# SUPERCOOLING AND ICE FORMATION IN OPEN WATERS

## (ICE STUDIES I)

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### SUMMARY

The supercooling of water plays a transient, but important part in static ice formation in still water, in so far as it necessarily occurs when the freezing process of the surface layer is being started. It is of lasting importance, however, when the process of dynamic ice formation takes place in running water. The present paper concerns measurements of the supercooling in both cases, the chief available material concerning static ice formation, comprising records of the surface temperature by means of the outgoing radiation, observed by a Moll thermopile combined with photographic registrering. The instrumental equipment is described, and examples are represented of surface temperature diagrams related to static ice formation. These records so far represent a documentation of a supercooling of the surface layer of open water descending below — 1° C. It is emphasized that the state of supercooling is a stable one, the formation of ice crystals being dependent upon the existence of nuclei in the water, or of solid boundary surfaces from which crystallization will start and the liberated heat of crystallization will flow. The process of thermal conduction necessarily needs time, and thus a state of supercooling may be retained outside the crystal boundary surface, which passes more or less slowly into the adjacent medium as the freezing proces goes on.

1. In a special treatise[1]) concerning the thermal and dynamic conditions of ice formation in rivers, the author has considered the ice formation both (a) in still or slowly moving water, which was termed *static ice formation*, and (b) that in running, turbulent water, which was termed *dynamic ice formation*.

In the case of static ice formation a surface cover is formed, the crystallization thereby starting partly from solid matter at the beach, and partly from solid material suspended or floating in the water, especially from the ever-occurring suspended particles which serve as nuclei. If the weather is calm and the water at rest, everyone who has seen a pool being covered by ice will have perceived the network which is formed by crystal beams, leaves, feathers, stars and other forms, which extending from the starting places, leave the water open for a time between the elements of ice structure. It will be shown in this paper that the ice formation in this case is regularly preceded by a supercooling of the uppermost water strata, which will continue to exist at the open parts of the water until they are all covered by ice. The transmission of heat from the water underneath, to the surface exposed to loss of heat into the surrounding atmosphere, will be chiefly due to conduction, the water particles of the surface layers approximately keeping their places. The thermal conductivity for water at rest being small, a considerable temperature gradient may accordingly be established in the water layer immediately below the surface of the water. Thus temperatures of the surface itself extending to below — 1° C may be observed (section 3).

In dynamic ice formation in running water, quite different conditions prevail. As long as the water is open, the individual particles of the water surface layer exposed to heat loss will be interchanged with others, within a period of time which is all the shorter the more turbulent the motion. The heat transmission in this case will be chiefly due to convection and mixing, and the thermal conductivity will greatly exceed that for resting water. Consequently, the temperature gradient

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[1]) (1) Olaf Devik: Thermische und dynamische Bedingungen der Eisbildung in Wasserläufen, auf norwegische Verhältnisse angewandt, Geof. Publ. IX, No. 1, 1931.

maintaining the heat transmission from the deeper strata will generally be small, and observations at different depths will show small differences of temperature.

When the whole mass of water has been cooled to nearly 0° C, the ice formation begins, but a coherent ice cover is generally not formed, the typical process in northern latitudes being the formation of ice particles distributed in the whole water flow, loose drifting aggregations of such particles and often the formation of anchor ice at the bottom of the river. In the paper mentioned (p. 82—92) the author has treated the ice formation in this case, which is dependent upon a supercooling of the whole water mass. *Altberg* was the first to emphazise the importance of supercooling in the formation of anchor ice and has reported measurements confirming this. As an example, we may quote a paper by Altberg[1]) reporting measurements of the *Neva.* Altberg then observed that the river water during the ice formation process was supercooled both at the surface and at the bottom, as well as in the intermediate layers. The supercooling was usually small, and would generally vary between 0.001° C and 0.01° C, rising in exceptional cases to as much as 0.1° C. During the period of the observations, there commonly occured formations of loose ice under water, on submerged objects and sometimes at the bottom. In section 5 below we will consider temperature measurements in dynamic ice formation more closely.

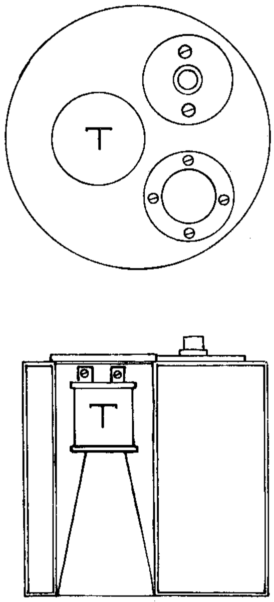

Fig. 1. Mounting used 1930. T-Thermopile.

2. A preliminary measurement of the supercooling occurring in open water in static ice formation was performed by the author in 1930 ((1), p. 51—53) by means of the heat radiated from the surface. As receiver was used a Moll thermopile (Fig. 1), which was mounted in a double-walled vessel, the space between the walls being filled with ice and water. The mean temperature of the thermopile was accordingly considered to be approximately zero. The potential of the thermopile was measured by a simple bridge coupling ((1), p. 53).

Several years later an error concerning the determination of the thermal sensitivity of the receiver was discovered, the numerical values of the surface temperature calculated being wrong and a critical revision of the arrangement of the thermopile made a new investigation desirable. The chief points concerning the revised apparatus will be mentioned here.

The receiving instrument of Fig. 1 is placed in cold air just over a much warmer water surface and strong temperature gradients thus characterise the immediate surroundings of the instrument. Moreover, the temperature distribution will change with every breath of wind, however small it may be. The heat transmission from the receiver instrument to the sorrounding air will be considerable in the case of Fig. 1, the receiver being approximately kept at the same temperature as the water surface. Of special influence to the measurements will be the heat current passing from the wall of the cone to the air.

The cone of the thermopile having a thickness of only one millimeter, considerable temperature waves may be propagated to the inner parts of the thermopile where the two groups of thermocouples (80 elements of constantan-manganine) are placed. To form an estimate of the influence of disturbing heat currents entering the material surrounding the two groups, as compared with the influence of the radiation changes which are to be measured, we first notice that the E. M. F. of the Moll thermopile is about $10.10^{-3}$ volts when the difference of temperature between the two groups of elements is 1° C. Next we have to consider, according to section 3 below, that an E. M. F. of $1.90.10^{-5}$ volts will be generated by the thermopile when it is exposed to the radiation from an extended water surface with a temperature differing 1° C from that of the thermopile. A temperature difference between the two groups of elements of the thermopile will thus produce an E. M. F. which will be about 150 times greater that that produced by an equal temperature change of the radiating surface. Consequently, if we wish to measure the surface temperature of water by radiation with an accuracy of say 0.05° C

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[1]) W. J. Altberg: Anchor Ice. On the Cause of the Formation of Ice at the Bottom of Rivers and Lakes, Quaterly J. of the Royal Met. Soc. Vol. XLIX No. 205, 1923.

we shall have to keep stray heat currents in the material surrounding the thermocouples, so small that the temperature difference caused between the said groups keeps below 0.0003° C. It is evident that this will be difficult to attain even if the mounting of the thermopile be constructed in a way allowing only slow and small temperature changes to take place during the observation period. To obtain reliable measurements we shall also have to make such arrangements that a correction, if necessary, may afterwards be possible.

With a view to these claims, we abandon the idea of keeping the receiver instrument at a temperature differing much from that of the air (as in the preliminary arrangement of Fig. 1), letting the receiver with its mounting obtain the mean temperature of the surrounding air.

Summarizing, we conveniently provide for:

a) considerable heat capacity of the receiving system as a whole,
b) good heat conduction in the material of the cone, in order to reduce temperature gradients that might sensibly alter the temperature distribution of the inner parts,
c) effective shielding of the thermopile itself,
d) diaphragms placed in the receiving cone to smoothe rapid air movements in the cone, constructed with due regard to b).

In order to be able to eliminate a moderate drifting of the galvanometer reading,

e) photographic registrering

should be provided for.

3. A mounting of the Moll thermopile, which has proved to be satisfactory for observations in open air, is given in Fig. 2. The copper cone with a series of diaphragms is machined from a solid copper tube with thick walls. The connection with the inner tubing is designed as a thread coupling, with spare room for a window of rock salt or fluorspar. In calm weather or wind velocities below 1—2 Beaufort, however, no window is necessary when photographic registering is used. Almost all the measurements given below are made without a window. The thermopile itself is enclosed in a cylindrical copper chamber with thick walls, closed by an ebony cover, through which the conducting wires are passed. As a mantle there are used two copper cylinders, in order to screen away undesirable radiation and reduce the influence of the temperature gradient of the air outside the mantle. The cylinders also serve as ventilation tubes, being connected with a small electrically driven ventilator at the top of the cylinders. Ventilation is used to accelerate the heat exchange when the temperature of the receiver differs too much from that of the surrounding air; the ventilator is stopped, however, when observation begins1). By this arrangement, the temperature of the thermopile receiver will approach the average temperature of the air column which it intersects at some distance from the water surface.

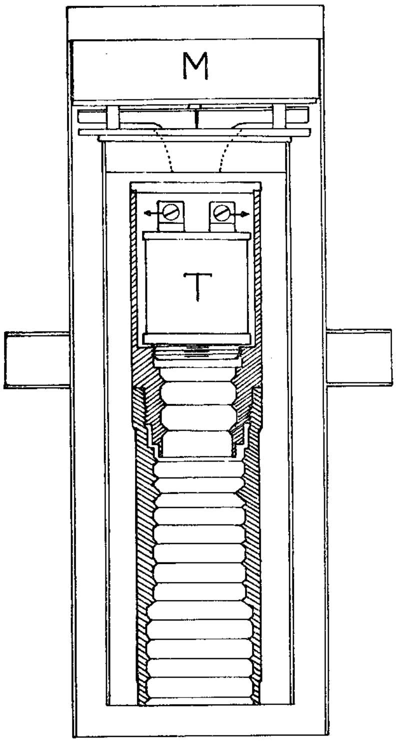

Fig. 2. T Thermopile. M Motorhousing for ventilator.

When the receiver is exposed to the radiation from the water surface, the thermopile will generate an E. M. F. = V, proportional to the total temperature difference T between the water surface and the thermopile. We are, however, interested in registrering only comparatively small changes of temperature of the water surface, with maximum sensitivity of the arrangement, and accordingly it will be necessary to compensate for the E. M. F. corresponding to the mean total temperature diffe-

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1) To control the temperature distribution of the inner parts of the thermopile, two special thermocouples are mounted at convenient places. Before measurement begins it may then be ascertained, according to experience, whether disturbing temperature gradients are sufficiently low.

rence without diminishing the sensitivity of the galvanometer. Popularly expressed, we are to force the deviated galvanometer light spot back to the starting point, either by torsion or most conveniently by introducing a compensating E. M. F. opposite and equal to V, as indicated by the potentiometer circuit given in Fig. 3. The potentiometer reading of the potential V will then be a measure of the mean temperature difference T.

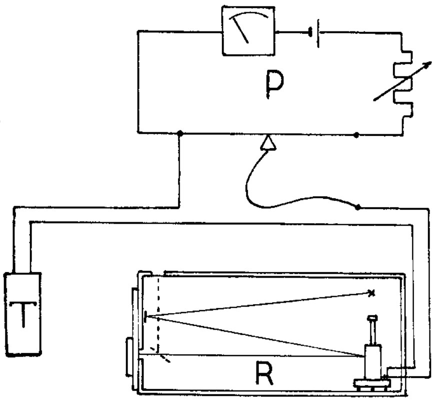

Fig. 3. T Thermopile. P Potentiometer. R Registering case.

When the receiver is at temperature equilibrium with the air, T will also be equal to the difference between the temperature of the water surface and that of the air surrounding the receiver, which may be observed directly with a thermometer. Doing this we obtain a control of the calibration of the instrument. An independant calibration is given below.

A Moll galvanometer was used as recording instrument, mounted in a transportable case containing light beam arrangement, a transparent scale for visual observation and photographic registering arrangement (Fig. 3). A plate registrator was used, driven by a gramophone motor or by a synchronous electric motor. For time marking, the light beam is reflected aside to the transparent scale for visual observation, thus giving simultaneous control observation.

The calibration of the receiving apparatus was performed by means of water flowing rapidly over a plate placed horizontally underneath the receiver, at the same distance as that generally used for the actual measurements. By using alternatively water from two reservoirs of different temperature the simultaneous registrering of the amplitude of the galvanometer may directly be turned into a temperature scale. According to calibration, the scale value on the original registering curve is $ds/dT = 18.1$ *mms/° C,* denoting by $ds$ the scale difference of the galvanometer reading and by $dT$ the corresponding temperature change of the radiating water surface. The practical limit of reading being $^1/_3$ mm, it will thus possible to determine the temperature of the radiating water surface with a maximum accuracy of 0.02° C. On the registering curves reproduced in Fig. 5 below, the temperature scale is added.

From the scale value thus determined is calculated the sensitivity $dV/dT = 1.90 . 10^{-5}$ *volts per degree centigrade*, representing the change $dV$ of E. M. F. generated by the thermopile for a temperature change $dT$ of the radiating water surface[1]).

The calibration thus attained applies, as a matter of course, to temperature measurements concerning a water surface. Within the actual accuracy of the reading it will, however, also be applicable to temperature measurements of an ice surface: neither was an appreciable change of the reading observed when water, cautiously kept at 0° C, was allowed to freeze, and was covered by a thin membrane of ice, nor when the ice cover was perforated allowing water to spread rapidly over it.

4. During April—May 1941 a series of observations were made at *Sörnesset* near *Atnasjöen*, at a height of 750 m above sea level. The ice formation was studied in a wooden water basin (2 m × 1 m × 0.5 m) through which water from a spring was slowly passing. Both at the inlet and at the outlet of the basin the water remained open, while the central part received a covering of ice. Here the receiver was placed 10 cm's above the surface (Fig. 4), the observations being made in the evening or in the early morning hours, when the temperature was at its lowest. At this time of the year temperatures below zero at this place only occurred with clear sky or light clouds.

At every registrering it is necessary to have at least one observation of the radiation from a 0° surface at the place of the water surface. The 0° surface is procured either by a freshly prepared snow stirabout, or more conveniently by the thin

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[1]) We have $\frac{dV}{dT} = \frac{dV}{ds}\,\frac{ds}{dT} = \frac{R_g + R_t}{R_g}\,\frac{dV_g}{ds}\,\frac{ds}{dT}$, $R_g$ being the resistance of the galvanometer, $R_t$ that of the thermopile, $dV_g/ds$ the known volt-sensitivity of the galvanometer, and $ds/dT$ known by calibration.

Fig. 4. Thermopile receiver mounted at Sörnesset 1941.

membrane of newly formed ice, the temperature of the top surface of a leaflet of floating ice being very nearly 0° C as will be shown below.

Is is to be observed that this procedure will enable a determination of the *actual* freezing point to be made, notwithstanding the fact that the water contains small quantities of solutable salts, which would lower the freezing point somewhat below 0°C. The determination of the actual freezing point is, however, of still greater importance in observations of the supercooling of running water, which require a higher accuracy of observation.

In order to start the freezing process afresh before observation, the ice-cover formed earlier was sometimes removed from the entire basin, and then the surface temperature registered by the radiation receiver, connected through a cable with the compensator and the photographic registrering apparatus, which were placed in a small house quite near. At other times a plate of ice was cut out of the ice cover and submerged to a depth of about an inch, a small shallow basin with a bottom temperature of 0° C, and with a very slow flow of water, thus being formed. These conditions were favourable to the attainment of great supercooling. To study rapid freezing, some water was simply poured over the ice cover.

In the course of the observation period, 59 registering curves showed a temperature fall of the radiating surface below 0° C, during that phase of the freezing process when some open water was still to be found within the area limited by the effective space angle of the receiving cone. The shape of the curves was generally similar to the typical curves of fig. 5 reproduced below, which were registered in January 1942 at a temperature considerably lower than that at Sörnesset. A summarized view of the observations is given in Table 1.

Table 1. *Observations of water surface temperature at Sörnesset 1941.*

n number of registerings.
p limit numbers of supercooling period in minutes.
t » » » minima of surface temperature (° C).
T » » » air temperature (° C).
v » » » wind (scale 0—12).
N » » » cloudiness (scale 0—10).
The observations reported are made before $7^h$ 30 M. S. T.

| | n | p | t<br>° C | T<br>° C | v | N |
|---|---|---|---|---|---|---|
| 19. April 1941 | 8 | 1—5 | —0.10<br>to<br>—0.40 | —5.6<br>to<br>—4.5 | 0 | 0 |
| 23. April 1941 | 10 | 2—8 | —0.12<br>to<br>—0.66 | —9.9<br>to<br>—9.0 | 0 | 0 |
| 24. April 1941 | 2 | 1 | —0.25<br>to<br>—0.18 | —7.6<br>to<br>—7.7 | 0 | 0 |
| 25. April 1941 | 10 | 2—18 | —0.22<br>to<br>—0.39 | —6.3<br>to<br>—6.0 | 0 | 0 |
| 3. May 1941 | 5 | 2—6 | —0.08<br>to<br>—0.25 | —5.7<br>to<br>—4.2 | 0 | 0—1CuStr |
| 8. May 1941 | 3 | 6<br>> 15 | —0.11<br>to<br>—0.70 | —9.4<br>to<br>—8.0 | 0 | 1 |
| —»— evening | 1 | > 10 | —0.11 | —2 | 0—1 | 8 ACu |
| 9. May 1942 | 2 | 1<br>3 | —0.12<br>—0.12 | —8.0<br>—7.8 | 0 | 5 Cu |
| 10. May 1941 | 6 | 2<br>> 10 | —0.27<br>to<br>—0.55 | —9.2<br>to<br>—6.0 | 0 | CiStr veil |
| 12. May 1941 | 7 | 0.1—1.5 | —0.03<br>to<br>—0.13 | —2.9<br>to<br>—1.5 | 0 | 6—7 CiStr |
| 14. May 1941 | 5 | 3—6 | —0.24<br>to<br>—0.49 | —4.6 | 0—1 | 0—2 |

The period of supercooling varied between 0.1 and more than 18 minutes, depending upon the different factors influencing the amount of supercooling, which will be discussed below. The maximum of supercooling observed, — 0.70° C, occurred on the 8th of May.

The experiences from these observations were used to improve the registering apparatus and observations were continued during December 1941 — January 1942 at *Tömte, Nannestad*, 275 m above sea level. Two wooden cylindrical vessels were placed in the open air, mounted on a platform between two horizontal wooden bars carrying the receiver1), which might easily be removed from one vessel to the other. Generally, the observation started by placing the receiver over the first vessel containing water with an ice cover, the surface temperature of which will be below zero, proportional to the thickness of the ice, as seen below. The registering curve may thus start somewhat below the zero line. Then water of a temperature 1—2° C was poured into the second vessels and the receiver swiftly placed above, while registering was proceeding. The galvanometer registering curve (see Fig. 5) shows correspondingly, first a rapid rise and then from the sharp apex an exponentially falling curve corresponding to the cooling of the water surface. The curve passes below the 0° line to a broad minimum and then slowly rises again. During this part of the curve ice formation is started and is going on, till the curve approaches the 0° line again, a continuous thin ice cover then being formed. As representative types are reproduced two curves in Fig. 5. During the observation period 46 registering curves were obtained showing a temperature fall of the radiating surface below 0° C, the typical shape being that of the curves reproduced, although the period of supercooling may be much longer. A list of observations of the maximum of supercooling registered is given for a series of days in the table 2 below.

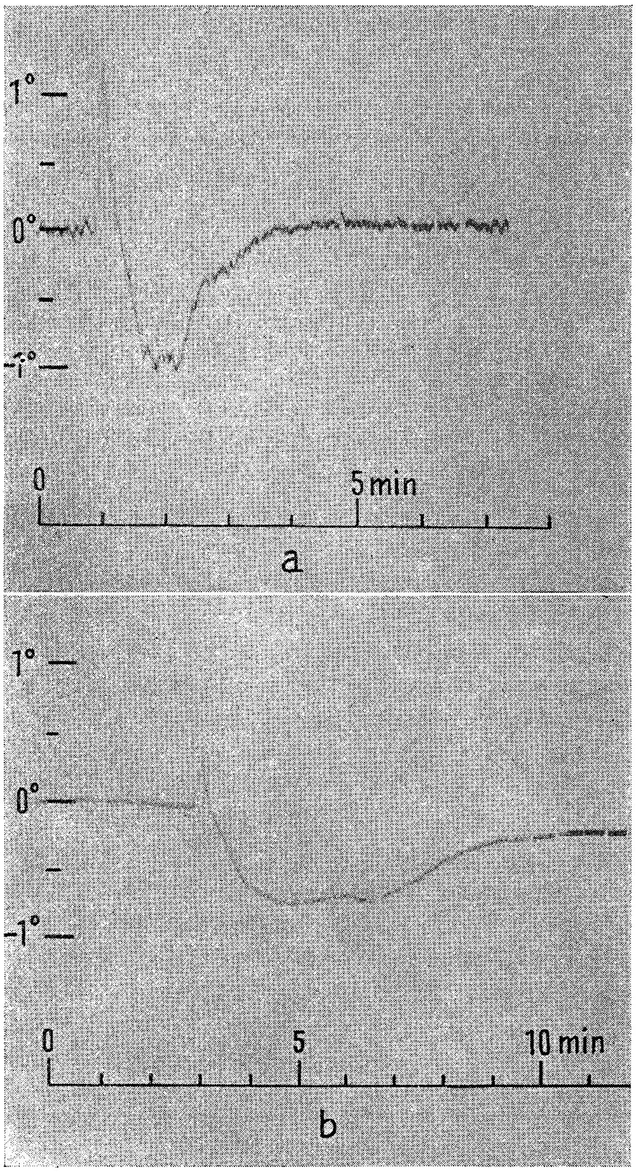

Fig. 5. Water surface temperature.
Photographic registering curves.
a. *Tömte*, 15. 1. 1942, $21^h$. b. *Tömte*, 8. 1. 1942, $12^h$.

Table 2. *Observations of water surface temperature at Tömte 1941—42.*

| | n | p | t °C | T °C | v | N |
|---|---|---|---|---|---|---|
| 27. Dec. 1941 | 5 | 1.5 | —0.66 | — 17 | 0—1 | 0 |
| $18^h$—$23^h$ | | to | to | to | | |
| | | 3 | —1.20 | — 20 | | |
| 28. Dec. 1941 | 8 | 2 | —0.60 | — 21 | 0 | 10 Str |
| $11^h$—$20^h$ | | to | to | to | | |
| | | 8 | —1.0 | — 17 | | |
| 2. Janr. 1942 | 3 | 5 | —0.58 | — 11 | 0 | 0 |
| $20^h$—$24^h$ | | to | to | to | | |
| | | 7 | —0.83 | — 12 | | |
| 6. Janr. 1942 | 5 | 2 | —0.28 | — 6 | 0—1 | 0 |
| $18^h$—$24^h$ | | to | to | to | | |
| | | 9 | —1.2 | — 13 | | |
| 7. Janr. 1942 | 8 | 2 | —0.39 | — 15 | 0—1 | 1—10 |
| $9^h$—$23^h$ | | to | to | to | | StrCu |
| | | > 23 | —0.90 | — 7 | | |
| 8. Janr. 1942 | 6 | 0.5 | —0.10 | — 12 | 0—1 | 1—10 Str |
| $11^h$—$22^h$ | | to | to | to | | |
| | | 7.5 | —0.78 | — 9 | | |
| 15. Janr. 1942 | 11 | 1.5 | —0.25 | — 20 | 0—1 | 0—10 Str |
| $9^h$—$22^h$ | | to | to | to | | |
| | | 4 | —1.06 | — 16 | | |

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1) If the receiver is placed right above the second vessel while water is rapidly being poured into it, the vertical air movement caused will sensibly influence the thermopile, so this will have to be avoided.

As pointed out before, the ice will grow from distinct starting points in the form of crystal beams, leaves, feathers, stars and other forms, being stretched out gradually. This process will leave open parts of the water between the growing elements of ice structure, till all the open parts are covered by an ice membrane, as thin as a leaf, but still showing some of the structural elements from which it has been formed. During this period the average surface temperature of the area limited by the effective spacing angle of the receiver cone will be represented by that part of the curve (Fig. 5) situated below the zero line. Judging from the fraction of open water area in proportion to the ice area at proper intervals during each observation, it was found that *the negative temperature will be approximately proportional to the open fraction.* In order to see the consequence of this, we should remember that the surface temperature of the ice elements first formed will be very near 0° C, the thickness being in fact only a small fraction of a millimeter. This is seen by considering the heat flow through an ice plate $S = -\lambda \frac{t}{H}$, t being the temperature of the surface exposed to the loss of heat S, H being the thickness of the plate and $\lambda$ the conductivity of ice = 0.0051.3600 cal/cm, hour, centigrade. In the paper previously mentioned, (1), formulae were given allowing a calculation of the heat loss S, when the meteorological conditions are known. At a moderate degree of cold, the value of S will be about 10—30 cal/cm² hour. Taking for instance $S = 20$, and an ice thickness $H = 0.01$ cm, the surface temperature will be $t = -HS/\lambda = -0.01°$ C, which is within the limit of accuracy of observation¹).

Evidently, *the supercooling of the open areas of water remains unaltered, even while they are limited by ice* that is only gradually diminishing the open areas. In some cases this could be directly observed by moving the receiver slowly across neighbouring areas that are either open or covered by ice. The size and duration of the open areas, and consequently the amount of supercooling, will depend upon the number of nuclei present when the freezing process begins. If we deliberately suspend a considerable number, the open areas will be small and numerous, the supercooling will only reach a small value, and a continuous cover will be formed in a short time. If we remove the ice and clean the surface, the number of nuclei will be reduced, the open areas will be greater and will exist for a longer time. If the water keeps calm the supercooling will reach a greater value, and it will take longer time to produce a continuous ice cover. In return, however, the elements of ice structure first formed, will have grown thicker and will be seen as ripples on the ice cover.

An interesting example of this was presented by one of the registerings in Table 2, from Jan. 8th, $13^{h}2^{m}$—$35^{m}$. The minimum of temperature, — 0.9°, was reached after 15 minutes, but a temperature of — 0.4° was still registered after 22 minutes, when more than half of the effective area was covered by ice, chiefly by rather strong ice beams. In the small area still open some fine icepowder was then added, which immediately caused the water to be covered by thin ice, while the registering curve simultaneously rose to 0° C. The temperature registered being the average value of the effective area, the actual supercooling of the small open area must have been several times greater than that registered (— 0.4°).

Otherwise it should be emphasized that the actual supercooling will also depend upon the tranquillity of the air. A breath of wind which sets the water surface layer in motion will rapidly diminish the temperature gradient of the surface layer.

The influence of chance numbers of nuclei and accidental air conditions may thus cause considerable variations of the actual supercooling. This may sometimes completely outweigh the influence of the general loss of heat, determined chiefly by air temperature and cloudiness. The actual observasions of supercooling referred to in the above tables illustrate this.

It is of interest to note that the maximum of supercooling observed at Tömte was — 1.2° C.

4. The observation series from the two winter periods treated in the preceding section, have shown that *the formation of ice in open water which is at rest or moving slowly, will regularly be preceded by a supercooling of the water surface layer.* The state of the supercooling is stable in so far as supercooling may remain unaltered at a sufficient distance from solid phase boundaries. Such boundaries are, for instance, the surfaces of nuclei suspended in the

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¹) Measurement of the surface temperature of an ice cover with subsequent measurement of the thickness, gives a simple method for determining the total heat loss from the ice surface.

water from which the crystal growth starts. The transmission of heat from the zone of crystallisation will partly pass through the ice to the adjacent air, and partly to the open water which is supercooled, as indicated by Fig. 6. The transmission of heat, however, is a process which necessarily needs time, depending upon the existing temperature gradients. The reason why the supercooling of water is generally regarded as a state which is unstable in itself, is probably due to the ordinary performance of demonstration experiments with marked supercooling, the crystallisation process then proceeding at a very fast rate, approximately instantaneously, when starting nuclei are provided for. If the water is cautiously cleaned from nuclei, it may in fact remain in a state of supercooling for an indefinite period, even if it be exposed to violent, turbulent motion, as was pointed out by *Altberg*[1]), in giving a detailed report of the investigations hitherto published on the subject.

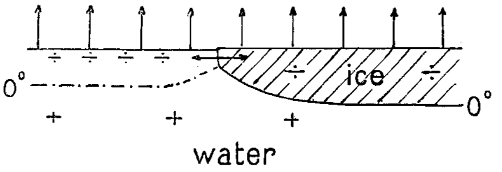

Fig. 6. Arrows indicate heat flow.

5. In section 1 it was pointed out that the formation of ice in running water, *dynamic ice formation*, will be dependent upon the supercooling of the surface layer and its mixing with the deeper strata. If we could observe the actual field of movement, the field of heat current and the field of temperature in the water, we should find it very complicated when nuclei of crystallisation are present. The growth of these will require a temperature gradient pointing outwards from the surface of each crystal, and the size of the gradient will again depend upon how rapidly the velocity changes with the distance from the surface. The growth will be greatest at those places where the field of velocity tends to increase the temperature gradient. This is the reason why sharp edges and points are not smoothed, on the contrary, the growth there will be great.

In rapidly running rivers, it is comparatively easy to observe a general supercooling of the water, provided the proper precautions are being taken. A favourable period for observation is either at the beginning or at the end of winter, when bottom ice is formed during the night. Solar radiation may then be sufficiently strong to loosen the bottom ice during the daytime, and a new bottom ice formation takes place the following night. At *Vosseelven* near *Skiple*, measurements were thus performed at Easter 1936 recording a temperature of —0.02° to —0.05° of the running water, while bottom ice was formed during a clear sky and atmospheric temperature —4° C. The measurements were performed with a mercury thermometer, division 0.01°.

In measuring the following precautions are to be taken:

a) Thermometer division 0.01°, permitting readings to 0.001°.
b) Thermometer to be placed in the shade also when in water.
c) The mercury column will exert a pressure in the elastic glass bulb, depending upon the inclination of the thermometer; the same inclination to be used in all observations.
d) To prevent ice formation on the bulb, the thermometer should be heated above 0° C before being placed in the water.
e) Determination of the actual freezing point is made on the spot, the thermometer being in its fixed position, and a mixture of ice and water from the river itself being used.

In a subsequent study the formation of bottom ice as a practical problem at water power stations in winter will be treated.

For the researches here published the author is indebted to the *Chr. Michelsen Institute* and to *Kr. Birkelands Fond.*

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[1]) *W. Altberg*, Flusseis und Winterregime, V. Hydr. Konf. d. Balt. Staaten, Finland, Juni 1936, Bericht 7 D.

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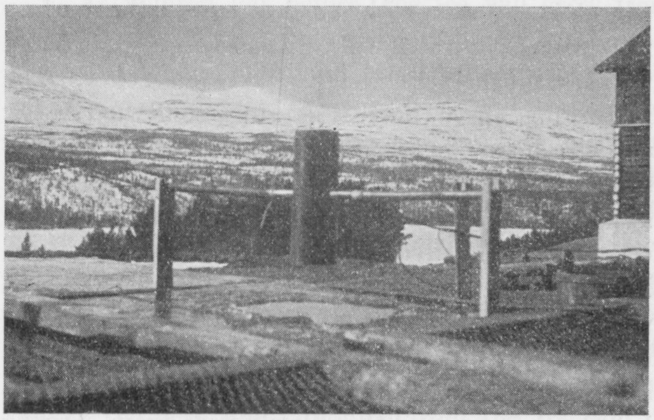

Fig. 4. Thermopile receiver mounted at Sörnesset 1941.

membrane of newly formed ice, the temperature of the top surface of a leaflet of floating ice being very nearly 0° C as will be shown below.

Is is to be observed that this procedure will enable a determination of the *actual* freezing point to be made, notwithstanding the fact that the water contains small quantities of solutable salts, which would lower the freezing point somewhat below 0°C. The determination of the actual freezing point is, however, of still greater importance in observations of the supercooling of running water, which require a higher accuracy of observation.

In order to start the freezing process afresh before observation, the ice-cover formed earlier was sometimes removed from the entire basin, and then the surface temperature registered by the radiation receiver, connected through a cable with the compensator and the photographic registrering apparatus, which were placed in a small house quite near. At other times a plate of ice was cut out of the ice cover and submerged to a depth of about an inch, a small shallow basin with a bottom temperature of 0° C, and with a very slow flow of water, thus being formed. These conditions were favourable to the attainment of great supercooling. To study rapid freezing, some water was simply poured over the ice cover.

In the course of the observation period, 59 registering curves showed a temperature fall of the radiating surface below 0° C, during that phase of the freezing process when some open water was still to be found within the area limited by the effective space angle of the receiving cone. The shape of the curves was generally similar to the typical curves of fig. 5 reproduced below, which were registered in January 1942 at a temperature considerably lower than that at Sörnesset. A summarized view of the observations is given in Table 1.

Table 1. *Observations of water surface temperature at Sörnesset 1941.*

n number of registerings.
p limit numbers of supercooling period in minutes.
t » » » minima of surface temperature (° C).
T » » » air temperature (° C).
v » » » wind (scale 0—12).
N » » » cloudiness (scale 0—10).
The observations reported are made before $7^h$ 30 M. S. T.

| | n | p | t<br>° C | T<br>° C | v | N |
|---|---|---|---|---|---|---|
| 19. April 1941 | 8 | 1—5 | —0.10<br>to<br>—0.40 | —5.6<br>to<br>—4.5 | 0 | 0 |
| 23. April 1941 | 10 | 2—8 | —0.12<br>to<br>—0.66 | —9.9<br>to<br>—9.0 | 0 | 0 |
| 24. April 1941 | 2 | 1 | —0.25<br>to<br>—0.18 | —7.6<br>to<br>—7.7 | 0 | 0 |
| 25. April 1941 | 10 | 2—18 | —0.22<br>to<br>—0.39 | —6.3<br>to<br>—6.0 | 0 | 0 |
| 3. May 1941 | 5 | 2—6 | —0.08<br>to<br>—0.25 | —5.7<br>to<br>—4.2 | 0 | 0—1CuStr |
| 8. May 1941 | 3 | 6<br>> 15 | —0.11<br>to<br>—0.70 | —9.4<br>to<br>—8.0 | 0 | 1 |
| —»— evening | 1 | > 10 | —0.11 | —2 | 0—1 | 8 ACu |
| 9. May 1942 | 2 | 1<br>3 | —0.12<br>—0.12 | —8.0<br>—7.8 | 0 | 5 Cu |
| 10. May 1941 | 6 | 2<br>> 10 | —0.27<br>to<br>—0.55 | —9.2<br>to<br>—6.0 | 0 | CiStr veil |
| 12. May 1941 | 7 | 0.1—1.5 | —0.03<br>to<br>—0.13 | —2.9<br>to<br>—1.5 | 0 | 6—7 CiStr |
| 14. May 1941 | 5 | 3—6 | —0.24<br>to<br>—0.49 | —4.6 | 0—1 | 0—2 |

The period of supercooling varied between 0.1 and more than 18 minutes, depending upon the different factors influencing the amount of supercooling, which will be discussed below. The maximum of supercooling observed, — 0.70° C, occurred on the 8th of May.

The experiences from these observations were used to improve the registering apparatus and observations were continued during December 1941 — January 1942 at *Tömte, Nannestad,* 275 m above sea level. Two wooden cylindrical vessels were placed in the open air, mounted on a platform between two horizontal wooden bars carrying the receiver[1]), which might easily be removed from one vessel to the other. Generally, the observation started by placing the receiver over the first vessel containing water with an ice cover, the surface temperature of which will be below zero, proportional to the thickness of the ice, as seen below. The registering curve may thus start somewhat below the zero line. Then water of a temperature 1—2° C was poured into the second vessels and the receiver swiftly placed above, while registering was proceeding. The galvanometer registering curve (see Fig. 5) shows correspondingly, first a rapid rise and then from the sharp apex an exponentially falling curve corresponding to the cooling of the water surface. The curve passes below the 0° line to a broad minimum and then slowly rises again. During this part of the curve ice formation is started and is going on, till the curve approaches the 0° line again, a continuous thin ice cover then being formed. As representative types are reproduced two curves in Fig. 5. During the observation period 46 registering curves were obtained showing a temperature fall of the radiating surface below 0° C, the typical shape being that of the curves reproduced, although the period of supercooling may be much longer. A list of observations of the maximum of supercooling registered is given for a series of days in the table 2 below.

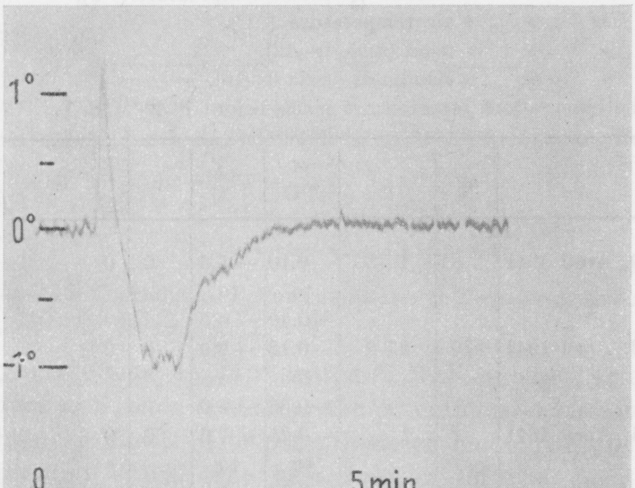

Fig. 5. Water surface temperature.
Photographic registering curves.
a. *Tömte,* 15. 1. 1942, 21$^h$. b. *Tömte,* 8. 1. 1942, 12$^h$.

Table 2. *Observations of water surface temperature at Tömte 1941—42.*

| | n | p | t °C | T °C | v | N |
|---|---|---|---|---|---|---|
| 27. Dec. 1941 | 5 | 1.5 | −0.66 | −17 | 0—1 | 0 |
| 18$^h$—23$^h$ | | to | to | to | | |
| | | 3 | −1.20 | −20 | | |
| 28. Dec. 1941 | 8 | 2 | −0.60 | −21 | 0 | 10 Str |
| 11$^h$—20$^h$ | | to | to | to | | |
| | | 8 | −1.0 | −17 | | |
| 2. Janr. 1942 | 3 | 5 | −0.58 | −11 | 0 | 0 |
| 20$^h$—24$^h$ | | to | to | to | | |
| | | 7 | −0.83 | −12 | | |
| 6. Janr. 1942 | 5 | 2 | −0.28 | −6 | 0—1 | 0 |
| 18$^h$—24$^h$ | | to | to | to | | |
| | | 9 | −1.2 | −13 | | |
| 7. Janr. 1942 | 8 | 2 | −0.39 | −15 | 0—1 | 1—10 |
| 9$^h$—23$^h$ | | to | to | to | | StrCu |
| | | > 23 | −0.90 | −7 | | |
| 8. Janr. 1942 | 6 | 0.5 | −0.10 | −12 | 0—1 | 1—10 Str |
| 11$^h$—22$^h$ | | to | to | to | | |
| | | 7.5 | −0.78 | −9 | | |
| 15. Janr. 1942 | 11 | 1.5 | −0.25 | −20 | 0—1 | 0—10 Str |
| 9$^h$—22$^h$ | | to | to | to | | |
| | | 4 | −1.06 | −16 | | |

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[1]) If the receiver is placed right above the second vessel while water is rapidly being poured into it, the vertical air movement caused will sensibly influence the thermopile, so this will have to be avoided.