THE RATE OF ICE SUBLIMATION

by

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INTRODUCTION

During the spring of 1931 some experiments were carried on by Paul W. Scates in the University of Tennessee laboratories to determine the effect of air temperature, humidity, and velocity on the melting rate of ice. The results of his research were published in the July '31 issue of "Refrigerating Engineering", and as far as is known, this is the only available data on the subject. His tests were made with air at temperatures above freezing (above 32° F.), and it is the purpose of this experimentation to continue the research on the rate of melting below the freezing temperature. This change of state from solid ice to water vapor at temperatures below freezing comes under the term sublimation instead of melting, hence the title contains the former word. In the carrying out of this research, however, limitations of the apparatus confined the range of air temperatures between 20° F. and 32° F.

STATEMENT OF PURPOSE

It is the purpose of this work to determine the rate of melting or sublimation of ice at different temperatures below freezing under different conditions of air velocity and humidity. Incidentally, it is hoped that some material relative to the individual effect of air velocities can be derived from the results of the research. No attempt was made to reproduce the conditions under which Mr. Scates performed his tests, because the rate of melting of ice at low temperatures is so much lower than the rate within the range of his tests. This research was carried on under independent conditions, although valuable suggestions were given by Mr. Scates personally.

GENERAL THEORY

When ice is allowed to stand in air below the freezing temperature, it soon reaches the temperature of the air surrounding it. The evaporation from the surface of the ice continues just the same as though the air were not below the greezing temperature. This is quite evident if one remembers that the air contains moisture down to a temperature as low as -40° F. According to authorities* the water vapor which is present in the air is made up of single molecules, while those which make up ice are triple molecules, scientifically known as trihydrols. The change in state between the ice and water consists of the breaking down of trihydrols into dihydrols or double molecules. These dihydrols and trihydrols are both present in water at all temperatures when it is a liquid. The theory of the sensible addition of heat to water is that the trihydrols are broken up into dihydrols as the temperature rises until at the boiling point only about 17% trihydrols remain. Now, when the vapor pressure of the air surrounding a block of ice becomes such that sublimation takes place, the total heat required to break down trihydrols into single molecules must be supplied. This amounts to

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* "Ice Engineering", _Refrigerating Engineering_, vol.16,p.93

nearly the total sum of the latent heats of ice and steam. To extract such an amount of heat from the ice would lower the temperature of the surrounding ice considerably because of the low value of the specific heat. This lowering of the temperature causes the moisture vapor in the air surrounding the block to condense on the surface. The condensation of the vapor gives up heat of vaporization, and while this is still a thin sheet of water on the surface of the ice, it freezes, giving up heat to the ice beneath. This combination of tendencies to heat and at the same time cool the ice, helped by radiation and convection of the air, soon brings the temperature of the ice to the temperature of the air surrounding it. When the air and ice are at the same temperature, it is logical to assume that the rate of direct heat transfer is zero. It has been stated* that the rate of melting of ice is directly proportional to the rate of heat transfer. If this were the only factor considered, it would be again logical to assume that the ice melting rate would be zero soon after the ice were placed in an atmosphere below freezing. Two other factors are present, however, which may affect the rate of sublimation. These are the humidity and velocity of the air. It may be safely assumed that a low humidity of the air surrounding ice would tend to

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* P.W.Scates, "The Rate of Ice Melting", Ref.Engr. vol.22, page 15.

cause sublimation, whereas a high humidity would tend to condense on the surface of the ice and freeze. The velocity of the air seems to have a peculiar effect on the ice. In the course of the experiments herein described, high velocity air was substituted for relatively low velocity with result that the surface of the ice became wet, although the temperature of the ice and the air were both nearly 22°F. The net result of the wet surface was that the rate of sublimation was slightly higher than had been encountered with the dry surface at low velocity. This may be explained by the fact that the heat required to vaporize water is less than the heat required to sublimate ice at the same temperature. The only question which cannot be reasonably explained is the presence of the film of liquid on the surface at high velocity. It has been suggested* that this may be due to the condensation of water vapor in the air at high humidity, or that there may be a reduction of the melting point of the ice due to the pressure of the high air velocity. It may be caused by either or both of these, but sufficient proof to support either claim is lacking.

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* This suggestion is one of many given by Prof. W.R.Woolrich University of Tennessee

THE METHOD AND APPARATUS USED

The method of determining the rate of sublimation which was chosen for this research was essentially the same as that used by Mr.Scates in his experiments on ice melting rates*, with few exceptions. This method seemed the one which would give quickest results due to the high air velocities available and the comparative ease of stabilizing constant values of temperature and humidity. An ammonia unit cooling coil with a two-speed fan discharging into two galvanized iron ducts, the whole being within a well insulated cold room, comprised the backbone of the apparatus. The cooling unit was connected so that air could be circulated around the cold room, or drawn from another room thru the coils and discharged into the cold room. A special pressure control valve was installed on the vacuum side of the coils, and this was suggested as a means of controlling the temperature of the ammonia in the coils, and consequently the temperature of the air blowing over the coils. When it came to requlating this valve, however, it was found that it did not work well in the attempt to keep the coils at a constant temperature because of the limits thru which it traveled before adjusting the pressure of

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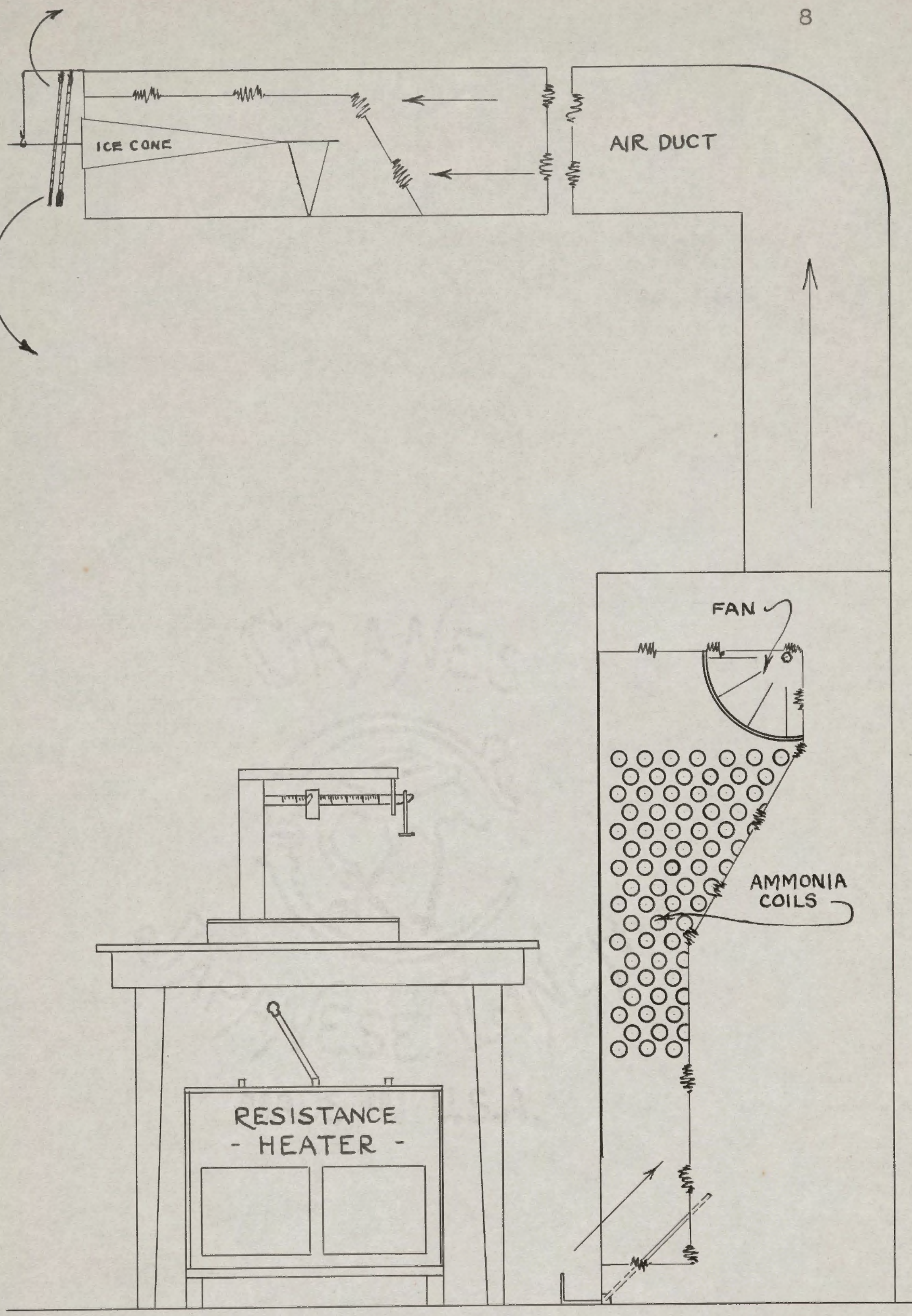
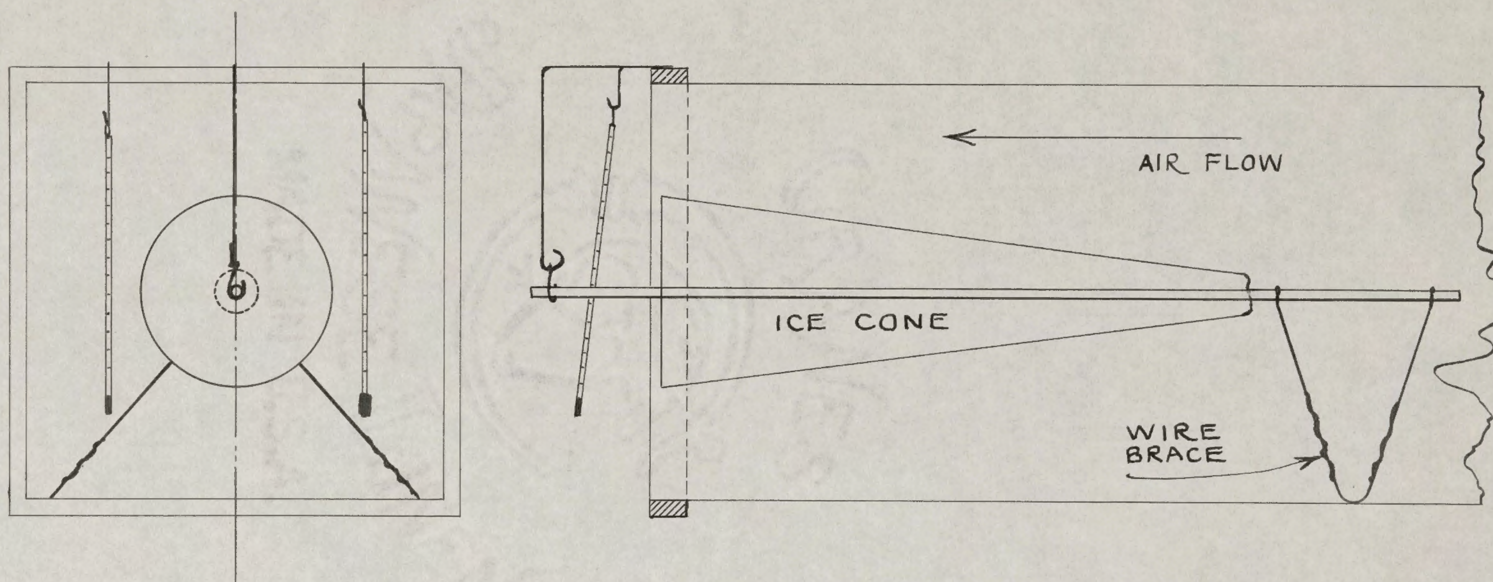
* "The Rate of Ice Melting", Ref.Engr., vol.22, p.15.

the ammonia. After a few attempts to control the room temperature this way it was discarded in favor of other methods. The final set up is shown in figures A and B. It will be noted that the scales are not connected for use with automatic signals, but are merely kept in the room to keep them near room temperature to prevent excessive melting of the ice during the periods of weighing.

The ice was made in cones frozen in special cans which were designed after considerable consultation with Professor W.R.Woolrich, the idea being to get as much surface as possible exposed to the air without suddenly diverting or obstructing the stream flow. The ducts which are connected to the discharge side of the fan are each one foot square, so that ordinary ice blocks each (8"x8"x30") frozen in the one ton ice plant at the University laboratory could not be used. The cans were made of galvanized iron with a 3/8" hole in the tip. Brass rods 5/16" in diameter and approximately 30" long were run thru the axes of the conical cans to be frozen into the finished blocks. The sealing of these rods to the tips of the cans was a problem which prevented any successful results for some time. At first a piece of rubber tubing was placed over the rod and one end forced over the end of the can, the other end being turned inside out for a distance sufficient to keep it in that position



- FIGURE A. -



- FIGURE B. -

- DETAIL of DUCT OPENING -

without tying. This did not seal the ends of the cans sufficiently well to prevent the leakage of brine into the cans before freezing. The result was that can after can came out of the brine with either the lower half entirely liquid brine or the core surrounding the rod filled with brine from top to bottom. Upon looking around it was decided to seal the cans with a paraffin, and this was done in addition to the rubber tubing mentioned before with satisfactory results. The cones thereafter were frozen solid throughout, but a new difficulty arose from the use of the paraffin. When an attempt was made to remove the ice from the cans, it was found that the paraffin was cemented securely between the cans and the rods. This was exactly what had been desired from a water-proofing standpoint, but it brought into play new methods of removing the ice from the can. At first an attempt was made to jar the wax loose by a blow on the rod with result that the entire cone of ice was ruined. Then twisting the can was tried with little success due mostly to the unsymmetrical shape of the cans. Finally a combination of excessive washing with tap water and application of considerable pressure on the cans was found to do the work. The ice in one instance froze partially because of leaking brine. The can was sealed more tightly, after which water was added to the can in place of the brine present. The result was that the top of the cone froze first, and, as the bottom froze, forced the seams on the side of the can despite the slope of one to eight.

The control of the temperature in the room was a problem which was first tackled using the pressure control valve mentioned before. After the poor success of control from this source, it was decided to use an electric heating unit to counterbalance the refrigerating effect of the cooling unit. A large heating unit was available, and this was connected to a convenient line and used in the later runs. By adjusting the resistance of this heater, and the flow of ammonia into the coils, it was possible to control the temperature within comparatively small limits as is shown by the curves in Runs 1 thru 6.

The apparatus was set up as shown in figure A with wet and dry bulb thermometers hung at the end of the ducts (see figure B), for in the first few runs it was found unsatisfactory to measure the temperature at a point just above the fan, or to measure the temperature in the room. The ice was swung from a wire hook which dropped over the center of the duct opening, and was supported on the other end by a wire frame as shown in figure B. It was arranged so that the axis of the cone should be in the geometric center of the duct, and this was accomplished by adjusting the wire support to the correct angle to give this height above the bottom.

The fan is a component part of the cooling unit, and is designed to give two speeds (1200 rpm and 1800rpm). All the runs, with the exception of one, were made at the low speed which gives an air velocity in the ducts of approximately 1150 feet per minute*.

Aside from keeping water out of the trough surrounding the cooling unit, no effort was made to keep the humidity constant. This extra effort was not expended because during the first three runs herein noted, and the few previous trial runs no effect on the weight of the ice was noticeable after four to six hours in the air duct at the above or higher velocity. From this lack of apparent results, it was decided that such pains would be useless, it seeming rediculous to compare the lack of results under one condition with an equal lack of results under another. This may have been the cause of poor results, for it is possible that under one condition of humidity the ice may actually gain weight due to the excessive condensation and freezing, whereas under another condition the ice may lose weight by sublimation. If both of these conditions were present in the humidity range for any one run, the effects would counterbalance each other. No statement, therefore, concerning the

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* This value determined by Paul W. Scates using a Pitot tube with water gage ratio of 20:1

justification of such can be made.

In the course of the run using high velocity, the surface was continually wet, as was mentioned before, and moisture gathered in a drop on the lower end of the cone of ice. The air velocity was such that this drop blew off every 20 to 30 seconds, yet the weight of the block at the end of five hours had changed so slightly that it could not be measured with the available scales. The scales used were small platform scales reading to the nearest ounce on the beam. Estimates of the nearest half ounce could only be approximated, and as the loss of weight of a cone weighing more than six pounds was often less than half an ounce, the change was charged to the inaccuracy of the scale and the results neglected.

In searching for the sources of error, the first and perhaps greatest source can be found in the thermometers used to measure the temperature of the air. The dry bulb thermometer was a laboratory type reading from -20° F. to 120° F. in intervals of one degree. The wet bulb thermometer was a hollow shell type with a capillary tube enclosed, reading from 20° F. to 120° F. in intervals of two degrees. The latter was the greatest source of error because the slightest change at the low temperatures encountered gave considerable change in the humidity reading. A change of one degree on the wet bulb thermometer often gave as large as a 15% difference in humidity reading*. As the limits of error for any scale are ordinarily one-half the smallest unit of the scale, the limits of error for this thermometer are ± one degree. This means that in some cases the limits of error of the relative humidity run as high as 15% or they may be within a range of 30%, neglecting any error in the dry bulb thermometer. For this reason it is possible that the wide variation in humidities which is shown in the curves (runs 1 thru 6) does not actually exist.

Another source of error lies in the lack of any practical method of controlling either the temperature or the humidity for any length of time. As the runs required four to six hours, this control became a factor of importance, but none of the methods used were very effective for such methods. Any type of sensitive thermostatic control would have been helpful, but was not available. The humidity was a probable source of error, but was not controlled for the reasons stated before.

Other errors, which might have come from the timing of the runs, the change in air velocity, the presence of large amounts of ammonia in the air for short periods, or the melting which took place during weighing, are so small compared with those previously described as to be negligible.

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*(from the previous page) "Psychrometric Chart", in Refrigerating Engineering, vol.23, p.97.

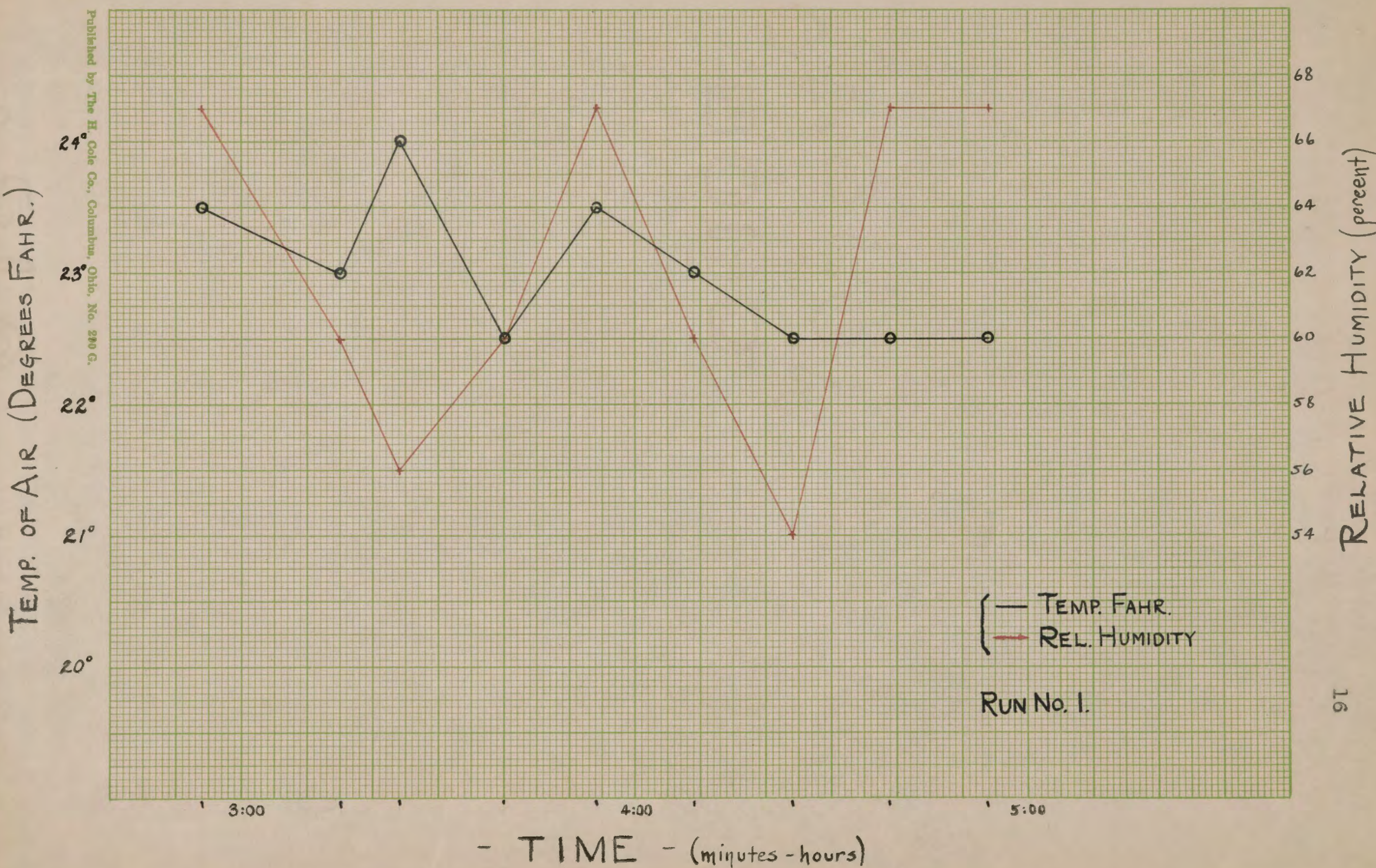
OBSERVATIONS

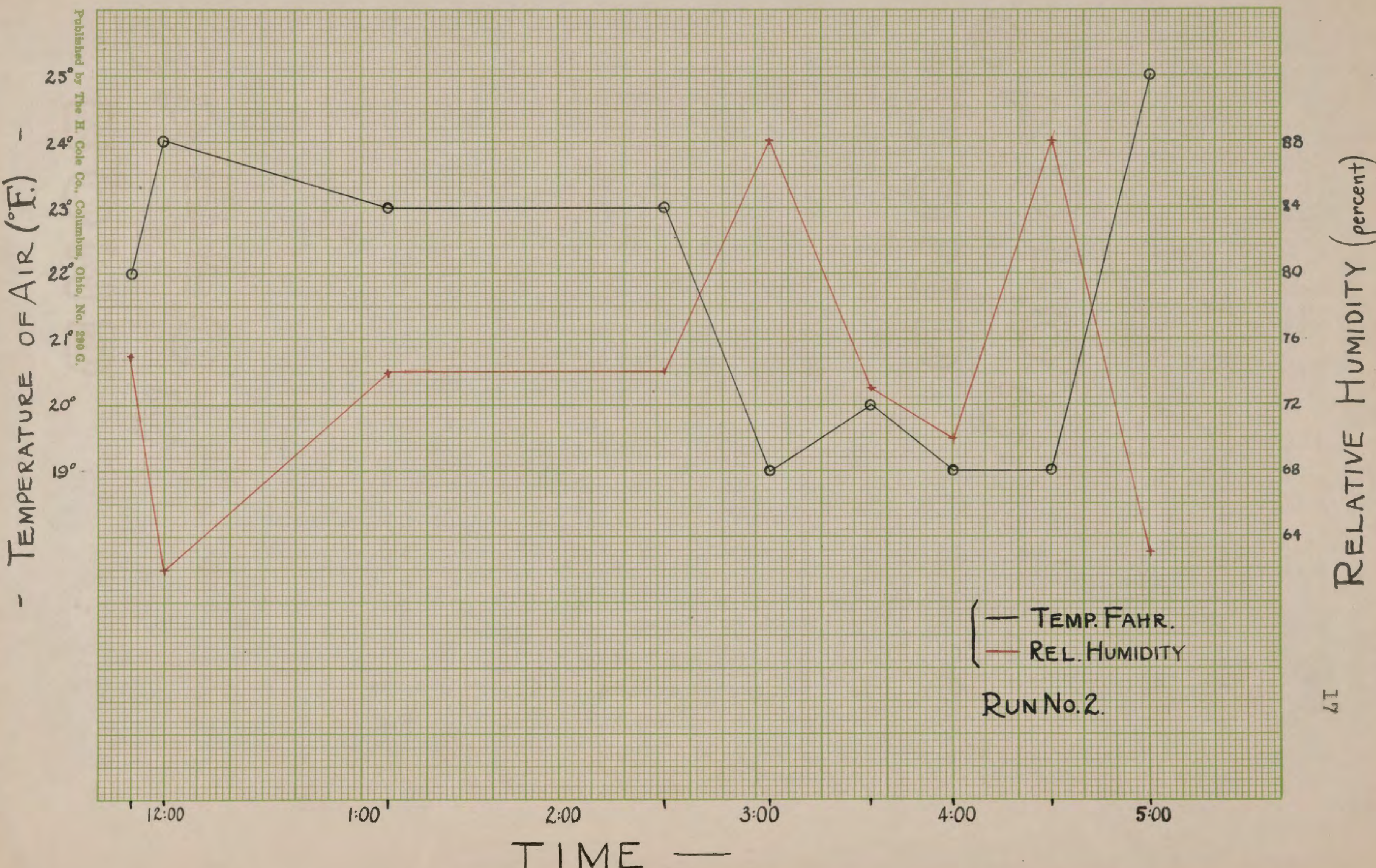
In the runs which are shown graphically in the curve sheets (Runs 1 thru 6), an effort was made to find the amount of ice which would sublimate by finding the loss of weight of the cones during a given period.

In the preliminary runs, no effort was made to hold any of the variables constant, the effort only being to keep the temperature below freezing. The main object was to get a rough estimate of the loss of weight per hour of a six pound block of ice under sub-freezing conditions. These were all short runs of one or two hours none of which showed any tendency of the ice to lose weight.

The first run (see curve sheet marked Run 1.) was made with the temperature controlled by the pressure control valve, which worked fairly well for the short run under constant observation. The temperature averaged slightly over 23 degrees, and the humidity about 62%, but during the two hours no apparent change in weight was noticed after conditions became stabilized.

In run No.2, the room was controlled by a combination of the pressure control valve and adjustments of the expansion valve and the air intake. In this five hour run the average temperature was nearly 22° F. and the humidity approximately 75%, but again no apparent change in weight could be noticed during the longer period,

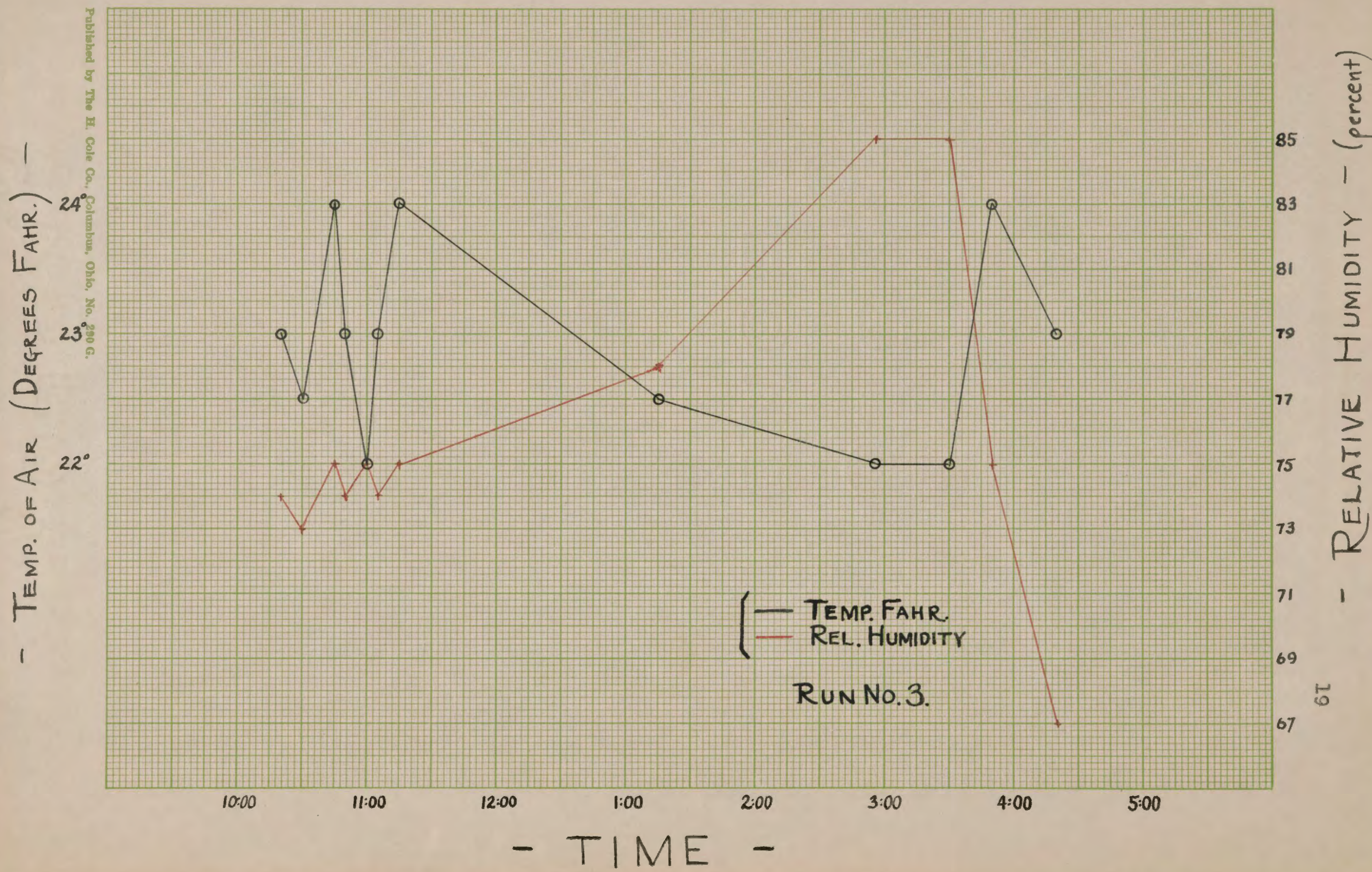

Temp. of Air (Degrees Fahr.)
24°
23°
22°
21°
20°
Published by The H. Cole Co., Columbus, Ohio. No. 200 G.
68
66
64
62
60
58
56
54
Relative Humidity (percent)
Temp. Fahr.
Rel. Humidity
Run No. 1.
3:00
4:00
5:00
- TIME - (minutes - hours)

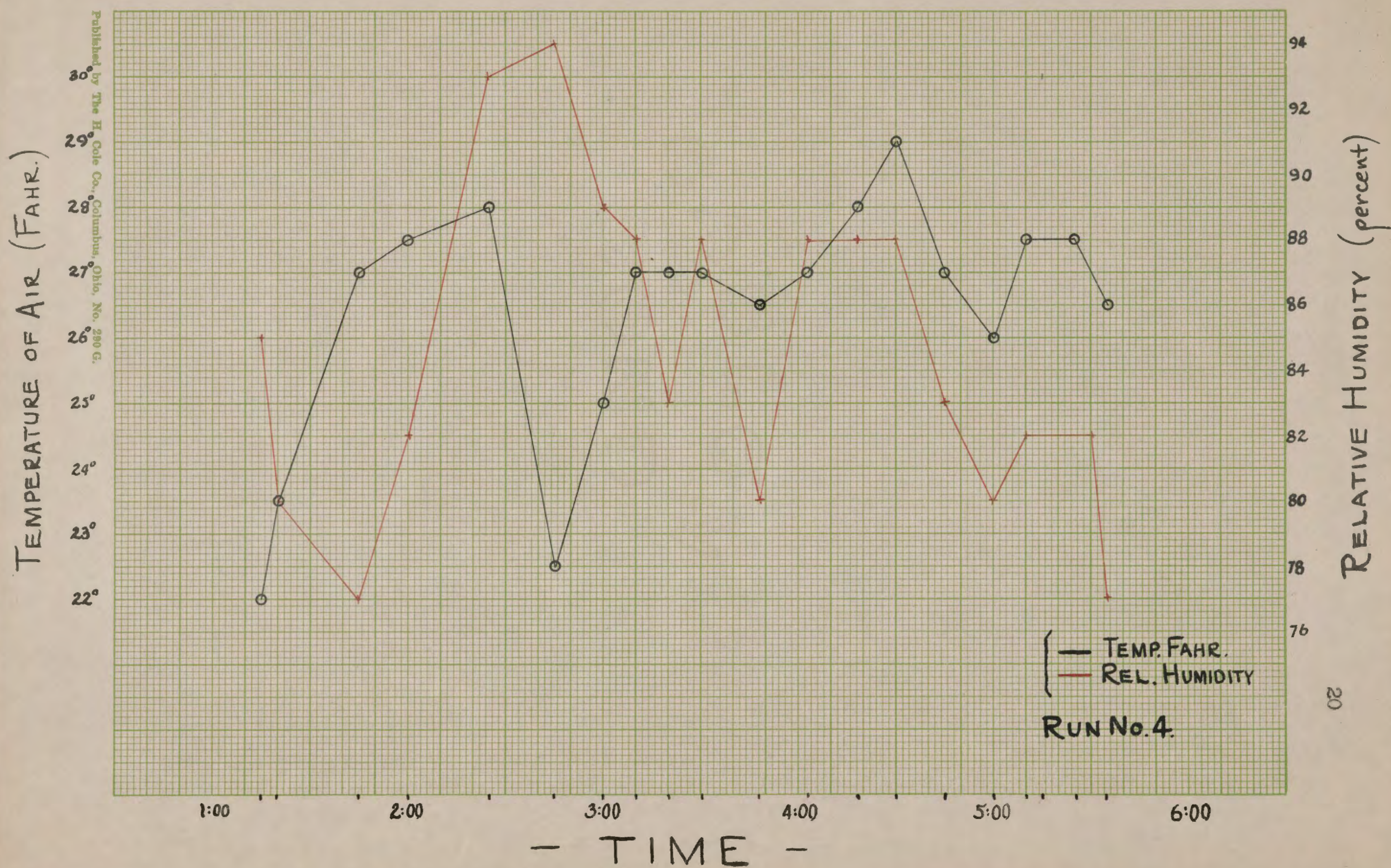

- Temperature of Air (°F.) -
25°
24°
23°
22°
21°
20°
19°
Published by The H. Cole Co., Columbus, Ohio, No. 390 G.
88
84
80
76
72
68
64
Relative Humidity (percent)
Temp. Fahr.
Rel. Humidity
Run No. 2.
12:00
1:00
2:00
3:00
4:00
5:00
TIME —

although this run was made using high air velocity. The fan was turned on the 1800 rpm. speed during the entire run, but no effect in the change of weight was noticeable. During this run, however, the wetted surface of the block and the drops of water mentioned previously were noticed as described in the treatment of the theory and method.

In the third run another attempt was made to find definite data about the same range of temperature as the two previous runs. This time the electric heater was used to advantage as can be clearly seen by referring to the curve for this run. The temperature was held within one degree plus or minus of 23°F. for six hours. This six hour run again did not yield enough change in weight to be definitely measured on the scales, although a slight change of less than half an ounce was noted. This was less than the limits of error of the scale, so that it may safely be said that the ice lost no weight during this run of six hours at low velocity. It was during this run, as in a few others, that the humidity changed radically, the mean value being in the neighborhood of 78%. During the run the surface of the ice was continually dry.

The fourth run was made at a temperature slightly less than 27°F. with an average humidity of 85%. The run lasted four hours and twenty minutes during which


- TEMP. OF AIR (DEGREES FAHR.) -
24°
23°
22°
85
83
81
79
77
75
73
71
69
67
- RELATIVE HUMIDITY - (percent)
10:00
11:00
12:00
1:00
2:00
3:00
4:00
5:00
- TIME -
TEMP. FAHR.
REL. HUMIDITY
RUN NO. 3.
Published by The H. Cole Co., Columbus, Ohio, No. 290 G.



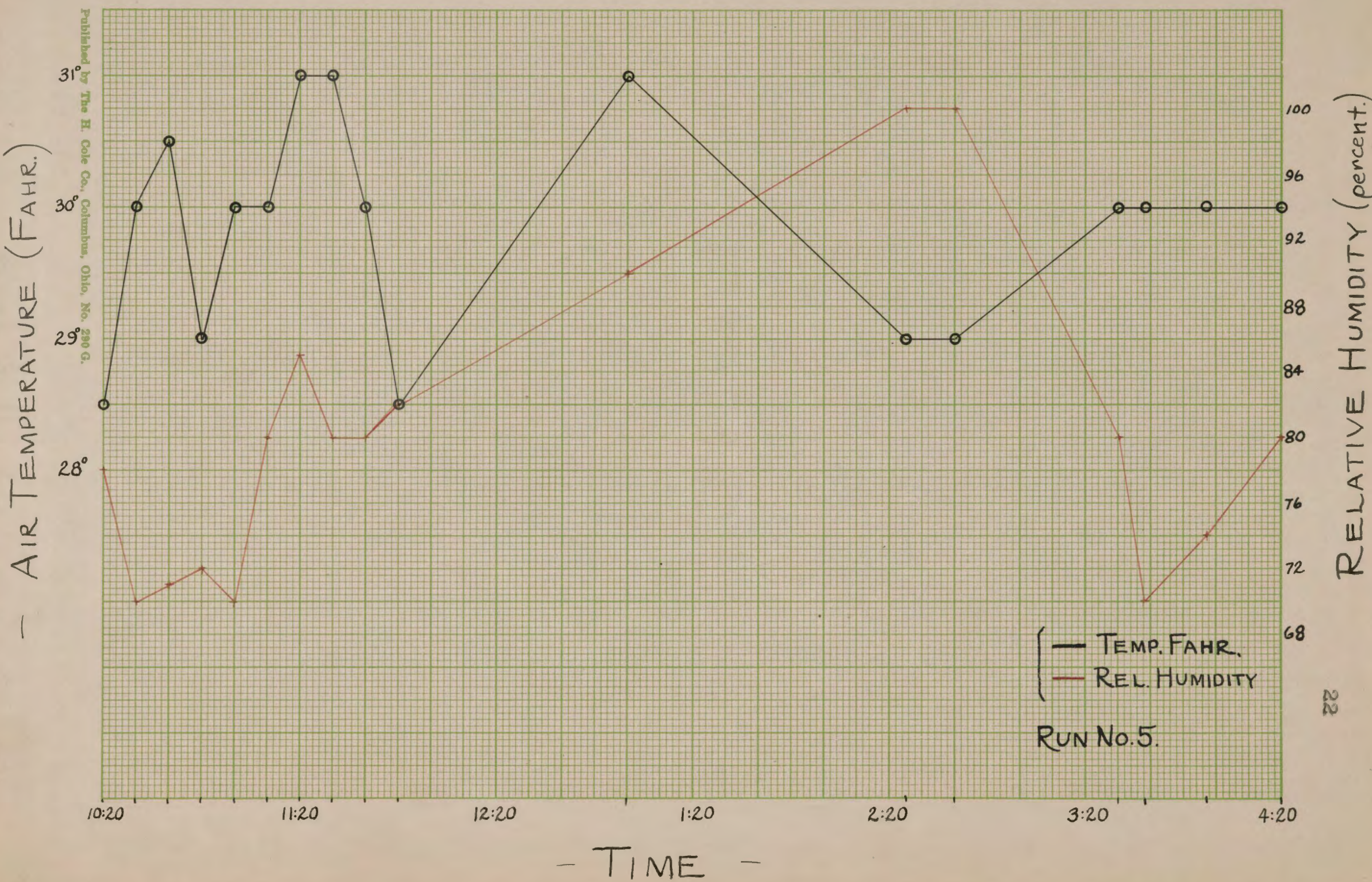
Temperature of Air (Fahr.)
30°
29°
28°
27°
26°
25°
24°
23°
22°
Relative Humidity (percent)
94
92
90
88
86
84
82
80
78
76
Temp. Fahr.
Rel. Humidity
Run No. 4.
1:00
2:00
3:00
4:00
5:00
6:00
- TIME -
Published by The H. Cole Co., Columbus, Ohio. No. 280 G.

20

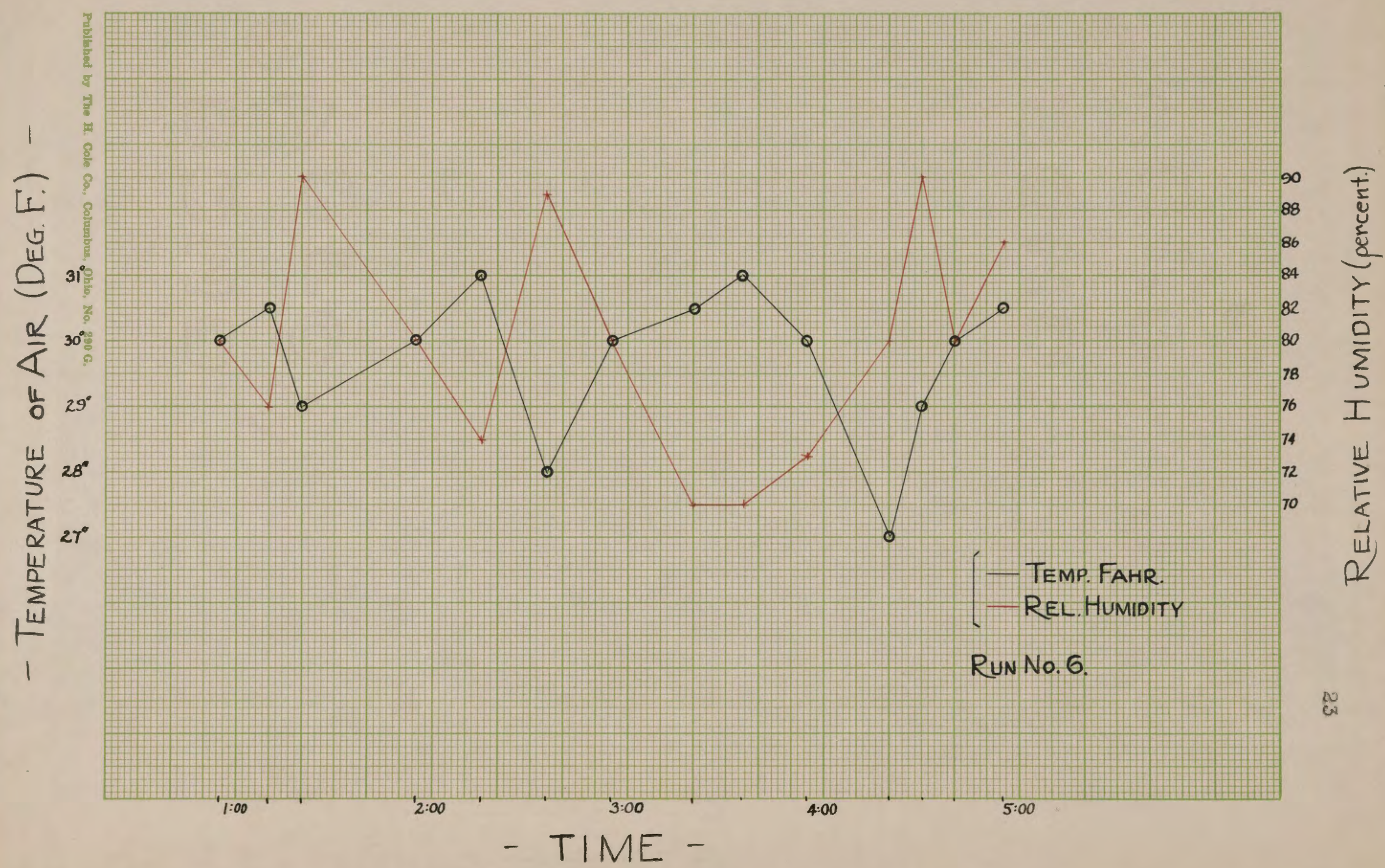
time the cone of ice which originally weighed about 6 lbs.10 oz. lost a little over an ounce. Neglecting the first half hour or slightly less of the run because of the temperature difference, this means that the block lost the weight in four hours under the influence of the low air velocity. Again the surface of the ice was dry throughout the run.

In run No.5, the temperature was kept very near to 30°F. for six hours as can be noticed in the curve sheet for this run. The low air velocity was used, but again the humidity ran out of control. The average humidity was near 85%, although it varied from 70% to 100%. During the period when the humidity was at 100%, the surface of the ice became wet as it had under the influence of high air velocity at a lower temperature, and drops of water formed on the lower edge of the cone. However, when the humidity was brought back to normal, the drops formed an icicle on the lower edge, and the surface became dry again. During the six hour run at low velocity, the cone of ice which originally weighed 6 lbs. 9 oz. lost two ounces.

In the sixth run, the temperature was again kept at approximately 30°F. for four hours under the influence of the low velocity air. For the four hours the ice which originally weighed 5 lbs.7 oz. lost about an ounce and an additional small fraction, which is a larger



Published by The H. Cole Co., Columbus, Ohio. No. 290 G.
AIR TEMPERATURE (FAHR.)
31°
30°
29°
28°
RELATIVE HUMIDITY (percent.)
100
96
92
88
84
80
76
72
68
TEMP. FAHR.
REL. HUMIDITY
RUN NO. 5.
10:20
11:20
12:20
1:20
2:20
3:20
4:20
TIME



- Temperature of Air (Deg. F.) -
31°
30°
29°
28°
27°
Relative Humidity (percent.)
90
88
86
84
82
80
78
76
74
72
70
1:00
2:00
3:00
4:00
5:00
- TIME -
Temp. Fahr.
Rel. Humidity
Run No. 6.
Published by The H. Cole Co., Columbus, Ohio, No. 290 G.

percentage and a greater rate than any of the previous runs. The humidity again varied from 70% to 90% but averaged about 80%. During this run a large amount of ammonia was set loose in the cold room from some apparatus which was working simultaneously with the cooling unit. The leak was soon stopped, and the ammonia blown out of the room at the expense of a drop in temperature. The ice throughout the run was dry, a small icicle at the beginning of the run being the only exception.

CALCULATIONS

Area of cones:

$$\frac{(5\frac{1}{2})(22)\pi}{2(12)^2} - \frac{(1\frac{1}{2})(4\frac{1}{2})\pi}{2(12)^2} = 1.32 - 0.061 = 1.26 \text{ sq.ft.}$$

7000/16 = 437.5 grains in one ounce

Run No.4.

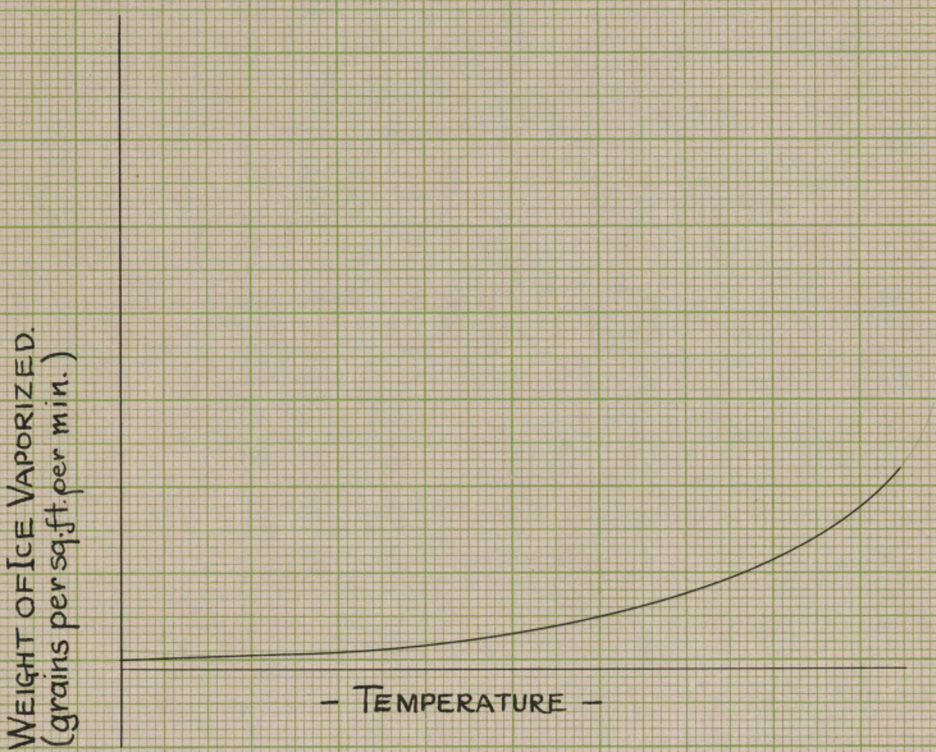
$$\frac{1\frac{1}{2}\ (437.5)}{1.26\ (240)} = 2.17 \text{ gr. per sq.ft. per min.}$$

Run No.5.

$$\frac{2\ (437.5)}{1.26\ (360)} = 1.93 \text{ gr. per sq.ft. per min.}$$

Run No.6.

$$\frac{1\frac{1}{2}\ (437.5)}{1.17\ (240)} = 2.34 \text{ gr. per sq.ft. per min.}$$



CURVE SHOWING THE GENERAL TENDENCY OF THE RATE OF ICE SUBLIMATION.

CONCLUSIONS

1. The rate of sublimation of ice decreases with lowered temperature.

2. At low temperatures, high air velocities cause the surface of ice to become wet.

3. Very high humidities at temperatures slightly below freezing produce the same effect as in (2).

4. Variations in humidity and air velocity have little effect on the sublimation rate of ice.

The application of these conclusions would lie in the direction of ice storage or transportation.

The phenomena of the wetted surface being caused, apparently by two distinct factors suggests further study to determine which of the two is the deciding factor. This would require absolute control of both the temperature and humidity, with which it would be possible to further study the exact laws of sublimation.

BIBLIOGRAPHY

H.T.Barnes, "Ice Engineering", *Refrigerating Engineering*, vol.16, Oct.'28, pp.93-8.

Paul W. Scates, "The Rate of Ice Melting", *Refrigerating Engineering*, vol.22,no.1 Jl'31 p15

"Psychrometric Chart..", *Refrigerating Engineering*, vol.23, Feb.'32, p.97.

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrent its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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