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4) KEEPING WATER FROM FREEZING BY MEANS OF COMPRESSED AIR

by

PENTTI KAITERA

In the winter of 1940 experiments were carried out in Finland with the object of keeping minor areas of water from being covered with ice. This was done by utilising the thermal reserve of water in such a way that compressed air was pumped into the water. When rising to the surface the air bubbles brought with them warm water from below and this water served to melt the ice cover. This method has been used in U.S.A. more than 30 years ago to protect the dams of water power plants from damages caused by the ice cover. In the following some results of experiments in connection with this matter are recorded together with some practical results achieved by the application of the method.

This method is entirely based on the utilisation of the thermal reserve of the water. By experiments carried out in laboratories and in the open air it has been established that water of even as low a temperature as 0.2-0.4° C will melt the ice though the melting process is very slow. But when the temperature rises to 1.0° and more the melting effect increases rapidly and thus it is possible to find an economically profitable solution by which this method can be applied in practice.

During the winter 1940-1941 experiments were carried out in some lakes of the interior, partly also in the Gulf of Finland. The procedure was generally as follows : Compressed air stored in bottles was conducted from them through tubes to various depths under the ice cover. The air was ejected from the tube through a special nozzle and the speed of the outflow could be regulated by the size of the opening of the nozzle and the pressure in the tube. The melting effect was determined by establishing how many cubic meters of ice were melted within a certain time-unit — usually 24 hours. In the majority of experiments only one nozzle was used, but some of the experiments were carried out by simultaneous ejection through 2-4 nozzles. These were placed at a distance of about 4 meters from one another.

When the bottle of compressed air was placed on the surface of the ice, the supply of air was conducted as follows : First a hole was drilled through the ice and through this hole the tube was conducted vertically down. The air then rose round about the hole through which it mainly escaped. When in some of the experiments air was conducted to such a point under the ice cover, cohere it did not escape, it formed under the ice air cavities which prevented the warm water rising from below from reaching the lower surafce of the ice. Then the melting effect was considerably reduced. The melting effect of this procedure is thus depending on the fact that a continuous flow of warm water is allowed to touch the lower surface of the ice.

During the winter referred to 44 experiments of at least 24 hours duration were carried out. The results of these experiments are shown in Table 1. The depth of water at the place of observation varied in the various experiments from 2.5 to 18 metres. In some of the experiments the nozzle was placed on the bottom, in others some distance from the bottom. The table shows its depth during the various experiments. The volume of compressed air ranged between 1.4 and 12 litres per minute. During the experiments in the early winter the atmospheric temperature was exceedingly low, sometimes almost — 40° C. During the end of the winter it was above freezing point. The temperature of the water during the various experiments varied considerably. As a rule the temperature of the water immediately below the ice was about 0° C. In the small lakes — such as Paljärvi and Tampaja — it was in the deeper strata above 3° C. Vanajavesi is a larger lake where the water is disturbed by the autumn gales at the time when it freezes. Here the temperature of the water was below 2.5° C during the time of the experiments. In the sea (Miessaari island) the temperature of the water was from immediately below the ice down to a depth of up to 5 metres below 0° C (— 0.2° C) and only at the very bottom there was a small region where the temperature was + 0.4° C. Comparing the best methods for the determination of the influence of the temperature of the water on the effect of melting, it was found most suitable to use the temperature of the water at the depth of the nozzle as a standard. This temperature varied, as the table shows, from 0.4-4.2° C. The

Table No 1. *Results of experiments during Winter* 1940-41.

Number of experiment	Experimental site	Date when experiment	Depth of water on the observation point — in metres	Mouth-piece was sunk to a depth of — meter	Number of began mouth-piesce	Volume of compressed air — litres/minute	Air temperature during the time of experiment	Watertem- erature at he' site of mouth-piece		Thickness of ice in cm	Melted ice-volume during 24 hours—in cubic metres
								Before experiment	after experiment		
1	Palojärvi	29. 11. 1940	16	10	1	8.0	—15.0	4.0	4.0	31	16.0
2	»	6. 1. 1941	17	10	1	1.6	2.0	4.0	4.0	48	1.7
3	»	15. 1. 1941	13.5	10	1	4.4	—39.0	4.0	4.0	50	12.0
4	»	28. 1. 1941	17	5	1	2.0	—26.5	3.6	3.5	59	1.5
5	»	»	17	5	1	3.2	—26.5	3.6	3.6	58	1.9
6	»	»	17	5	1	4.1	—26.5	3.6	3.6	56	2.1
7	»	17. 1. 1941	17	10	1	1.4	—38.7	4.0	4.0	51	2.7
8	»	»	17	10	1	2.3	—38.7	4.0	4.0	51	4.4
9	»	»	17	10	1	2.8	—38.7	4.0	4.0	52	5.6
10	»	20. 1. 1941	17	10	1	3.6	— 6.4	4.0	4.0	62	5.0
11	»	21. 1. 1941	17	10	1	3.6	—28.6	4.0	4.0	55	4.2
12	»	31. 1. 1941	17	2.5	1	2.3	—11.4	2.5	2.7	60	1.3
13	»	»	17	2.5	1	3.5	—11.4	2.5	2.8	58	2.0
14	»	»	17	2.5	1	4.6	—11.4	2.4	2.7	56	2.1
15	»	5. 2. 1941	3	2.5	1	2.7	—23.8	4.0	4.0	53	0.55
16	»	»	2.7	2.5	1	4.0	—23.8	3.9	3.8	51	1.06
17	»	»	3	2.5	1	5.3	—23.8	4.0	3.8	52	1.5
18	»	7. 2.1941	7	5	1	2.3	—17.4	3.6	3.0	52	1.0
19	»	»	7.5	5	1	3.4	—17.4	3.6	3.5	51	1.7
20	»	«	6.5	5	1	4.5	—17.4	3.6	3.7	54	1.9
21	»	14. 2. 1941	17	10	1	2.0	—12.0	4.0	4.0	63	4.0
22	»	18. 2. 9141	17	10	1	6.5	—12.9	4.0	4.2	62	7.7
23	»	3. 4. 1941	18	10	1	3.1	— 9.4	4.1	4.2	61	3.3
24	Vanajavesi	6. 3. 1941	11	10	2	8.0	— 5.0	1.9	1.4	59	3.1
25	»	»	11	10	3	8.0	— 5.0	1.9	1.4	67	4.8
26	»	»	11.5	10	4	8.0	— 5.0	1.9	1.4	47	5.5
27	»	10. 3. 1941	16.5	16	2	6.0	— 2.5	2.5	7	56	5.7
28	»	»	16.5	16	2	3.0	— 2.5	2.5	2.6	59	2.8
29	»	11. 3. 1941	11	10	2	8.0	— 7.5	1.7	1.6	56	2.6
30	»	»	6	5	2	11.0	— 7.5	1.7	1.6	64	2.9
31	»	29. 4. 1941	8	8	1	9.0	— 3.3	1.6	1.7	65	3.0
32	»	»	8	8	2	9.0	3.3	1.6	1.7	70	3.5
33	»	»	8	8	3	9.0	3.3	1.5	1.6	65	3.4
34	Tampaja	15. 4. 1941	9.5	7.5	1	9.5	1.1	2.7	3.6	67	6.0
35	»	»	10	7.5	2	9.5	1.1	2.7	3.6	68	5.6
36	»	»	10	7.5	3	9.0	1.1	3.4	3.7	67	11.8
37	»	16. 4. 1941	6	5	1	11.0	0.7	2.4	3.2	75	3.5
38	»	»	6	5	2	11.0	0.7	2.4	3.2	75	5.2
39	»	»	6	5	3	11.0	0.7	2.4	3.2	70	5.5
40	»	18. 4. 1941	2.5	2.5	1	11.5	0.8	1.8	2.2	76	0.85
41	»	»	2.8	2.5	2	12.0	0.8	2.2	3.5	70	2.12
42	»	»	3	2.5	3	12.0	0.8	2.2	2.5	71	2.4
43	Miessaari	6. 4. 1941	8	8	1	9.5		0.4	0.4	70	0.25
44	»	»	8	8	1	9.5		0.4	0.4	65	0.25

table also shows how the value of this temperature changed during the time of the experiment. The table records, in addition, the thickness of ice and the volume of ice melted within 24 hours. The volume of ice melted varied from 0.25-16.0 m^3/24 hours. In some experiments, not recorded in the table, the volume of ice melted was 30 m^3/24 hours. The volume of melted ice was measured in the following way: Along lines perpendicular to one another through the centre observation holes were drilled in the ice at a distance of 1 metre from one another. Through these the thickness of the ice was measured before and after the experiment. Fig. 1 shows a cross of the hole in the ice caused by experiment 1.

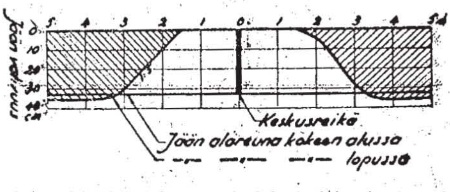

FIG. 1. Section of opening melted in 24 hours. At lake Palojärvi 30-11-1940 (Exp. 1).
Jään vahvuus = Thickness of ice.
Keskusreikä = Central hole.
Jään alareuna kokeen alussa = Lower face of ice at beginning of exp.
» » » lopussa = » » » » » end of experience.

Already a cursory study of Table 1. shows that the temperature of the water decisively affects the melting of the ice. In the same way the melting effect increases with an increased volume of compressed air. It is also obvious that the position of depth of the bubbling point affects the volume melted.

In order to draw conclusions from material at hand as to the influence of the various factors we shall first study only the influence of the temperature of the water and the quantity of compressed air. Disregarding the observations where the nozzle was at a depth of 2.5 m and where compressed air was distributed through three or four nozzles, we arrange the experiments in three groups according to the quantity of air (quantity of compressed air < 3.0 1/min., 3.0-6.0 1/min and > 6.0 1/min) and according to the temperature of the water at nozzle into four groups (temperature < 1.0° C, 1.1° C - 2.0° C, 2.0 - 3.0° C and > 3.0° C) and then get the average group-values recorded in Table 2.

Table No 2. — *Average-values of experimental results of groups based on the quality of compressed air and on the temperature of water at the nozzle.*

Number of in group experiments in group	Compressed air volume. 1/min.	Depth. site of mouth piece. m.	Water temperature at site of mouth-piece	Melted ice-volume m^3/24 hours
2	9.5	8.0	0.4	0.25
1	9.0	8.0	1.6	3.0
1	11.0	5.0	2.4	3.5
3	8.0	9.2	3.6	9.9
4	4.5	8.2	1.7	1.55
2	4.2	10.5	2.4	2.7
9	3.85	7.5	3.7	3.9
1	1.5	16.0	2.5	1.4
7	2.05	8.6	3.9	3.0

The table shows that in case the temperature of the water and the position of the nozzle are constant the volume of melted ice increases in approximately direct proportion to the increase of the quantity of air.

Table No 3. — *Altered group average values based on the values recorded on table No 2 when depth site of mouth-piece is 8 m.*

Compressed air volume. l/min.	Water temperature at site of mouth-piece ° C.	Melted ice-volume m^3/24 hours
8	0.4	0.2
8	1.6	2.7
8	2.4	4.2
8	3.6	8.7
4	1.7	1.4
4	2.4	2.3
4	3.7	4.1
2	2.5	1.5
2	3.9	3.0

The results are shown in Table 3 and Fig. 2. The average group-values in Fig. 2 show fairly accurately that the melting effect increases as the quantity of compressed air and temperature of the water increase. The increase of the quantity of air causes a strong current of water which quickens the transfer of heat from the water to the ice. It is evident that by using larger quantities of air the addition of a certain quantity of air causes more and more reduced increases of quantities melted. This was established by the experiments conducted between 28.3 and 3.4 1946. On these occasions an air quantity of 100 1–min was used. The results of these experiments are shown by the dash line in Fig. 2.

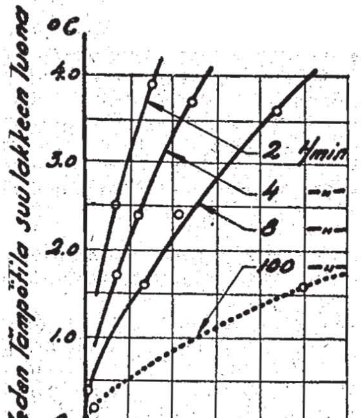

FIG. 2. Dependance of quantity of ice melted (m^3/24 h) on quantity of compressed air and temperature of water at nozzle — depth 8 m.
Veden lämpötila = Temperature of water at nozzle.
Sulanut jäämäärä = Quantity of ice melted.

The figure also shows that by increasing the quantity of compressed air the same melting effect can be achieved up to a certain limit in cold as well as in warm water. For instance, by using a quantity of air of 8 1–min the same melting effect can be achieved in water of a temperature of 0.9° C as by using an air quantity of 4 1–min the temperature of the water being 1.5° C at the nozzle. The using of larger quantities of air is subject to greater initial- and running costs. Here the question arises

How to determine the limit for an economically profitable undertaking ? The curves in Fig. 2 give an indication to the solution where this matter is concerned. When the temperature of the water is low the thermal reserve might prove inadequate to keep the water area from freezing during a cold period.

If there is available a compressor the effect of which is, for instance, 3.5 m³–min and which requires a motor of 35 H.P., a 20 m wide hole in the ice, the thickness of which is 0.5 m, can be worked under the average conditons stated in Fig. 2, on condition that the compressed air tubes are placed in the most advantageous places — approximately corresponding to the values shown in Table 4.

Table No 4. — *A compressor the effect of which is 3.5 m³/min. and equipped with a 35 H.P. motor. To melt a 20 m wide crack in ice, thickness of ice being 0.5 m. Time for melting operation : 24 hours.*

Water temperature on a depth of 8 m. ° C.	Lenght of crack. m.	Theoretical motor effect to melt the crack. H.P.	Rate of machine effect (theoretical) compared with effect of 35 H.P. compressor
0.5	15	700	20
1.0	65	3100	90
2.0	160	7500	220
3.0	290	13500	390
4.0	450	21000	600

Table 4 also shows the amount of energy required for the melting of the openings in case all the energy necessary for the melting should have to be mechanically produced. Further, the summary accounts for the multiplied increase of the effect of the compressor in each case. When the temperature of the water is 0.5° C the gain of energy is 20-fold, at 2.0° C water it is 220-fold and at 4.0° C water 600-fold. This shows the advantage of this method with regard to economy of energy in comparison with methods in which the energy necessary for the melting is mechanically produced.

For the sake of finding out the influence of the depth of the bubbling point the observation material — not counting experiments in which the temperature of the water has been below 0.5° C or in which the number of nozzles has been 3 or 4— has been grouped on the basis of depth on four groups and on the basis of the temperature of the water and quantity of compressed air in two groups when — by making further use of the curves in fig. 2 — the average group-values shown in table 5 are arrived at.

Table 5. Average group-values showing the influence the depth of nozzle, the temperature of the water being 4° C and 2° C and the quantity of compressed air 8 1–min and4 1–min.

Water temperature at site of mouth-piece	Volume of compressed air. l/min.	Depth site of mouth-piece. m.	Melted ice-volume m³/24 hours
4	8	7.5	9.2
		10.0	13.2
4	4	2.5	1.1
		5.0	2.6
		10.0	7.2
		2.5	1.0
2	8	5.0	2.3
		9.0	3.7
		16.0	5.7
2	4	2.5	1.5
		16.0	2.8

The results are also shonw in Fig. 3 where the points of the same quantity of compressed air and the same temperature of water are connected. The curves

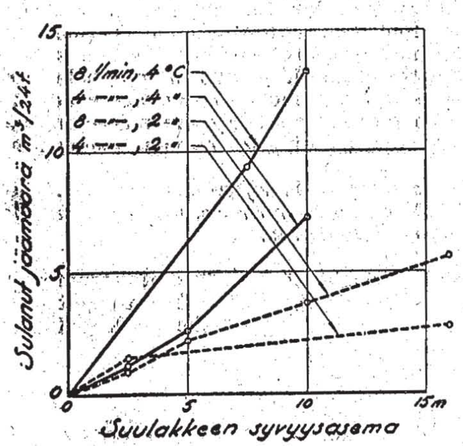

FIG. 3. Dependence of quantity of melted ice on depth of nozzle under various conditions.
Sulanut jäämäärä l° /24 t = Quantity of ice melted m° /24 h.
Suulakkeen syvyysasema = Depth of nozzle.

show that when the bubbling point is lower the effect of melting grows greater the higher the temperature of the water is. When the quantity of compressed air is constant, the bubbles, when rising from a deeper position, move a greater mass of warm water than in shallow water, in which latter case the method thus offers less favourable prospects than in deep water. In deep water a greater amount of energy is certainly needed to eject the same quantity of air from the tubes than in shallow water but, on the other hand, a greater depth of water generally means a higher temperature and a greater thermal reserve in the mass of water which is set moving by the bubbles. It is also evident that in 10-20 m deep water the transfer of thermal reserve can take place from a further peripheral distance than in shallow water, which also increases the available thermal reserve.

The melting effect is also influenced by the number of nozzles used for the ejection of a certain quantity of air into the water. After certain adjustments the following data concerning the influence of the number of nozzles are arrived at:

Number	of	nozzles	1,	quantity of	ice	melted	3,5 m³–24 h
»	»	»	2	»	»	»	3,9 »
»	»	»	3	»	»	»	4,9 »
»	»	»	4	»	»	»	5.0 »

In each group the other average conditions are as follows:

Average depth of nozzles	6.6 m
Quantity of compressed air	9.7 l/m.
Temperature of water at nozzle	2.2° C

From this it can be noticed that the melting effect accomplished by the same quantity of air grows as the number of nozzles grows. The result tallies with the previously stated facts as larger masses of water are set in motion in this case.

Further, attention should be given to the influence by the temperature of the atmosphere. As shown in table 5, experiments have been carried out under as low a temperature as —39° C. It is evident that such a severe frost will decrease the effect of the melting process as compared with a similar process during thaw. The observation material is, however, too inadequate to allow a numerical representation of the influence of temperature, as it depends inter alia on the thickness of the ice and the size and shape of the opening which varied considerably during the experiments. It is, all the same, to be noted that the temperature of the atmosphere is not a decisive factor as long as the surface to be melted is not too big. A continuous keeping of a surface of water from freezing during a whole winter season makes the importance of the influence of the temperature grow. In the winter 1946-47, when an opening 30 × 80 m for floating timber was kept free from ice, the compressor had to be kept running 20-22 hours a day during hard frost but during light frost the time was reduced to 2-4 hours a day.

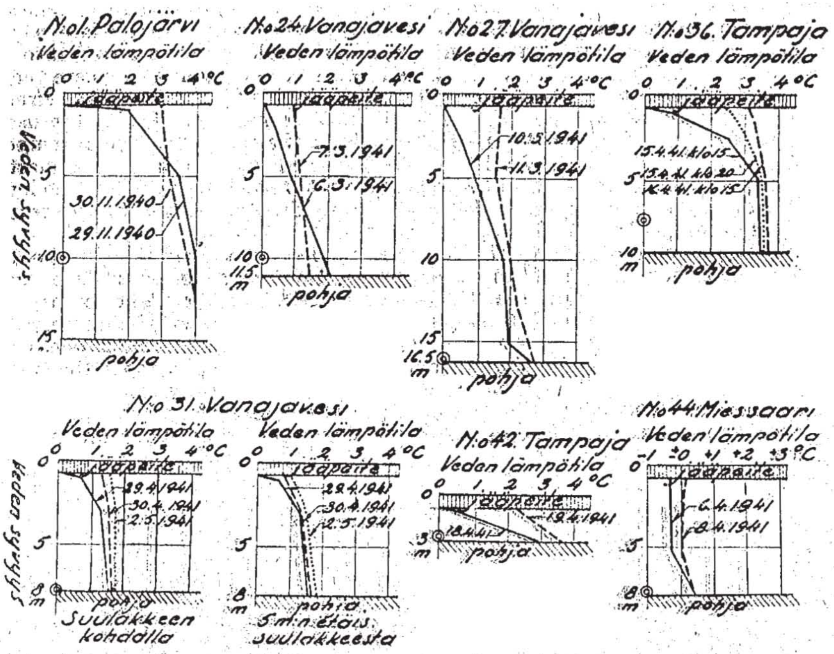

FIG. 4. Temperature of water at various depths before trial (drawn line), after 24 hours trial (dash line) and at various phases of the trial (dotted line). Doubble circle denotes depth of bubbling point.
Veden lämpötila = Temperature of water.
Jääpeite = Ice cover.
Veden syvyys = Depth of water.
Pohja = Bottom.
Pohja suulakkeen kohdalla = Bottom at nozzle.
Pohja 5 m:n etäis. suulakkeesta = Bottom 5 metres from nozzle.

During the experiments attention was paid to the fact that the temperature of the water near to the melting opening did not fall as much as could be expected considering the quantity of heat necessary for melting the ice and keeping the water from freezing. This did not happen even when the depth of water was remarkably shallow : 2.5-5.0 m. In order to demonstrate this fact Fig. 4 shows the temperatures of the water at the beginning and end of experiments with various depths (continuous lines). The depth position of the bubbling point is marked with a double circle. The experiments demonstrated in this figure are the same as those marked in Table 1 with corresponding numbers. As shown in the figure the temperature of the water of the strata, including at the depth of the bubbling point, has risen in many experiments independent of the fact that considerable quantities of heat has been required for melting the ice.

Table 1 shows that, taking into consideration the whole observation material, the temperature at the bubbling point has risen an average of 0.1° C. The number of experiments where the temperature of the water has remained unchanged or has risen has been 34, while a fall of temperature has taken place in 10 experiments. It is possible that in several cases there has been near the bubbling point hollows in the bottom from where warmer water has risen. The experiences which have been got later from practical applications of the method, confirm the idea that thermal reserves are transferred to such an extent from peripheral points that, under known conditions, there is no fear of their exhaustion.

Considering the conditions under which the method is applicable in practice, the temperature of the water during the winter months must be taken into account. In this respect the sea, the rivers and the lakes differ very much from one another.

During the early Winter the autumn gales mix the surface layers of sea water The water remains a long time open and, as the temperature of it can fall below 0° C before any freezing takes place, because of the percentage of salt, the surface layers up to a depth of 30-40 metres is cooled to about the freezing point. Generally the temperature of this top layer is 0.1-0.3° C and even below 0° C in the late winter. The wind also causes currents in the surface water. Cold water is forced into the bays of the shore and cooles the water there down to the bottom also where the ice cover protects it from the influence of winds and cold air. Under these circumstances the conditions for keeping even small surfaces free from ice by the use of compressed air are not at hand. Exceptions do, however, exist. Thus temperatures of 1.0-2.0° C at a depth of 5-10 m were recorded in some bays in connection with the experiments. It can also be assumed, that in such bays into which larger rivers discharge, the temperature of the water mainly depends on the thermal reserve of the water brought by the river.

In the winter of 1946-47 experiments were carried out to find if it was possible to transfere thermal reserves from deeper water through a colder surface layer. The experiments were arranged near the lighthouse of Söderskär. The temperature of the water down to a depth of 30 m was below 0° C. Lower down the temperature rose rather abruptly, being 1.3° C at 40 m and 3.2° C at 50 m. Through one nozzle 200 l /min. air was ejected. During the experiment currents appeared in the surface water in such a way, that the bubbles at times rose 10-20 m away from the opening above the nozzle. This as well as the depth of the cold surface layer caused the temperature of the water to rise only 0.1° C and could not bring about any melting of the ice.

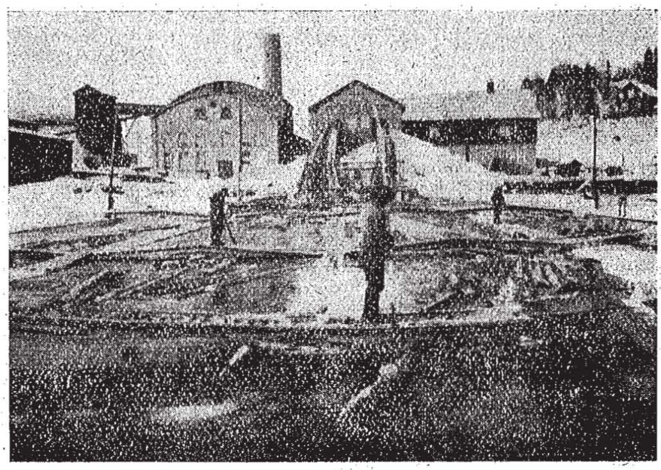

FIG. 5.

The temperature of river water depends essentially on the situation of rapids. In these water comes into contact with the cold air and its temperature easily falls to about 0° C. In rivers, however, new thermal reserves are brought from the upper courses and there is no fear of exhaustion of the thermal reserve. By using sufficiently large quantities of air the method can be applied inter alia for the protection of the dams of power stations from damages caused by the ice.

In lakes the thermal reserves are essentially more favourable than in the sea or the rivers as far as the application of the method is concerned. Already at a depth of 5-10 metres the temperature of the water in the Finnish lakes usually is above 1.0° C, whereby the effect of melting grows high enough to make it possible to find paying solutions for practical purposes. Also in the lakes the gales of early winter cause a mixing of the surface water. Because of this the temperature of big lakes is considerably lower than in small lakes. Investigations, have shown that in such lakes, where the area exposed to the wind is at least 3 km, the temperature of the water at a depth of 5 metres varied between 0,5-2.0° C during the winter months. In small lakes the neasured variations at the same depth were 1.5-4.0° C.

Because the results of the experiments accounted for here above, the saw-mills on the banks of the Finnish lakes have started to keep the sorting basins open by using compressed air. The method has shown itself very economic and by applying it labour has been saved and the result of sawing has increased to such an extent that the cost of the plant ahs been paid within one winter. At the Ilola saw-mill on the shores of lake Päijänne measuring of temperatures was arranged in the winter of 1946-1947. to find out to what extent there was a danger of the thermal reserve being exhausted as a large surface had to be kept continuously melted. The size of the sorting basin of that saw-mill is 30 × 80 m (Fig 5) and the depth of water there varied between 4-8 metres. Air from the compressor is conducted trough a net of tubes on the bottom. To keep the opening melted it has been necessary to use about 3.0 m^3/min air. The performed measurings of temperature have shown that during the whole winter the temperature of the water in the melting opening as well as outside it remained constant at a depth of 3 metres i.e. 0.7-0.8° C. On the bottom the variations were somewhat greater, the temperature at the melting area being 0.2° C lower than at a distance to the side, where it remained 1.2° C the whole winter. The winter mentioned above was exceptionally cold and during January-March the temperature of the air varied between — 10 and — 30° C. During the days of hardest frost air had to be compressed up to 22 hours a day, but at a temperature of appr. — 10° C 10-15 hours work was suffficient. When the temperature rose to 1-4° of frost towards the end of March, there was no more need to use the compressor. These as well as other applications show that transfer of heat from peripherical areas takes place with the currents of water in such a way that there is no fear of the thermal reserve being exhausted.

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