

CHAPTER 30

WINTER REGIME OF A TIDAL INLET IN THE ARCTIC AND THE USE OF AIR BUBBLES FOR THE PROTECTION OF WHARF STRUCTURES

Simon Ince

Hydraulics Laboratory, National Research Council
Canada

INTRODUCTION

Shipping in the Canadian Arctic is limited to about $2\frac{1}{2}$ months in summer. During this short period all communities have to be supplied with sufficient provisions and fuel to last the long winters. The Department of Public Works of Canada has built wharves and docking facilities in various Arctic centres to speed up the unloading operations. Many of the conventional pile structures have been destroyed by the 6 ft. thick ice laye which grips the piles and moves them up and down in response to the tide. To prevent this, an air bubbler system was installed three years ago at Tuktoyaktuk, N.W.T. to inhibit the formation of ice around the wharf. This unit has been operating successfully since that time and no further damage has been reported. This first success inspired the installation of a second unit at Cambridge Bay, N.W.T. where similar difficulties were being encountered. The air bubbler system at Cambridge Bay did not fulfill its promise and the wharf was damaged. This had been predicted, but the success at Tuktoyaktuk - despite the suspected influence of the Mackenzie River - was a mystery. In April 1961 the author investigated the bubbler system and its oceanographic environment at Cambridge Bay, and in April 1962 those in Tuktoyaktuk. The results of these surveys are reported in the following paragraphs.

AIR BUBBLER SYSTEMS

Air bubblers have been extensively used in lakes - in most cases successfully - to prevent the formation of ice or melt the existing ice cover. There is a voluminous literature on the subject; the essential hydrodynamic and thermodynamic features have been summed up by Baines (1961), Bulson (1961) and Williams (1961). Pounder (1961) has analysed the thermodynamic aspects in sea water.

According to Baines, when an air jet is discharged from an orifice under water a heterogeneous mixture of bubbles rises at rates varying with size in a cone with a total include angle of 12 degrees. Viscosity and lateral turbulent fluctuations induce a vertical water current with maximum velocity over the air source and decreasing along an s-curve outward. Upon reaching the water surface, the momentum of the water jet is

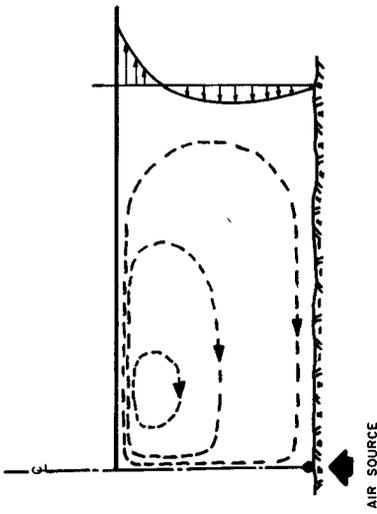


Fig. 1. Circulation pattern and velocity profile (after Baines).

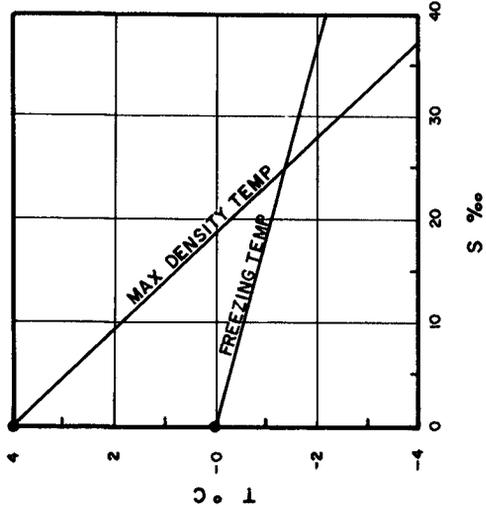


Fig. 3. Maximum density and freezing temperatures as a function of salinity.

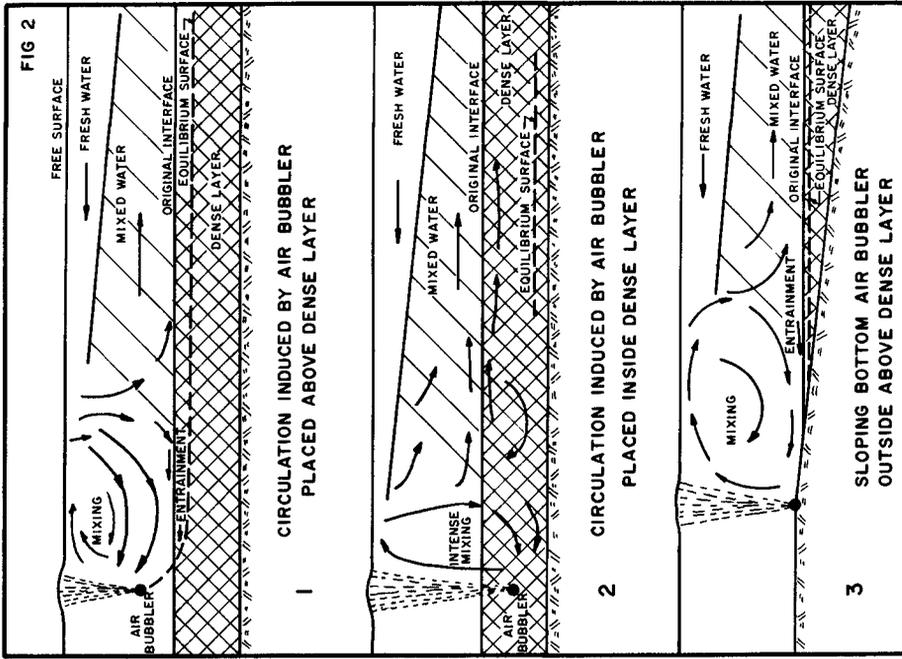


Fig. 2. Circulation in stratified liquids.

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converted into a horizontal surface jet. This jet has the characteristics of free turbulence; kinetic energy is obtained entirely from the vertical jet and hence decreases in the direction of flow. The vertical and surface jets consist entirely of water which has entered the jet from the side as entrainment. The large scale circulation induced by the air bubbles is a ring vortex (Fig. 1).

The circulation pattern shown by Baines applies to homogeneous fluids. In stratified fluids the initial stages of the circulation are quite different. Fig. 2 shows the results of experiments made in a narrow flume at the Hydraulics Laboratory of the National Research Council. Although the investigation was of an exploratory nature, it showed clearly the mechanism by which the denser liquid was mixed with the overlying lighter water. The most noteworthy fact was the relatively rapid establishment of a near equilibrium interface, after which entrainment progressed at a very slow rate.

Whether Fig. 1 or Fig. 2 is taken as the starting point, it is clear that if the water has some thermal reserve within the range of action of the bubbler, heat will be brought to the open surface or transferred to the ice sheet. If the water is well mixed and the temperature uniform and close to the freezing point - a case frequently encountered in fast flowing rivers - no heat will be available on the surface.

Instances are reported, however, where an air bubbler has kept an ice-free surface despite the lack of any thermal reserve in the water. This is entirely possible if the air bubbler has been installed before freeze-up. The agitation on the surface prevents the formation of a solid ice cover; instead, tiny discs of frazil ice are formed which are carried away by the induced current to be deposited at the underside of the surrounding ice sheet. Each gram of water releases upon freezing its latent heat which compensates for the losses to the atmosphere.

FREEZING CHARACTERISTICS OF SEA WATER

In Fig. 3 are shown the freezing and maximum density temperatures of water as a function of salinity. With increasing salinity the temperature of maximum density decreases more rapidly than that of the freezing. At a salinity of 24.70 p.p.t. both temperatures are -1.33°C . From these characteristics it is seen that up to a salinity of 24.70 p.p.t. a layer of sea water of uniform salinity has the freezing characteristics of a lake. Cooling will increase the density of the surface water, and a vertical convection will develop until the whole layer reaches the temperature of maximum density. From this point on only the surface will be cooled until ice begins to form. There will then be a positive temperature gradient between the surface and bottom.

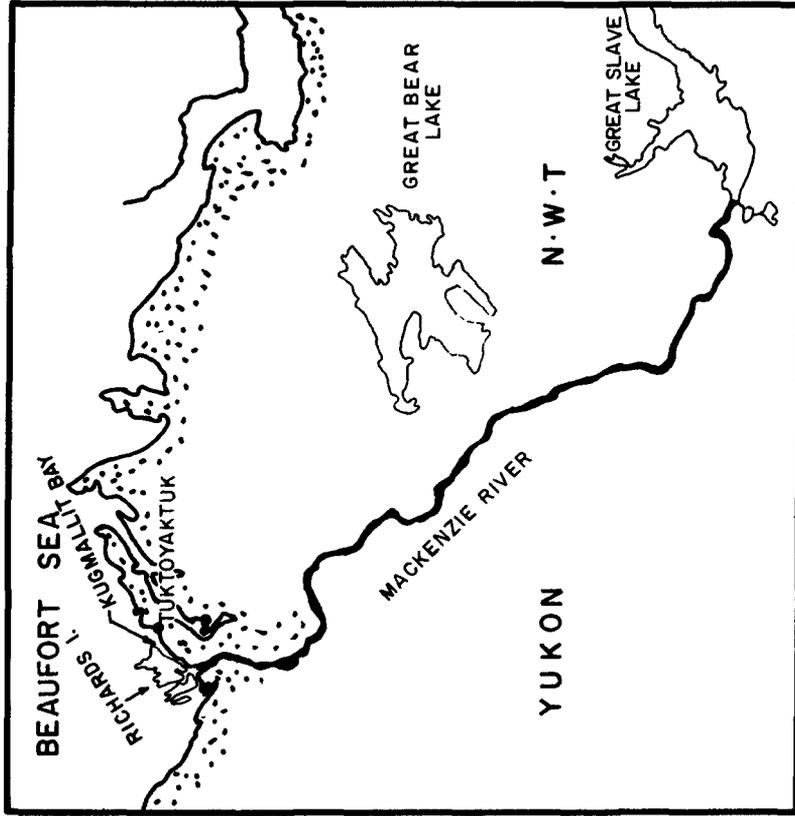


Fig. 5. Mackenzie River and Tukttoyaktuk.

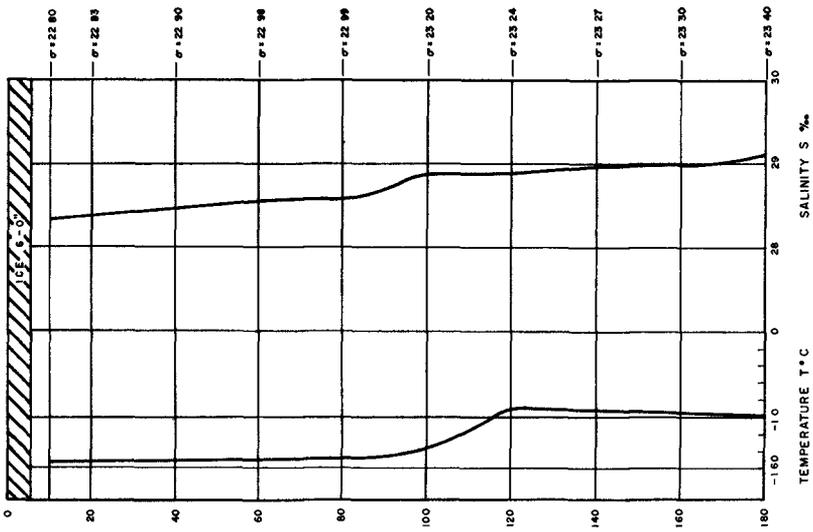


Fig. 4. Temperature and salinity structure at Cambridge Bay.

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of the layer. Here the analogy to a lake structure ends. During the freezing of sea water, the salt is expelled from the ice crystals and collects in small pockets of brine. This process continues until the brine becomes more and more concentrated and leeches out. Thus the water below the ice surface increases in salinity, and hence density, and the convection continues until all the salt is leached out. If the salinity is greater than 24.70 p.p.t. the freezing point is reached before the temperature of maximum density and the layer is isothermal at the freezing temperature corresponding to the salinity.

Thus, depending upon the oceanographic conditions, a layer of warmer water may or may not be present. The success of the air bubbler will depend on the size of the heat reservoir at its efficient utilization. In sea water, in addition to the temperature, the influence of the salinity must be taken into account. In a stratified system, mixing will increase the salinity of the upper layers and make available more energy.

INVESTIGATION OF FIELD INSTALLATIONS

It is evident that the success of any air bubbler unit depends upon the oceanographic conditions existing not only in the immediate vicinity of the installation, but in the system of connecting waters. To evaluate properly and quantitatively the operation of air bubblers systematic and detailed measurements of currents, salinity, temperature, ice growth, and meteorological factors is necessary. The surveys made at Cambridge Bay and Tuktoyaktuk were of an exploratory nature; nevertheless, they were extremely useful in confirming in broad lines the prognostications based on theory.

CAMBRIDGE BAY

Not much is known about the general oceanographic features at Cambridge Bay. Fig. 4 shows the temperature and salinity structure found in the bay. This is representative for the region within a 2 mile radius of the air bubbler. It is unnecessary to cut the curves at the appropriate depth to get the structure of the water at any point of lesser depth than shown in the figure. The air bubblers were installed in 20 ft. of water on a shelf very gradually increasing in depth to 45 ft. and then dropping abruptly. It is obvious from the figure that within the zone of influence of the bubbler the temperature is nearly constant at the freezing temperature $T = -1.52^{\circ}\text{C}$ of water at $S = 28.4$ p.p.t. Hence it is not surprising that the installation was not effective in maintaining an open water belt around the wharf.

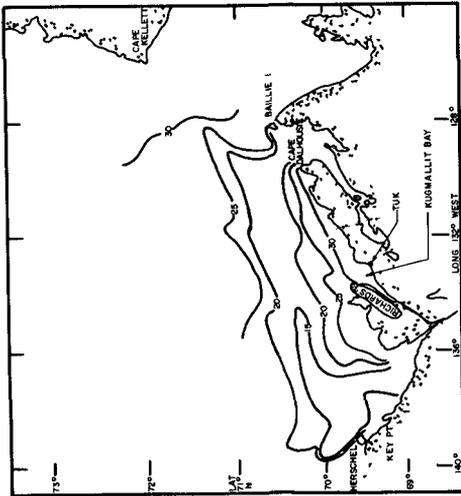


Fig. 6. Surface salinity (p.p.t.). Beaufort Sea, 1952 under conditions of easterly winds. (I.O.U.B.C. Report)

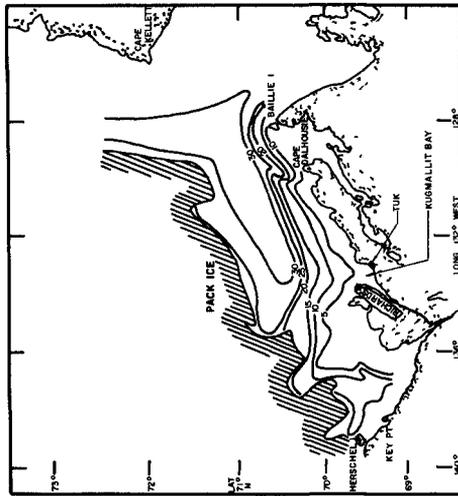


Fig. 7. Surface salinity (p.p.t.). Beaufort Sea, 1952 under conditions of westerly winds.

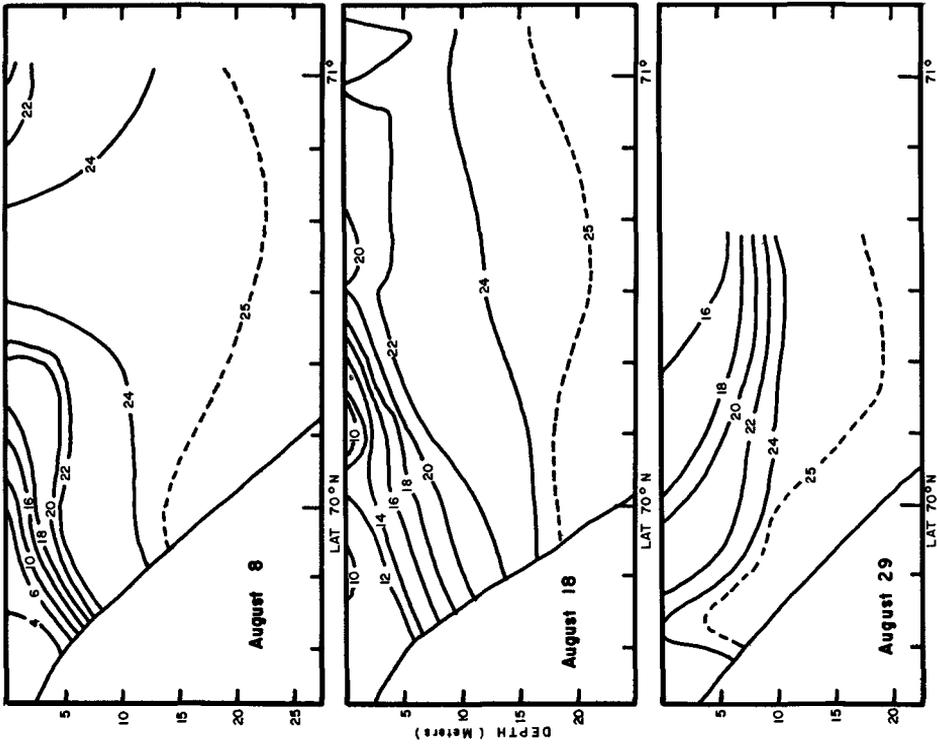


Fig. 8. σ_t sections northward from Kugmallit Bay illustrating extensive upwelling with easterly winds.

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TUKTOYAKTUK

In the summer of 1952 the Institute of Oceanography of the University of British Columbia made hydrographic and oceanographic observations in the Beaufort Sea and in Kugmallit Bay, which shed a great deal of light on the estuarine dynamics of this area (Fig. 5). The following observations are taken from the report of Dr. W.M. Cameron, senior scientist on this expedi-

"The principal oceanographic features of the southeastern Beaufort Sea are established by the interaction of river discharge and wind.

In the absence of wind the river water reacts to the influence of the Coriolis force and hugs the right-hand mainland boundary, moving eastward along the coast. Salt water is contributed by a southeasterly flow past Herschel Island. Mixing is relatively slow because of the high stability of the water column and the absence of strong tidal currents. A significant proportion of the river water moves into Amundsen Gulf mixing with oceanic water and flowing westward past Cape Kellett. Westerly winds accentuate the magnitude of the circulation.

Easterly winds of force 5 or more are sufficient to reverse the circulation. The river water moves offshore to the north and west. A compensating shoreward movement of saline water is set up in the deeper levels and a westward circulation is established along the mainland coast.

Local vertical density gradients are altered drastically by wind. The study in the Beaufort Sea indicates that reduction in the stability of a vertical column is not due primarily to vertical mixing, but rather to horizontal advection of water layers of different density. The direction of the wind is an important feature in coastal waters of this type. The areas of Herschel Island and northeast of Richards Island increase or decrease in vertical stability not in reaction to the speed of the wind but instead to its direction."

The situations described by Cameron are graphically demonstrated in Fig. 6, 7, 8 which are reproduced from the same report. The U.B.C. expedition did not investigate conditions in Tuktoyaktuk harbour (Fig. 9). but it is obvious that it will react to situations in Kugmallit Bay. This was confirmed by the local residents, Eskimo and Caucasian; and in particular, by Father Lemeur who has widely travelled in this region. Kugmallit Bay opens up in July, but ice floes still exist on the Beaufort Sea (Fig. 7). During calm periods, Mackenzie River water can be seen, due to its muddy colour, as far out as Baillie Point and Herschel Island. Due to mixing by wind and waves this surface water is brackish. With easterly winds the water in the inlet becomes more saline, cold, and clear, indicating inflow from the Beaufort Sea. With westerly winds, the water in Tuktoyaktuk

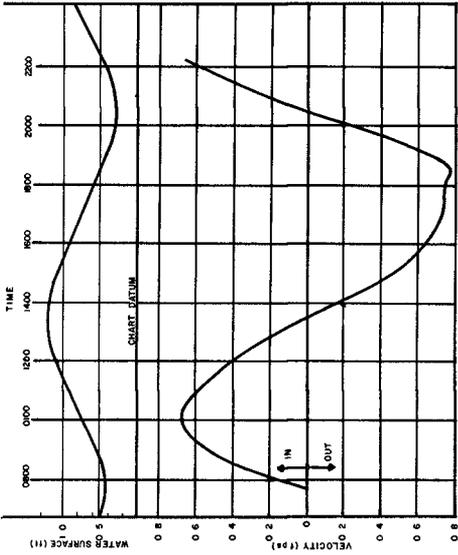


Fig. 10. Typical tide curve in Tuktoyaktuk Harbour and mean velocities at East Entrance (April 30, 1962).

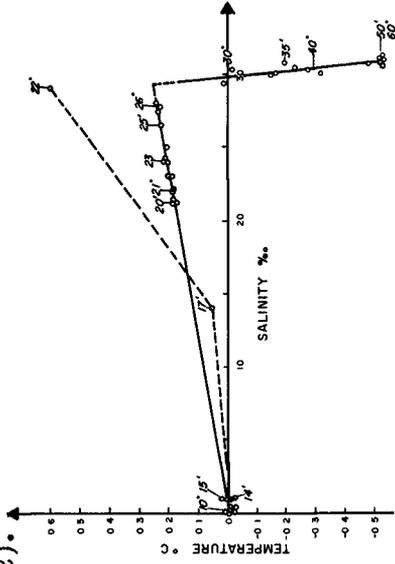


Fig. 11. Characteristic T-S diagram, Tuktoyaktuk.

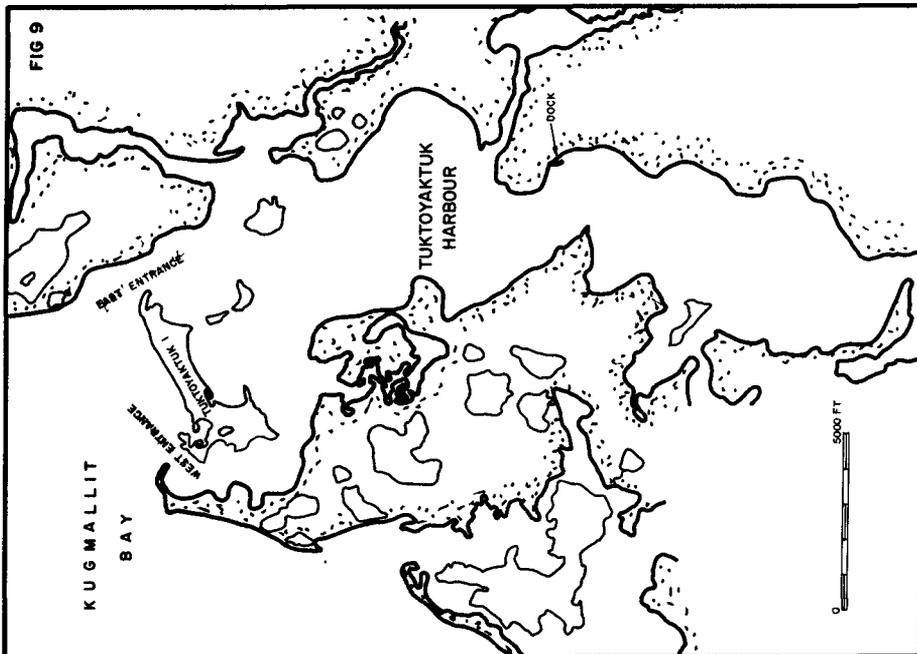


Fig. 9. Tuktoyaktuk Harbour.

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Harbour is brownish, brackish and warm, indicating inflow of Mackenzie River water. Perhaps the most characteristic feature of the area - confirmed by the Canadian Hydrographic Service - is the high set-up produced by North-westerly winds, raising the water in the harbour as much as 4 ft. above mean sea level. With south-easterly winds the water level falls as low as 3 ft. below mean sea level. The higher tide range is about 1.5 ft., while the average tide range is 1.1 ft. The flow of the Mackenzie River has not been accurately gauged, but Water Resources Branch of Canada estimate that the flood discharge may be in the order of 400,000 c.f.s.

Once the ice cover has formed the wind ceases to have a predominant effect on the dynamics of the inlet. The water in Kugmallit Bay, where the depth does not exceed 18 ft., is practically fresh Mackenzie water.

Winter Regime of Tuktoyaktuk Harbour - It is clear that the winter regime of the inlet will be dominated by the oceanographic conditions prevalent during freeze-up, modified gradually by the tide.

Tuktoyaktuk Harbour is connected to Kugmallit Bay by the East and the West Entrances. The West Entrance is very narrow and shallow and the tidal flow through it is only 12% of the total. The main tidal flow is through the East Entrance, which is the navigation channel. A typical tide curve for the harbour and mean velocity curve through the East Entrance are shown in Fig. 10. The characteristic T-S diagram for the inlet and temperature and salinity profiles are shown in Fig. 11 and 12 in solid line. Although the depth within the harbour varies, it is only necessary to cut Fig. 12 at the desired depth to get the salinity and temperature structure at any point. This remarkable stratification extends practically unaltered 15 miles into Kugmallit Bay. Since this bay is very shallow (15-18 ft.) the water here has very low salinity (0.3-0.5 p.p.t.). The ice cover protects this structure from the mixing effect of the wind. Temperature and salinity measurements at the East Entrance over a tide cycle indicated that the tidal flow consists only of this top layer of fresh Mackenzie River water, except for entrainment at the interface.

The wharf and air bubbler installation are shown in Fig. 13. A cross-section of the inlet opposite the wharf is shown in Fig. 14. This is remarkably similar to the stylized scheme 3 of Fig. 2. Although no quantitative statements can be made at this time, it is clear that the air bubbler line on the side facing the harbour will entrain more saline and warmer water and be effective in preventing the formation of ice or in melting the existing ice. In April the open water was 3 ft. wide. The airline facing the shore was not nearly as effective.

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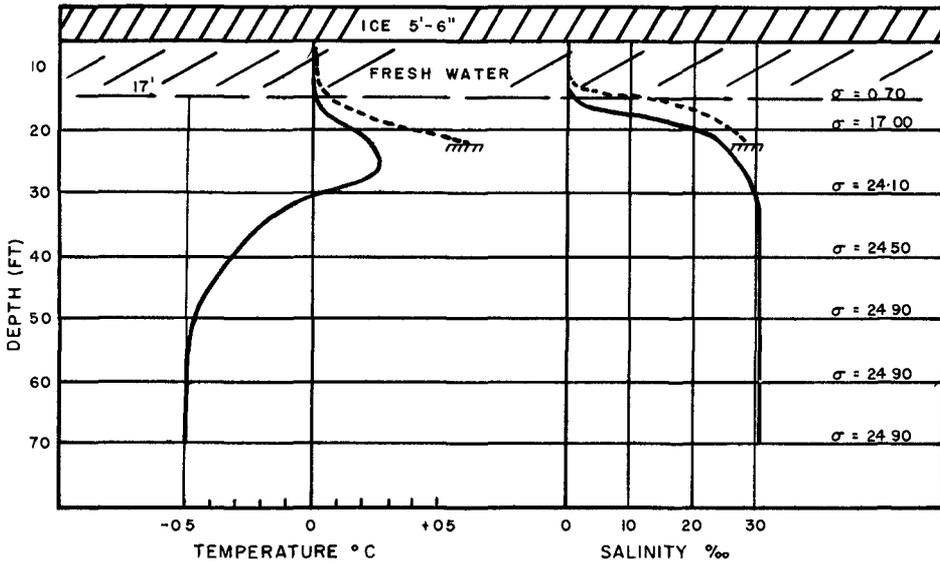


Fig. 12. Characteristic temperature and salinity structure at Tuktoyaktuk.

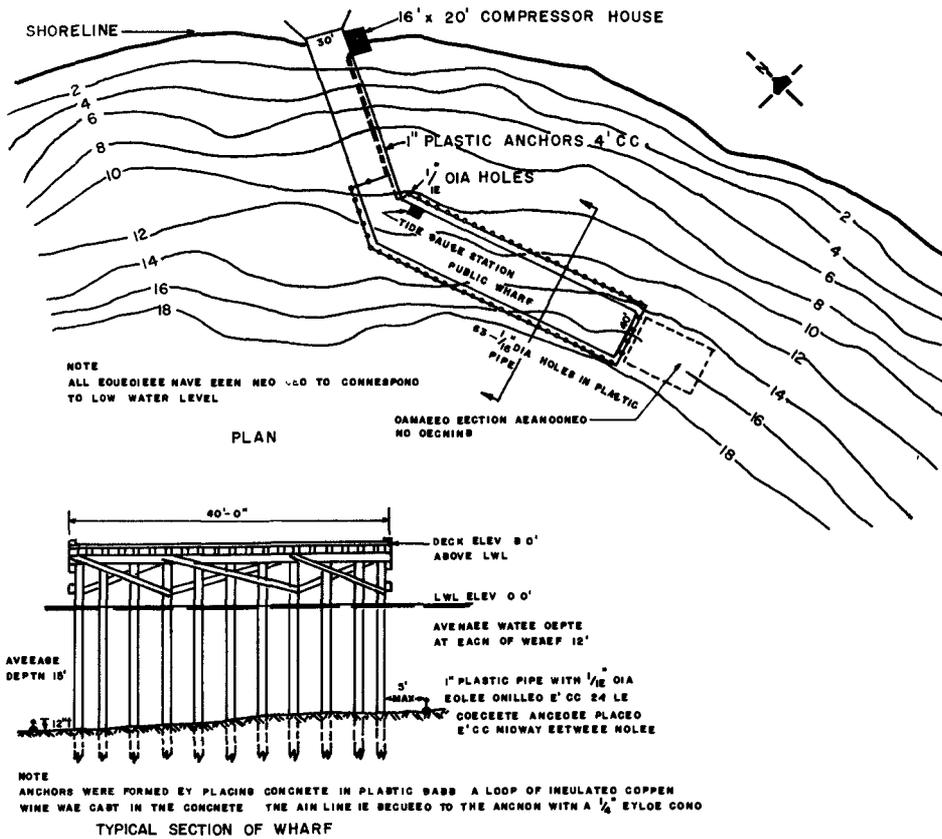


Fig. 13. Wharf and air bubbler system.

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The advection of saline and warmer water could not be unequivocally measured. Under conditions observed in April, there appears to be a delicate balance between heat losses and energy supply. It is hard to imagine that during the severe Arctic winter, when temperatures fall to 40 below zero, there is sufficient heat supplied to keep the water open. The operation of the air bubbler under these conditions may consist partly of the mechanical action of preventing the formation of an ice cover, and supplying additional heat by producing frazil ice. In fact, a rough cross-section of the ice cover near the bubbler (Fig. 14) indicates frazil ice deposition. On the other hand, the technician in charge reported that several times during the winter, the compressors had been deliberately or accidentally shot down and each time a 6-12" layer of ice had been formed over the air bubbler. When the compressors were turned on again, the ice disappeared within a short time, indicating supply of heat appreciable quantities. This could happen if the original interface between fresh and salt water had been higher so that the air bubbler was submerged along its entire length in the dense layer and the operation was similar to scheme 2 of Fig. 2. In Fig. 1 and 12 are plotted the salinity and temperature at an isolated depression with a sill of 17 ft. inside the inlet. Below 17 ft the water is warmer and more saline. This may have been the structure in the harbour at freeze-up time and may have changed gradually to the conditions observed in April.

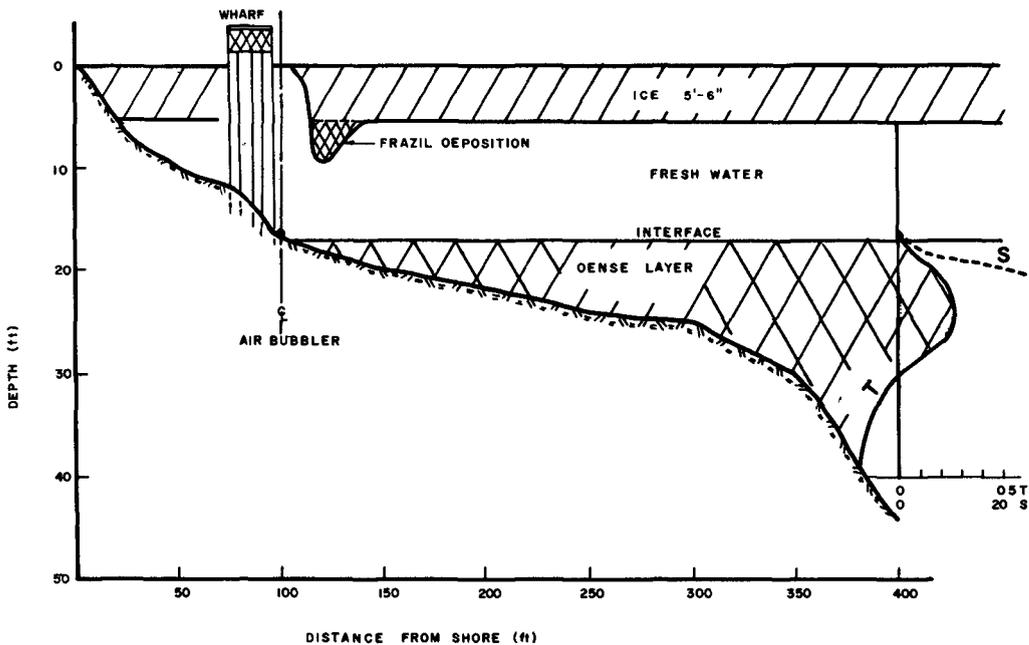


Fig. 14. Cross-section of inlet near wharf.

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CONCLUSIONS

More questions have been raised than answered. This was intentional; the author himself does not know the answers. It is planned to study the estuarine dynamics and the energy budget of the Tuktoyaktuk area in greater detail.

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