entrainment of water on the underside. Consequently, the velocity of the surface jet rapidly dissipates and it is absorbed into the general pattern of circulation.

LARGE SCALE CIRCULATION

It has been seen that the vertical and surface jets consist entirely of water which has entered each jet from the side as entrainment. The streamlines of the flow field must thus be perpendicular to the jets and, since the body of water was originally static, must be connected to the dissipated surface jet. It can thus be deduced that the large scale circulation induced by the air bubbles is a giant ring vortex as shown on Fig. 2. The flow velocities are very small everywhere except in the jets and decrease with distance away from the bubbler. These are not, however, zero and thus the zone of influence of the bubbler cannot be clearly defined but tends towards the whole body of water. The pattern drawn on Fig. 2 is for an infinite lake. If the bubbler is near a wall, the streamlines are closer together and the return velocities larger. In practical cases the distance to a boundary of several hundred feet can produce noticeable proximity effects.

TRANSPORT OF HEAT

The transport of heat by the air bubbler has two distinct phases: the convection of heat from the bottom of a lake by the vertical jet and the transfer of heat to the ice or open water surface by the surface jet. The first is a simple mixing process which is relatively easy to analyse but the second is a problem in turbulent shear flow which is relatively difficult.

When the air bubbler in a lake is first started the vertical jet moves through the natural temperature gradient and the volume of flow increases steadily. Mixing is so intense that the jet has a virtually constant temperature at any given depth. This temperature reflects the integrated total of the heat of the entrained water. Thus the temperature at any point can be obtained by calculating the rate of entrainment and multiplying by the local temperature. If broad assumptions are made about the temperature gradient and the rate of entrainment then it can be shown that the vertical jet temperature at the surface is roughly the lake temperature at mid-depth. More accurate analysis shows that the jet temperature is actually slightly less than this figure but for rough design purposes this approximation suffices. In rivers and other cases where the water is mixed temperature gradients do not exist and the air bubbler does not transport heat from the lower levels. This is also true of the later stages of operation in a lake. The circulation pattern of Fig. 2 shows the means by which the mixed water of constant temperature returns to the bottom and thence back into the vertical jet. This means that the temperature along a streamline would be constant and hence the whole field would come to a constant temperature were not heat conducted laterally from more distant parts of the lake into the circulation pattern.

Considering the surface jet in detail it is seen that this provides a fast moving zone of water very close to the under surface of the ice sheet. This surface must of necessity be at 32°F and thus the jet tends to sweep away the cold film in immediate contact with the sheet and replace it with the warmer water from below. It is this velocity effect that leads to the large melting rates of the ice. The mathematical statement of this effect as a rate of heat transfer is most clearly presented in the equation of Sidorov (3)

$$\nu = \frac{1}{2} c_y \text{ Re Pr}^{1/3} \quad (1)$$

in which ν = Nusselt number = $\frac{qr}{k \Delta T}$ is primarily a statement of the rate of heat transfer; q , in Btu/ft² sec divided by ΔT , the temperature of the jet above 32°F, r the radial distance away from the air bubbler centre line, and k the conductivity of the water are relatively uniform among all of these applications. c_y is a shear coefficient dependent on the flow field which can be determined from one of the studies of wall jets such as that of Sigalla (4). Re is the Reynolds number of the jet, $\frac{u_1 r}{\nu}$ and thus is primarily an expression of u_1 the maximum

jet velocity, ν being the kinematic viscosity of the water. The final factor Pr is the Prandtl number of water at the freezing point and has the value 13.6. This is relatively large compared to most engineering situations indicating that the fluid properties are conducive to heat transfer.

The equation given above is not particularly useful in this form. However, the shear coefficient can be approximated from Sigalla results and thus

$$\frac{qr}{k \Delta T} = 0.08 \left(\frac{u_1 r}{\nu} \right)^{0.8} \quad (2)$$

As noted above u_1 cannot be evaluated from the imposed conditions and thus Eq. (2) is not directly applicable. However, as an example, take typical values of the conditions in a surface jet at radius of 1 foot a maximum velocity of 1 ft/sec. The resulting heat transfer rate will be found from Eq. (2) to be

$$\frac{q}{\Delta T} = 0.04 \text{ Btu/ft}^2 \text{ sec } ^\circ\text{F.}$$

This is the same order as that existing in a fast flowing river (5) and this comparison leads to the conclusions that

(i) the action of the air bubbler is identical to that of a river flowing under an ice sheet

(ii) if installed in a river with velocities of 3 ft/sec or greater the bubbler will have no effect on the flow. This is because the air bubbler cannot materially increase the natural heat transfer rate. There will, of course, be situations of lower velocity in which the bubbler will be effective. It is the writer's opinion that the velocity will need to be less than one foot per second for the installation to be economically feasible.

As the surface jet flows outward it becomes cooler due to loss of heat and by entrainment of water from below (if a temperature gradient exists). Thus the heat transfer rate, q , decreases with radial distance. The actual effective distance depends on water temperature and the existence of an open water surface. Thus one cannot predict the optimum spacing of bubblers in any practical installation.

CHIMNEY VERSION OF THE AIR BUBBLER

It has been suggested that installing a vertical open-ended tube above the air bubbler ending just below the ice surface would increase the effectiveness. From the above discussion it can be seen that such a tube would eliminate the entrainment by the vertical jet and thus result in a more concentrated and faster surface jet. It would also deliver warmer water as long as temperature gradient exists.

However, the volume of flow would certainly be less than that for a simple bubbler so it is not possible to conclude that the total effect would be an improvement.

REMARK

The above is an outline of the flow mechanism of an air bubbler. It is hoped that it will lead to a better understanding of the principles underlying its operation. However, the detailed analysis of any given installation cannot be performed with accuracy by methods now available. Thus the engineer must experiment with pilot installations if a large and expensive project is planned.

REFERENCES

1. Baines, W.D. On the flow of water induced by a rising column of air bubbles. Proc., Int. Assn. for Hydraulic Research, 8th Congress, Vol. 2, Paper No. 7-D. Montreal, 1959.
2. Silberman, E. Production of bubbles by the disintegration of gas jets in liquid. Proc. 5th Midwestern Conference on Fluid Mechanics, Univ. of Michigan, 1957, p. 263.
3. Sidorov, A. The relation of surface friction and heat transfer. Soviet Physics (Technical Physics), Vol. 2, No. 3, p. 499-504.
4. Sigalla, A. Experimental data on turbulent wall jets. Aircraft Engineering, Vol. XXX, No. 351, May 1958, p. 131-4.
5. Baines, W.D. On the transfer of heat from a river to an ice sheet, Trans., Engineering Institute of Canada, (in press).

DISCUSSION

J. N. HINDE asked whether the bubbles used by Dr. Baines were in the range of 1/16 in. to 1 in. in diameter.

W. D. BAINES replied that unless holes of microscopic size were used, he found that the bubbles were always in this range.

J. N. HINDE pointed out that the upward velocity varies with the size of the bubble. A bubble 35 ft below the water surface is half the size of the same bubble just under the surface.

W. D. BAINES pointed out that it was the volume that was one-half.

J. N. HINDE stated that the bubble size could be controlled so that the rate of rise of the water and hence the melting of the ice could be influenced.

B. LEMEHAUTE stated that a large bubble with a corresponding high velocity has a tendency to split into smaller bubbles. Thus, in effect, the bubbles rise with sensibly constant velocity.

I. W. McCAIG stated that he was pleased to hear Dr. Baines discuss the mechanism of heat transfer. Measurement made at McCormick Dam and reported by Messrs. Clinch, Millman and Erickson in Vol. 3, Proceedings of the IAHR, 1959, indicated that only one-half of the water estimated to be raised by the bubbler actually contributed to keeping the water surface clear.

FIGURE 1 FLOW FIELD NEAR AIR BUBBLER

FIGURE 2 FLOW FIELD DISTANT FROM AIR BUBBLER

FIGURE 3 TYPICAL VELOCITY PROFILE IN THE VERTICAL JET

FIGURE 4
TYPICAL VELOCITY PROFILE IN THE
SURFACE JET

RECENT EXPERIMENTAL OBSERVATIONS ON
THE USE OF AIR BUBBLING SYSTEMS

by

S. Ince

A great number of air bubbling systems have been installed in Canadian waters to melt the ice in winter. As was pointed out by Mr. G. Williams (1) earlier in the symposium, the success of any installation depends upon the thermal reserve of the body of water. Where there is no warm water available, no amount of bubbling will help. The experiments conducted at the manoeuvring basin of the Hydrodynamics Section of the Division of Mechanical Engineering, National Research Council during the winter of 1960-61 were designed to compare various bubbling systems under the same external conditions. This was a pilot installation within a larger program of research on the efficiency of air bubbler installations and was intended to provide experience in outdoor installations and information about temperature changes in the body of water before, during, and after the operation of the bubbler units.

Four different bubbler systems were used. In unit No. 4, the air discharged through a 1/16-in. orifice shown in Fig. 1. This type has been extensively used and recently was investigated by Dr. W. D. Baines (2), and is accepted more or less as the standard bubbler system.

Unit No. 3 consisted of the same 1/16-in. orifice surmounted by a 4-in. diameter pipe (Fig. 2).

Unit No. 2 (Fig. 3) was an inverted syphon (patented by Marine Developments) which collected the air and released it intermittently in large bubbles 15 cu in. in volume. Colloquially, this type is known as a "burper."

Unit No. 1 consisted of a "burper" surmounted by a 4-in. diameter pipe.

The top of the stackpipes, in both cases, was 16 in. below the water surface.

The four units were set in the 400 - by 200-ft manoeuvring basin in the array indicated in Fig. 4. Figure 5 shows the installation of one of

the stackpipe units. Separate 1-in. diameter polyethylene pipe connected the units to a compressor housed in a heated building. The air flow was measured with rotameters (Fig. 6). The outlet pressure from the compressor was maintained at about 20 to 25 psi, but this is only a function of the losses in the system and the desired pressure at the discharge orifice. The discharge pressure was estimated to be about 2 psi above hydrostatic pressure.

Before the air was turned on, the temperature gradient was measured at a number of points in the basin with a thermistor thermometer to an accuracy of 0.02°C . All points had the same temperature gradient shown in Fig. 7. The ice cover at the start of the experiments (24 Jan. 1961) was 14 in. A 7-in. diameter hole was drilled above each unit to allow the air to escape. For the first run the air discharge was 0.144 cfm for all units. This discharge was maintained for four days and each day the area of each hole and the temperature gradient at various points in the basin were measured. To have a consistent measure of the ice melted by each unit the effective edge of the open water was taken where the ice thickness was 1 in. To calculate the heat losses from the body of water to the atmosphere, records of temperature, humidity and wind were obtained from the Meteorological Service of the Department of Transport. For the present discussion, however, they are of no importance since the purpose is to compare various air bubbling systems under identical conditions. The results of these tests are shown in Fig. 8(a). Although the open areas were still growing after four days, the curves tended to flatten out and a valid comparison was possible. From the point of view of melting ice, the "burper" (unit 2) had a somewhat better efficiency than indicated in Fig. 8(a), as can be judged by the profile of the ice layers over each hole (Fig. 9). This cross-section also indicates a more effective circulation of the water, in contrast to units 1, 3 and 4, where the water currents seem to be confined to a thin layer near the surface. It was intended to measure this circulation pattern but the small current meter failed to operate properly in cold water.

The temperature profiles at the end of the experiments at various points in the basin are shown in Figs. 10 and 11. They illustrate clearly that the mixing has effectively spread over the entire basin. Figure 11 also shows that there must be a heat inflow from the bottom. This is not as clearly discernible near the bubbler units because of the more intense mixing in this zone.

The experiments were discontinued and resumed on 6 February with a reduced air flow of 0.072 cfm and with the tops of the pipes set 30 in. below the water surface. The ice cover over the units had grown to 10 in.

The temperature profile in the basin before and after these experiments is shown in Fig. 12. This corroborates the heat recovery from the bottom and shows the trend toward the original stratification in Fig. 7. The results of these experiments are shown in Fig. 8(b). Unit No. 2 is again conclusively better.

The strange behaviour of unit No. 4 can be explained: This unit was kept in operation between 27 January and 6 February with an air flow of 0.015 cfm to prevent damage to the basin walls due to ice pressure. There was a small open area above unit No. 4 when all bubblers were started with 0.072 cfm air flow. Although the area of this original open surface was subtracted when preparing Fig. 8(b), an error here could explain the indicated initial rapid rate of melting. After three days, however, the effective limit of the hole had been reached. Figure 13 shows the four holes on 10 February.

CONCLUSIONS

As stated earlier, the scope of the experiments described in this paper was very limited. There are still a great many variables that may influence the efficiency of operation of one unit or another. For example, the interval between "burps", which is dependent upon the rate of flow of air, may have an effect upon the efficiency. The depth below the water surface of the top of the stackpipes may influence the effectiveness of these units. The depth of water is certain to have an effect. Moreover, the units were not operated for a sufficiently long time for the holes to reach their ultimate size. Despite all these recognized limitations, it is believed that the experiments brought out certain facts and raised certain questions which will be useful in future installations.

Under the conditions of these experiments unit No. 2 with the 15 cu in. bubbler outperformed all the others. It is believed that this is due to the more effective circulation pattern set up. A confirmation of this view should be possible with current meter measurements.

It was also shown that the stackpipe does not contribute, at least in shallow depths, to the effectiveness of the "burper" unit. In fact, it significantly reduces the efficiency. Moreover, the performance of a simple orifice with stackpipe is practically the same as that of a "burper" with stackpipe. This was also corroborated by laboratory experiments. Temperature measurements indicated that the idea of the stackpipe unit drawing the warm water from the bottom and delivering it to the surface without mixing with the intervening layers of colder water is false. The

original temperature stratification is very quickly broken up by the circulation and the temperature gradient in the vicinity of any bubbler installation is zero. There is, of course, despite the 70-ft spacing, some mutual interference of the bubbler units. This will, however, manifest itself more in temperature equalization rather than in perceptible currents interfering with each other's mechanical action. From this point of view, the effect was welcome since it allowed the comparison of the mechanical action of each unit under identical conditions.

REFERENCES

- (1) Williams, G.P. The Thermal Regime of Lakes and Rivers with Reference to the Use of Air Bubbling Systems. (Included in these Proceedings.)
- (2) Baines, W.D. The Principle of the Operation of Bubbling Systems. (Included in these Proceedings.)

DISCUSSION

Dr. Ince was asked if the vertical temperature gradient was the same throughout the tank at the end of the experiment. If so, did this indicate that one bubbler is influenced by another.

S. INCE replied in the affirmative. The main purpose of the experiment, however, was to compare bubblers and therefore he considered that the interaction between the bubblers for the symmetrical layout used could be ignored for these preliminary observations.

P. F. ANDERSON pointed out that the curves which show the open water area were still rising; this indicated that the maximum area of free water would be larger if the experiment had been continued for a longer time.

S. INCE replied that this was true but that the curves were levelling off and would probably remain in the same relative positions.

A. BERGS asked Dr. Ince if his figures showed a cooling of the water during the winter.

S. INCE confirmed that the water cooled when the bubbler was in operation but that the water temperatures increased between experiments so that there was very little net heat loss during the winter. He was not sure where the additional heat came from but thought it possible that it was caused by ground water seepage.

L. W. GOLD asked whether the temperature distribution around the bubblers was more favourable for one than for the other.

S. INCE considered that the distribution, after a short period of operation, would be no more favourable for one bubbler than for another.

W. DOTSON reported that on starting the U.S. Navy System at Thule, the initial bubble was about 3 in. in diameter and he asked Dr. Ince if he had observed similar large bubbles.

S. INCE replied that he had seen this effect but was not sure of the size of the initial bubble.

J. N. HINDE inquired about the length of time after the system was shut down were temperatures taken and whether ice formed over the holes after the bubbler was shut down.

S. INCE replied that the bubble was shut down on 10 February and the open area subsequently froze over. Temperatures were measured up to 25 March.

J. N. HINDE inquired if heat from the ground had any effect.

S. INCE replied that he thought it might, but the heat gained from the underlying bottom material was not measured.

J. N. HINDE suggested that the presence of CO_2 or some other gas dissolved in the water might increase the density to a value even greater than the maximum density at 4°C . This might possibly explain why the temperature of the water at the bottom was higher than 4°C .

L. W. GOLD asked whether a single bubbler had been used the previous winter and whether this one bubbler had affected the whole tank.

S. INCE replied in the affirmative. The experiments of the past winter with the four bubblers had been a start in the sorting out of the various factors involved.

J. N. HINDE inquired about the diameter of the stack pipe.

S. INCE said it was 4 in.

P. SHANKS wanted to know how the orifice diameter had been chosen.

S. INCE replied that they tried a $1/32$ in. orifice that was too small; a $1/16$ in. orifice proved more satisfactory.

J. N. HINDE wanted to know whether the air was oil-free or would include some crank case oil.

S. INCE replied that he used a conventional compressor.

J. N. HINDE said that the conventional compressor was probably lubricated with oil.

Figure 1 Air bubbler unit No. 4.
Simple orifice.

Figure 2 Air bubbler unit No. 3.
Simple orifice with stackpipe.

Figure 3 Air bubbler unit No. 2. "Burper"

FIG. 4

SECTION-AA

ARRANGEMENT OF BUBBLER UNITS
IN THE BASIN

Figure 5 Installation of a bubbler unit.

Figure 6 Rotameter stand for air flow measurement.

FIG. 7

TEMPERATURE GRADIENT IN BASIN
BEFORE AIR BUBBLING EXPERIMENTS

RATE OF MELTING ICE OF BUBBLER UNITS

FIG. 8

CROSS-SECTION OF ICE SHEET OVER EACH BUBBLER UNIT

TEMPERATURE GRADIENT AT EDGE OF HOLE NO. 1

FIG. II

TEMPERATURE GRADIENT AT POINTS C-20 AND C-33

FIG. 12

VARIATION TEMPERATURE GRADIENT AT POINT C-33

Figure 13 View of the area of the 4 bubbling units.

THERMODYNAMIC CONSIDERATIONS ON THE USE
OF AIR BUBBLING SYSTEMS IN SALT WATER

by

E. R. Pounder

Air bubbling systems have been very successful in preventing ice formation in local areas in fresh water lakes and rivers. The principle of the method is to mix warmer water from appreciable depths with surface water to supply the necessary heat. The availability of warmer water depends on the existence of a density inversion temperature of 4°C in pure water, leading to thermocline formation. If salts, in the proportions found in the oceans, are dissolved in water both the freezing point and the inversion temperature are depressed. The inversion temperature decreases more rapidly with increasing concentration, becoming equal to the freezing point of -1.3°C for a salinity of 24.7 ‰*. For salinities greater than this figure a density thermocline will not form, and a still body of salt water cooled by the air will develop convective circulation to maintain a uniform temperature right to the bottom.

These considerations suggest that air bubbling should serve no purpose in sea water. Nevertheless a few experimental installations, such as Operation Polynya at Thule, have shown that air bubbling in salt water can retard or prevent ice formation and even melt an ice cover which has formed. In the Thule experiments the water temperature showed no increase with depth, in agreement with the discussion above. An explanation of the success of air bubbling in salt water must be sought in some secondary effects.

ENERGY SOURCES IN AIR BUBBLING

If we assume a uniform sea-water temperature, a vertical circulation induced by air bubbling, air burping, or propellers might alter the energy distribution in the following ways:

(a) If a salinity gradient exists and $\frac{dS}{dx} > 0$ where x is depth, and S is the salinity, mixing will increase the salinity of the upper layers. Since the heat of solution of the various salts is positive, dilution of a saline solution reduces its heat content. Thus mixing will not alter the temperature but results in increasing the available energy of the surface layers at the expense of the lower, formerly more saline layers, and some ice can be melted. This is the only relevant property unique to sea water.

* ‰ = parts per thousand or grams per kilogram.

(b) In the absence of mixing, the heat losses through the surface rapidly reduce the temperature of a thin surface layer. With complete mixing the same heat is abstracted from a much greater volume of water whose temperature therefore decreases much more slowly.

(c) The air discharged will reach the surface at the water temperature and will form a thin boundary layer which will help insulate the water from the colder air. The importance of boundary layer effects in heat transfer is well known. However a boundary layer will exist without air bubbling. This boundary layer is unstable from the point of view of pressure and exists only because of the viscosity of air. It is hard to see how the layer could be thickened by the air bubbling process whose very nature is to disturb the steady conditions which favour boundary layer formation.

(d) The mechanical energy supplied by the bubbling or other system is converted to heat.

(e) The heat flow from the underlying solid earth will be brought to the surface more rapidly by mixing.

Items (d) and (e) are too small to be of significance. A later calculation will show that a heat removal of the order of 100 calories per square metre per second is to be expected from open water in the Gulf of St. Lawrence area in winter. A most optimistic value for the heat flow from the earth is $0.03 \text{ cal/m}^2/\text{sec}$. Similarly, in a typical bubbler system a 10-hp compressor may keep open an area of 20,000 sq ft. If all the energy is converted to heat this amounts to $1.9 \text{ cal/m}^2/\text{sec}$.

SALINITY GRADIENT

Consider the following example. Take a water depth of 20 m and assume a linear salinity gradient from $32 \text{ }^\circ/\text{oo}$ at the surface to $34 \text{ }^\circ/\text{oo}$ at 20 m. The freezing point of sea water is given by

$$\theta_f(^{\circ}\text{C}) = -5.36 \times 10^{-2} S \text{ (in } ^\circ/\text{oo}). \quad (1)$$

The surface water would thus freeze at -1.72°C and we assume this to be the uniform temperature of the water column. After complete mixing the salinity will be $33 \text{ }^\circ/\text{oo}$ and the new $\theta_f = -1.77^{\circ}\text{C}$. The water column could thus be cooled an additional 0.05 Centigrade degrees without freezing or could melt sufficient ice to reduce its mean salinity to $32 \text{ }^\circ/\text{oo}$ without change of temperature.

Suppose there is an ice cover of specific gravity 0.88 and salinity $10 \text{ }^\circ/\text{oo}$, which are reasonable figures for ice forming rapidly on open sea water in winter. Let x metres of water equivalent of ice be melted. Then

$$x [0.010] + 20 [0.033] = (x + 20) [0.032] \quad (2)$$

$$\begin{aligned} x &= 0.0909 \text{ m} = 9.09 \text{ cm of water equivalent} \\ &= 10.3 \text{ cm thickness of ice.} \end{aligned}$$

All available energy of the water column is now used and further melting of ice and compensation for surface heat losses can only come from a circulation into this zone of more saline water. A very modest circulation of water with the assumed salinity gradient would suffice, but any process for producing and maintaining such a large salinity gradient is difficult to postulate.

WINTER HEAT LOSSES FROM OPEN WATER

The following calculation is based on empirical equations, and follows closely the methods used in NRC Report MD-42 (1) which gives relevant references. Most of the equations use FPS units, with heat losses in Btu/ft²/day. Four terms are considered and the following parameters are assumed:

Air temperature $\theta_a = 0^\circ\text{F} = -17.8^\circ\text{C}$

Water temperature $\theta_w = 28.9^\circ\text{F} = -1.72^\circ\text{C}$

Relative humidity = 50%

Wind speed at 30 ft = 25 mph

Saturated vapour pressure in equilibrium with salt water
at $-18^\circ\text{C} = 0.047$ in. Hg, at $-2^\circ\text{C} = 0.165$ in. Hg.

Evaporation

Using Meyer's formula, the evaporative loss can be found from

$$E = 0.37 (1 + 0.1 V_o)(e_w - e_a) \quad (3)$$

where E is the evaporation in inches per day, V_o the wind speed in mph, e_a is the actual vapour pressure in the air, and e_w the saturated vapour pressure at the water temperature, both in inches of mercury.

$$\begin{aligned} E &= 0.37 (1 + 0.1 \times 25)(0.165 - 0.023) \\ &= 0.184 \text{ in. per day.} \end{aligned}$$

The heat loss owing to evaporation is

$$q_e = 1030 \text{ Btu/ft}^2/\text{day}$$

taking the heat of vaporization as 1075 Btu/lb.

Convection

The convective heat loss q_c can be found from the previous result using the Bowen ratio formula

$$\frac{q_c}{q_e} = 0.0108 \left(\frac{\theta_w - \theta_a}{e_w - e_a} \right) \quad (4)$$

$$q_c = 1030 \times 0.0108 \left(\frac{28.9 - 0}{0.165 - 0.023} \right) = 2260 \text{ Btu/ft}^2/\text{day}.$$

Radiation

This highly variable factor depends on latitude, date, amount of cloud, and even wind speed. For the Gulf region, a reasonable guess is a net loss in winter of the order of

$$q_r = 200 \text{ Btu/ft}^2/\text{day}.$$

Snowfall

A guess is adequate. Take an average loss of

$$q_s = 75 \text{ Btu/ft}^2/\text{day}$$

corresponding to a daily snowfall of about 1 in. per day.

Adding these four losses, the total is

$$q = 3565 \text{ Btu/ft}^2/\text{day} = 113 \text{ cal/m}^2/\text{sec}.$$

THERMAL ENERGY OF WATER COLUMN

If the water column is thoroughly mixed, the heat extracted (of $113 \text{ cal/m}^2/\text{sec}$) comes from a volume of 20 m^3 , using the same example discussed above. Taking the specific heat to be 0.941 (normal sea water at 0°C)

$$\frac{\Delta \theta}{\Delta t} = \frac{113}{20 \times 106 \times 0.941} = 6 \times 10^{-6} \text{ deg C/sec}.$$

Any excess temperature of the water above its freezing point would result in a very considerable time delay before freezing would result. Thus with the assumed, but improbable salinity gradient, $\Delta \theta = 0.05$ and the corresponding time is $\Delta t = 2.3$ hours. More usefully this result can be interpreted in terms of a current. If an open water pool of length 1000 m parallel to the current direction were to be kept open, a mean current of

$$\frac{1000}{2.3} = 435 \text{ m/hr} = 0.4 \text{ mph}$$

would be sufficient.

Even if the water had a uniform salinity and was initially at its freezing point, the rate of ice formation would be at most

$$\frac{113}{55} = 2 \text{ gm/m}^2/\text{sec},$$

taking the latent heat of freezing as 55 calories per gram. Air bubbling would still be useful as this ice would form as frazil. The turbulence would distribute this frazil through a layer of considerable vertical extent and prevent the immediate formation of a continuous ice cover. A small horizontal current would be sufficient to sweep this frazil out of the local area as fast as it was formed. The effect would be to thicken the ice on the down current side of open water.

MELTING OF AN ICE COVER

From the above arguments, air bubbling systems can be expected to maintain an open water pool provided there is sufficient current. The magnitude of the current needed will depend on the extent, or lack, of a positive salinity gradient, on the degree to which turbulent salt water can be supercooled (no information available), and, of course, on the size of the pool to be kept open.

Turning to the melting of an in situ ice cover, the situation is quite different. The heat losses are much smaller because of the greatly reduced evaporation and the insulating action of the cover. There is no use expecting to find any temperature gradient in the water under the cover. This water will almost certainly all be at the freezing point corresponding to its salinity. If the salinity is uniform, it appears that air bubbling should have no appreciable effect in reducing the ice thickness. Mechanical erosion of the lower surface would probably be trivial.

CONCLUSIONS

The use of air bubbling or equivalent systems in keeping limited areas in salt water free of ice presents interesting possibilities, but the method has limitations which should be recognized. In particular, a regular horizontal water exchange is essential, and a positive salinity profile is most desirable. If the salinity is uniform it will probably be easier to prevent ice formation than to remove an existing ice cover.

A trial installation, properly instrumented, is needed. Data on the salinity profile (with the bubbling system off), current measurements, temperature and ice thickness measurements both up stream and down stream, and supporting meteorological information would go far toward allowing quantitative predictions regarding the usefulness of bubbler installations at future sites.

REFERENCES

- (1) Pruden, F.W., Wardlaw, R.L., Baxter, D.C., and Orr, J.L.
1954. A study of wintertime heat losses from a water surface and of heat conservation and heat addition to combat ice formation in the St. Lawrence River. National Research Council of Canada, Report No. MD-42, Ottawa.

DISCUSSION

H. B. HACHEY referred to various observations of supercooled sea water and indicated the difficulty of substantiating these observations. He pointed out that various ocean phenomena have the same effect as bubbling systems and make available large quantities of comparatively warm water. He suggested that, when considering bubbling systems on the Atlantic coast, each area will present a problem of its own and in some cases bubblers may be quite efficient.

A MODEL DESCRIBING THE PHYSICAL PROCESSES OF PROJECT POLYNIA

by

Charles W. Senior
(presented by G. MacDowell)

Successful application, during the fall of 1958, of the air bubbling technique for preventing ice formation enabled the Military Sea Transportation Service to extend the shipping season into the port at Thule Air Base, Greenland. Although the technique had originally been developed in fresh water, an ice free area or "polynya" was maintained adjacent to Delong Pier at Thule harbor despite normal ice formation in the surrounding waters of North Star Bay. Safeguarded against becoming iced-in at the pier, the supply convoy remained at Thule until 25 October 1958, the latest date any MSTS ships had ever operated that far north.

Success of the temporary 1958 installation prompted Commander Military Sea Transportation Service Atlantic Area to formulate plans for a permanently installed air bubbling system to be established at Delong Pier in the fall of 1959. This installation is shown in Fig. 1. The U.S. Navy Hydrographic Office was requested to conduct oceanographic studies in North Star Bay, concurrent with operation of the system, to obtain information on the physical processes impeding ice formation and growth in salt water. The over-all operation was dubbed "Project Polynya".

OCEANOGRAPHIC DATA COLLECTION

Commencing 9 September and terminating 21 October 1959, serial temperature and salinity data were obtained at locations in the vicinity of the pier shown in Fig. 2. The polynya area was designated station 1, while a location situated just off one end of the pier, approximately 15 feet outside the bubbled area, was designated station 1A. Data were collected daily from within the bubbled area through use of a small winch mounted on the pier to lower the thermometers and water sampling bottles. Station 2, located approximately 200 feet from the pier, was occupied through use of a small boat provided by USCGC WESTWIND. Depths at station 1 ranged between 9 and $11\frac{1}{4}$ meters at low and high tide respectively while the depth at station 2 was approximately 25 meters. In addition, several other stations at greater depths further from the pier were made.

Meteorological observations, made daily on Delong Pier, included wind speed and direction, wet and dry bulb air temperature, cloud cover and type, and visibility. In addition, a copy of the weather logs maintained at Thule Air Base was obtained for later analysis.

A supplementary survey was conducted during April of 1960

by ice observers from the Hydrographic Office to determine the late winter temperature profiles at stations 1 and 2. Ice thickness measurements were also made at this time.

A program of oceanographic data collection, similar to that of the previous year, was also conducted during the fall of 1960. Commencing 10 October and terminating 7 November, serial temperature and salinity data were obtained at stations 1, 1A and 2. Station 2 was occupied through use of a small boat provided by USNS REDBUD.

OCEANOGRAPHIC DATA ANALYSIS (SEASON 1959-1960)

The oceanographic structure at each station was examined for factors contributing to the formation and growth of ice. Surface temperatures indicating heat loss at the sea surface and physical properties showing the distribution of heat loss throughout the water column were studied. Data obtained outside the polynya area were compared to those obtained adjacent to the pier to determine the effect of the bubbling system on the oceanographic structure.

The surface temperature at station 1 was found to be 1.53°C with a salinity of 31.26 parts per thousand on 9 September 1959. A pronounced increase in salinity was observed during the latter part of September which was attributed to cessation of fresh water runoff.

By 27 September 1959 the bubble system was fully operative. The compressors were test-run for short periods daily until the first indications of appreciable ice formation were discerned on 6 October. With newly formed patches of pancake ice drifting past the pier, the system was turned on and all ice was quickly dispersed from the agitated area. The compressors thereafter went into permanent operation with but few inactive periods.

By 12 October the surface temperature at station 2 had diminished to -1.42°C while the salinity had increased to 32.32 parts per thousand. The calculated freezing point for water of this salinity, -1.76°C , was attained outside the bubbled area on 13 October while a surface temperature of -1.09°C was observed at station 1.

Concurrent with ice growth the salinity of the underlying water increased with a consequent decrease in the freezing point. Data obtained at station 2 on 26 April 1960 show the entire water column to be isothermal with a temperature of -1.82°C . Similarly the temperature of the isothermal water column at station 1, on the same date, was found to be -1.83°C .

With the bubbling system in operation the data collected during the pre- and initial ice formation periods consistently show the density of the surface water adjacent to the pier to be equal to that found at approximately the 20 meter level outside the polynya area. Evidently the compressed-air bubble system acts as a huge pump capable of doing

work on the contiguous subsurface water. Theoretical ice potential calculations using the data of the deeper stations show that prior to initial ice formation thermohaline convection will take place to a depth of 15.5 meters.* Consequently, the water below this level will temporarily serve as a source of sensible heat. However, as ice forms, the salinity of the upper layer increases resulting in a greater density and an increase in the depth of convective mixing. Finally, cooling to the freezing point will occur throughout the entire water column. At the known average rate of heat loss from the sea surface in the latitude of Thule the entire supply of warmer water at depth will be eliminated within two weeks subsequent to the initial formation of ice.

The effectiveness of the bubbler system with warmer bottom water available is manifest by the temperature data taken on 13 October 1959 (Table 1). The temperature profile obtained just outside the bubbler field at station 1A, shows that the surface had cooled to the freezing point. With ice forming all around the perimeter of the agitated area, the profile obtained at station 1 shows the surface temperature to be 0.67°C above the freezing point. It can be assumed that the data obtained at station 1A indicate the temperature profile that would have been observed at station 1 had the bubbler system not been in operation. The data of 11 and 12 October (Tables 2 and 3) indicate that water from a depth greater than 15 meters is circulated into the agitated water columns adjacent to the pier.

A model, presented in Fig. 3, of the circulation induced within the bubble field was formulated from hydrodynamic principles. With ascending motion there is divergent flow at the surface. Approximately midway between bubble streams a region of convergent flow exists with consequent descending motion. Beyond the outermost pipe, surface flow extends outward to a distance dependent upon the horizontal momentum of the water particles.

The eventual cooling of the entire water column to the freezing point as shown by the April data mentioned previously indicates that vertical transport of sensible heat from depth was not a factor, except during the initial stage of ice formation, in the maintenance of the artificially created polynya. Consequently, an understanding of the physical processes involved must be sought along other lines of approach.

The elementary ice particles are probably disk-like and devoid of crystal form. Ordinarily they flocculate and grow into true crystals. The turbulent energy of the induced currents either break up the crystals before they become large or effectively prevent crystalline growth about elementary ice nuclei. Ice particles at the surface of the bubbled area are rapidly swept from regions of divergent flow into regions of convergence where, with descending currents, they are transported beneath the surface to be eventually dispersed from the polynya area.

Naval ice observers, stationed at Thule Air Base throughout

* In 1958 this depth was computed to be 10.7 m, in 1960 it was 10.1 m.

the winter of 1959-60, observed that as the season progressed the polynya gradually narrowed. By the end of December the polynya width ranged between 12 feet at the eastern end to 50 feet at the western end where an auxillary hose was employed to augment the bubbling activity, inducing a more vigorous current. Dimensions of the ice-free area increased during the spring concurrent with a rise in air temperature to approximately 0°F.

It is well known that sea ice tensile strength shows a marked increase as the temperature of the ice drops below -9.2°F. At this point sodium chloride is precipitated from the brine pockets. With extremely low air temperatures during the winter months the weakest point within the ice should be right at the undersurface where the temperature is close to that of the water.

Measurements made during April of 1960 showed ice thickness directly above one of the polyethylene pipes averaged approximately 10 inches, while thicknesses ranging between 41 and 44 inches were reported for locations 60, 200 and 375 yards north-northeast of the pier. Evidently abrasive action of the induced currents inhibited ice growth in the zone where the flow was most vigorous.

The erosive capability of a stream of fast moving water is manifest by recent accounts received from the Antarctic. Specially shaped propellers driven by small motors were hung through holes made in the ice of McMurdo Sound. The propellers created a vigorous flow that eroded the ice from below. Reportedly, a 10-horsepower device took 183 hours to open an area 30 feet by 85 feet in ice 8 feet thick. An additional swath of ice 200 feet long was undercut to a thickness of 18 inches and soon afterward fell through. Future Products Research, Inc. of Skokie, Illinois developed the system.

OCEANOGRAPHIC DATA ANALYSIS (SEASON 1960-1961)

Initial ice formation in the surrounding portion of North Star Bay occurred at a later date during the fall of 1960 than had been the case the previous fall. The surface temperature at station 1 was found to be -1.54°C with a salinity of 32.30 parts per thousand on 10 October 1960. The bubbling action was started on 14 October. On 15 October a surface temperature of -1.77°C was recorded at station 2 with grease ice forming in the area while a surface temperature of -1.68°C was recorded for the ice-free bubbled area. Except on 20 October, no bubbling occurred from 16 through 29 October. On 29 October a considerable amount of grease and slush ice formed on the bay and the water column at station 1 was essentially isothermal (-1.80°C $\pm$.01) with a constant salinity of 32.82 parts per thousand.

The compressors were turned on the following day and all ice was quickly dispersed from the bubbled area. Observations of light grease and slush ice being swept from regions of divergent flow and transported beneath the surface in regions of convergence confirmed

one aspect of the proposed model of induced circulation. Surface temperature within the bubbled area was -1.82°C .

With the bubbling system in operation the water column at station 1 was found to be isothermal on 6 November with a temperature of -1.83°C and a salinity of 32.96 parts per thousand. The temperature of freezing for water of this salinity is -1.79°C , indicating supercooling. Identical values were obtained at station 1A where a hole had to be broken through the approximately one-inch-thick ice in order to lower the thermometers and water sampling bottles. The bubbled area was completely devoid of ice.

Subsequent history of the polynya was similar to that of the previous winter.

CONCLUSIONS

The compressed-air bubble system operates as a huge pump capable of doing work on the contiguous subsurface water. The rising streams of bubbles initiate a system of circulatory cells which extend from the bubbled region into the adjacent water. Water from depths exceeding 15 meters is circulated into the agitated columns adjacent to the pier and brought to the surface.

At the time of initial ice formation in 1959, convective mixing had occurred throughout the upper 15.5 meters of North Star Bay. Concurrent with ice growth, the density gradient below the 15.5 meter level gradually weakened and the entire water column cooled to the freezing point. With elimination of the supply of warmer water maintenance of an open water area adjacent to the pier was attributed to the ice-dispersive and erosive activity of the induced currents coupled with the probability that turbulent energy of the water particles sufficed to prevent crystalline growth. Efficiency of the system varied directly with the vigor of the induced currents.

By mid-winter the polynya had narrowed considerably. This was attributed to the marked increase in tensile strength as the temperature of the ice dropped below -9.2°F with consequent increased resistance to the erosive action of the induced currents. Vertical growth of the ice cover, newly formed within the bubbled area, was inhibited by the erosive capability of the induced currents acting on the undersurface of the ice where, with its temperature equal to that of the water, the ice is weakest. Concurrent with a rise in air temperature to approximately 0°F , early in the following spring, an increase in the dimensions of the ice-free area was observed. This was attributed to the marked decrease in tensile strength as the temperature of the ice rose above -9.2°F with consequent decreased resistance to erosion.

The unique properties of fresh water make the compressed-air bubble system highly suitable for use in rivers and lakes and to a somewhat lesser extent in brackish estuaries. The fact that for water

of any given salinity in excess of 24.7 parts per thousand the maximum density is attained at the freezing point makes the system less effective for use in salt water. However, factors other than the upward transport of warmer water, as previously discussed, contribute to the maintenance of an ice-free area.

In regions where upward circulation of sensible heat is not a factor, maintenance of an ice-free area is predominantly dependent upon the velocity and intensity of the induced currents. The compressed-air bubble system is not the most efficient method of inducing vigorous vertical currents. In this regard, the tests conducted at McMurdo Sound indicated the marked superiority of the propeller technique.

TABLE 1

13 October 1959

Station 1		Station 1A	
Depth (meters)	Temp. (°C)	Depth (meters)	Temp. (°C)
0	-1.09	0	-1.76
3.5	-1.08	3	-1.60
6.5	-1.06	6	-1.25
9.5	-1.06	9	-1.24

TABLE 2

11 October 1959, Station 1

Depth (meters)	Temp. (°C)	Salinity (p. p. t.)	σ_t
0	-0.90	32.42	26.08
3.5	-0.91	32.42	26.08
6.5	-0.91	32.42	26.08
9.5	-0.89	32.43	26.09

TABLE 3

12 October 1959, Station 2

Depth (meters)	Temp. (°C)	Salinity (p. p. t.)	σ_t
0	-1.42	32.32	26.02
15	-1.42	32.32	26.02
22	-0.69	32.52	26.16
24	-0.78	32.52	26.16

DISCUSSION

F.G. BARBER asked if the water in the harbour is in free communication with the water of Smith Sound.

G. MacDOWELL replied that there are no restrictions. A tidal current exists but probably provides little extra mixing. In any case, this tidal mixing would slow down the freezing not only in the area of air bubbling but throughout the whole area.

F.G. BARBER asked if MacDowell had calculated the change in density which likely occurs through cooling and evaporation at the polyna and the depth to which this water subsequently sinks.

MacDOWELL replied in the affirmative. The depth of mixing caused by cooling plus added salinity due to freezing was given in the paper. Dynamic current calculations, however, based on the density difference between the water under the opening in the ice and the water in the surrounding area were not made.

FIGURE 1. COMPRESSED-AIR BUBBLE SYSTEM AT DELONG PIER

FIGURE 2 NORTH STAR BAY SHOWING LOCATION OF THE POLYNYA PROJECT

FIGURE 3. CIRCULATION PRODUCED BY COMPRESSED—
AIR BUBBLE SYSTEM

OPERATIONAL DETAILS OF PROJECT POLYNYA

by

William A. Dotson

In the fall of 1958 COMSTSLANTAREA was confronted with the task of extending the shipping season at Thule, Greenland, into the freezeup season. Using information obtained from published accounts of successful air-bubble de-icing and ice prevention techniques utilized in Scandinavian countries, United States and Canada, it was decided to attempt the installation of a de-icing system at Thule, Greenland.

As a result of experience in air bubble de-icing and ice prevention in both Sweden and Canada, Atlas Copco Eastern Inc., of Toronto, Ontario, was contacted for advice and technical assistance. Several other possible suppliers of desired equipment were contacted but the necessity of immediate delivery of equipment proved to be a problem. Further, owing to lack of experience, no agency could furnish the technical assistance required. Atlas Copco Eastern, Inc., at Paramus, New Jersey, contracted to furnish all technical and material assistance for initial installation.

Sufficient technical data were obtained in 1958 to encourage the design of a more effective and permanent ice prevention installation at Thule. The installation of such a design was made in 1959, followed by further modification in 1960. The ultimate aim of the Thule installation is to develop a permanent de-icing system to (1) extend the shipping season, (2) prevent ice damage to the DeLong Pier during the winter months, and (3) develop precise formulae for designing such installations for other Arctic ports to suit all conditions.

LOCATION

The DeLong Pier at Thule, Greenland, is located in a portion of Wolstenholme Fjord known as North Star Bay. The bay (Fig. 1) is approximately 3 square miles in area and opens to the west. A narrow peninsula to the north separates the bay from the fjord. Water in the bay is continually mixed with that of the fjord. The DeLong Pier (Fig. 2) is situated at the end of a dirt causeway which extends 0.5 miles northwest from the coastline. The pier, 50 by 1000 ft, is positioned adjoining and parallel to the causeway. Water depths adjacent to the pier range from 30 ft at low tide to 37 ft at high tide. The bottom is a mixture of silt and rocks.

INSTALLATION

All previously known air bubble installations were in fresh and/or brackish water with a temperature differential of from 4 to 7°F between

upper and lower strata of water. It was hoped at Thule that a temperature differential of at least 0.5°F could be found between the bottom and surface in order to assure success. The Hydrographic Office determined that an isothermal condition existed except for the first few days after the initial freezeup. It was thought we could depend upon increased salinity, coupled with an unknown, and as yet undefined, contribution of heat generated by molecular friction.

Air bubbles have a tendency to spread out when rising in water, forming an inverted cone with a diameter at the surface approximately equal to the distance of air travel from the point of emission to the surface. This gave a fair indication as to what the hose and orifice spacing should be, once depth was known, to obtain full surface coverage. Having a depth variable from 38 to 60 ft one would normally conclude, therefore, that hose and orifice spacing should likewise vary. However, not knowing what the surface effect for ice prevention would be, and with no temperature differential, it was decided that the best evaluation could be achieved by maintaining uniform spacing and studying the effect in various depths. It was therefore decided to maintain orifice and hose spacing at 25 feet throughout the de-icing area.

The 1958 air bubble installation shown in Fig. 3 consisted of three 1000-ft hoses. The first hose was installed 15 ft from the steel caissons with the second hose 25 ft from the first. The third hose was 65 ft from the pier caissons. All lines were anchored to the bottom by $1\frac{1}{4}$ -in. wire rope.

In this installation 2-in. rigid polyethylene hose was used in 200-ft lengths. These lengths were spliced together with steel nipples and hose clamps into 1000-ft lengths.

Ideal air delivery for given water depth was considered to be from 0.85 to 1.0 cu ft per min (cfm) per orifice at 80 to 100 psi. To allow for air and friction losses, it was therefore decided to use a $3/64$ -in. diameter orifice with approximately 100 orifices in the initial system. A 125 cfm air-cooled compressor with delivery at 100 psi was used.

Results of this initial installation indicated that (a) although orifice and hose spacing equal to depth would prove full surface coverage, reduced peripheral action allowed some ice growth. It was therefore decided to stagger orifice openings in future installations and for improved ice removal effect to figure hose and orifice spacing at $\frac{1}{2}$ the water depth. (b) The installation accomplished the designed purpose of keeping the pier area open approximately 45 days beyond the normal shipping season. During this period ice outside the bubble area reached a thickness of 12 in.

The rigid polyethylene hose proved unsatisfactory for cold weather installation. The hose becomes brittle when exposed to outside air temperatures and fractured easily.

During September 1959 a redesigned air bubble system was installed at Thule. Four lines of heavy-duty flexible cold weather polyethylene hose were installed in 1000-ft lengths and pre-sealed at one end. This was done to overcome problems experienced with fittings in the 1958 installation, to expedite handling, and to reduce air losses in fitted joints. This hose, 0.824-in. inside diameter and 1.082-in. outer diameter, was rated at 150 psi capacity. The open end of the polyethylene hoses was joined to heavy-duty two-braid, abrasion-resistant, low-temperature neoprene air hoses (to eliminate hose blow outs experienced in 1959); these hoses, in turn were joined at the water's edge to $1\frac{1}{4}$ -in. rigid steel pipe, which ran underground to the compressor house. Brass couplings were used for all connections to maintain positive coupling and reduce air leakage.

Four 1000-ft lengths of 1-in. diameter polyethylene hose (each anchored to $\frac{3}{4}$ -in. diameter wire rope) were installed parallel to the DeLong Pier shown in Fig. 4: line No. 1 2 to 6 ft from the caissons, line No. 2 20 ft from line 1, line No. 3 20 ft from line 2, line No. 4 20 ft from line 3. The orifice spacing in lines 1 and 2 were 15 ft apart and 30 ft apart in lines 3 and 4.

All orifices were $\frac{3}{64}$ -in. diameter with orifices in each line staggered with respect to adjacent lines. This was done to reduce the stable area created at the peripheral zone of each orifice.

A second 125-cfm 100-psi compressor was added to take up the additional load.

Two test lines were also installed. Line No. 5 located 300 ft seaward from the outer edge of the pier contained one $\frac{3}{4}$ -in diameter opening. This line was used to test the effect of large volume air discharge. Line No. 6 extended 700 ft seaward from the edge of the pier and contained six test orifices spaced 100 ft apart. Specially designed baffle plates were fixed to the first four orifices. Line breakage prevented testing of baffles under ice removal conditions.

An alcohol de-icing system was included in the air bubble installation to allow easy injection of alcohol to iced lines. It was discovered in the 1958 operation that, under conditions of high pressure or warm air temperatures, orifices would ice up and that the introduction of alcohol into the system was needed for quick removal of the ice. The alcohol system consisted of a 60-gallon tank with copper tubing connections to each $1\frac{1}{4}$ -in.

rigid steel pipe. Valving was designed to provide for either slow or fast feed (35 gallons per 24 hours for all lines or 7 gallons per minute for a single line respectively). It was generally observed that at fast feed, an injection period of one to three minutes was sufficient to open an iced line.

To protect the neoprene feeder hoses from ice damage they were encased in a 10-in. diameter flexible fuel hose. This protecting hose extended above and below the tidal change.

The 1960 installation is generally the same as that of 1959 except that line No. 4 was relocated inside the caissons and crosses over lines No. 1, 2 and 3 at caisson No. 4 shown in Fig. 5. A break occurred in line No. 4 at this point and only the first 200 ft is usable. In addition a 125-gallon accumulator tank was installed to help maintain a steady flow of pressure throughout the system, provide a means for compressor cycling and to serve as a collection point for moisture. Pressure and temperature gauges were also installed to record changes in the system.

A pressure of 60 to 65 psi is maintained with two compressor operations. Air temperature at the accumulator tank ranges from 140 to 190°F and drops to 80 to 100°F at the connecting joint of the $1\frac{1}{4}$ -in. steel pipe and feeder hose located 80 ft from the compressor hut.

OBSERVATIONS

During the 1958 operation 250 ft of $\frac{3}{4}$ -in. diameter air hose was lowered through a 6-in. diameter hole cut in 6 in. of ice; the hose was anchored at a depth of 50 ft. Twelve hours later an opening 8 to 10 ft in diameter was observed and large air pockets (ice domes) had formed beneath the surrounding ice. A series of ice domes covering an area approximately 100 ft in diameter was supported by air and separated from the water surface by about 10 in. at the centre of the domes. The air domes remained after their source of air was cut off. Ice thickness measurements the next day showed that although ice thickness increased in the surrounding area no measurable growth developed in the air domes.

During periods of heavy or blowing snow, or short periods of power outage, a thin layer of ice crust forms over the bubble area. Air pockets or ice domes will form over each orifice area when air is applied. Should these domes exceed $\frac{1}{2}$ in. in ice thickness the bubble system usually cannot melt away or break through the domes. Under this situation the ice thickness slowly increases around the peripheral zone of each dome covered orifice area. Only an increase in the air temperature or manual breakup of the domes will clear the area of ice. Once the air is removed, the dome lowers to water level and melting action resumes.

It was observed that although ice will grow within the bubble area when the latter is covered by ice domes, the rate of growth is one-third that of surrounding areas. Observations for three years bear this out.

In November 1959 while repairing a break in line No. 1 it was observed that ice inside the polyethylene hose had reduced the inner diameter to approximately $\frac{1}{4}$ in. Prior to repairing the hose approximately 20 ft of the hose was exposed to an outside air temperature of -20°F , it is assumed that the condensate produced by the air compressor froze to the inner walls of the hose in the exposed area.

During the same repair it was observed by watching an orifice located near the surface that a hollow cone-shaped icicle formed over the orifice to a length of $\frac{1}{4}$ to $\frac{1}{2}$ in. It was assumed that the condensate discharged through the orifice was fresh water and froze on contact with the cold temperature of the sea water (28.2°F). Further inspection showed that these ice icicles are common for all orifices in water temperature below 32°F .

Icing usually occurs in the lines when a pressure of 80 psi is reached or exceeded. It will also occur when the outside air temperature remains about 0°F . Since the installation of accumulator tank and scheduled drainage of condensate the icing of lines has greatly reduced. Systematic injection of alcohol, usually once a day, will eliminate icing of the lines. Icing at temperatures below 0°F seldom occurs.

Not all orifices in a given line will ice up and icing will occur at random throughout a line.

Average pressure during the three years of operation of all lines varies from 30 psi for one compressor to 55 to 95 psi for two. With the installing of the accumulator tank two-compressor, continuous operation has averaged 60 to 65 psi.

In the three years of operation the system has delayed the initial freezeup in the designed area an average of 45 days. After the initial freezing (usually caused by short periods of power outage or by surrounding ice moving into the area) the system will retard ice growth within the designed area to one-third that of normal ice thickness. This ratio is observed throughout the winter. It should be pointed out that even after the initial freezeup the system has periodically removed up to 75 per cent of the ice in the designed area. On one occasion between 4 and 8 January 1959 with air temperatures ranging from -18°F to $+10^{\circ}\text{F}$ with ice thickness in bubble area 12 in. and 25 in. outside the area 75 per cent of the ice was melted away. Power outage on 9 and 10 January allowed refreezing to 4 in. in the bubble area.

The main function of the present system has been to create a buffer zone between the fast ice and the caissons. In years prior to the system heavy pressure ridges formed at and under the DeLong pier causing damage to the caissons. The bubble system, by reducing and weakening the ice in the area of the pier, has greatly reduced these pressure ridges. Ridges which have formed soon topple over due to undermining by the bubble system.

In 1959 and 1960 by the end of April with continuous daylight and above 0°F temperatures the polynya has slowly removed ice from the designed area and by 15 June the area was ice free as shown in Fig. 6.

CONCLUSIONS

Under stable conditions with initial formation of fast ice outside the bubble area not breaking up and drifting into the bubble area and with no power outages, it is thought that the present polynya system could maintain open water at the pier at Thule. But the present design does not have built into it any reserve power to overcome the freezing resulting from electrical failure.

It is estimated that a system with the same spacing of lines Nos. 1, 2, and 3, but relocating line No. 4 inboard the caissons, with 1/8-in. diameter orifices at 15-ft intervals would keep an area of 30 by 1000 ft ice-free throughout the winter. This, of course, would require approximately 5 cfm per orifice. Either a single compressor or multiple compressor delivering 1600 cfm would be required for the system. Hose sizes would, of course, require redesign accordingly.

DISCUSSION

T. A. HARWOOD suggested that there was a possibility that the system at Thule was successful because warmer and more saline water occasionally flushed into Thule Harbour from outside.

FIGURE 1 NORTH STAR BAY

- 65 -

SOUNDINGS MADE AT MEAN LOW TIDE
SOUNDINGS IN FEET

FIGURE 2 SOUNDINGS AREA DELONG PIER

FIGURE 3 1958 INSTALLATION

FIGURE 4 1959 INSTALLATION

	LINE SPACING FROM PIER	ORIFICE SPACING
LINE # 1	2-10 FEET	15 FEET
LINE # 2	15-20 FEET	15 FEET
LINE # 3	40-45 FEET	30 FEET
LINE # 4	70-73 FEET	30 FEET

FIGURE 5 1960 INSTALLATION

2 NOVEMBER 1960

ICE FREE

DE LONG PIER

22 MARCH 1961

3 MAY 1961

FIGURE 6 POLYNYA COMPARISON DATA 1960-1961

DESCRIPTION OF AIR BUBBLING SYSTEMS
AT CAMBRIDGE BAY AND TUKTOYAKTUK N. W. T.

by

T. M. Dick

Owing to their remote location, wharves in Arctic waters are costly to repair when damaged by ice. To combat this, the Harbours and Rivers Branch (Department of Public Works) has installed pneumatic de-icing systems at Tuktoyaktuk, at the mouth of the Mackenzie River, and at Cambridge Bay on the southern shore of Victoria Island. It is hoped that the air bubbles will prevent thick ice freezing to the piles and lifting them as the tide rises. Open water is not necessary to prevent uplift. It is sufficient to reduce the thickness of the ice so that it will fail before the pile is lifted.

TUKTOYAKTUK (TUK-TUK) INSTALLATION

In September 1959 a plastic perforated pipe, 1 in. in diameter, was laid around the perimeter of the wharf and attached to a 155-cfm compressor. Another compressor of the same capacity was supplied to provide continuity in case of breakdown. Most of the details of this installation can be seen in Figure 1(a) and (b). The compressor was set initially to discharge 124 cfm but this was shortly increased to 155 cfm which is an average of 2.46 cfm per hole. Joints in the polyethylene plastic pipe were made by metal inserts with clamps. Although this joint has the disadvantage of reducing the size of the pipe, no failures have been reported so far. No allowance was made in the hole spacing of 8 ft for changes in the depth of water which varies from 10 to 18 ft. The tide is quite small and has a range of about 1 ft, but wind set up may cause much larger changes in water level.

CAMBRIDGE BAY

A different type of air bubbler was placed at Cambridge Bay on 23 October 1960. This consisted of three patented units (dubbed burpers) placed in front of the wharf as shown in Figure 2.

These units have a special nozzle, placed at the bottom of a vertical 1-ft diameter plastic pipe. This nozzle emits at intervals of several seconds a large bubble of air. As the bubble rises up the pipe, a flow is induced carrying water at the bottom to the surface. In the beginning this installation was equipped with a 15-cfm compressor driven by an electric motor. A diesel driven standby unit of the same capacity was also installed. This system was unable to prevent ice formation and by the beginning of November the burpers were frozen over and the main ice sheet was 17 in. thick.

On 8 December, the diesel-driven compressor was replaced by another electrically driven compressor having a capacity of 32 cfm. Holes were broken through the ice to allow the air to escape. Mr. A. H. Laurie, a Director of Penumatic Breakwaters Limited, set each burper himself to discharge "burps" at intervals of 4.5 seconds and hence each burper consumed slightly more than 10 cfm. From all reports the holes in the ice did not persist but soon froze over. However, it is difficult to say just exactly when this occurred owing to drifting snow filling the holes. Certainly by 20 April when Dr. Simon Ince, N.R.C. and the writer visited Cambridge Bay, there was 4 ft-6 in. to 6 ft of ice along the face of the dock. Humps in the ice were reported by the operator at each of the burper locations. In April the main ice sheet was 6 to 7 ft thick.

The tidal range at Cambridge Bay, as at Tuk-tuk, is not great being about 1 ft range.

EFFECTIVENESS OF INSTALLATION

Some idea of the weather at Tuktoyaktuk can be gained from the diagram prepared from the operator's weekly reports (Figure 3) and it may be assumed that similar weather is experienced at Cambridge Bay.

The Tuk-tuk bubbler has been quite effective, maintaining thin ice 9 to 12 in. all around the wharf often with open spots throughout the winter. Any snow drifting and arching over open water was left to provide insulation. A few notes on the progress of the bubbler over the winter (1959-60) are also shown on Figure 3.

Cambridge Bay burpers appear to have been unable to cope effectively with the ice. Indeed, one of the piles has been lifted 6 in. this winter. The failure of the burpers to melt the ice is probably due to the site conditions. Indications are that the water at Cambridge Bay has a salinity of 2.9 per cent with a temperature of 29°F whereas at Tuk-tuk the salinity is 0.5 per cent and temperature close to 32°F. While the water at

Cambridge Bay is definitely salt, the water at Tuk-tuk is no more than brackish. The salt content at Cambridge Bay allows the water to be cooled to a low temperature and the heat available is not sufficient to raise the ice to its melting point. Melting of the ice is further hindered because ice forming on salt water tends to be fresher and may have a melting point above the temperature of the water. The Tuk-tuk installation may also be helped by "warmer" water brought down by the mighty Mackenzie River.

COMPARISON OF BUBBLERS AND BURPERS

Generally speaking, a bubbler system is very easy to install and maintain. If repairs are needed, this can be done with a length of plastic hose, some couplings and an electric drill. The burpers are more complicated, and not so easy to repair.

Regulation of the bubbler is by one or two valves, whereas each burper requires its own regulating valve and supply line. It was estimated that 15 burpers would be required to protect Tuk-tuk. This means 15 valves and 15 separate supply lines. The bubbler uses one valve for each perforated pipe.

Burper units must be removed in the Spring to prevent damage by shipping and replaced in the Autumn. There is no urgency with the bubbler as ships can sail right over it. This is quite important where the units are in remote areas.

The area of ice melted by a burper is circular which is not easily adaptable to protecting the face of a wharf. The perforated pipe is easier to apply in this case.

OPERATING DIFFICULTIES

Apart from breakdowns in the diesel-driven compressors, the bubbler at Tuktoyaktuk has been singularly free from troubles. Joints in pipes have remained firm and freezing of the air lines has not occurred. In the Autumn, at the beginning of the bubbler operation, a number of holes in the pipe become plugged. However, they seem to clear themselves later and this trouble does not recur over the winter. It is thought that conditions in the Autumn are suitable for formation of ice in the holes owing to adiabatic expansion of the air. It is not known why they should clear later in the winter.

Ventilation of the diesel engines at Tuk-tuk proved to be a problem, as air must be allowed to enter without allowing the hut to fill with snow. Details of the vents are indicated in Figure 1.

Electrically driven compressors where power is available as at Cambridge Bay, are much cleaner and easier to maintain. Starting difficulties and freezing of fuel lines and fuel is avoid. Control is simple and a mechanic is not required to maintain the equipment.

A review of the operator's reports from Tuk-tuk shows that radiator troubles are quite frequent. It may be preferable in Arctic regions to use air-cooled motors and compressors. Maintenance costs could possibly be reduced by using larger compressors and running them at two thirds of their capacity.

Since the ice sheet at Cambridge Bay is thicker than the clearance allowed from the top of the stand pipe to the surface of the water, failure of a burper may result in its becoming embedded in the ice. This could be avoided by shortening the pipe, a procedure which tends to defeat the object of having a pipe over the burper. Water vapour freezing in the supply lines, eventually blocking them could be avoided by either extracting the moisture from the air at the intake or by introducing anti-freeze (alcohol or ethyl glycol) into the line. Either solution is desirable.

COSTS

Costs will not be discussed here, as they are of little general use owing to the remote location of the air de-icing systems. Let it suffice to say that maintenance and operation only of the bubbler at Tuk-tuk cost \$7,000.00 for the winter of 1959-60. A breakdown of costs for Cambridge Bay is not yet available.

DISCUSSION

T. A. HARWOOD pointed out that temperature and salinity measurements are very difficult to make in winter and that most individuals without experience do not recognize the pitfalls. Thus persons who wish to make such measurements might do well to consult oceanographers or someone familiar with taking such observations under extreme winter conditions.

PLAN

NOTE

COMPRESSOR HOUSE

WOOD FRAME CONSTRUCTION 16' x 20' WITH 8' CEILING
 FOUNDATION - WOOD PILING
 FLOOR - 4" x 8" JOIST AT 24" cc ON 8" x 12" PILE CAPS
 INSULATED WITH 3" OF FIBRE GLASS 2" T and G FLOORING
 WALLS - EXTERIOR SHEATHING $\frac{1}{2}$ " PLYWOOD
 INTERIOR $\frac{1}{4}$ " PLYWOOD, 3" FIBRE GLASS INSULATION
 CEILING - SHEATHED $\frac{1}{4}$ " PLYWOOD 3" INSULATION
 ROOF - SHEATHED $\frac{1}{2}$ " PLYWOOD 210 LB ASPHALT SHINGLE
 ELECTRIC GENERATORS - SUPPLY POWER FOR LIGHTS IN THE COMPRESSOR HOUSE, LIGHTS AND HEATER COILS IN THE TIDE GAUGE STATION

NOTE

ADDITION TO ORIGINAL SYSTEM

- (1) A $\frac{1}{2}$ " LINE WITH CONTROL VALVE TO METER 1 TO 3 BUBBLES PER SECOND INTO THE TIDE GAUGE WELL.
- (2) A $\frac{1}{4}$ " LINE 650' LONG WAS LAID FROM THE COMPRESSOR HOUSE TO THE OIL DOCK TERMINATING ALONG THE FACE OF THE DOCK. FOUR $\frac{1}{32}$ " HOLES SPACED AT 8' cc PROTECT THE STRUCTURE. THIS LINE HAS A CONTROL VALVE.

FIGURE 1 (a) COMPRESSOR HOUSE DETAILS

FIGURE 1 (b) INSTALLATION ALONG WHARF

BURPER LAYOUT

SKETCH OF COMPRESSOR HOUSE

FIGURE 2 INSTALLATION AT CAMBRIDGE BAY

FIGURE 3 AIR TEMPERATURE AND ICE THICKNESS AT TUKTOYAKTUK, WINTER 1959-60

INVESTIGATION OF A COMPRESSED AIR BUBBLER SYSTEM USED FOR ICE MELTING

by

W. D. Bonisteel and A. Bergs

Rainy Lake is the main obstacle in the path of a highway between Atikokan and Ft. Frances, Ontario. When completed, the Rainy Lake Causeway will carry the highway across the lake providing a direct route for traffic between the two centres.

Two islands in the lake divide the causeway into three separate bridge sections. The two easterly spans support the highway about 15 ft above the water and are together known as the low-level section. The westerly spans are elevated to accommodate logging and navigational operations on the lake and are referred to as the high-level section.

To limit the effect of ice pressure on the steel piles supporting the superstructure a "bubbler" system will be utilized. The first portion of the bubbler system was installed during December 1960. The remainder of the system will follow construction of the high-level section of the causeway.

The purpose of the investigation was to collect information on the de-icing system as installed on the low-level section of the Rainy Lake Causeway. The data obtained from the experiments with this system are correlated with those of other installations as recorded in the technical literature. It is expected that this information will be useful for the design of the remainder of the bubbler system on the Causeway. It is also intended to provide design information for bubbler systems in general.

The low-level section of the Rainy Lake Causeway consists of two bridge sections 1800 ft and 450 ft long, separated by an earth embankment 1196 ft long. Figure 1 shows this section of the Causeway in elevation, with a detail of the arrangement of the air pipes at a typical group of piles. The 1800-ft section of the bridge contains piers E-12 to E-29 inclusive and the 450-ft section contains Piers E-32 to E-35 inclusive. A temporary compressor was located on top of the concrete pier cap on Pier E-12, with the air supply hose leading straight down into the water.

The "low-level" part of the de-icing system was designed to maintain an ice-free area of 600 to 800 square feet around each pier (see plates 1 and 2). This was to be achieved by discharging compressed air at approximately 45 psig through orifices located in pipe at 25 to 35 ft below the water surface. Two orifices per pier were provided each discharging 1.7 cfm of 36°F air expressed in terms of atmospheric pressure. The

tests described below were started on January 24, 1961. The system had been in operation previously from December 12, 1960 until January 10, 1961. During this time an area 70 ft in diameter had been melted in the ice, (see Fig. 2 and plate 3). It is assumed that equilibrium conditions had been reached at this stage as the openings remained constant during the latter week of observation.

At the start of the tests the ice was 13 in. thick where it had been melted previously and over 2 ft thick elsewhere. As the compressor was started up (at 3.45 p.m.) the air pressure increased to 70 psig, and the compressor unloaded. It cut in again when the pressure in the receiver tank (and the air pipe line) dropped to 60 psig. The submerged air line was mostly full of water. Bubbling action started at the pier nearest to the compressor approximately 20 minutes later (at 4.05 p.m.). As time went on and the air pipe was cleared of water, bubbling action became apparent at the subsequent piers. On January 26, 1961, 10 a.m., bubbling action was observed at all piers on the 1800-ft portion of the bridge, and the compressor was in constant operation, supplying air at a pressure of 42 psig. The system is provided with a water outlet valve at the far end of the line but due to some obstruction in the pipe it was made ineffective. Further investigation will be carried out by the local FENCO staff to ascertain the feasibility of "blowing" the main air pipe clear of water by opening up the pipe at the far end of the 1800-ft section.

The quantity of air escaping through the nozzles was measured at both ends of the 1800-ft section and was found to be as follows:

When the main air line pressure at the compressor was 40 psig, 2.82 cfm escaped through each of the 1/16-in. diameter nozzles at the near end (Pier E-12) and 2.35 cfm at the far end of the 1800-ft section (Pier E-29); at 25 psig in the main air line (and 22 psig at the far end) the air quantities were 2.2 cfm at Pier E-12 and 2.1 cfm at Pier E-29. Thus the outlet air quantity can be varied by adjusting the pressure of the supply air. As the size of the opening in the ice is directly dependent on the air quantity, it is possible to obtain the desired ice-free area by adjusting the air pressure. With this in mind, flow tests were made with nozzles of 1/32 to 1/16 in. diameter, and pressures ranging from 5 psig up to 50 psig. The results are shown in Figs. 3 and 4.

In order to find the heat content of the water available for ice melting, the lake temperature was measured at points vertically down to 32 ft below the surface. The resulting temperature gradient is shown in Fig. 5. This graph also shows as a comparison, temperature gradients obtained by others and recorded in the technical literature (1, 2). It should be noted that the temperature gradient is somewhat different for deep waters

(100 ft or more) and shallow waters (less than 100 ft in depth. The lake bottom under the low-level section of the bridge consists of clay, and it was found that this clay is warmer than the water directly above it by approximately 1°F . In a deep lake the large volume of bottom water surrenders heat constantly to the surface layers. In a shallow lake there is no such heat reservoir. The clay on the bottom is not a good heat conductor and the heat of the earth is not transmitted readily to the water. Hence the difference in the temperature gradient between deep and shallow lakes. If the lake bottom were rock, which is a slightly better conductor of heat than clay or mud, there might be some difference in the water temperature.

Thus in the design of a bubbler system, if the actual water temperature gradient is not available, a close estimate can be obtained from recorded data, always taking into consideration the actual depth of the body of water which is to be used as the heat source. It should be emphasized that the lake water temperature is affected by currents, wind action, etc., before the build-up of ice cover. Hence the lake water temperature may vary considerably for different winters (2).

During the test it was observed that the bubbles were rising to the surface at a velocity of approximately 2 fps, in a column 8 in. to 12 in. in diameter. This column was observed to bend and change its position continuously within a radius of 12 in. from the outlet nozzle as shown by Fig. 6. The path did not seem to be affected by the piles, i. e., no bubbles adhered to the piles on their travel upward. Water was brought up to the surface at a velocity sufficient to push it $1\frac{1}{2}$ in. above the surface at times. The water elevated by the bubbles was of a temperature equivalent to that found at the level of the air outlet nozzle in the water body, i. e., the water was coming up in a column from the bottom of the lake as through a pipe, without mixing noticeably with the surrounding, relatively cooler water near the surface. On reaching the surface, this water flowed radially outward some 10 to 15 ft without any noticeable drop in temperature. At a radial distance of 20 ft the outward flow was hardly noticeable, and the surface water temperature was reduced by $\frac{3}{4}^{\circ}\text{F}$ to 1°F . It was observed that wind action can move this water within the ice-free area quite readily and so enlarge the area (2). The ice immediately surrounding the ice-free area is quite thin for some distance from the edge. There is usually some flow of water directly under the ice sheet. As the surrounding ice is usually covered with a blanket of snow which is a fairly good insulator, comparatively small amounts of heat in the water will reduce its thickness.

At the start of one of our experiments the ice was 13 in. thick. In 24 hours of bubbling action, the thickness was reduced to 8 in. at the bubble bursting point (a point on the water surface directly above the outlet nozzle) (see Fig. 6).

In this system, the piles introduced a complication not normally encountered. As the underside of the ice sheet was melted, the water and ice surfaces became separated (the ice forming a bridge between the piles). This hollow filled with air and as the water only rises about $1\frac{1}{2}$ in. above the surface at the bubble bursting point, the ice remained 8 in. thick during a one week period of observation. (See Fig. 7). At some piers the ice sheet was deliberately cut at a point somewhere amid the piles to let the accumulated air escape. In all such cases the 8 in. to 9 in. thickness of ice was melted around the hole, over an area 10 ft in diameter, within 24 hours (see Fig. 8, and plates 4 and 5). At two piers there were cracks in the ice of sufficient size to let air escape in quantity. These cracks produced the same effect as the chopped holes described above.

From the foregoing it can be concluded that this particular system cannot be depended upon to open up the ice around the piers if the ice cover has reached a thickness of 6 in. or more before the system is started up. The system will, however, prevent the ice from increasing in thickness and causing any damage to the structures.

In some installations of bubble systems problems with ice closure of the air outlet nozzles have been experienced (3). The information as to how and exactly where this build up of ice occurs has been vague. In the installation investigated here no ice build-up was observed in the main air-supply pipe, nor were any of the nozzles blocked by ice build-up. When the nozzle was allowed to discharge to the atmosphere, no ice was formed on the tip. The air escaping through the nozzle was cooled down to 0°F to -5°F when the inside temperature was approximately 55°F to 60°F and inside pressure 40 psig. When this same nozzle was immersed in the water, ice started to build up immediately around the escaping air stream, firmly attached to the nozzle (see Fig. 9, and plate 6).

The ice increased in porosity as it grew in size. The full size as shown in Fig. 9 was obtained in approximately 2 minutes, after this the ice deteriorated in density and strength until large chunks were blown off. When this happened, new ice started forming again and the cycle repeated. This build-up of ice had no noticeable retarding effect on the air flow through the nozzle.

It appears to the writer that sufficient information has been gathered, both through literature and experiments, to enable the designer to choose with reasonable accuracy the right air quantity for the required size of opening in the ice sheet. The problem yet to be solved is that of clearing the air-supply pipes of water in a short time, say 2 to 3 hours. This may take up to a week with a long supply pipe and no special provision for water expulsion. As the obstruction in the pipe around island No. 2

did not allow for testing the efficiency of the existing method of water expulsion through the end valve, several other methods were discussed, the most attractive being the double pipe system. This would require a $1\frac{1}{4}$ -in. pipe back to the compressor house from the far end of the main bubbler pipe. Both the main supply pipe and this return pipe would be connected to the receiver tank in such a manner that air could be forced into either one, or both, at the same time. It is expected that by blowing through the return pipe, with the main pipe open to the atmosphere at the compressor house, the water would be forced out through the opening in the main pipe. This action could be conveniently observed by an operator starting up the system without leaving the compressor house. When air starts coming out, indicating that most of the water has been expelled, the main pipe would again be connected to the receiver tank, and compressed air forced through both pipes.

Another, more expensive method, would be to provide each of the three sections (one high level and two low level) of the system with a separate supply pipe. Both these suggestions require extra pipe. Subsequent tests with the present system and the pipe cleared of obstructions may show that there is no need for water removing apparatus other than the end valve. The double pipe system, however, does seem to be a convenient arrangement and the extra cost is only a few per cent of that of the whole system. A system in which the main air-supply pipe remains dry at all times might be investigated. The water expulsion equipment would then be superfluous.

This report is a summary of general observation and test data obtained during the winter 1960-1961, with the bubbler system described above. (Plates 7, 8 and 9 show some general views of icing at this particular installation.) It is intended to contribute some practical observations to the existing information on bubbler systems recorded in the technical literature. The references are used to compare the test data with those of similar tests conducted by others.

REFERENCES

1. Cousineau, J.E. Some Aspects of Ice Problems Connected with Hydro-Electric Developments. Engineering Journal, March 1959, p. 50-54, and p. 88.
2. Williams, G.P. Winter Water Temperatures and Ice Prevention by Air Bubbling. Engineering Journal, March 1961, p. 79-84.
3. Personal communication with Foundation Company of Canada Staff at Fort William, Ontario.

4. Flow of Fluids Through Valves, Fittings and Pipe by Crane Ltd.
Technical Paper N. m-409, November 1950, p. 86.

BIBLIOGRAPHY

- "Frazil Ice ... A Review of its Properties, with a Selected Bibliography"
by G. P. Williams. The Engineering Journal, November 1959,
p. 55-59.
- "Ground Temperature Investigations in Canada" by C. B. Crawford and
R. F. Legget. Engineering Journal, March 1957, p. 263-269.
- "Bubble Bubble No Trouble" by "Staynew Filter Facts". Compressed
Air Magazine, March 1960, p. 23.
- "Thwarting Ice Pressure With Air Bubbles" by R. G. Skerrett. Compressed
Air Magazine (Volume Unknown).
- "Safeguarding a Dam Against Harmful Ice Pressures" by R. G. Skerrett.
Compressed Air Magazine, January 1923.
- "Air Bubbler System Maintains Open Channel in Ice Sheet" by P. M. Hees.
Electrical World, March 9, 1953.
- "Safeguarding Hydro Plant Against the Ice Menace", by Paul E. Gisiger.
Civil Engineering, January 1947.
- "The Prevention of Ice at Hydraulic Structures" by P. J. Bier, Water Power,
May 1954.
- "Air Bubbles Keep Sawmill Log Pond Free of Ice". Ingersoll-Rand Co.
Stationary Compressor Manual, September 1, 1951.
- "Can Bubble Machine Keep Seaway Open?". The Toronto Daily Star, Friday,
January 22, 1960, p. 25.
- "Battling with a Bubble Gun", by A. H. Laurie. Compressed Air Magazine,
January 1961, p. 26-29.
- "De-icing Test Rig. Roches Point, Lake Simcoe, Ont.", by B. R. Cauthery.
Beardmore and Co. Ltd.
- "Can We Break the St. Lawrence Ice Barrier?", by William Eccles.
The Star Weekly Magazine, April 16, 1960, p. 20-23.

"Snow Density and Climate" by G. P. Williams and L. W. Gold. Transactions of the E. I. C., Vol. 2, No. 2, May 1958. p.91-94.

"Frazil Ice and Flow Temperature Under Ice Covers", by Ernest Pariset and Rene Hausser. Engineering Journal, January 1961, p.46.

"The Preparation of Ice Landing by Pulp and Paper Companies in Eastern Canada", by L. B. Rose and C.R. Silversides. Transactions of the E. I. C., Vol. 2, No. 3, September 1958, p.101-107.

DISCUSSION

T. A. HARWOOD asked if it was intended to keep the system at the Causeway in operation for 40 to 50 years and questioned whether it was economical to design a bridge that needed bubblers for protection.

A. BERGS replied that it might not prove necessary to keep the bubblers operating indefinitely. The bridge is designed to tolerate some lateral movement. During some winters the ice movement may be within this tolerance, and hence the system need not even be started.

J. N. HINDE cited the case of a system that protected a railway trestle bridge and used less than one-half horsepower for two trestles.

FIGURE 1A DE-ICING SYSTEM GENERAL ARRANGEMENT

FIGURE 1B TYPICAL AIR OUTLET ARRANGEMENT

FIGURE No. 2

CLEAR OPENINGS IN ICE SHEET USING
3.8 CFM OF AIR PER PIER. OUTLET NOZZLES
LOCATED 19' TO 31' BELOW WATER SURFACE.
DEC. 1960 & JAN. 1961 AMBIENT TEMP 15° F AVE.
DOTTED LINE SHOWS APPROX. CLEAR OPENING
USING 1.8 CFM OF AIR PER PIER AT AMBIENT
TEMPERATURE OF -5° F AVE.

LEGEND :

- MAIN AIR SUPPLY PIPE
- BRANCH AIR SUPPLY PIPE
- ⊙ OUTLET NOZZLE LOCATION (2 PER PIER)

FIGURE 3

RATE OF DISCHARGE OF AIR THROUGH NOZZLES OF VARIOUS SIZES

FIGURE 4
RATE OF DISCHARGE OF AIR THROUGH NOZZLES OF VARIOUS SIZES.

FIGURE 5

TEMPERATURE GRADIENT CURVES FOR ICE COVERED
BODIES OF STILL WATER OF VARIOUS DEPTHS.

FIGURE Nc 6

BUBBLE PATH FROM NOZZLE UP TO THE SURFACE.

ELEVATION

FIGURE No. 7

ICE COVER PARTLY MELTED FROM BELOW.

AIR THAT COLLECTS UNDER THE ICE
WILL SLOWLY DIFFUSE THROUGH CRACKS
AND PORES TO THE ATMOSPHERE.

FIGURE No. 8

RATE OF MELTING ICE WHEN A HOLE IS
CHOPPED THROUGH FOR THE AIR TO
ESCAPE. AMBIENT AIR TEMP. -10°F AVE.

a) ICE PROFILE WHEN HOLE CHOPPED.

b) ICE PROFILE 24 HRS. AFTER HOLE CHOPPED.
2.5 CFM OF AIR USED.

c) ICE PROFILE 48 HRS AFTER HOLE CHOPPED.
2.5 CFM OF AIR USED.

ELEVATION

FIGURE No. 9

ICE BUILD-UP ON AIR OUTLET NOZZLES.
INSIDE AIR PRESSURE 40 PSIG. INSIDE AIR
TEMP 55° TO 60° F. EXPANDED AIR TEMP 0° TO -5° F.
NOZZLE DISCHARGING INTO WATER UNDER
ATMOSPHERIC PRESSURE. NOZZLE DIA. 1/16".

SCALE: FULL SIZE

PLATE NO. 1

Design size of openings in ice sheet around piers.

PLATE NO. 2

Design size openings as seen from island No. 1.

PLATE NO. 3

Actual size of openings in ice sheet around piles, showing capacity of present system.

PLATE NO. 4

6" diameter opening in 8" thick ice above air outlet hole. Air accumulated under the ice cover is shown escaping and forcing up a water spray.

PLATE NO. 5

Above opening 24 hrs later. (Using 2.5 cfm of air at a depth of 30'.) Piles 20" dia.

PLATE NO. 6

Porous ice formed on outside of nozzle. Tip of nozzle cooled to below freezing by the expanding air. The ice has no noticeable effect on the quantity of air escaping.

PLATE NO. 7

Previous to freeze-up wave action causes heavy icing of the piles.

PLATE NO. 8

General view of low level section before installation of bubbler system.

PLATE NO. 9

View showing air piping and supporting framework during installation through the ice.

OTHER CONTRIBUTIONS AND GENERAL DISCUSSION

C. H. Duff presented some slides and described an air bubbling system used by the Canadian International Paper Co. to keep water open in the autumn before the ice is thick enough to place wood upon it. This installation is described in a paper by Duff published in the Woodlands Review, April 1959. A film showing application of air bubbling systems was shown by the Atlas Copco Company.

T. A. HARWOOD noted the circular effect of the individual bubbles and the line of bubbles. He suggested (referring to the slide) that air bubblers might be used as an aid to navigation since radar might pick up this discontinuity and follow a line of bubbles marking the centre of a channel. This might be of some importance where buoys could not be used. He also remarked that air bubbling systems had been used as a breakwater for suppressing waves but they were not successful in suppressing long swells.

T. A. HARWOOD opened the general discussion saying that although no serious thought had been given to the optimum in bubbler systems he could discern some order for the necessary parameters. He indicated that perhaps the major parameter was orifice size and that the contributions given had indicated that an orifice of 0.02 in. or larger appeared to result in air bubbles between 1/16 and 1 in. in diameter.

S. INCE said that he was doubtful if the size of the orifice was important in determining the bubble diameter. If the pressure were much above the static water pressure the diameter of the bubbles might be affected.

P. SHANKS stated that Atlas Copco recommend 1/32 in. orifice size, a standard 2 stage 100 cfm compressor and some means of reducing the discharge temperatures and consequently the moisture content of the air at the orifice.

C. H. DUFF remarked that the Canadian International Paper Company used a 1/32 in. orifice size at their Washoka Bay installation.

W. DOTSON said that for the installation at Thule to maintain an ice-free area throughout the winter would require increasing the orifice size to 1/8 in. The orifice spacing should be 15 ft apart and the air discharge 5 cu ft per minute per orifice. This orifice size and associated air discharge rate will ensure a more active mixing which is considered necessary at the Thule installation due to the absence of sensible bottom heat.

F. SOMERSET said that Ontario Hydro used $1/8$ in. orifice and the pressure was about 3 psi above the static water pressure.

J.N. HINDE considered that the orifice should be of a type which allowed bubble size to be controlled. He found that $1/32$ in. bubbles melt more ice than any other size under similar conditions. He emphasized the use of oil-free air and recommended a pressure of 5 psi above static water pressure. He said also that with very small bubbles the water circulation could be considered to be caused by the difference in density between the water containing bubbles and that free of bubbles. This type of flow gives a linear upward movement of the warm bottom water without mixing it with the cold top water. The greater temperature differential of the water brought to the surface will melt more ice and will also conserve the warm bottom water for melting ice late in the season.

T. A. HARWOOD inquired about the air pressure used by Ince in his experiments.

S. INCE replied that it was just enough to overcome frictional losses and was about 2 psi above static water pressure.

G. MacDOWELL said that the pressure used at Thule was about 65 psi and remarked that higher pressures appear to be necessary in salt water. T. A. Harwood then asked Mr. Dick what was used at Cambridge Bay.

T. DICK replied 8 psi, the water being about 18 ft deep.

S. INCE pointed out that this was a burper system and hence the pressure was hardly significant.

I. McCAIG stated "For fresh cold water at approximately 32.05°F , it is our experience that pressure should be below 10 psi if blockage of the orifice by freezing is to be avoided. The diameter of nozzle can therefore be between $1/8$ and $1/32$ in. depending on the amount of air required to keep the surface ice-free. For a $1/16$ in. diameter hole, the maximum discharge per hole is about 0.75 cfm."

A. BERGS stated that the Foundation of Canada Engineering Corp. had used a pressure of 40 psi in water 40 ft deep. They had used this high pressure in order to overcome the problem of balancing the air discharge at the outlets. He said that they had observed the formation of spongy ice about the orifices but this did not appear to interfere with the operation of the system.

It was pointed out during the discussion that the discharge rate is fixed by the drop in pressure at the orifice and the orifice size. The information on orifice size, discharge pressure, and rate of discharge per orifice contributing to the general discussion is summarized in the table that follows.

GENERAL TECHNICAL FIELD EXPERIENCE ON VARIOUS BUBBLER INSTALLATIONS
(PREPARED FROM COMMENTS MADE DURING GENERAL DISCUSSION)

Spacing per hole	CFM per orifice	Size of Orifice	Discharge pressure	Source
	0.1	1/16"	2 psi greater than hydro-static pressure	Ince, National Research Council
$\frac{1}{2}$ water depth	0.75 to 1.0	3/64"	65 psi (At 80 psi line froze)	Thule installation, U.S. Navy Hydrographic office
Depends on installation	2	1/8"	3 psi greater than hydro-static pressure	Ontario Hydro
2 ft for depth less than 20 ft; 4 ft for depth greater than 20 ft	1/200 to 1/100	Die-formed check-valves to control bubble size to 1/32" to 1/4". Orifices this small would clog.	5 psi above hydrostatic pressure	Hinde Engineering Co.
Depends on installation	0.75 for 1/16 in. nozzle	1/32" for water temperature 39°F, 1/8" for water temperature 32.05°F	less than 10 psi above hydro-static pressure for water temperatures near the freezing point	I. W. McCaig, H. G. Acres Co.
Depends on installation	0.8 for air temperature -10°F	1/32"	Greater than 40 psi	FENCO
About equal to water depth	0.8	1/32"	65 psi	C. H. Duff, Canadian International Paper Co.
About $\frac{1}{2}$ water depth	2.4	1/16"	45 psi	T. M. Dick, Dept. Public Works
About equal to water depth	0.75	1/32"		Atlas Copco Company

APPENDIX A

SUMMARY OF REPORTS RECEIVED ON AIR BUBBLING INSTALLATIONS

REPORT NO. 1

Installation by H. G. Acres and Co. Ltd. at McCormick Dam.
(Lat. 49°, 12' North, Long. 48°, 16' West.)

The average depth of the water at the site is between 15 and 20 ft and the rate of flow of the water 0.5 mph. The normal ice thickness is 36 in. and the temperature of the water between 32.04 and 32.07 °F.

The installation was an experimental system installed at McCormick Dam near Baie Comeau, Quebec. It consisted of two sections. One section was 100 ft long and contained eight 1/16-in. holes spaced 10 ft apart; the second section, also 100 ft long, contained sixteen 1/32-in. holes spaced 5 ft apart. A 10-cfm compressor supplied air to both bubbler pipes. This air was measured by an orifice meter and manometer installed in the main header. Pressure gauges, valves and a thermometer were also installed in the main header and supply pipes for measuring flow. A deep sea thermometer was used to measure the water temperatures near the bubbler pipes. Observations of air temperature and wind velocity were made approximately 2,000 ft from the bubbler installation.

The bubbler system was installed after an ice cover had formed on the reservoir. A trench approximately 5 ft wide and 200 ft long was cut through the ice to allow the bubbler pipes to be suspended in the water approximately 10 ft below the water surface. The bubbler pipes were centred along the centreline of the trench and discharged up through the trench.

A practical observation made while the bubbler was in operation concerned the formation of ice bubbles around the pipe at the orifices. These ice bubbles caused an intermittent discharge and sometimes complete blocking of the orifices at pressures over 10 to 14 psig. This indicated that best results would be obtained if the pressure differential across the orifice did not exceed 8 to 10 psig.

The system was operated from 20 January to 7 March 1959. During this period the minimum air temperature was about -18°F and the maximum about 25°F. There was no ice cover at the beginning of the operation. The system maintained open areas of about 1 sq ft above the 1/16-in. holes and about 1/4 sq ft above the 1/32-in. holes. These open

areas increased to about 3 ft in diameter above the 1/16-in. hole and 2 ft in diameter above the 1/32-in. hole for air temperature at 25°F. It is estimated that the heat loss during operation was between 17 to 100 Btu/hr/sq ft.

The rate of air discharge used was 0.35 cfm through the 1/16-in. orifices and 0.10 cfm through the 1/32-in. orifices. The orifice pressure differential was 6 psi.

The results of the tests at McCormick Dam are reported in the paper "Ice Problems at McCormick Dam, Tests on Pilot Bubbler Systems", Vol. 3, Proceedings I.A.H.R., 1959.

REPORT NO. 2

Installation by H. G. Acres and Co. Ltd., in Northeastern Quebec.

This installation is in a surge tank 130 ft in diameter and 245 ft deep excavated in rock. The top of the tank is exposed to the atmosphere. The bubbler system was installed to prevent ice from forming on the water surface adjacent to the tank walls.

The bubbler system was made with 375 ft of 1/2-in. plastic pipe mounted on concrete pedestals 5 ft in from the circumference of the tank and 2 1/2 ft above the bottom. The orifices are 1/16 in. in diameter and spaced 5 ft between centres. Air is supplied from a compressor rated at 60 cfm at 100 psi. The maximum water level in the tank is 240 ft and the minimum 30 ft. The bubbler system was installed in November 1959 and has since operated successfully.

REPORT NO. 3

Installation by the Canadian International Paper Co. in the Cabonga Reservoir. (Lat. 47°, 29' North, Long. 76°, 29' West.)

The average water depth at the site is about 20 ft and the normal maximum ice thickness about 22 in.

Air is supplied by 3 Gardner Denver WH-105 2-stage compressors driven by gasoline engines. These are rated 120 cfm at 100 psig. Air

from these compressors discharges to an extra air receiver 30 in. in diameter 85 in. long arranged for easy drainage of condensate. Black iron pipe, 3 and 2 in. in diameter, along the shore serves as a header for the 14 lines of 3/4-in. plastic pipe. Each line is 1200 ft long and has 1/32-in. diameter holes drilled every 20 ft. These lines of plastic pipe are placed 120 ft apart, and anchored with 5 lb of scrap iron wired on every 20 ft, i. e. midway between air holes. The lines are connected to the header through 3/4-in. angle valves. The valves are introduced as an air saving device since the operation is such that the entire area need not be kept ice-free at all times. Air discharge to the 14 lines is approximately 320 cu ft per minute. Air measurements were made with a thin plate orifice meter using radius taps.

It should be noted that three steel hulled winch boats are operated in the bubble area to handle the wood. These boats act as ice breakers when the temperature falls below -20°F. At -20°F the boats are breaking ice 24 hours a day.

The system has been in operation annually since 1957 between the dates of approximately 23 November to 12 December. During this period the minimum air temperature is about -32°F and the maximum about 29°F. There is usually no ice on the lake when the bubbler is put into operation.

The system will maintain an ice-free area about 1700 ft long and 1200 ft wide. Between -5 and -10°F ice forms between the lines of air bubbles. This ice is broken up by the movement of wood and boats and usually drifts outside the influence of the bubbles. When the air temperature is below -10°F, 1 to 2 in. of ice will form but is still broken up by the normal activity in the area. Below -20°F ice forms readily and boats must work continuously as ice breakers.

A description of this installation has been prepared by C. H. Duff and published in the April 1959 issue of "Woodlands Review". A copy can be obtained from the Canadian Pulp and Paper Association, Woodlands Section (Woodlands Section Index No. 1842 B-10).

REPORT NO. 4

Installation by the Foundation of Canada Engineering Corporation Ltd. at Rainy Lake, Manitoba. (Lat. 49° North, Long. 93° West.)

The average water depth at the site is 30 ft and the normal

maximum ice thickness is between 32 and 36 in. The average water temperature during the winter at the 30-ft depth is about 35°F.

The system was operated intermittently between 12 December 1960 and the beginning of March 1961. The minimum air temperature during this period was approximately -30°F and the maximum air temperature approximately 45°F. The ice thickness at the beginning of the operation was about 13 in. During the coldest part of the winter ice-free areas some 60 ft in diameter were maintained above 18 bubble sites. These areas increased to approximately 70 ft in diameter when the average air temperature was about 30°F.

The discharge rate was approximately 2 cfm through 1/16-in. diameter orifices. It was observed that 10 cu ft/24 hours/cfm of ice was melted when the ice was not punctured to allow the air to escape. If the air escaped, the melting rate increased between 50 and 70 cu ft /24 hours/cfm.

A complete technical description of this installation is given in the paper by W. D. Bonisteel, "Investigation of the Performance of a Compressed Air Bubbler System used for Ice Melting", contained in these proceedings.

REPORT NO. 5

Installation by the Harbours and Rivers Engineering Branch of the Department of Public Works at Cambridge Bay. (Lat. 69°, 7' North, Long. 105°, 4' West).

This bubbler system was installed in the Arctic Ocean in water of an average depth of 18 ft. The normal maximum ice thickness is 7 ft. The installation was operated through the winter of 1960-61 beginning 23 October. The average minimum temperature during this period was about -44°F.

A complete technical description of this installation is contained in the paper by T. M. Dick "Pneumatic De-Icing Installations", published in these proceedings.

REPORT NO. 6

Installation by the Harbours and Rivers Branch, Dept. of Public Works, At Tuktoyaktuk. (Lat. 68°, 26' North, Long. 133° West.)

This bubbler system was installed in the Arctic Ocean at a site where the average depth of water was between 10 and 17 ft. The normal maximum ice thickness during the winter is between 73 and 90 in.

It was observed that during the winter the temperature of the water was about 32°F with no gradient from top to bottom.

The system operates annually from 2 October to 1 May. During this period the minimum air temperature is about -55°F and the maximum about 28°F. There is usually no ice on the water when the system is put into operation. It has been observed that this system, with 1/16-in. diameter orifices spaced 8 ft between centres, operates satisfactorily at this site.

At the beginning of each season, for the first month's operation, some orifices become blocked with ice for short periods of time. They normally clear themselves and remain open for the balance of the season.

No problems have been encountered with freezing in the lines; the use of anti-freeze solutions in the lines has therefore been unnecessary.

During December of 1959 the diesel engines were shut down for a period of 36 hours when the air temperature was between -25°F and -30°F. A sheet of ice formed 2 to 4 in. thick over the open water. When the compressors resumed operation, however, the open water began to appear after 14 to 16 hours.

Some ice measurements were taken during February 1960, to determine the extent of influence of the bubbler system. It was found that the bubblers reduced thickness up to 25 ft from the wharf face and also beneath the wharf structure. Near the open water area, overflow from the tidal rise tends to build up snow and ice. Late in the winter, steam from the open water and drifting snow will build an ice bridge over the open water. This insulation is very helpful in reducing the heat losses. This snow cover will remain for a long period of time with some sections breaking down and falling into the water. Because of this snow bridge, it is very difficult to ascertain the exact width of open water maintained by the bubbler system.

A system of intermittent operation of the compressor was tried - 16 hours on, 8 hours off; this was found to be unsatisfactory as the compressors and engines became so cold that they were difficult to start, and consequently much time was lost. It was then considered better to operate the diesel engines continuously and divide the total operation time between the two engines.

To date the greatest difficulty in the operation of the system has been maintaining the diesel engines for continuous operation during the extreme cold. The bubbler system itself has given no problems.

The system is left in the water during the summer months and it has not presented any hazard to navigation. The system is tested during the open water season for leakages.

REPORT NO. 7

Installation by the Manitoba Power Corporation at Seven Sisters Falls on the Winnipeg River. (Lat. 50°, 7' North, Long. 96°, 1' West.)

The average depth of water at this site is 45 ft and the rate of flow between 1 and 3 mph. Normally maximum ice thickness is between 2 and 10 ft.

The main header of the system is on the upstream edge of the dam, outdoors, and consists of a total of 1120 ft of iron pipe of which 940 ft is 4 in. and 180 ft is 2 in. The header is fed by a 4-in. line from either of 2 compressors, through an accumulator tank and a pressure reducing valve. The compressors are rated at 868 cfm at 100 psi. The header is equipped with 3 strap heaters with 2.5 kw capacity each evenly spaced on the 4-in. section of the header. There are also 3/4-in. valves every 30 ft for blow down. Bubbler pressure is kept from 25 to 30 psi.

The bubbler pipe is 1 1/2-in. iron pipe connected to the header by rubber down-pipes, and suspended from the dam railing at 20-ft intervals by wires which are insulated from the railing. The insulation makes it convenient for connecting a thawing transformer to the bubbler pipe. The bubbler section in front of the 2 sluice gates is connected to hand winches for ease of raising when it becomes necessary to raise a gate. The bubbler pipe is suspended approximately 16 ft below water level and has 1/16-in. orifices at 3-ft centre.

This system has been used annually since 1931, to protect a dam from ice damage. The minimum air temperature normally encountered is about -50°F and the maximum about 40°F. The thickness of the ice at the beginning of the operation of the system is about 1 in. The bubbler maintains an open strip in front of the dam 10 in. wide and 1120 ft long. The air temperature will affect this open area slightly.

REPORT NO. 8

Installation by the Manitoba Hydro Corporation at Great Falls
on the Winnipeg River. (Lat. 50°, 27' North, Long. 96° West.)

This installation is used to protect the face of the dam from ice action.

The average water depth at this site is about 40 ft and the speed of the water between 1 and 3 mph. The normal ice thickness is between 2 and 10 ft. Once ice has formed on the water surface, the temperature of the water is 32°F throughout the full depth.

The Great Falls bubbler system is fed by a single air compressor (capacity 640 cfm), and the air passes through an accumulator tank to a 4-in. header which runs the length of the powerhouse in the gate room. A 4-in. down-pipe at each end feeds into 2 bubbler pipes, one going in each direction, to protect the concrete dam structures at each end of the powerhouse. The bubbler pipe is 4-in rigid plastic pipe with Victaulic-type couplings. Two brackets per 20-ft length of pipe are anchored to the wall which hold the pipe down and away from the wall approximately 8 in. Hole size is #54 drill (approximately 3/64 in.), and 3-ft spacing with the holes downward. The pipe is approximately 21 ft below the surface of the water. At the sluiceway section when there are 4 stoney roller-type gates, the bubbler pipe rises, forming a header, and goes across the gate structure at dam elevation and then downward again to the end of the dam.

There are 4 Tees at the sluiceway header and from each there is a flexible down-pipe which is attached to a 1 1/2-in. iron bubbler pipe which is lowered and hung on wire in front of each gate for their respective protection.

The bubbler system is not required along the face of the powerhouse where an upward current of water is created naturally by the physical construction of the intakes.

The total length of protected dam is approximately 1600 ft. The original installation of 4-in. iron pipe was replaced in 1960 by 4-in. plastic pipe.

The pressure on the bubbler system is 40 psi.

The bubbler has been in operation since 1924. The minimum air temperature is about -50°F and maximum about 40°F. The ice thickness

at the beginning of operation of the system is usually about 1 in. The system will maintain open a channel 16 in. wide and 1600 ft long. This open area will vary slightly with the temperature.

REPORT NO. 9

The following information was supplied by the Ontario Hydro Corporation and is a résumé of their experience with air bubbling systems for ice prevention.

DETAILS ON THE LOCATION OF AIR BUBBLER SYSTEMS

Generating Station	Installation	1960-61 Winter, min Temp °F	Approx Latitude	Approx Longitude	Depth of Water to River Bottom, ft	Water to Nozzles, ft
Kakabeka Falls	Headpond	-33	48° 20'	89° 40'	16½	4
Cameron Falls	Dam wing wall	-33	49° 10'	88° 20'	35	3
Upper Notch	Sluice gate	-38	47° 20'	79° 40'	59	23
Whitedog Falls	Sluice gate		50° 10'	94° 40'	56	20
Abitibi Canyon	Sluice gate	-45	49° 50'	81° 30'	46	25
Manitou Falls	Unit intakes	-36	50° 40'	93° 30'	50	30
Red Rock	Sluice gate and Unit intakes		46° 20'	83° 10'	64	32
					75	52
Otter Rapids	Sluice gates		50° 20'	81° 30'		

Prior to 1956 interest in air bubbler systems at Ontario Hydro was minor and was confined to the prevention of ice pressure on 2 small concrete dam structures. In 1956 an experimental installation was made at the intakes of a new station for use in minimizing ice pressure on the

headworks during complete plant shutdowns. Since 1958 there have been several trial installations in existing plants aimed at reducing heating requirements for sluice gates. In 1960 an installation was made at another new station for the purpose of reducing electric heating requirements for the many steel sluice gates. A system is also being installed for a similar reason at a station presently under construction.

Since sluice gates will be referred to a number of times, it should perhaps be explained that they are all of the vertical type guided in steel-lined "gains" or slots in the concrete. The water is released under the gate by raising it. Their design provides some allowance for ice conditions; however, it is Ontario Hydro's practice to always apply heat to the gates and gains. This requires 40 to 80 kilowatts depending on the size of the gate which varies from 18 to 45 ft in width and 25 ft in height.

It should also be noted that the areas protected are beyond the general flow of the water. Consequently there is not much dispersion of air bubbles from a bubbler system due to water currents.

Following is a description of the various installations. All the locations are in northern Ontario and in this last winter minimum temperatures recorded were from -25°F to -45°F:

1. Kakabeka Falls GS - on Kaministiquia River about 20 miles west of Fort William.

An air bubbler system was in operation at the headpond when Ontario Hydro assumed control of the station in 1949 and has been operated intermittently since then. The head on the dam is about 16 ft and there are five 20-ft wide stoplog sluices. The system, when last used, consisted of a header running along the deck with 1/2-in. diameter down-pipes open at the end about 2 ft under water. It worked satisfactorily to about -10°F air temperature. The installation was lifted out after each winter. It has not been used for a few years and ice is now cut manually using a chain saw. Air was supplied from an old reciprocating compressor.

2. Cameron Falls Headworks - 1952 - on Nipigon River about 70 miles northeast of Port Arthur.

A temporary air bubbler system was installed to relieve pressure on a wing wall where the concrete was considered to be in poor condition. The station air supply was connected to a header above water which ran the length of the wall, with down-pipes at 6-ft intervals extending 3 ft below the surface of the water and 6 in. from the wall. The system was in

operation only one winter and worked satisfactorily although the winter was quite mild for the district. The concrete was repaired the next year which made further operation unnecessary. Had the system been continued, it would have been improved by placing the down-pipes at 4-ft intervals and 11 in. from the wall. Air volume was not measured.

3. Upper Notch GS 1959 - 1960 - 1961 - on Montreal River about 13 miles south of Cobalt.

The amount of heat installed in the sluice gate is on the low side for winter operation; it was decided to ascertain if an air bubbler system would assist in keeping the front of the gates ice-free.

For the 1959-60 winter, a test installation consisting of a plastic pipe with 1/8-in. holes at about 10-ft centres was mounted on the face of one 32 1/2-ft wide gate near the bottom. This was only partially successful; the installation was damaged by debris on sluicing water through the gate. There was also freezing in air lines that were exposed to the concrete.

For the 1960-61 winter, a pipe with 1/8-in. holes at 8-ft spacing was anchored 23 ft below water level, 12 ft upstream of the gate, and just over the edge of the sill apron for protection. This worked very well until the gate was raised for spilling water at which time the bubbler was turned off.

A report of 1 March 1961, after the resumption of the bubbler operation, indicated that the water surface was not entirely clear but was reduced to skim ice, on one side of the sluice being better than the other.

It was considered that the nozzles were too far out as it was possible to get ice at the gate behind the clear patch. Installed electric heat with some temporary heating cable was on the gains, but gate heat was turned off. The staff commented on the great difficulty of installing equipment in an existing plant and securing piping so that it would not be torn off by water forces or debris. Air consumption was estimated at 18 cfm, supplied by a small reciprocating air compressor. Air pressure was about 13 psi, or 2 psi greater than the water pressure at the nozzle location.

4. Whitedog Falls GS - 1959 - on Winnipeg River about 13 miles northwest of Minaki.

A preliminary test of a few weeks' duration was made at two sluice gates by the Commission's Generation Design Department to gain design

information for a new station. The trial installation was made of 1-in. plastic pipe, held in position by ropes, with two 1/8-in. diameter holes at 20 ft depth, 4 to 8 ft in front of the gate. The air holes were 2 ft from the sides of the 17-ft wide opening between piers. With electric heat on the two gains but not on the gate, the installation kept the surface clear at a night temperature of -34°F. Installed heating is 12 kw in each gain and 40 kw in each gate, or 64 kw total. With air pressure at 13 psi, air bubble distribution was good but at 20 psi it was somewhat excessive.

5. Abitibi Canyon GS - 1958 - 1959 - 1960 - on Abitibi River 62 miles north of Cochrane.

In the 1958-59 winter, a trial installation was made in front of a 45-ft wide sluice gate to test whether an air bubbler system could be used to reduce gate heating requirements on gates not required for opening until the spring run-off. A steel pipe was lowered to the sill about 3 ft in front of the gate in about 20 ft of water. The pipe had a series of holes that kept the surface free of ice until the temperature dropped below 0°F when the ice-free areas gradually reduced in diameter to small holes. Considering the results obtained the system required considerable air. Air was taken from the station service. Flow meters were not used.

The next year a further trial installation was made with four nozzles directed downwards and spaced 10 ft apart, with a discharge diameter of 1/32 in. The nozzles were at 24-ft depth, 15 ft in front of the gate, and 1 ft above the gate sill at the extreme upstream edge of the concrete. This worked in much the same manner as the first but required less air. As the weather cooled below 0°F, the open width reduced to four circular areas which gradually decreased in diameter until they disappeared. Results indicated that the air holes were too small and the supply pressure too high.

6. Manitou Falls GS - 1956 - on English River about 11 miles west of Ear Falls.

The system was designed by the Engineering Division and installed partly on an experimental basis, but particularly for use during extended complete flow shut-off, in extreme winter weather to provide an open area in front of the unit intakes. Studies on ice pressures were being made at that time and the geography of the forebay gave the possibility of high ice pressures under these conditions.

The piping was embedded in the headwork concrete during construction with the nozzles at the intake pier noses. The piers are at 24-ft centres and have three 1/8-in. diameter nozzles at 2-ft horizontal spacing in each pier

nose with the air discharge downward. Nozzles are about 1 in. from the face of the concrete and 30 ft below water level.

Air is supplied by a rotary air compressor at a pressure of 15 psi via 4 air flow meters to the 4 sections of the system. The compressor is 7 1/2 hp with a capacity of 65 cfm free air or roughly 2 cfm of free air per nozzle. An emergency supply is available from the 100 psi station service.

In the earlier stages of plant operation the system was operated in winter with the units running. Some of the air drawn into the intakes entered auxiliary piping, creating a nuisance with air bubbles in flow meters, and it was thought that the additional oxygen accelerated the corrosion of the steel-water piping in the plant.

The equipment has not been tested to any great degree as the whole plant flow is never completely shut off. The bubbler system is not used on individual units for flow shut-offs under 48 hours or longer, depending on the severity of the weather, since due to the grouping of the nozzles there would be some spill-over of air to an operating unit.

From incidental operating experience it is considered that the equipment should do the duty intended.

For those who wonder why the term "flow shut-off" rather than "plant shutdown" has been used, it should be explained that three of the units can operate as synchronous condensers at which time no water passes through the turbines.

7. Red Rock Falls GS - 1960 - on Mississagi River about 20 miles west from town of Blind River.

The station was put into service in late 1960. It has an air bubbler installation designed by the Commission's Engineering Division for the 7 steel sluice gates and for the unit intakes of the 2 turbines. The supply pipes are copper, embedded in the concrete.

The air bubbler system at the unit intakes will not be used unless the 2 units are shut down, or operated as synchronous condensers, for an extended period in severe weather. The heated headgate houses normally provide enough heat to the area immediately over the headgates.

The installation in front of the sluice gates is intended as the first major test of an air bubbler system by the Commission in reducing

sluice gate electrical heating requirements to a minimum, especially on the 5 gates only normally used at high river flows in the spring. Since the effectiveness of the method has not yet been proved, normal electric heating capacity was installed in the gates and gains with some switching facilities provided for the purpose of varying the heat input. As the plant has just been placed in service no performance testing has yet been done, and the electric heating was left on during winter. There is every indication however, that the system may do a good job. Air bubble distribution at the surface in front of the sluice gates is very good.

The system is supplied via a reducing valve from a 100 psi compressed air system which was installed primarily for other duties. Design figures are 17 psi with 42 scfm going to the 21 nozzles on the 7 sluice gates (2 cfm per nozzle) and 12 scfm when required, to 6 nozzles on each of the 2 unit intakes. There is a flow meter in the sluice gate system and each unit intake system. The sluice gates are 18 ft wide with 3 nozzles, 1/8-in. diameter, one at the centre line and the other two 6 ft each side, pointing downward 60° from the horizontal. Nozzles are within 1 in. of being flush with the concrete, 32 ft below water level, 7 ft below the gate sill and about 7 ft in front of the gate. The water disturbance at the surface consists of 3 connected circular areas about 7 ft in diameter.

It is planned to carry out tests next winter.

8. Otter Rapids GS - on Abitibi River 85 miles north of Cochrane.

The first two units of this station are scheduled for service in 1961. An air bubbler system has been installed in front of the sluice gates.

Conclusion

It will be seen from the foregoing that Ontario Hydro has had rather limited experience with air bubbler systems to date, but should be able to provide some interesting information in a year or so. The difficulties of installation and maintenance of this type of equipment in existing plants to prevent freezing in lines and to prevent damage to under-water parts, have been stressed. The great advantage to be gained in new plants by embedding the piping in the concrete, where it is away from harm, has also been stressed. It is for this reason that installations in new plants are being continued before testing has been completed. When obtaining performance data, it should be emphasized that a list of items to be recorded should be provided so that no relevant data will be overlooked. Also, personnel observing the tests should record any abnormal conditions which may affect the results.

REPORT NO. 10

Installation by the Hinde Engineering at Kenosha Trout Lake,
Colorado. (Lat. 40° North, Long. 105° West.)

The average depth of water at this site is between 7 and 15 ft. The normal ice thickness is about 36 in.

Three, 1/2 hp oil-less air compressors, direct-drive, piston-type with sealed bearings and carbon-teflon rings, deliver 3.8 cfm of air at 30-lb gauge pressure to 400 ft of feeder tube (3/4-in. I. D. polyethylene) and 4,000 ft No. 586-10 air-aqua tube (1/2-in. I. D. polyethylene). The 4,000 ft of tubing contain 8,000 special check valves on 6-in. centres. The tubing is weighted with brick at 4-ft centres.

The feeder tube was run out to the deep water. Two parallel lines, 2000 ft long of aerating tube, were laid on the bottom of the lake 200 ft apart. The feeder tube was connected to the centre of each line so that the air was being fed 1000 ft on each side of the feeder tube. The aerating tube was laid in 7- to 14-ft deep water.

This installation was made 5 October 1958, just prior to the lake freezing over. Installation was started at 10 am and completed at 4 pm. Difficulty was encountered in laying the tube weighted with bricks as the bricks would kink the tube while it was sinking to the bottom.

This system has been operated annually from October to May since 1958. During this time the minimum air temperature was about -54°F and the maximum 70°F. An area approximately 1200 by 200 ft was kept open during the coldest weather.

No water temperatures were recorded. The system was started up before ice formed and run continuously until ice left the lake 2 May 1959. Some of the open area was skimmed over with ice during drifting snow and snow built up on the skim ice. Within 24 hours, there would be an air space between the snow and the water. The snow would then collapse and the area would again be open.

The ice-free area was not greatly affected by changes in air temperature although drifting snow did cause some difficulties. The lake was free of ice a month ahead of other lakes in the area.

In the fall of 1959, 3/16-in. lead wire was taped to the tubing to weight it to the bottom. Difficulties were encountered with this system of

weighting the tubing but they have been overcome by extruding the lead weight directly into the tubing.

During the fall of 1960, the tubing was laid down the centre of the lake in a straight line in 7- to 14-ft deep water. During most of the winter, an area 60 ft wide and 4000 ft long was kept open. Two of the oil-less air compressors failed in January 1961, but were rebuilt and put back in operation. The ice froze over during the time the system was not in operation but melted out within two days after the system was put back in operation.

During 1959 and 1960, 8 systems were installed in high mountain lakes. One of these systems was put in Echo Lake by the Colorado Conservation Department in 1959. Echo Lake is about 18 acres with a maximum depth of 7 ft, an average depth of 4 ft and an altitude of 10,350 ft. About 25 per cent of the area of the lake was kept open with one 1/2 hp oil-less air compressor.

In other experiments conducted with the Wisconsin Conservation Department in 1958 and 1959, a 10-acre lake was allowed to go to winter fish kill conditions. The system was turned on at this time and a volume of ice 3 to 15 ft wide and 1200 ft long was melted through 20-to 22-in. thick ice in 36 hours with a 1/3 hp oil-less air compressor. The air temperature at that time was -1° to -15°F.

In a 40-ft deep quarry, two 1/2 hp oil-less air compressors melted a volume of ice 15 to 40 ft wide and 4000 ft long through 18 to 20 in. of ice in 48 hours. The tubing was laid in a rectangular pattern and the wind and waves cleared the ice from the centre portion of the rectangle within 4 days.

Altogether, 93 systems have been installed in northern United States and Canada in fish culture operations. Some are installed in 3-ft deep raceways to melt ice to feed trout; others are in 90-ft deep lakes. Three of these installations have not functioned properly. One failure was caused by 31°F water entering the raceways. The other two failures were caused by soluble iron in the water which formed iron oxide around the check valves in the tubing.

APPENDIX B

LIST OF THOSE ATTENDING MEETING

Anderson, P. F.,
Foundation of Canada Engineering
Corporation Limited,
8 Spadina Road,
Toronto, Ontario.

Arklie, T.,
Asst. to Chief Engineer,
Anglo-Nfld. Development Co. Ltd.,
Grand Falls, Newfoundland.

Baines, D.,
Mechanical Engineering Dept.,
University of Toronto,
Toronto, Ontario.

Barber, F. G.,
Oceanographic Research,
Mines and Technical Surveys,
No. 8 Temporary Building,
Ottawa, Ontario.

Bergs, A.,
Foundation of Canada Engineering
Corporation Limited,
8 Spadina Road,
Toronto, Ontario.

Betournay, J. N.,
Canals Division,
Department of Transport,
Ottawa, Ontario.

Boyd, D. W.,
Division of Building Research,
National Research Council,
Montreal Road,
Ottawa, Ontario.

Boyden, M. B.,
21-5th Street,
Quebec Cartier Mining Company,
Port Cartier, P.Q.

Brascugli, N.,
Quebec Cartier Mining Company,
Port Cartier, P.Q.

Brebner, A.,
Department of Civil Engineering,
Queen's University,
Kingston, Ontario.

Brownridge, F. C.,
Department of Highways Ontario,
Parliament Buildings,
Toronto 2, Ontario.

Connelly, Brigadier A. B.,
Department of Northern Affairs
and National Resources,
Ottawa, Ontario.

Croal, J. P.,
1239 Evans Blvd.,
Spartan Air Services Limited,
Ottawa, Ontario.

Cuerrier, J. B.,
Canadian Wildlife Service,
Department of Northern Affairs
and National Resources,
150 Wellington Street,
Ottawa, Ontario.

Dick, T. M.,
Harbours and Rivers Engineering
Branch,
Department of Public Works,
Ottawa, Ontario.

Dotson, W., Lieut.,
U. S. Navy Hydrographic Office,
Washington, D. C.,
U. S. A.

Duff, C.H.,
Canadian International Paper Co.,
820 Sun Life Building,
Montreal, P.Q.

Evans, R.J.,
Roots-Connersville Blower,
116 Oakridge Avenue,
Pointe Claire, P.Q.

Ganong, W.F.,
Director of Naval Weather Service,
Naval Headquarters,
Ottawa, Ontario.

Gauthier, G.C.,
Saguenay Terminals Ltd.,
Port Alfred, P.Q.

Gold, L.W.,
Division of Building Research,
National Research Council,
Montreal Road,
Ottawa, Ontario.

Hachey, N.B.,
Fisheries Research Board,
Sir Charles Tupper Building,
Ottawa, Ontario.

Hausser, R.,
LaSalle Hydraulic Laboratory,
0250 Rue St. Patrick,
Ville Lasalle, P.Q.

Harwood, T.A.,
Defence Research Board,
Ottawa, Ontario.

Hewson, G.C.V.,
Beardmore and Co. Ltd.,
37 Front St. E.,
Toronto 1, Ontario.

Hinde, J.N.,
Hinde Engineering Co.,
224 Linden Park Place,
Highland Park,
Illinois, U.S.A.

Ince, S.,
Mechanical Engineering Division,
National Research Council,
Montreal Road,
Ottawa, Ontario.

Johnson, C.C.,
Department of Northern Affairs
and National Resources,
Ottawa, Ontario.

Kennedy, R.J.,
Department of Civil Engineering,
Queen's University,
Kingston, Ontario.

Keys, G.T.,
Woodlands Section,
Canadian Pulp and Paper Association,
2280 Sun Life Bldg.,
Montreal, P.Q.

King, E.N.,
Technical Information Service,
National Research Council,
Bank Street,
Ottawa, Ontario.

Klein, G.J.,
Mechanical Engineering Division,
National Research Council,
Montreal Road,
Ottawa, Ontario.

Kuhring, P.,
Chairman,
Montreal Harbour Planning Committee
Room 831,
400 Youville Square,
Montreal, P.Q.

Land, H. L.,
St. Lawrence Ship Channel,
305 Dorchester West,
Room 731,
Montreal, P. Q.

Lane, J. F.,
Gatineau Power Co.,
65 St. Redempteur St.,
Hull, P. Q.

Lazier, S. S.,
Department of Civil Engineering,
Queen's University,
Kingston, Ontario.

Leask, G. G.,
Marine Operations Branch,
Department of Transport,
Room 444, Hunter Bldg.,
Ottawa, Ontario.

Legget, R. F.,
Division of Building Research,
National Research Council,
Montreal, Road,
Ottawa, Ontario.

Le Mehaute, B.,
264 Park Street,
Queen's University,
Kingston, Ontario.

Long, J.,
Northern Canada Power Commission,
251 Bank Street,
Ottawa, Ontario.

Marsden, M.,
Arctic Institute of North America,
3485 University Street,
Montreal, P. Q.

Mathews, W. H.,
Department of Geology,
University of British Columbia,
Vancouver 8, B. C.

McCaig, I. W.,
H. G. Acres and Co. Ltd.,
Dorchester Road,
Niagara Falls, Ontario.

McKinnon, J.,
Division of Building Research,
(Summer student),
National Research Council,
Montreal Road,
Ottawa, Ontario.

MacDowell, G.,
U. S. Navy Hydrographic Service,
Washington D. C.,
U. S. A.

MacQuarrie, L. G.,
Department of Northern Affairs
and National Resources,
Ottawa, Ontario.

McWatt, P.,
Department of Highways Ontario,
Bridge Division,
Parliament Buildings,
Queen's Park,
Toronto, Ontario.

Meehan, O. M.,
Canadian Hydrographic Service,
300A, Surveys and Engineering Bldg.,
615 Booth Street,
Ottawa, Ontario.

Mitenko, P.,
Division of Building Research,
(Summer student),
National Research Council,
Montreal Road,
Ottawa, Ontario.

Morrison, I. E.,
Canadian Hydrographic Service,
Department of Mines and Technical
Surveys,
Ottawa, Ontario.

Murchison, M.,
Montreal Engineering Co. Ltd.,
276 St. James St. West,
Montreal, P.Q.

Orlando, F. W.,
The Shawinigan Engineering Co. Ltd.,
625 Belmont Street,
Montreal, P.Q.

Pounder, E. R.,
Physics Department,
McGill University,
Montreal, P.Q.

Robinson, A.,
Northern Canada Power Commission,
251 Bank Street,
Ottawa, Ontario.

Rodgers, G. K.,
University of Toronto,
c/o Ontario Department of Lands
and Forests,
Maple, Ontario.

Rustom, B. J.,
Worthington (Canada) Ltd.,
5415 Pare Street,
Montreal, P.Q.

Samolewicz, J. J.,
National Research Council,
Montreal Road,
Ottawa, Ontario.

Seheult, L. R.,
University of New Brunswick,
Fredericton, N.B.

Schaerer, P.,
Division of Building Research,
National Research Council,
Montreal Road,
Ottawa, Ontario.

Shanks, P. H. F.,
Atlas Copco Canada Ltd.,
Montreal Airport,
Montreal, P.Q.

Slaght, L. E.,
Aids to Navigation Division,
Department of Transport,
Ottawa, Ontario.

Smallwood, J. P.,
Canadian Ingersoll-Rand Co. Ltd.,
620 Cathcart,
Montreal, P.Q.

Somerset, F. M.,
Ontario Hydro,
620 University Ave.,
Room 914,
Toronto 1, Ontario.

Soprou, A. A.,
Products Development Division,
Ingersoll-Rand, N. Y.,
U. S. A.

Soucy, A.,
LaSalle Hydraulic Laboratory,
0250 St. Patrick,
Ville Lasalle, P.Q.

Thomas, M. K.,
Meteorological Service,
315 Bloor St. W.,
Toronto 5, Ontario.

Watt, J. S.,
Engineering Department,
National Harbours Board,
Room 736, Hunter Bldg.,
Ottawa, Ontario.

Williams, G.P.,
Division of Building Research,
National Research Council,
Montreal Road,
Ottawa, Ontario.

Williams, P.J.,
Division of Building Research,
National Research Council,
Montreal Road,
Ottawa, Ontario.