BOILING HEAT TRANSFER TO LIQUID NITROGEN AND LIQUID HELIUM

by

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ABSTRACT

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Experimental data on free convection and nucleate boiling was taken in liquid nitrogen and liquid helium using platinum wires as heating elements. The results in liquid helium and particularly in liquid nitrogen were found not to agree with the generally accepted results in other liquids. In particular it was found that the transition from free convection to nucleate boiling would not take place until the temperature of the wire was much greater than that found for nucleate boiling. An "extended region" thus must be added to the free convection curve. This extended region did not reoccur in the reverse transition from nucleate boiling to free convection.

It is usual to represent nucleate boiling heat transfer data to liquids as an equation of the form $q/a = C\Delta T^n$ where q/a is the rate of heat transferred per unit area, ΔT is the excess temperature of the heating surface and C and n are independent constants. There is

universal agreement that $2.5 \leq n \leq 4$ for all liquids. However, it is found for liquid nitrogen that n is not in this region but is about 11. It is then shown that C is a function of n and the equation in liquid nitrogen reduces to one with a single arbitrary constant of the form.

$$q/a = \exp^{(10.25 - 2.45n)} \Delta T^{n} \qquad 5 \leq n \leq \infty$$

This equation represents a family of curves which intersect at the maximum observed value of q/a for 0.008 inch wires.

The existing mechanisms used to explain the high heat transfer rates in nucleate boiling are reviewed and shown to be quantitatively invalid in liquid nitrogen.

A "hot" molecule hypothesis is proposed, wherein a single hot molecule is assumed to supply all of the energy requirements for the growth of a bubble. It is shown that this hypothesis is invalid in itself but the calculations lead to an alternative hypothesis. This alternative hypothesis proposes that the excess energy stored in the bubble boundary acts as an energy sorting mechanism which must be present to keep a growing bubble from violating the laws of thermodynamics.

Experimental data is presented for nucleate boiling from platinum wires in liquid helium. This data is also unusual but is more or less consistent with the results obtained in liquid nitrogen. An extended region is not, however, observed in liquid helium.

ACKNOWLEDGEMENTS

I wish to express my great appreciation and indebtedness to the late Professor John E. Younger, Chairman of the Department of Mechanical Engineering of the University of Maryland, and to my Advisor, Professor Charles A. Shreeve, Jr., for their untiring efforts and guidance in this work. I also wish to acknowledge the interest and support of the Department of Defense in this research. Also, without the steadfast faith and encouragement of my wife Lorraine I would never have completed this work.

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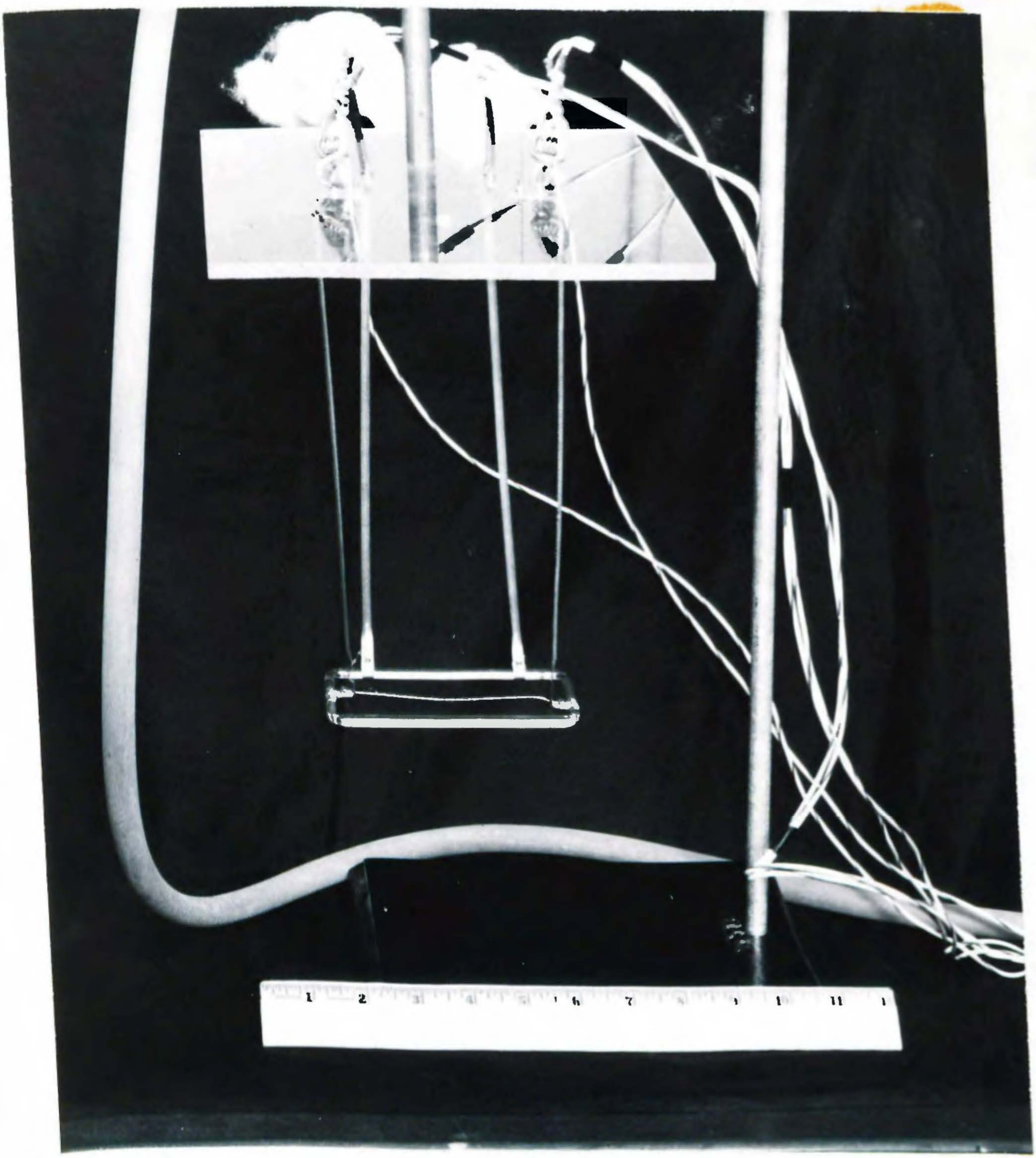
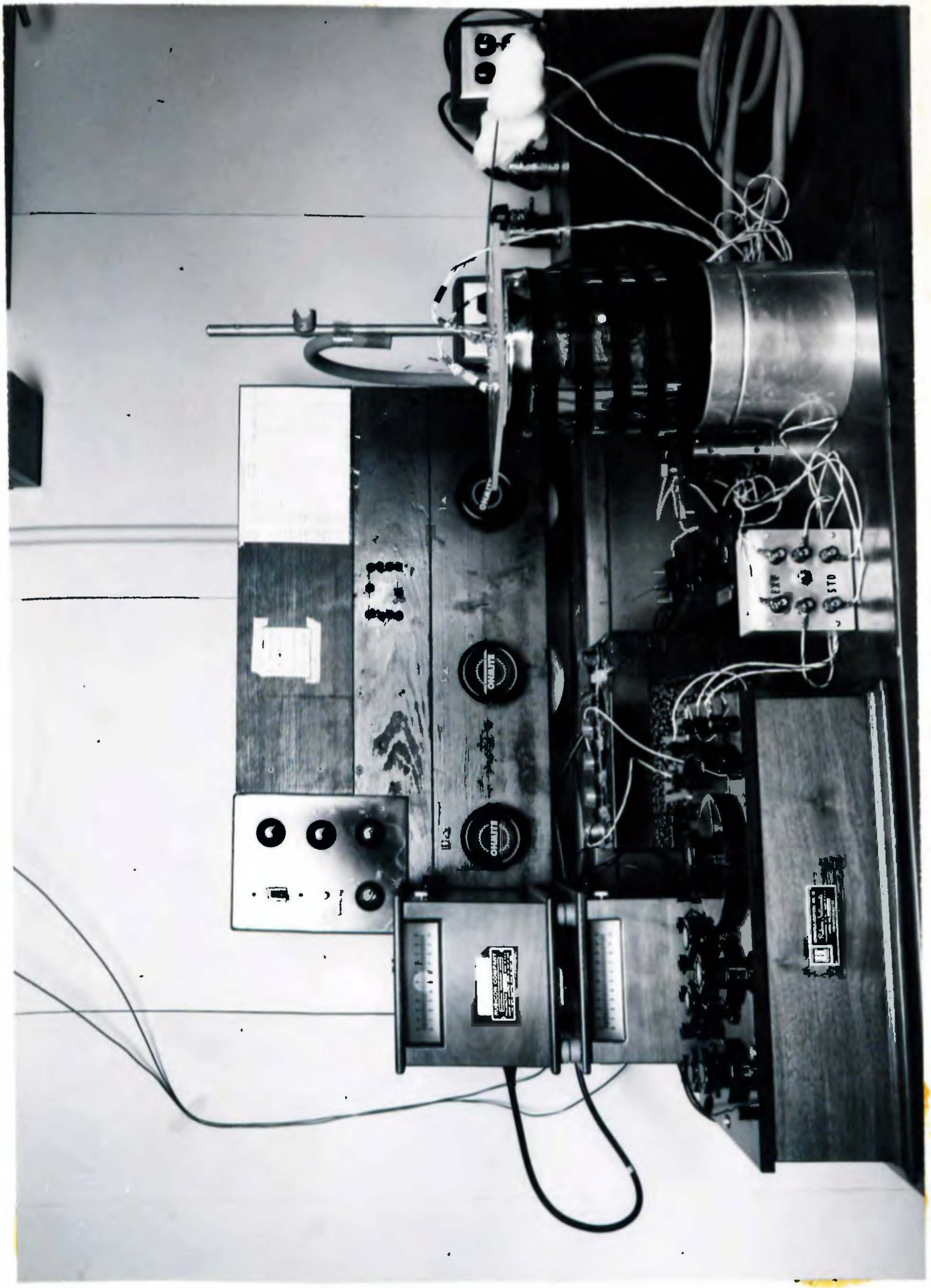


PHOTOGRAPH 1



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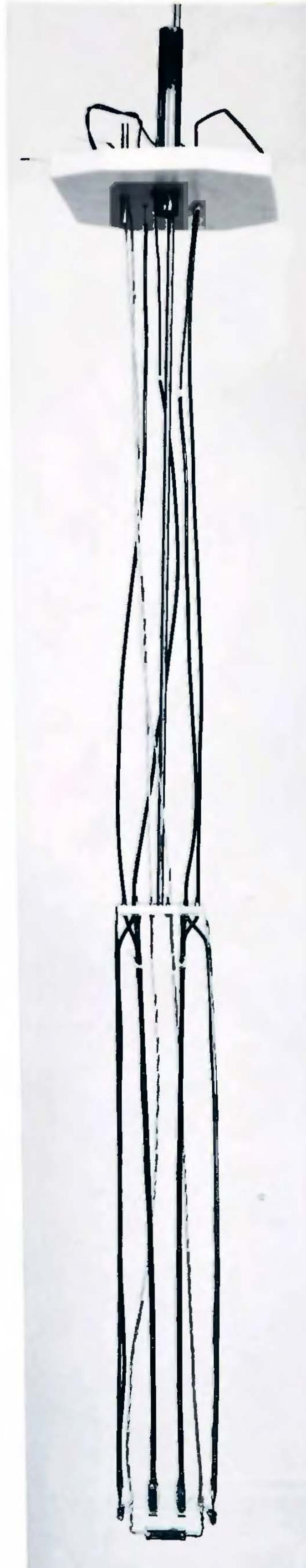

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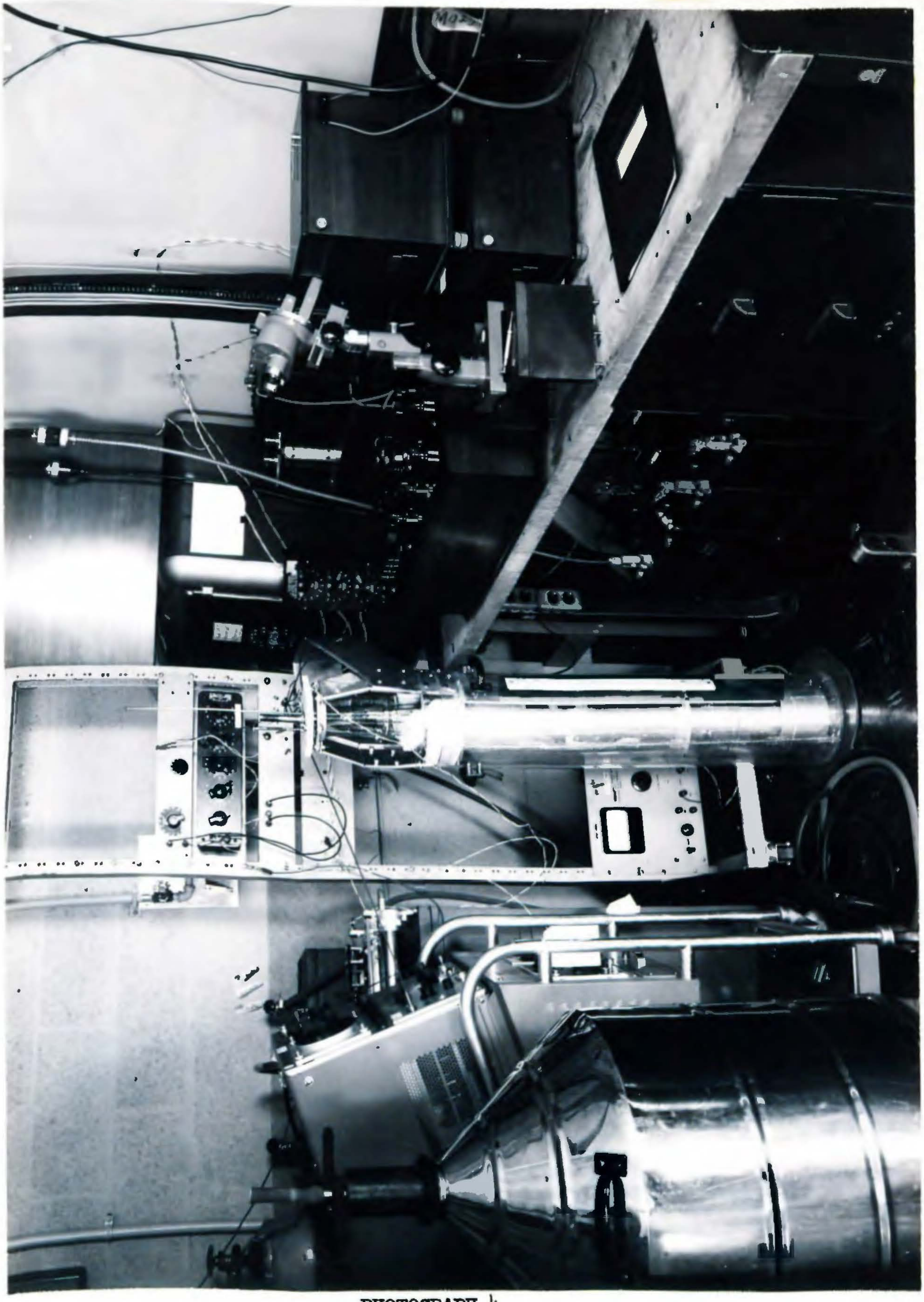


PHOTOGRAPH 4

INTRODUCTION

People have always known that liquids boil. Their acquaintance with this phenomena is probably as old as their discovery of fire. Probably equally venerable is the observation that no matter how hot the fire, a pot set to boil will become blackened. Relatively speaking then, the pot is never much hotter than the liquid. By the early 1800's it was well understood that another state of boiling occurred which was referred to as the spheroidal state or the Leidenfrost state.[1*] The word spheroidal arose because of the observation that drops of water dropped onto a very hot surface would form small spheroids and dance around on the surface instead of spreading out and wetting the surface. Another 100 years was to pass before a careful examination and discussion of multiple boiling regimes appeared.

In 1934 Nukiyama[2] electrically heated a platinum wire in water to produce boiling. He observed that the rate of heat transfer to the water increased steadily until the wire reached about 300°F. In attempting to go slightly above 300°F by increasing the electric current a small amount the wire temperature jumped suddenly to about 1800°F. Reducing the current slightly did not return the wire to the 300°F point on the curve Further reduction of the current lowered the temperature of the wire continuously to about 600°F at which point the

* Superscripts refer to Literature cited.

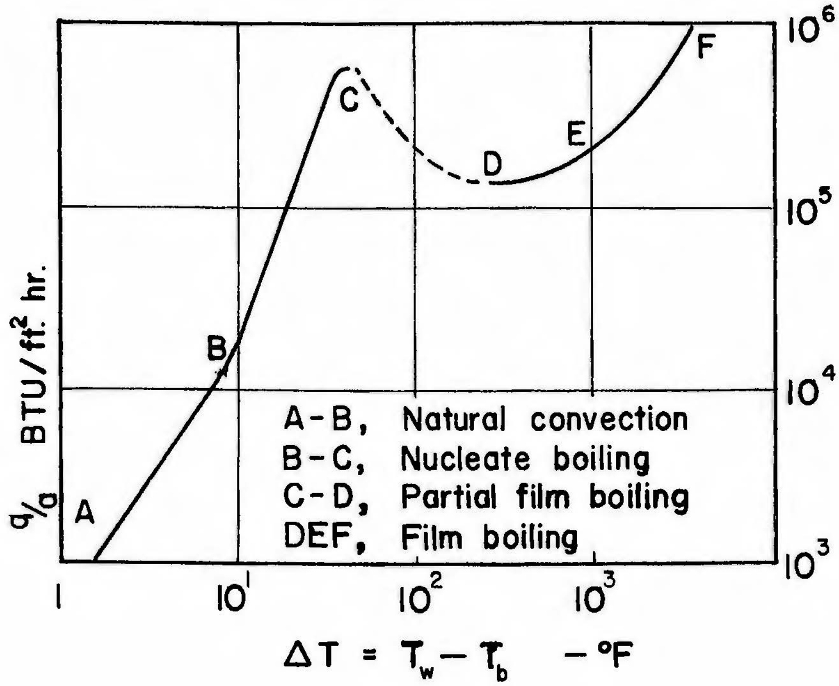


Figure 1

temperature fell rapidly to the original curve. Nukiyama concluded that one type of boiling occurred below 300°F and another above 600°F and he guessed that a third, abnormal kind of boiling might take place between 300°F and 600°F. One of Nukiyama's curves is shown as Figure 1 for boiling from a 0.0055 inch platinum wire in water at one atmosphere pressure.

Subsequent research by many investigators has shown that this state of affairs can be duplicated in other liquids and there are indeed three types of boiling. They are usually called nucleate transition and film boiling. As the heating surface (wire) becomes progressively warmer the following events are seen to happen. First the wire merely warms the surrounding liquid but not sufficiently to produce bubbles. This is region A-B where heat transfer is by natural convection. At point B the wire is warm enough to cause bubbles to form at points along the wire and nucleate boiling becomes progressively more vigorous. Between C and D an unstable transition takes place from nucleate boiling to film boiling. The region DEF represents film boiling which is characterized by a film of gas which surrounds the wire and from which large volumes of gas grow and separate irregularly.

Invention of the Cryotron[3], a superconductive electronic switch a few years ago has made it highly desirable to obtain heat transfer data to liquid helium. In its present state of development it appears that an upper limit to the ultimate speed of operation of a Cryotron may be temperature related. Thus it follows that for a very high speed superconductive digital computer the thermal time constant may be a limiting factor. Boiling heat transfer, while a steady state phenomena, should provide an upper bound for the necessary calculations.

The original intent of this research was to take most of the data in liquid helium. Because of the difficulty of working in helium and the very high cost of the liquid it was decided to do some preliminary investigations in liquid nitrogen. The results obtained in liquid nitrogen were so unusual that the majority of this thesis is devoted to liquid nitrogen. However, brief data on liquid helium and a discussion of the necessary experimental techniques are included.

CHAPTER I

EXPERIMENTAL TECHNIQUES IN LIQUID NITROGEN

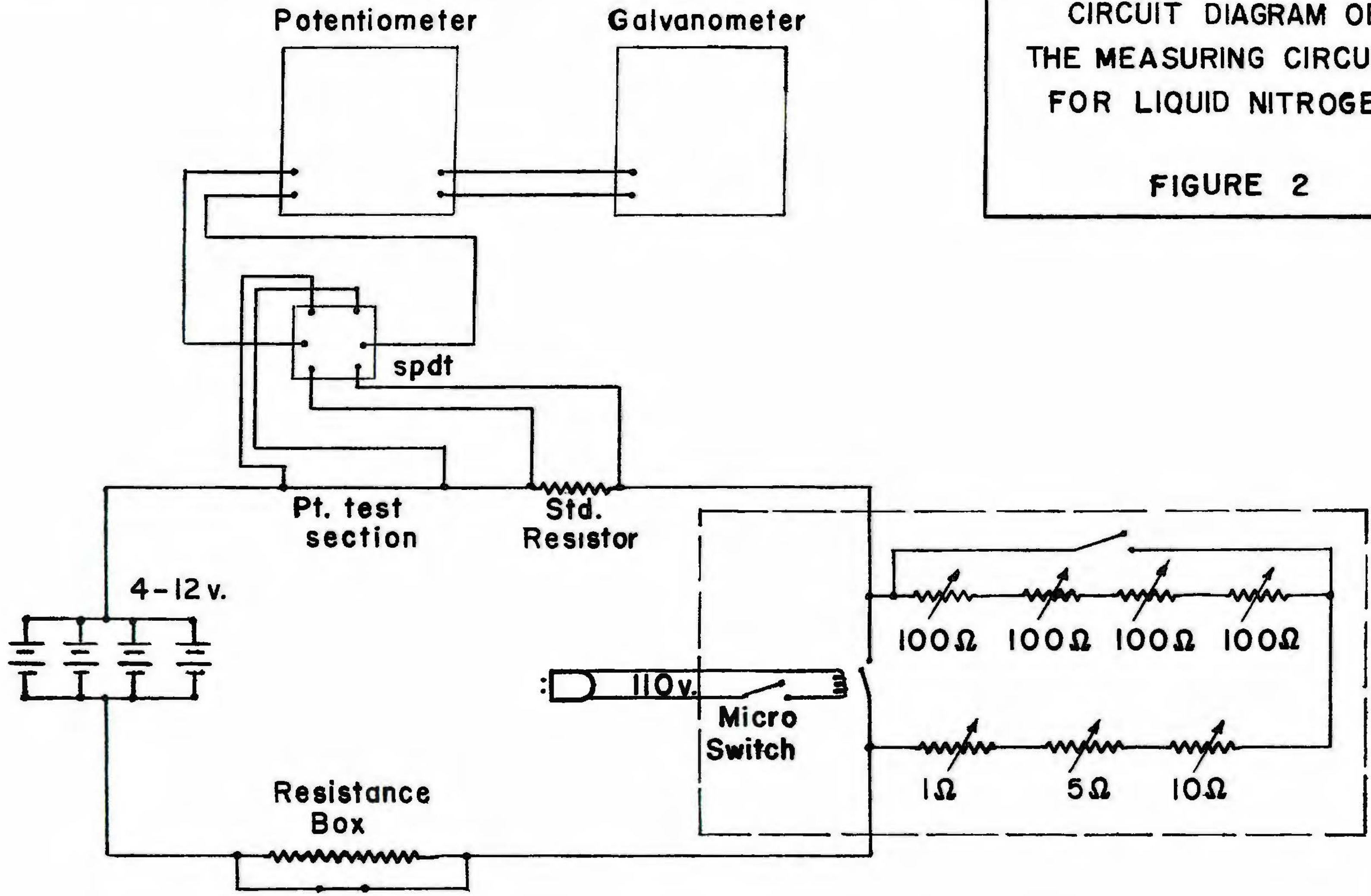
General. A frequently used material in studying boiling heat transfer is platinum wire because the resistance of pure platinum as a function of temperature is extremely well known over a wide range of temperatures. Platinum wire of sufficient purity for resistance therometry is obtainable from a number of commercial sources, and is available in any desired wire size. Wires of 0.004 inch and 0.008 inch diameter were used in these experiments. The wire was hard drawn from a completely fused ingot.

In their excellent paper[4] on heat transfer from single horizontal wires to boiling water, McAdams et. al. describe an experimental setup which formed the basis for present work. However, the anti-corrosion circuit which McAdams et. al. included was not found necessary in liquid nitrogen and was eliminated. As they suggest, only the central portion of the platinum wire was used as a test element by spot welding platinum potential leads at least one half inch from the points at which the wire joined the brass binding posts. The potential leads were in all cases 0.002 inch wire. The holder of the heating element and potential leads consists of a 5/32 inch glass rod formed into a rectangle about 2 inches by 4 inches (shown in photograph I). Four brass legs extend downward from a 10 x 10 plexiglass plate and are clamped to the glass rectangle with 2-56 brass nuts and brass machine screws. These clamps also serve to hold the test wire and potential leads. The external electrical connections are made to similar brass machine screws which act as feed thrus for the plexiglass. A 1/2 inch diameter rod is fastened to the plexiglass plate and serves as a handle and as a support for an air hose. The entire assembly is then lowered into an open mouthed Dewar vessel which holds the liquid nitrogen. The assembly can be seen in place in the right foreground of Photograph 2. The air hose which points downward toward the plexiglass plate was used to insure that the plate remained dry. Moisture condensing from the air on the top of the plate was found to short circuit a small electric current. This moisture was prevented from condensing by a continuous stream of warm air.

The cotton balls which can be seen in both Photograph I and 2 enclose the alligator clips which connect the potential measuring circuit. Convection currents of room air were producing small thermo-electric voltages at the junction of the brass and the alligator clips. These parasitic voltages were not observed after wrapping the junctions in cotton.

The Measuring Circuit and Its Operation. A circuit diagram of the measuring circuits is given in Figure 2 on the following page. The circuit diagram can be correlated with Photograph 2 which shows all but the four 12 volt wet cells in parallel which were used as a current source. The method of operation was as follows:

1. The resistance box which was used only in calibration of the wire at the ice point was shorted out of the circuit.



CIRCUIT DIAGRAM OF THE MEASURING CIRCUIT FOR LIQUID NITROGEN

FIGURE 2

2. The remaining six rheostats were adjusted to give the desired electric current thru the platinum wire. All six rheostats are mounted on a panel which can be seen at the back of Photograph 2.

3. The potential across the experimental test section was determined using a Rubicon Type B potentiometer* and a galvanometer*. A null method was used.

4. Current thru the wire was determined by measuring the potential across a 0.1 ohm standard resistor* using the same potentiometer and galvanometer.

5. A double pole double throw switch was used to select the desired potentiometer input.

6. A shorting switch, shown in Figure 2 was used to eliminate the four 100 ohm resistors from the circuit when, in the process of increasing the current, the resistors had all been reduced to zero.

It was observed that the accuracy of the measurement was limited by the stability of the boiling phenomena rather than the precision of the equipment. Between each setting of the external resistance which controlled the current, time was allowed for thermal and electrical equilibrium to be reached. Admittedly exact equilibrium is difficult to determine so the galvanometer drift was observed and when no longer

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* The potentiometer had a stated error of no more than 0.015% over the range 0 to 1.6 volts.

* The deflection of the galvanometer was 0.5 microvolts per millimeter.

* The 0.1 ohm standard resistor had an error of less than 0.001% within the range of currents encountered.

discernable, readings were taken. Some thought was also given to the fact that both current and voltage were not determined simultaneously. To minimize this possible source of error the order of the readings was alternated, current first then voltage first. Since the ratio of current and voltage appears in the final result ($E/I = R = f(t)$) this should produce a random scatter in the calculated points rather than a bias.

McAdams et. al.[4] reported a problem in the vicinity of the maximum nucleate boiling heat flux. In attempting to cross the discontinuity to film boiling their wire frequently burned out. They proposed the explanation that this was more current than the wire could carry continuously in the film boiling state without melting. Their solution to this dilemma was a knife switch with which they could momentarily short out the remaining external resistance of the circuit. By thus sending a current pulse thru the wire they were able to drive a fairly large section of the wire into film boiling, and its own increased resistance acted as a subsequent current limiter. In the present work a knife switch proved inadequate and was replaced by a normally open 36 ampere relay. The relay was controlled by a normally open micro-switch in a 110V actuating circuit. Much shorter pulses were obtained and the transition to film boiling became routine. This did not eliminate the problem of accidental spontaneous film boiling when taking data close to the maximum for nucleate boiling. This usually destroyed the wire and these readings were taken with caution.

It should be noted that the reverse transition from film boiling back to nucleate boiling presents no problem. The film slowly decays and the temperature of the wire drops.

Preparation and Calibration. After spot welding the potential leads to the experimental wire the wire was annealed in still air for 20 minutes at 1000°C. During this anneal several wires were observed with a radiation pyrometer and no discernable temperature gradient was found within the test section. Since the wires were used at a much lower temperature it was assumed that no significant temperature gradient would exist along the test section. Also during the experimental runs it was further observed that boiling took place as readily and as vigorously at the ends of the wires as it did in the central test section. Since the presence and intensity of nucleation centers is directly related to the temperature of the wire this was taken as confirmation of the assumption that the linear gradient was small. Following the anneal the wire was mounted in the glass frame and its length measured to the closest 0.01 inch.

The electrical resistance ratio $\frac{100\,R_x}{R_o}$ vs. T_x for several samples of platinum is given in the International Critical Tables[5] (hereafter referred to as the ICT). Examination of this data shows that the change of resistance between nitrogen temperature and the ice point is so nearly linear that use of a linear assumption is justified. Thus calibration at two points will establish the R vs. T curve. Obviously the ice point is a good choice as a fixed point because of its known reproducibility[6]. However, reproduction of the ice point proved not a trivial task. The following method was used.

1. The inside of an open mouthed Dewar flask was precooled with liquid nitrogen.

2. About a teacup of distilled water was poured into the cold Dewar and the Dewar was tilted and rotated slowly to allow a layer of ice to freeze on the sides and bottom of the Dewar.

3. More liquid nitrogen was added and steps 1 and 2 above repeated until an ice mantle about 1/4 inch thick had formed on the inside of the Dewar.

4. Concurrently a block of distilled water ice was being frozen by suspending a 500 mililiter polyethelyne beaker in a second Dewar which was full of liquid nitrogen.

5. When frozen this block of ice was removed from the beaker, crushed and mixed with more distilled water.

6. The glass frame was lowered into the Dewar onto which was frozen the 1/4 inch ice mantle.

7. The chilled distilled water was slowly poured into the Dewar until it covered the platinum wire to a depth of about two inches.

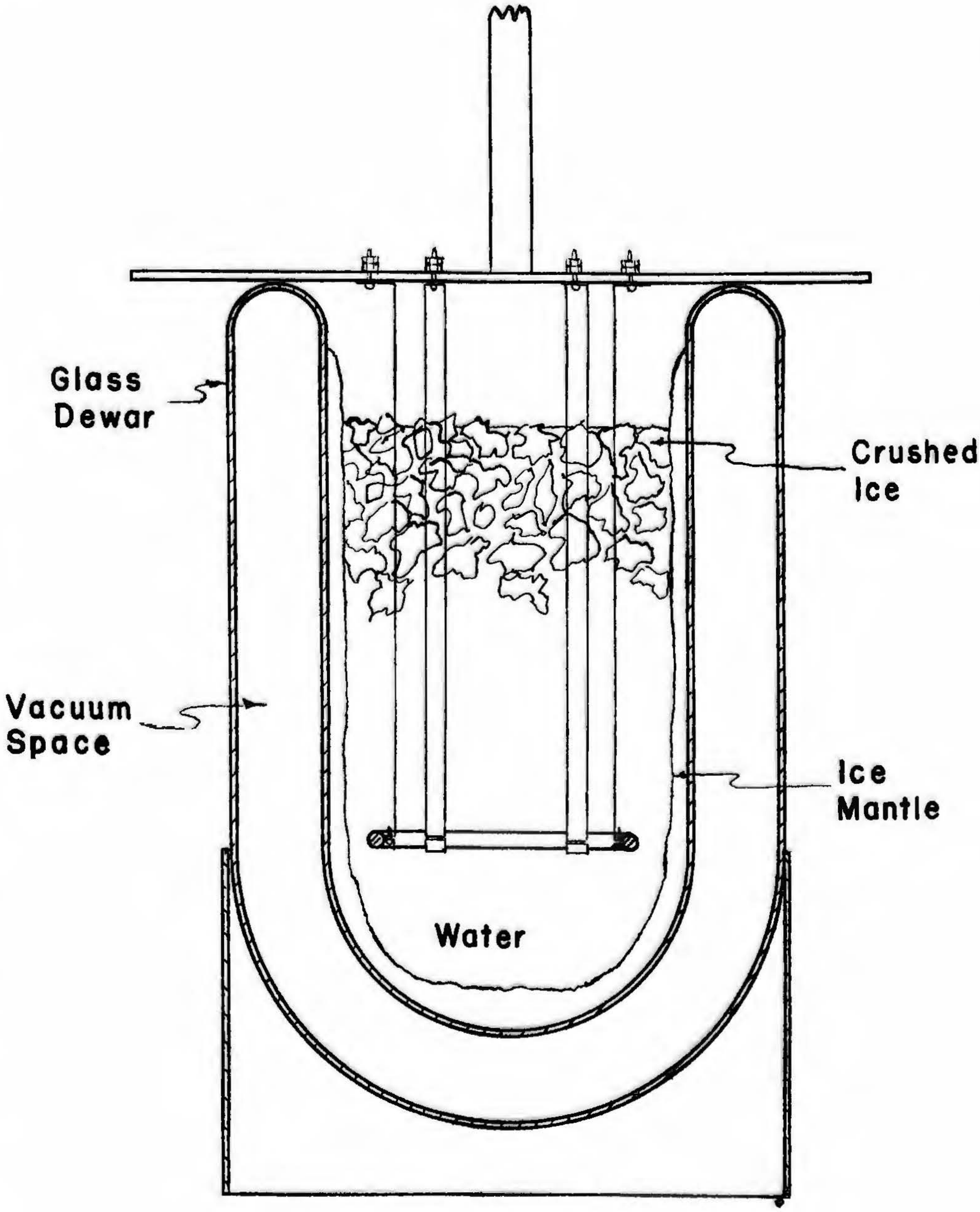
8. The remaining crushed ice was carefully added.

Now the wire was completely surrounded by ice and any heat flow from the surroundings should melt ice instead of increasing the bath temperature. It was observed in subsequent readings that the ice mantle frozen to the sides of the Dewar usually melted first. As soon as a small hole, say a square inch in area, appeared the temperature of the bath began rising preceptably. A drawing of the arrangement of the ice bath is shown as Figure 3.

Having prepared the ice point bath the resistance of the wire was found. This was done by passing a small current thru the wire and recording the voltage across the wire and the standard resistor.

ICE POINT BATH

FIGURE 3



The resistance of the wire was then calculated using the following formula where R_{Std} is known.

$$R_O = \frac{E_{Exp} \cdot R_{Std}}{E_{Std}}$$

The subscripts Std and Exp are used thruout this thesis and always have the same meaning. Exp. always refers to the platinum test wire and Std. to the standard resistor.

It would be desirable to measure the resistance of the wire using zero measuring current since any current will produce a small heating effect and thus raise the temperature of the wire slightly. In theory it is possible to use progressively smaller measuring currents and extrapolate the results to zero. In practice a compromise must be effected because there is a limit below which any potentiometer will indicate its maximum number of significant digits. In this experiment five significant digits could be read on the Rubicon Type B potentiometer only when the current was greater than about 10 milliamperes. However, readings as great as 20 milliamperes produced no determinable variation in resistance. Consequently in the initial ice point calibration about a dozen pairs of readings (Exp and Std) were taken with various currents between 10 and 20 milliamperes. R_O was calculated from each pair of readings and then all of the values of R_O were averaged.

Only one step remains in the ice point calibration. The wire must be removed from the bath without its breaking or bending. The crushed ice must be removed before removing the wire.

The boiling point of liquid nitrogen is a function of pressure and can be represented over a limited range by[7]

$$T_{N_2} = -195.80^{\circ}C + 0.0109(P-760) \qquad P \text{ in mm. Hg.}$$

Barometric pressure was measured whenever necessary for use in the above formula. In the same manner as the ice point calibration the minimum current which gave five significant digits was used as a limiting value. Several sets of readings were taken and R_{N_2} calculated from the same expression used for R_O. It was observed that R_{N_2} sometimes drifted slightly during or between experimental runs. For this reason redetermination of R_{N_2} was frequent and for each new R_{N_2} a new curve was drawn. The two sets of curves, one for the 0.004 inch wires and the other for the 0.008 inch wires are Figures 4 and 5 which are included with the experimental data on liquid nitrogen. It should be noted that these curves are plotted as $\frac{100R}{R_O}$ vs. T. It can be expected[8] that $\frac{100R}{R_O}$ will remain constant even though R_{N_2} and R_O drift and for each new R_{N_2} a new R_O has been calculated. By plotting as $\frac{100R}{R_O}$ these curves could be drawn parallel to the similar data of reference 5. Plotting in this fashion also has the effect of normalizing the data which frequently made it possible to reuse a prior resistance curve.

The completes the description of the calibration of the platinum wire.

CHAPTER II

EXPERIMENTAL RESULTS IN LIQUID NITROGEN

When work began in liquid nitrogen it was expected that the data would result in a series of curves which were similar in shape and details to Figure 1 since previously reported curves agreed for all liquids. And, in fact, the results of Tables 2, 3 and 4 do correspond to the expected shape of the curve. It was with some surprise that a new and easily measurable extension of the basic curve appeared in run 5. This extension first occurs in the data of Table 5 and its significance with relation to the nucleate boiling region of the curve is first shown in Table 6*. The data of Table 6 appears on the next page. Note that the gradual transition from free convective heat transfer to nucleate boiling does not occur. The free convective region extends well beyond the ΔT at which nucleate boiling should begin. Only a relatively large ΔT does nucleation begin at a

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* A total of 42 experimental runs were made in nitrogen exclusive of calibration runs. Each run is given in Appendix 1 as both a Table of experimental data and calculations, and a log. log. plot of the results of each run. Typical curves have been abstracted and appear in the body of the thesis wherever needed in order to save thumbing thru the mass of experimental data.

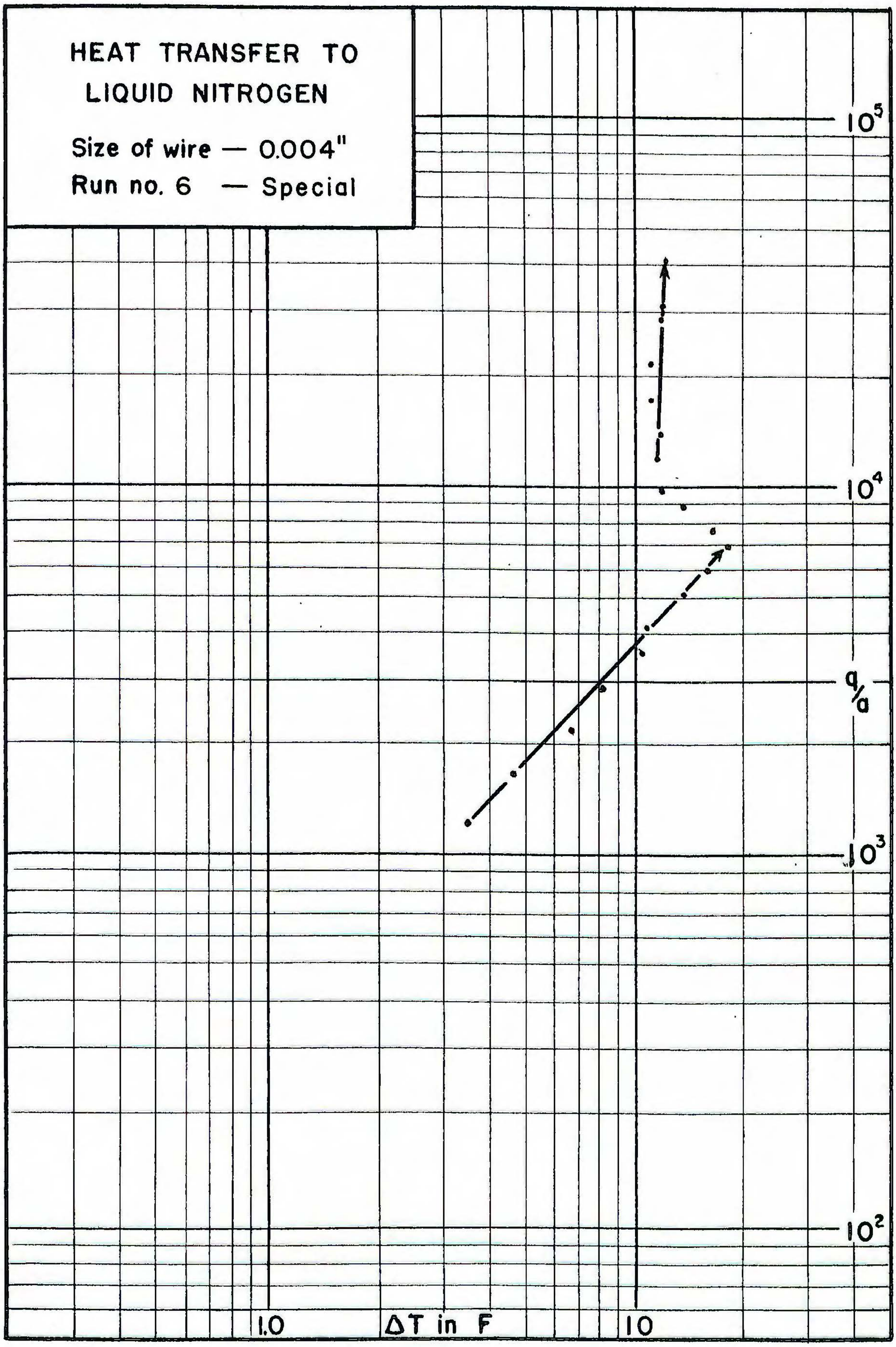
HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.004"
Run no. 6 — Special
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

FIGURE 6

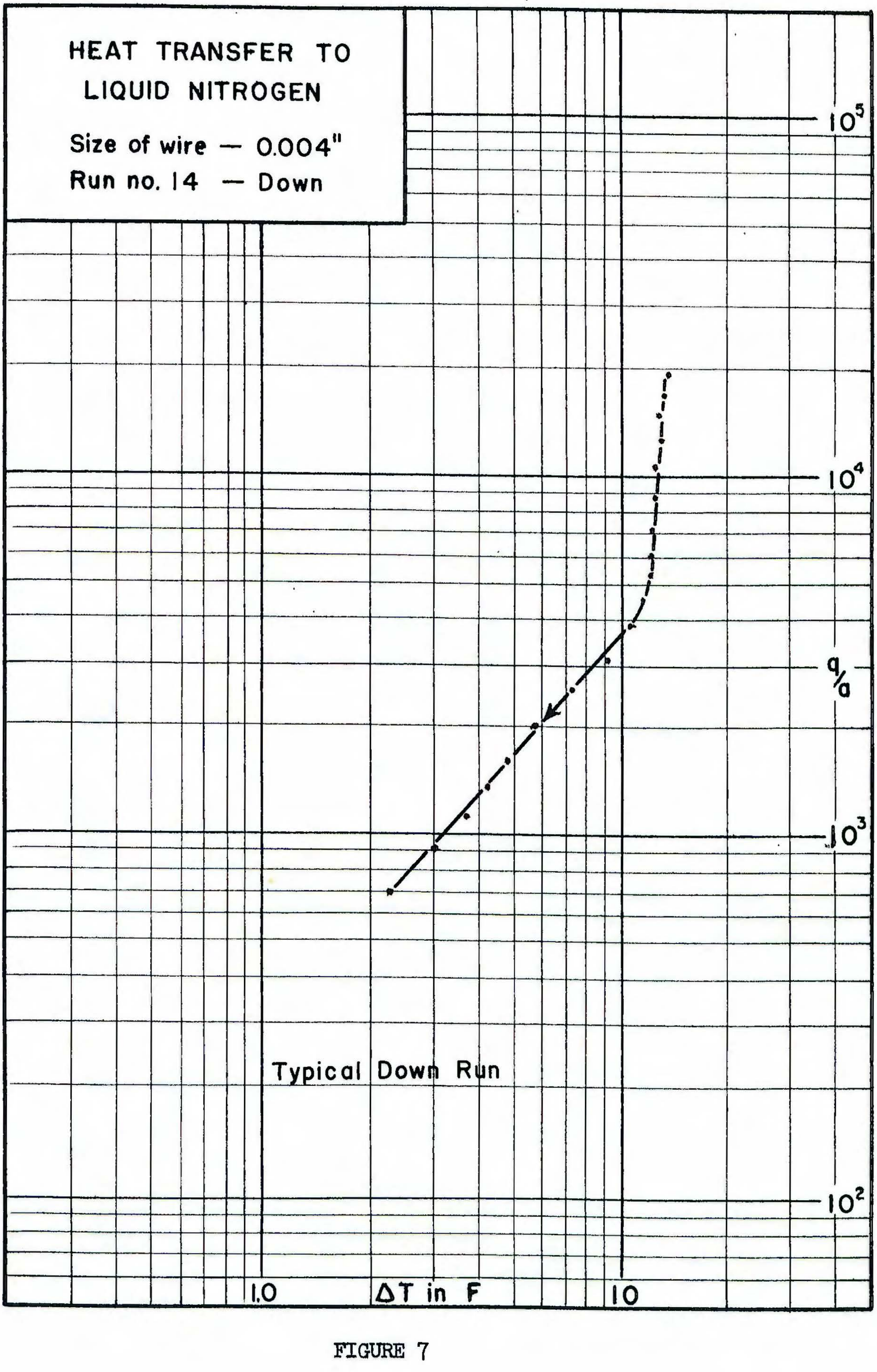
HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.004"
Run no. 14 — Down
10^5
10^4
q/a
10^3
10^2
Typical Down Run
1.0
ΔT in F
10

FIGURE 7

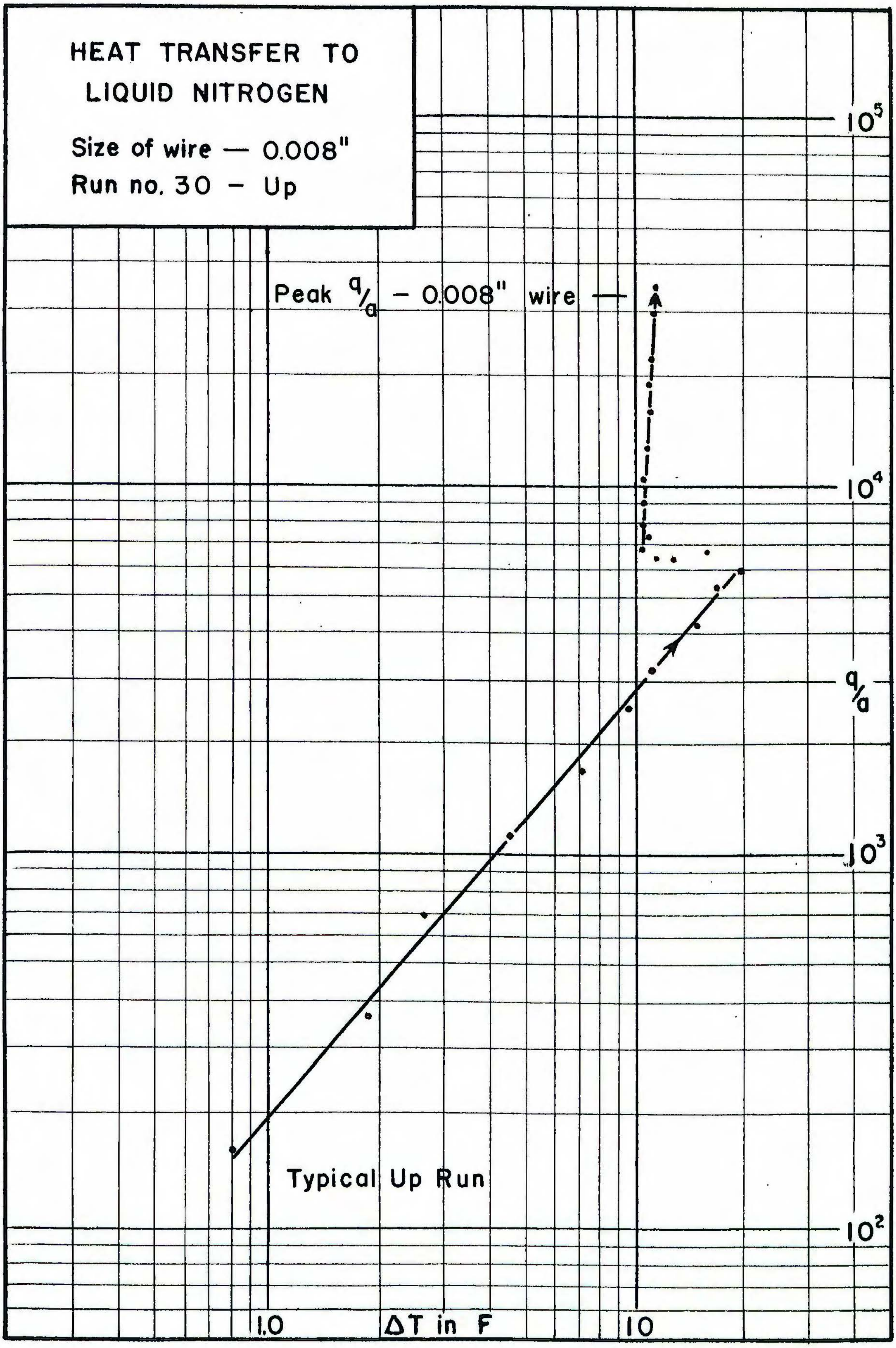
HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 30 - Up
Peak q/a - 0.008" wire
Typical Up Run
1.0
ΔT in F
10
10^5
10^4
q/a
10^3
10^2

FIGURE 8

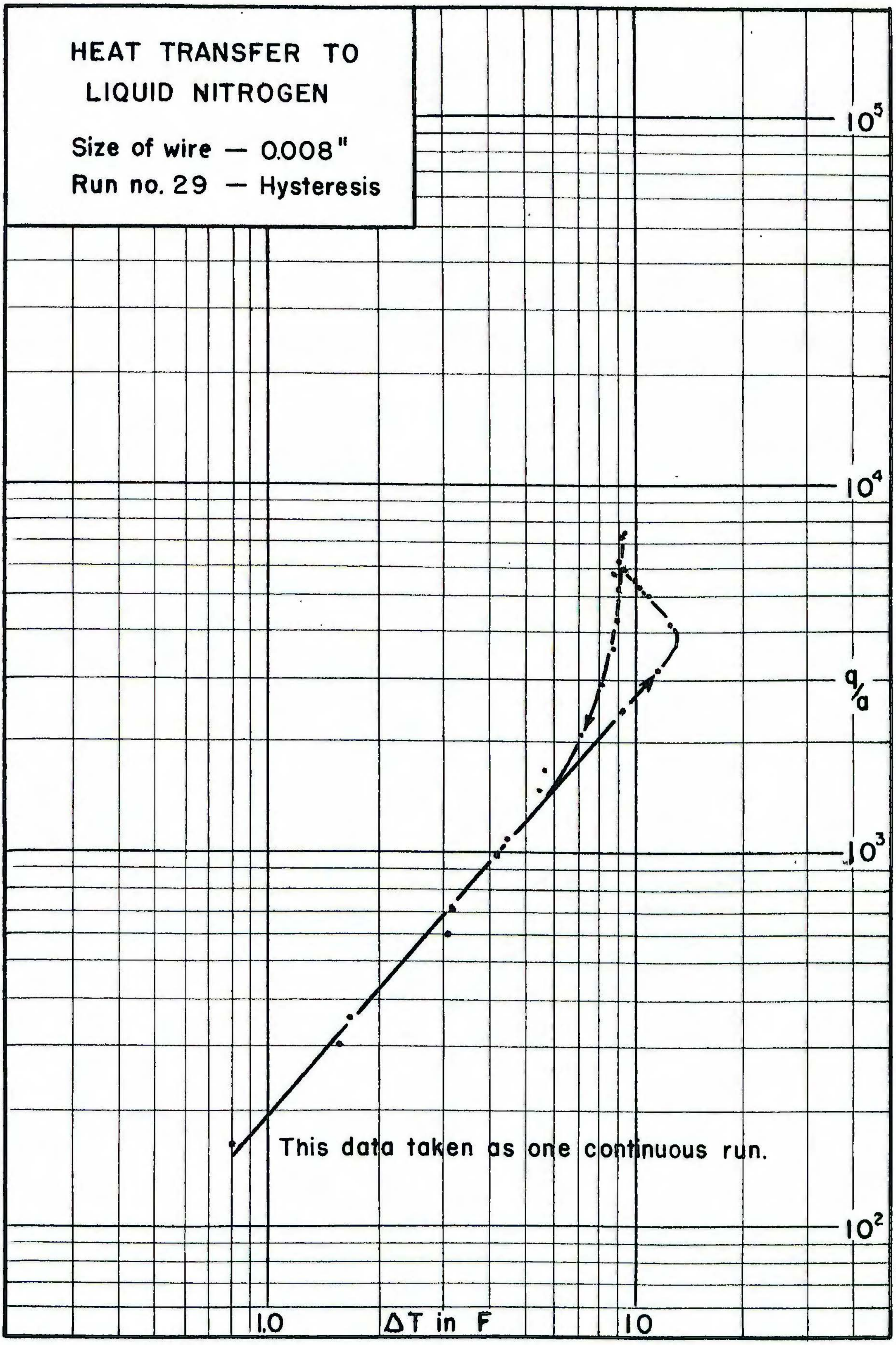
HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 29 — Hysteresis
This data taken as one continuous run.
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

FIGURE 9

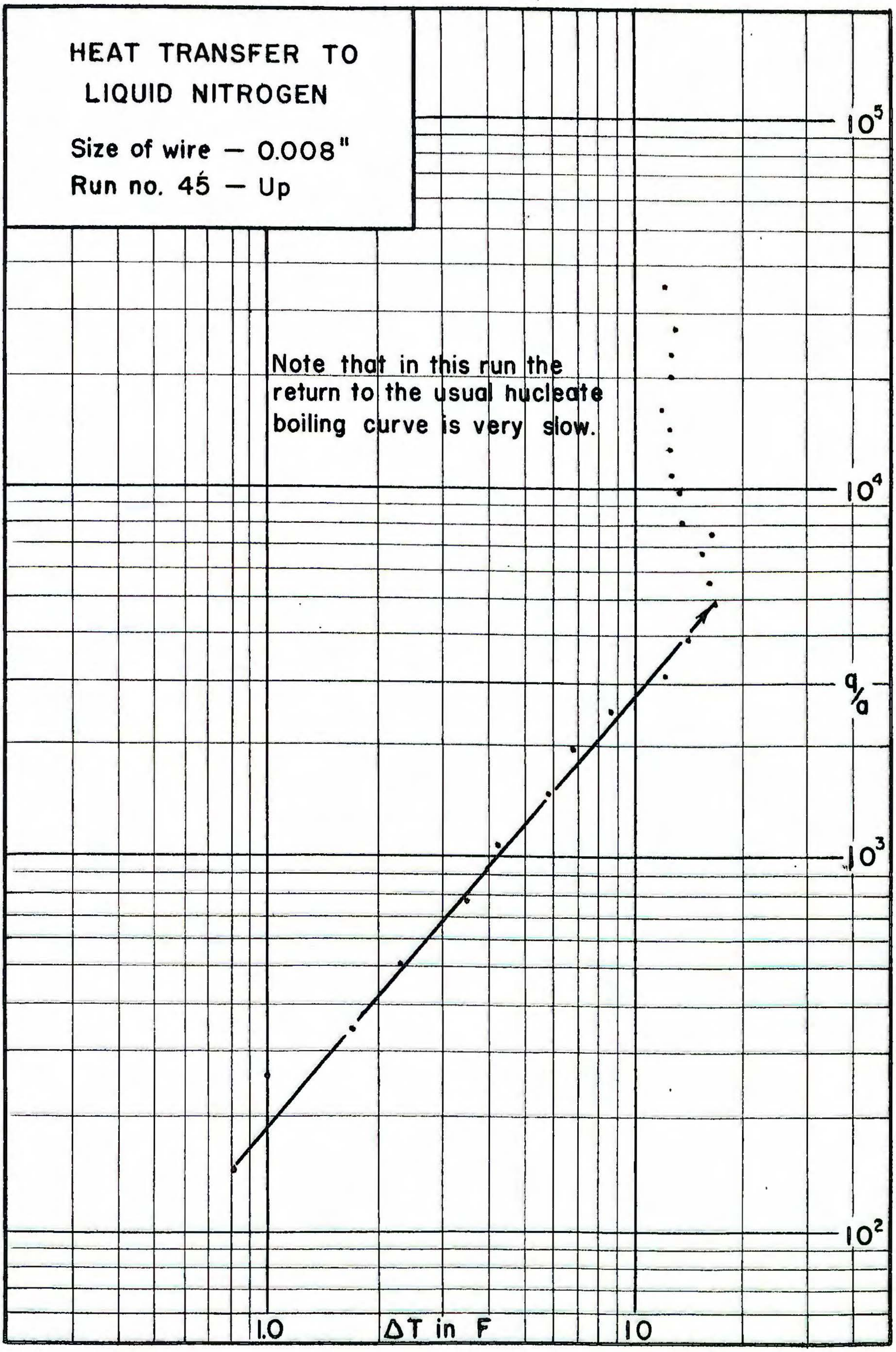
HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 45 — Up
Note that in this run the return to the usual nucleate boiling curve is very slow.
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

FIGURE 10

number of points on the wire. Further increase in the value of q/a establishes more nucleation centers but instead of continuing to rise, the value of ΔT drops. This decrease in ΔT goes on until the region of the normal nucleate boiling curve is reached and from then on ΔT behaves normally as q/a increases.

If this describes a true state of affairs why does it not appear in Tables 2, 3 and 4? The answer to this question for Tables 2 and 3 in the direction in which the run was made. In the data of Tables 2 and 3 each succeeding point is at a lower value while in Tables 5 and 6 the reverse is true and each point represents a progressively greater q/a. Table 4 requires further explanation. The data of Table 4 is an Up run as are Tables 5 and 6 but no extended region is found in Table 4. The reason for this is that prior to taking the data of Table 4 the wire had never been boiled in liquid nitrogen for more than a few minutes. Thus for the data of Table 4 the wire has some past history which is largely unknown. The wire had at least been exposed to room air and to distilled water. Runs similar to that of Table 4 were observed for most of the wires prior to their prolonged boiling in liquid nitrogen but were not recorded because the data was not consistent. This indicated that pre-contamination of the wire was significant but could be removed by vigorous boiling. Typical curves for both Up and Down runs are shown in Figures 7, 8, 9 and 10.

In general, except for a few runs made under non-normal conditions, these results are always true and may be summarized as follows.

An extended region of the free convection curve occurs prior to the establishment of nucleate boiling but does not re-occur during the decay transition from nucleate boiling back to free convection. The maximum ΔT of free convection is frequently significantly greater the maximum ΔT obtainable with nucleate boiling.

The portion of the free convection curve which extends beyond the normal beginning point for nucleate boiling will be called the "extended region". In the beginning of the extended region the phenomena is apparently very stable. Observation indicates that no bubbles are generated even after several hours. At about the middle of the extended region bubbles arise from one or more distinct nucleation centers after a delay of several minutes. The maximum of the extension represents a point where stability was only sufficient to insure two potentiometer readings. Perhaps 30-60 seconds. Metastable does not quite tell the whole story. Furthermore, both metastable[9] and transition[10] have been used in the description of the discontinuity between nucleate boiling and film boiling.

Having found a transition phenomena which does not correspond to the general body of information on nucleate boiling a further search of the literature was made. There are a few references to the superheating of water[11, 12, 13] and it is generally known that extremely pure gas free liquids, in contact with their own vapor in a closed very clean container, will superheat extensively. The work of Larson[12] is perhaps the most informative and he found only the end point of the extended region for water as a function of the type of heating surface. Unfortunately in water the sudden release of the stored energy when boiling began frequently destroyed the apparatus. No provision was made for determination of a rate of heat transfer (q/a) in his work. Signposts existed for discovery of the extended region but apparently liquid nitrogen has a combination of properties which make observation more straightforward.

So far the discussion has been qualitative. What about the numbers which can be associated with the curves for liquid nitrogen? These too prove unusual. The two regions, free convection and nucleate boiling are reasonably representable by straight lines in a plot of q/a versus ΔT on log-log paper. Each then may be represented by an equation of the form,

$$q/a = C\ \Delta T^n \qquad C \text{ and } n = \text{constants.}$$

McAdams[14] summarizes the work of many investigators in a number of liquids by assigning a value to n of 3 or 4 in the region of nucleate boiling. This number has been thought to be a constant for all liquids. The value of n obtained for liquid nitrogen is much greater than this and actually two values for n are necessary since n is dependent on the direction of the run, Up or Down. In the free convective data n is the same within limits of experimental error for both wire sizes. The median values of the resulting equations are given in the following Table which is the first of the two tables on the next page. The equations of Table A are plotted as Figure 11 which in turn may be compared with Figures 12 and 13. Figures 12 and 13 show the extent of scatter of all the observed data.

Values of the constant C in the equations in Table A have been tabulated for a number of other liquids in the nucleate boiling region[1] as Table B.

Table A

Liquid Nitrogen

$q/a = 251\ \Delta T^{1.10}$	Free convection 0.004" wire
$q/a = 8.52 \times 10^{-10}\ \Delta T^{13.2}$	Nucleate Up Run 0.004" wire
$q/a = 2.34 \times 10^{-8}\ \Delta T^{11.7}$	Nucleate Down Run 0.004" wire
$q/a = 206\ \Delta T^{1.13}$	Free convection 0.008" wire
$q/a = 5.52 \times 10^{-13}\ \Delta T^{16.2}$	Nucleate Up Run 0.008" wire
$q/a = 9.67 \times 10^{-6}\ \Delta T^{9.27}$	Nucleate Down Run 0.008" wire

Table B

Value of C

n-Butanol----	5.05×10^{-1}	25% Sucrose-----	9.16×10^{0}
CCl_4---------	6.45×10^{-1}	26% Glycerol----	2.90×10^{1}
Gasoline-----	8.18×10^{-1}	9.1% NaCl-------	3.65×10^{1}
Kerosene-----	1.31×10^{0}	9.6% Na_2SO_4-----	4.05×10^{1}
Methanol-----	1.95×10^{0}	Water-----------	6.08×10^{1}
26% NaCl-----	4.38×10^{0}		

Note: $2.5 \leq n \leq 4$ for all liquids of this table.

The coefficient C for liquid nitrogen is seen to bear little relation to those of the other liquids. It will later be shown that this is because n is not in the range 2.5 to 4 as is thought to be universally true for liquids and C is a function of n.

No such tabulation is available in the free convection region, however a comparison of the two extremes may be made by calculating the equation for water from McAdams et. al.[4] The equations are found

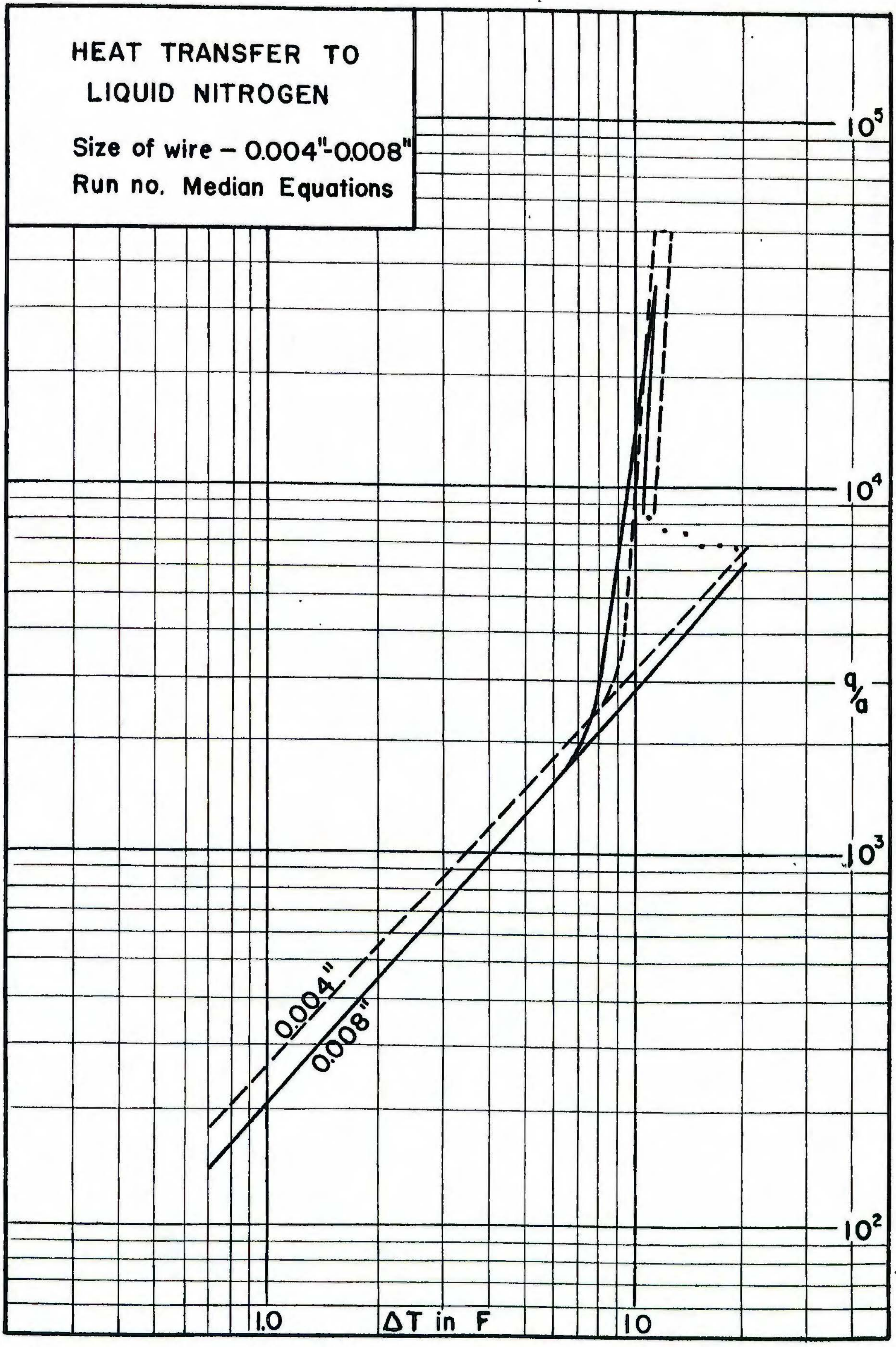
HEAT TRANSFER TO LIQUID NITROGEN
Size of wire – 0.004"-0.008"
Run no. Median Equations
10^5
10^4
q/a
10^3
10^2
0.004"
0.008"
1.0
ΔT in F
10

FIGURE 11

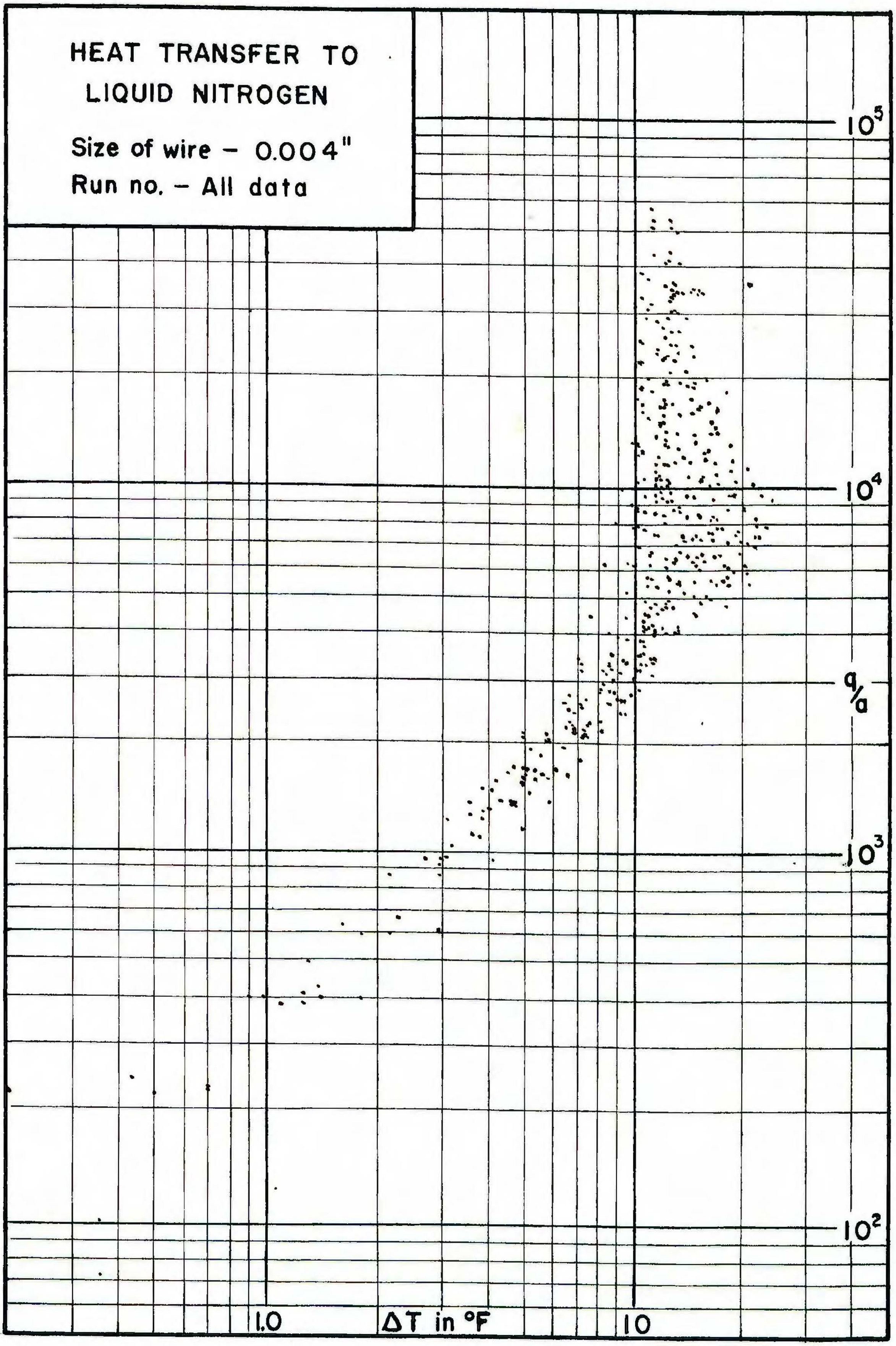
HEAT TRANSFER TO LIQUID NITROGEN
Size of wire - 0.004"
Run no. - All data
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in °F
10

FIGURE 12

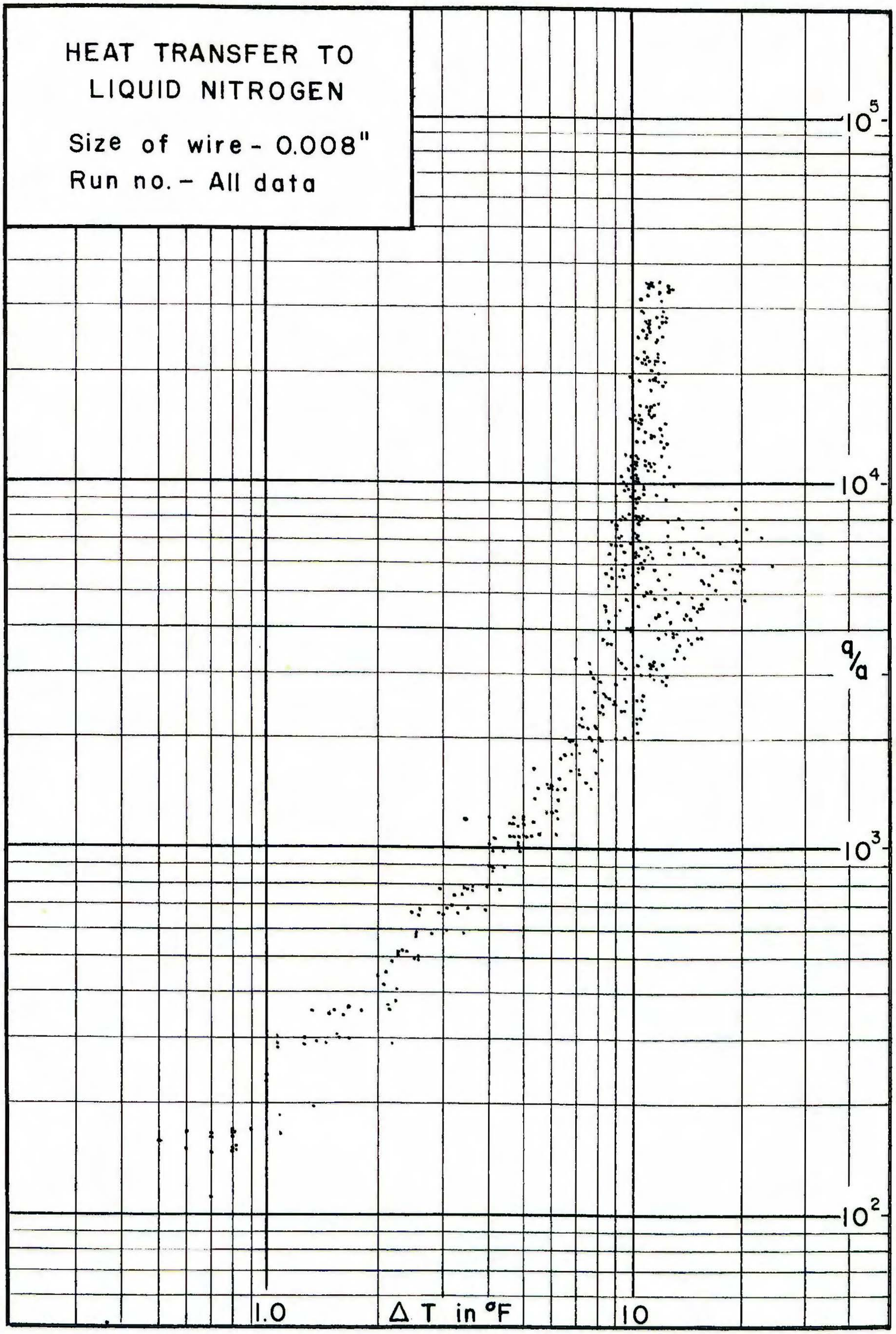
HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire - 0.008"
Run no. - All data
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in °F
10

FIGURE 13

to be:

<u>0.004" Wire in Water</u>

$$q/a = 740\ \Delta T^{1.35}$$

<u>0.008" Wire in Water</u>

$$q/a = 390\ \Delta T^{1.41}$$

and from this data

<u>0.004" Wire in Liquid Nitrogen</u>

$$q/a = 251\ \Delta T^{1.10}$$

<u>0.008" Wire in Liquid Nitrogen</u>

$$q/a = 206\ \Delta T^{1.13}$$

It is interesting to note that the coefficient C changes inversely with wire size in both liquids. Also the exponent n is seen to increase directly with wire size in both liquids. It is doubtful that this is accidental. Further research with additional wire sizes would be desirable.

<u>Additional Observations on Boiling in Liquid Nitrogen.</u> In the course of gathering the experimental data a number of phenomena were observed. Some bear relation to the ensuing calculations and some are merely interesting. All are worth recording.

The first is on the presence of impurities in liquid nitrogen. Dissolved gases have been shown to play an important part in the boiling of some liquids[15, 29] and it is inferred that the shape and size of the resulting bubbles are related in some fashion to the quantity and nature of the dissolved gases. The presence of water in boiling liquids has been shown to alter the nature of boiling[12]. It further has been speculated that ions and dust particles may have some role in the heat transfer process.

The very low boiling point of liquid nitrogen (-196°C or -132°F) eliminates all but helium, hydrogen, and neon as possible gaseous contaminants. These three elements are present only as traces in the atmosphere and it is doubtful that any of them would be absorbed in sufficient quantity to have any effect on boiling in nitrogen. Oxygen and argon are absorbed by liquid nitrogen when it is exposed to air but these gases promptly liquify. The boiling point of the resulting mixture can be found from data in the International Critical Tables[16] and it changes very little for small percentages of liquid oxygen. The fact that the N_2 calibration resistances did not increase with the age of the liquid nitrogen is good indication that very little liquid oxygen was present. Carbon dioxide and water are also absorbed but they solidify even before they fall into the liquid. Water in the form of microscopic ice crystals entered the liquid nitrogen in such large quantities in early runs that it changed the liquid from clear to milky in color but produced no change in the heat transfer data. The effect was probably the same as the addition of a handful of clean sand. The possibility of ions in liquid nitrogen looks remote.

The size, shape and frequency of bubbles in nitrogen is of some interest. An attempt was made to measure the rate of bubble formation from a single nucleation center on the wire. This was done by connecting a neon glow bulb to the output of a variable frequency pulse generator. The frequency of the pulse generator was continuously variable from one pulse every sixty seconds to 100,000 pulses per second. The neon glow bulb was lowered directly into the nitrogen and surprisingly enough continued to function. The wire was then observed thru a 10x binocular microscope. It was hoped that the stroboscopic effect of the neon bulb would "freeze" the column of rising bubbles at some frequency and thus give the desired information. This proved impossible because the rate of bubble formation from a given nucleation center is not a constant. The variation in frequency of bubble formation is more or less sinusoidal with a period of 10-20 seconds but could not be synchronized manually. A rough estimate of the number of bubbles per second per nucleation center might be 20. There is a tremendous variation for this number in other liquids as recorded in the literature with 17 per second[10] on the low end and 1000 per second[15] on the high end. The observation of 1000 per second is well documented and has been used by others in subsequent calculations[17] while the 17 per second is not. This research tends to confirm the lower frequency.

Even though the rate of formation of bubbles could not be found the neon glow bulb provided information on the size and shape of the bubbles. By using the wire size as a reference (0.004") it was determined that a bubble grew to a size about 0.003 inches in radius before moving upward away from the wire and increased only slightly in size thereafter. The growth from zero to 0.003 inches was too rapid to be seen. It should be noted that 0.003 inch radius bubbles are much smaller than those usually appearing in photographs in the literature[1, 15]. On the other hand the number of nucleation centers per unit area which could be generated at peak nucleate boiling rates is high, perhaps 5000-10,000 per square inch.* The only other number found in the literature[17] is 100 per square inch which is so low that it is questionable.

The stability of the extended region likewise deserves additional study. As a rule of thumb it can be said that the further out on the tail of the extended region one moves the shorter the wait for nucleation. However, at any given point the time delay is not uniform from run to run. Probably the underlying phenomena is statistical in nature and with sufficient data a time distribution curve could be plotted. If this could be shown to be say, Maxwellian it would add another piece of information to the nature of bubble formation.

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* Further research could be done on this problem. The free convection curve in liquid nitrogen can be established with considerable precision. Also, it is easy to establish a single nucleation center on the wire and for this point or series of points find q/a and ΔT. The q/a displacement of the curve for a single nucleation center from the free convection curve is reasonable and can thus be found. If now the number of bubbles per second is determined with a high speed camera the heat transferred per bubble can be determined. This might shed further light on the mechanism of boiling heat transfer.

CHAPTER III

BOILING IN NITROGEN FROM THE ANALYTIC VIEWPOINT

Possible Mechanisms. Forster and Grief have recently discussed[17] the various mechanisms which have been proposed for the high heat transfer rates observed in nucleate boiling. They conclude that neither micro-convection in the laminar sub-layer nor bubbles acting in the manner of surface roughness are satisfactory. The first because it will not correlate with findings on subcooled liquids where boiling heat flux is almost insensitive to the level of subcooling. The second fails to explain boiling inside tubes where the ratio of bubble diameter to tube diameter has been shown not to be significant. A third mechanism, latent heat transport by bubbles, is worthy of numerical calculation in liquid nitrogen even though Jakob and others have shown that this concept of itself is not sufficient to explain high heat transfer rates. Thus from Table 4

$q/a = 6.65 \times 10^3$ BTU/ft^2 hr for 35 nucleation centers

$q/a = 5.82 \times 10^3$ BTU/ft^2 hr for 20 nucleation centers

Thus $6.65 \times 10^3 - 5.82 \times 10^3 = 0.83 \times 10^3$ BTU/ft^2 hr from 15 nucleation centers is observed. By dividing by the wire area this becomes 1.81×10^{-1} BTU/hr.

Now using the rough approximations of the preceding chapter

Radius = 0.003 inches so Vol = 6.54×10^{-11} ft^3/bubble

Number of Bubbles = 20 per second per nucleation center

Total volume of gas generated = $(6.54 \times 10^{-11})(20.15.60.60)$

$= 7.06 \times 10^{-5}$ ft^3/hr

But from Figure 22 the density of saturated nitrogen gas is 0.005 gram/ mililiter or 0.302 pounds/ft^3. Also from Figure 21 the latent heat of vaporization of liquid nitrogen can be taken as 88 BTU/lb more or less. Thus the total latent heat transport = 7.06×10^{-5} . 0.302 . 88

$= 1.87 \times 10^{-3}$ BTU/hr

Note that 1.81×10^{-1} BTU/hr was actually transferred. Thus latent heat transport accounts for slightly less than 1% of the total heat transferred by the bubble action. In order for latent heat transport to transfer the total Δq the observations of the total volume of gas generated would have to be in error by a total of two orders of magnitude.

The mechanism favored by Forster and Grief is a vapor liquid exchange action. In effect they consider each bubble to act as a piston in the process of its growth at the surface of the wire. Each bubble pushes a slug of liquid at least equal to its own volume away from the hot wire and into the bulk liquid. This liquid is then replaced by an equal volume of colder bulk temperature liquid which is heated by the hot wire while awaiting the appearance of the next bubble.

To verify the merit of this mechanism in liquid nitrogen two methods of calculation may be used. Both require extensive assumptions. First using some of the data of the previous latent heat transport calculation and making the calculation for the same point in Table 4,

$$q = m\ Cp\ (T_W - T_B).$$

Note that this equation implies that the amount of liquid moved (m) is known. It is not, and this is the weak point in the argument.

Assuming that the amount of liquid moved (pumped) is equal to the volume of bubbles generated and further assuming that all of the liquid moved is as hot as the wire, then:

$m = V\rho$ where V = volume in ft^3/hr

ρ = density lb./ft (Figure 22)

$= (7.06 \times 10^{-5})(48)$

$= 3.39 \times 10^{-3}$ lb./hr from 15 nucleation centers

$q = (3.39 \times 10^{-3})(0.475)(11.5)$

$= 1.85 \times 10^{-2}$ btu/hr from 15 nucleation centers

But 1.81×10^{-1} btu/hr was observed from 15 n.c. The above calculation relies on not only knowing the amount of liquid pumped per bubble but also on the number and size of the bubbles. An error of more than two in the observed radius of the bubbles would fix things up.

The possibility of mistaking a 0.003 inch radius bubble for one of 0.006 inch radius exists but is small.

The problem may be approached from another fashion which does not require knowledge of either bubble radius or bubble frequency. For some liquids (notably water) it has been shown that latent heat transport accounts for about 4% of the total heat removed. Now taking the ratio of the answers in the two prior examples.

$$M = \frac{\text{Heat removed by pumping}}{\text{Heat removed by latent heat}}$$

$$= \frac{V\,P_L\,C_p\,(T_W - T_B)}{V\,P_g\,L} = \frac{P_L\,C_p\,(T_W - T_B)}{P_g\,L}$$

$$= \frac{1.85 \times 10^{-2}}{1.87 \times 10^{-3}}$$

= about 10:1

Since V cancels in the above equation both bubble frequency and bubble size are eliminated as variables. Now it appears that if latent heat removes 4% then pumping will remove another 40%. Only 50% remains unaccounted for.

The calculation of M for water on the basis of supposedly good data leads to values of 50 to 250 which in turn lead Forster and Grief to rest their case.[17] They consider the answer valid for liquids in general.

The insufficiency of this mechanism to explain quantatatively boiling in liquid nitrogen does not rule it out entirely. Intuitively it has, at this time, the most appeal. If it could be shown that latent heat transport accounts for as much as 10% instead of 1% of the total heat removed then pumping action would barely make the grade, but that would be good enough. Or if it can be assumed that pumping moves a quantity of liquid greater than the volume of bubbles generated then the mechanism would be quantatatively valid.

Modification of $q/a = C\Delta T^n$ for Nucleate Boiling. The determination of the equation

$$q/a = C\Delta T^n$$

for each of the curves accompanying Tables 1-48 lead to the conclusion that the constant C is related to the constant n. The values of C vs. n for all of the curves, both for 0.004 inch and 0.008 inch wire were thus plotted on semi-logarithmic paper as Figure 14. The points fall surprisingly well on a straight line which extends over 20 decades.

A straight line on semi-log paper must obey the following relation:

$$\frac{-\mathrm{Log}_{10} X_1 - \mathrm{Log}_{10} X_2}{Y_1 - Y_2} = k \qquad k = \text{constant}$$

Thus

$$\frac{\mathrm{Log}_{10} C_1 - \mathrm{Log}_{10} C_2}{n_1 - n_2} = k$$

From Figure 14

$$C_1 = 10^{-18} \text{ and } n_1 = 21.05$$

$$C_2 = 10^{-2} \text{ and } n_2 = 6.05$$

Substituting

$$\frac{\mathrm{Log}_{10} (10)^{-18} - \mathrm{Log}_{10} (10)^{-2}}{21.05 - 6.05} = \frac{-16}{15} = k$$

$$k = -1.067$$

Now

$$\frac{\mathrm{Log}_{10} C - \mathrm{Log}_{10} (10)^{-2}}{n - 6.05} = -1.067$$

Solving for $\mathrm{Log}_{10} C$

$$\mathrm{Log}_{10} C = -1.067\, n + 4.445$$

But $\mathrm{Log}_{10} C = \mathrm{Ln}_e C \div 2.3$

Or $\quad \mathrm{Ln}_e C = 2.45\, n + 10.25$

Or $\quad C = \exp.^{10.25 - 2.45\, n}$

Thus

$$q/a = \frac{2.83 \times 10^4}{\exp.^{2.45\, n}} \cdot \Delta T^n$$

or

$$q/a = \exp.^{10.25 - 2.45\, n} \cdot \Delta T^n$$

Note: $5 \leq n \leq \infty$

This equation which proves simpler to use in the second of the two forms has been plotted for a few values of n as Figure 15. The fit as compared to Figure 11 is seen to be good and the number of arbitrary constants is reduced from two to one.

The point at which the several curves of Figure 15 cross has some physical significance. The point is approximately 3.5×10^4 BTU/ ft^2 hr which corresponds to the peak of nucleate boiling for 0.008 inch wires but is somewhat under the peak for 0.004 inch wires. This seems to agree with the idea expressed by several authors[15, 17] that peak flux is determined by bubble choking and thus occurs at a predetermined spot on the curve.

The Formation of Bubbles. At this point it was decided that further progress in the analysis of nucleate boiling in liquid nitrogen depended on an understanding of the underlying physical processes which govern the initial formation and subsequent growth of a bubble. On this subject the literature is extensive but not enlightening. While the process of bubble formation is probably kinetic in nature the state of affairs is summed up by Frenkel[19] in his book "Kinetic Theory of Liquids" by saying, "We thus see that the kinetic theory of the process of condensation of a supersaturated vapor and especially of the boiling up of an overheated liquid possesses only a very limited practical significance."

Fundamentally the problem of formation and growth of a bubble is related to a very simple equation which relates the surface tension of the bubble to the excess pressure inside the bubble necessary to balance the surface tension.

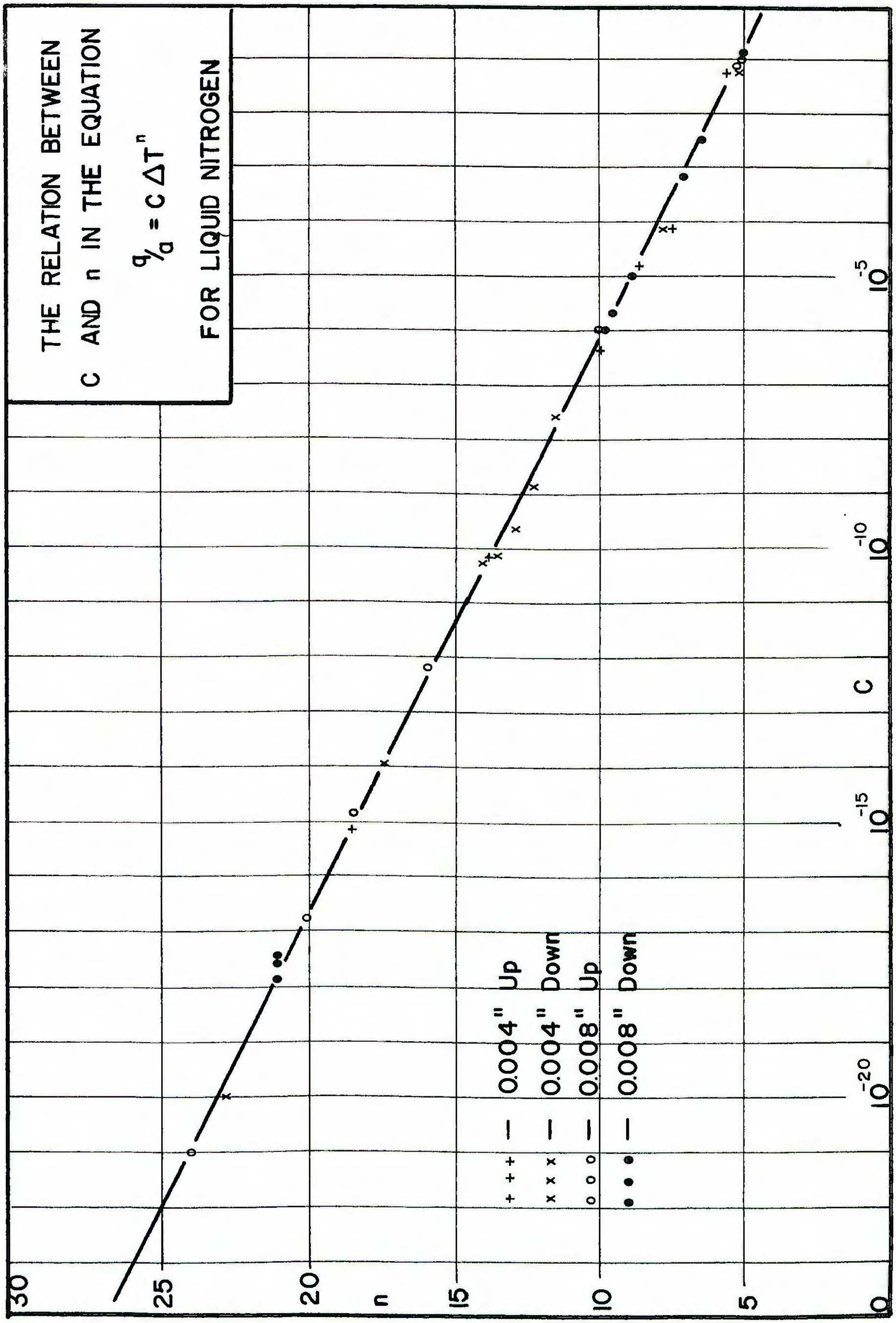
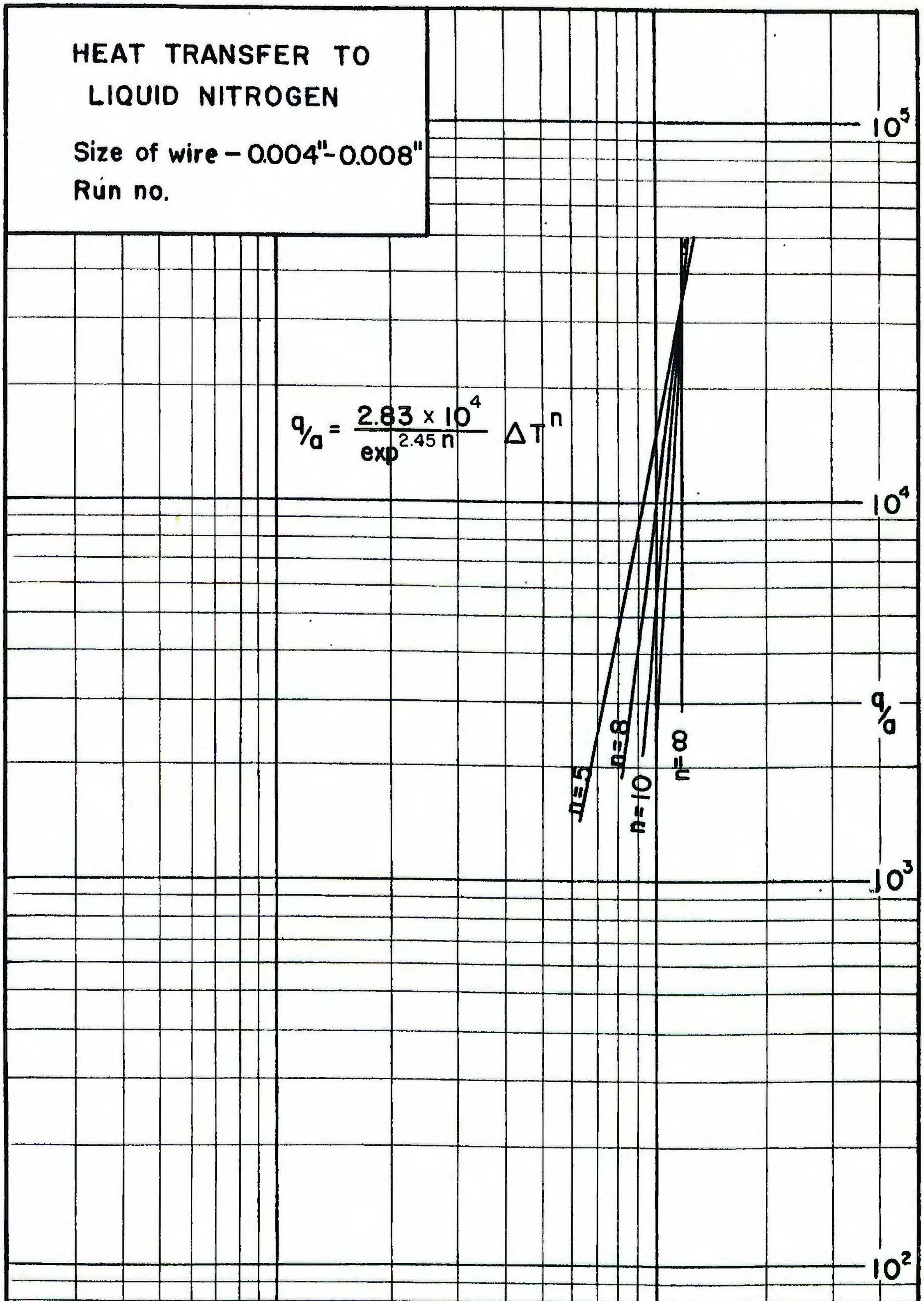

THE RELATION BETWEEN
C AND n IN THE EQUATION
q/a = C ΔT^n
FOR LIQUID NITROGEN
+ + + — 0.004" Up
x x x — 0.004" Down
o o o — 0.008" Up
• • • — 0.008" Down
n
C
0
5
10
15
20
25
30
10^-20
10^-15
10^-10
10^-5

FIGURE 14



HEAT TRANSFER TO LIQUID NITROGEN
Size of wire – 0.004"-0.008"
Run no.
$q/a = \frac{2.83 \times 10^4}{\exp^{2.45n}} \Delta T^n$
n=5
n=8
n=10
n=∞
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

FIGURE 15

Thus

$$P_g - P_L = \frac{2\sigma}{r}$$

Where P_g = Pressure inside bubble

P_L = Pressure in surrounding liquid

σ = Surface tension

r = Bubble radius

The trouble with this equation is the term r which initially must be extremely small. This leads to the correspondingly large values for P which must be explained in any theory of bubble formation. But, like the bumblebee who doesn't know that he is aerodynamically unstable and goes ahead and flies anyway, bubbles do form in heated liquids. Certainly the surface of the wire has some role in this process because nucleation is observed to begin at the same point repeatedly. The complication added by including a surface and thus a liquid solid interfacial energy has been included to some extent in Larsons work[12] but will not be considered here. If the mechanism of bubble growth can be shown it might then be possible to show that bubbles form at points on a surface where the contribution of the surface energy term is a local maximum.

Now it becomes desirable to advance an hypothesis about the origin of a bubble. It will be assumed that a single molecule with extremely high energy, arising from Maxwellian energy fluctuations within the liquid, is responsible for the beginning of a bubble. This would be a nice thing to prove because as previously noted the stability of the extended region may have a Maxwellian distribution in time.

The fact that P_g in the preceding equation varies, means that the growth of a bubble should be representable as a "state" line on a Mollier Chart for liquid nitrogen. Such a Mollier Chart exists[19] and a copy is included in the pocket in the back cover. This chart proved not quite adequate for all of the necessary calculations because high pressure data was necessary. Consequently an Extended Mollier Chart was constructed and also is included in the pocket in the back cover. The properties of the Extended Mollier Chart were determined in the following fashion.

High pressure Pv data for gaseous nitrogen is available[20] and is plotted as Figure 16. The linearity of this data is fortunate because some extrapolation was necessary. The two volume lines were found by dividing Pv by v. Also available[21] is high pressure on Cp for nitrogen which was plotted and extrapolated in Figure 17. By combining the data of Figures 16 and 17 it is indicated that Cp becomes constant at about 600°C. Consequently the 600°C isotherm on the Extended Mollier Chart must be parallel to a line of constant enthalpy. The enthalpy at this point was found to be

$$H = \text{Enthalpy at } 0^{\circ}\text{C} + Cp\,(T_{600} - T_0)$$

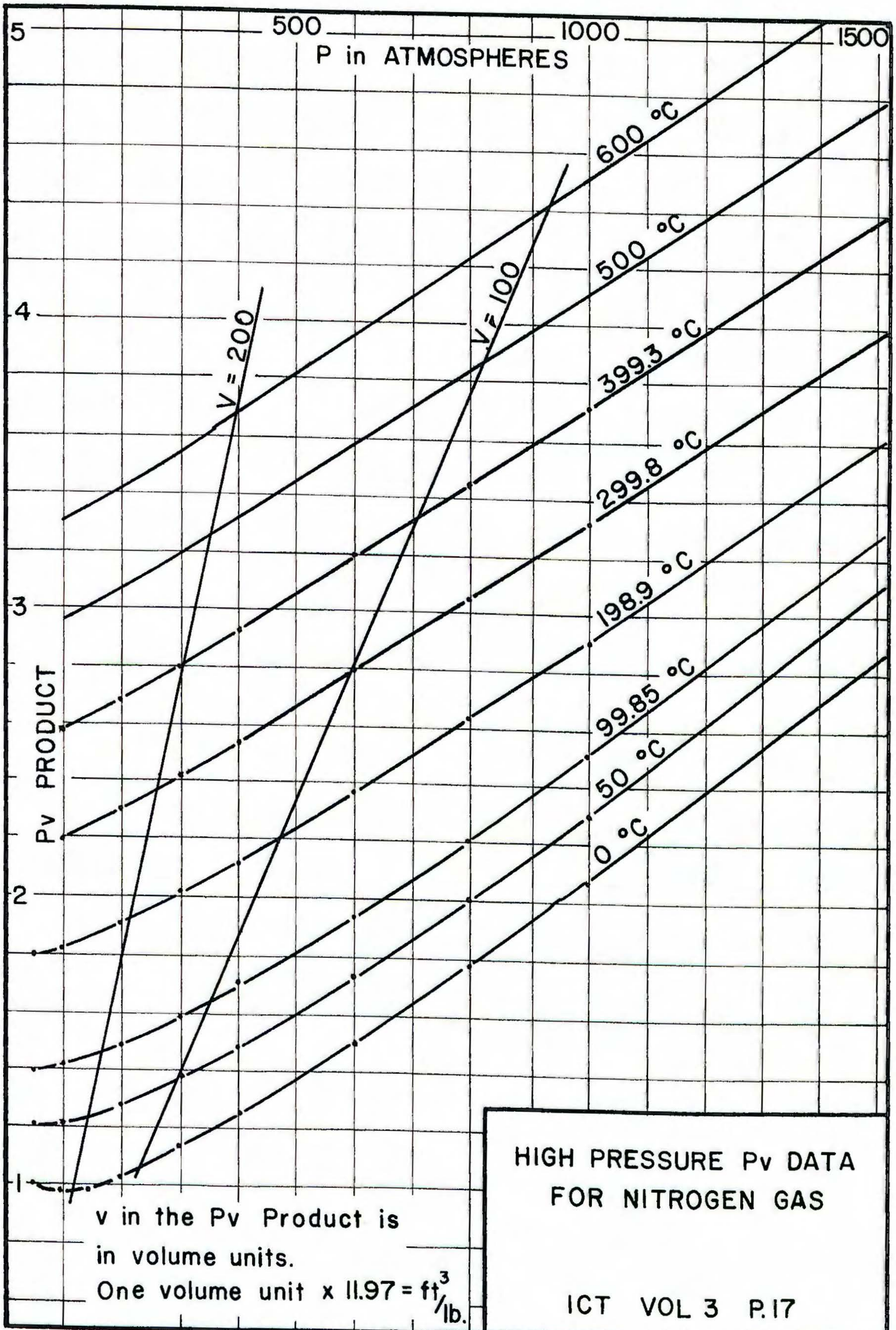
$$= 2700 \text{ (from Mollier Chart)} + \frac{29.5}{4.181}(600-0)$$

$$= 6933 \text{ gram calories/mole}$$

$$= 443 \text{ BTU/lb*}$$

---

*To convert gram calories/mole to BTU/lb divide by 15.65. To convert cc/mole to ft^3/lb divide by 1.749×10^3.



P in ATMOSPHERES
500
1000
1500
5
4
3
2
1
Pv PRODUCT
600 °C
500 °C
399.3 °C
299.8 °C
198.9 °C
99.85 °C
50 °C
0 °C
V = 200
V = 100
v in the Pv Product is
in volume units.
One volume unit x 11.97 = ft³/lb.
HIGH PRESSURE Pv DATA
FOR NITROGEN GAS
ICT VOL 3 P.17

FIGURE 16

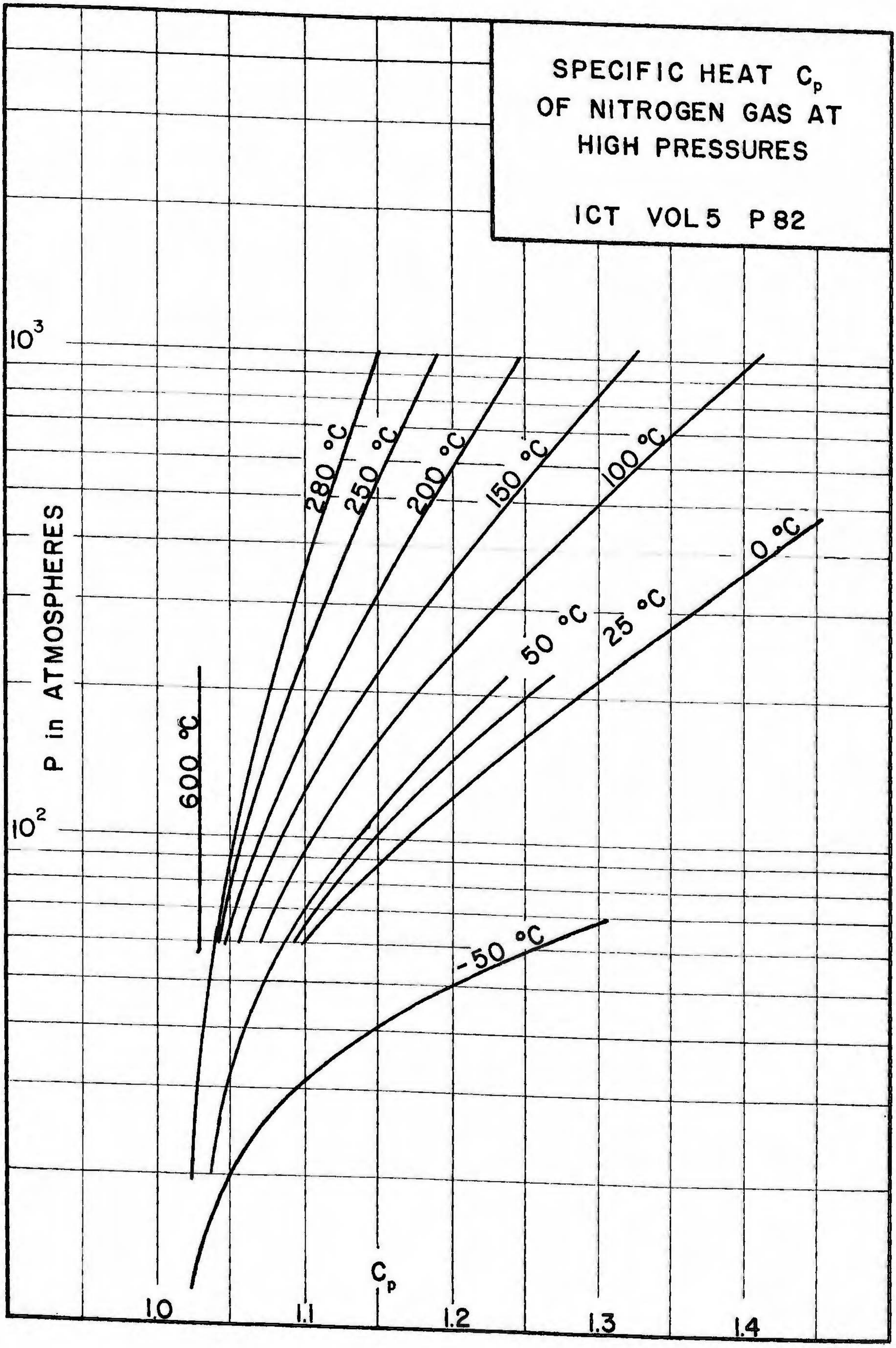

SPECIFIC HEAT C_p
OF NITROGEN GAS AT
HIGH PRESSURES
ICT VOL 5 P 82
10^3
10^2
P in ATMOSPHERES
600 °C
280 °C
250 °C
200 °C
150 °C
100 °C
50 °C
25 °C
0 °C
-50 °C
C_p
1.0
1.1
1.2
1.3
1.4

FIGURE 17

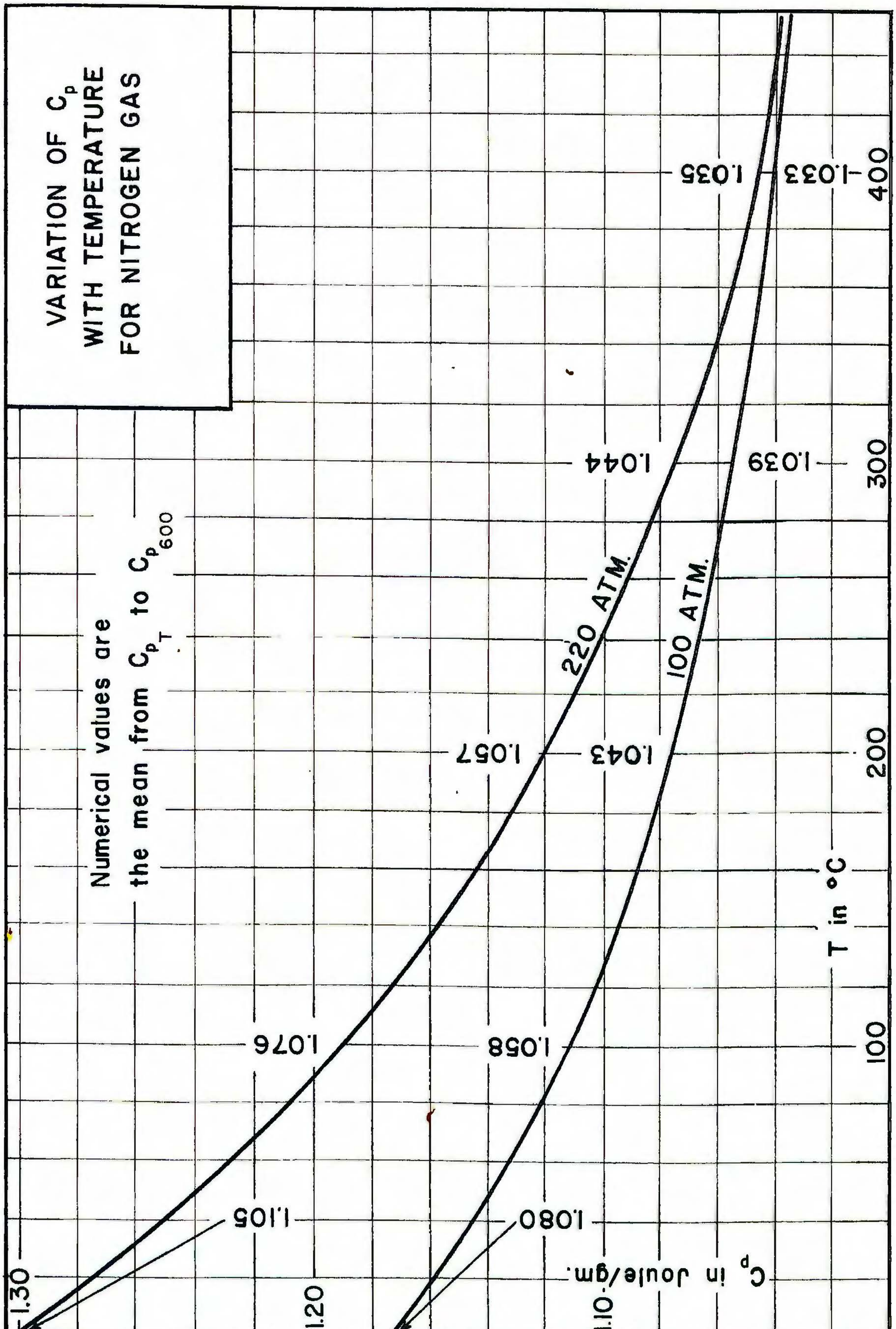

VARIATION OF C_p WITH TEMPERATURE FOR NITROGEN GAS
Numerical values are the mean from C_{p_T} to $C_{p_{600}}$
220 ATM.
100 ATM.
1.105
1.076
1.057
1.044
1.035
1.080
1.058
1.043
1.039
1.033
1.30
1.20
1.10
C_p in Joule/gm.
100
200
300
400
T in °C

FIGURE 18

The 600°C isotherm was drawn on the Extended Mollier Chart to find points on other isotherms as a function of pressure Figure 18 was drawn by combining the data of Figures 16 and 17. The variation of Cp with temperature was found by graphic integration of Figure 18 at the pressure shown and used in the formula

$$H_x = 2700 + Cp\ (T_{600} - T_x)$$

Some smoothing was done on the resulting lines on the Extended Mollier Chart.

The Path of the Process. It is of interest to find the path of the process. One way to do this is to consider many types of paths and see which ones make sense. These paths were in general representable on the Mollier charts which presents data for one gram mole, however by suitable conversion factors this may be converted to a pound, BTU, ft^3, etc. basis, or for that matter to a per molecule basis. This per molecule basis turned out to have great utility and was used frequently, with the understanding that this meant an average molecule, not a particular molecule. This of course placed a limitation on the smallness of the bubble in the sense that talking about an average molecule implied the average molecule was a member of a population which was large enough for the concept of "average" to have meaning. How many molecules should be members of the bubble before thermodynamics and averages become useful tools? Unfortunately no definite answer exists for this question. A sample of about 10,000 or larger was taken for this analysis. In other words thermodynamics was used to chart the growth of bubbles after they reached a size of about 10,000 molecules. In general this occurred when the bubble had a radius of about one millionth of an inch (10^{-6} inches).

The System and the Limitations on the Path of the Process. The system which was used for the ensuing calculations consisted of the volume of gas which was inside the bubble and the layer of molecules which surrounded this gas and were assumed to form the surface of the bubble. The surface layer was assumed monomolecular and was included in the system because its energy differed from that of the bulk liquid.

The possible state lines which are considered will first be limited by placing a restriction on the end point of the state line. Since the growth of a bubble is a natural process the bubble should tend toward equilibrium with its surroundings. Thus state lines whose end points differ significantly from the temperature of the bulk liquid which may vary from 139°R to 161°R will not be calculated. Also state lines whose end points are far into the wet region of the Mollier Chart will not be calculated. This latter condition would require that condensation be a significant factor in the final stages of bubble growth. No evidence of bubble condensation was found in liquid nitrogen.* All bubbles which were observed appeared to grow larger monotonically.

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* Bubble condensation (collapse) has however been observed[15] in boiling in subcooled liquids and has been used to explain high heat transfer rates in subcooled lqiuids.[14]

Isothermal Expansion. A little study of the Mollier Chart reveals that isothermal expansions fall into two classes, those isothermals which pass thru the "wet" region and those which do not. Following any of the "dry" isotherms down to 14.7 psia., the end point of the path of the process leads one to the conclusion that the bubble is hotter than the surrounding liquid throughout its entire life. Thus it must be losing heat to its surroundings continuously. The initial energy requirements for a bubble of this type can be shown to be unreasonable.

The bubble which follows an isotherm thru the "wet" region must follow a process which moves from left to right thru this region. This forces the bubble to spend most of its early life as a liquid and suddenly to find sufficient energy to convert to gas after it has reached fairly large size. A doubtful process at best. Isothermal expansions will not be considered further.

Constant Enthalpy Expansion. For processes of constant enthalpy the Mollier Chart needs to be divided into three regions, that for which $H < 1350$, that for which $H > 1500$, and the part in between where $1350 \leq H \leq 1500$. For the region where $H < 1350$ the bubble must spend the majority of its lifetime condensing which is contrary to observation. For $H > 1500$ the bubble also must spend its entire lifetime hotter than the surrounding liquid. This also conflicts with the requirement that a bubble should tend to the thermal equilibrium.

In the remaining region ($1350 \leq H \leq 1500$) calculations were made for several combinations of enthalpy and liquid temperatures. These are included in Appendix 2. The results will be discussed later in this chapter.

<u>Constant Entropy Expansion.</u> The region where the value of entropy is greater than 19 is eliminated because the end points of those constant entropy state lines are at a higher temperature than the maximum observed superheat in the liquid.

For the other bound the adiabatics which are less than 17 are excluded because they terminate well into the wet region. A series of calculations were made for adiabatics between 17 and 19 which are included in Appendix 2. The method of calculation is included here because of its significance in the understanding of boiling in liquid nitrogen.

<u>Method of Calculation - Appendix 2</u>

1 - r in cm. - assumed

2 - v_1 in ft^3 - $v_1 = 4/3\ \pi r^3$

3 - ΔP in psi - $\Delta P = \frac{2\sigma}{r} \cdot \frac{1}{6.89 \times 10^4}$

An assumption was made here that $\Delta P = 2\sigma/r$ which has the following physical limitations:

a) σ is a function of temperature as shown in Figure 19. Consequently some bubble surface temperature must be assumed. For these calculations the temperature of the superheated liquid was chosen and it was further assumed that this temperature remained constant throughout the growth of the bubble.

b) The concept of surface tension is of doubtful analytic validity when r is very small and very few molecules are involved. Thus the calculation for $r = 10^{-7}$ cm is separated from the remaining calculations by a line to indicate the questionability of the results.

c) The temperature of the bulk liquid is not a constant but falls off as the bubble grows away from the wire. For bubbles which have a radius greater than 10^{-1} cm. this might introduce significant error but bubbles this large seldom form in nucleate boiling in liquid nitrogen.

4 - P_g in psia. - The total pressure inside the bubble.

$P_g = \Delta P + 14.7$

5 - T_g in ^oR - The gas temperature inside the bubble.

T_g found from the Mollier Chart

6 - V in $ft^3/lb.$ - The specific volume of the bubble.

V found from the Mollier Chart. $V = \dfrac{V}{1.75 \times 10^3}$

7 - H in gram calories/mole

H found from the Mollier Chart

H in BTU/lb. = H/15.65

8 - nm in pounds. The weight of the bubble.

Let $Pv_1 = nmR'T$. Note that this differs from the perfect gas law in that R' is substituted for R. Now if no restriction is placed on R' then $Pv_1 = nmR'T$ should be universally valid. In fact it should be valid even for liquids and solids. A determination of the numerical value of R' might be difficult (or easy depending on the information at hand) but one significant statement can be made about R'. It is a point function. That is, given values for

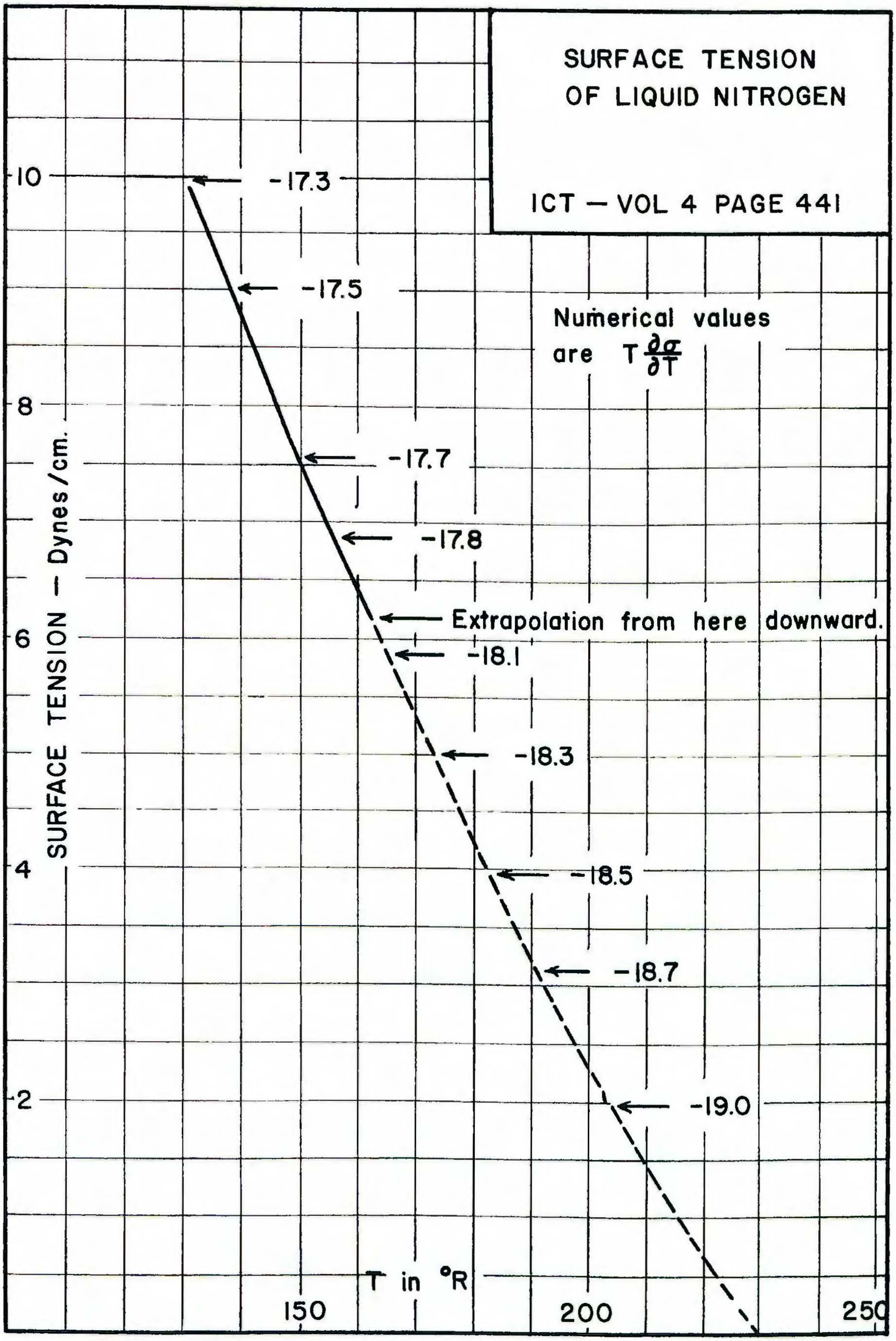

SURFACE TENSION
OF LIQUID NITROGEN
ICT — VOL 4 PAGE 441
Numerical values
are $T\frac{\partial\sigma}{\partial T}$
-17.3
-17.5
-17.7
-17.8
Extrapolation from here downward.
-18.1
-18.3
-18.5
-18.7
-19.0
10
8
6
4
2
SURFACE TENSION — Dynes/cm.
T in °R
150
200
250

FIGURE 19

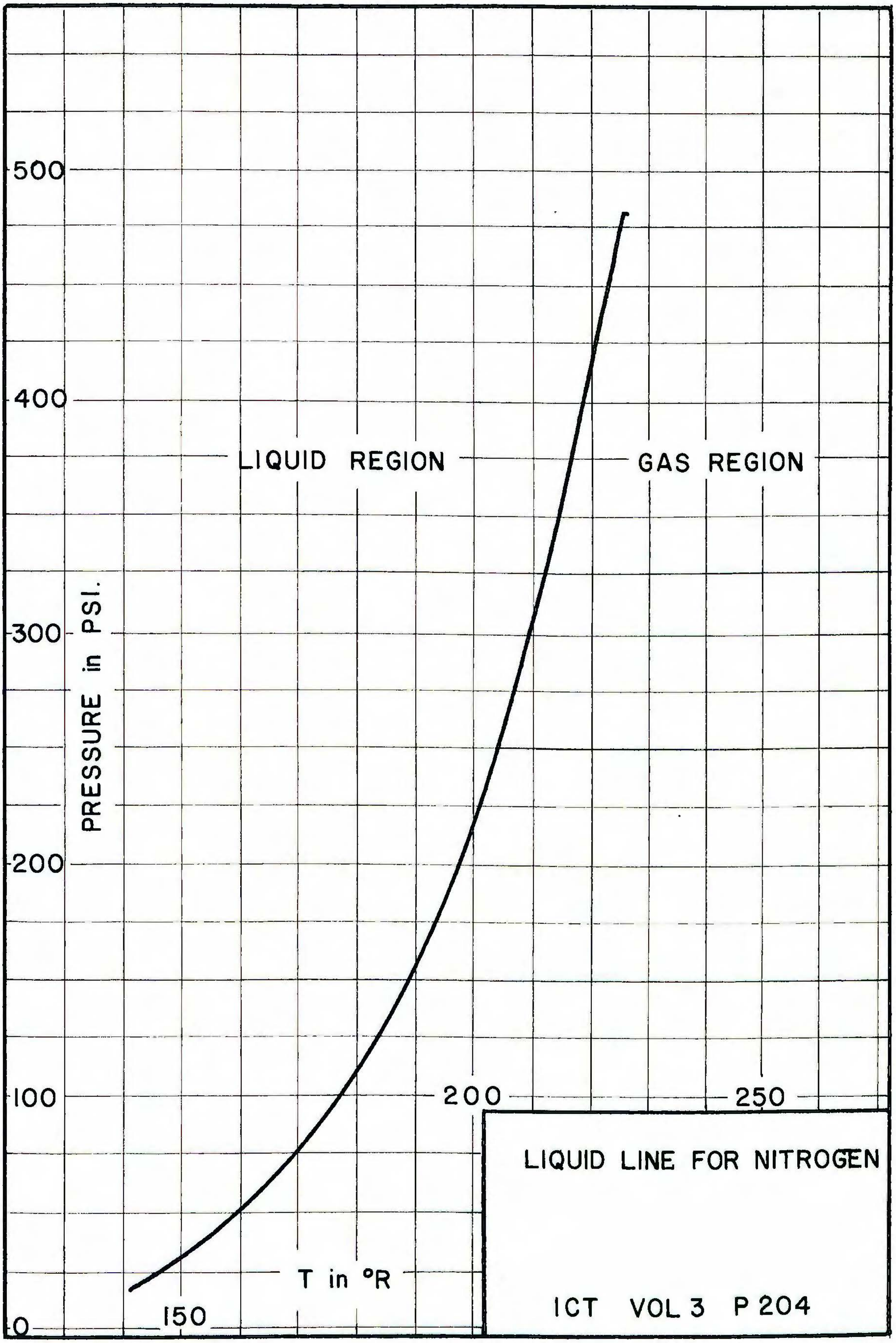

500
400
300
200
100
0
PRESSURE in PSI.
LIQUID REGION
GAS REGION
150
200
250
T in °R
LIQUID LINE FOR NITROGEN
ICT VOL 3 P 204

FIGURE 20

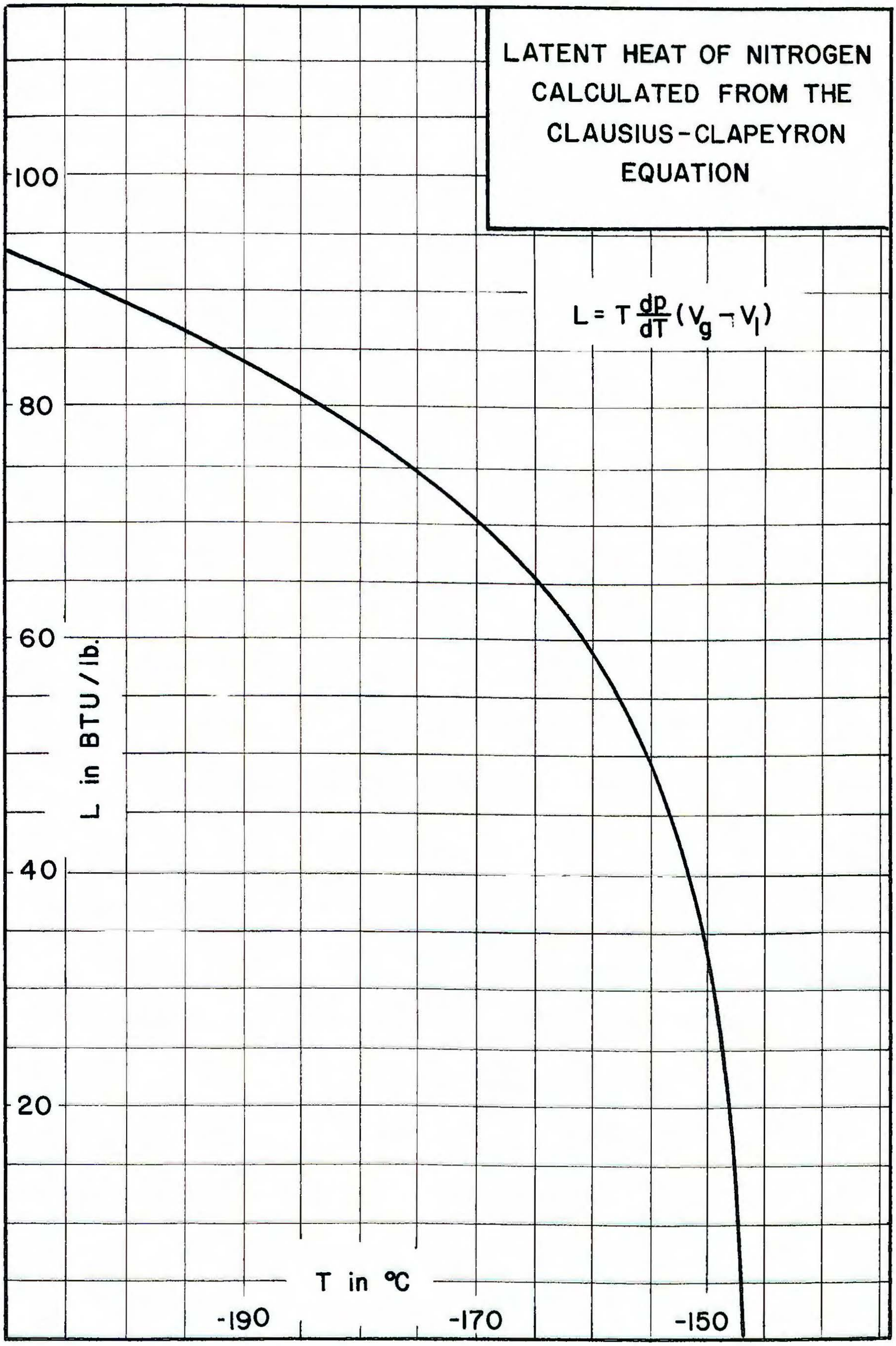

LATENT HEAT OF NITROGEN CALCULATED FROM THE CLAUSIUS-CLAPEYRON EQUATION
$L = T\frac{dp}{dT}(V_g - V_l)$
100
80
60
40
20
L in BTU / lb.
T in °C
-190
-170
-150

FIGURE 21

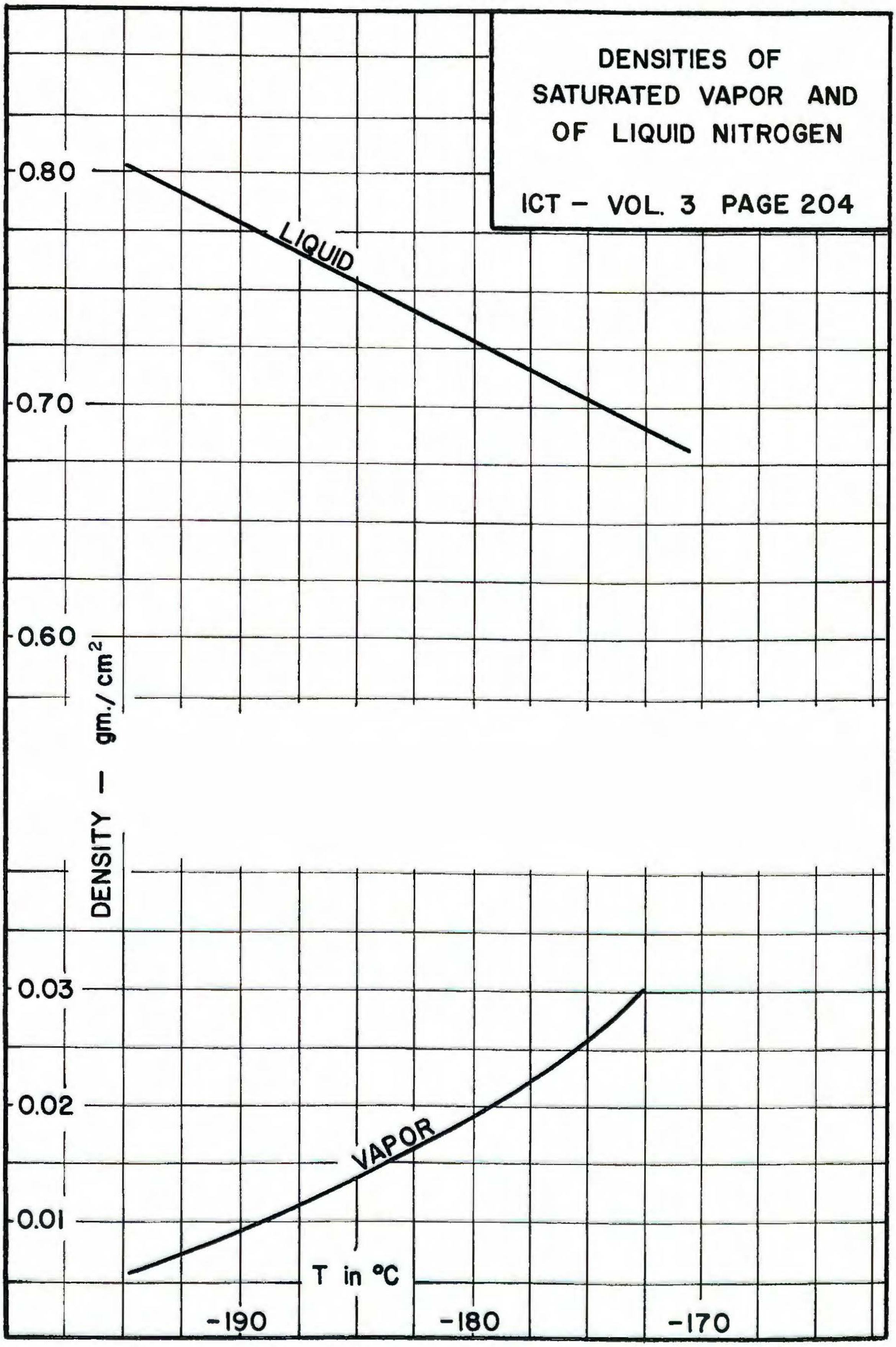

DENSITIES OF
SATURATED VAPOR AND
OF LIQUID NITROGEN
ICT – VOL. 3 PAGE 204
LIQUID
VAPOR
0.80
0.70
0.60
0.03
0.02
0.01
DENSITY — gm./cm²
T in °C
-190
-180
-170

FIGURE 22

P, v_1, nm, T at a point this is sufficient to determine R' at that point. Now also at any given point $PV = R'T$ where V is the specific volume. Thus,

$$nm = \frac{Pv_1}{R'T} \text{ but also } R' = \frac{PV}{T}$$

so

$$nm = \frac{Pv_1}{\frac{PV}{T} \cdot T}$$

thus $\qquad nm = \frac{v_1}{V}$ regardless of the state of the fluid.

9 - n - The number of molecules

$$n = \frac{nm}{m} \text{ and } m = 1.024 \times 10^{-25} \text{ pounds per molecule}$$

10 - Average energy per liquid molecule - BTU per molecule.

This was found by summing C_pT from 0^oR to the temperature of the superheated liquid. The data used was taken from the ICT.

$C_{p\ solid} = 23$ Joule/gm. atom

$C_{fusion} = 356$ Joule/gm. atom

$C_{p\ liquid} = 27.8$ Joule/gm. atom

11 - Average energy per gas molecule.

This was found by combining the data of 10 and the additional enthalpy determined from the Mollier Chart.

12 - Inside surface area of the bubble = $4\pi r^2$, ft^2

13 - Number of surface molecules = $\frac{\text{Item 12}}{1.95 \times 10^{-18}\ ft^2}$

The average cross sectional area of a nitrogen molecule was calculated using the density of the liquid and assuming the molecule a sphere. There are other methods of calculating cross sectional areas of molecules which do not necessarily lead to the same answer. Thus the area occupied by a surface molecule is open to question from both the area of a single molecule and the method of packing at the surface.

14 - Total surface energy - BTU/bubble

The excess surface energy stored per bubble is given by[22]

$$\Delta E = (\sigma - T \frac{\partial\sigma}{\partial T}) A$$

Where σ = surface tension in dyne/cm.

T = temperature in ^{o}R.

A = area in cm^2.

E = energy in dyne/cm.

Now $A = 3v_1/r$

So

$$\Delta E = \frac{3 (\sigma - T \frac{\partial\sigma}{\partial T}) v_1}{r} \cdot 2.685 \times 10^{-6}$$

Where v_1 in ft^3 (Item 2)

r in cm (Item 1)

$(\sigma - T \frac{\partial\sigma}{\partial T})$ in dyne/cm.

2.685×10^{-6} conversion factor which results in ΔE = BTU/bubble in excess of liquid energy.

The values for σ and $T \frac{\partial \sigma}{\partial T}$ are taken from Figure 20.*

15 - Average Energy of a Surface Molecule - BTU/molecule.

This was found by dividing the surface energy per bubble by the number of molecules in the surface and adding this to the average energy per liquid molecule.

Thus, $\frac{\text{Item 14}}{\text{Item 13}}$ + Item 10 = Item 15.

---

* The validity of the expression $\Delta E = f(\sigma - T \frac{\partial \sigma}{\partial T})$ is open to question at any but modest pressures. A look at Figure 20 indicates that σ decreases to zero monotonically at the critical point. This is in line with experimental evidence. However, the calculated values of $T \frac{\partial \sigma}{\partial T}$ are fairly constant at all values below the critical point and disappear discontinuously at the critical point. If this is really so then the energy given by $\Delta E = (\sigma - T \frac{\partial \sigma}{\partial T}) A$ must have a discontinuity at the critical point. If then this is so all of the energy stored in the surface must be dumped out when the surface disappears at the critical point. It should be possible to build an apparatus to determine the resulting increase in temperature in the system when the critical point is reached.

It is much more reasonable to believe that $\Delta E = (\sigma - T \frac{\partial \sigma}{\partial T})$ decreases monotonically to zero at the critical point and that the term $T \frac{\partial \sigma}{\partial T}$ should be multiplied by some factor such as $(\frac{P_L - P_3}{P_L})$. This incidentally would be more in line with the nearest neighbor concept of surface tension.[18]

16 - Total Energy - Gas + Surface - BTU/bubble.

This was found by multiplying the number of gas molecules by their average energy and adding this to the product of the average energy of a surface molecule and the number of surface molecules. Thus, Item 16 = (Item 11 · Item 9) + (Item 15 · Item 13).

17 - Total Molecules - Gas and Surface.

Item 17 = Item 9 + Item 13.

18 - Energy of an Equal Number of Liquid Molecules - BTU.

Item 18 = Item 10 · Item 17.

Having made the calculations some conclusions may be drawn from the resulting numbers. It will be shown presently that the "hot molecule" concept will not hold and with this in mind some clue to the bubble forming mechanism may emerge from the tabulated calculations.

The first thing of interest is the contribution of surface energy to the total energy of the bubble. Regardless of the path of the process chosen, the contribution of the surface energy to the total energy of the bubble is nil except when the bubble is very small. The surface energy is not a storehouse which can supply the later energy requirements of the growing bubble. Even when $r = 10^{-7}$ cm. and the concept of surface tension is questionable (60 to 100 molecules enclosing another 60 to 100) the surface contributes less than half of the total bubble energy.

The second point of interest is the great change of magnitude of all of the numbers as r increases. This far exceeds any variation from path to path. For each process path chosen there is little difference in the resulting numbers at any given radius and thus little basis for a correct choice of the path of the process. It could well lie anywhere within the region of these calculations. Some general statements may be made however.

When, in the course of the bubble expansion, the temperature of the gas and the surrounding liquid are equal, then the state line (path) must be tangent to a line of constant entropy. After reaching this tangent point, if the pressure in the bubble is still greater than the surrounding liquid the bubble should continue to expand and the bubble temperature must fall below that of the liquid. Heat transfer would now be <u>into</u> the bubble. Before reaching the tangent point the bubble is very much hotter than the liquid and the direction of heat transfer outward. This would be typical of a normal polytropic expansion. The probable shape of this state line is shown in Figure 23 but its exact location is not specified.

The last and probably most significant point of interest is the ratio of the average energy of a liquid molecule to that of a molecule which is part of the bubble. This may be seen by inspection and is not calculated but can be approximated by comparing Items 10 and 11 since the contribution of the surface energy has been shown to be small. This ratio turns out to be reasonably constant and of the order of one to two. This is a very interesting thing. Here is a bubble which is growing in a liquid by appropriating molecules from the liquid yet it seems to be very choosy about which molecules it will accept. If the bubble were to draw its members at random from a population with low energy such as the liquid then shortly the liquid and bubble would have the same energy since the bubble has been shown to have very little stored energy available to give to the incoming members. This leads to the conclusion that the bubble

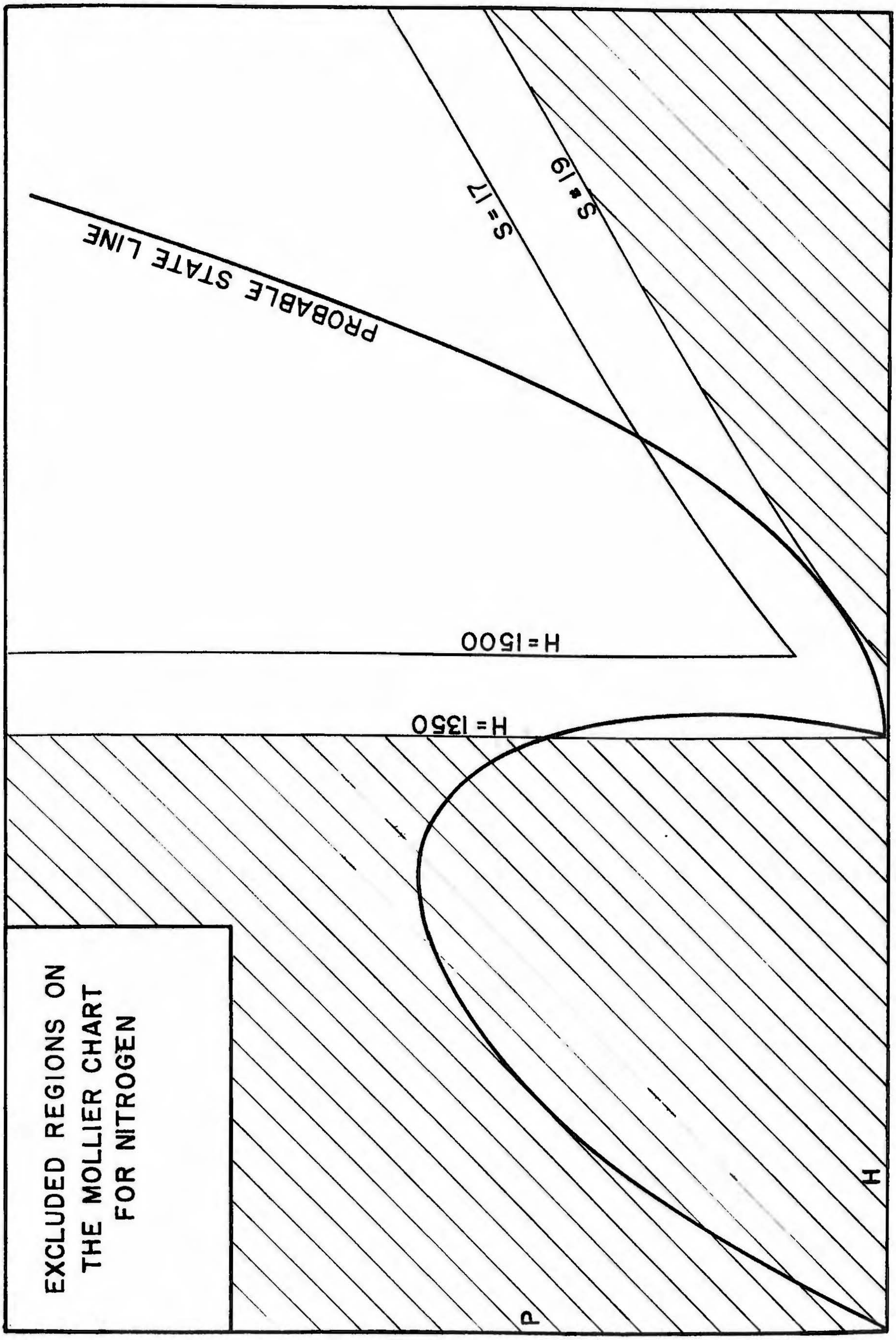

EXCLUDED REGIONS ON
THE MOLLIER CHART
FOR NITROGEN
PROBABLE STATE LINE
S = 17
S = 19
H = 1500
H = 1350
H
P

FIGURE 23

has some built in energy sorting mechanism which rejects average molecules from the liquid when they attempt to enter and accepts only those molecules whose energy is sufficient to maintain the interior population at the required level.

This energy sorting mechanism must be the excess energy contained in the surface molecules and the sequence of events this.

The surface molecules are, in effect, bound in place by surface forces which are in excess of the liquid energy. The average liquid molecule does not have sufficient energy to displace a surface molecule and thus, when striking a surface molecule, is repelled. On the other hand a molecule with sufficient energy should dislodge a surface molecule upon collision and one or the other or perhaps both should enter the bubble. It does not follow that after a time the energy of gas molecules and surface molecules should be equal because some molecules with very high (relatively) energy will always be entering.

Unfortunately limitations in the ability to calculate the exact number of surface molecules and limitations in the known solutions of the Maxwell-Boltzman distribution function preclude exact analysis of the energy sorting hypothesis. However some indication of the plausability of the mechanism is available and will be considered later.

<u>The Maxwell-Boltzman Distribution Function.</u> On Page 38 a "hot" molecule hypothesis was advanced. This hypothesis proposed that all of the excess energy required by a bubble was provided by a single very high energy molecule. This "hot" molecule was to be the nucleus of the bubble and growth was to take place by dissipation of energy from this "hot" molecule to its neighbors at random. The

set of state line calculations was expected to provide the data necessary to support this hypothesis. Enough information is at hand to now make the calculation for a "hot" molecule after some preliminary discussion of the Maxwell-Boltzman equation.

The problem is to determine what fraction of nitrogen molecules in an assembly have energies greater than some value E_1. It is usual, in texts which consider Maxwellian distribution, to limit the discussion to molecules which can be represented as hard sphere with various properties such as perfect elasticity, variable radius, perfect roughness, etc.[23] Thus only the energy of translation is considered. Since the theorem of equipartition of energy indicates that a large fraction of the energy of a diatomic is not translitory some extension of the usual treatment should be considered. A derivation of the required function could not be found, although it no doubt exists, and is thus included as Appendix 3. The result is given by:

$$\text{Fraction} = \frac{K \int_0^{E_1} E^{1/2} \exp^{-\frac{E}{kT}} dE}{K \int_0^{\infty} E^{1/2} \exp^{-\frac{E}{kT}} dE}$$

Which upon integration becomes*

$$\text{Fraction} = \text{Erf.} \sqrt{\frac{E_1}{kT}} - \frac{2}{\sqrt{\pi}} \sqrt{\frac{E_1}{kT}} \exp^{-\frac{E_1}{kT}}$$

---

* A word here about the error function (Erf.). This function is zero for Erf (0) and rises rapidly to one for Erf (∞). The complimentary function is given by $\text{Erf}_c(x) = 1 - \text{Erf}(x)$. An excellent tabulation is available.[24]

This expression actually gives the fraction of molecules with energy less than same number E_1, but the computation of the complimentary $N > E$ is trivial.

Now to compute the fraction of all molecules having energy sufficient to provide all of the energy necessary for formation of a bubble. The constant entropy (19.0) tabulation of Appendix 2 will be used as an example. This is the last page of tabulated values in Appendix 2.

Total energy of a 0.003 inch bubble ($r = 10^{-2}$ cm.) is found to be

$$5.32 \times 10^{-9} \text{ BTU}$$

Total energy of an equal number of liquid molecule is found to be

$$2.58 \times 10^{-9} \text{ BTU}$$

Extra energy required of a "hot" molecule

$$5.32 \times 10^{-9} - 2.58 \times 10^{-9} = 2.74 \times 10^{-9} \text{ BTU}$$

Average energy of a liquid molecule is found to be

$$8.09 \times 10^{-24} \text{ BTU/molecule}$$

The problem can now be stated as, "What fraction of molecules have energy of $\frac{2.74 \times 10^{-9}}{8.09 \times 10^{-24}} = 3.39 \times 10^{14}$ greater than average.

Applying the following constants to the fraction equation

$$T = 164^{\circ}R$$

$$R = 1544/\text{molecular weight} = 55.11$$

$$778/RT = 0.086081$$

a curve may be plotted of E_1 vs. Fraction and this has been done for $T = 164^{\circ}R$ and a number of other temperatures as Figure 24.

Two comments are in order about Figure 24. The first is the small effect of temperature in the range of interest, and the second is to note the arbitrary units of the energy. The numerical value of

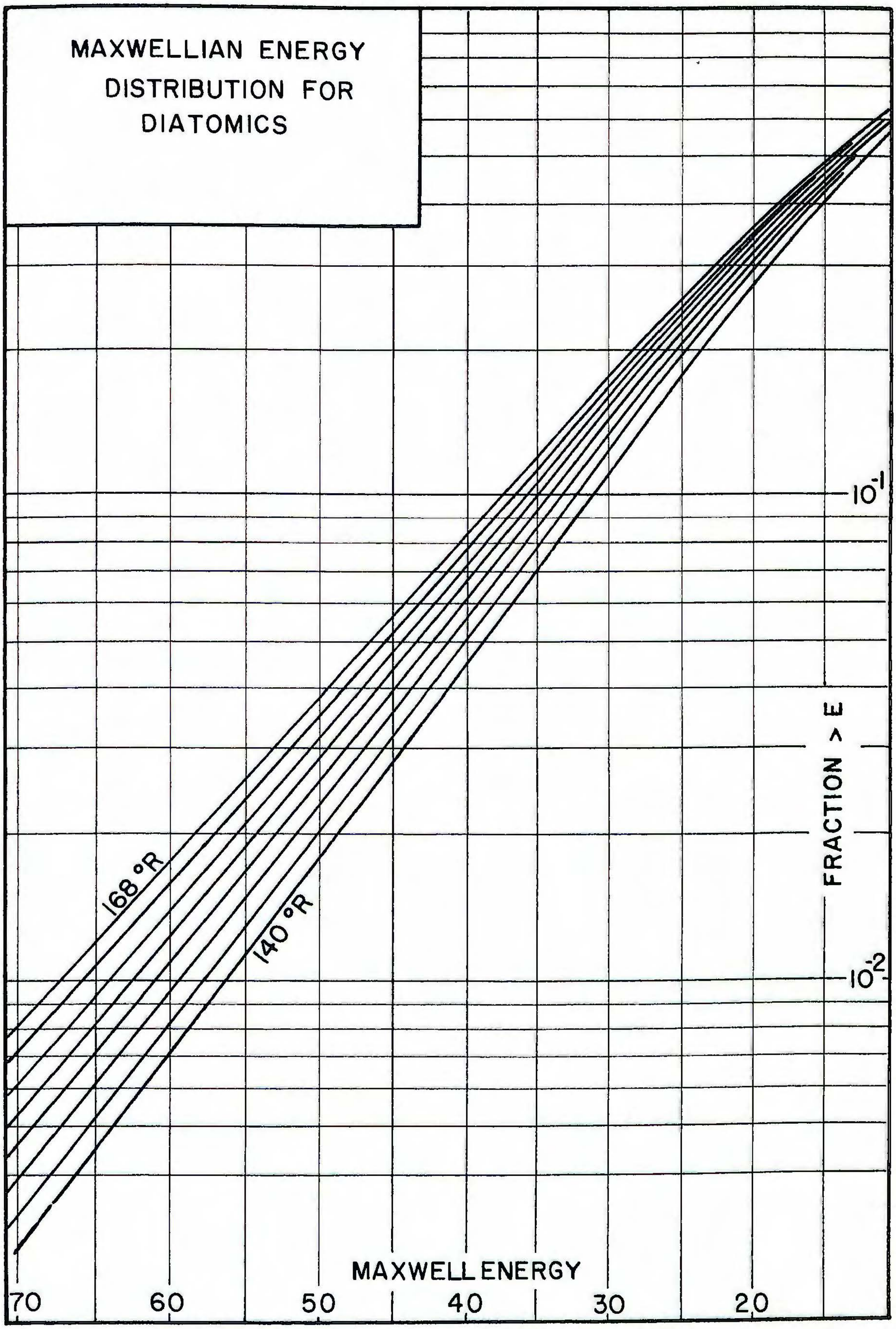

MAXWELLIAN ENERGY DISTRIBUTION FOR DIATOMICS
168 °R
140 °R
10^-1
10^-2
FRACTION > E
MAXWELL ENERGY
70
60
50
40
30
20

FIGURE 24

the energy differs from that of the Mollier Chart by a factor of 1.8×10^{-23}. This is expected because of the value of R used in the Fraction equation. Obviously R of a liquid is not defined by $R = 1544/MW$ but is a much larger number. However E increases proportionally* and numerical values of E are mutually convertible.

Now from Figure 24, E_{mean} is found to be 17 energy units. Thus $17 \cdot 3.39 \times 10^{14} = 5.8 \times 10^{15}$ Maxwellian Energy Units are required by the "hot" molecule. Extrapolation of Figure 24 results in the conclusion that one molecule in $10^{10,000,000,000}$ has the required energy. That ends the "hot" molecule hypothesis.

<u>The "Warm" Molecule Hypothesis.</u> The downfall of the "hot" molecule hypothesis was the tremendous amount of energy required by that molecule in order to heat neighboring molecules at random. Now on Page 55 another condition is added to the mechanism of bubble growth. This is the hypothesis that surface tension acts as a molecule sorting mechanism which rejects molecules of average energy and allows only molecules of higher energy to enter the bubble and contribute to its growth. If this condition is included then the nucleating "hot" molecule need only have sufficient energy to sustain growth until the bubble is of sufficient size to have the concepts of a surface and surface tension becomes valid. The size of the bubble when it becomes meaningful to discuss surface tension is not known but should be very small. In other words only a relatively small number of

---

* And thus should make it possible to calculate R of a liquid by using E_{mean}.

molecules must be heated by the "warm" molecule. A calculation similar to that which invalidated the "hot" molecule hypothesis was made again using the data of Table 28, Appendix 2 only this time for $r = 10^{-7}$ cm. The results indicate that one molecule in 10^{40} has the required energy. Thus for a "warm" molecule hypothesis the numbers are still too large but not unreasonably so. Considering the necessary crudeness of the assumptions because of lack of good physical constants the calculation looks promising and far better than the "hot" molecule hypothesis.

A second calculation in support of the "warm" molecule hypothesis may also be made. Using the same table as before and choosing $r = 10^{-2}$ cm. again for convenience.

Average energy liquid molecule = 8.09×10^{-24}

Average energy surface molecule = 12.23×10^{-24}

$$\text{Ratio} = \frac{12.23 \times 10^{-24}}{8.09 \times 10^{-24}} = 1.51$$

Thus an average surface molecule has 1.51 times the energy of an average liquid molecule. From Figure 24 it is seen that 23% of all liquid molecules have energies greater than that of the surface. This 23% is the part of the liquid from which the bubble population is being accepted.

The average energy of the incoming molecules can be computed again with recourse to Figure 24. Since this is nothing more than the value of energy corresponding to $\frac{23}{2}$ or 11.5%. The value of energy is found to be 33 Maxwell units of 1.65×10^{-23} BTU/molecule. The comparison with the Tabular value of 1.67×10^{-23} is fortuitous considering the underlying assumptions.

CHAPTER IV

CONCLUSIONS ON LIQUID NITROGEN

The experimental results in liquid nitrogen are significantly different from those of other liquids. The transition from free convective heat transfer to nucleate boiling heat transfer is not smooth but takes place via an "extended region" as illustrated by Figure 6. The reverse transition from nucleate boiling back to free convection is, however, normal and no extended region occurs. The numerical values associated with liquid nitrogen are much lower than those of other liquids with the exception of the exponent n in the relation

$$q/a = C\Delta T^n$$

which is not in the range $2.5 \leq n \leq 4$ reported for all other liquids but is of the order of $n = 10$.

It is also shown that C in the above equation is not an arbitrary constant but is dependent on the observed value of n such that

$$q/a = \frac{2.83 \times 10^4}{\exp 2.45\, n} \cdot \Delta T^n \qquad 5 \leq n \leq \infty$$

These unusual results in liquid nitrogen are attributed in part to the cleanliness of the liquid in a heat transfer sense.

The mechanism of bubble pumping action which is currently held most logically responsible for the high heat transfer rates in nucleate boiling is shown to be insufficient in liquid nitrogen on the basis of observed physical data.

In the free convective region, heat transfer is shown to be a function of wire size as reported for other liquids. This dependence on wire size is not present in nucleate boiling.

A mechanism is proposed for the initial formation of a single bubble which depends on the presence of "hot" molecules. The "hot" molecule is required to provide all of the energy necessary for the bubble's further growth. On the basis of data calculated for a number of state lines on the Mollier Chart the "hot" molecule concept is shown to be impossible because of the extreme energy requirements. Subsequently in a warm molecule hypothesis it is postulated that the surface energy associated with a bubble is the governing mechanism and that this surface energy acts as a molecular energy sorter during bubble growth. Present limitations in the knowledge of bubble surface molecular packing densities preclude exact proof or disproof of the energy sorting hypothesis, however, it is shown that the mechanism reduces initial bubble energy requirements to more reasonable values.

CHAPTER V

EXPERIMENTAL TECHNIQUES IN LIQUID HELIUM

General. The techniques required in liquid helium are somewhat more elaborate than those of other liquids because of the extremely low latent heat of vaporization (9.06 BTU/lb.). Considerable care must be taken to minimize heat leakage from room temperature surroundings. The standard procedure is to use a nitrogen dewar similar to that of Figure 3 but much deeper and inside this to place a second smaller dewar which actually holds the liquid helium. Heat leakage from the surroundings will boil away the liquid nitrogen which is replenished from time to time. Figure 25 shows an experimental dewar similar to that used in the experiment. The actual dewar is shown in Photograph 4.

Liquid helium cannot be poured from container to container as can liquid nitrogen so a special transfer tube must be used to fill the experimental dewar from a larger storage dewar. Transfer tubes are available commercially and consist of a thin walled stainless steel tube surrounded except at the ends by a larger copper tube. A very hard vacuum is maintained in the annular space between the two tubes in order to minimize heat transfer. A cylinder of dry helium gas is used to maintain a positive pressure of about ten ounces inside the storage dewar and this forces the liquid helium thru the transfer tube and into the experimental dewar. Transfer rates are about two liters a minute after the transfer tube and experimental dewar have cooled to liquid helium temperature.

<u>The Measuring Circuit and Its Operation.</u> The resistance of Platinum while known[5] at liquid helium temperatures is not a strong function of temperature. This forced the use of a higher degree of precision and stability then was found necessary in liquid nitrogen. While the circuit is identical in its function to that of Figure 2 and thus will not be redrawn the following refinements were found necessary.

1. The external resistances which are panel mounted (Figure 2 and Photograph 2) change value when heated by an electric current and were replaced by two water cooled 60 ampere resistances which can be seen protruding from behind the cathode ray oscilloscope in Photograph 4. Current stability was then found to be acceptable.

2. The Rubicon Type B potentiometer was replaced by a Rubicon 6 Dial thermofree potentiometer capable of reading to 10^{-8} volts which is designed so that internal parasitic thermal emfs will be less than the minimum observable reading. A 10x binocular microscope was used to observe the galvanometer which was used as a null instrument. The entire measuring circuit between the experimental test wire, standard resistor, and potentiometer was constructed of platinum wire in order to minimize external thermocouple voltages and external rectifying junctions.

3. Four more 12 volt storage batteries as a current source were added in parallel for a total of eight 12 volt batteries.

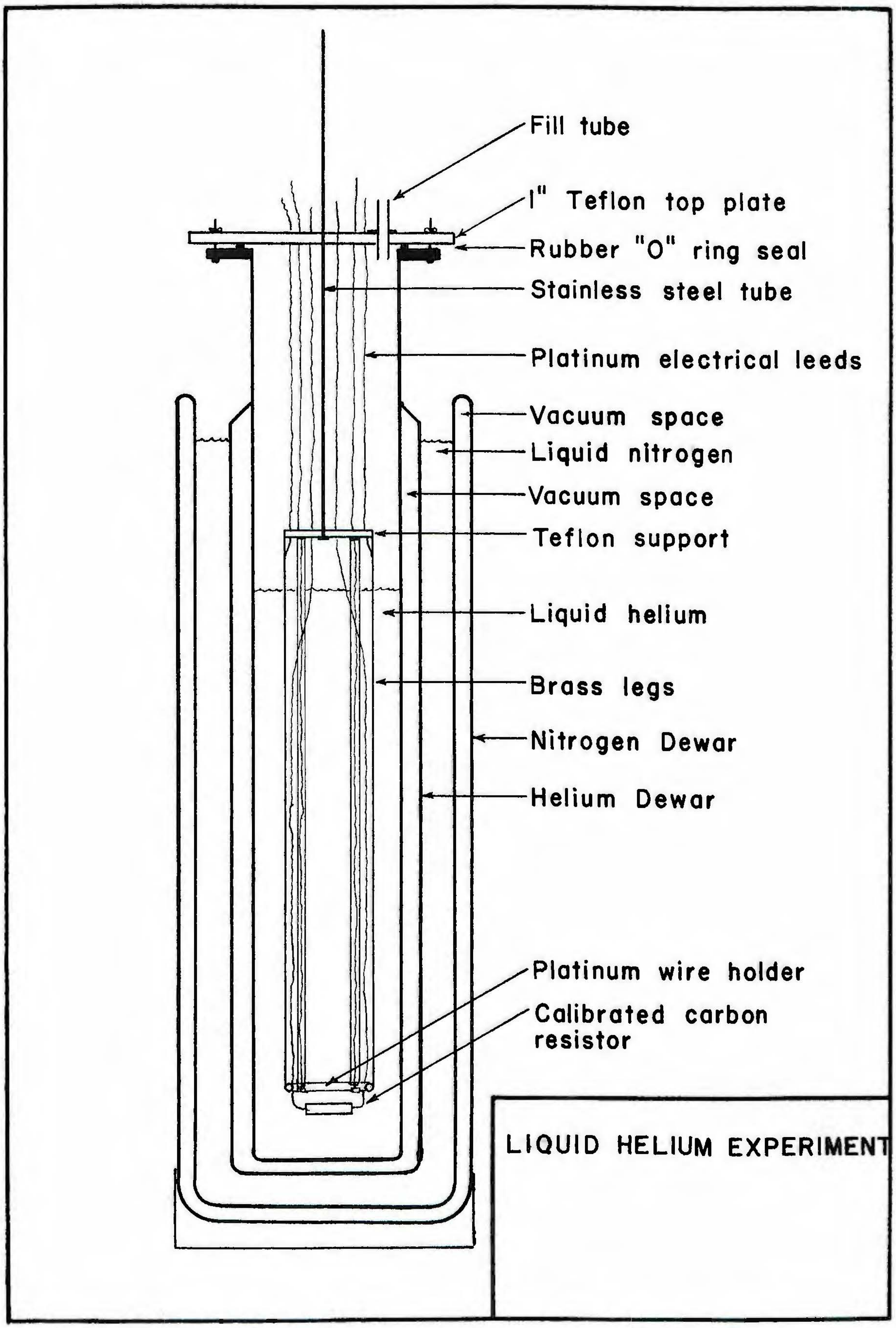

Fill tube
1" Teflon top plate
Rubber "O" ring seal
Stainless steel tube
Platinum electrical leeds
Vacuum space
Liquid nitrogen
Vacuum space
Teflon support
Liquid helium
Brass legs
Nitrogen Dewar
Helium Dewar
Platinum wire holder
Calibrated carbon resistor
LIQUID HELIUM EXPERIMENT

FIGURE 25

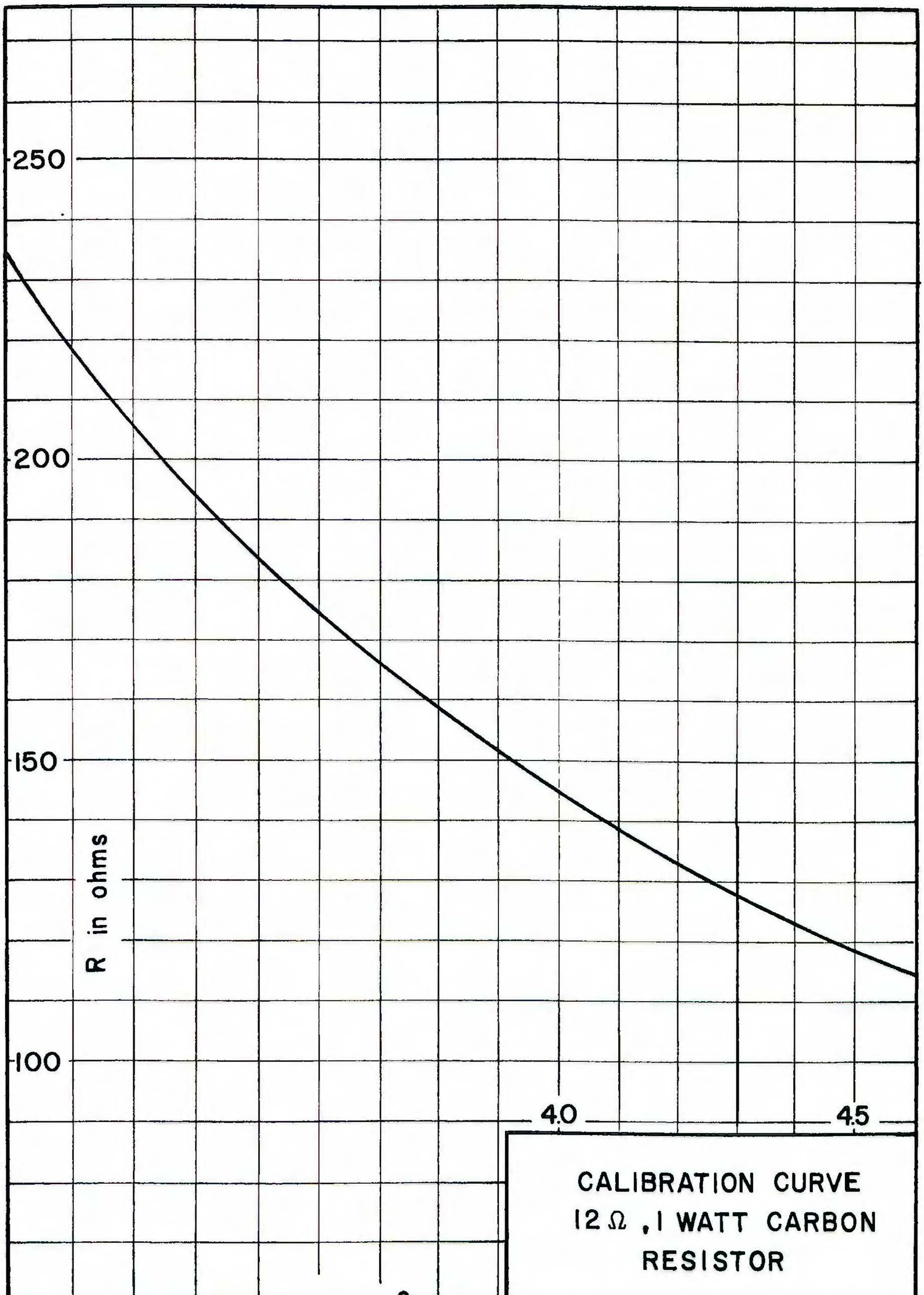

250
200
150
100
R in ohms
3.5
4.0
4.5
T in °K
CALIBRATION CURVE
12 Ω , 1 WATT CARBON
RESISTOR

FIGURE 26

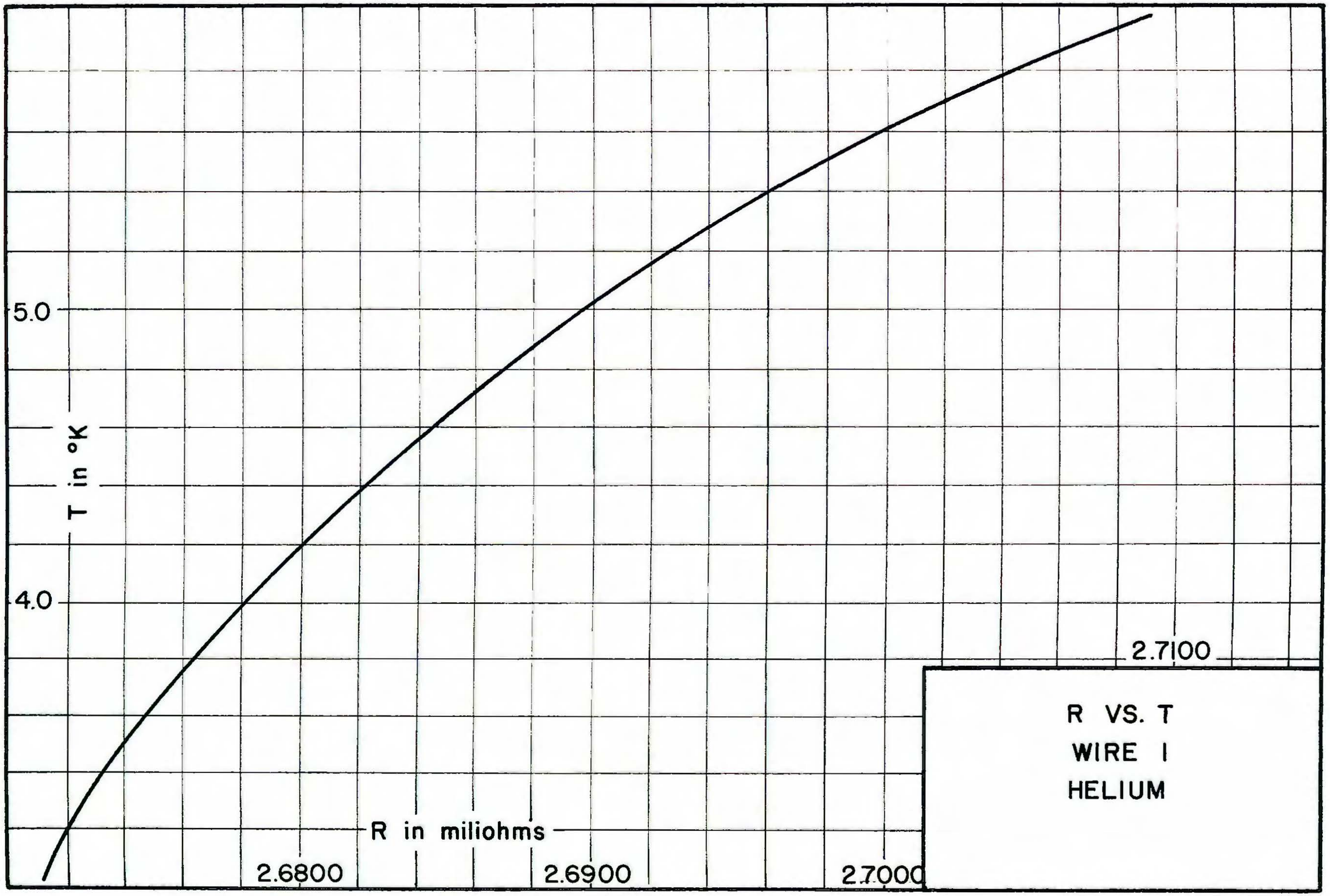

5.0
4.0
T in °K
R in miliohms
2.6800
2.6900
2.7000
2.7100
R VS. T
WIRE I
HELIUM

FIGURE 27

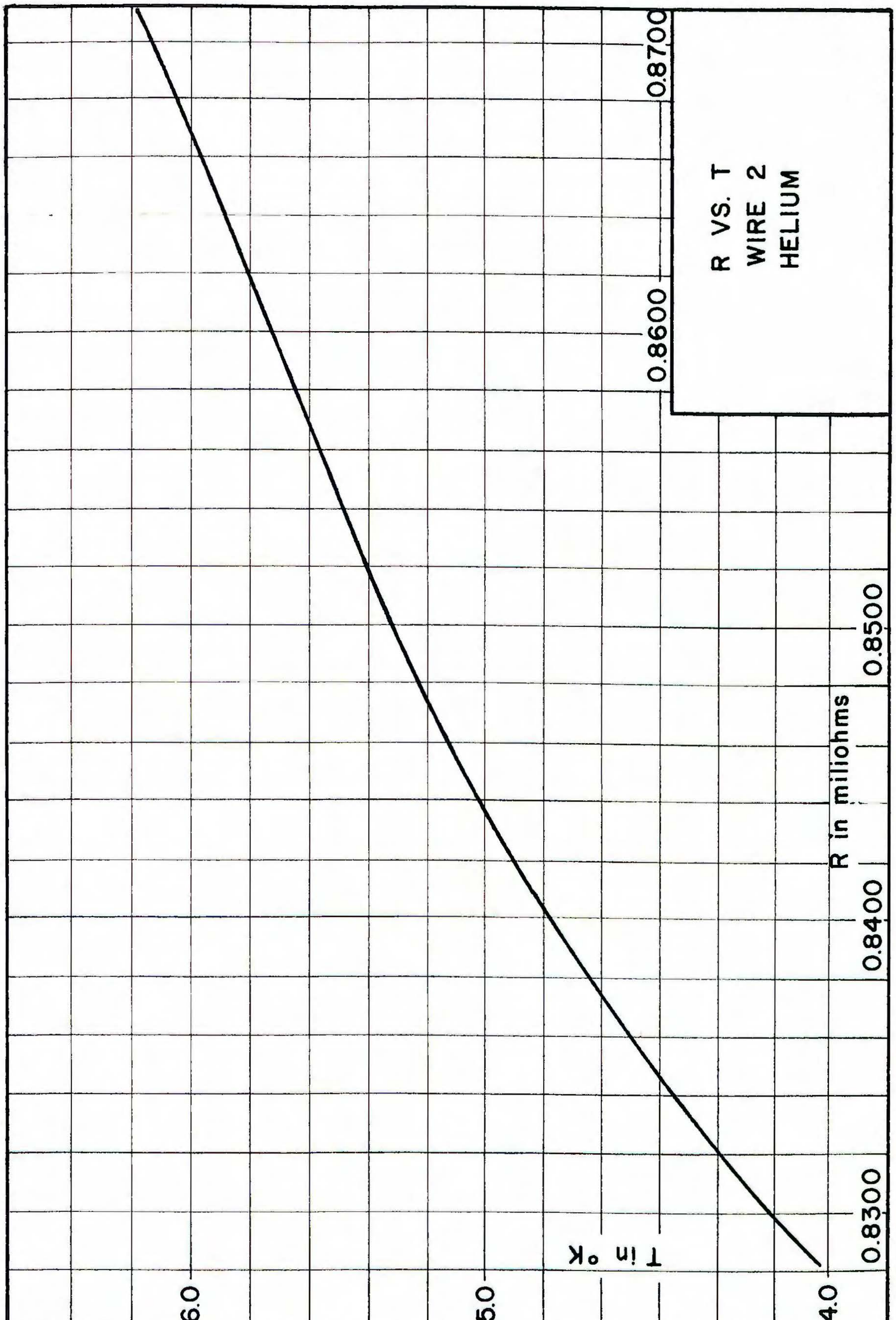

R VS. T
WIRE 2
HELIUM
R in miliohms
T in °K
0.8300
0.8400
0.8500
0.8600
0.8700
4.0
5.0
6.0

FIGURE 28

4. The temperature of the liquid helium was determined with a calibrated carbon resistor which was read to the closest 1/10 ohm using an A.C. bridge.[26] The copper cased resistor, calibration curve, and A.C. bridge were provided thru the courtesy of Ltjg. J. L. Edwards, USN. The calibration curve is shown as Figure 26. An accuracy of 0.01°K is possible in the measurement of T_b[27].

<u>Preparation and Calibration.</u> The platinum wires used in liquid helium were prepared in the same manner as those used in liquid nitrogen and were held in the frame shown in Photograph 3. The calibration was however, different. A single ice point calibration was made to find R_O and then R_{He} was determined in the same manner as R_{N_2}. The computed ratio showed that N was reasonably close to the values of N given in the ICT.[5] A curve identical in shape to the resistance curves of PT given in the ICT[5] was then drawn which intersected the experimentally determined value of R_{He}. Considerable experimental justification of this procedure is available[5].

Before each experimental run the value of R_{He} was redetermined since this number proved not be constant. The variation of R_{He} was not random but had a steady downward drift. Exactly the same phenomena was observed in liquid nitrogen and in nitrogen the drift was found to stabilize only after the wire had been driven into the film boiling region for a period of a number of minutes. This was done for the second of the two wires used in helium and the resistance then showed little further variation. No explanation of this phenomena is given.* For some of the experimental runs then the resistance vs. temperature curve of wire 1 (Figure 27) must be displaced horizontally until the observed calibration value of R_{He} corresponds to the observed T_b. The corresponding curve (Figure 28) for wire 2 requires no such displacement.

---

* Some speculation is possible however. In liquid nitrogen the film boiling temperature did not equal the temperature used in the original air anneal. In liquid helium the film boiling temperature probably did not exceed 50°K. Thus changes in the volume resistivity were not due to an annealing process.

The bubbles in film boiling are generated by a very explosive process so perhaps some resistance change was possible by shock induced cold working.

Langmuir[28] held that the loss of heat from wire was independent of convection and depended only on conduction very close to the wire. Now film boiling may drastically alter the character of the layers of molecules which are thought to be bound to the surface of wires. If the film boiling is violent enough these surface molecules, which may be water, oxygen, nitrogen or anything depending on the past history of the wire, may be stripped free. They would then be replaced by molecules which compose the bath. How this would lower the temperature of the wire is not known but an analogy between electrical impedance mismatch and thermal mismatch may exist.

CHAPTER VI

EXPERIMENTAL RESULTS AND CONCLUSIONS IN LIQUID HELIUM

The experimental data and calculations for liquid helium are included as Appendix 4. The results are shown as Figures 29 and 30. The equation for nucleate boiling for each Figure has been calculated and is found to be:

$$q/a = 3 \times 10^{-25} \Delta T^{53.5} \quad \text{- Wire 1}$$

$$q/a = 1.2 \times 10^{-8} \Delta T^{34.2} \quad \text{- Wire 2}$$

As in liquid nitrogen the nucleate boiling curves are very steep and cannot be represented by an equation where $2.5 \leq n \leq 4$. In fact the exponent in helium is even larger than that in liquid nitrogen. No further explanation can be given other than to observe that no contamination other than solid particles can be present in the liquid or on the surface of the wire. All foreign gases have solidified at liquid helium temperatures.

The maximum ΔT for nucleate boiling is only a little more than $3^{o}F$ but this is not surprising when it is noted that for many liquids boiling at atmospheric pressure the maximum ΔT is roughly related to the boiling point on the absolute scale. Also the low maximum q/a of 1.2×10^{3} BTU/ft^2 hr is not as surprising in retrospect.

It was hoped that an extended region could be observed in liquid helium but such was not the case. Such an extended region may or may not exist but it will require more sensitive measuring equipment to resolve the question.

As a final observation it should be noted that the bubbles generated in liquid helium during nucleate boiling are difficult to see their maximum diameter is probably no more than two to three thousandths of an inch. Correspondingly there are many of them and they appear to move away from the wire as clouds of bubbles. Their size increases when film boiling begins and the entire dewar of liquid is churned into a rolling boil which raises the level of the liquid on the order of 10%.

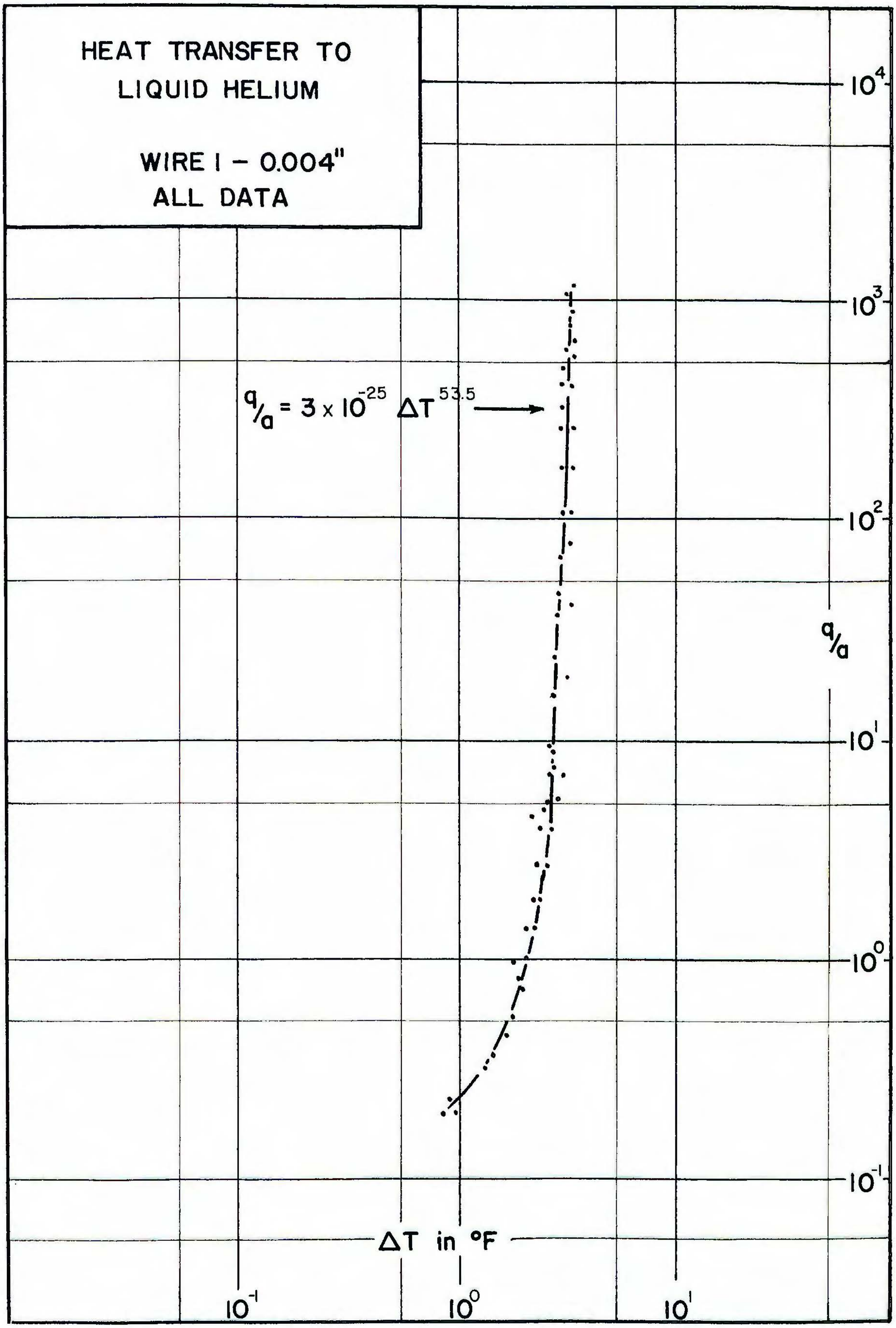

HEAT TRANSFER TO
LIQUID HELIUM
WIRE I - 0.004"
ALL DATA
$q/a = 3 \times 10^{-25}\,\Delta T^{53.5}$
10^4
10^3
10^2
10^1
10^0
10^{-1}
q/a
ΔT in °F
10^{-1}
10^0
10^1

FIGURE 29

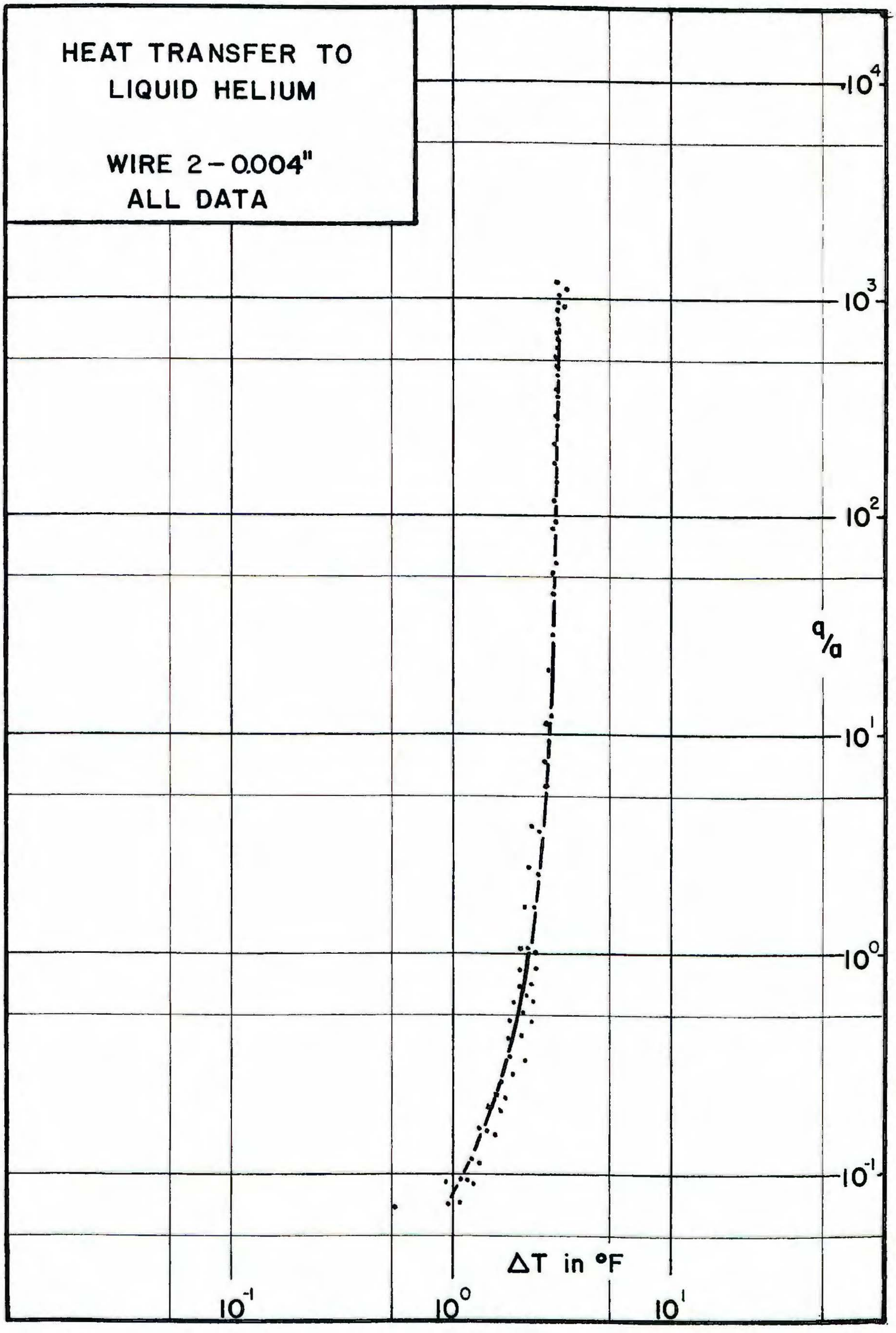

HEAT TRANSFER TO
LIQUID HELIUM
WIRE 2 - 0.004"
ALL DATA
10^4
10^3
10^2
q/a
10^1
10^0
10^{-1}
ΔT in °F
10^{-1}
10^0
10^1

FIGURE 30

SUMMARY

The following are considered to be the most significant points of this thesis.

1. The transition from free convective heat transfer to nucleate boiling in liquid nitrogen is shown experimentally to be gradual but takes place only after the free convection curve has passed thru an extended region.

2. The equations representing the nucleate boiling region for 0.004 inch diameter and 0.008 inch diameter wires in liquid nitrogen are shown to be a family of curves of the form

$$q/a = \exp^{10.25 - 2.45n} \cdot \Delta T^{n}$$

Note $5 \leq n \leq \infty$

The value of n for other liquids is much lower and is usually found to be $2.4 \leq n \leq 4$.

3. The usually assumed explanation of nucleate boiling heat transfer is not quantitatively valid in liquid nitrogen.

4. An molecular energy sorting mechanism is postulated to explain the nucleation and growth of a bubble along a state line.

5. Data is presented on nucleate boiling heat transfer to liquid helium.

APPENDIX 1

EXPERIMENTAL DATA, CALCULATIONS

AND THE RESULTING CURVES

FOR LIQUID NITROGEN

<u>Sample Calculations - Liquid Nitrogen.</u> As a random example the calculations will be carried thru for the first row of Table 25

Exp - volts	(2.295×10^{-2})	Observed data
Std - volts	(7.5145×10^{-2})	Observed data
R - ohm	(0.03054)	Substituting the value for

Std - volts and the Std resistor (0.1Ω) in $E = IR$.

$7.5145 \times 10^{-2} = I \cdot 0.1$, thus $I_{Std} = 7.5145 \times 10^{-1}$

ampere. Now $R = \dfrac{(\text{Exp - volts})}{I} = \dfrac{(\text{Exp - volts})(\text{Std})}{\text{Std - volts}}$

so $R = \dfrac{2.295 \times 10^{-2} \cdot 0.1}{7.5145 \times 10^{-2}} = 0.03054$ ohm.

$\dfrac{100R}{R_o}$ The value of R_o is taken from the last N_2 calibration which in this case is Table 24, $R_o = 0.15960$ ohm.

$$\frac{100R}{R_o} = \frac{100 \cdot 0.03054}{0.15960} = 19.14$$

T - ^oC Using Figure 5 for 0.008 inch wires and the curve for Wire 4 the preceding value of 19.14 locates a point on the proper curve. This point corresponds to a temperature in degrees Centigrade of -195.40.

EI - watts Having found I_{Std} above in R-ohm the product of this and Exp - volts becomes EI.

$EI = 2.295 \times 10^{-2} \cdot 7.5145 \times 10^{-1} = 1.725 \times 10^{-2}$ watt

BTU/ft^2 hr. The surface area of the wire in ft^2 is needed.

$$A = \pi DL/144 = \frac{\pi \cdot 0.008 \cdot 2.065}{144} = 3.604 \times 10^{-4}$$

Now 1 watt = 3.413 btu/hr.

$$\text{So } EI \cdot \frac{3.413}{3.604 \times 10^{-4}} = EI \cdot 0.9470 \times 10^{-4} = BTU/ft^2 \text{ hr}$$

Thus $1.725 \times 10^{-2} \cdot 0.9470 \times 10^{-4} = 1.63 \times 10^{2}$ BTU/ft^2 hr

ΔT - ^{o}C The boiling point of liquid Nitrogen is needed.

Using the formula on page 11 and the observed barometric pressure

$$T_{N2} = -195.80^{o}C + 0.0109 \quad (P - 760)$$

$$= -195.80 \quad + 0.0109 \quad (760 - 760)$$

$$= -195.80$$

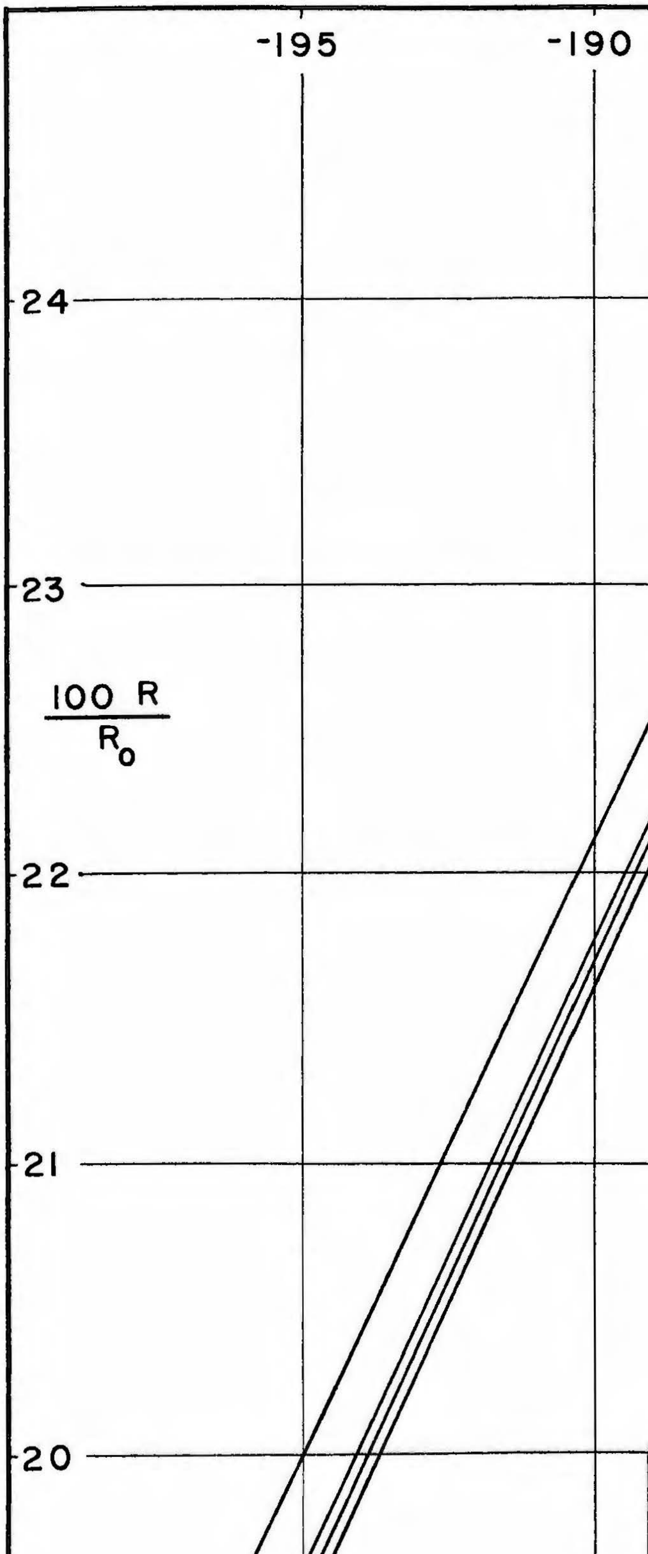
Now $T = (T_{N_2} - T) - {}^{o}C$

$$= -195.80 - (-195.40)$$

$$= 0.40 \ ^{o}C$$

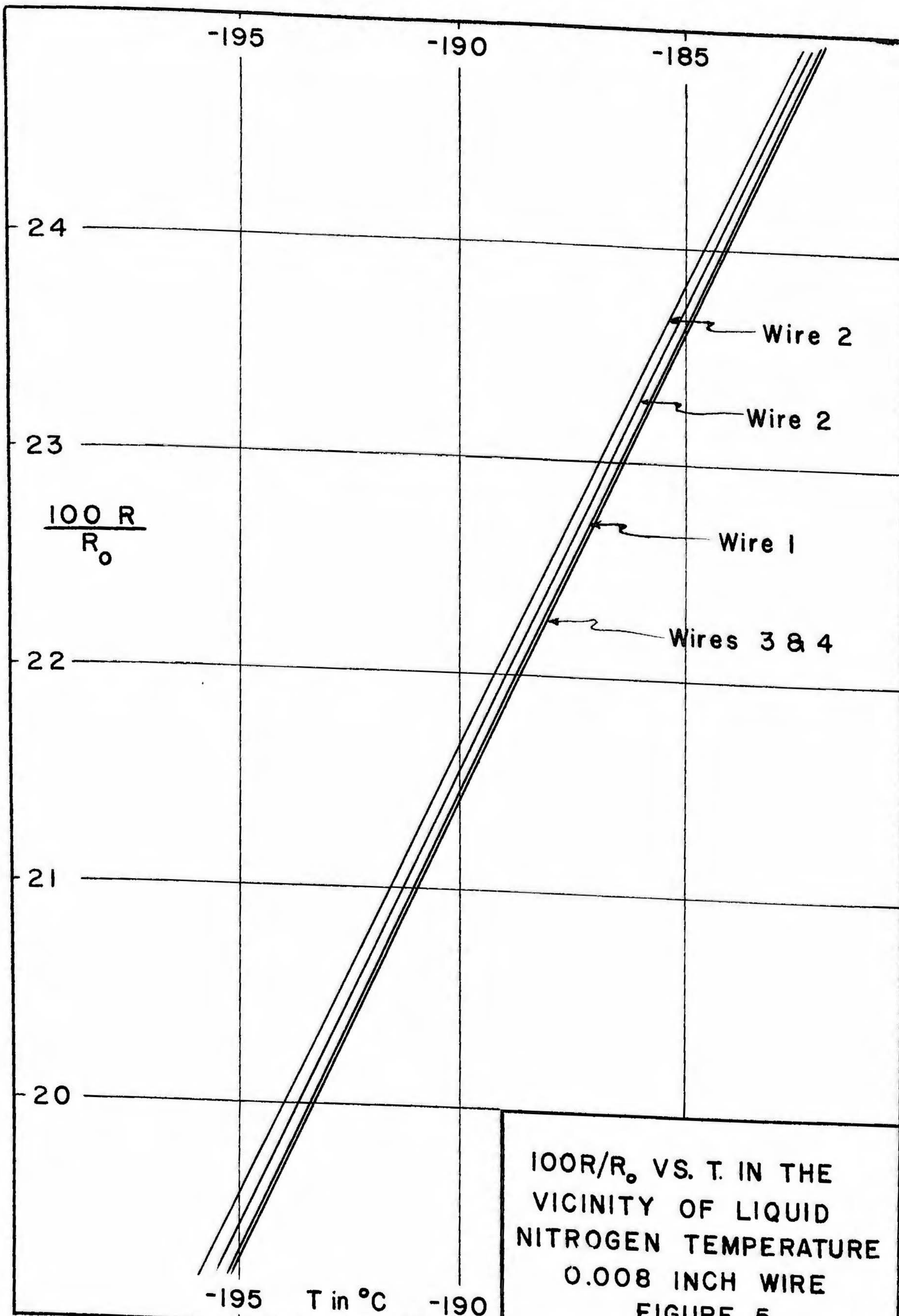
ΔT - ^{o}F ΔT-^{o}F = $T^{o}C \cdot 1.8$

$$= 0.7 \ ^{o}F$$



$100R/R_o$ VS. T IN THE VICINITY OF LIQUID NITROGEN TEMPERATURE 0.004 INCH WIRE

FIGURE 4



$100R/R_o$ VS. T. IN THE VICINITY OF LIQUID NITROGEN TEMPERATURE
0.008 INCH WIRE
FIGURE 5

1.0 Ω std. resistor

Table 1
Ice Point Calibration

Wire 1
0.004"

Exp. - volts	Std. - volts	R - ohms
3.8702×10^{-2}	3.2022×10^{-2}	0.82740
6.3996	7.7322	0.82766
1.0654	1.2873	0.82762
1.3682	1.6533	0.82756
1.5950	1.9271	0.82767
1.9111	2.3090	0.82767
2.1218	2.5635	0.82770
2.3847	2.8814	0.82762
2.6476	3.1987	0.82771
2.9751	3.5946	0.82766
3.3952	4.1016	0.82777
3.9537	4.7767	0.82770
4.7337	5.7177	0.82790

Average R_o = 0.82770 Ω

Length of wire = 2.505"

0.1 Ω std.

Table 2

Down Run

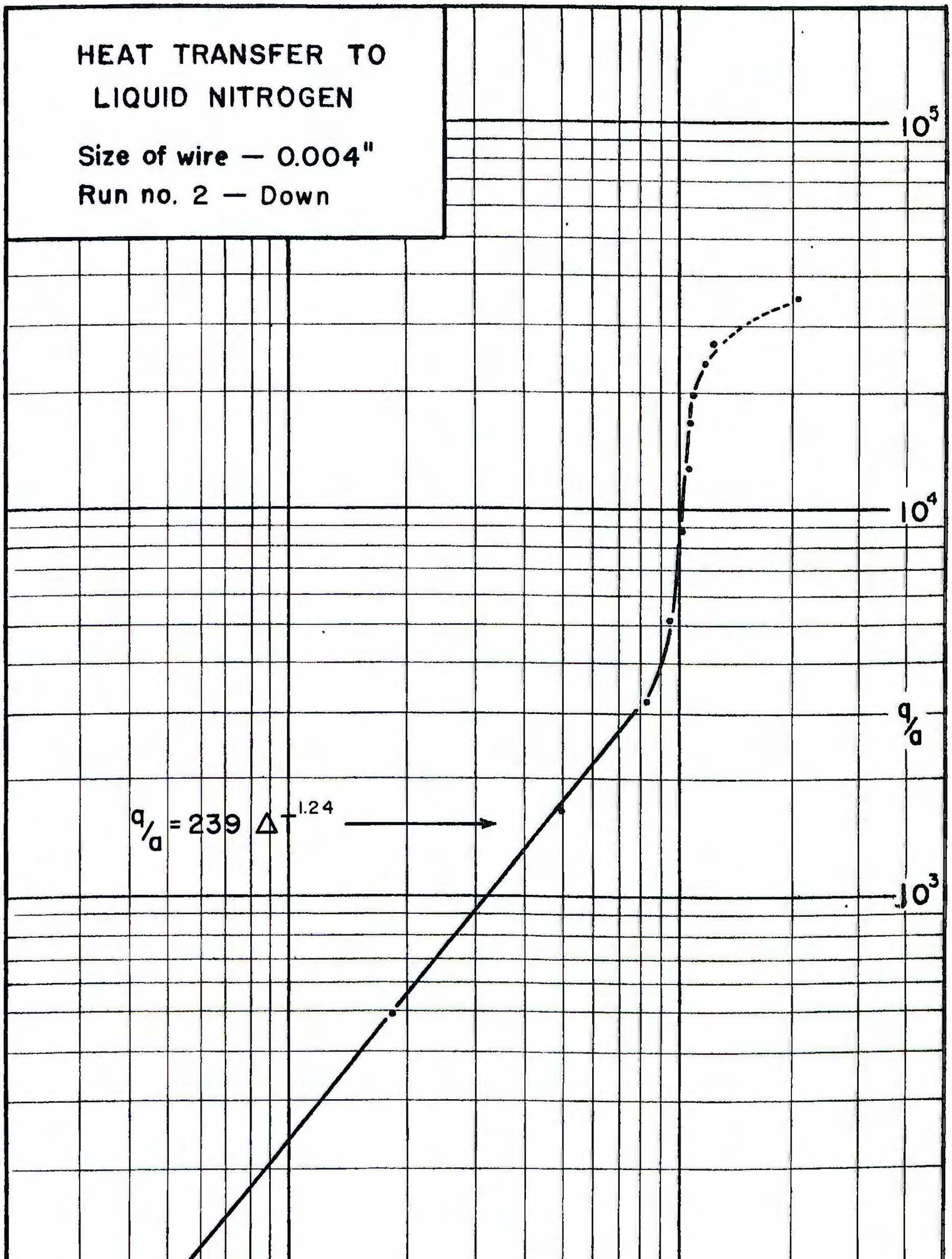
Wire 1
0.004"

Exp. - volts	Std - volts.	R-ohm	$100R/R_0$	T-°C	EI- watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
3.403×10^{-1}	6.255×10^{-1}	0.1838	24.33	-184.1	2.129×10^{0}	3.59×10^{4}	11.75	21.1	
5.440	2.979	0.1826	22.21	-188.9	1.621	2.71	6.9	12.4	
5.080	2.788	0.1822	22.01	-188.4	1.416	2.37	6.5	11.7	
4.649	2.565	0.1812	21.89	-189.7	1.192	1.99	6.1	11.0	
4.261	2.357	0.1808	21.84	-189.8	1.004	1.68	6.0	10.8	
3.688	2.038	0.1809	21.85	-189.8	7.516×10^{-1}	1.26	6.0	10.8	
3.064	1.709	0.1793	21.66	-190.2	5.236	8.77×10^{3}	5.6	10.1	
2.336	1.315	0.1778	21.48	-190.6	3.072	5.14	5.2	9.4	
1.850	1.051	0.1760	21.26	-190.1	1.944	3.25	4.6	8.3	
1.292	7.614×10^{-2}	0.1696	20.49	-192.9	9.835×10^{-2}	1.65	2.8	5.0	
7.578×10^{-2}	5.877	0.1629	19.68	-194.8	3.524	5.90×10^{2}	1.0	1.8	
2.634	1.646	0.1600	19.33	-195.6	4.336×10^{-3}	7.26×10^{1}	0.2	0.36	
1.338	8.392×10^{-3}	0.1594	19.26	-195.8	1.123	1.88	0.0	0.00	
1.1273	7.065	0.1596	19.28	-195.8	7.964×10^{-4}	1.33	0.0	0.00	
9.372×10^{-3}	5.877	0.1595	19.27	-195.8					
7.007	4.395	0.1594	19.26	-195.8					
5.178	3.248	0.1594	19.26	-195.8					
4.609	2.892	0.1594	19.26	-195.8					

Conversion: Watts to BTU/ft² hr

$$\text{Watts} \cdot \frac{3.413\ \text{BTU/Watt}}{\text{Aerea of Wire}} = \text{BTU/ft}^2\ \text{hr}$$

$$\text{Watts} \cdot \frac{3.413 \cdot 144}{\pi(0.004)(2.505)} = \text{Watts} \times 1.684 \times 10^{4}$$


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.004"
Run no. 2 — Down
$q/a = 239\ \Delta T^{1.24}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

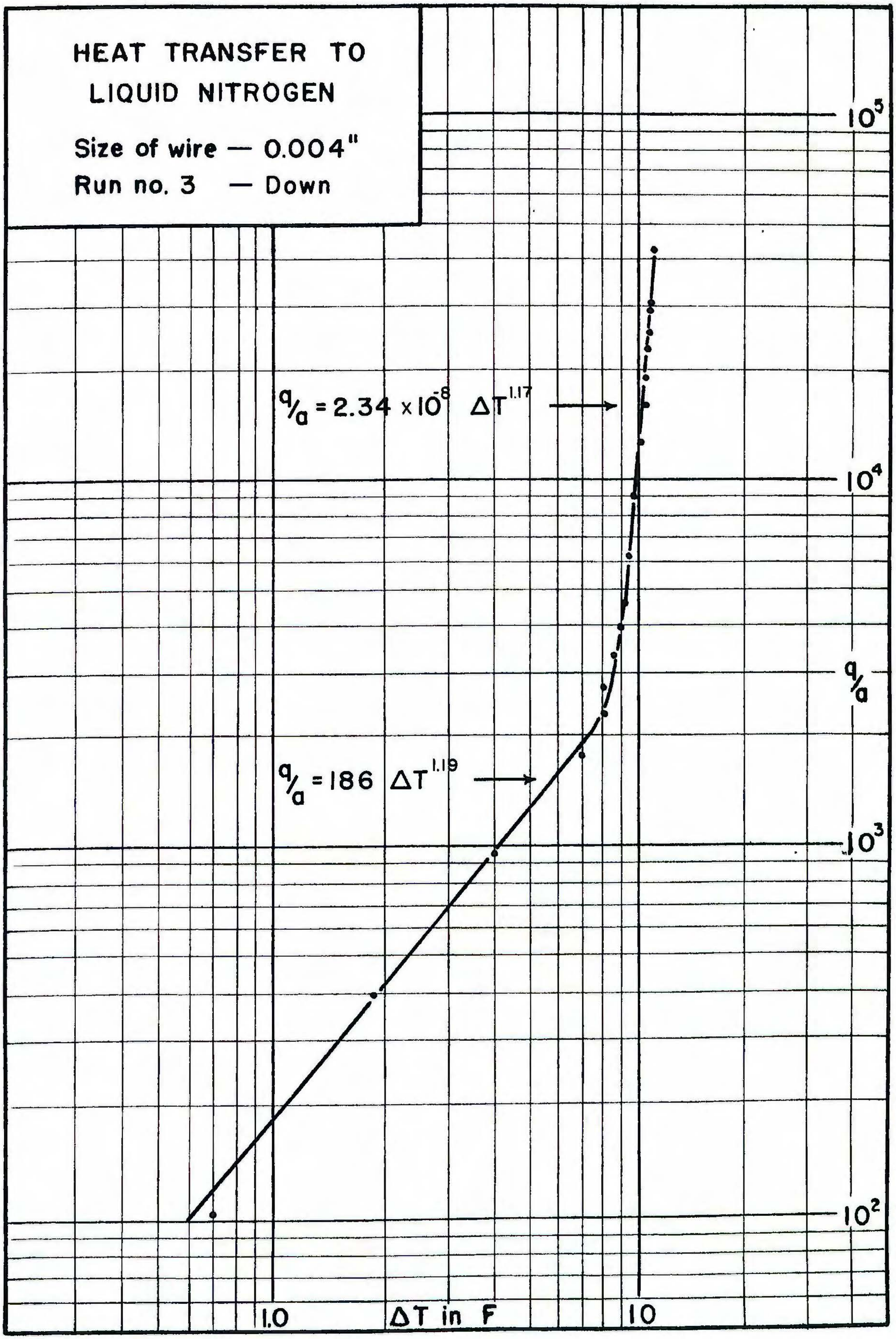
0.1 Ω std.

Table 3
Down Run

Wire 1
0.004

Exp.-volts	Std.-volts	R-ohm	100R/R_o	T-°C	EI-watts	BTU/ft^2 hr	ΔT-°C	ΔT-°F	Notes
6.288×10^{-1}	3.459×10^{-1}	1.818	21.96	-189.5	2.715×10^{0}	4.24×10^{4}	6.3	11.3	
5.961	3.287	1.814	21.92	189.6	1.959	3.06	6.2	11.2	
5.815	3.212	1.810	21.87	189.7	1.868	2.91	6.1	11.0	
5.403	2.991	1.806	21.82	189.8	1.616	2.52	6.0	10.8	
5.077	2.815	1.804	21.80	189.9	1.429	2.23	5.9	10.6	
4.675	2.598	1.799	21.73	190.0	1.215	1.90	5.8	10.4	
4.303	2.393	1.798	21.71	190.1	1.030	1.61	5.8	10.4	
3.781	2.110	1.792	21.65	190.2	7.978×10^{-1}	1.25	5.6	10.1	
3.209	1.797	1.786	21.58	190.4	5.767	9.00×10^{3}	5.4	9.7	
2.669	1.497	1.783	21.54	190.5	3.996	6.24	5.3	9.5	
2.107	1.190	1.771	21.40	190.8	2.507	3.91	5.0	9.0	
1.947	1.104	1.764	21.31	191.0	2.150	3.36	4.8	8.6	
1.765	1.006	1.754	21.19	191.3	1.776	2.77	4.5	8.1	
1.596	9.110×10^{-2}	1.752	21.17	191.9	1.454	2.27	4.5	8.1	
1.400	8.087	1.731	20.91	193.5	1.132	1.77	3.9	7.0	
1.008	6.023	1.674	20.22	194.8	6.073×10^{-2}	9.48×10^{2}	2.3	4.1	
6.457×10^{-2}	3.962	1.629	19.68	194.8	2.558	3.99	1.0	1.8	
3.271	2.034	1.608	19.43	195.4	6.652×10^{-3}	1.04×10^{2}	0.4	0.7	
1.268	7.935	1.598	19.31	195.6	1.006	1.57×10^{1}	0.2	0.4	
6.227×10^{-3}	3.899	1.597	19.29	195.7	2.428×10^{-4}	3.79×10^{0}	0.1	0.2	

Conversion 1.561×10^{4}



HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 3 — Down
$q/a = 2.34 \times 10^{-8}\ \Delta T^{1.17}$
$q/a = 186\ \Delta T^{1.19}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

0.1 Ω std.
764 mm. Hg.

Table 4
Up Run

Wire 1
0.004"

Exp - volts	Std - volts	R - ohm	100R/R_0	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
9.901×10^{-2}	5.950×10^{-2}	1.664	19.89	-194.3	5.892×10^{-2}	9.20×10^{2}	1.6	2.9	
1.192×10^{-1}	7.092×10^{-2}	1.688	20.17	193.7	8.411	1.31×10^{3}	2.2	3.9	
1.368	8.067	1.696	20.27	193.4	1.103×10^{-1}	1.72	2.5	4.5	1/
1.527	8.953	1.705	20.38	193.2	1.367	2.13	2.7	4.9	2/
1.753	1.009×10^{-1}	1.737	20.76	192.3	1.769	2.76	3.6	6.5	3/
1.934	1.104	1.753	20.94	191.9	2.134	3.33	4.0	7.2	4/
2.147	1.210	1.775	21.21	191.2	2.597	4.05	4.7	8.5	5/
2.412	1.298	1.858	22.20	188.9	3.131	4.89	7.6	12.6	
2.613	1.427	1.832	21.89	189.6	3.728	5.82	6.3	11.3	6/
2.795	1.523	1.835	21.93	189.5	4.257	6.65	6.4	11.5	7/
2.976	1.614	1.843	22.02	189.3	4.804	7.50	6.6	11.9	8/
3.171	1.714	1.850	22.11	189.3	5.435	8.49	6.8	12.2	
3.345	1.814	1.844	22.04	189.2	6.068	9.47	6.7	12.1	
3.780	2.039	1.854	22.16	189.0	7.708	1.20×10^{4}	6.9	12.4	
4.150	2.234	1.857	22.19	189.0	9.270	1.45	6.9	12.4	
4.514	2.425	1.861	22.24	188.8	1.094×10^{0}	1.71	7.1	12.8	
4.929	2.646	1.863	22.26	188.8	1.304	2.04	7.1	12.8	
5.280	2.834	1.863	22.26	188.8	1.496	2.34	7.1	12.8	
5.651	3.032	1.864	22.28	188.7	1.713	2.67	7.2	13.0	
6.071	3.254	1.866	22.30	188.7	1.975	3.08	7.2	13.0	
6.486	3.477	1.868	22.32	188.6	2.252	3.52	7.3	13.1	
7.167	3.837	1.868	22.32	188.6	2.750	4.29	7.3	13.1	
7.742	4.140	1.870	22.35	188.5	3.286	5.13	7.4	13.3	

Notes from Table 4

N_2 Calibration

Std.	10282	11256	12441	12437	11254	10277
Exp.	16557	18134	20043	20038	18133	16552
R_{N_2}	0.16103	0.16110	0.16111	0.16112	0.16112	0.16106

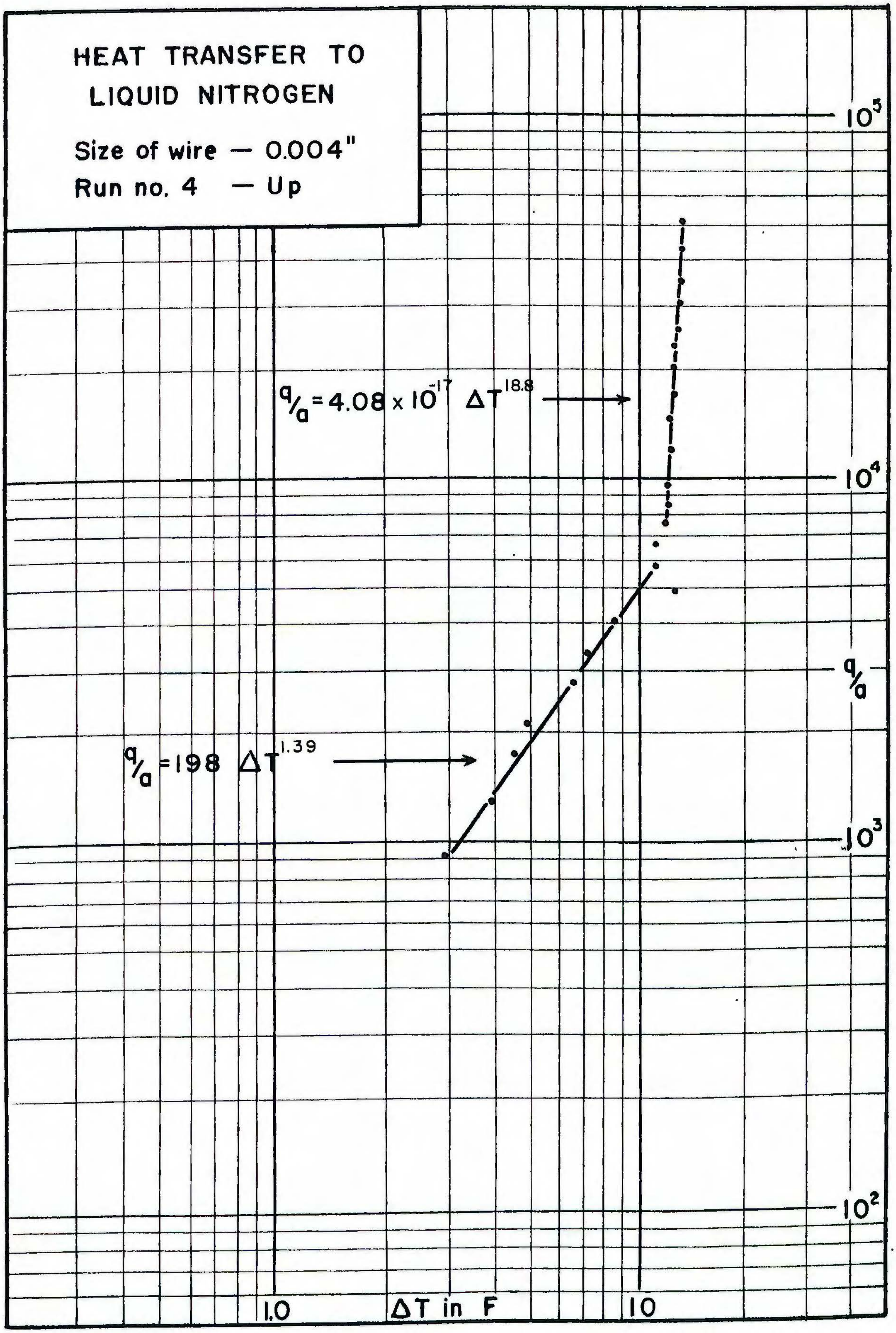
Use R_{N_2} (764 mm) as 0.16109

Last previous claibration R_{N_2} (760 mm) = 0.16084

New R_o = 0.83678

1/ 2-5 Nucleation centers which are not all continuous
2/ 8 " " " " " " "
3/ 12 " " " " " " "
4/ 14 " " " " " " "
5/ 15 " " " " " " "
6/ About 20 nucleation centers
7/ " 35 " "
8/ Too many to count

In attempting to reach a Std value of 4.2×10^{-1} the wire melted and broke outside the potential taps. The wire is still usable but this indicated the top of this curve is very close to a limiting value for q/A


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 4 — Up
q/a = 4.08 x 10^-17 ΔT^18.8
q/a = 198 ΔT^1.39
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

0.1 Ω std
764 mm. Hg.

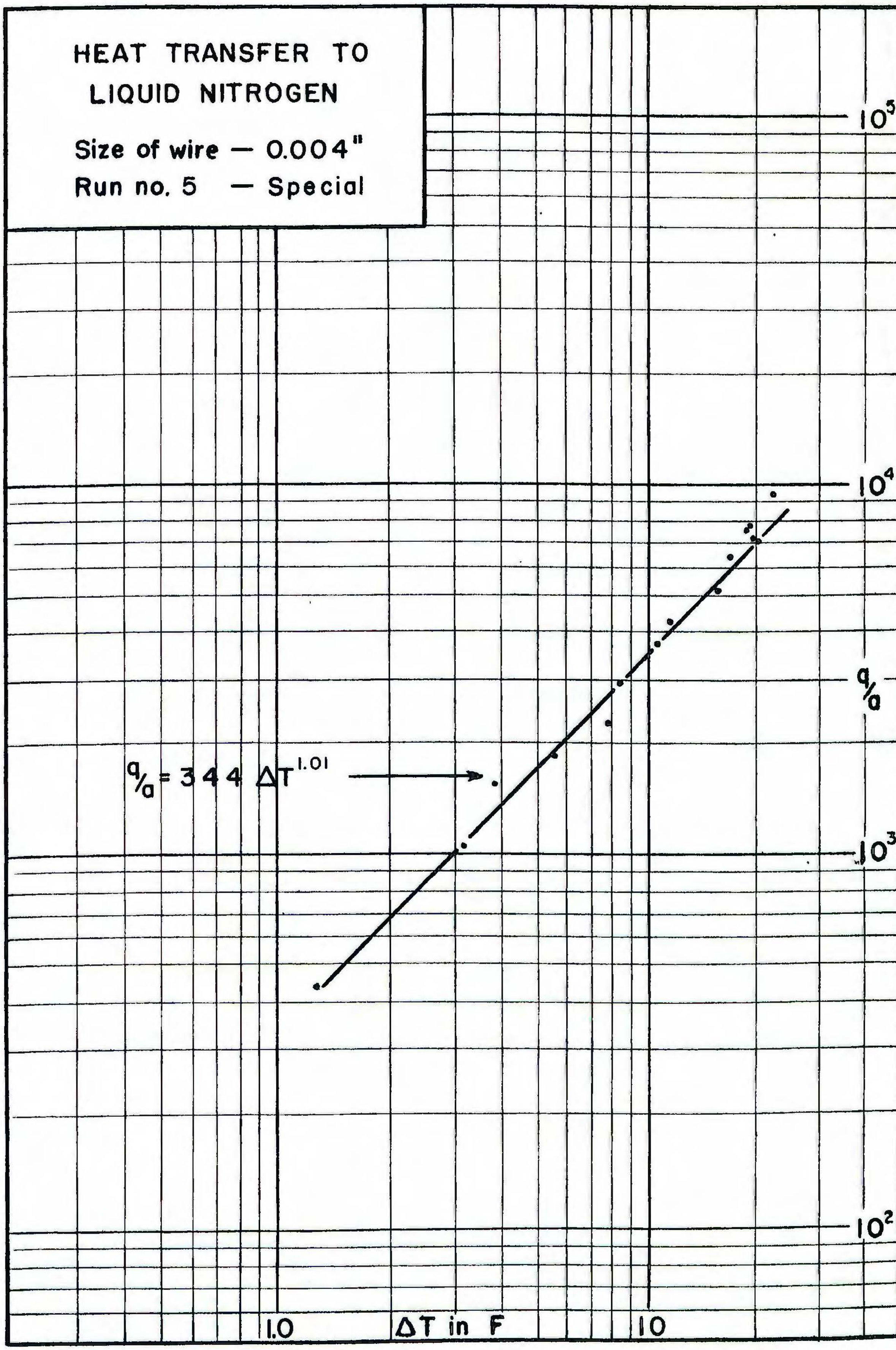
Table 5
Special Run

Wire 1
0.004"

Exp.-volts	Std.-volts	R-ohm	100R/R_0	T-°C	EI-watts	BTU/ft^2 hr	ΔT-°C	ΔT-°F	Notes
6.776×10^{-2}	4.150×10^{-2}	0.1633	19.51	-195.2	2.812×10^{-2}	4.39×10^{2}	0.7	1.3	
1.063×10^{-1}	6.356	0.1673	19.99	194.1	6.759	1.06×10^{3}	1.8	3.2	
1.200	7.131	0.1682	20.10	193.8	8.554	1.56	2.1	3.8	1/
1.418	8.243	0.1721	20.56	192.8	1.169×10^{-1}	1.83	3.1	5.6	2/
1.596	9.157	0.1743	20.82	192.1	1.461	2.28	3.8	6.8	3/
1.835	1.035×10^{-1}	0.1773	21.19	191.3	1.898	2.96	4.6	8.3	
2.089	1.145	0.1824	21.80	189.9	2.391	3.73	6.0	10.8	
2.230	1.210	0.1842	22.01	189.4	2.699	4.21	6.5	11.7	
2.521	1.308	0.1928	23.04	187.0	3.297	5.15	8.9	16.0	
2.841	1.438	0.1975	23.60	186.4	4.084	6.38	9.5	17.1	
3.011	1.491	0.2019	24.13	184.5	4.489	7.01	11.4	20.5	
3.025	1.509	0.2005	23.96	184.9	4.564	7.13	11.0	19.8	4/
3.140	1.573	0.1997	23.86	185.1	4.938	7.71	10.9	19.6	
3.120	1.569	0.1989	23.77	185.3	4.880	7.62	10.6	19.1	
3.570	1.730	0.2064	24.66	183.3	6.180	9.65	12.6	22.7	5/

Notes
1/ 1 Nucleation center
2/ 2 " "
3/ Nucleation centers gone
4/ 1 Nucleation center again
5/ Perhaps 1 nucleation center

This special run involved driving the wire briefly into the film boiling region before each pair of readings. After the film boiling decayed the readings were taken.


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 5 — Special
$q/a = 344\ \Delta T^{1.01}$
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω std
758 mm. Hg.

Table 6
Special Run

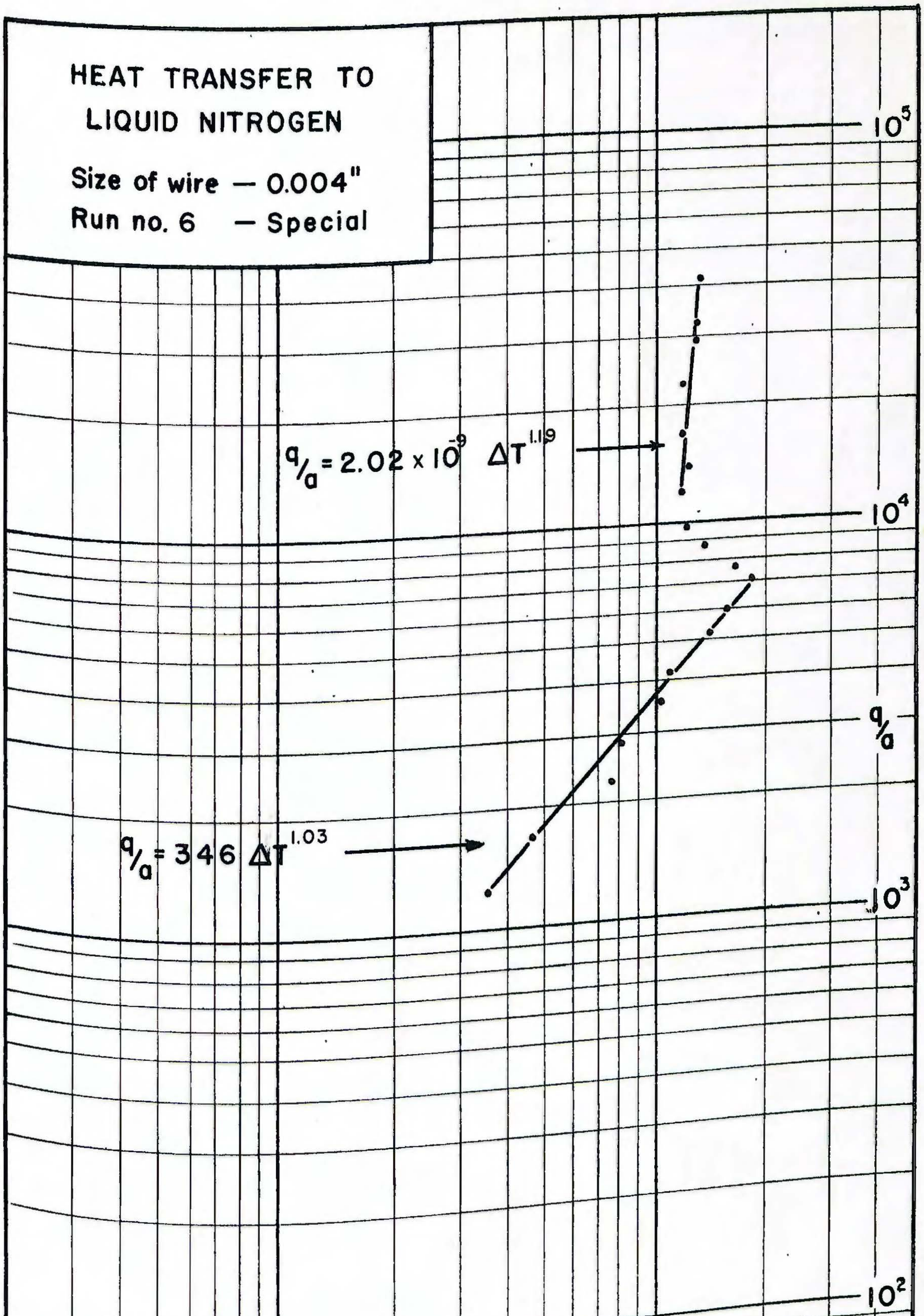
Wire 1
0.004"

Exp - volts	Std - volts	R - ohm	100R/R_o	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
1.170×10^{-1}	6.963×10^{-2}	0.1680	20.10	-193.8	8.140×10^{-2}	1.27×10^{3}	2.0	3.6	
1.361	8.002	0.1701	20.35	193.2	1.089×10^{-1}	1.70	2.6	4.7	
1.589	9.038	0.1758	21.04	191.6	1.436	2.24	4.2	7.6	
1.791	1.012×10^{-1}	0.1770	21.18	191.3	1.812	2.83	4.5	8.1	
2.024	1.210	0.1812	21.69	190.1	2.260	3.53	5.7	10.3	
2.210	1.328	0.1827	21.86	189.7	2.670	4.17	6.1	11.0	
2.510	1.330	0.1890	22.62	187.9	3.330	5.20	7.9	14.2	
2.724	1.416	0.1924	23.03	187.0	3.856	6.00	8.8	15.8	
2.995	1.514	0.1978	23.67	185.5	4.534	7.08	10.3	18.5	
3.094	1.595	0.1940	23.21	186.6	4.935	7.71	9.2	16.6	
3.236	1.722	0.1879	22.49	188.2	5.572	8.70	7.6	13.7	
3.048	1.840	0.1852	22.16	189.0	6.270	9.79	6.8	12.2	
3.646	1.972	0.1849	22.13	189.1	7.190	1.12×10^{4}	6.7	12.1	
3.904	2.109	0.1851	22.15	189.0	8.230	1.29	7.0	12.6	
4.484	2.424	0.1850	22.14	189.1	1.087×10^{0}	1.70	6.7	12.1	
5.159	2.772	0.1861	22.29	188.8	1.430	2.23	7.0	12.6	
5.658	3.034	0.1865	22.32	188.6	1.869	2.92	7.2	13.0	
6.193	3.317	0.1867	22.35	188.6	2.065	3.21	7.2	13.0	
7.054	3.768	0.1872	22.46	188.4	2.658	4.15	7.4	13.3	
7.031	3.760	0.1870	22.38	188.6	2.646	4.13	7.3	13.1	

Calibration check

Exp	16888	18533	20564	23081	205595	0.18536	168815
Std	10463	11489	12738	14298	12738	11486	10457
R_{N_2}	0.16141	0.16131	0.16143	0.016142	0.16140	0.016138	0.16144

Use R_{N_2} = 0.16140


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.004"
Run no. 6 — Special
q/a = 2.02 x 10-9 ΔT1.19
q/a = 346 ΔT1.03
10^5
10^4
10^3
10^2
q/a
1.0
10
ΔT in F

1.0 Ω std

Wire 2
0.004"

Table 7
Ice Point Calibration

Exp - volts	Std - volts	R - ohm
1.3015×10^{-2}	1.6892×10^{-2}	0.77051
9.1744×10^{-3}	1.1906	0.77056
7.0837	9.193×10^{-3}	0.77055
1.3014×10^{-2}	1.6887×10^{-2}	0.77068
9.1753×10^{-3}	1.1910	0.77039
7.0850	9.196×10^{-3}	0.77044
1.3016×10^{-2}	1.6894×10^{-2}	0.77048
9.1764×10^{-3}	1.1907	0.77067
7.0847	9.195×10^{-3}	0.77050

Average R_0 = 0.77055 Ω

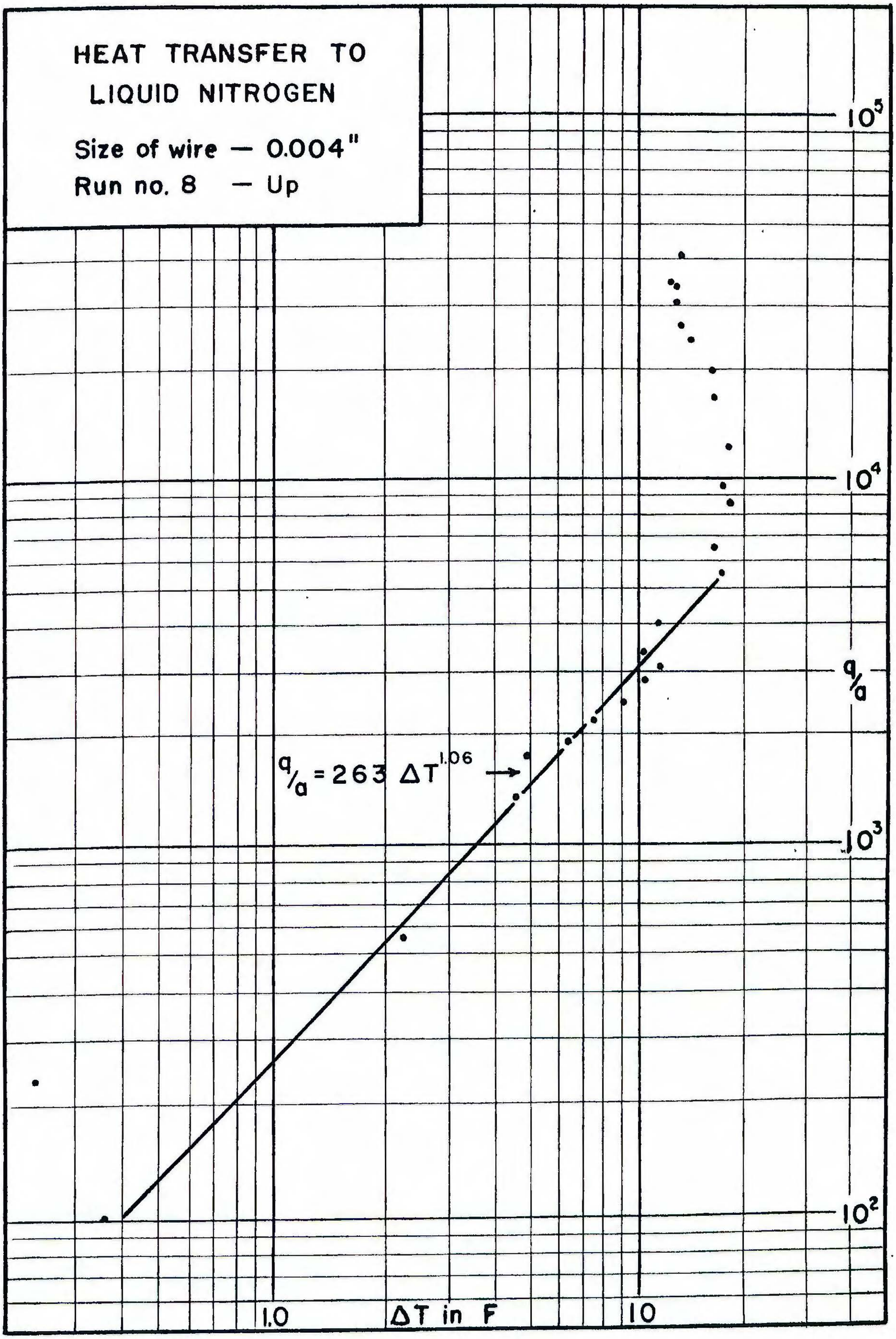
Length of wire = 2.400"

0.1 Ω std
760 mm Hg

Table 8
Op Run

Wire 2
0.004"

Exp - volts	Std - volts	R-ohm	100R/Ro	T-°C	EI - watts	BTU/ft²hr	ΔT-°C	ΔT-°F	Notes
6.351×10^{-3}	4.258×10^{-2}	0.1493	19.37	-195.75	2.710×10^{-4}	4.42×10^{0}	0.05	0.09	
1.206×10^{-2}	8.069	0.1494	19.39	195.70	9.730	1.59×10^{1}	0.10	0.18	
3.796	2.055	0.1499	19.45	195.60	6.327×10^{-3}	1.03×10^{2}	0.20	0.36	
4.647	3.164	0.1496	19.42	195.65	1.471×10^{-2}	2.40	0.15	0.24	
7.885	5.138	0.1534	19.91	194.55	4.052	6.60	1.25	2.25	
1.145×10^{-1}	7.255	0.1579	20.49	193.25	8.311	1.35×10^{3}	2.55	4.59	
1.296	8.174	0.1585	20.57	193.05	1.059×10^{-1}	1.73	2.75	4.95	
1.375	8.537	0.1611	20.90	192.25	1.174	1.91	3.55	6.39	
1.476	9.049	0.1630	21.16	191.65	1.335	2.18	4.15	7.47	
1.587	9.558	0.1660	21.54	190.75	1.516	2.47	5.05	9.09	
1.713	1.017×10^{-1}	0.1685	21.86	190.00	1.743	2.84	5.80	10.44	
1.805	1.057	0.1708	22.17	189.30	1.907	3.11	6.50	11.70	
1.861	1.105	0.1684	21.85	190.00	2.057	3.35	5.80	10.44	
2.051	1.204	0.1703	22.10	189.45	2.470	4.03	6.35	11.43	
2.721	1.494	0.1821	23.60	186.00	4.066	6.63	9.80	17.64	
2.882	1.598	0.1803	23.40	186.45	4.607	7.51	9.35	16.83	
3.111	1.705	0.1825	23.68	185.80	5.304	8.65	10.00	18.00	
3.281	1.800	0.1823	23.66	185.90	5.906	9.63	9.90	17.82	
3.705	2.029	0.1826	23.70	185.75	7.517	1.23×10^{4}	10.05	18.10	
4.326	2.042	0.1801	23.37	186.55	1.039×10^{0}	1.69	9.25	16.65	
4.661	2.610	0.1786	23.18	186.70	1.217	1.98	9.10	16.38	
4.955	2.806	0.1766	22.92	186.60	1.390	2.29	8.20	14.76	
5.351	3.050	0.1754	22.76	187.95	1.632	2.66	7.65	13.77	
5.633	3.235	0.1741	22.59	188.30	1.882	3.07	7.50	13.50	
5.971	3.432	0.1740	22.58	188.30	2.049	3.34	7.50	13.50	
6.143	3.570	0.1720	22.33	188.90	2.193	3.57	6.90	12.42	
6.594	3.786	0.1742	22.60	188.25	2.496	4.07	7.55	13.59	

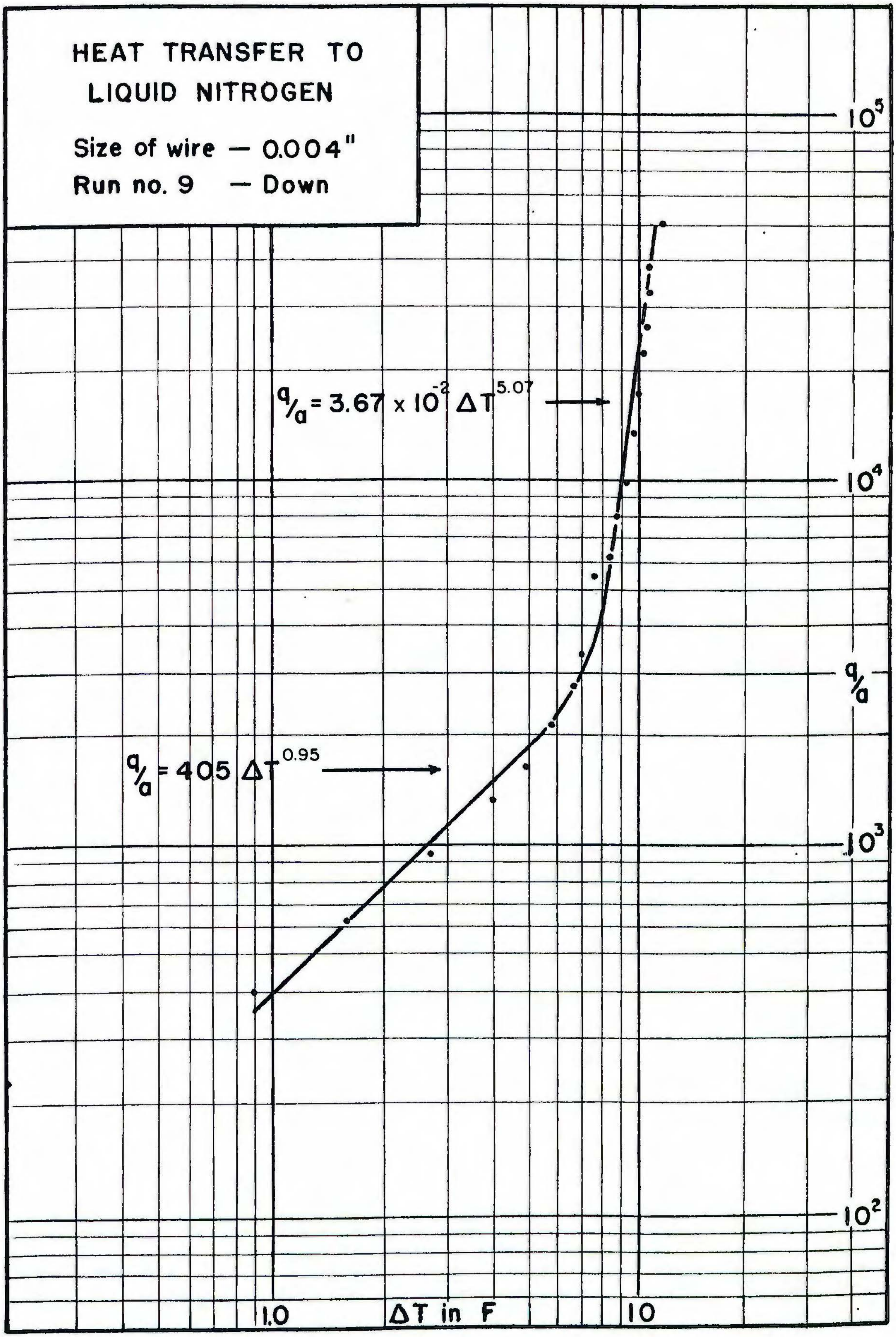

HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 8 — Up
$q/a = 263\ \Delta T^{1.06}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

0.1 Ω std
760 mm Hg.

Table 9
Down Run

Wire 2
0.004"

Exp - volts	Std. - volts	R - ohm	$100R/R_o$	T - °C	EI - watts	$BTU/ft^2 hr$	ΔT - °C	ΔT - °F	Notes
7.294×10^{-1}	4.273×10^{-1}	0.1707	22.15	-189.3	3.117×10^{0}	5.08×10^{4}	6.5	11.7	
6.339	3.748	0.1691	21.94	189.8	2.376	3.87	6.0	10.8	
5.823	3.441	0.1692	21.96	189.8	2.004	3.27	6.0	10.8	
5.239	3.101	0.1689	21.91	189.9	1.625	2.65	5.9	10.6	
4.782	2.844	0.1681	21.82	190.1	1.360	2.22	5.7	10.3	
4.234	2.525	0.1677	21.76	190.2	1.609	1.74	5.6	10.1	
3.711	2.222	0.1670	21.67	190.4	8.246×10^{-1}	1.34	5.4	9.7	
3.190	1.922	0.1660	21.54	190.7	6.131	9.99×10^{3}	5.1	9.2	
2.851	1.724	0.1654	21.47	190.9	4.914	8.01	4.9	8.8	
2.512	1.527	0.1645	21.34	191.2	3.835	6.25	4.6	8.3	
2.141	1.311	0.1632	21.18	191.6	2.807	4.58	4.2	7.6	
1.830	1.128	0.1623	21.06	191.9	2.063	3.36	3.9	7.0	
1.657	1.026	0.1616	20.97	192.1	1.700	2.77	3.7	6.7	
1.453	9.087×10^{-2}	0.1599	20.75	192.6	1.320	2.15	3.2	5.8	
1.267	8.003	0.1583	20.54	193.1	1.014	1.65	2.7	4.9	
1.129	7.210	0.1566	20.32	193.6	8.141×10^{-2}	1.33	2.2	4.0	
9.490×10^{-2}	6.149	0.1543	20.02	194.3	5.835	9.51×10^{2}	1.5	2.7	
7.630	5.010	0.1523	19.77	194.9	3.822	6.23	0.9	1.6	
6.063	4.024	0.1507	19.56	195.3	2.440	3.98	0.5	0.9	
4.534	3.033	0.1495	19.40	195.7	1.375	2.24	0.1	0.2	
3.037	2.038	0.1490	19.34	195.8	6.189×10^{-3}	1.01	0.0	0.0	


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.004"
Run no. 9 — Down
q/a = 3.67 x 10^-2 ΔT^5.07
q/a = 405 ΔT^0.95
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω std
760 mm. Hg.

Wire 2
0.004"

Table 10
Up-Down Run

Exp-volts	Std-volts	R-ohm	100R/R_0	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
7.207 × 10^{-1}	4.224 × 10^{-1}	0.1706	22.60	-188.3	3.045 × 10^{0}	4.96 × 10^{4}	7.5	13.5	
6.164	3.608	0.1708	22.62	188.2	2.224	3.63	7.6	13.7	
5.094	3.000	0.1698	22.49	188.5	1.528	2.49	7.3	13.1	
3.726	2.213	0.1684	22.30	189.0	8.247 × 10^{-1}	1.34	6.8	12.2	See next page
2.872	1.710	0.1679	22.24	189.1	4.912	8.01 × 10^{3}	6.7	12.1	
2.576	1.534	0.1683	22.24	189.1	3.950	6.44	6.7	12.1	
2.036	1.232	0.1644	21.89	189.9	2.508	4.09	5.9	10.6	
1.787	1.107	0.1581	21.38	191.2	1.979	3.23	4.6	8.3	
1.453	9.186 × 10^{-2}	0.1531	20.94	192.1	1.334	2.17	3.7	6.7	
1.077	7.035	0.1531	20.28	193.7	7.577 × 10^{-2}	1.24	2.1	3.8	
9.464 × 10^{-2}	6.229	0.1519	20.12	194.1	5.896	9.61 × 10^{2}	1.7	3.1	
6.125	4.120	0.1487	19.70	195.0	2.466	4.00	0.8	1.4	
4.559	3.090	0.1475	19.54	195.4	1.408	2.30	0.4	0.7	
1.557	3.088	0.1475	19.54	195.4	1.407	2.29	0.4	0.7	
5.922	3.989	0.1485	19.67	195.1	2.362	3.85	0.7	1.3	
8.985	5.925	0.1516	20.07	194.2	5.324	8.68	1.6	2.9	
1.025 × 10^{-1}	6.705	0.1528	20.23	193.8	6.879	1.12 × 10^{3}	2.0	3.6	
1.453	9.112	0.1595	21.12	191.9	1.324 × 10^{-1}	2.16	4.1	7.4	
1.853	1.109 × 10^{-1}	0.1670	22.4	189.4	2.055	3.35	6.4	11.5	
2.190	1.321	0.1657	21.94	189.8	2.894	4.72	6.0	10.8	
2.662	1.516	0.1755	23.24	186.8	4.037	6.58	9.8	17.6	
3.000	1.709	0.1755	23.24	186.8	5.129	8.36	9.8	17.6	
3.755	2.217	0.1694	22.43	188.6	8.326	1.36 × 10^{4}	7.2	13.0	
4.804	2.832	0.1697	22.48	188.5	1.361 × 10^{0}	2.22	7.3	13.1	
5.954	3.500	0.1701	22.53	188.4	2.084	3.40	7.4	13.4	
7.524	4.422	0.1701	22.53	188.4	3.328	5.42	7.4	13.4	

Notes from Table 10

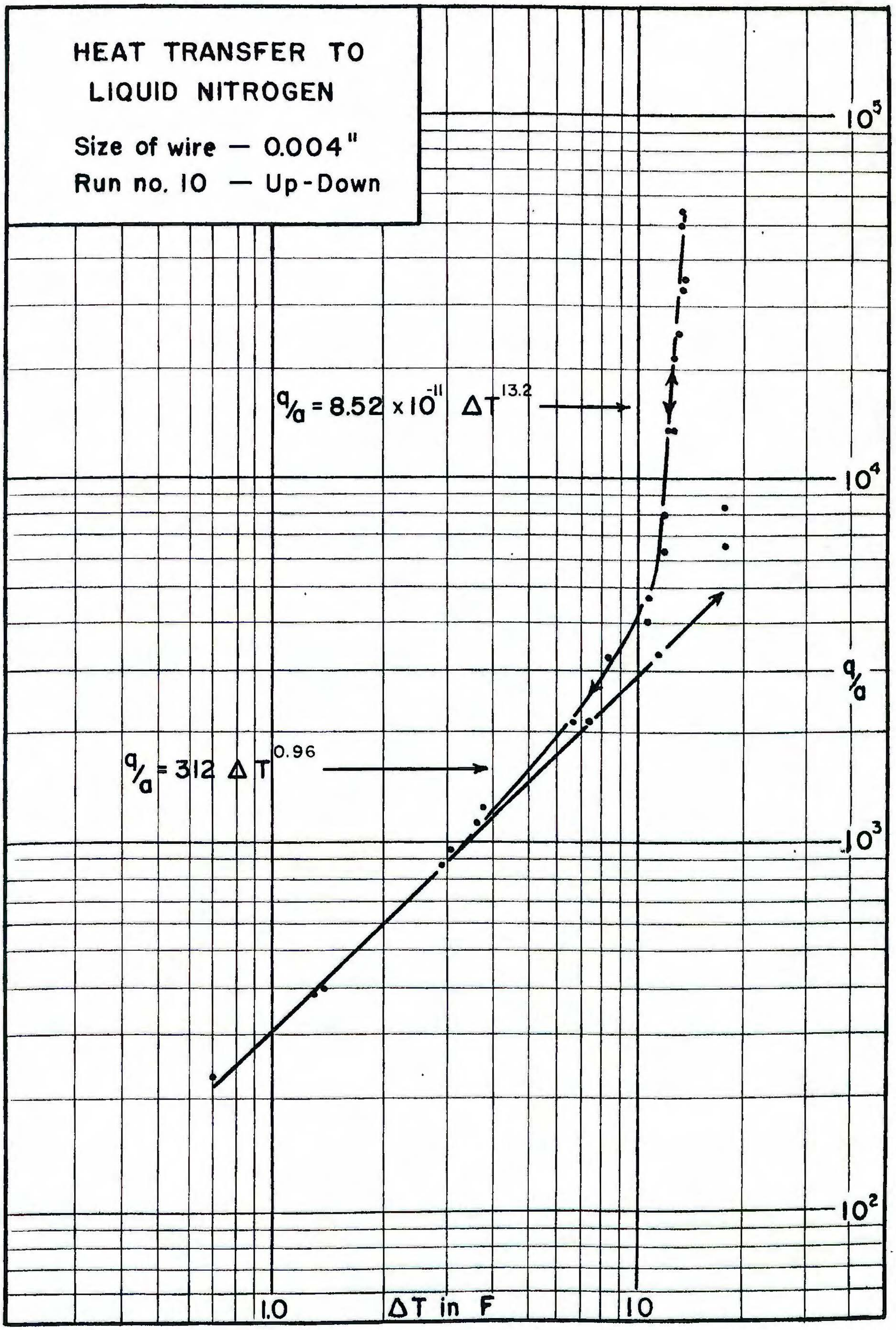
N_2 Calibration

Exp	15713	15723	21490	21486	21488
Std	10754	10752	14696	14699	14696
R_{N_2}	0.14611	0.14623	0.14623	0.14617	0.14621

Use R_{N_2} (760 mm) as 0.14620

Since "Temperature--" [6] says resistance changes are proportional I will adjust the ice point value so that I can use the present curve for Wire 2. I checked this for Wire 1 runs 1 & 2 and it was valid.

Thus $\frac{14.620}{19.363} = 0.7550$ or $R_o = 0.7550$

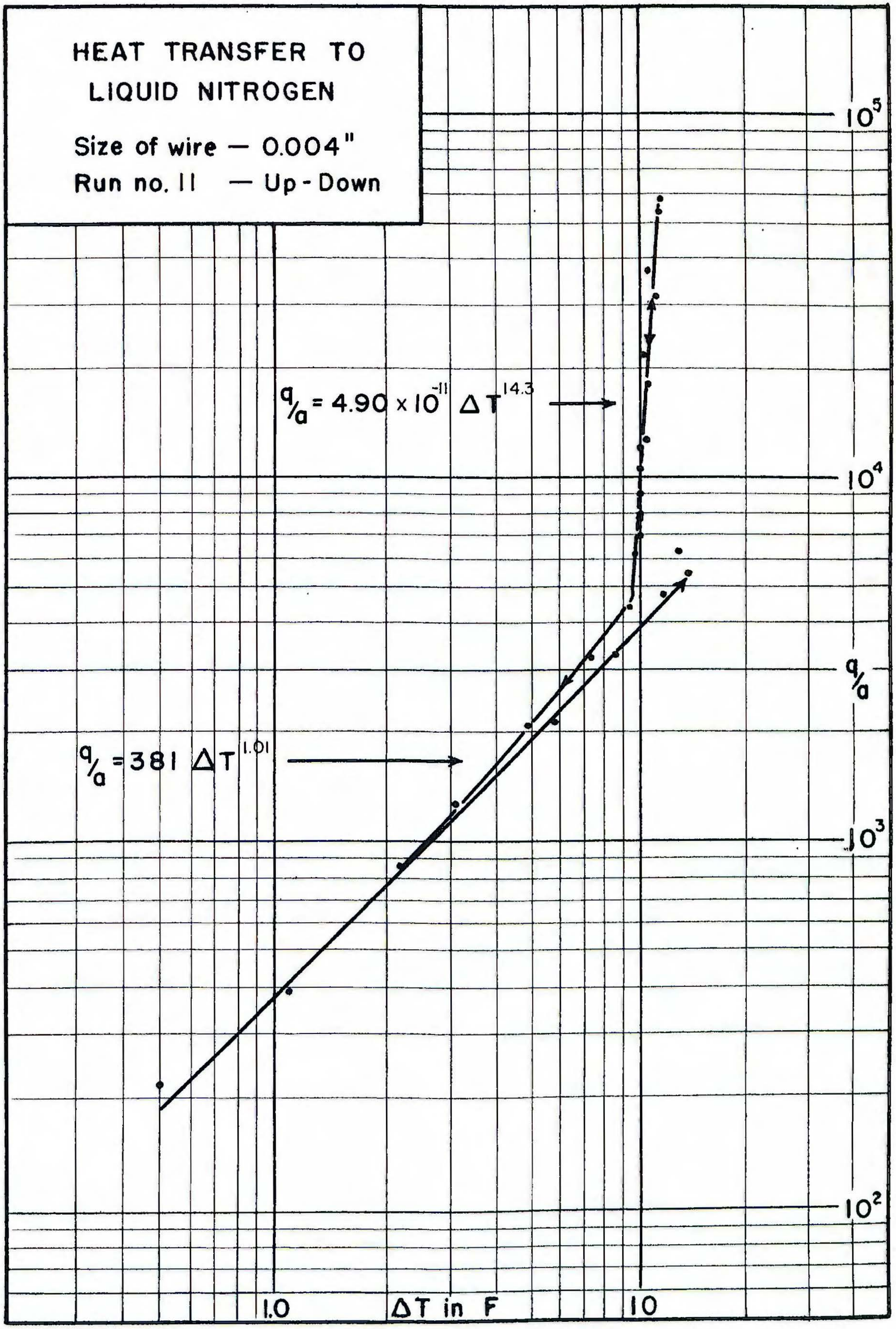

HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.004"
Run no. 10 — Up-Down
$q/a = 8.52 \times 10^{-11}\ \Delta T^{13.2}$
$q/a = 312\ \Delta T^{0.96}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

0.1 Ω std
760 mm. Hg.

Table II
Up-Down Run

Wire 2
0.004"

Exp-volts	std-volts	R-ohm	100R/Ro	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
4.429 $\times 10^{-2}$	3.011 $\times 10^{-2}$	0.1471	19.48	-195.5	1.335 $\times 10^{-2}$	2.17 $\times 10^{2}$	0.3	0.5	
5.916	3.996	0.1480	19.60	195.2	2.364	3.85	0.6	1.1	
8.900	5.929	0.1501	19.88	194.6	5.277	8.60	1.2	2.2	
1.090 $\times 10^{-1}$	7.171	0.1591	20.11	194.1	7.812	1.27 $\times 10^{3}$	1.7	3.1	
1.401	9.019	0.1552	20.55	193.1	1.263 $\times 10^{-1}$	2.06	2.7	4.9	
1.806	1.118 $\times 10^{-1}$	0.1616	21.40	191.1	2.020	3.29	4.7	8.5	
2.205	1.315	0.1677	21.22	189.2	2.898	4.72	6.6	11.9	
2.394	1.401	0.1708	21.62	188.2	3.354	5.47	7.6	13.7	
2.571	1.517	0.1695	22.45	188.6	3.900	6.36	7.2	13.0	
2.645	1.610	0.1643	21.76	190.2	4.259	6.94	5.6	10.1	
2.830	1.723	0.1642	21.75	190.2	4.877	7.95	5.6	10.1	
2.978	1.813	0.1642	21.75	190.2	5.399	8.80	5.6	10.1	
3.320	2.019	0.1644	21.77	190.2	6.704	1.09 $\times 10^{4}$	5.6	10.1	
3.646	2.213	0.1647	21.81	1.90.1	8.069	1.32	5.7	10.3	
4.339	2.625	0.1652	21.88	189.9	1.139 $\times 10^{0}$	1.86	5.9	10.6	
5.680	3.412	0.1664	22.03	189.6	1.938	3.16	6.2	11.2	
7.432	4.451	0.1670	22.12	189.4	3.308	5.39	6.4	11.5	
7.689	4.601	0.1672	22.14	189.3	3.541	5.77	6.5	11.7	
6.171	3.709	0.1664	22.04	189.6	2.289	3.73	6.2	11.2	
4.676	2.827	0.1654	21.91	189.9	1.322	2.15	5.9	10.6	
3.633	2.209	0.1645	21.79	190.2	8.025 $\times 10^{-1}$	1.31	5.6	10.1	
2.813	1.716	0.1640	21.72	190.3	4.826	7.87 $\times 10^{3}$	5.5	9.9	
2.482	1.515	0.1638	21.69	190.4	3.761	6.13	5.4	9.7	
2.105	1.292	0.1630	21.59	190.6	2.719	4.43	5.2	9.4	
1.778	1.111	0.1600	21.19	191.6	1.975	3.22	4.0	7.2	
1.405	9.009 $\times 10^{-2}$	0.1560	20.66	192.8	1.266	2.06	3.2	5.8	


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 11 — Up - Down
$q/a = 4.90 \times 10^{-11}\ \Delta T^{14.3}$
$q/a = 381\ \Delta T^{1.01}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

0.1 Ω std
768 mm Hg

Wire 3
0.004"

Table 12
Up Run

Exp - volts	Std - volts	R - ohm	100 R/Ro	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
1.056 $\times 10^{-1}$	7.566 $\times 10^{-2}$	0.1396	20.22	-193.2	7.990 $\times 10^{-2}$	1.42 $\times 10^{3}$	2.6	4.7	
1.139	8.070	0.1411	20.44	192.7	9.190	1.63	3.1	5.6	
1.307	9.083	0.1438	20.83	191.8	1.187 $\times 10^{-3}$	2.11	4.0	7.2	
1.474	1.007 $\times 10^{-1}$	0.1463	21.19	191.0	1.485	2.64	4.8	8.6	
1.682	1.117	0.1506	21.82	189.5	1.879	3.34	6.3	11.3	
1.879	1.217	0.1544	22.36	188.3	2.285	4.06	7.5	13.5	
2.105	1.324	0.1590	23.03	186.7	2.786	4.95	9.1	16.4	
2.259	1.421	0.1590	22.58	186.7	3.209	5.70	9.1	16.4	1/
2.366	1.517	0.1559	22.12	187.8	3.589	6.37	8.0	14.4	2/
2.487	1.629	0.1527	21.54	188.8	4.051	7.19	7.0	13.6	3/
2.561	1.723	0.1487	21.53	190.1	4.412	7.84	5.7	10.3	
2.697	1.815	0.1486	21.53	190.1	4.894	8.69	5.9	10.6	
2.833	1.902	0.1490	21.58	190.0	5.390	9.57	5.9	10.6	
3.002	2.011	0.1493	21.63	189.9	6.036	1.07 $\times 10^{4}$	5.9	10.6	
3.311	2.215	0.1495	21.66	189.9	7.333	1.30	5.8	10.4	
3.631	2.409	0.1507	21.83	189.5	8.747	1.55	6.3	11.3	
3.953	2.615	0.1512	21.90	189.3	1.034 $\times 10^{0}$	1.84	6.5	11.7	
4.442	2.929	0.1516	21.96	189.2	1.301	2.31	6.6	11.9	
4.934	3.241	0.1522	22.05	189.0	1.599	2.84	6.8	12.2	
5.366	3.509	0.1529	22.15	188.74	1.883	3.34	7.12	12.82	5/
5.416	3.504	0.1546	22.39	188.18	1.897	3.37	7.70	13.86	
5.434	3.500	0.1553	22.50	188.00	1.902	3.38	7.94	14.29	
5.452	3.498	0.1559	22.58	187.74	1.907	3.39	8.12	14.62	
5.463	3.495	0.1563	22.64	187.60	1.909	3.39	8.20	14.76	
5.467	3.493	0.1565	22.67	187.54	1.910	3.39	8.32	14.98	
5.470	3.489	0.1567	22.70	187.46	1.909	3.39	8.40	15.12	
5.470	3.489	0.1568	22.71	187.44	1.909	3.39	8.42	15.16	

Table 12 contd.

Exp - volts	Std - volts	R - ohm	100R/R_o	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
5.4729×10^{-1}	3.487×10^{-1}	0.1569	22.73	-187.40	1.909×10^{0}	3.390×10^{4}	8.46	15.23	
5.472	3.486	0.1569	22.73	187.40	1.908	3.390	8.46	15.23	
5.468	3.481	0.1571	22.76	187.32	1.904	3.381	8.54	15.37	
5.467	3.481	0.1571	22.76	187.32	1.903	3.379	8.54	15.37	
5.465	3.479	0.1571	22.76	187.32	1.901	3.376	8.54	15.37	
5.463	3.477	0.1571	22.76	187.32	1.900	3.374	8.54	15.37	

Ice point calibration

10829	156655	0.69129
10819	156655	0.69062
10812	156650	0.69020
10181	147485	0.69030
101815	147480	0.69036

Average R_o = 0.69029 Ω

Length of wire = 2.192"

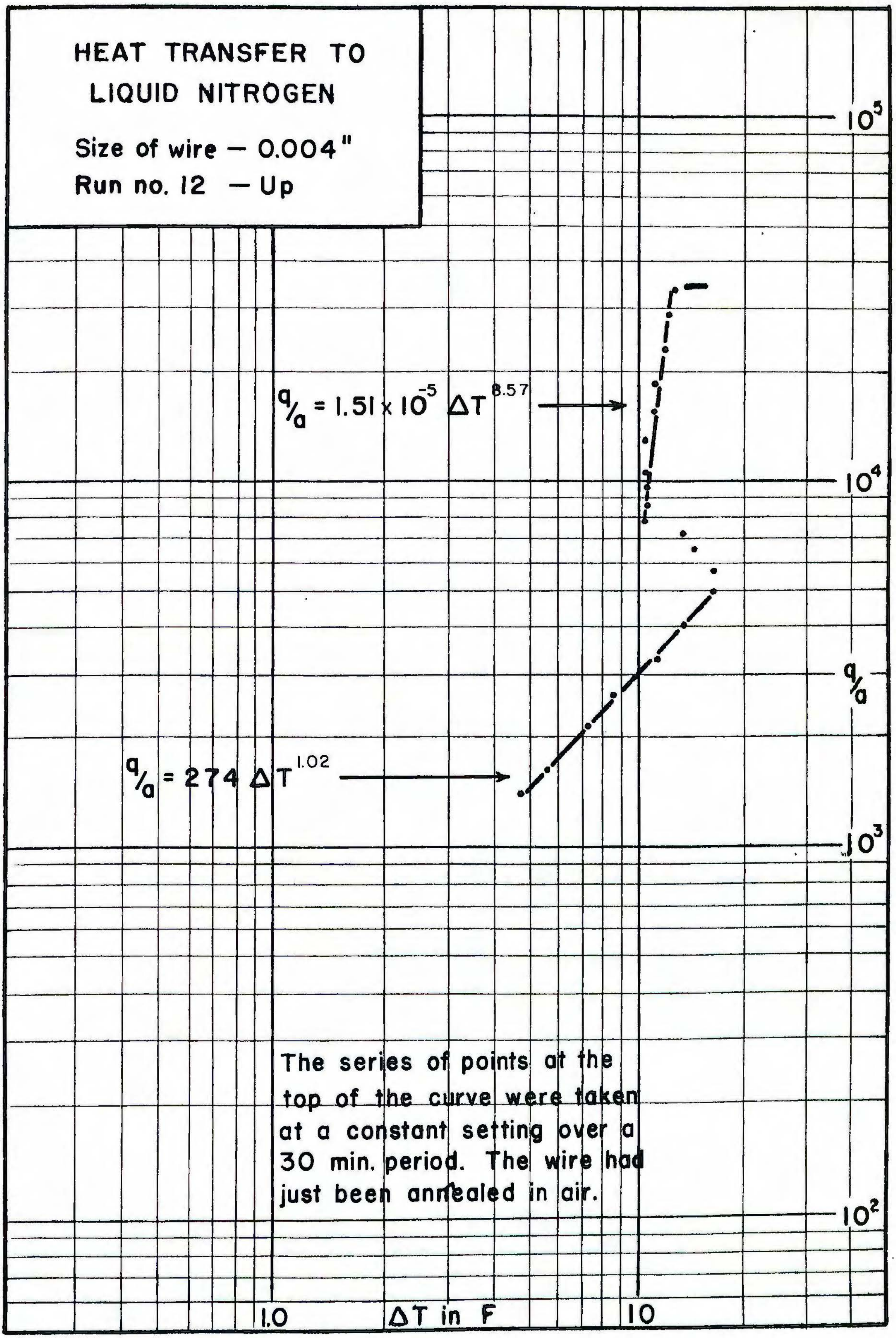
N_2 Calibration

15062	114355	0.13171
16577	12580	0.13177
18421	13978	0.13179
16590	12582	0.13185
15080	11443	0.13178

Average R_{N_2} (768 mm) = 0.13178

Wire freshly annealed in air.

1/ About 4 nucleation centers
2/ 1/2 of wire boiling
3/ All of wire boiling
5/ Next 13 readings taken over a 30 min. period


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 12 — Up
q/a = 1.51 x 10^-5 ΔT^8.57
q/a = 274 ΔT^1.02
The series of points at the top of the curve were taken at a constant setting over a 30 min. period. The wire had just been annealed in air.
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω std
768 mm Hg.

Wire 3
0.004"

Table 13
Lots of Bubbles Run

Exp.-volts	Std-amps	R-ohm	$100R/R_o$	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
6.0915×10^{-2}	4.5496×10^{-2}	0.1339	19.40	-195.1	2.771×10^{-2}	4.90×10^{2}	0.7	1.3	
1.0302×10^{-1}	7.4669	0.1380	19.99	193.8	7.692	1.37×10^{3}	2.0	3.6	1
1.1127	8.0003	0.1391	20.15	193.4	8.902	1.58	2.4	4.3	2
1.274	9.0168	0.1413	20.47	192.6	1.149×10^{-1}	2.04	3.2	5.8	3
1.430	9.990	0.1431	20.73	191.0	1.429	2.54	3.8	6.8	4
1.6185	1.1085×10^{-1}	0.1460	21.15	190.5	1.794	3.19	4.8	8.6	5
1.7806	1.2053	0.1477	21.40	189.1	2.146	3.81	5.3	9.5	6
1.9923	1.3124	0.1581	21.99	188.2	2.615	4.64	6.7	12.1	7
2.1763	1.4072	0.1546	22.40	187.6	3.062	5.44	7.6	13.7	8
2.3907	1.5289	0.1564	22.65	187.5	3.655	6.49	8.2	14.8	9
2.535	1.6123	0.1572	22.77	187.3	4.087	7.26	8.5	15.3	10
2.7198	1.7003	0.1600	23.18	186.4	4.624	8.21	9.4	16.9	11
2.9020	1.8164	0.1598	23.15	186.5	5.271	9.36	9.3	16.7	12
3.0321	1.906	0.1591	23.05	186.7	5.779	1.03×10^{4}	9.1	16.4	13
3.1687	2.0117	0.1575	22.82	187.2	6.393	1.14	8.6	15.5	14
3.5023	2.2191	0.1578	22.86	186.8	7.772	1.38	9.0	16.2	
3.7803	2.4136	0.1566	22.69	187.5	9.124	1.62	8.3	14.9	
4.0653	2.6060	0.1560	22.60	187.7	1.059×10^{0}	1.88	8.1	14.6	

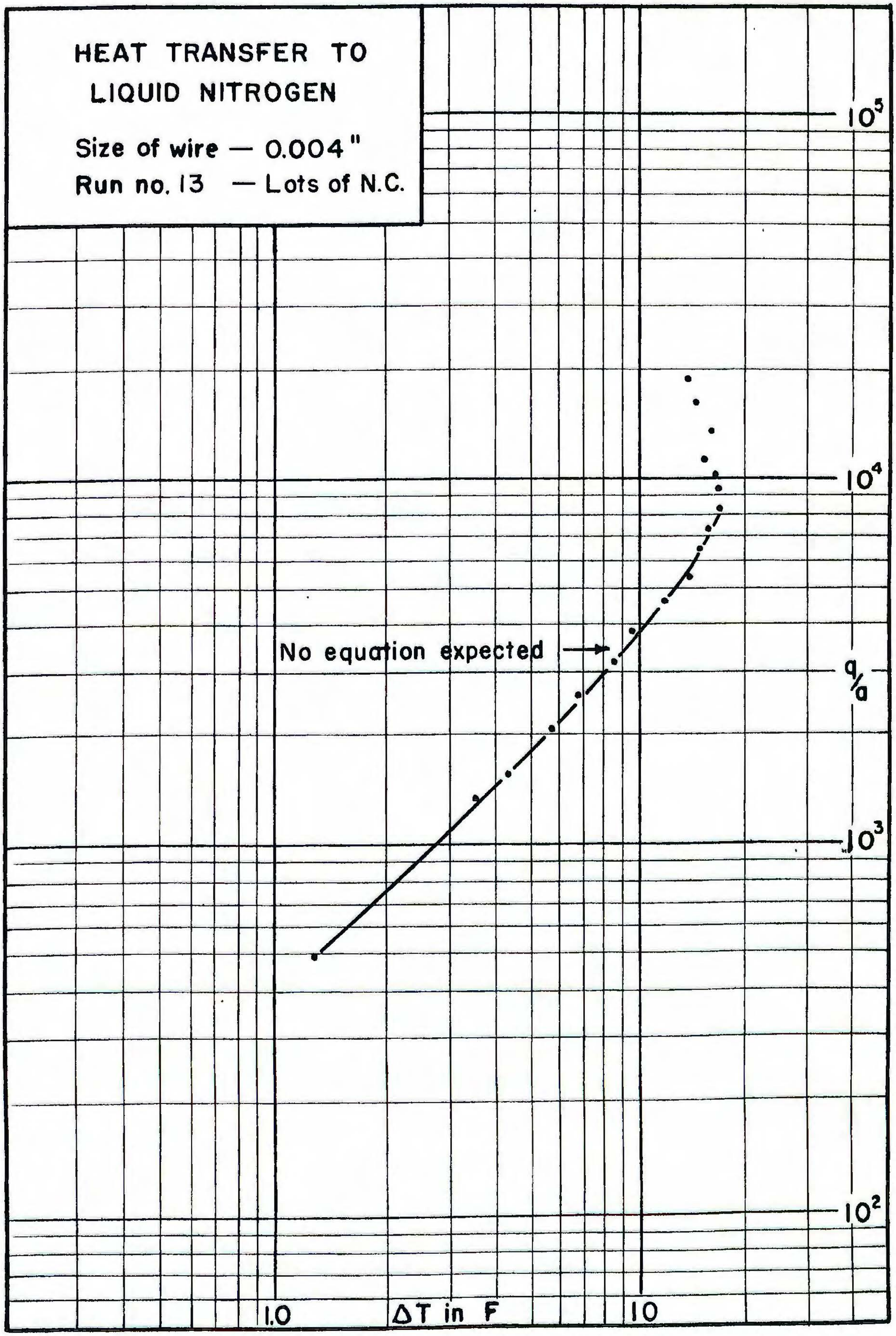
This run taken by letting the boiling decay from a film pulse

Notes from Table 13

1 - 3	nucleation centers	
2 - 4	" "	
3 - 4	" "	
4 - 5	" "	
5 - 7	" "	
6 - 10	" "	
7 - 9	" "	
8 - 10-11	" "	
9 - About 14	nucleation centers	
10 - " 16	" "	
11 - " 12	" "	Are some of these doublets?
12 - " 17		
13 - " 25		
14 - Too many to count		

In attempting to reach a Std value of 2.9×10^{-1} the wire went into film boiling. The wire has been in N_2 continuously for many hours. Am I out gasing the surface?

This run is more stable than the special runs where boiling does not begin until late in the run.


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.004"
Run no. 13 — Lots of N.C.
No equation expected
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

Std - 0.1 Ω
768 mm. Hg.

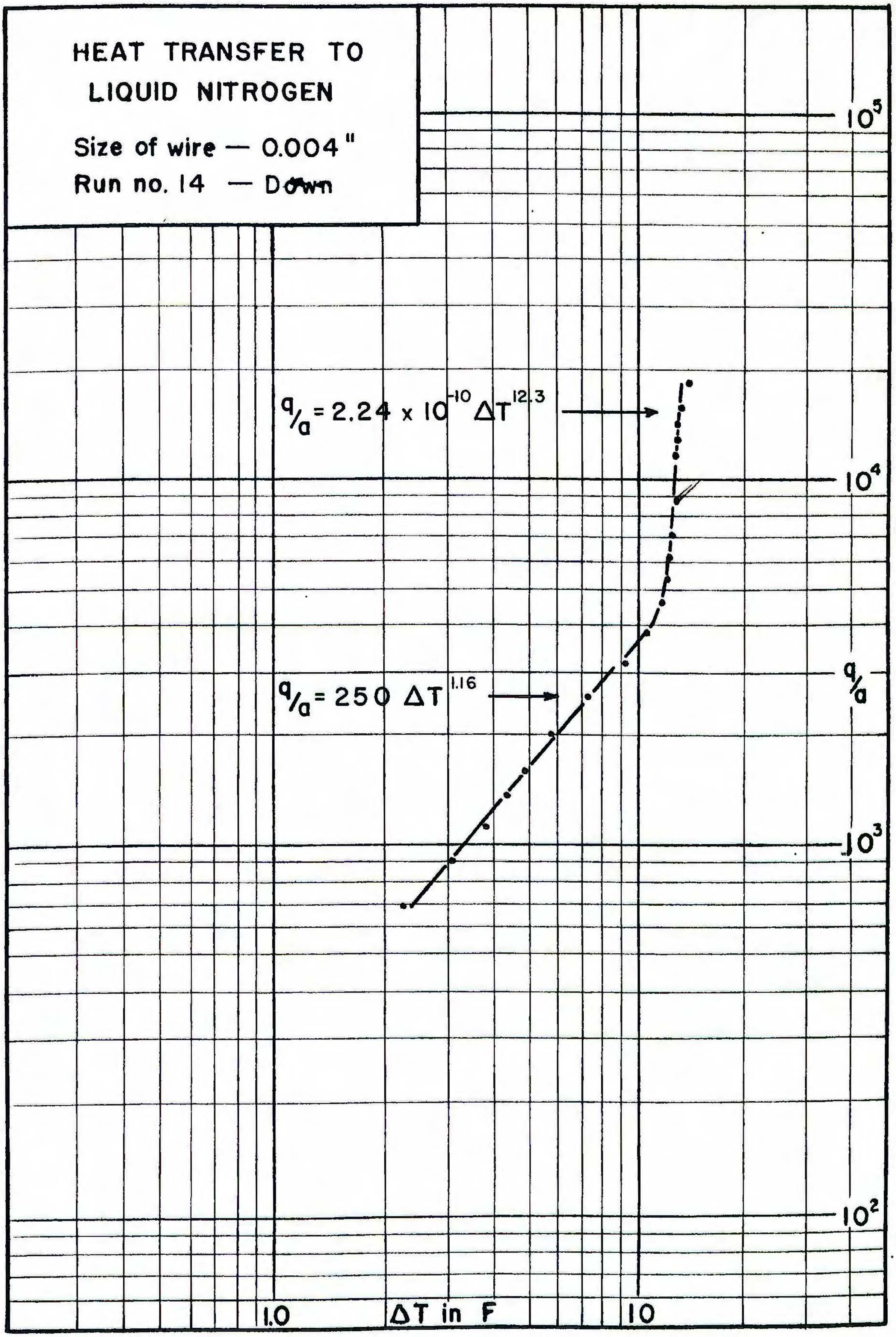
Table 14
Down Run

Wire 3
0.004"

Exp-volts	Std-volts	R-ohm	$100R/R_0$	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
4.0718×10^{-1}	2.6328×10^{-1}	0.1549	22.44	-188.1	1.072×10^{0}	1.90×10^{4}	7.7	13.9	*
3.7095	2.4063	0.1542	22.34	188.3	8.926×10^{-1}	1.58	7.5	13.5	
3.4820	2.2681	0.1535	22.24	188.5	7.898	1.40	7.3	13.1	
3.3253	2.1670	0.1535	22.24	188.5	7.206	1.28	7.3	13.1	
3.1835	2.0770	0.1532	22.19	188.7	6.612	1.17	7.1	12.8	
2.7550	1.7986	0.1532	22.19	188.7	4.955	8.80×10^{3}	7.1	12.8	
2.4524	1.6091	0.1524	22.08	188.9	3.946	7.01	6.9	12.4	
2.2844	1.5063	0.1517	21.98	189.1	3.441	6.11	6.7	12.1	
2.1397	1.4146	0.1512	21.90	189.3	3.027	5.38	6.5	11.7	
1.9806	1.3102	0.1512	21.90	189.3	2.595	4.61	6.5	11.7	
1.7977	1.2022	0.1495	21.66	189.9	2.161	3.84	5.9	10.6	1
1.6192	1.1012	0.1470	21.30	190.7	1.783	3.17	5.1	9.2	2
1.4342	9.9843×10^{-2}	0.1436	20.80	191.8	1.432	2.54	4.0	7.2	3
1.271	8.990	0.1414	20.48	192.6	1.143	2.03	3.2	5.8	
1.121	8.0205	0.1398	20.25	193.1	8.991×10^{-2}	1.60	2.7	4.9	4
1.0373	7.4702	0.1388	20.11	193.4	7.748	1.38	2.4	4.3	5
9.2585×10^{-2}	6.700	0.1382	20.02	193.7	6.203	1.10	2.1	3.8	
6.7639	4.9817	0.1358	19.67	194.5	3.370	5.98×10^{2}	1.3	2.3	

* Maximum q/A which could be reached just after film boiling

1 - About 9 nucleation centers
2 - " 6 " " some of them intermittant
3 - " 4 " " " " " "
4 - " 2 " " " " " "
5 - " 3 " " all intermittant


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 14 — Down
$q/a = 2.24 \times 10^{-10} \Delta T^{12.3}$
$q/a = 250 \Delta T^{1.16}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

0.1 Ω std
768 mm Hg.

Table 15
Up Run

Wire 3
0.004"

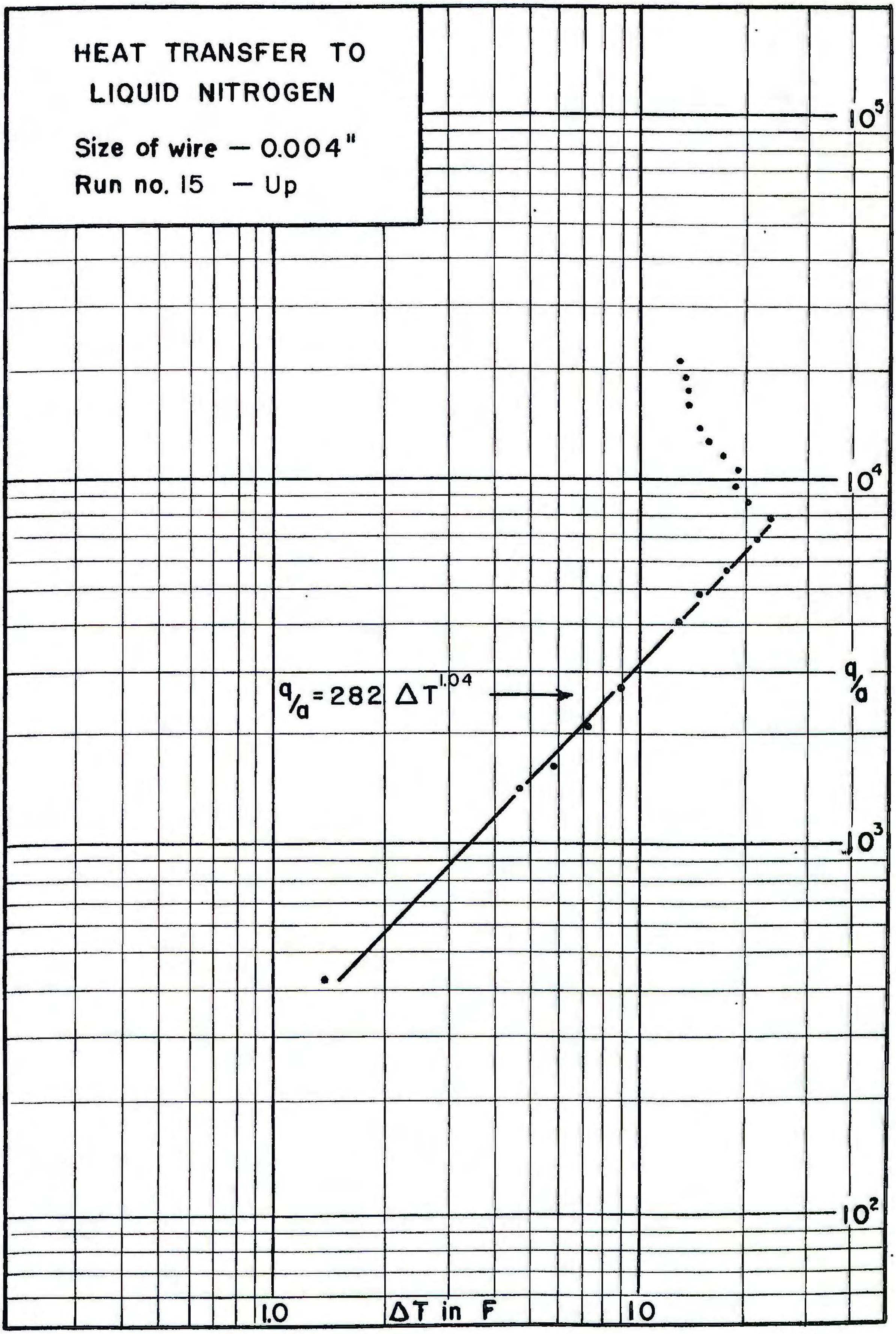
Exp.- volts	Std.- volts	R- ohm	100R/Ro	T- °C	EI- watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
5.6574×10^{-2}	4.2086×10^{-2}	0.1334	19.47	-195.0	2.381×10^{-2}	4.23×10^{2}	0.8	1.4	
1.0406×10^{-1}	7.4523	0.1396	20.22	-193.2	7.755	1.38×10^{3}	2.6	4.7	
1.1395	8.0587	0.1414	20.48	192.6	9.183	1.63	3.2	5.8	
1.2941	9.0000	0.1438	20.83	191.8	1.165×10^{-1}	2.07	4.0	7.2	
1.4809	1.0091×10^{-1}	0.1467	21.25	190.8	1.494	2.65	5.0	9.0	
1.8696	1.2188	0.1534	22.22	188.6	2.279	4.05	7.2	13.0	
2.0703	1.3113	0.1579	22.87	187.1	2.715	4.82	8.7	15.7	
2.2710	1.4106	0.1610	23.32	186.0	3.203	5.69	9.8	17.6	
2.5535	1.5272	0.1672	24.22	183.9	3.900	6.93	11.9	21.4	
2.747	1.609	0.1707	24.73	182.8	4.420	7.85	13.0	23.4	1
2.855	1.7267	0.1653	23.95	184.6	4.930	8.76	11.2	20.2	
2.974	1.8207	0.1633	23.66	185.3	5.415	9.62	10.5	18.9	
3.122	1.9099	0.1635	23.68	185.2	5.963	1.06×10^{4}	10.6	19.1	
3.234	2.0188	0.1602	23.21	186.3	6.529	1.16	9.5	17.1	
3.347	2.1225	0.1577	22.85	187.1	7.104	1.26	8.7	15.7	
3.491	2.227	0.1568	22.71	187.5	7.774	1.38	8.3	14.9	
3.7547	2.403	0.1563	22.64	187.6	9.022	1.60	8.2	14.8	
3.900	2.5063	0.1556	22.54	187.8	9.775	1.74	8.0	14.4	
4.071	2.6188	0.1555	22.52	187.9	1.066×10^{0}	1.89	7.9	14.2	
4.241	2.7323	0.1552	22.48	188.0	1.159	2.06	7.8	14.0	2

Notes from Table 15

1. About 5 nucleation centers as compared to all the wire boiling at this point in Table 14.

2. Std. of 2.7323×10^{-1} is the highest obtainable point. The wire went spontaneously to film boiling just above this value.

   The last few runs make it look like adsorbed gas promotes nuclear boiling since the first run after a long anneal period is far to the left of the others. See what this may indicate: A long boiling period is necessary to remove all the adsorbed gas although much of it may go in a hurry. But when it is gone it is harder to transfer heat and the n.b. curve moves to the right.



HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 15 — Up
$q/a = 282\ \Delta T^{1.04}$
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω Std
768 mm Hg

Wire 3
0.004"

Table 16
Up Run - Wire Freshly Reannealed

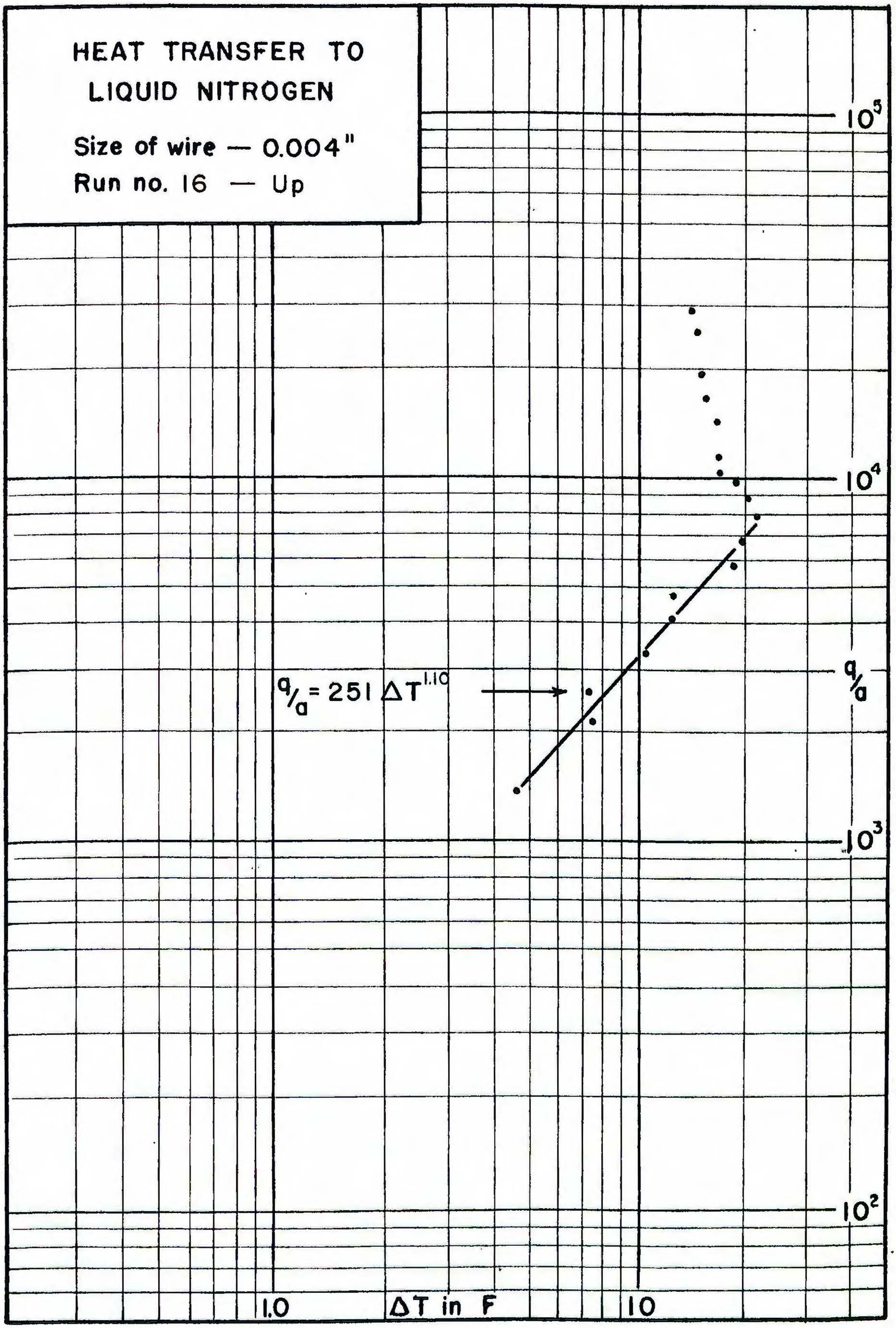
Exp - volts	Std - volts	R - ohm	100R/R_o	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
1.0463 x 10^{-1}	7.4448 x 10^{-2}	0.1405	20.21	-193.2	7.789 x 10^{-2}	1.38 x 10^{3}	2.6	4.7	
1.3106	9.0624	0.1446	20.80	191.7	1.188 x 10^{-1}	2.11	4.1	7.4	
1.4535	1.0036 x 10^{-1}	0.1448	20.83	191.8	1.459	2.59	4.0	7.2	
1.6555	1.1043	0.1459	21.57	190.1	1.828	3.25	5.7	10.3	
1.868	1.2145	0.1538	22.13	188.8	2.269	4.03	7.0	12.6	
2.022	1.3157	0.1537	22.12	188.8	2.660	4.72	7.0	12.6	
2.306	1.4095	0.1636	23.54	185.5	3.250	5.77	10.3	18.5	
2.510	1.516	0.1656	23.83	184.9	3.780	6.71	10.9	19.6	
2.746	1.626	0.1689	24.30	183.8	4.465	7.93	12.0	21.6	
2.879	1.725	0.1669	24.01	184.5	4.966	8.82	11.3	20.3	
2.999	1.826	0.1642	23.63	185.3	5.476	9.73	10.5	18.9	
3.084	1.913	0.1612	23.19	186.4	5.900	1.05 x 10^{4}	9.4	16.9	
3.261	2.0225	0.1612	23.19	186.4	6.595	1.17	9.4	16.9	
3.594	2.2315	0.1610	23.17	186.4	8.020	1.42	9.4	16.9	
3.878	2.434	0.1593	22.92	187.0	9.439	1.68	8.8	15.8	
4.148	2.621	0.1582	22.76	187.4	1.087 x 10^{0}	1.93	8.4	15.1	
4.626	2.935	0.1576	22.68	187.5	1.358	2.41	8.3	14.9	
5.054	3.216	0.1571	22.60	187.7	1.625	2.89	8.1	14.6	

Calibration check

Exp	14746	16189
Std	11112	12203
R	13289	13266

Average R_{N_2} (768 mm) = 0.13268 Ω
New R_o = 0.6950 Ω

The wire has just been reannealed. If the curve moves back to the left it is a good indication that the annealing process does something to the wire. Or else a long period of boiling does something to the wire. (Moves it to the right)
The data does not return to the curve of Table 12. Why not?


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.004"
Run no. 16 — Up
$q/a = 251\,\Delta T^{1.10}$
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω std
767 mm. Hg.

Table 17
Up Run - Wire Freshly Reannealed

Wire 3
0.004"

Exp - volts	Std - volts	R - ohm	100R/Ro	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
5.6286×10^{-2}	4.0446×10^{-2}	0.1392	19.40	-195.1	2.277×10^{-2}	4.10×10^{2}	0.7	1.3	
8.737	6.155	0.1419	19.80	194.2	5.378	9.68	1.6	2.9	
1.061×10^{-1}	7.3615	0.1441	20.09	193.5	7.811	1.41×10^{3}	2.3	4.1	
1.185	8.1035	0.1462	20.39	192.8	9.603	1.73	3.0	5.4	See next page
1.350	9.065	0.1489	20.76	192.0	1.224×10^{-1}	2.20	3.8	6.8	
1.533	1.0077×10^{-1}	0.1521	21.21	190.9	1.545	2.78	4.9	8.8	
1.746	1.119	0.1560	21.75	189.7	1.954	3.52	6.1	11.0	
1.996	1.221	0.1635	22.80	187.2	2.437	4.39	8.6	15.5	
2.2395	1.328	0.1686	23.51	185.6	2.974	5.35	10.2	18.4	
2.425	1.410	0.1719	23.97	184.6	3.419	6.15	11.2	20.2	
2.689	1.5255	0.1763	24.58	183.1	4.102	7.38	12.7	22.9	
2.692	1.609	0.1673	23.33	186.0	4.331	7.80	9.8	17.6	
2.767	1.702	0.1626	22.67	187.6	4.709	8.48	8.2	14.8	
2.857	1.805	0.1583	22.07	188.9	5.157	9.28	6.9	12.4	
3.010	1.907	0.1578	22.00	189.1	5.740	1.03×10^{4}	6.7	12.1	
3.173	2.017	0.1573	21.93	189.2	6.400	1.15	6.6	11.9	
3.491	2.214	0.1577	21.99	189.1	7.729	1.39	6.7	12.1	
3.806	2.410	0.1579	22.01	188.9	9.172	1.65	6.9	12.4	
4.107	2.591	0.1585	22.10	188.7	1.064×10^{0}	1.91	7.1	12.8	
4.644	2.918	0.1591	22.18	188.5	1.355	2.44	7.3	13.1	
5.166	3.239	0.1595	22.24	188.5	1.673	3.01	7.3	13.1	
5.660	3.545	0.1596	22.26	188.5	2.006	3.60	7.3	13.1	

Notes from Table 17

N_2 Calibration

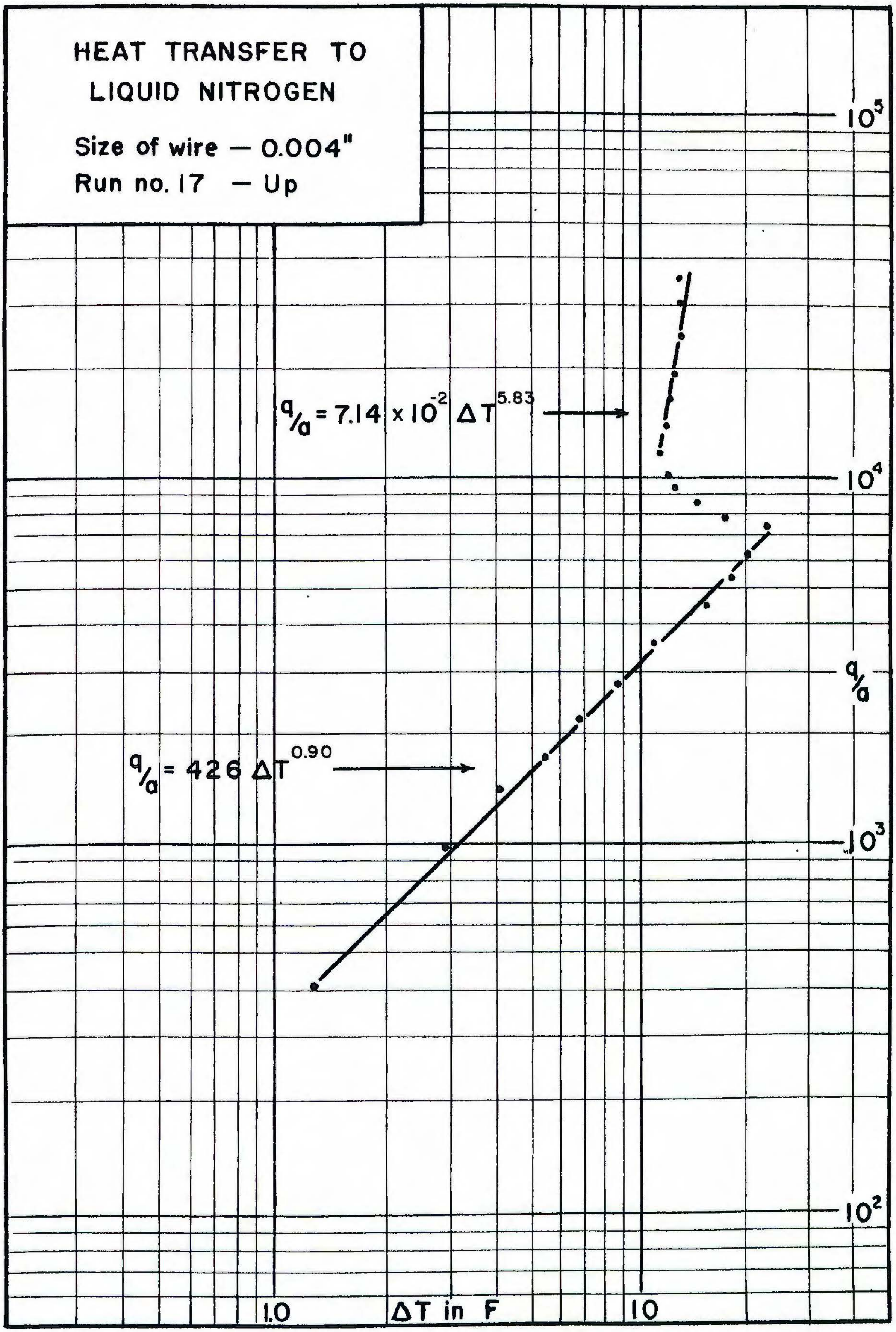
Exp	152115	16718	18536	18535	16693	15202
Std	111115	12202	13532	13530	12198	11104
R	136898	13701	13698	13699	13685	13690

Average R_{N_2} (767 mm) = 0.13694

New R_o = 0.7171

Redetermination of L. L = 2.222 inches. Prior value 2.192. This is about $1\frac{1}{2}$ %. I shall not recalculate the prior wire 3 data. Not significant.

This run about returns to the first run which is pretty good confirmation that boiling is doing something to the wire. I will now boil the wire for an hour and see if the curve changes in the expected fashion.


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 17 — Up
$q/a = 7.14 \times 10^{-2} \Delta T^{5.83}$
$q/a = 426 \Delta T^{0.90}$
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω std
767 mm. Hg.

Table 18
Up Run

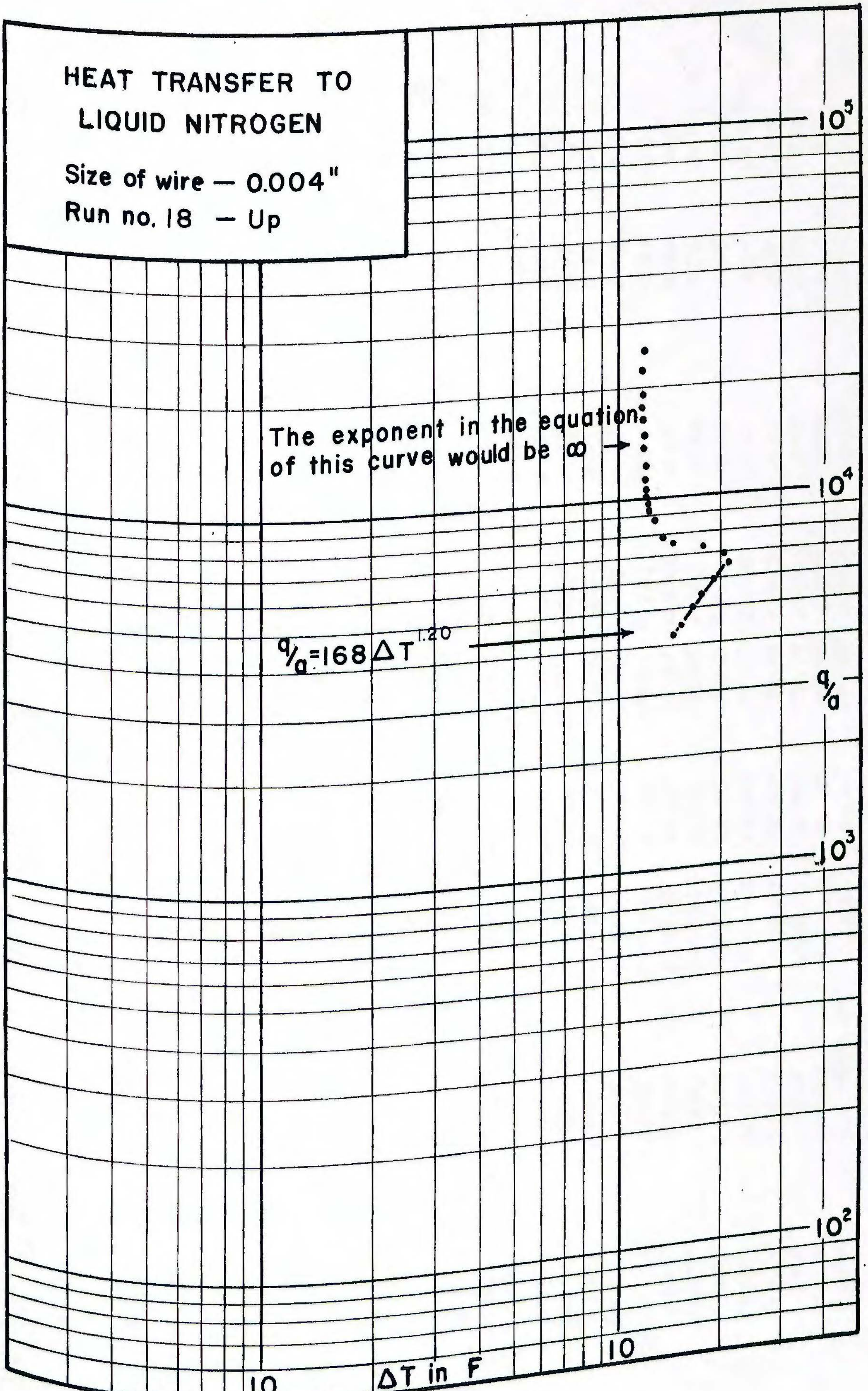
Wire 3
0.004"

Exp-volts	Std-volts	R-ohm	100R/Ro	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
1.9207×10^{-1}	1.2018×10^{-1}	0.1598	22.55	-187.81	2.308×10^{-1}	4.16×10^{3}	8.08	14.5	
2.0188	1.2526	0.1612	22.74	187.38	2.529	4.55	8.51	15.3	
2.1354	1.3097	0.1630	23.01	186.76	2.797	5.03	9.13	16.4	
2.2283	1.3516	0.1649	23.26	186.23	3.012	5.42	9.66	17.4	
2.3587	1.4076	0.1676	23.64	185.26	3.220	5.98	10.63	19.1	*
2.4756	1.4508	0.1706	24.08	184.16	3.592	6.46	11.74	21.1	
2.5575	1.5013	0.1704	24.04	184.26	3.840	6.91	11.53	20.8	
2.5677	1.5531	0.1653	23.32	186.07	3.988	7.18	9.82	17.7	
2.5713	1.6073	0.1600	22.57	187.76	4.133	7.44	8.13	14.6	
2.6077	1.6520	0.1579	22.27	188.46	4.308	7.75	7.43	13.4	
2.7595	1.7588	0.1569	22.13	188.78	4.853	8.74	7.11	12.8	
2.8262	1.8050	0.1566	22.09	188.87	5.101	9.18	7.02	12.6	
2.9066	1.8570	0.1565	22.09	188.87	5.398	9.72	7.02	12.6	
2.9723	1.9045	0.1561	22.02	189.03	5.661	1.02×10^{4}	6.86	12.3	
3.0530	1.9504	0.1565	22.09	188.87	5.955	1.07	7.02	12.6	
3.1246	2.0008	0.1562	22.04	188.99	6.252	1.13	6.90	12.4	
3.2842	2.1058	0.1560	22.01	189.05	6.916	1.24	6.84	12.3	
3.4587	2.2169	0.1560	22.01	189.05	7.668	1.38	6.85	12.3	
3.5990	2.3067	0.1560	22.02	189.03	8.302	1.49	6.86	12.3	
3.7594	2.4113	0.1559	22.00	189.08	9.065	1.63	6.81	12.3	
3.9052	2.5053	0.1559	21.99	189.10	9.784	1.76	6.79	12.2	
4.0807	2.6157	0.1560	22.01	189.05	1.067×10^{0}	1.92	6.84	12.3	
4.3793	2.8055	0.1561	22.02	189.03	1.229	2.21	6.86	12.3	
4.7041	3.0101	0.1563	22.05	188.96	1.416	2.55	6.93	12.5	x

* Boiling at voltage tap
x Max q/A

R_{N_2}(767 mm) = 0.1352 Ω

R_o = 0.7087 Ω



HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 18 — Up
The exponent in the equation of this curve would be ∞
q/a=168 ΔT^1.20
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω Std
762 mm. Hg

Table 19
Down Run

Wire 3
0.004"

Exp - volts	Std - volts	R-ohm	100R/Ro	T- °C	EI - watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
4.5295 x 10⁻¹	2.8365 x 10⁻¹	0.1597	22.30	-188.39	1.285 x 10⁰	2.31 x 10⁴	7.42	13.4	
4.1350	2.6129	0.1583	22.10	188.85	1.080	1.94	6.96	12.5	
3.7938	2.4117	0.1573	22.03	189.16	9.150 x 10⁻¹	1.65	6.65	12.0	See next page
3.6193	2.3067	0.1569	21.97	189.28	8.349	1.50	6.53	11.8	
3.4653	2.2131	0.1566	21.87	189.38	7.669	1.38	6.43	11.6	
3.3067	2.1157	0.1563	21.83	189.48	6.996	1.26	6.33	11.4	
3.1247	1.9997	0.1563	21.82	189.50	6.249	1.12	6.31	11.4	
3.0463	1.9517	0.1561	21.80	189.54	5.946	1.07	6.27	11.3	
2.9699	1.9044	0.1559	21.78	189.58	5.656	1.02	6.23	11.2	
2.8882	1.8525	0.1559	21.78	189.58	5.350	9.63 x 10³	6.23	11.2	
2.8206	1.8092	0.1559	21.78	189.58	5.103	9.18	6.23	11.2	
2.7213	1.7480	0.1557	21.74	189.68	4.757	8.56	6.13	11.0	
2.6553	1.7064	0.1556	21.73	189.70	4.531	7.60	6.11	11.0	
2.5627	1.6484	0.1555	21.71	189.74	4.224	6.72	6.07	10.9	
2.4087	1.5505	0.1553	21.70	189.77	3.734	6.16	6.04	10.9	1
2.3056	1.4856	0.1552	21.68	189.81	3.425	5.87	5.97	10.7	
2.2492	1.4500	0.1551	21.67	189.84	3.261	5.49	5.92	10.7	
2.1732	1.4022	0.1550	21.65	189.89	3.047	4.92	5.88	10.6	
2.0576	1.3283	0.1549	21.63	189.93	2.733	4.59	5.84	10.5	
1.9873	1.2842	0.1548	21.61	189.97	2.552	4.41	5.80	10.4	
1.8977	1.2281	0.1545	21.58	190.05	2.331	4.20	5.76	10.4	2
1.8238	1.1822	0.1543	21.55	190.12	2.156	3.88	5.69	10.2	
1.7581	1.1403	0.1542	21.53	190.17	2.005	3.61	5.64	10.2	
1.6934	1.1022	0.1539	21.50	190.24	1.863	3.35	5.57	10.0	
1.6148	1.0505	0.1537	21.47	190.31	1.696	3.05	5.50	9.9	
1.5416	1.0057	0.1533	21.41	190.45	1.550	2.79	5.36	9.6	
1.4562	9.5257 x 10⁻²	0.1529	21.35	190.59	1.387	2.50	5.22	9.4	3

Notes from Table 19

N_2 Calibration

Exp	14201	14201	15465	16988
Std	10395	10385	11317	12426
R	13661	13674	13665	13671

Average R_{N_2} (762 mm) = 0.13668

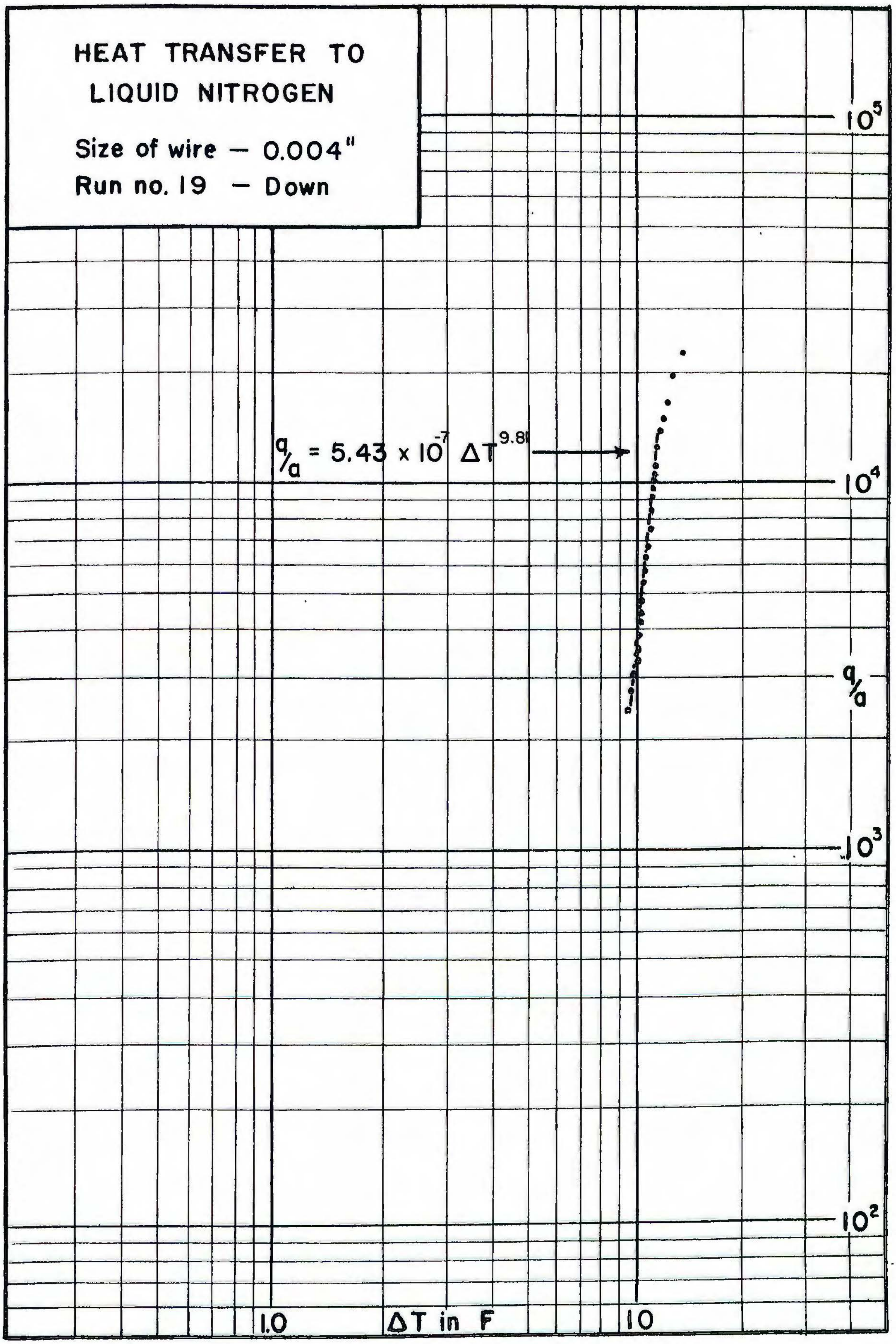
New R_o = 0.71597

1/ Many nucleation centers
2/ " " "
3/ About the end of boiling

This wire has been sitting in air for two days. This is the first run today.

In this run no boiling pulses were used to clean the wire between readings. At the end of the run a layer of ice powder was seen to be covering the wire. This perhaps insulated the wire and caused unusual values. The next run will be taken with a boiling pulse between each set of values. In order for the next run to be a true down run the maximum current will be only that from which film boiling will decay spontaneously.

This run was very stable.


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 19 — Down
q/a = 5.43 x 10^-7 ΔT^9.81
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω std
762 mm. Hg

Table 20
Down Run - With Boiling Pulses

Wire 3
0.004"

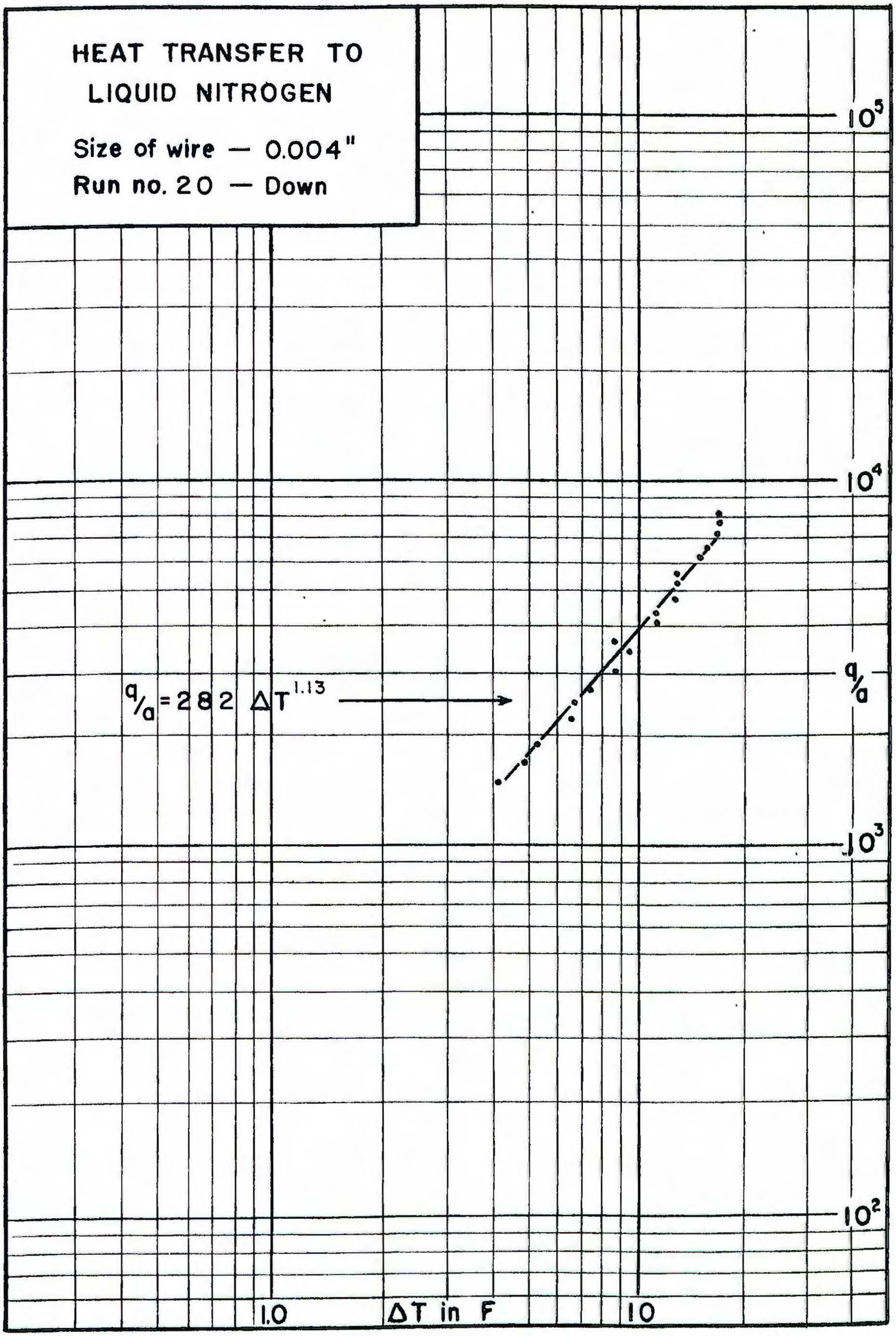
Exp - volts	std - volts	R - ohm	100R/R_o	T - °C	EI - watts	BTU/ft²hr	ΔT - °C	ΔT - °F	Notes
2.749×10^{-1}	1.6432×10^{-1}	0.1673	23.17	-186.4	4.517×10^{-1}	8.13×10^{3}	9.4	16.9	
2.693	1.6095	0.1673	23.17	186.4	4.334	7.80	9.4	16.9	
2.583	1.552	0.1664	23.04	186.7	4.009	7.22	9.1	16.4	✓
2.470	1.501	0.1646	22.79	187.3	3.707	6.67	8.5	15.3	
2.378	1.452	0.1638	22.68	187.5	3.452	6.21	8.3	14.9	
2.248	1.409	0.1595	22.09	188.9	3.167	5.70	6.9	12.4	
2.155	1.353	0.1593	22.06	189.2	2.916	5.25	6.9	12.4	
2.052	1.294	0.1585	21.95	189.2	2.655	4.78	6.6	11.9	
1.957	1.246	0.1571	21.76	189.6	2.438	4.39	6.2	11.2	
1.895	1.206	0.1571	21.76	189.6	2.285	4.11	6.2	11.2	
1.756	1.149	0.1528	21.16	191.0	20.17	3.63	4.8	8.6	
1.706	1.106	0.1542	21.35	190.6	18.87	3.40	5.2	9.4	
1.603	1.046	0.1533	21.23	190.9	16.67	3.02	4.9	8.8	
1.503	9.985×10^{-2}	0.1505	20.84	191.7	15.01	2.71	4.1	7.4	
1.423	9.515	0.1496	20.71	192.1	13.54	2.44	3.7	6.7	
1.350	9.062	0.1488	20.63	192.2	12.24	2.20	3.6	6.5	
1.245	8.481	0.1468	20.33	192.9	10.56	1.90	2.9	5.2	
1.176	8.039	0.1463	20.26	193.1	94.59×10^{-2}	1.70	2.7	4.9	
1.091	7.520	0.1451	20.09	193.5	8.204	1.48	2.3	4.1	

✓ Only a few nucleation centers

Calibration check

Exp	17290	15741	14450
std	12541	11423	10480
R_{N_2}	13787	13780	13788

R_{N_2} (762 mm) = 0.13785 Ω R_o = 0.7221 Ω



HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 20 — Down
$q/a = 282\ \Delta T^{1.13}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

0.1 Ω Std
762 mm Hg

Table 21

Down Run - With Taps

Wire 3
0.004"

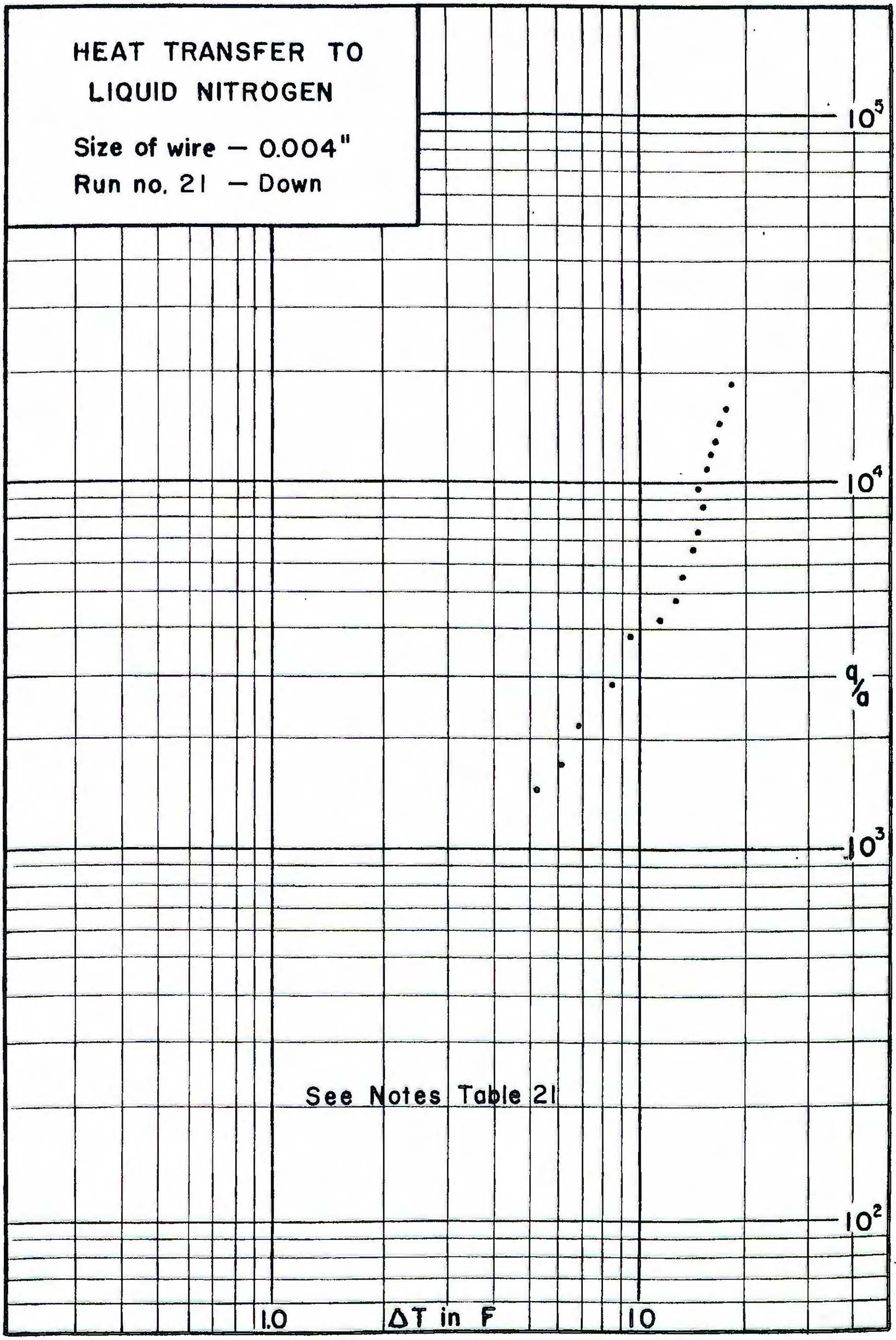
Exp.-volts	Std-volts	R-ohm	100R/R₀	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
4.109×10^{-1}	2.444×10^{-1}	0.1681	23.49	-185.7	1.004×10^{0}	1.81×10^{4}	10.1	18.2	
3.850	2.302	0.1672	23.36	186.0	8.864×10^{-1}	1.60	9.8	17.6	
3.671	2.209	0.1662	23.22	186.3	8.107	1.46	9.5	17.1	
3.403	2.067	0.1646	23.00	186.8	7.034	1.27	9.0	16.2	
3.289	2.005	0.1640	22.92	187.0	6.594	1.19	8.8	15.8	
3.084	1.887	0.1634	22.83	187.2	5.820	1.05	8.6	15.5	
2.923	1.807	0.1618	22.60	187.7	5.282	9.51×10^{3}	8.1	14.6	
2.765	1.699	0.1627	22.73	187.4	4.698	8.46	8.4	15.1	
2.553	1.581	0.1615	22.56	187.8	4.036	7.26	8.0	14.4	
2.427	1.508	0.1609	22.49	188.0	3.660	6.59	7.8	14.0	
2.230	1.397	0.1596	22.30	188.4	3.115	5.61	7.4	13.3	
2.051	1.294	0.1585	22.14	188.7	2.654	4.78	7.1	12.8	
1.890	1.209	0.1562	21.82	189.5	2.287	4.12	6.3	11.3	
1.693	1.016	0.1529	21.33	190.6	1.878	3.38	5.2	9.4	
1.536	9.056×10^{-2}	0.1512	21.12	191.1	1.561	2.81	4.7	8.5	
1.343	8.056	0.1483	20.70	192.0	1.216	2.19	3.8	6.8	
1.177	8.001	0.1471	20.55	192.4	9.417×10^{-2}	1.70	3.4	6.1	
1.091	7.487	0.1457	20.36	192.9	8.168	1.47	2.9	5.2	

N_2 calibration

Exp	14035	15335	16855	15324
Std	10283	11210	12326	11222
R_{N_2}	13649	13679	13674	13654

R_{N_2}(762 mm) = 0.13664 Ω R_0 = 0.71576 Ω

Before each reading the dewar was tapped to dislodge the accumolated snow from the wire. The run was preceeded by an hour of film boiling which should make nucleation difficult. This should move the curve to the right of the preceeding run.


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.004"
Run no. 21 — Down
10^5
10^4
q/a
10^3
10^2
See Notes Table 21
1.0
ΔT in F
10

0.1 Ω std
760 mm. Hg

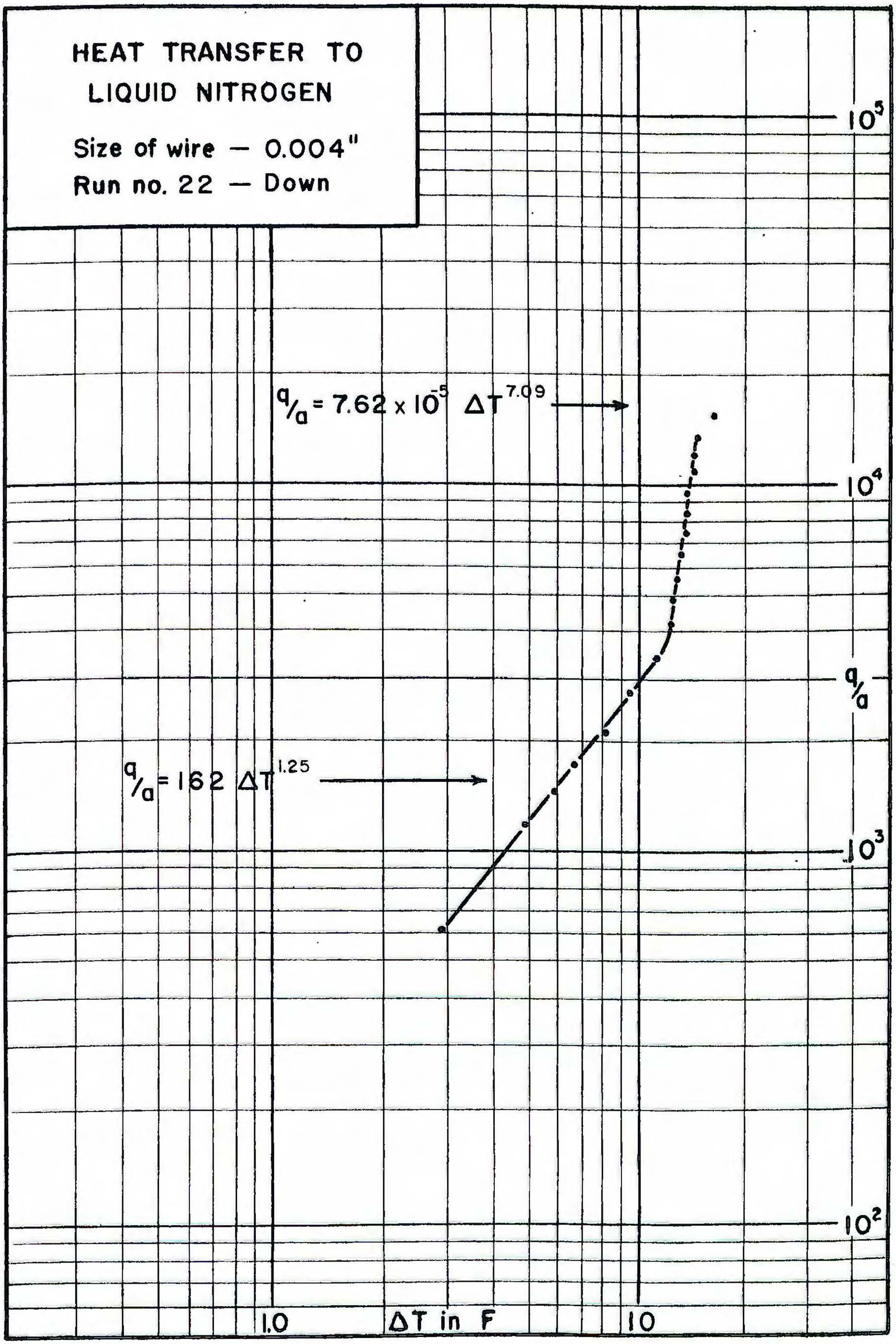
Table 22
Down Run

Wire 3
0.004"

Exp - volts	Std - volts	R - ohm	100R/R₀	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
3.751×10^{-1}	2.2615×10^{-1}	0.1659	23.17	-186.8	8.483×10^{-2}	1.53×10^{4}	9.0	16.2	*
3.472	2.1415	0.1621	22.64	187.6	7.435	1.34	8.2	14.8	
3.237	2.0065	0.1613	22.52	187.9	6.495	1.17	7.9	14.2	
3.072	1.906	0.1612	22.51	187.9	5.855	1.06	7.9	14.2	
2.906	1.807	0.1608	22.46	188.2	5.251	9.45×10^{3}	7.6	13.7	
2.740	1.703	0.1609	22.47	188.2	4.666	8.40	7.6	13.7	
2.569	1.607	0.1599	22.33	188.3	4.128	7.43	7.5	13.5	
2.394	1.505	0.1591	22.22	188.6	3.603	6.48	7.2	13.0	
2.233	1.4105	0.1583	22.11	188.8	3.150	5.67	7.0	12.6	
2.071	1.3125	0.1578	22.04	189.0	2.718	4.89	6.8	12.2	
1.900	1.2075	0.1573	21.97	189.2	2.294	4.13	6.6	11.9	
1.732	1.1075	0.1563	21.83	189.5	19.18	3.45	6.3	11.3	
1.527	9.984×10^{-2}	0.1529	21.35	190.6	1.525	2.75	5.2	9.4	
1.358	9.022	0.1505	21.02	191.3	1.225	2.21	4.5	8.1	
1.190	8.027	0.1483	20.71	192.1	9.554×10^{-2}	1.72	3.7	6.7	
1.100	7.4785	0.1471	20.54	192.5	8.229	1.48	3.3	5.9	
9.481×10^{-2}	6.542	0.1449	20.24	193.1	6.203	1.17	2.7	4.9	
6.893	4.861	0.1418	19.80	194.2	3.351	6.03×10^{2}	1.6	2.9	

* Maximum value of q/A

Prior to this run the wire had been in liquid Nitrogen continuously for 24 hours


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.004"
Run no. 22 — Down
$q/a = 7.62 \times 10^{-5}\ \Delta T^{7.09}$
$q/a = 162\ \Delta T^{1.25}$
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω std
760 mm. Hg.

Table 23
Up Run

Wire 3
0.004"

Exp.-volts	Std-volts	R-ohm	100R/Ro	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
1.1673×10^{-1}	8.0058×10^{-2}	0.1458	20.38	-192.8	9.345×10^{-2}	1.68×10^{3}	3.0	5.4	
1.361	9.098	0.1496	20.92	191.6	1.238×10^{-1}	2.23	4.2	7.6	
1.524	1.0000×10^{-1}	0.1524	21.31	190.7	1.524	2.74	5.1	9.2	
1.7337	1.1095	0.1563	21.86	189.4	1.924	3.46	6.4	11.5	
1.9225	1.206	0.1594	22.29	188.4	2.319	4.17	7.4	13.3	
2.1395	1.315	0.1627	22.75	187.4	2.813	5.06	8.4	15.1	1/
2.382	1.4153	0.1683	23.53	185.6	3.371	6.07	10.2	18.4	
2.677	1.5322	0.1747	24.43	183.5	4.102	7.38	12.3	22.1	2/
2.823	1.6125	0.1751	24.49	183.4	4.577	8.24	12.4	22.3	3/
3.0335	1.7022	0.1782	24.92	182.4	5.164	9.30	13.4	24.1	
3.1405	1.8090	0.1736	24.28	183.8	5.681	1.02×10^{4}	12.0	21.6	
3.309	1.9228	0.1721	24.07	184.3	6.362	1.15	11.5	20.7	
3.415	2.018	0.1692	23.66	185.3	6.891	1.24	10.5	18.9	
3.5825	2.1225	0.1688	23.60	185.4	7.604	1.37	10.4	18.7	
3.7045	2.2265	0.1663	23.21	186.3	8.248	1.48	9.5	17.1	

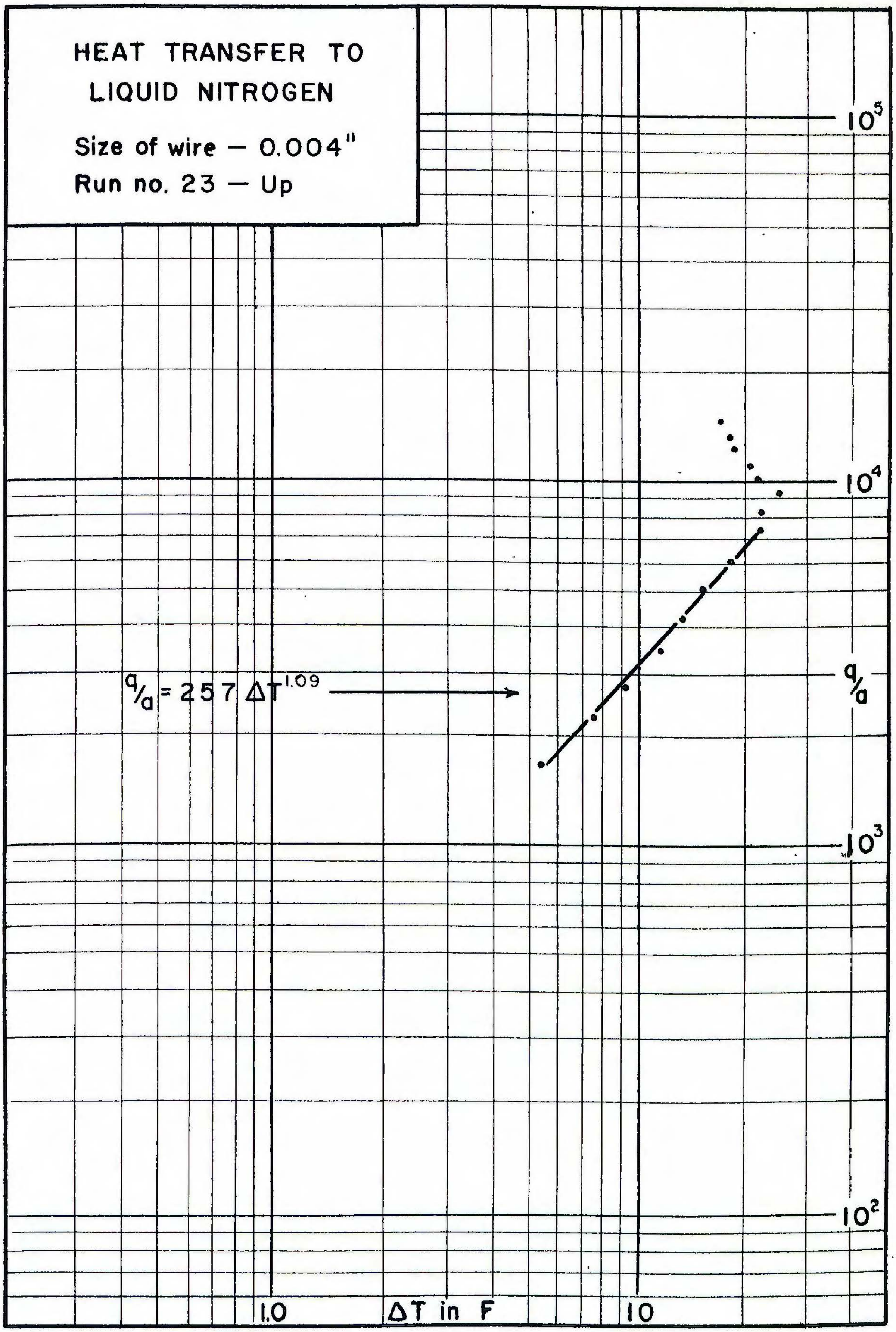
1/ Bumped the dewar. Will this change the curve (No)
2/ Boiling at the voltage taps only
3/ About 3 nucleation centers

Wire was driven into film boiling for two hours prior to this run.

N_2 Calibration

Exp	14093	14126	15457	17038	15499	14211
Std	10373	10393	11340	12482	11352	10409
R	13585	13591	13630	13651	13652	13652

Use R_{N_2}(760 mm) = 0.13652 Ω R_o = 0.7151 Ω


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.004"
Run no. 23 — Up
q/a = 257 ΔT^1.09
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω std
760 mm Hg.

Table 24
Ice Point Calibration

Wire 4
0.008"

Exp - volts	std - volts	R - ohm
1.6492×10^{-3}	1.03315×10^{-2}	0.15963
1.79845	1.1266	0.15964
1.9771	1.23865	0.15962
2.1962	1.37615	0.15959
2.19585	1.3761	0.15957
1.9767	1.2388	0.15957
1.7975	1.1263	0.15959
1.6485	1.0328	0.15961

Average R_o = 0.15960 Ω

N_2 Calibration

1.0017×10^{-3}	3.3143×10^{-2}	0.03022
1.0588	3.5037	0.03022
1.1224	3.7137	0.03022
1.2331	4.0796	0.03023
1.2329	4.07965	0.03022
1.1225	3.7148	0.03022
1.0595	3.5054	0.03022
1.0028	3.3188	0.03022

Average R_{N_2}(760 mm) = 0.030221 Ω

Length of wire 2.065 inches
$100\, R/R_o$ = 18.935

This wire boiled in N_2 prior to either calibration

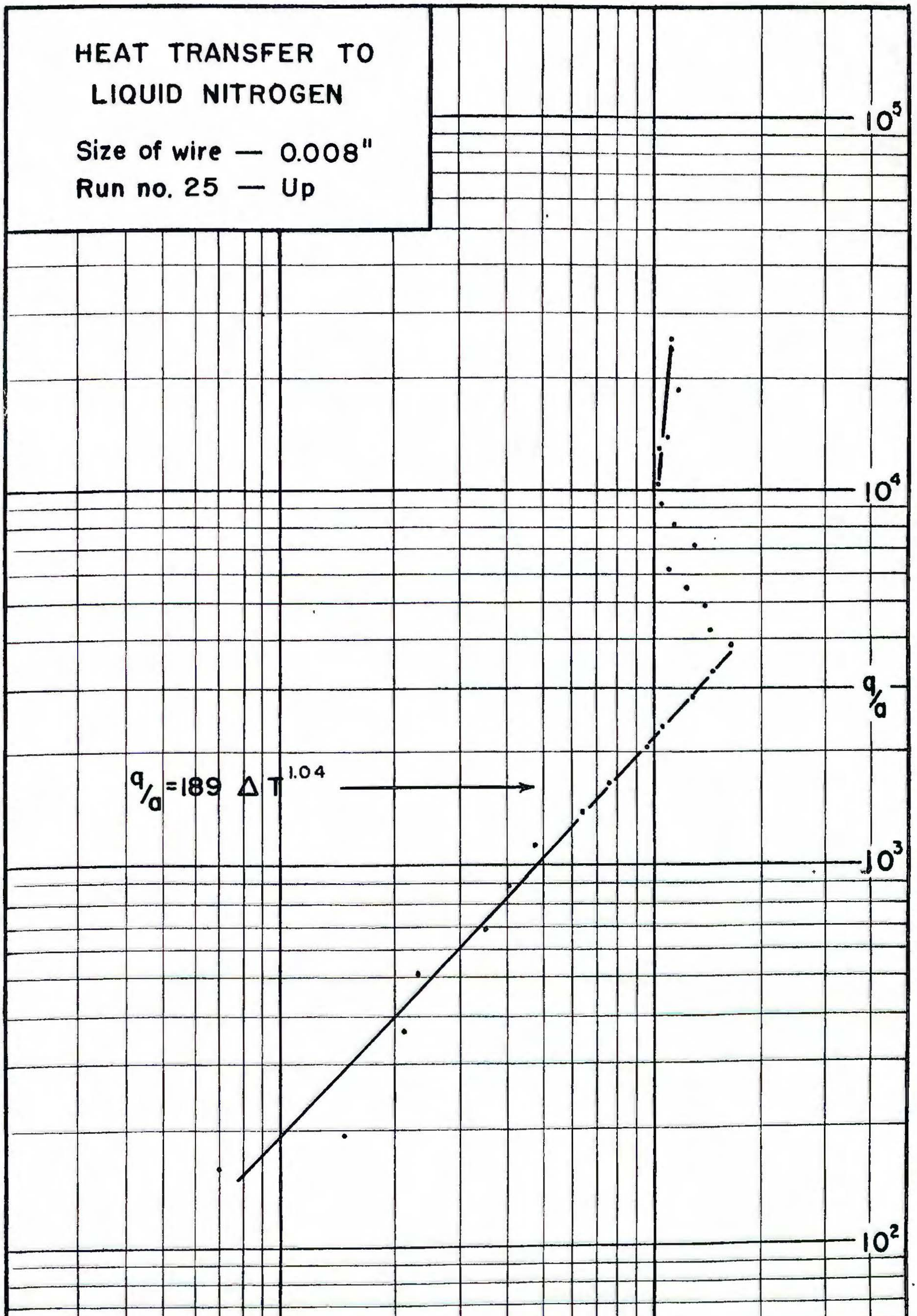
0.1 Ω Std
760 mm Hg.

Table 25
Up Run

Wire 4
0.008"

Exp-volts	Std-volts	R-ohm	100R/Ro	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
2.295 x 10^{-2}	7.5145 x 10^{-2}	0.03054	19.14	-195.40	1.725 x 10^{-2}	1.63 x 10^{2}	0.40	0.7	
2.7755	9.0183	0.03078	19.29	195.05	2.054	1.94	0.75	1.4	
3.458	1.1139 x 10^{-1}	0.03104	19.45	194.65	3.852	3.65	1.15	2.1	
4.1025	1.3158	0.03118	19.54	194.50	5.398	5.11	1.30	2.3	
4.805	1.5205	0.03160	19.80	193.85	7.306	6.92	1.95	3.5	
5.472	1.7202	0.03181	19.93	193.55	9.413	8.91	2.25	4.1	
6.155	1.919	0.03207	20.10	193.15	1.181 x 10^{-1}	1.12 x 10^{3}	2.65	4.8	
6.923	2.1215	0.03263	20.45	192.35	1.469	1.39	3.45	6.2	
7.646	2.3085	0.03312	20.75	191.65	1.765	1.67	4.15	7.5	
8.552	2.5205	0.03393	21.24	190.50	2.156	2.04	5.30	9.5	
9.224	2.690	0.03429	21.48	189.95	2.481	2.35	5.85	10.5	
1.0269 x 10^{-1}	2.9235	0.03513	22.01	188.75	3.002	2.84	7.05	12.7	
1.116	3.1125	0.03586	22.47	187.80	3.474	3.29	8.00	14.4	
1.2145	3.3298	0.03647	22.85	186.80	4.044	3.83	9.00	16.2	
1.2625	3.535	0.03571	22.37	187.90	4.463	4.23	7.90	14.2	
1.373	3.7305	0.03680	23.06	188.05	5.122	4.85	7.75	14.0	1/
1.426	4.074	0.03500	21.93	188.90	5.810	5.50	6.90	12.4	2/
1.4975	4.337	0.03453	21.63	189.60	6.495	6.15	6.20	11.2	
1.6295	4.6155	0.03530	22.12	188.50	7.521	7.12	7.30	13.1	
1.722	4.970	0.03465	21.71	189.40	8.558	8.10	6.40	11.5	
1.821	5.3095	0.03430	21.49	189.90	9.669	9.16	5.90	10.6	
1.9555	5.719	0.03419	21.42	190.10	1.118 x 10^{0}	1.06 x 10^{4}	5.70	10.3	
2.1555	6.285	0.03429	21.48	189.95	1.354	1.28	5.85	10.5	
2.2545	6.523	0.03456	21.65	189.55	1.470	1.39	6.25	11.3	
2.6290	7.520	0.03496	21.90	189.00	1.977	1.87	6.80	12.2	
3.046	8.812	0.03456	21.65	189.50	2.684	2.54	6.30	11.3	

1/ No n.c. 2/ Many n.c.


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 25 — Up
$q/a = 189\ \Delta T^{1.04}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in °F
10

0.1 Ω Std
768 mm. Hg.

Table 26
Down Run

Wire 4
0.008"

Exp-volts	Std-volts	R-ohm	100R/Ro	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Note
3.555×10^{-1}	1.0161×10^{-0}	0.03499	21.73	-189.40	3.612×10^{0}	3.42×10^{4}	6.30	11.3	
3.1683	9.014×10^{-1}	0.03515	21.83	189.15	2.856	2.70	6.55	11.8	
3.060	8.737	0.03502	21.75	189.30	2.674	2.53	6.40	11.5	
2.761	7.849	0.03517	21.84	189.10	2.167	2.05	6.60	11.9	
2.639	7.5275	0.03506	21.78	189.25	1.987	1.88	6.45	11.6	
2.457	7.032	0.03494	21.70	189.45	1.728	1.64	6.25	11.3	See next page
2.286	6.543	0.03494	21.70	189.45	1.496	1.42	6.25	11.2	
2.076	5.948	0.03490	21.68	189.50	1.235	1.17	6.20	11.2	
1.864	5.350	0.03484	21.64	189.60	9.972×10^{-1}	9.44×10^{3}	6.10	11.0	
1.738	5.002	0.03475	21.58	189.70	8.693	8.23	6.00	10.8	
1.586	4.538	0.03495	21.71	189.40	7.197	6.82	6.30	11.3	
1.457	4.222	0.03451	21.44	189.05	6.151	5.82	5.65	10.2	
1.307	3.785	0.03453	21.45	189.00	4.947	4.68	5.70	10.3	
1.211	3.522	0.03438	21.35	190.25	4.265	4.04	5.45	9.8	
1.087	3.190	0.03408	21.17	190.45	3.467	3.28	5.25	9.4	
9.859×10^{-2}	2.918	0.03379	20.99	191.10	2.877	2.72	4.60	8.3	
8.719	2.605	0.03347	20.79	191.50	2.271	2.15	4.20	7.6	1
7.615	2.298	0.03314	20.51	192.20	1.750	1.66	3.50	6.3	
6.578	2.009	0.03274	20.34	192.60	1.322	1.25	3.10	5.6	
5.937	1.827	0.03250	20.19	192.95	1.085	1.03	2.75	5.0	
5.165	1.603	0.03222	20.02	193.30	8.279×10^{-2}	7.84×10^{2}	2.40	4.3	
4.477	1.404	0.03188	19.80	193.80	6.286	5.95	1.90	3.4	
3.156	1.018	0.03100	19.26	195.10	3.213	3.04	0.60	1.1	
2.472	7.977×10^{-3}	0.03099	19.26	195.10	1.972	1.87	0.60	1.1	
1.937	6.277	0.03086	19.18	195.30	1.216	1.15	0.40	0.7	
1.245	4.049	0.03074	19.10	195.50	5.041×10^{-3}	4.77×10^{1}	0.20	0.4	
1.244	4.052	0.03070	19.08	195.55	5.041	4.77	0.15	0.3	2

Notes for Table 26

N_2 Calibration

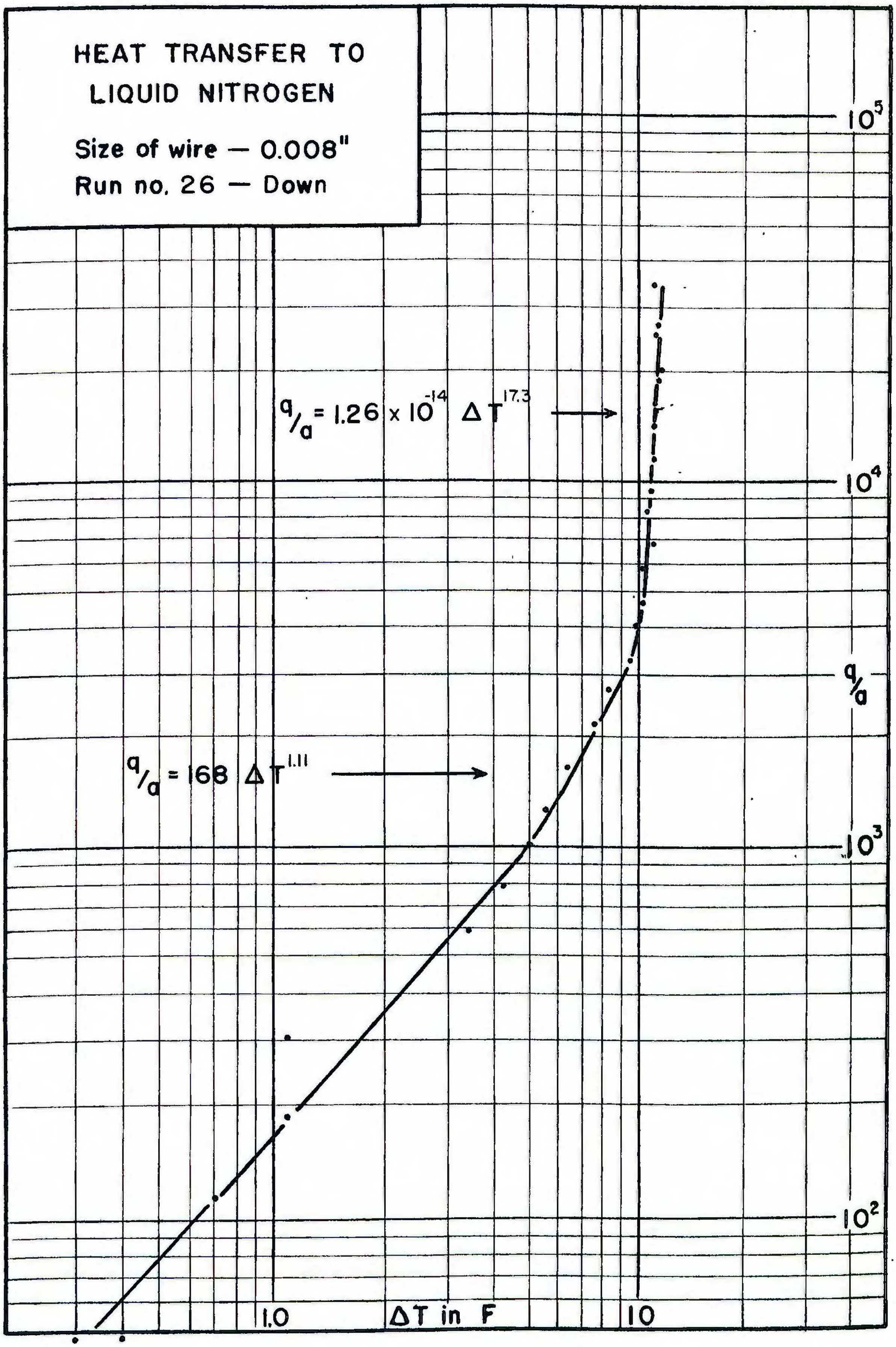
Exp.	101585	10153	107215	113625
Std.	33180	33181	35043	371275
R_{N_2}	30616	30598	30595	30603

Average R_{N_2} (768 mm) = 0.030604

New R_o = 0.1610

1. Very few nucleation centers

2. Duplicate point.


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 26 — Down
q/a = 1.26 x 10^-14 ΔT^17.3
q/a = 168 ΔT^1.11
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

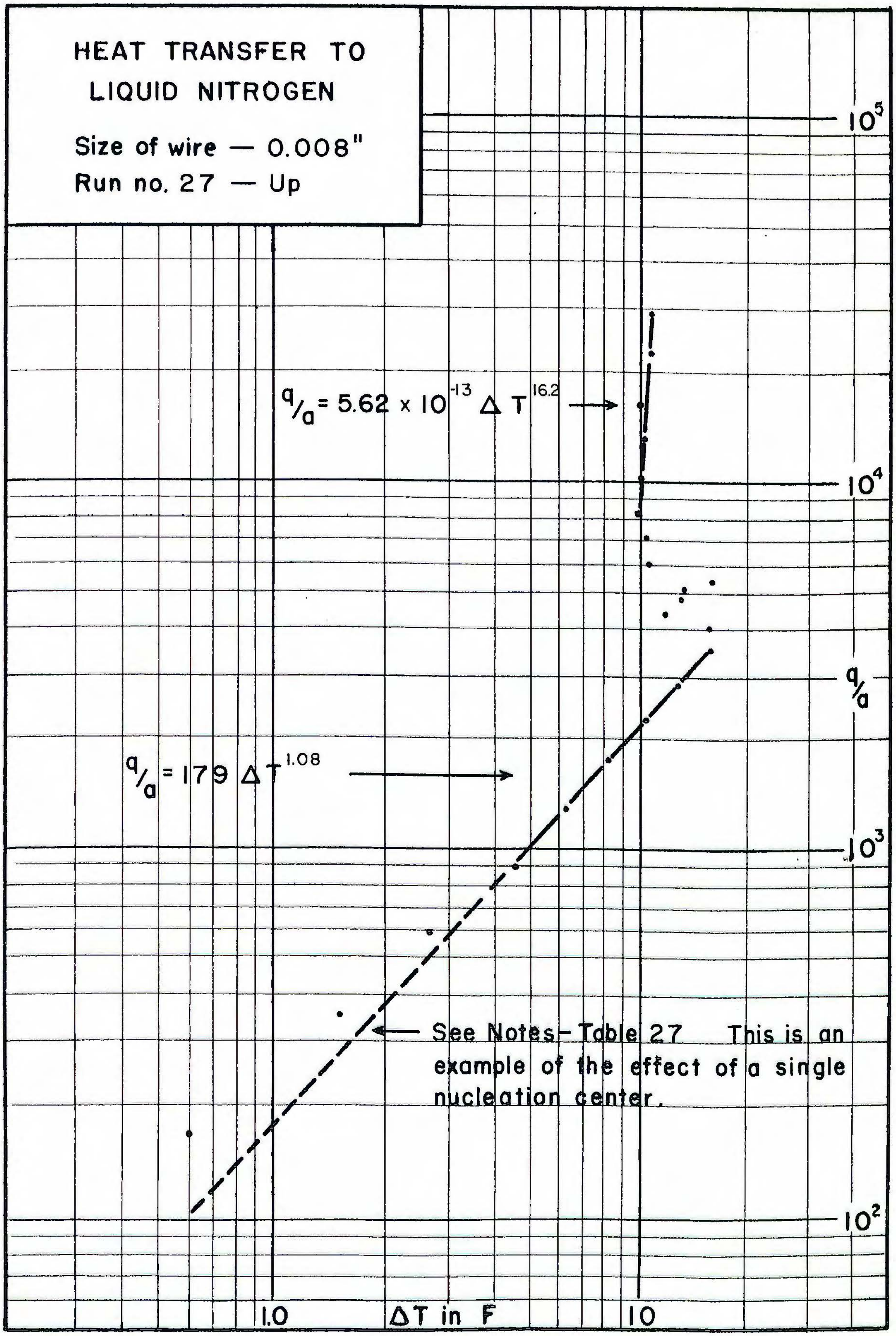
0.1 Ω std
768 mm. Hg.

Table 27
Up Run

Wire 4
0.008"

Exp. - volts	Std. - volts	R - ohm	100R/R_0	T - °C	EI - watts	BTU/ft²hr	ΔT - °C	ΔT - °F	Notes
2.3455×10^{-2}	7.6017×10^{-2}	0.03085	19.16	-195.35	1.783×10^{-2}	1.69×10^{2}	0.35	0.6	1
3.431	1.1002×10^{-1}	0.03118	19.37	194.85	3.775	3.57	0.85	1.5	1
4.4255	1.3995	0.03162	19.64	194.20	6.193	5.86	1.50	2.7	1
5.525	1.7127	0.03226	20.03	193.25	9.463	8.96	2.45	4.4	1
6.687	2.027	0.03299	20.48	192.20	1.355×10^{-1}	1.28×10^{3}	3.50	6.3	1
7.872	2.334	0.03372	20.95	191.15	1.837	1.74	4.55	8.2	1
9.068	2.623	0.03457	21.46	190.00	2.379	2.25	5.70	10.3	1
1.0341×10^{-1}	2.908	0.03556	22.09	188.65	3.007	2.85	7.05	12.7	1
1.179	3.2085	0.03674	22.82	186.85	3.783	3.58	8.85	15.9	1
1.253	3.411	0.03673	22.81	186.85	4.274	4.05	8.85	15.9	1
1.330	3.614	0.03680	22.86	186.75	4.807	4.55	8.95	16.1	2
1.271	3.611	0.03520	22.86	189.05	4.590	4.35	6.65	12.0	3
1.352	3.800	0.03558	22.10	188.50	5.138	4.87	7.20	13.0	
1.440	4.040	0.03564	22.14	188.45	5.818	5.15	7.25	13.1	
1.483	4.270	0.03473	21.57	189.75	6.332	6.00	5.95	10.7	
1.619	4.672	0.03465	21.52	189.85	7.564	7.16	5.85	10.5	
1.732	5.039	0.03437	21.34	190.25	8.728	8.27	5.45	9.8	
1.975	5.734	0.03444	21.39	190.15	1.1325×10^{0}	1.07×10^{4}	5.55	10.0	
2.200	6.372	0.03452	21.45	190.00	1.4018	1.33	5.70	10.3	
2.432	7.064	0.03443	21.39	190.15	1.7180	1.63	5.55	10.0	
2.876	8.277	0.03475	21.58	189.70	2.380	2.25	6.00	10.8	
3.272	9.397	0.03482	21.63	189.60	3.075	2.91	6.10	11.0	
3.597	1.0298×10^{0}	0.03493	21.70	189.45	3.704	3.51	6.25	11.3	

1 – 1 n.c.
2 – About 3 n.c.
3 – " 7-8 n.c.


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 27 — Up
q/a = 5.62 x 10^-13 ΔT^16.2
q/a = 179 ΔT^1.08
See Notes-Table 27 This is an example of the effect of a single nucleation center.
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

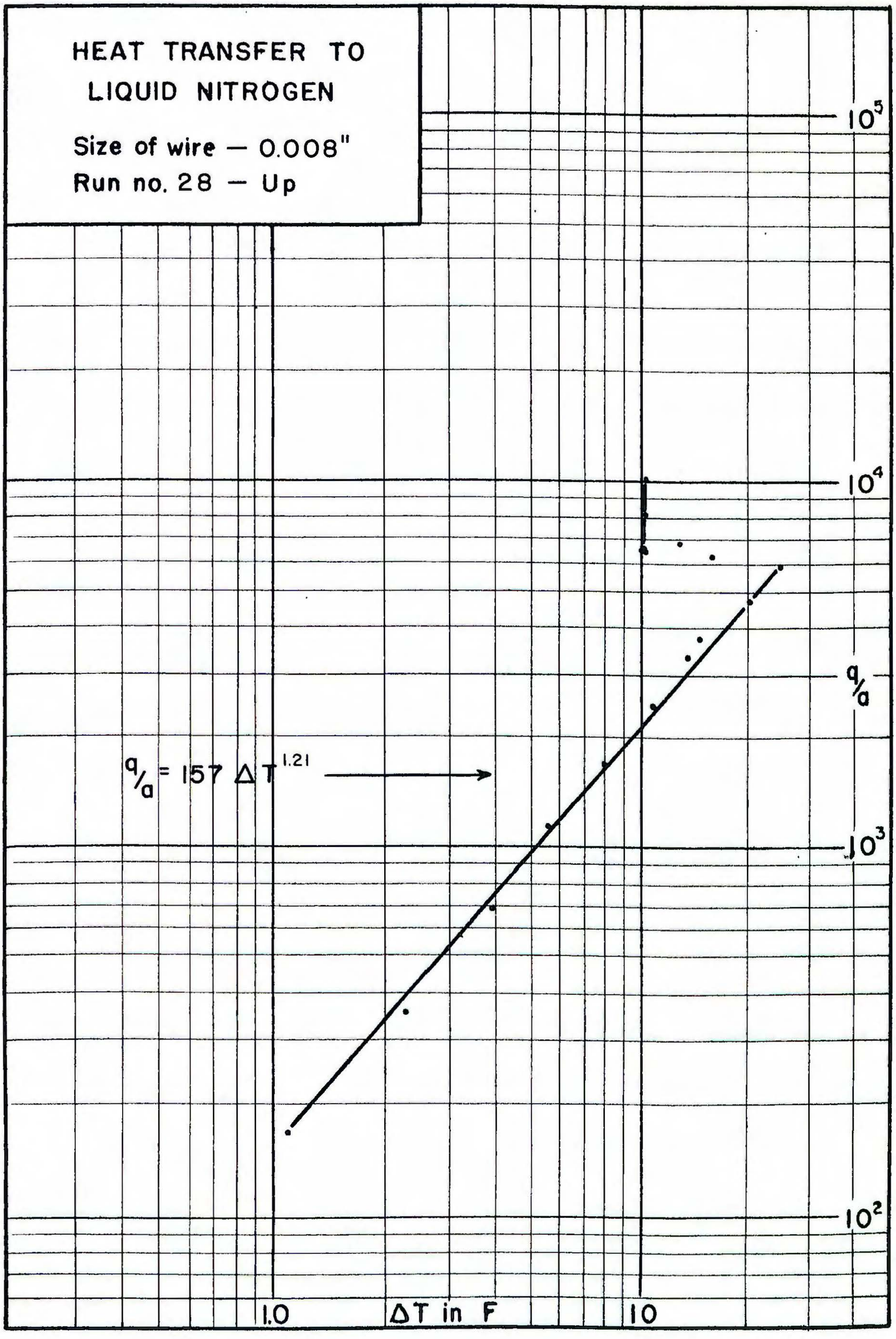
0.1 Ω Std
768 mm. Hg

Table 28
Up Run

Wire 4
0.008"

Exp - volts	Std - volts	R - ohm	100R/Ro	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
2.359×10^{-2}	7.610×10^{-2}	0.03100	19.26	-195.10	1.795×10^{-2}	1.70×10^{2}	0.60	1.1	
3.491	1.110×10^{-1}	0.03145	19.54	195.45	3.875	3.67	1.25	2.3	
4.815	1.501	0.03208	19.93	193.25	7.227	6.84	2.15	3.9	
6.268	1.916	0.03271	20.32	192.60	1.201×10^{-1}	1.14×10^{3}	3.10	5.6	
7.762	2.308	0.03363	20.89	191.30	1.791	1.70	4.40	7.9	
9.455	2.716	0.03481	21.62	189.60	2.568	2.43	6.10	11.0	
1.1216×10^{-1}	3.139	0.03573	22.19	188.30	3.521	3.33	7.40	13.3	
1.2000	3.300	0.03636	22.58	187.40	3.960	3.75	8.30	14.9	
1.385	3.610	0.03837	23.82	187.50	5.000	4.74	11.20	20.2	1
1.584	3.950	0.04010	24.89	182.15	6.257	5.93	13.55	24.4	2
1.563	4.250	0.03678	22.84	186.80	6.643	6.29	8.90	16.0	3
1.596	4.488	0.03556	22.08	188.55	7.163	6.78	7.15	12.9	4
1.547	4.482	0.03451	21.43	140.05	6.933	6.56	5.65	10.2	
1.545	4.482	0.03447	21.41	190.10	6.925	6.55	5.60	10.1	
1.548	4.486	0.03450	21.43	190.05	6.944	6.58	5.65	10.2	
1.720	4.984	0.03451	21.43	190.95	8.572	8.12	5.65	10.2	
1.928	5.573	0.03460	21.49	189.90	1.075×10^{0}	1.02×10^{4}	5.80	10.4	

1 - No nucleation centers
2 - " " "
3 - ½ of wire went suddenly to nucleate boiling
4 - All of wire boiling

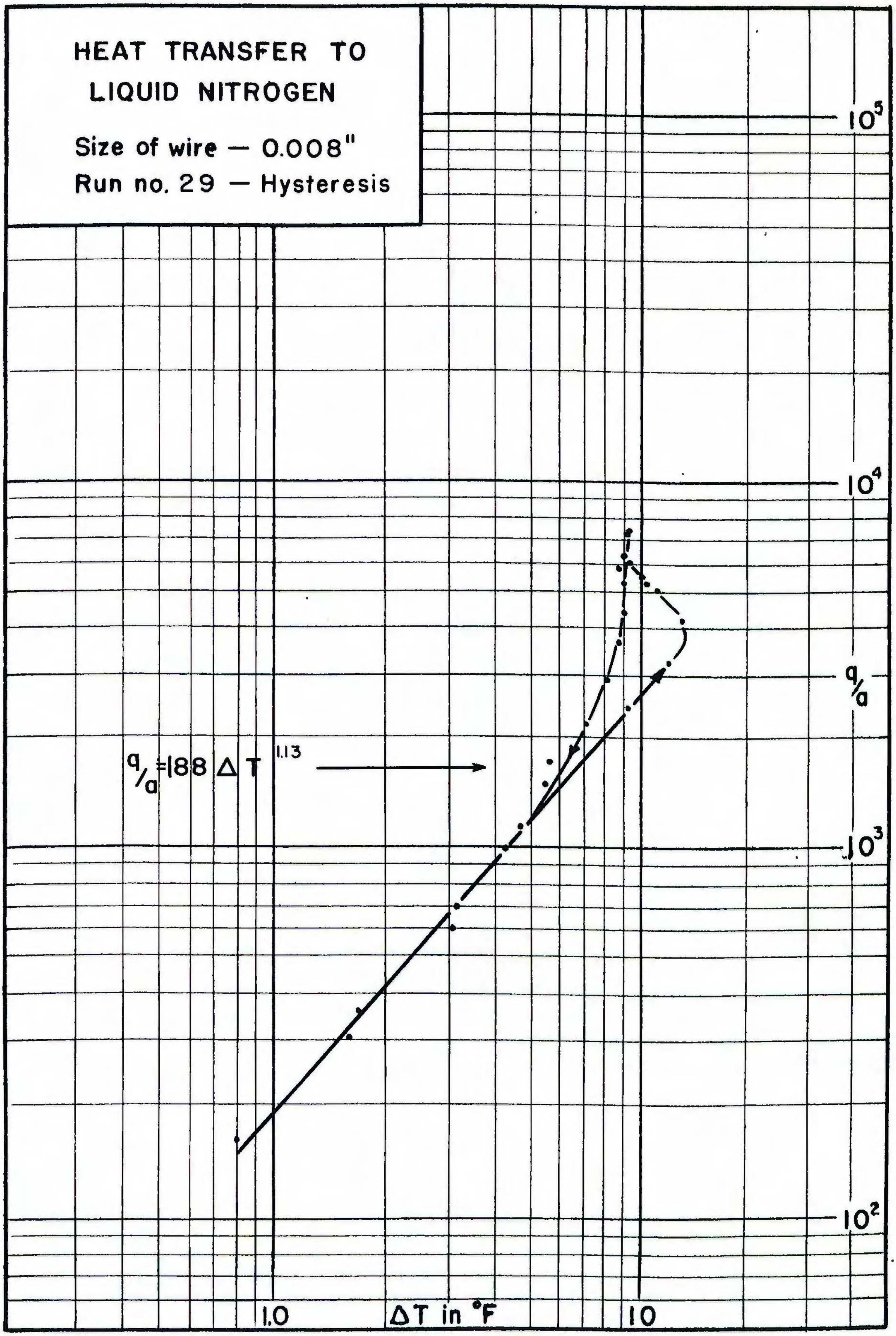

HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 28 — Up
q/a = 157 ΔT^1.21
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω std
772 mm. Hg.

Table 29
Hysteresis Run

Wire 4
0.008"

Exp - volts	Std - volts	R - ohm	100R/R₀	T - °C	EI - watts	BTU/ft²hr.	ΔT - °C	ΔT - °F	Notes
2.348×10^{-2}	7.552×10^{-2}	0.03109	19.23	-195.20	1.773×10^{-2}	1.68×10^{2}	0.45	0.8	
3.482	1.1085×10^{-1}	0.03141	19.44	194.70	3.860	3.66	0.95	1.7	
4.856	1.519	0.03197	19.78	193.90	7.376	6.99	1.75	3.2	
6.243	1.919	0.03253	20.13	193.05	1.198×10^{-1}	1.13×10^{3}	2.60	4.7	
7.701	2.312	0.03331	20.61	191.95	1.780	1.69	3.70	6.7	
9.343	2.721	0.03434	21.25	190.50	2.542	2.41	5.15	9.3	
1.1004×10^{-1}	3.105	0.03544	21.93	188.90	3.417	3.24	6.75	12.2	
1.262	3.522	0.03583	22.17	188.35	4.445	4.21	7.30	13.1	
1.367	3.900	0.03505	21.69	189.35	5.331	5.05	6.30	11.3	
1.399	4.025	0.03476	21.51	189.90	5.631	5.33	5.75	10.4	
1.424	4.113	0.03462	21.42	190.10	5.857	5.55	5.55	10.0	
1.451	4.251	0.03413	21.12	190.80	6.168	5.84	4.85	8.7	
1.501	4.386	0.03422	21.18	190.65	6.583	6.23	5.00	9.0	
1.617	4.716	0.03429	21.22	190.55	7.626	7.22	5.10	9.2	
1.625	4.733	0.03433	21.24	190.50	7.691	7.28	5.15	9.3	
1.476	4.296	0.03436	21.26	190.45	6.341	6.00	5.20	9.4	
1.386	4.047	0.03425	21.19	190.65	5.609	5.31	5.00	9.0	
1.261	3.682	0.03425	21.19	190.65	4.643	4.40	5.00	9.0	
1.155	3.386	0.03411	21.11	190.80	3.911	3.70	4.85	8.7	
1.022	3.013	0.03392	20.99	191.10	3.079	2.92	4.55	8.2	
8.759×10^{-2}	2.616	0.03349	20.72	191.70	2.291	2.17	3.95	7.1	
7.232	2.201	0.03286	20.33	192.65	1.592	1.51	3.00	5.4	
5.820	1.796	0.03240	20.05	193.25	1.045	9.90×10^{2}	2.40	4.3	
4.500	1.410	0.03191	19.75	193.95	6.345×10^{-1}	6.01	1.70	3.1	
3.197	1.018	0.03140	19.43	194.75	3.254	3.08	0.90	1.6	


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 29 — Hysteresis
q/a = 188 ΔT 1.13
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in °F
10

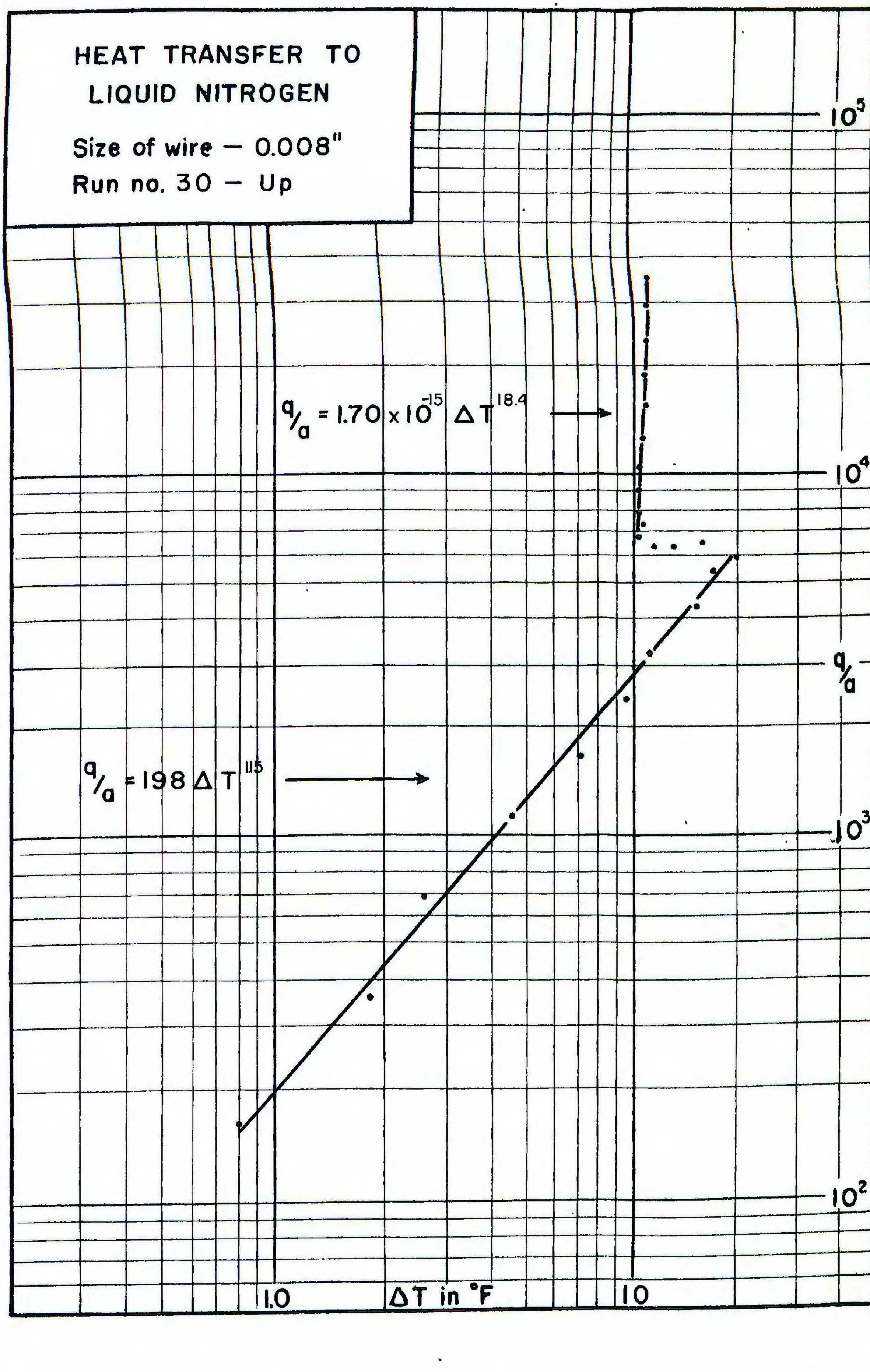
0.1 Ω std
772 mm. Hg.

Table 30
Up Run

Wire 4
0.008"

Exp-volts	Std-volts	R-ohm	100R/R_0	T-°C	EI-watts	BTU/ft^2hr	ΔT-°C	ΔT-°F	Notes
2.327×10^{-2}	7.489×10^{-2}	0.03107	19.23	-195.20	1.743×10^{-3}	1.64×10^{2}	0.45	0.8	
3.485	1.108×10^{-1}	0.03485	19.46	194.65	3.861	3.62	1.00	1.8	
4.834	1.522	0.03176	19.65	194.20	7.357	6.91	1.45	2.6	
6.239	1.918	0.03252	20.12	193.10	1.197×10^{-1}	1.12×10^{3}	2.55	4.6	
7.706	2.301	0.03349	20.72	191.70	1.773	1.66	3.95	7.1	
9.346	2.717	0.03340	21.28	190.40	2.539	2.38	5.25	9.5	
1.095×10^{-1}	3.115	0.03515	21.74	189.35	3.411	3.20	6.30	11.3	
1.290	3.534	0.03650	22.66	187.25	4.559	4.28	8.40	15.1	
1.470	3.940	0.03731	23.07	186.30	5.792	5.44	9.30	16.7	
1.551	4.044	0.03835	23.72	184.75	6.272	5.89	10.90	19.6	
1.602	4.356	0.03678	22.75	187.05	6.978	6.55	8.60	15.5	
1.560	4.354	0.03581	22.15	188.40	6.795	6.38	7.75	13.0	
1.535	4.354	0.03525	21.81	189.20	6.683	6.27	6.45	11.6	
1.582	4.538	0.03486	21.57	189.75	7.179	6.74	5.90	10.6	
1.645	4.704	0.03497	21.64	189.60	7.738	7.26	6.05	10.9	
1.710	4.909	0.03483	21.55	189.80	8.394	7.88	5.85	10.5	
1.824	5.248	0.03476	21.51	189.90	9.572	8.99	5.75	10.4	
1.988	5.713	0.03480	21.53	189.85	1.136×10^{0}	1.07×10^{4}	5.80	10.5	
2.167	6.217	0.03486	21.57	189.75	1.347	1.26	5.90	10.6	
2.400	6.866	0.03495	21.62	189.65	1.648	1.55	6.00	10.8	
2.657	7.605	0.03494	21.62	189.65	2.021	1.90	6.00	10.8	
2.949	8.421	0.03502	21.65	189.55	2.483	2.33	6.10	11.0	
3.311	9.434	0.03510	21.73	189.40	3.124	2.93	6.25	11.3	
3.625	1.030×10^{0}	0.03519	21.78	189.25	3.734	3.51	6.40	11.5	

Recalibration R_{N_2} (772 mm) = 0.030789 Ω   New R_0 = 0.1616 Ω

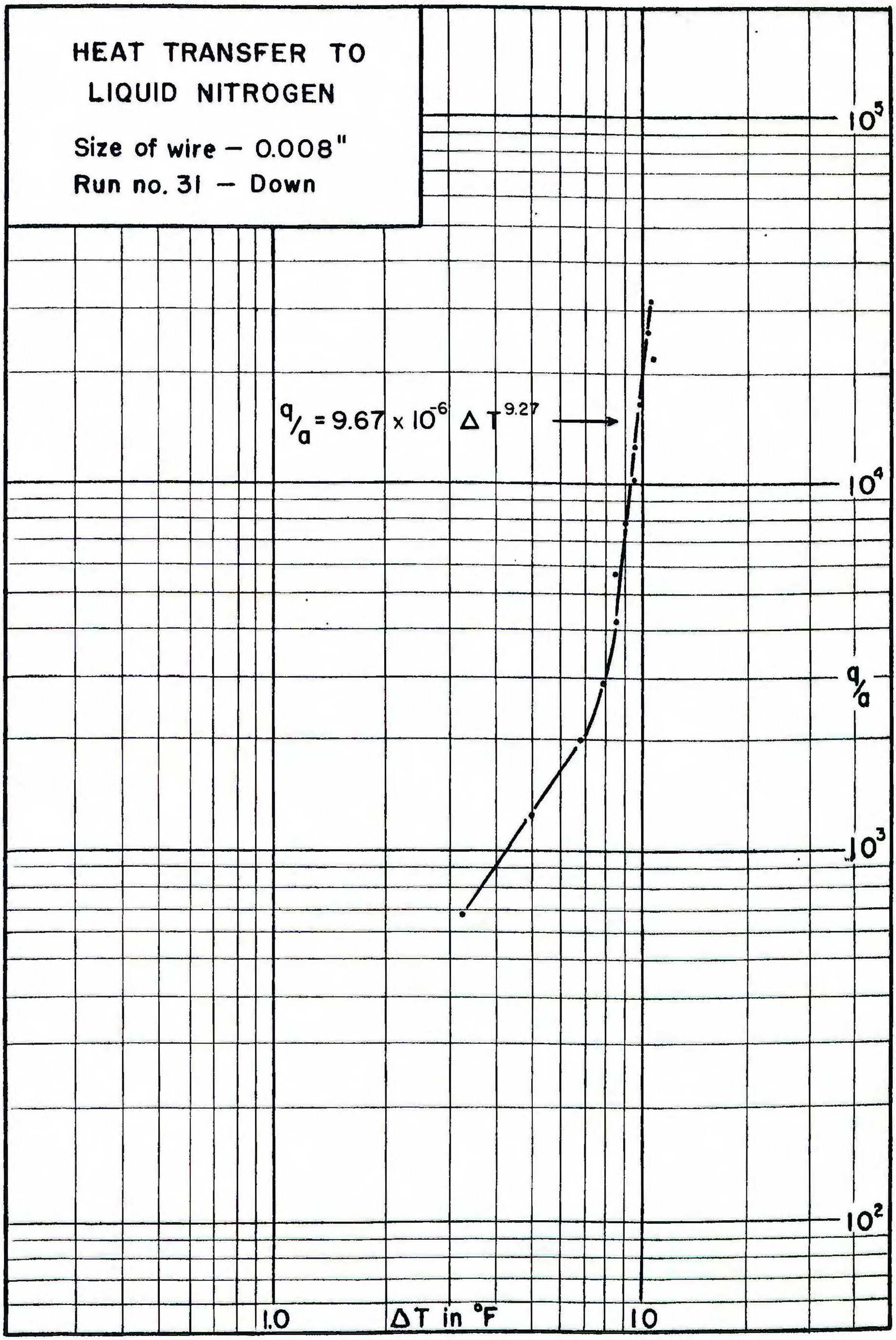

HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 30 — Up
q/a = 1.70 x 10^-15 ΔT^18.4
q/a = 198 ΔT^1.15
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in °F
10

0.1 Ω Std
772 mm. Hg.

Table 31
Down Run

Wire 4
0.008"

Exp.-volts	Std-volts	R-ohm	100R/Ro	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
3.406 $\times 10^{-1}$	9.750 $\times 10^{-1}$	0.03493	21.62	-189.65	3.321 $\times 10^{0}$	3.14 $\times 10^{4}$	6.00	10.8	
3.098	8.904	0.03479	21.53	189.85	2.758	2.61	5.80	10.4	
2.834	8.107	0.03496	21.63	189.60	2.298	2.18	6.05	10.9	
2.455	7.105	0.03455	21.38	190.20	1.744	1.65	5.45	9.8	
2.150	6.250	0.03440	21.29	190.70	1.344	1.27	5.25	9.5	
1.932	5.622	0.03436	21.26	190.45	1.086	1.03	5.20	9.4	
1.680	4.907	0.03424	21.19	190.65	8.244 $\times 10^{-1}$	7.81 $\times 10^{3}$	5.00	9.0	
1.428	4.202	0.03398	21.03	191.00	6.000	5.68	4.65	8.4	
1.233	3.626	0.03440	21.04	191.00	4.471	4.23	4.65	8.4	
1.014	3.004	0.03375	20.89	191.30	3.046	2.88	4.35	7.8	
8.366 $\times 10^{-2}$	2.510	0.03333	20.63	191.90	2.100	1.99	3.75	6.8	
6.533	2.000	0.03267	20.22	192.85	1.307	1.24	2.80	5.0	
4.784	1.494	0.03202	19.82	193.80	7.150 $\times 10^{-2}$	6.77 $\times 10^{2}$	1.85	3.3	



HEAT TRANSFER TO LIQUID NITROGEN
Size of wire – 0.008"
Run no. 31 – Down
$q/a = 9.67 \times 10^{-6}\ \Delta T^{9.27}$
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in °F
10

0.1 Ω std
748 mm Hg

Table 32
Ice Point Calibration

Wire 6
0.008"

Exp.-volts	Std-volts	R-ohm
1.6282×10^{-3}	1.0030×10^{-3}	0.16233
1.7740	1.0929	0.16232
1.9479	1.2005	0.16226
1.9486	1.2004	0.16233
1.7738	1.0930	0.16229
1.6282	1.0031	0.16231

$R_0 = 0.16231\ \Omega$

Nitrogen Calibration

1.0075×10^{-3}	3.2827×10^{-3}	0.030691
1.0648	3.4694	0.030691
1.1291	3.6787	0.030693
1.1293	3.6786	0.030699
1.0643	3.4688	0.030682
1.0070	3.2817	0.030685

R_{N_2} (748 mm) = $0.030690\ \Omega$

Length of wire = 2.077 inches

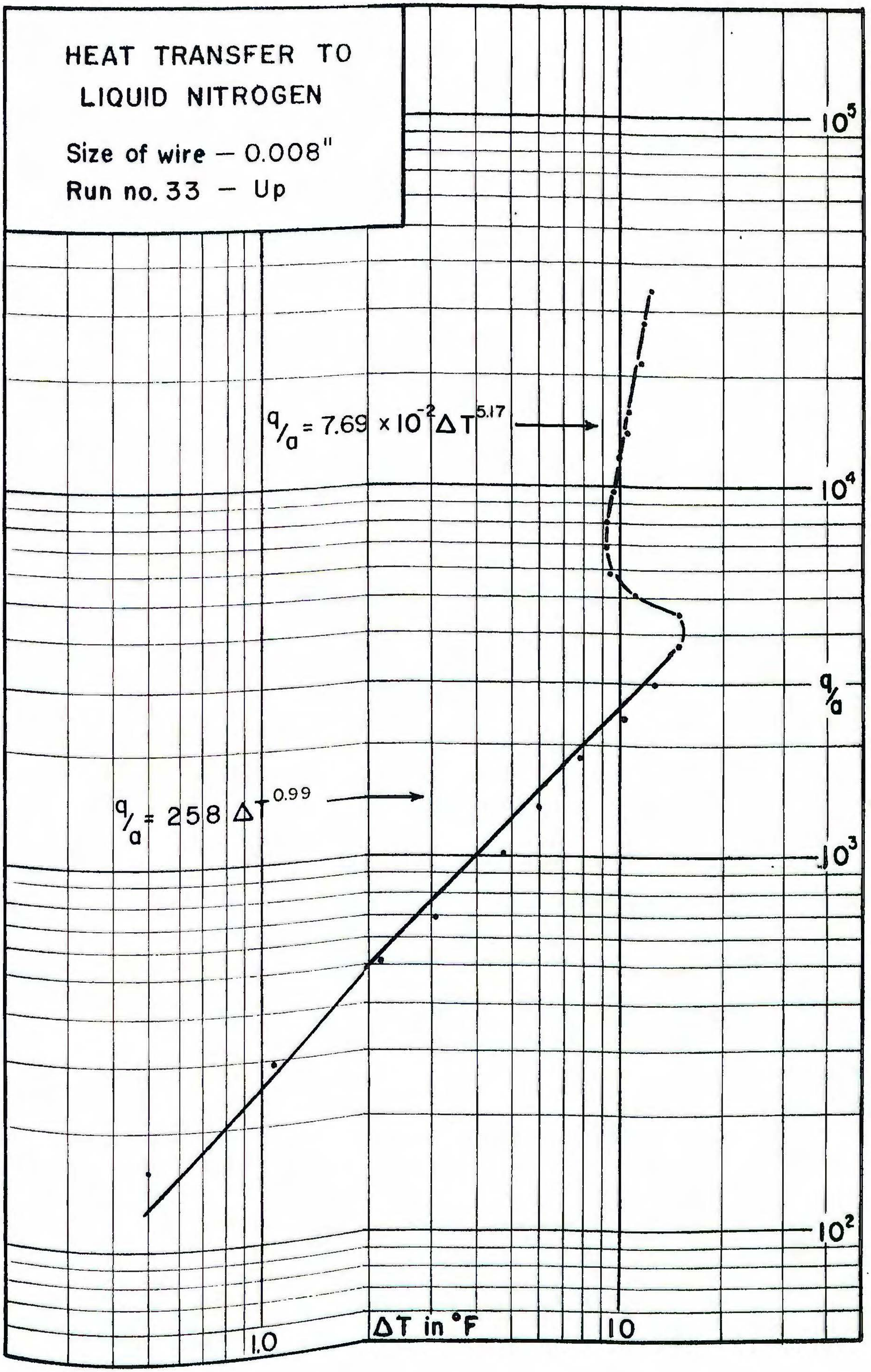
$100 R_{N_2}/R_0 = 18.90$ at $-195.90°C$

0.01 Ω Std
748 mm. Hg.

Table 33
Up Run

Wire 6
0.008"

Exp - volts	Std - volts	R - ohm	100R/R_0	T - °C	EI - watts	BTU/ft^2 hr	ΔT - °C	ΔT - °F	Notes
2.298 × 10^{-2}	7.442 × 10^{-3}	0.03088	19.02	−195.60	1.710 × 10^{-2}	1.60 × 10^{2}	0.30	0.5	
3.103	9.975	0.03111	19.06	195.30	3.095	2.91	0.60	1.1	
4.128	1.308 × 10^{-2}	0.03156	19.44	194.60	5.399	5.08	1.30	2.3	
4.823	1.514	0.03186	19.63	194.20	7.320	6.87	1.70	3.1	
5.938	1.827	0.03250	20.02	193.25	1.085 × 10^{-1}	1.02 × 10^{3}	2.65	4.8	
6.956	2.109	0.03298	20.32	192.55	1.467	1.38	3.35	6.0	
8.104	2.407	0.03367	20.75	191.55	1.951	1.84	4.35	7.8	
9.381	2.711	0.03460	21.32	190.20	2.543	2.39	5.70	10.3	
1.063 × 10^{-1}	2.991	0.03554	21.90	188.90	3.179	2.99	7.00	12.6	
1.202	3.321	0.03619	22.30	187.75	3.992	3.76	8.15	14.7	
1.315	3.626	0.03626	22.48	187.60	4.768	4.49	8.30	14.9	
1.376	3.929	0.03502	21.58	189.65	5.406	5.09	6.25	11.3	
1.459	4.256	0.03428	21.12	190.70	6.209	5.85	5.20	9.4	
1.579	4.616	0.03421	21.08	190.80	7.289	6.86	5.10	9.2	
1.707	4.993	0.03419	21.07	190.80	8.523	8.02	5.10	9.2	
1.883	5.473	0.03440	21.19	190.55	1.031	9.70	5.35	9.6	
2.094	6.065	0.03452	21.27	190.35	1.270	1.20 × 10^{4}	5.55	10.0	
2.275	6.558	0.03462	21.37	190.15	14.92	1.40	5.75	10.4	
2.422	6.957	0.03481	21.45	189.90	1685	1.59	6.00	10.8	
2.850	8.102	0.03517	21.67	189.40	2.309	2.17	6.50	11.7	
3.226	9.152	0.03526	21.72	189.30	2.952	2.78	6.60	11.9	
3.571	1.005 × 10^{-1}	0.03553	21.89	188.90	3.589	3.38	6.90	12.6	



HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 33 — Up
$q/a = 7.69 \times 10^{-2} \Delta T^{5.17}$
$q/a = 258\ \Delta T^{0.99}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in °F
10

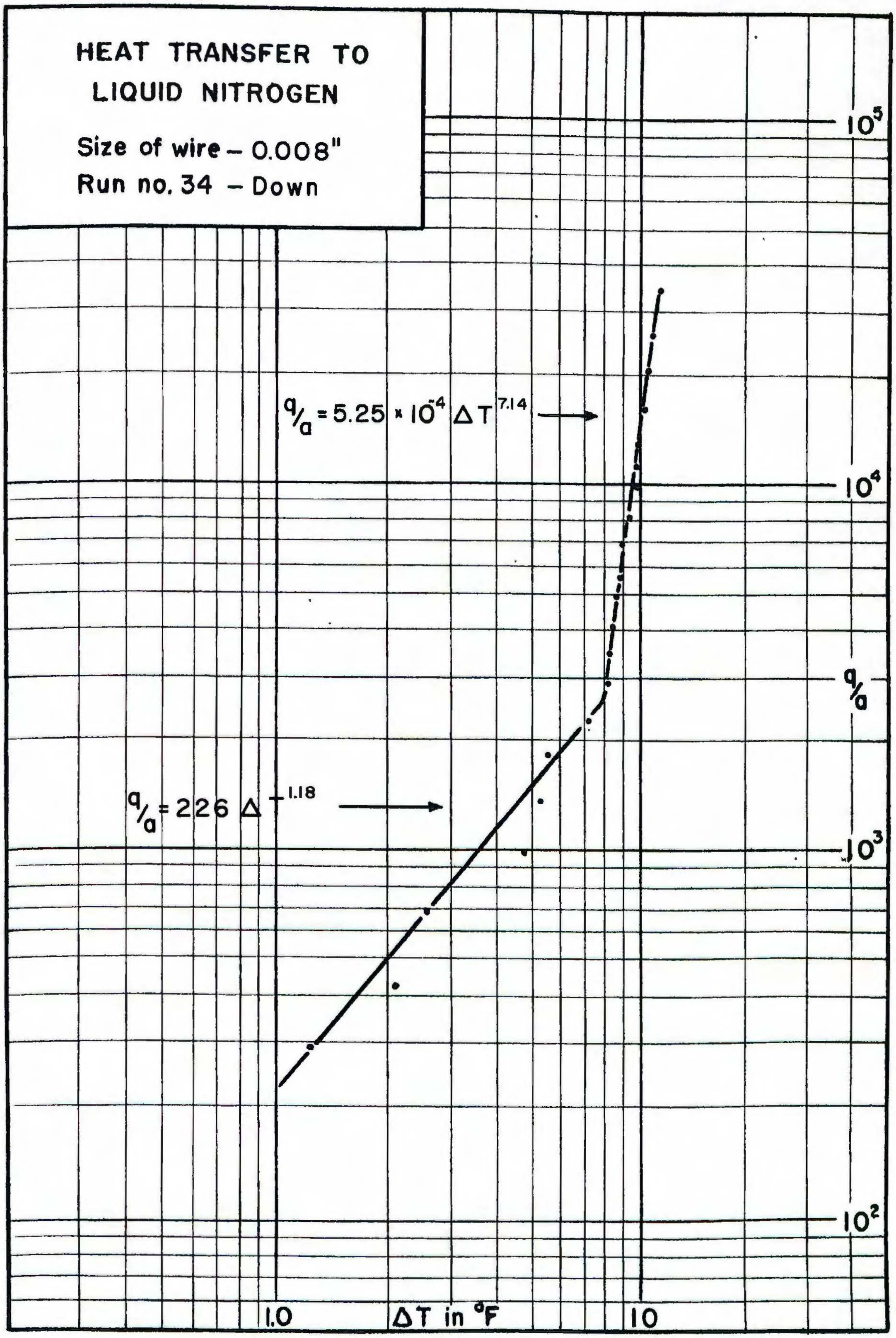
0.01 Ω std
748 mm. Hg.

Table 34
Down Run

Wire 6
0.008"

Exp - volts	std - volts	R-ohm	100R/Ro	T-°C	EI- watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
3.556 x 10^{-1}	1.011 x 10^{-1}	0.03517	21.67	-189.40	3.595 x 10^{0}	3.38 x 10^{4}	6.50	11.7	
3.099	8.885 x 10^{-2}	0.03488	21.49	189.85	2.753	2.59	6.05	10.9	
2.755	7.931	0.03473	21.40	190.05	2.185	2.06	5.85	10.5	
2.430	7.021	0.03461	21.32	190.25	1.706	1.61	5.65	10.2	
2.190	6.351	0.03448	21.24	190.40	1.391	1.31	5.50	9.9	
2.031	5.904	0.03440	21.19	190.50	1.199	1.13	5.40	9.7	
1.898	5.517	0.03440	21.19	190.50	1.047	9.86 x 10^{3}	5.40	9.7	
1.719	5.020	0.03424	21.10	190.75	8.629 x 10^{-1}	8.12	5.15	9.3	
1.575	4.616	0.03412	21.02	190.90	7.270	6.84	5.00	9.0	
1.423	4.178	0.03406	20.99	191.00	5.945	5.60	4.90	8.8	
1.332	3.924	0.03394	20.91	191.15	5.227	4.92	4.75	8.6	
1.213	3.579	0.03389	20.88	191.25	4.341	4.09	4.65	8.4	
1.119	3.311	0.03380	20.83	191.35	3.705	3.49	4.55	8.2	1
1.013	2.994	0.03383	20.84	191.35	3.033	2.86	4.55	8.2	2
9.010 x 10^{-2}	2.695	0.03343	20.60	191.90	2.428	2.29	4.00	7.2	3
7.987	2.409	0.03315	20.42	192.30	1.924	1.81	3.60	6.5	
6.925	2.095	0.03305	20.36	192.45	1.451	1.37	3.45	6.2	
5.850	1.800	0.03250	20.02	193.25	1.053	9.91 x 10^{2}	2.65	4.8	
4.800	1.514	0.03170	19.53	194.45	7.267 x 10^{-2}	6.84	1.45	2.6	
3.743	1.190	0.03145	19.38	194.75	4.454	4.19	1.15	2.1	
3.096	9.923 x 10^{-3}	0.03120	19.22	195.15	3.072	2.89	0.75	1.3	

1 - Current quite unstable
2 - About the end of boiling
3 - " & intermittant R.C.

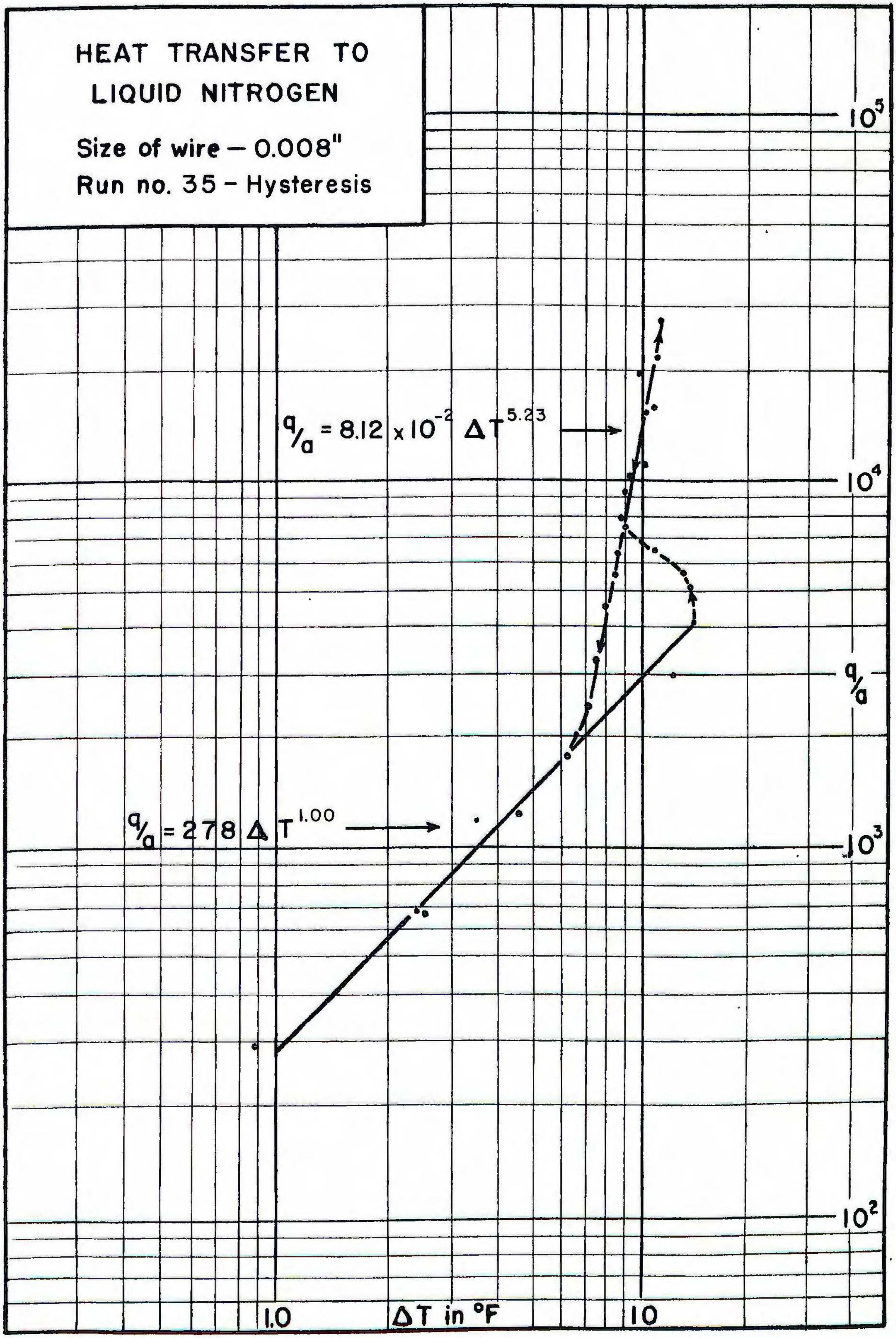

HEAT TRANSFER TO LIQUID NITROGEN
Size of wire – 0.008"
Run no. 34 – Down
q/a = 5.25 × 10⁻⁴ ΔT^7.14
q/a = 226 ΔT^1.18
10⁵
10⁴
10³
10²
q/a
1.0
ΔT in °F
10

0.01 Ω std
748 mm.Hg.

Table 35
Hysteresis Run

wire 6
0.008"

Exp - volts	Std - volts	R - ohm	100R/Ro	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
4.765×10^{-2}	1.507×10^{-2}	0.03162	19.48	-194.55	7.181×10^{-2}	6.76×10^{2}	1.35	2.4	
6.043	2.000	0.03202	19.73	193.95	1.281×10^{-1}	1.21×10^{3}	1.95	3.5	
8.402	2.530	0.03321	20.46	192.25	2.126	2.00	3.65	6.6	
1.059×10^{-1}	2.994	0.03537	21.79	189.15	3.171	2.98	6.75	12.2	
1.260	3.488	0.03612	22.26	188.05	4.395	4.14	7.85	14.1	
1.392	3.862	0.03604	22.21	188.20	5.376	5.06	7.70	13.9	
1.465	4.100	0.03573	22.01	188.65	6.006	5.65	7.25	13.1	
1.551	4.432	0.03500	21.53	189.75	6.874	6.47	6.15	11.1	
1.655	4.851	0.03412	21.02	190.90	8.028	7.55	5.00	9.0	
1.951	5.696	0.03425	21.10	190.75	1.111×10^{0}	1.05×10^{4}	5.15	9.3	
2.063	5.970	0.03455	21.29	190.30	1.232	1.16	5.60	10.1	
2.450	7.036	0.03482	21.45	189.90	1.724	1.62	6.00	10.8	
2.847	8.149	0.03494	21.53	189.75	2.320	2.18	6.15	11.1	
3.214	9.168	0.03506	21.60	189.55	2.947	2.77	6.35	11.4	
2.686	7.798	0.03444	21.22	190.45	2.094	1.97	5.45	9.8	
2.395	6.934	0.03454	21.28	190.30	1.661	1.56	5.60	10.1	
1.842	5.397	0.03413	21.03	190.90	9.941×10^{-1}	9.36×10^{3}	5.00	9.0	
1.693	4.974	0.03404	20.97	191.05	8.421	7.93	4.85	8.7	
1.541	4.537	0.03397	20.93	191.15	6.714	6.32	4.75	8.6	
1.428	4.215	0.03388	20.87	191.25	6.019	5.67	4.65	8.4	
1.280	3.792	0.03376	20.80	191.45	4.854	4.57	4.45	8.0	
1.077	3.208	0.03357	20.68	191.70	3.455	3.25	4.20	7.6	
9.334×10^{-2}	2.794	0.03341	20.59	191.90	2.608	2.46	4.00	7.2	
7.899	2.385	0.03312	20.41	192.35	1.883	1.77	3.55	6.4	
6.513	2.005	0.03248	20.01	193.30	1.306	1.23	2.60	4.7	
4.727	1.491	0.03170	19.53	194.45	7.047×10^{-2}	6.63×10^{2}	1.45	2.6	



HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 35 - Hysteresis
q/a = 8.12 x 10^-2 ΔT^5.23
q/a = 278 ΔT^1.00
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in °F
10

0.01 Ω std
748 mm. Hg.

Table 36
Up Run

Wire 6
0.008"

Exp - volts	std - volts	R - ohm	$100R/R_o$	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
2.227×10^{-2}	7.221×10^{-3}	0.03084	19.06	−195.55	1.608×10^{-2}	1.51×10^{2}	0.35	0.6	
3.105	9.958	0.03118	19.27	195.05	3.092	2.91	0.85	1.5	
4.082	1.294×10^{-2}	0.03154	19.49	194.50	5.282	4.97	1.40	2.5	
5.127	1.604	0.03196	19.75	193.90	8.224	7.74	2.00	3.6	
6.190	1.906	0.03248	20.07	193.15	1.180×10^{-1}	1.11×10^{3}	2.75	5.0	
7.236	2.201	0.03288	20.32	192.55	1.593	1.50	3.35	6.0	
8.441	2.505	0.03370	20.83	191.35	2.114	1.99	4.55	8.2	
9.642	2.815	0.03425	21.17	190.55	2.714	2.55	5.35	9.6	
1.114×10^{-1}	3.120	0.03570	22.06	188.50	3.476	3.27	7.40	11.3	
1.210	3.393	0.03566	22.04	188.55	4.105	3.86	7.35	13.2	

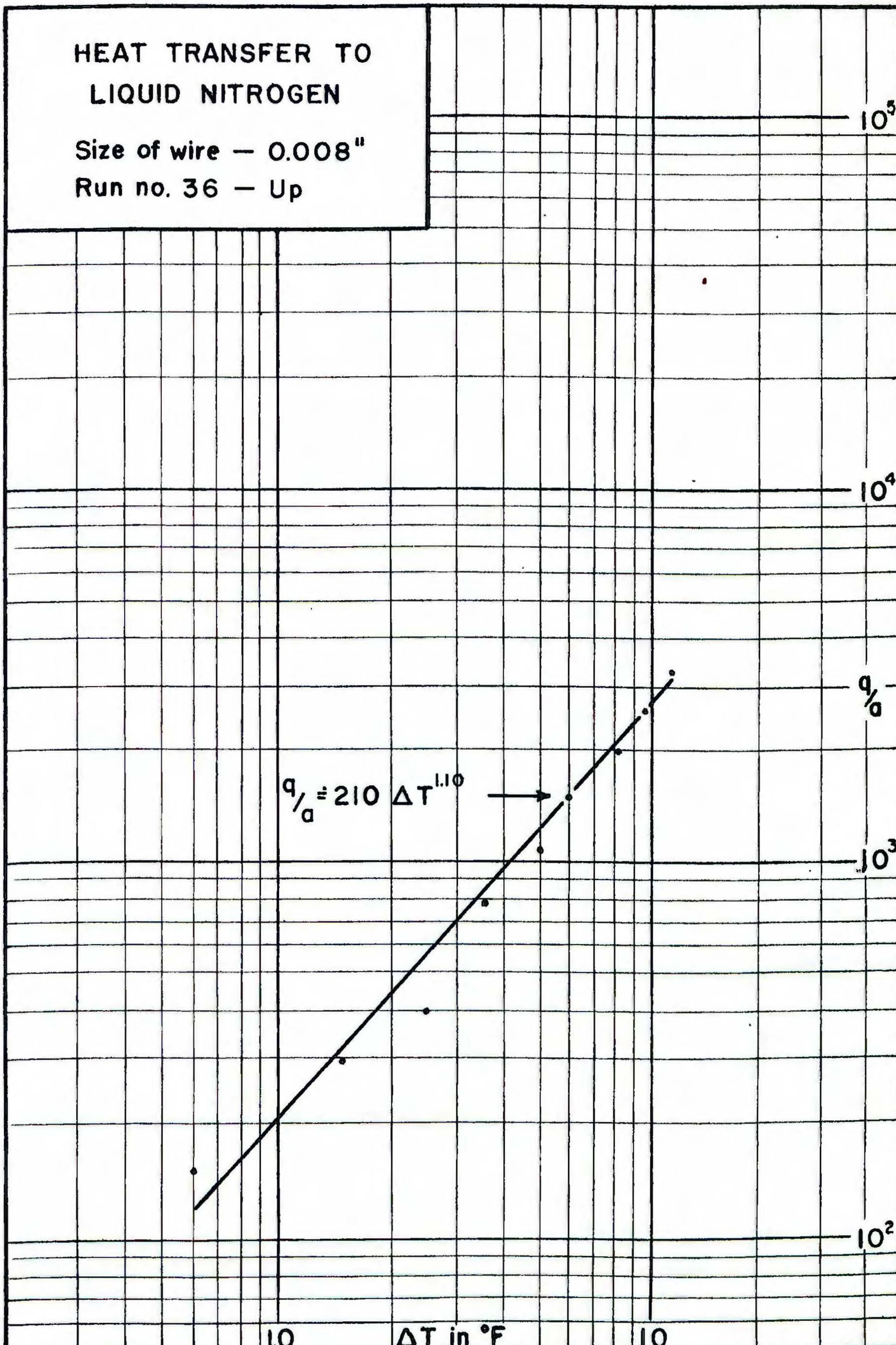
This run preceeded by 50 min. of film boiling

N_2 Calibration

Exp	10016	10614	11279	10618	10025
Std	32771	34707	36881	34718	32798
R_{N_2}	30563	30581	30582	30584	30566

Average R_{N_2} (748 mm) = 0.030575 Ω

New R_o = 0.1618 Ω


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 36 — Up
$q/a \doteq 210\,\Delta T^{1.10}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in °F
10

0.01 Ω std.
768 mm. Hg.

Table 37
Up Run

Wire 6
0.008"

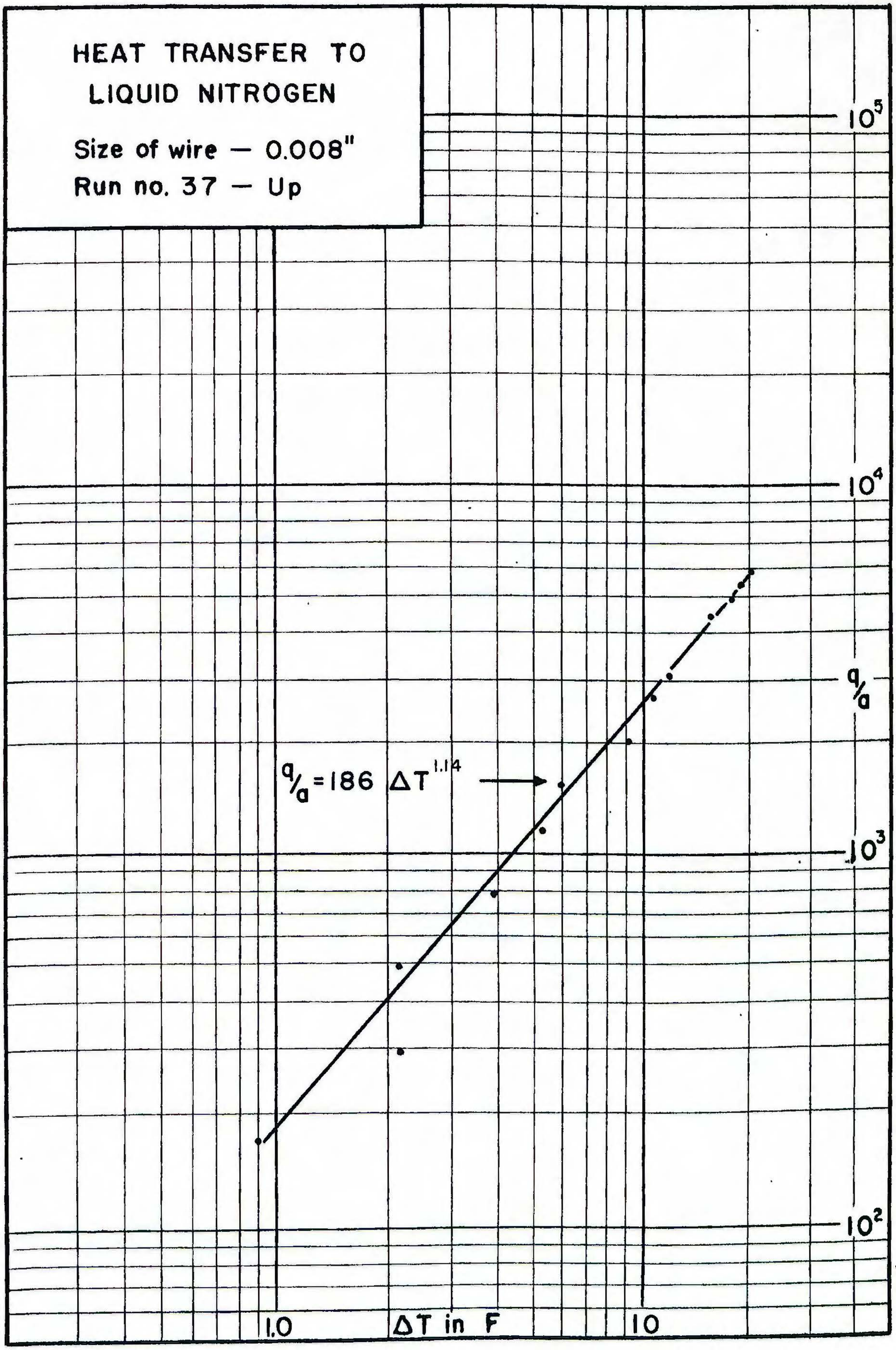
Exp-volts	Std-volts	R-ohm	$100R/R_o$	T-°C	EI-watts	BTU/ft^{2}hr	ΔT-°C	ΔT-°F	Notes
2.380×10^{-2}	7.645×10^{-3}	0.03113	19.19	-195.20	1.819×10^{-2}	1.71×10^{2}	0.50	0.9	
3.129	9.876	0.03168	19.53	194.45	3.090	2.91	1.25	2.2	
4.053	1.282×10^{-2}	0.03161	19.48	194.50	5.196	4.89	1.20	2.2	
5.185	1.607	0.03226	19.89	193.55	8.333	7.84	2.15	3.9	
6.335	1.929	0.03284	20.24	192.75	1.222×10^{-1}	1.15×10^{3}	2.95	5.3	
7.349	2.219	0.03311	20.41	192.35	1.631	1.53	3.35	6.0	
8.585	2.503	0.03430	21.14	190.65	2.149	2.02	5.05	9.1	
1.000×10^{-1}	2.863	0.03493	21.54	189.70	2.866	2.70	6.00	10.8	
1.085	3.072	0.03532	21.78	189.15	3.333	3.14	6.55	11.8	
1.320	3.585	0.03682	22.70	187.05	4.732	4.45	8.65	15.6	
1.396	3.694	0.03779	23.30	185.65	5.157	4.85	10.05	18.1	
1.478	3.858	0.03831	23.62	184.90	5.702	5.37	10.60	19.1	
1.545	4.008	0.03855	23.77	184.55	6.192	5.83	11.15	20.1	

N_2 Calibration

Exp	10610	11240	10622	10063
Std	34466	36498	34479	32675
R_{N_2}	30783	30796	30807	30797

Average R_{N_2} = 0.030796 Ω

New R_o = 0.1622 Ω

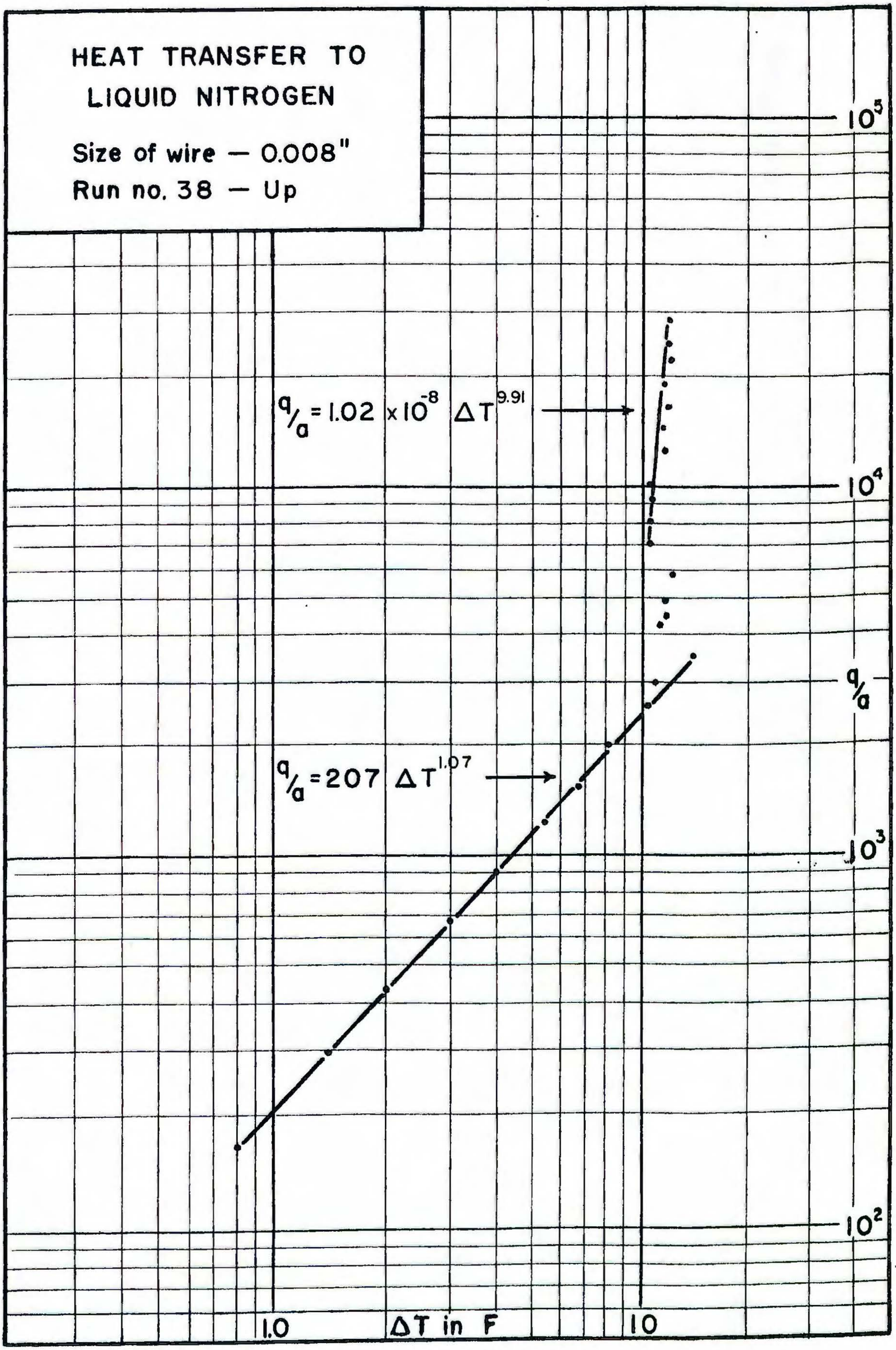

HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 37 — Up
$q/a = 186\,\Delta T^{1.14}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

0.01 Ω Std
768 mm. Hg.

Table 38
Up Run

Wire 6
0.008"

Exp-volts	Std-volts	R-ohm	$100R/R_o$	T-°C	EI-watts	BTU/ft²hr	ΔT-°C	ΔT-°F	Notes
2.369×10^{-2}	7.620×10^{-3}	0.03109	19.17	-195.25	1.805×10^{-2}	1.70×10^{2}	0.45	0.8	
3.130	9.988	0.03134	19.32	194.90	3.127	2.94	0.80	1.4	
3.807	1.206×10^{-2}	0.03157	19.46	194.60	4.591	4.32	1.10	2.0	
4.749	1.487	0.03194	19.69	194.05	7.062	6.65	1.65	3.0	
5.555	1.718	0.03233	19.93	193.50	9.543	8.98	2.20	4.0	
6.587	2.004	0.03287	20.26	192.70	1.320×10^{-1}	1.24×10^{3}	3.00	5.4	
7.340	2.202	0.03333	20.55	192.00	1.616	1.52	3.70	6.7	
8.524	2.516	0.03388	20.89	191.20	2.145	2.02	4.50	8.1	
9.744	2.797	0.03483	21.47	189.90	2.725	2.57	5.80	10.4	
1.053×10^{-1}	3.011	0.03497	21.56	189.70	3.171	2.99	6.00	10.8	
1.160	3.212	0.03611	22.26	188.05	3.726	3.51	7.65	13.8	
1.245	3.543	0.03514	21.66	189.45	4.411	4.15	6.25	11.3	
1.280	3.600	0.03555	21.92	188.85	4.608	4.34	6.85	12.3	
1.356	3.816	0.03553	21.90	188.90	5.174	4.87	6.80	12.2	
1.488	4.164	0.03573	22.03	188.60	6.196	5.83	7.10	12.8	
1.618	4.644	0.03484	21.48	189.85	7.514	7.07	5.85	10.5	
1.732	4.964	0.03489	21.51	189.80	8.598	8.09	6.90	10.6	
1.851	5.299	0.03493	21.54	189.70	9.808	9.23	6.00	10.8	
1.947	5.588	0.03484	21.48	189.85	1.088×10^{0}	1.02×10^{4}	5.85	10.5	
2.161	6.132	0.03524	21.72	189.30	1.325	1.25	6.40	11.5	
2.341	6.645	0.03523	21.72	189.30	1.555	1.46	6.40	11.5	
2.493	7.042	0.03540	21.82	189.10	1.755	1.65	6.60	11.9	
2.680	7.590	0.03530	21.77	189.20	2.034	1.91	6.50	11.7	
2.901	8.152	0.03559	21.94	188.80	2.365	2.23	6.90	12.4	
3.030	8.528	0.03553	21.90	188.90	2.584	2.43	6.80	12.2	
3.280	9.208	0.03562	21.96	188.75	3.020	2.84	6.95	12.5	


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 38 — Up
$q/a = 1.02 \times 10^{-8}\ \Delta T^{9.91}$
$q/a = 207\ \Delta T^{1.07}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

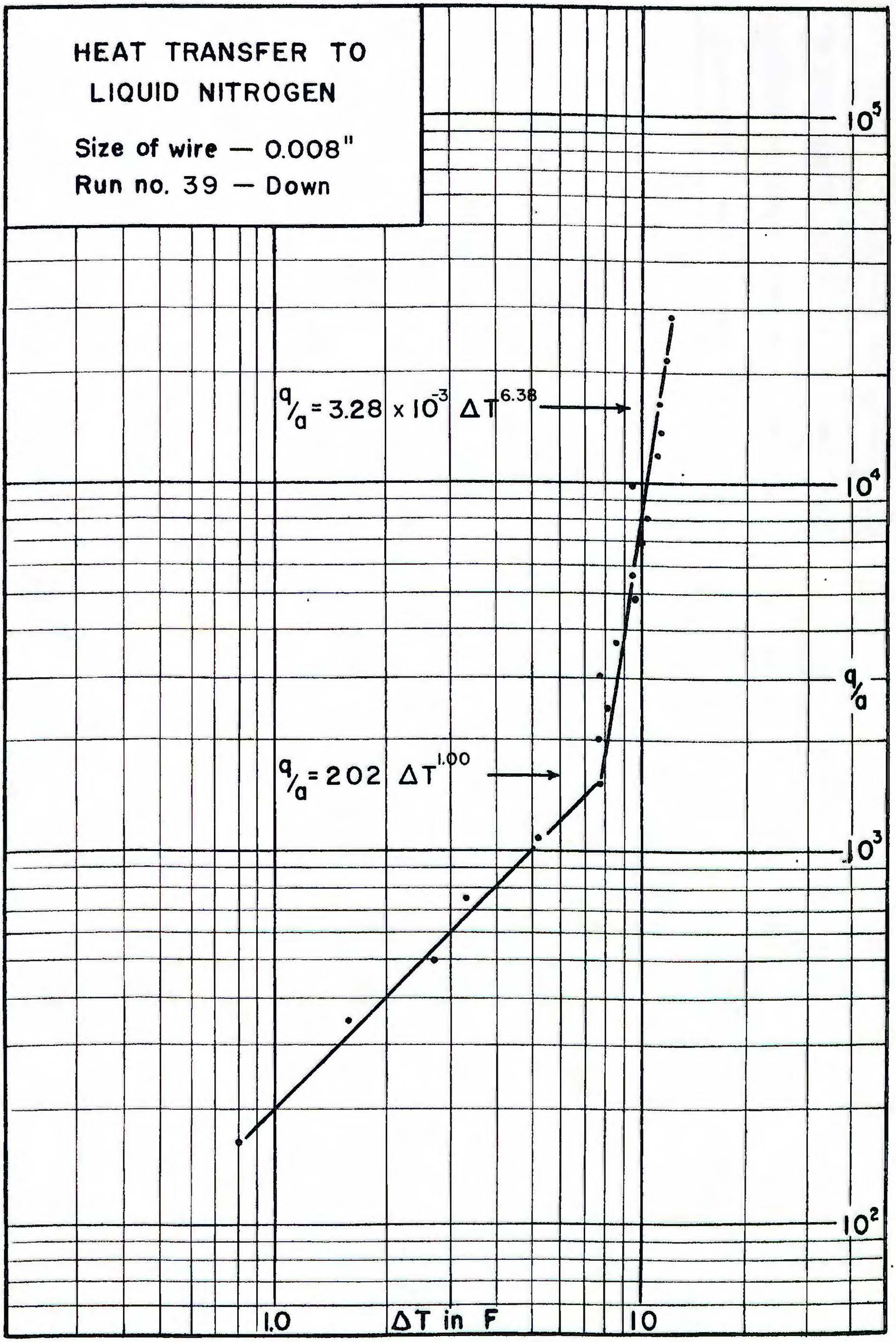
0.01 Ω std.
768 mm. Hg

Table 39
Down Run

Wire 6
0.008"

Exp.-volts	Std.-volts	R-ohm	100R/R_0	T-°C	EI-watts	BTU/ft²hr	ΔT-°C	ΔT-°F	Notes
3.278×10^{-1}	9.209×10^{-2}	0.03560	21.95	-188.80	3.016×10^{0}	2.84×10^{4}	6.90	12.4	
2.836	8.027	0.03533	21.78	189.15	2.276	2.14	6.55	11.8	
2.469	7.018	0.03518	21.69	189.40	1.733	1.63	6.30	11.3	
2.261	6.438	0.03512	21.65	189.45	1.456	1.37	6.25	11.3	
2.098	5.992	0.03501	21.58	189.60	1.257	1.18	6.10	11.0	
1.894	5.503	0.03441	21.21	190.50	1.042	9.80×10^{3}	5.20	9.4	
1.723	4.946	0.03483	21.47	189.85	8.522×10^{-1}	8.02	5.85	10.5	
1.596	4.616	0.03458	21.32	190.20	7.367	6.94	5.50	9.9	
1.439	4.185	0.03438	21.20	190.50	6.022	5.67	5.20	9.4	
1.331	3.857	0.03450	21.27	190.35	5.134	4.83	5.35	9.6	
1.158	3.402	0.03403	20.98	191.00	3.940	3.71	4.70	8.5	
1.047	3.104	0.03373	20.79	191.45	3.250	3.06	4.25	7.7	
9.345×10^{-2}	2.757	0.03389	20.89	191.20	2.576	2.43	4.50	8.1	
8.522	2.525	0.03375	20.80	191.45	2.152	2.03	4.25	7.7	
7.425	2.202	0.03372	20.79	191.45	1.635	1.54	4.25	7.7	
6.242	1.904	0.03278	20.21	192.80	1.188	1.12	2.90	5.2	
5.070	1.581	0.03207	19.77	193.85	8.016	7.55×10^{2}	1.85	3.3	
4.093	1.286	0.03183	19.62	194.20	5.263	4.95	1.50	2.7	
3.414	1.087	0.03141	19.36	194.80	3.711	3.49	0.90	1.6	
2.342	7.516×10^{-3}	0.03116	19.21	195.25	1.760	1.66	0.45	0.8	

Note: In this run the temperature goes straight down from 3.06×10^{3} BTU/ft²hr to 1.54×10^{3} BTU/ft² hr. which corresponds to the region where the nucleation centers are vanishing. Is this the usual state of affairs.


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 39 — Down
q/a = 3.28 x 10^-3 ΔT^6.38
q/a = 202 ΔT^1.00
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.01 Ω std
770 mm. Hg.

Table 40
Unusual Up Run

Wire 6
0.008"

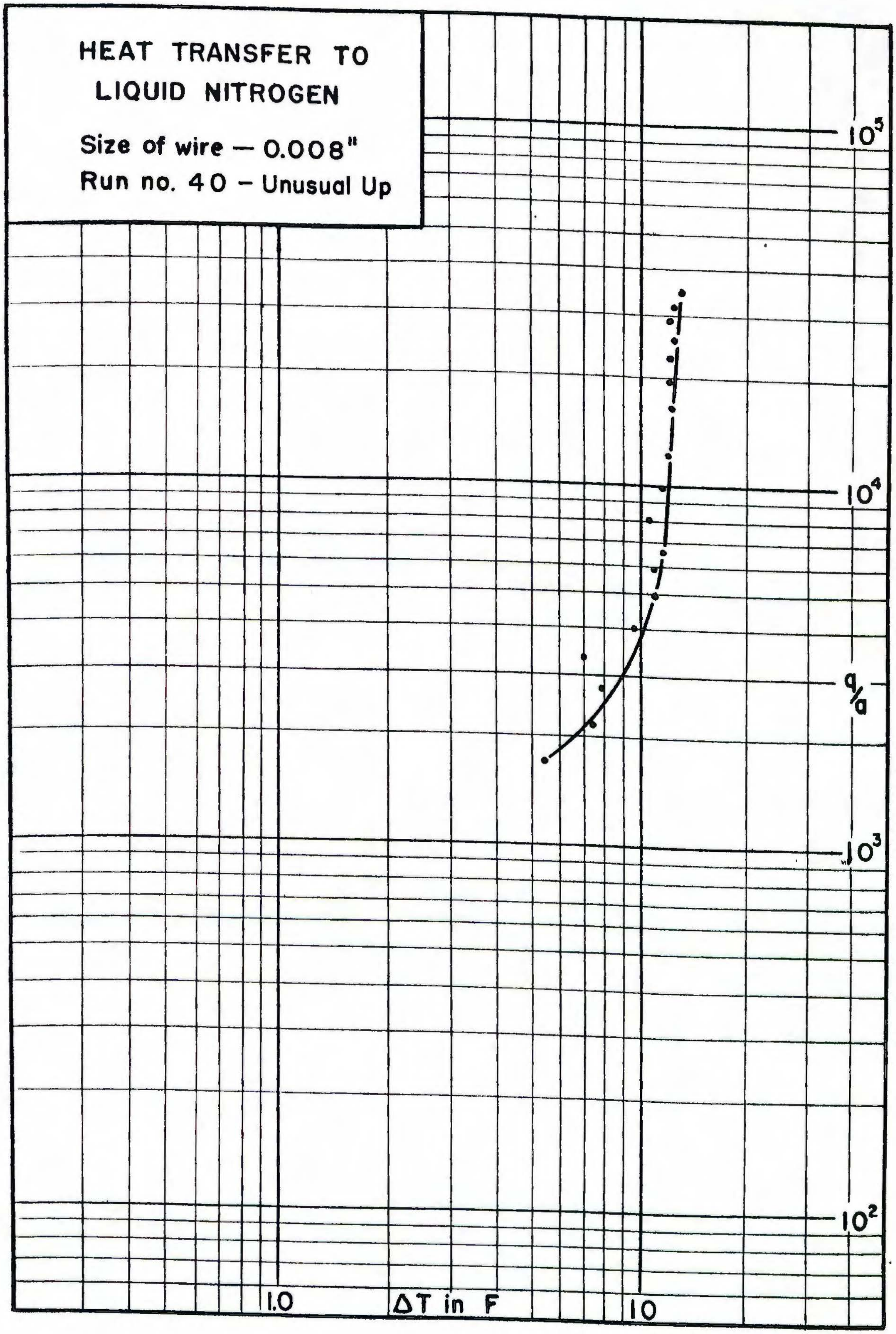
Exp. - volts	Std - volts	R - ohm	100 R/R₀	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
7.842×10^{-2}	2.372×10^{-2}	0.03306	20.25	-192.70	1.825×10^{-1}	1.72×10^{3}	3.00	5.4	*
8.746	2.586	0.03382	20.72	191.60	2.262	2.13	4.10	7.4	
9.920	2.915	0.03403	20.85	191.30	2.892	2.72	4.40	7.9	
1.090×10^{-1}	3.235	0.03369	20.64	191.80	3.526	3.32	3.90	7.0	
1.216	3.500	0.03474	21.29	190.30	4.256	4.01	5.40	9.7	
1.364	3.863	0.03530	21.63	189.50	5.269	4.96	6.20	11.2	
1.481	4.199	0.03527	21.61	189.55	6.219	5.85	6.15	11.1	
1.574	4.423	0.03559	21.80	189.10	6.962	6.55	6.60	11.9	
1.736	4.949	0.03507	21.49	189.85	8.591	8.09	5.85	10.5	
1.930	5.443	0.03546	21.72	189.30	1.050×10^{0}	9.88	6.40	11.5	
2.156	6.060	0.03558	21.80	189.10	1.307	1.23×10^{4}	6.60	11.9	
2.581	7.045	0.03574	21.90	188.90	1.774	1.67	6.80	12.2	
2.710	7.578	0.03576	21.91	188.85	2.054	1.93	6.85	12.3	
2.936	8.191	0.03584	21.96	188.75	2.405	2.26	6.95	12.5	
3.126	8.682	0.03600	22.06	188.50	2.714	2.55	7.20	13.0	
3.312	9.234	0.03587	21.98	188.70	3.058	2.88	7.00	12.6	
3.452	9.596	0.03597	22.04	188.55	3.313	3.12	7.15	12.9	
3.645	1.0124×10^{-1}	0.03600	22.06	188.50	3.690	3.47	7.20	13.0	

N_2 Calibration.

Exp	10010	10601	11250	11257	10617	10048
Std	32381	34244	36328	36330	34270	32422
R	30913	30957	30968	30985	30980	30991

Use R_{N_2} (770 mm) = 0.03098

* Normally on an up run I would go thru the extended region. However, consider this case.
1 - Establish many nucleation centers with a pulse.
2 - Lower the current slowly until the bottom of nucleate boiling occurrs.
3 - Now do an up run.


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 40 – Unusual Up
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.1 Ω std
761 mm. Hg.

Table 41
Ice Point Calibration

Wire 7
0.008"

Exp - volts	Std - volts	R - ohm
2.4887 $\times 10^{-3}$	1.3402 $\times 10^{-3}$	0.18570
2.4893	1.3398	0.18580
2.2386	1.2052	0.18575
2.0338	1.0953	0.18568
1.8626	1.0028	0.18574
1.8627	1.0029	0.18573
2.0335	1.0946	0.18577
2.2160	1.1933	0.18570

Average R_o = 0.18578 Ω

Nitrogen Calibration

1.1154	3.1713	0.035171
1.1780	3.3490	0.035174
1.1783	3.3493	0.035180
1.1153	3.1716	0.035165
1.0593	3.0120	0.035169
1.0082	2.8672	0.035163

Average R_{N_2} = 0.035172 Ω

Length of wire = 2.400 inches

$100 R_{N_2}/R_o$ = 18.93 at -195.80 °C

Calibration after ½ hour boiling in Nitrogen

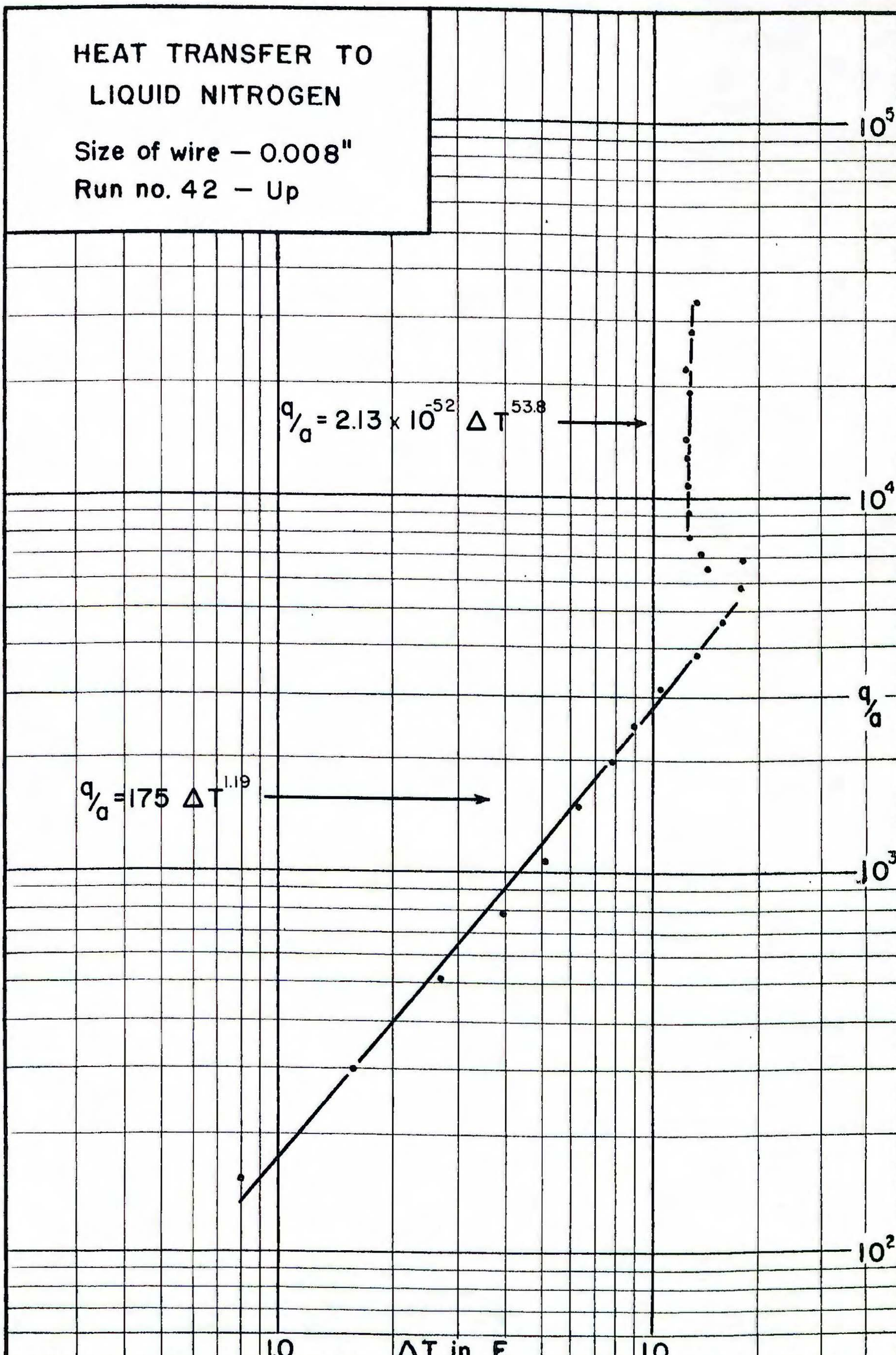
0.01 Ω Std
761 mm. Hg

Wire 7
0.008"

Table 42
Up Run

Exp.-volts	Std-volts	R-ohm	100R/Ro	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
2.601×10^{-2}	7.296×10^{-3}	0.03565	-195.35	19.18	1.898×10^{-2}	1.55×10^{2}	0.45	0.8	
3.623	1.009×10^{-2}	0.03591	19.33	194.90	3.656	2.98	0.90	1.6	
4.758	1.307	0.03640	19.59	194.30	6.219	5.07	1.50	2.7	
5.982	1.621	0.03690	19.86	193.65	9.697	7.90	2.15	3.9	
7.174	1.915	0.03746	20.16	192.95	1.374×10^{-1}	1.12×10^{3}	2.85	5.1	
8.370	2.206	0.03794	20.41	192.30	1846	1.50	3.50	6.3	
9.700	2.511	0.03863	20.79	191.45	2.436	1.98	4.35	7.8	
1.101×10^{-1}	2.812	0.03915	21.07	190.80	3.096	2.52	5.00	9.0	
1.234	3.100	0.03981	21.42	190.00	3.825	3.12	5.80	10.4	
1.399	3.401	0.04113	22.14	188.35	4.758	3.88	7.45	13.4	
1.557	3.705	0.04202	22.61	187.25	5.769	4.70	8.65	15.6	
1.748	4.060	0.04305	23.17	185.95	7.097	5.78	9.85	17.7	1
1.914	4.453	0.04298	23.13	186.00	8.523	6.94	9.80	17.6	2
1.836	4.447	0.04129	22.22	188.15	8.165	6.65	7.65	13.8	
1.902	4.615	0.04121	22.17	188.30	8.777	7.15	7.50	13.5	
1.994	4.901	0.04069	21.90	188.90	9.772	7.96	6.90	12.4	
2.138	5.248	0.04074	21.92	188.85	1.122×10^{0}	9.14	6.95	12.5	
2.328	5.712	0.04076	21.94	188.80	1.330	1.08×10^{4}	7.00	12.6	
2.534	6.213	0.04078	21.95	188.80	1.574	1.28	6.95	12.5	
2.668	6.547	0.04075	21.93	188.85	1.747	1.42	7.00	12.6	
3.087	7.559	0.04083	21.98	188.70	2.333	1.90	7.10	12.8	
3.308	8.113	0.04077	21.94	188.80	2.684	2.19	7.00	12.6	
3.744	9.140	0.04096	22.05	188.85	3.422	2.79	7.25	13.1	
4.127	1.0035×10^{-1}	0.04113	22.13	188.35	4.141	3.37	7.45	13.4	

1- No n.c.
2- Many (10-15) n.c.



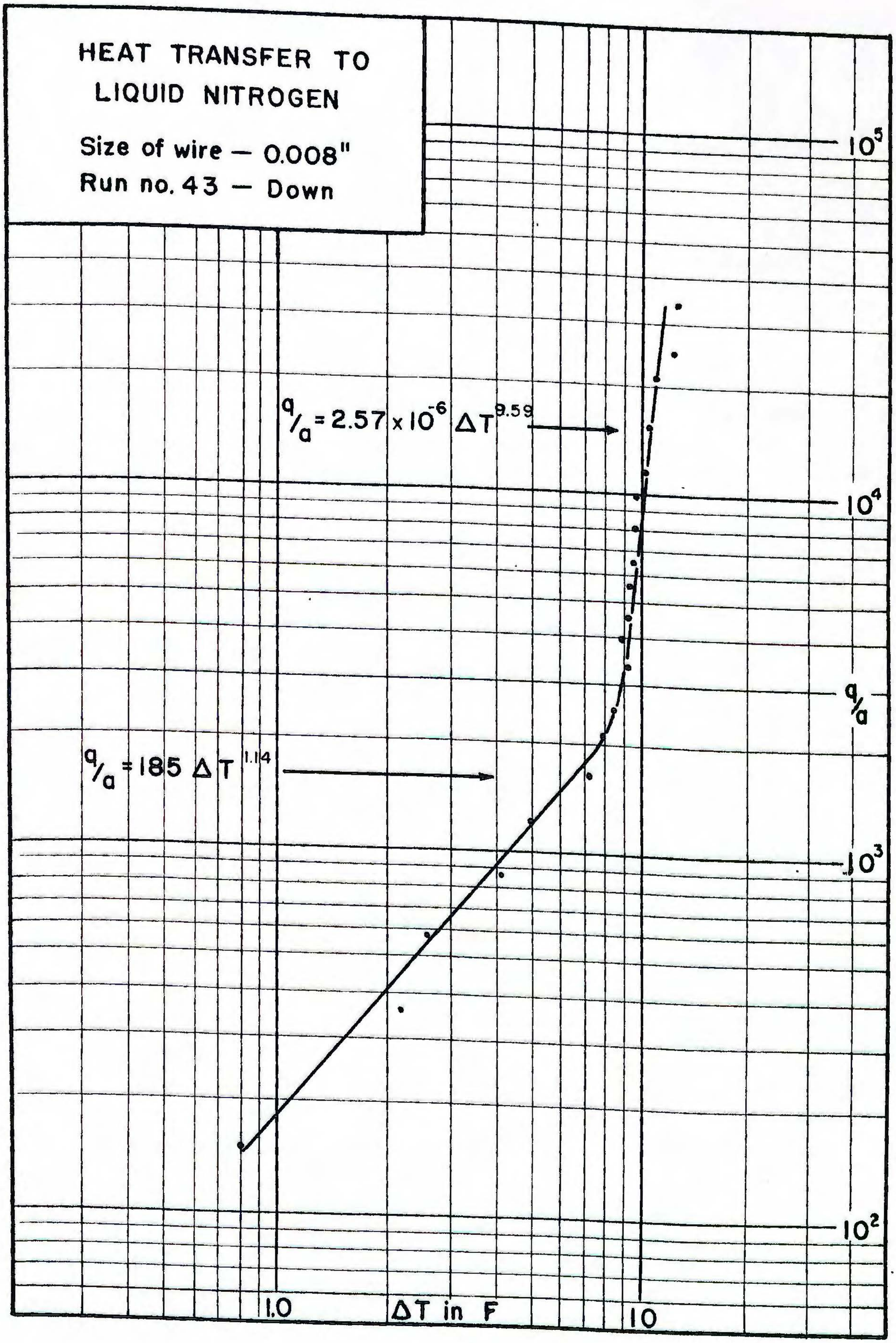
HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 42 — Up
$q/a = 2.13 \times 10^{-52}\ \Delta T^{53.8}$
$q/a = 175\ \Delta T^{1.19}$
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.01 Ω std
7.61 mm. Hg.

Table 43
Down Run

Wire 7
0.008"

Exp-volts	Std-volts	R-ohm	100R/Ro	T-°C	EI-watts	BTU/ft² hr	ΔT-°C	ΔT-°F	Notes
4.1340 × 10⁻¹	1.0160 × 10⁻¹	0.04073	21.92	-188.85	4.196 × 10⁰	3.42 × 10⁴	6.95	12.5	
3.525	8.700 × 10⁻²	0.04052	21.81	189.10	3.067	2.50	6.70	12.1	
3.232	8.065	0.04007	21.57	189.65	2.607	2.12	6.15	11.1	
2.739	6.880	0.03981	21.43	189.95	1.884	1.54	5.85	10.5	
2.364	5.966	0.03962	21.32	190.20	1.417	1.15	5.60	10.1	
2.107	5.344	0.03943	21.22	190.45	1.126	9.91 × 10³	5.35	9.6	
1.968	4.994	0.03941	21.21	190.50	9.828 × 10⁻¹	8.01	5.30	9.5	
1.778	4.521	0.03933	21.17	190.60	8.038	6.55	5.20	9.4	
1.639	4.178	0.03923	21.11	190.70	6.848	5.58	5.10	9.2	
1.486	3.785	0.03926	21.13	190.65	5.624	4.58	5.15	9.3	
1.377	3.521	0.03911	21.05	190.85	4.848	3.95	4.95	8.9	
1.263	3.220	0.03922	21.11	190.70	4.067	3.31	5.10	9.2	
1.126	2.895	0.03889	20.93	191.15	3.260	2.66	4.65	8.4	
1.008	2.607	0.03866	20.81	191.40	2.628	2.14	4.40	7.9	
8.774 × 10⁻²	2.289	0.03833	20.63	191.80	2.008	1.64	4.00	7.2	
7.472	1.997	0.03742	20.14	193.00	1.492	1.22	2.80	5.0	
6.283	1.696	0.03705	19.94	193.45	1.006	8.69 × 10²	2.35	4.2	
5.078	1.398	0.03632	19.55	194.35	7.099 × 10⁻²	5.78	1.45	2.6	
4.017	1.111	0.03616	19.46	194.60	4.463	3.64	1.20	2.2	
2.568	7.208 × 10⁻³	0.03563	19.18	195.35	1.851	1.51	0.45	0.8	



HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 43 — Down
$q/a = 2.57 \times 10^{-6}\, \Delta T^{9.59}$
$q/a = 185\, \Delta T^{1.14}$
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

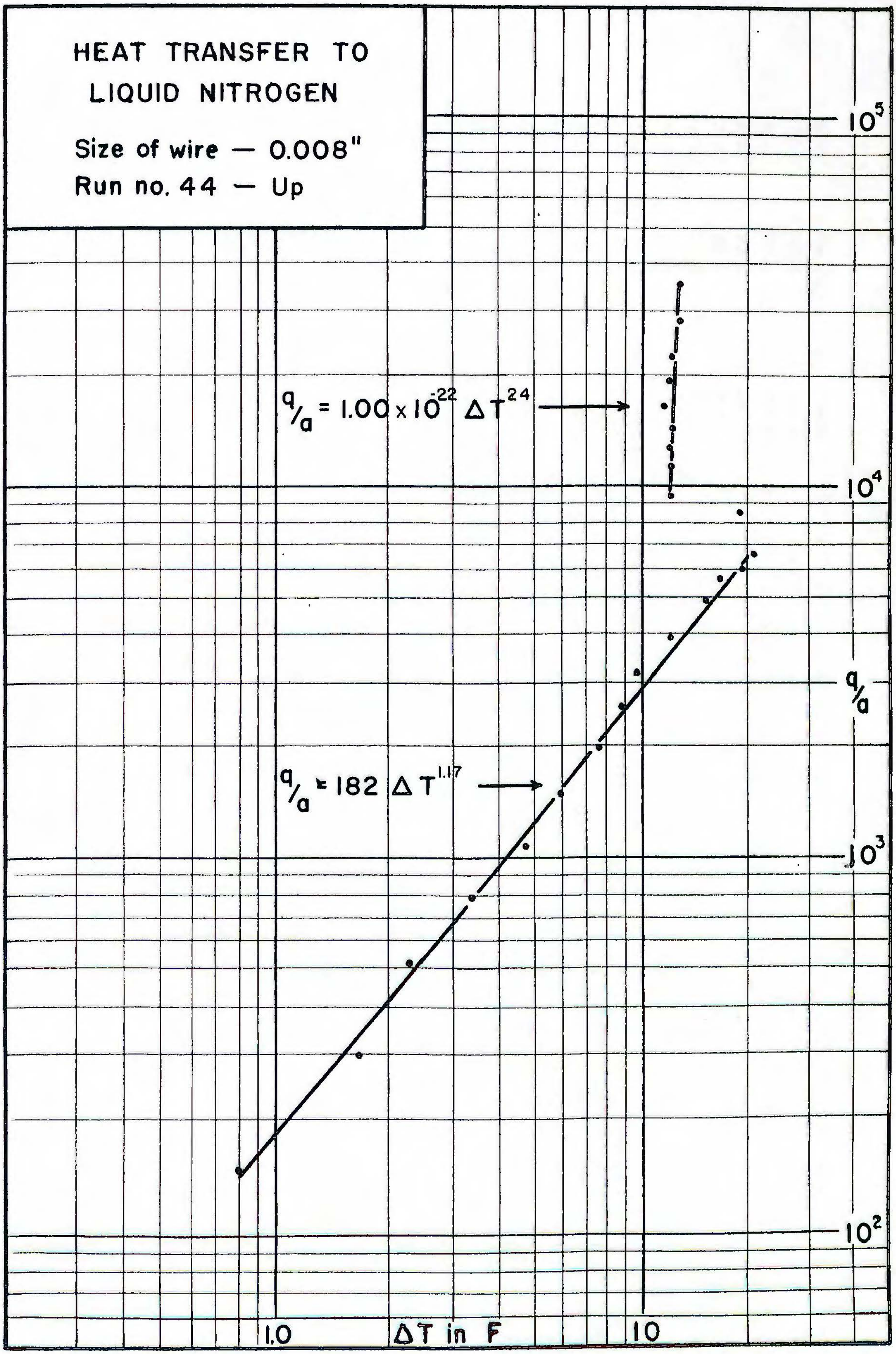
0.01 Ω std.
760 mm Hg.

Table 44
Op Run

Wire 7
0.008"

Exp-volts	std-volts	R-ohm	100R/R_o	T-°C	EI-watts	BTU/ft^2hr	ΔT-°C	ΔT-°F	Notes
2.559 x 10^{-2}	7.166 x 10^{-3}	0.03571	19.16	-195.30	1.834 x 10^{-2}	1.49 x 10^{2}	0.45	0.8	
3.640	1.009 x 10^{-2}	0.03608	19.36	194.80	3.673	2.99	0.95	1.7	
4.808	1.322	0.03637	19.51	194.45	6.356	5.18	1.30	2.3	
5.977	1.622	0.03685	19.77	193.85	9.695	7.90	1.90	3.4	
7.076	1.891	0.03742	20.08	193.10	1.338 x 10^{-1}	1.09 x 10^{3}	2.65	4.8	
8.354	2.198	0.03801	20.39	192.40	1.836	1.50	3.35	6.0	1
9.736	2.513	0.03874	20.78	191.50	2.447	1.99	4.25	7.7	1
1.115 x 10^{-1}	2.840	0.03926	21.06	190.85	3.167	2.58	4.90	8.8	1
1.239	3.127	0.03962	21.25	190.40	3.874	3.16	5.35	9.6	1
1.389	3.412	0.04071	21.84	189.05	4.739	3.86	6.70	12.1	1
1.588	3.773	0.04209	22.58	187.35	5.992	4.88	8.40	15.1	1
1.722	4.027	0.04276	22.94	186.50	6.934	5.65	9.25	16.7	1
1.935	4.444	0.04354	23.58	185.00	8.599	7.01	10.75	19.4	2
2.042	4.587	0.04452	23.88	184.30	9.367	7.63	11.45	20.6	
2.138	4.882	0.04379	23.49	185.20	1.044 x 10^{0}	8.51	10.55	19.0	
2.158	5.312	0.04063	21.80	189.10	1.146	9.34	6.65	12.0	
2.375	5.840	0.04067	21.81	189.10	1.387	1.13 x 10^{4}	6.65	12.0	
2.497	6.142	0.04065	21.81	189.10	1.534	1.25	6.65	12.0	
2.657	6.514	0.04079	21.88	188.95	1.731	1.41	6.80	12.2	
2.879	7.105	0.04052	21.74	189.25	2.046	1.67	6.50	11.7	
3.099	7.622	0.04066	21.81	189.10	2.362	1.92	6.65	12.0	
3.351	8.217	0.04078	21.88	188.95	2.754	2.24	6.80	12.2	
3.759	9.135	0.04115	22.08	188.50	3.434	2.80	7.25	13.1	
4.208	1.021 x 10^{-1}	0.04121	22.11	188.40	4.296	3.50	7.35	13.2	

1 - 1 n.c.
2 - 3 n.c.



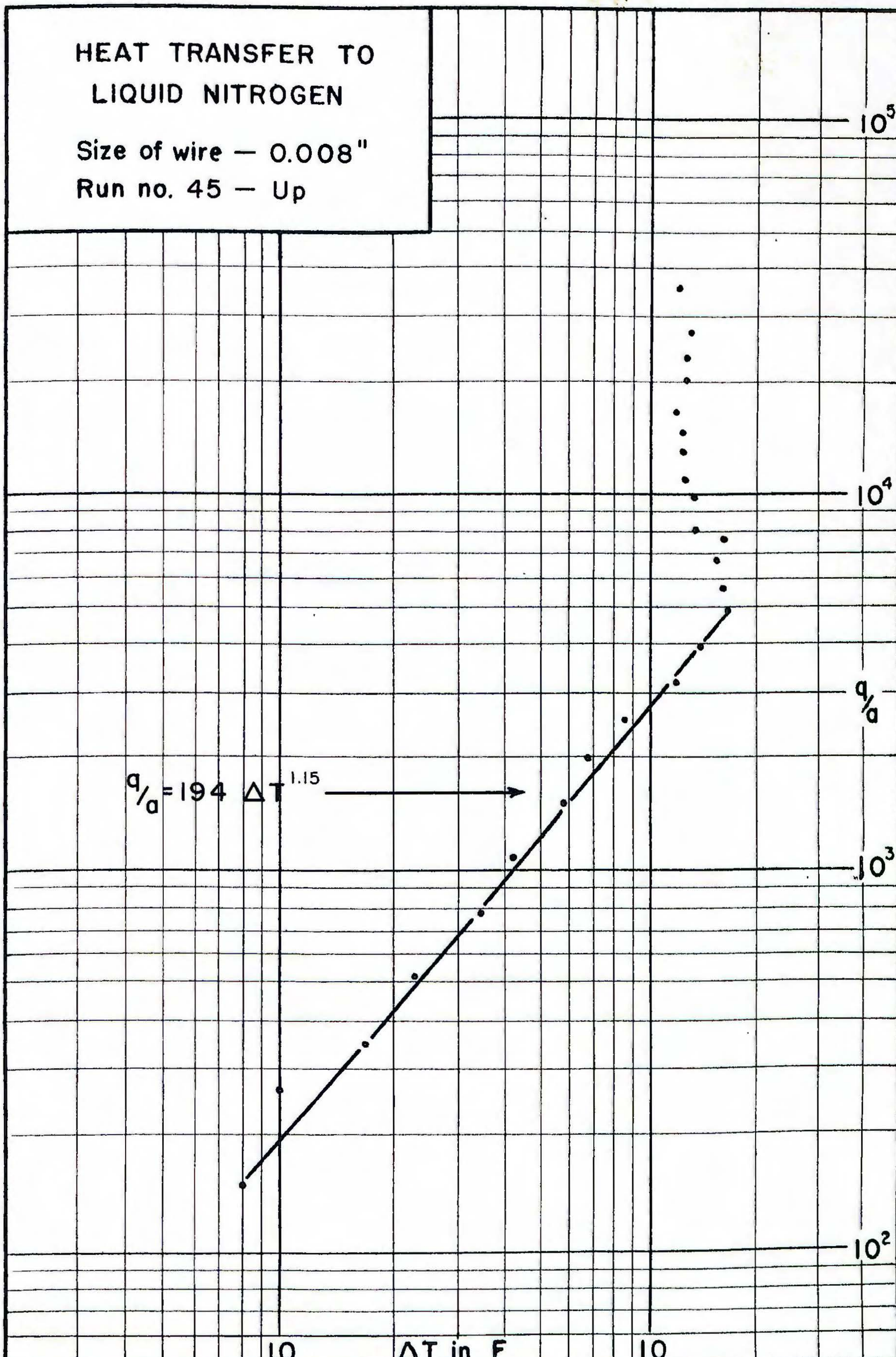
HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 44 — Up
q/a = 1.00 x 10^-22 ΔT^24
q/a = 182 ΔT^1.17
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

0.01 Ω std
760 mm. Hg.

Table 45
Up Run

Wire 7
0.008"

Exp - volts	Std. - volts	R - ohm	$100R/R_0$	T - °C	EI - watts	BTU/ft^2 hr	ΔT - °C	ΔT - °F	Notes
2.554×10^{-2}	7.163×10^{-3}	0.03566	19.12	-195.35	1.829×10^{-2}	1.49×10^{2}	0.45	0.8	
3.221	9.003	0.03578	19.18	195.25	2.900	2.36	0.55	1.0	
3.970	1.101×10^{-2}	0.03606	19.34	194.85	4.371	3.56	0.95	1.7	
4.782	1.316	0.03634	19.49	194.50	6.293	5.13	1.30	2.3	
5.946	1.612	0.03689	19.78	193.85	9.585	7.81	1.95	3.5	
7.105	1.911	0.03718	19.94	193.45	1.358×10^{-1}	1.11×10^{3}	2.35	4.2	
8.349	2.205	0.03786	20.30	192.60	1.841	1.50	3.20	5.8	
9.650	2.518	0.03832	20.55	192.00	2.430	1.98	3.80	6.8	
1.113×10^{-1}	2.843	0.03915	20.99	191.00	3.164	2.58	4.80	8.6	
1.260	3.108	0.04054	21.74	189.25	3.916	3.19	6.55	11.8	
1.410	3.402	0.04145	22.23	188.15	4.797	3.91	7.65	13.8	
1.593	3.737	0.04263	22.86	186.70	5.953	4.85	9.10	16.4	
1.712	4.033	0.04245	22.76	186.90	6.904	5.63	8.90	16.0	
1.872	4.439	0.04217	22.61	187.25	8.310	6.77	8.55	15.4	
1.995	4.696	0.04248	22.78	186.85	9.369	7.63	8.95	16.1	
2.017	4.885	0.04129	22.14	188.35	9.853	8.03	7.45	13.4	
2.232	5.408	0.04127	22.13	188.35	1.207×10^{0}	9.83	7.45	13.4	
2.348	5.740	0.04091	21.94	188.80	1.348	1.10×10^{4}	7.00	12.6	
2.547	6.222	0.04094	21.95	188.80	1.585	1.29	7.00	12.6	
2.693	6.585	0.04090	21.93	188.85	1.773	1.44	6.95	12.5	
2.882	7.079	0.04071	21.83	189.05	2.040	1.66	6.75	12.2	
3.169	7.739	0.04095	21.96	188.75	2.452	2.00	7.05	12.7	
3.293	8.035	0.04098	21.97	188.75	2.646	2.16	7.05	12.7	
3.725	9.066	0.04109	22.03	188.60	3.377	2.75	7.20	13.0	
4.203	1.031×10^{-1}	0.04077	21.86	189.00	4.333	3.53	6.80	12.2	

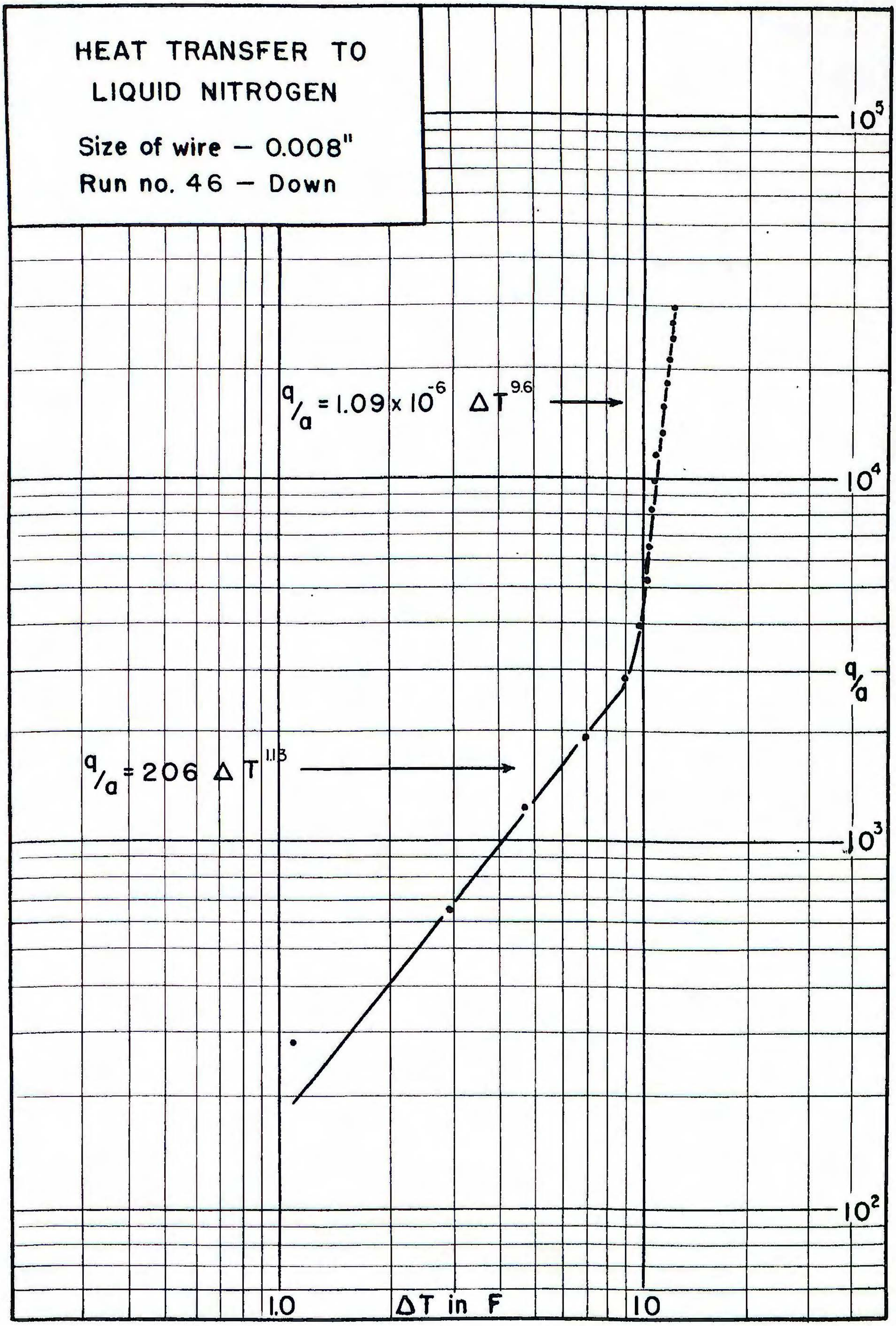

HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 45 — Up
$q/a = 194\ \Delta T^{1.15}$
10^5
10^4
10^3
10^2
q/a
1.0
ΔT in F
10

0.01 Ω std
754 mm. Hg.

Table 46
Down Run

Wire 7
0.008"

Exp - volts	Std - ohm	R - ohm	100R/Ro	T - °C	EI - watts	BTU/ft²hr	ΔT - °C	ΔT - °F	Notes
3.844 x 10⁻¹	9.433 x 10⁻²	0.04075	21.85	-189.00	3.626 x 10⁰	2.95 x 10⁴	6.80	12.2	
3.661	8.999	0.04068	21.81	189.10	3.295	2.68	6.70	12.1	
3.461	8.532	0.04056	21.75	189.25	2.953	2.41	6.55	11.8	
3.233	7.984	0.04049	21.71	189.35	2.581	2.10	6.45	11.6	
2.997	7.410	0.04045	21.69	189.40	2.221	1.81	6.40	11.5	
2.782	6.908	0.04027	25.59	189.60	1.922	1.57	6.20	11.2	
2.568	6.365	0.04035	21.64	189.45	1.635	1.33	6.35	11.4	
2.383	5.941	0.04011	21.51	189.80	1.416	1.15	6.00	10.8	
2.215	5.526	0.04008	21.49	189.85	1.224	9.97 x 10³	5.95	10.7	
1.997	5.009	0.03987	21.38	190.05	1.000	8.15	5.75	10.4	
1.790	4.484	0.03992	21.40	190.05	8.026 x 10⁻¹	6.54	5.75	10.3	
1.600	4.018	0.03982	21.35	190.15	6.429	5.24	5.65	10.2	
1.390	3.506	0.03965	21.26	190.35	4.873	3.97	5.45	9.8	
1.170	2.977	0.03930	21.07	190.80	3.483	2.84	5.00	9.0	
9.550 x 10⁻²	2.486	0.03842	20.60	191.90	2.374	1.93	3.90	7.0	
7.544	2.019	0.03737	20.04	193.20	1.523	1.24	2.60	4.7	
5.480	1.498	0.03658	19.61	194.20	8.209 x 10⁻²	6.69 x 10²	1.60	2.9	
3.526	9.848 x 10⁻³	0.03580	19.20	195.20	3.472	2.83	0.60	1.1	

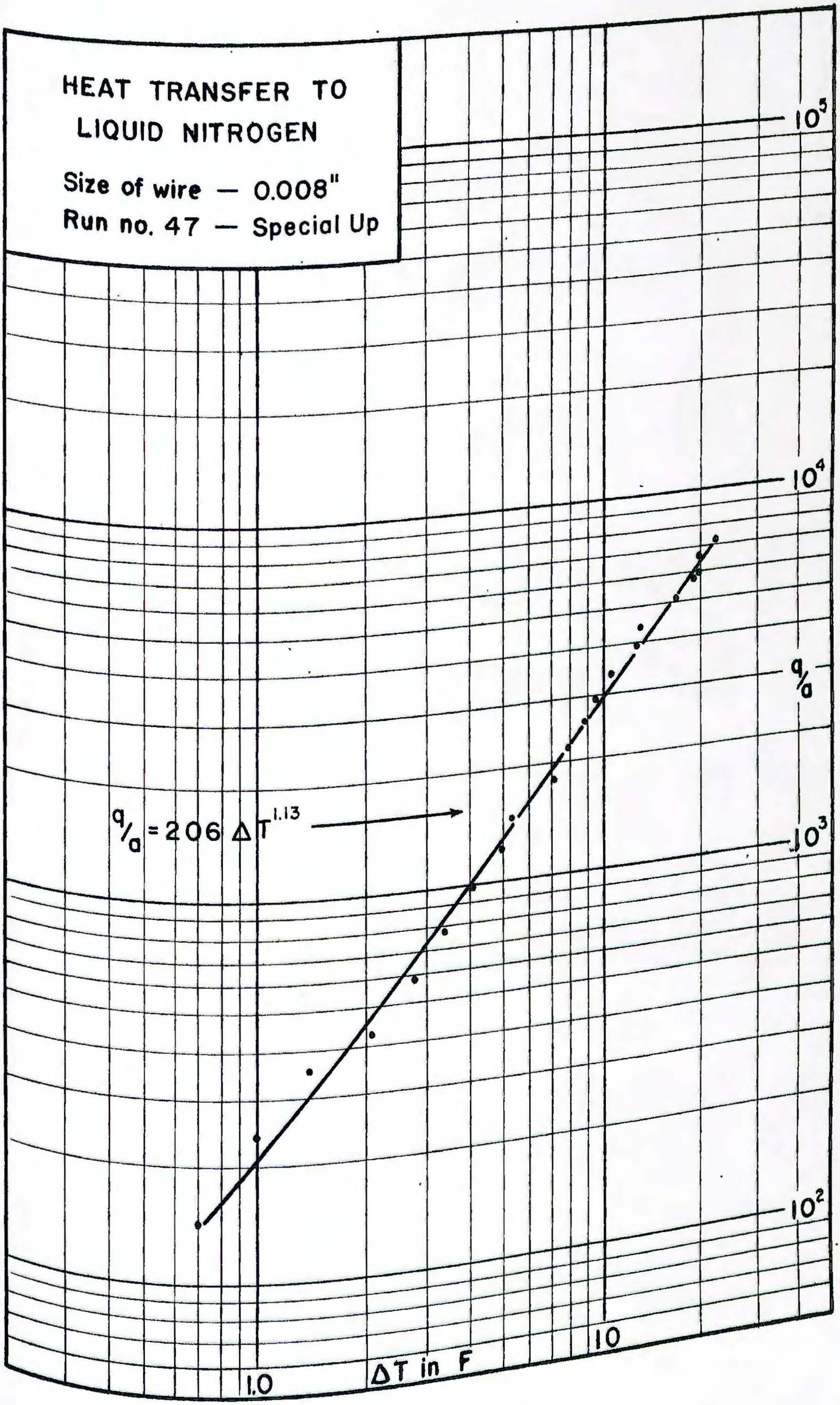

HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 46 — Down
$q/a = 1.09 \times 10^{-6}\ \Delta T^{9.6}$
$q/a = 206\ \Delta T^{1.13}$
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

0.01 Ω std
754 mm. Hg.

Table 47
Special Run

Wire 7
0.008"

Exp. - volts	Std - volts	R - ohm	100R/R₀	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
2.529×10^{-2}	7.112×10^{-3}	0.03556	19.06	-195.45	1.799×10^{-2}	1.47×10^{2}	0.40	0.7	
3.233	9.052	0.03572	19.15	195.30	2.927	2.38	0.55	1.0	
3.984	1.109×10^{-2}	0.03592	19.26	195.05	4.418	3.60	0.80	1.4	
4.350	1.202	0.03619	19.40	194.70	5.229	4.26	1.15	2.1	
5.110	1.399	0.03651	19.58	194.30	7.149	5.83	1.55	2.8	
5.910	1.606	0.03680	19.73	193.95	9.491	7.73	1.90	3.4	
6.706	1.808	0.03709	19.89	193.55	1.212×10^{-1}	9.88	2.30	4.1	
7.530	2.008	0.03750	20.11	193.05	1.512	1.23×10^{3}	2.80	5.0	
8.307	2.207	0.03763	20.18	192.90	1.833	1.49	2.95	5.3	
9.223	2.401	0.03841	20.60	191.90	2.214	1.80	3.95	7.1	
1.020×10^{-1}	2.631	0.03877	20.79	191.45	2.683	2.19	4.40	7.9	
1.106	2.822	0.03919	21.01	190.95	3.121	2.54	4.90	8.8	
1.188	3.007	0.03951	21.18	190.55	3.592	2.91	5.30	9.5	
1.288	3.223	0.03996	21.43	189.95	4.151	3.38	5.90	10.6	
1.400	3.422	0.04091	21.94	188.80	4.791	3.90	7.05	12.7	
1.486	3.621	0.04104	22.00	188.65	5.381	4.38	7.20	13.0	
1.640	3.823	0.04289	23.00	186.35	6.270	5.11	9.50	17.1	
1.762	4.030	0.04372	23.44	185.30	7.101	5.78	10.55	19.0	
1.797	4.072	0.04413	23.66	184.80	7.317	5.96	11.05	19.9	
1.898	4.299	0.04415	23.67	184.80	8.160	6.65	11.05	19.9	
2.003	4.413	0.04539	24.33	183.35	8.839	7.20	12.45	22.4	


HEAT TRANSFER TO LIQUID NITROGEN
Size of wire — 0.008"
Run no. 47 — Special Up
$q/a = 206\,\Delta T^{1.13}$
10^5
10^4
10^3
10^2
q/a
1.0
10
ΔT in F

0.01 Ω std
752 mm. Hg.

Table 48
Up Run

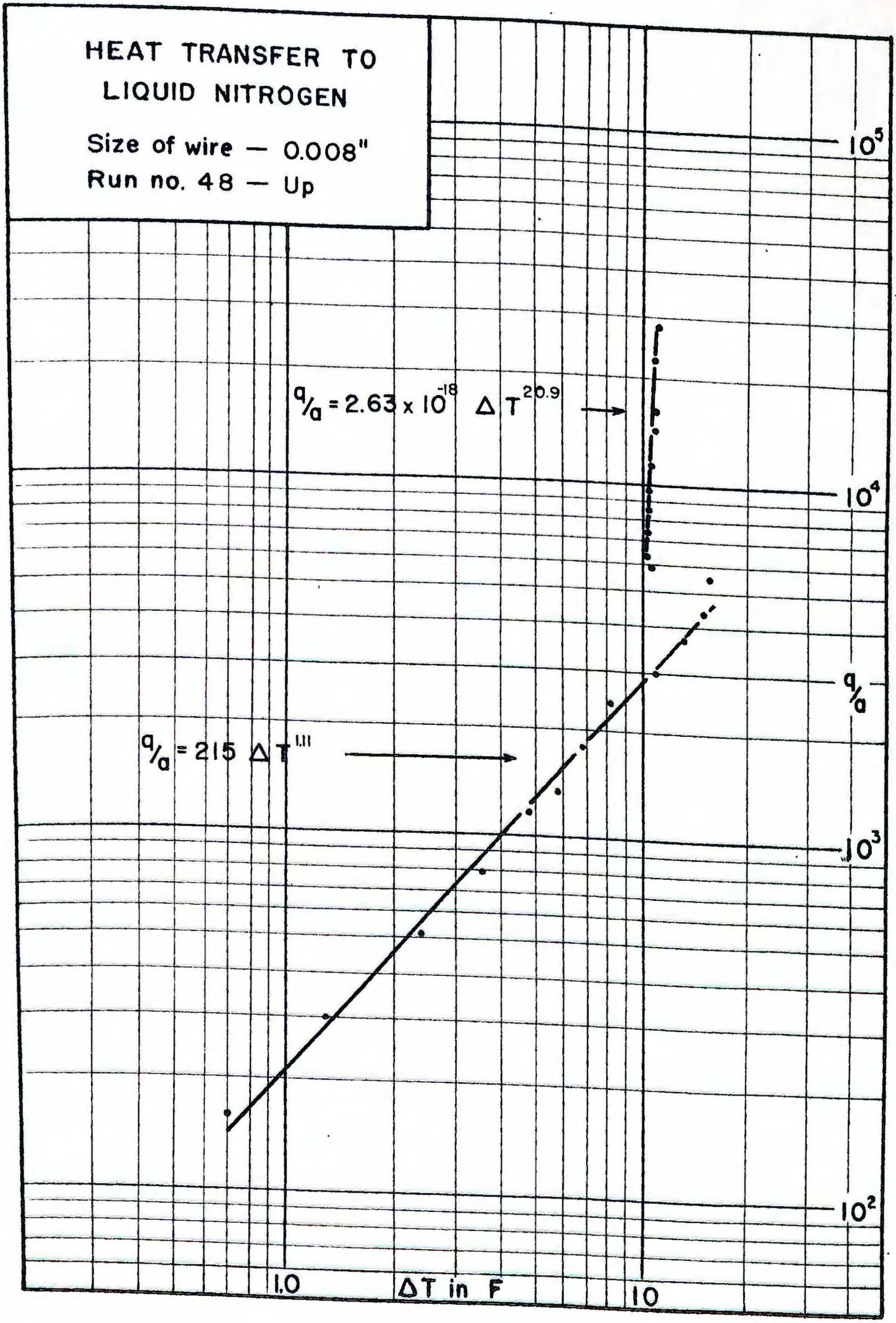
Wire 7
0.008"

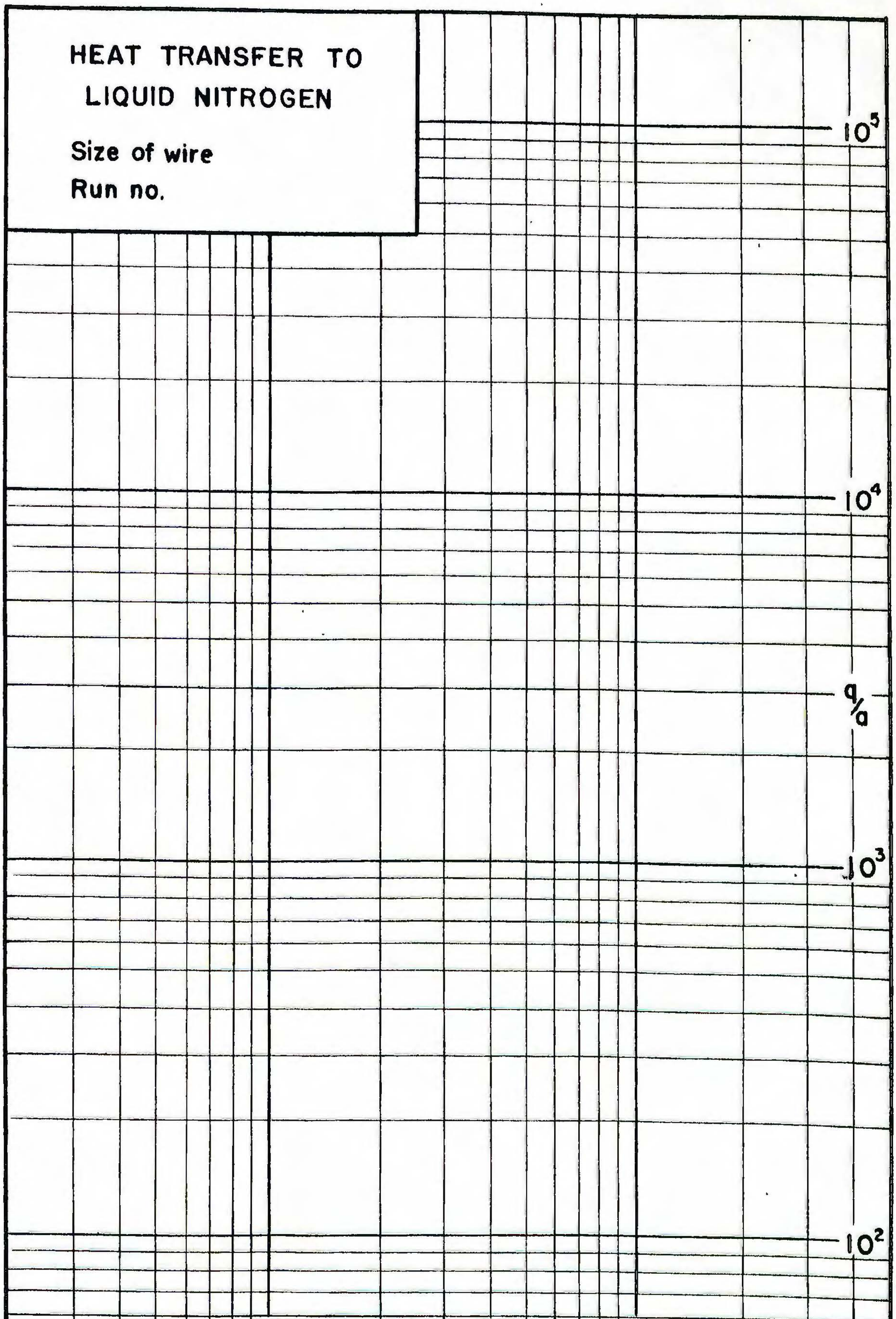
Exp - volts	Std - volts	R - ohm	$100R/R_0$	T - °C	EI - watts	BTU/ft² hr	ΔT - °C	ΔT - °F	Notes
2.684×10^{-2}	7.495×10^{-3}	0.03581	19.09	-195.45	2.012×10^{-2}	1.64×10^{2}	0.40	0.7	
3.648	1.011×10^{-2}	0.03608	19.24	195.10	3.688	3.00	0.70	1.3	
4.795	1.312	0.03655	19.49	194.50	6.291	5.13	1.35	2.4	
6.010	1.622	0.03705	19.76	193.85	9.748	7.94	2.00	3.6	
7.310	1.945	0.03758	20.04	193.20	1.422×10^{-1}	1.16×10^{3}	2.65	4.8	
7.866	2.068	0.03804	20.28	192.65	1.627	1.33	3.20	5.8	
9.210	2.394	0.03847	20.52	192.10	2.205	1.80	3.75	6.8	
1.074×10^{-1}	2.744	0.03914	20.87	191.30	2.947	2.40	4.55	8.2	
1.221	3.020	0.04043	21.56	189.66	3.687	3.00	6.20	11.2	
1.370	3.308	0.04141	22.08	188.45	4.532	3.69	7.40	13.3	
1.510	3.584	0.04213	22.47	187.60	5.412	4.41	8.25	14.9	
1.674	3.945	0.04243	22.63	187.25	6.604	5.38	8.60	15.5	
1.701	4.214	0.04011	21.39	190.05	7.214	5.88	5.80	10.4	
1.766	4.418	0.04000	21.32	190.20	7.802	6.36	5.65	10.2	
1.907	4.761	0.04005	21.36	190.15	9.079	7.40	5.70	10.3	
2.058	5.134	0.04009	21.38	190.10	1.057×10^{0}	8.61	5.75	10.4	
2.187	5.452	0.04011	21.39	190.05	1.192	9.71	5.80	10.4	
2.413	6.006	0.04018	21.43	189.95	1.449	1.18×10^{4}	5.90	10.6	
2.641	6.563	0.04024	21.46	189.95	1.733	1.41	5.95	10.7	
2.829	7.011	0.04035	21.52	189.80	1.983	1.62	6.10	11.0	
3.323	8.239	0.04033	21.51	189.80	2.738	2.23	6.05	10.9	
3.764	9.311	0.04043	21.56	189.65	3.505	2.86	6.20	11.2	
4.022	9.905	0.04060	21.65	189.45	3.984	3.25	6.40	11.5	

N_2 Calibration

Exp	11482	12119	12828
std	32352	34141	36147
R_{N_2}	35491	35497	35488

Average R_{N_2}(752 mm) = 0.03549 Ω


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire — 0.008"
Run no. 48 — Up
$q/a = 2.63 \times 10^{-18}\ \Delta T^{20.9}$
$q/a = 215\ \Delta T^{1.11}$
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10


HEAT TRANSFER TO
LIQUID NITROGEN
Size of wire
Run no.
10^5
10^4
q/a
10^3
10^2
1.0
ΔT in F
10

APPENDIX 2

THEORETICAL CALCULATIONS ALONG

ASSUMED STATE LINES

FOR LIQUID NITROGEN

Table I

Constant Enthalpy - 1350

$T_{liq} = 140°R$

r - cm	v_1 - ft^3	ΔP - psi	P_g - psia	T_g - °R	v - ft^3/lb	H - chart	$nm = v_1/v$	$n = \frac{nm}{m}$	Ave energy Liq molec.
10^{-7}	1.479×10^{-25}	2.56×10^{3}	2.57×10^{3}	328	0.020	1350	9.40×10^{-24}	7.23×10^{1}	6.93×10^{-24}
10^{-6}	$\times 10^{-22}$	" $\times 10^{2}$	2.71×10^{2}	205	0.200	"	7.40×10^{-22}	7.40×10^{3}	"
10^{-5}	$\times 10^{-19}$	" $\times 10^{1}$	4.03×10^{1}	147	1.260	"	1.174×10^{-19}	1.146×10^{6}	"
10^{-4}	$\times 10^{-16}$	" $\times 10^{0}$	1.73×10^{0}	143	3.09	"	4.786×10^{-17}	4.674×10^{8}	"
10^{-3}	$\times 10^{-13}$	" $\times 10^{-1}$	1.50×10^{-1}	142	3.57	"	4.143×10^{-14}	4.046×10^{11}	"
10^{-2}	$\times 10^{-10}$	" $\times 10^{-2}$	1.47×10^{1}	"	3.61	"	4.097×10^{-11}	4.001×10^{14}	"
10^{-1}	$\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec	Surface area bubble	Number of surf. molec.	Extra surf energy	Ave energy surf. molec.	Total energy surf + gas	Total molec surf + gas	Energy of equal liq.
1.577×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.13×10^{-22}	11.45×10^{-24}	1.933×10^{-21}	1.42×10^{2}	9.84×10^{-22}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.96×10^{-19}	1.43×10^{4}	9.91×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.60×10^{-17}	1.84×10^{6}	1.27×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	8.16×10^{-15}	5.39×10^{8}	3.22×10^{-15}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.46×10^{-12}	4.12×10^{11}	2.86×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.32×10^{-9}	4.01×10^{14}	2.78×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.31×10^{-6}	4.00×10^{17}	2.79×10^{-6}

Table 2
Constant Enthalpy · 1350
$T_{Liq} = 148°R$

r - cm	v_i - ft³	ΔP - psi	P_g - psia	T_g - °R	V - ft³/lb.	H - chart	$nm = v_i/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	2.25×10^{3}	2.277×10^{3}	320	0.0226	1350	6.544×10^{-24}	6.39×10^{1}	7.32×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.399×10^{2}	200	0.226	"	6.544×10^{-22}	6.39×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.722×10^{1}	146	1.371	"	1.079×10^{-19}	1.054×10^{6}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.695×10^{1}	143	3.17	"	4.666×10^{-17}	4.56×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.493×10^{1}	142	3.56	"	4.154×10^{-14}	4.06×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.49×10^{1}	"	3.61	"	4.097×10^{-11}	4.00×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	"	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number of surf. molec.	Extra surf energy	Ave energy surf. molec.	Total energy surf + Gas	Total molec surf + gas	Energy of equal Liq.
1.577×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.03×10^{-22}	11.69×10^{-24}	1.818×10^{-21}	1.33×10^{2}	9.73×10^{-22}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.818×10^{-19}	1.33×10^{4}	9.73×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.47×10^{-17}	1.79×10^{6}	1.28×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	8.00×10^{-16}	6.25×10^{8}	3.84×10^{-15}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.48×10^{-12}	4.13×10^{11}	3.02×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.32×10^{-9}	4.01×10^{14}	2.93×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.31×10^{-6}	4.00×10^{17}	" $\times 10^{-6}$

Table 3
Constant Enthalpy - 1350
$T_{Liq} = 156\ ^{\circ}R$

r-cm	v_l - ft³	ΔP-psi	P_g - psia	T_g - °R	V-ft³/lb.	H-chart	$nm = v_l/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	1.985×10^{3}	2.000×10^{3}	312	0.0257	1350	5.75×10^{-24}	5.62×10^{1}	7.71×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.132×10^{2}	195	0.261	"	5.89×10^{-22}	5.75×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.466×10^{1}	146	1.490	"	9.92×10^{-20}	9.69×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.668×10^{1}	143	3.250	"	4.55×10^{-17}	4.44×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.490×10^{1}	142	3.56	"	4.15×10^{-14}	4.06×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	"	3.61	"	4.10×10^{-11}	4.00×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	"	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number of surf. molec.	Extra surf energy	Ave energy surf molec.	Total energy surf + Gas	Total molec surf + Gas	Energy of equal Liq.
1.577×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.94×10^{-22}	11.95×10^{-24}	1.71×10^{-21}	1.26×10^{2}	9.71×10^{-22}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.73×10^{-19}	1.27×10^{4}	9.79×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.36×10^{-17}	1.66×10^{6}	1.28×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.83×10^{-15}	5.13×10^{8}	3.96×10^{-15}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.46×10^{-12}	4.11×10^{11}	3.19×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.32×10^{-9}	4.01×10^{14}	3.09×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.31×10^{-6}	4.00×10^{17}	3.08×10^{-6}

Table 4
Constant Enthalpy - 1350
$T_{Liq} = 164\,°R$

r - cm	v_i - ft^3	ΔP - psi	P_g - psia	T_g - °R	V - ft^3/lb.	H - chart	$nm = v_i/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	1.736×10^{3}	1.751×10^{3}	304	0.0291	1350	5.08×10^{-24}	1.96×10^{1}	8.09×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	1.883×10^{2}	189	0.283	"	5.23×10^{-22}	5.11×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.206×10^{1}	146	1.605	"	9.21×10^{-20}	8.99×10^{6}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.643×10^{1}	143	3.26	"	4.54×10^{-17}	4.43×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.487×10^{1}	142	3.56	"	4.15×10^{-14}	4.05×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	"	3.61	"	4.10×10^{-11}	4.00×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	"	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surf area. bubble	Number of surf molec	Extra surf energy	Ave energy surf molec.	Total energy surf + Gas	Total molec. surf + Gas	Energy of equal Liq.
1.577×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.87×10^{-22}	12.23×10^{-24}	1.63×10^{-21}	1.19×10^{2}	9.63×10^{-22}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.65×10^{-19}	1.20×10^{4}	9.71×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.27×10^{-17}	1.59×10^{6}	1.29×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.83×10^{-16}	5.12×10^{8}	4.14×10^{-15}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.47×10^{-12}	4.12×10^{11}	3.33×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.32×10^{-9}	4.01×10^{14}	3.24×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.31×10^{-6}	4.00×10^{17}	" $\times 10^{-6}$

Table 5
Constant Enthalpy - 1400
$T_{Liq} = 140\ °R$

r - cm	v_1 - ft³	ΔP - psi	P_g - psia	T_g - °R	v - ft³/lb.	H - chart	$nm = v_1/v$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	2.56×10^{3}	2.57×10^{3}	331	0.0216	1400	6.85×10^{-24}	6.69×10^{1}	6.93×10^{-34}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.71×10^{2}	211	0.207	"	7.14×10^{-22}	6.97×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	4.03×10^{1}	158	1.39	"	1.064×10^{-19}	1.04×10^{6}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.73×10^{1}	156	3.29	"	4.50×10^{-17}	4.39×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.50×10^{1}	"	3.87	"	3.82×10^{-14}	3.73×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.47×10^{1}	"	4.00	"	3.70×10^{-11}	3.61×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number of surface mol.	Extra surf energy	Ave. energy surf. molec.	Total energy surf + Gas	Total molec surf + Gas	Energy of equal Liq.
1.610×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.13×10^{-22}	11.45×10^{-24}	1.89×10^{-21}	1.36×10^{2}	9.42×10^{-22}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.91×10^{-19}	1.39×10^{4}	9.63×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.46×10^{-17}	1.73×10^{6}	1.20×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.86×10^{-15}	5.08×10^{8}	3.52×10^{-15}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	4.08×10^{-12}	3.80×10^{11}	2.63×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.82×10^{-9}	3.62×10^{14}	2.51×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.81×10^{-6}	3.61×10^{17}	2.50×10^{-6}

Table 6
Constant Enthalpy - 1400
$T_{Liq} = 148\,^\circ R$

r-cm	v_1 - ft³	ΔP-psi	P_g-psia	T_g-°R	V-ft³/lb.	H-chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy of Liq. molec.
10^{-7}	1.479×10^{-25}	2.262×10^{3}	2.277×10^{3}	323	0.0232	1400	6.38×10^{-24}	6.23×10^{1}	2.32×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.399×10^{2}	204	0.234	"	6.32×10^{-22}	6.17×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.722×10^{1}	158	1.490	"	9.92×10^{-20}	9.69×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.695×10^{1}	156	3.410	"	4.34×10^{-17}	4.23×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.493×10^{1}	"	3.87	"	3.82×10^{-14}	3.73×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	"	4.00	"	3.70×10^{-11}	3.61×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec	Surface area bubble	Number surf. molec.	Extra surf. energy	Ave energy surf. molec.	Total energy surf + Gas	Total molec Surf + Gas	Energy of equal Liq.
1.610×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.03×10^{-22}	11.69×10^{-24}	1.81×10^{-21}	1.32×10^{2}	9.66×10^{-23}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.80×10^{-19}	1.31×10^{4}	9.59×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.37×10^{-17}	1.66×10^{6}	1.22×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.62×10^{-15}	4.92×10^{8}	3.60×10^{-15}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.08×10^{-12}	3.80×10^{11}	2.78×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.82×10^{-9}	3.62×10^{14}	2.66×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.81×10^{-6}	3.61×10^{17}	2.64×10^{-6}

Table 7
Constant Enthalpy - 1400
$T_{Liq} = 156\ °R$

r - cm	v_b - ft^3	ΔP - psi	P_g - psia	T_g - °R	V - ft^3/lb.	H - chart	nms = v_b/V	n = nm/m	Ave energy Liq molec.
10^{-7}	1.479×10^{-25}	1.985×10^{3}	2.000×10^{3}	315	0.0280	1400	5.28×10^{-24}	5.15×10^{1}	7.71×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.132×10^{2}	202	0.257	"	5.76×10^{-22}	5.62×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.455×10^{1}	158	1.63	"	9.07×10^{-20}	8.86×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.668×10^{1}	156	3.48	"	4.26×10^{-17}	4.15×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.490×10^{1}	"	3.87	"	3.82×10^{-14}	3.73×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	"	4.00	"	3.70×10^{-11}	3.61×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec.	Extra surf energy	Ave energy surf. molec.	Total energy surf + Gas	Total molec. surf + Gas	Energy of equal Liq.
1.61×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.94×10^{-22}	11.95×10^{-24}	1.66×10^{-21}	1.21×10^{2}	9.33×10^{-22}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.73×10^{-19}	1.26×10^{4}	9.71×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.25×10^{-17}	1.58×10^{6}	1.22×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.61×10^{-15}	4.84×10^{8}	3.73×10^{-15}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.01×10^{-12}	3.80×10^{11}	2.93×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.82×10^{-9}	3.62×10^{14}	2.79×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.81×10^{-6}	3.61×10^{17}	2.78×10^{-6}

Table 8

Constant Enthalpy -1400

$T_{Liq} = 164\ ^\circ R$

r-cm.	v_1 - ft^3	ΔP-psi	P_g-psia	T_g-°R	V-ft^3/lb.	H-chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	1.736×10^{3}	1.751×10^{3}	307	0.0309	1400	4.79×10^{-24}	4.67×10^{1}	8.09×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	1.883×10^{2}	195	0.296	"	5.00×10^{-22}	4.88×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.206×10^{1}	158	1.765	"	8.38×10^{-20}	8.18×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.643×10^{1}	156	3.53	"	4.19×10^{-17}	4.09×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.487×10^{1}	"	3.89	"	3.80×10^{-14}	3.71×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	"	4.00	"	3.70×10^{-11}	3.61×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	3.61×10^{17}	"

Ave energy Gas molec	Surface area bubble	Number surf molec	Extra energy surf molec	Ave energy surf molec	Total energy surf + Gas	Total molec Surf. + Gas	Energy of equal liq.
1.610×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.87×10^{-22}	12.23×10^{-24}	1.59×10^{-21}	1.16×10^{2}	9.38×10^{-22}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.63×10^{-19}	1.18×10^{4}	9.55×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.17×10^{-17}	1.51×10^{6}	1.22×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.43×10^{-15}	4.72×10^{8}	3.82×10^{-15}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.06×10^{-12}	3.78×10^{11}	3.06×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.82×10^{-9}	3.62×10^{15}	2.93×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.81×10^{-6}	3.61×10^{17}	2.92×10^{-6}

Table 9
Constant Enthalpy - 1450
$T_{Liq} = 140\,^{\circ}R$

r - cm	v_1 - ft³	ΔP - psi	P_g - psia	T_g - °R	V - ft³/lb	H-chart	$nm = \frac{v_1}{V}$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	2.56×10^{3}	2.57×10^{3}	338	0.0228	1450	6.49×10^{-24}	6.33×10^{1}	6.93×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.71×10^{2}	229	0.228	"	6.49×10^{-22}	6.33×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	4.03×10^{1}	171	1.498	"	9.87×10^{-20}	9.64×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.73×10^{1}	169	3.66	"	4.04×10^{-19}	3.94×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.50×10^{1}	168	4.22	"	3.50×10^{-14}	3.42×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.47×10^{1}	"	4.31	"	3.43×10^{-11}	3.35×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec	Surface area bubble	Number surf. molec	Extra surf. energy	Ave energy surf molec.	Total energy surf + Gas	Total molec surf + Gas	Energy of equal Liq.
1.64×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.13×10^{-22}	11.45×10^{-24}	1.83×10^{-21}	1.33×10^{2}	9.22×10^{-22}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.83×10^{-19}	1.33×10^{4}	9.22×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.37×10^{-17}	1.60×10^{6}	1.11×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.25×10^{-15}	4.63×10^{8}	3.21×10^{-16}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	5.69×10^{-12}	3.49×10^{11}	2.42×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.50×10^{-9}	3.36×10^{14}	2.33×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.49×10^{-6}	" $\times 10^{17}$	2.32×10^{-6}

Table 10
Constant Enthalpy - 1450
$T_{Liq} = 148\,°R$

r-cm	v_1 - ft³	ΔP-psi	P_g - psia	T_g - °R	V - ft³/lb.	H-chart	$n_m = v/V$	$n = \frac{n_m}{m}$	Ave energy Liq. molec
10^{-7}	1.479×10^{-26}	2.262×10^{3}	2.277×10^{3}	330	0.0263	1450	5.62×10^{-24}	5.49×10^{1}	7.32×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.399×10^{2}	211	0.257	"	5.75×10^{-22}	5.61×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.722×10^{1}	173	1.64	"	9.02×10^{-20}	8.81×10^{5}	"
10^{-4}	" $\times 10^{-18}$	" $\times 10^{0}$	1.695×10^{1}	169	3.71	"	3.99×10^{-17}	3.90×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.493×10^{1}	168	4.21	"	3.51×10^{-14}	3.43×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	"	4.31	"	3.43×10^{-11}	3.35×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec	Extra Surf energy	Ave. energy surf. molec.	Total energy surf+Gas	Total molec. surf+Gas	Energy of equal liq.
1.64×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.03×10^{-22}	11.69×10^{-24}	1.71×10^{-21}	1.24×10^{2}	9.08×10^{-22}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.73×10^{-19}	1.25×10^{4}	9.15×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.26×10^{-17}	1.57×10^{6}	1.15×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.21×10^{-15}	4.53×10^{8}	3.32×10^{-15}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	5.84×10^{-12}	3.50×10^{11}	2.56×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.50×10^{-9}	3.36×10^{14}	2.46×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.49×10^{-6}	3.35×10^{17}	2.45×10^{-6}

Table 11
Constant Enthalpy - 1450
$T_{Liq.} = 156\,°R$

r - cm	v_1 - ft^3	ΔP - psi	P_g - psia	T_g - °R	V - ft^3/lb	H-chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	1.985×10^{3}	2.000×10^{3}	322	0.0297	1450	4.98×10^{-24}	4.86×10^{1}	7.71×10^{-24}
10^{-6}	" $\times10^{-22}$	" $\times10^{2}$	2.132×10^{2}	206	0.286	"	5.17×10^{-22}	5.06×10^{3}	"
10^{-5}	" $\times10^{-19}$	" $\times10^{1}$	3.456×10^{1}	171	1.885	"	7.84×10^{-20}	7.66×10^{5}	"
10^{-4}	" $\times10^{-16}$	" $\times10^{0}$	1.668×10^{1}	169	3.49	"	4.24×10^{-17}	4.14×10^{8}	"
10^{-3}	" $\times10^{-13}$	" $\times10^{-1}$	1.490×10^{1}	168	4.20	"	3.52×10^{-14}	3.44×10^{11}	"
10^{-2}	" $\times10^{-10}$	" $\times10^{-2}$	1.490×10^{1}	"	4.31	"	3.43×10^{-11}	3.35×10^{14}	"
10^{-1}	" $\times10^{-7}$	" $\times10^{-3}$	" $\times10^{1}$	"	"	"	" $\times10^{-8}$	" $\times10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec.	Extra surf. energy	Ave energy surf. molec.	Total energy Surf + Gas	Total molec Surf + Gas	Energy of equal Liq.
1.64×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.94×10^{-22}	11.95×10^{-24}	1.63×10^{-21}	1.18×10^{2}	9.10×10^{-22}
"	" $\times10^{-14}$	" $\times10^{3}$	" $\times10^{-20}$	"	1.66×10^{-19}	1.20×10^{4}	9.25×10^{-20}
"	" $\times10^{-12}$	" $\times10^{5}$	" $\times10^{-18}$	"	2.08×10^{-17}	1.46×10^{6}	1.13×10^{-17}
"	" $\times10^{-10}$	" $\times10^{7}$	" $\times10^{-16}$	"	7.62×10^{-15}	4.83×10^{8}	3.72×10^{-15}
"	" $\times10^{-8}$	" $\times10^{9}$	" $\times10^{-14}$	"	5.72×10^{-12}	3.51×10^{11}	2.71×10^{-12}
"	" $\times10^{-6}$	" $\times10^{11}$	" $\times10^{-12}$	"	5.50×10^{-9}	3.36×10^{14}	2.59×10^{-9}
"	" $\times10^{-4}$	" $\times10^{13}$	" $\times10^{-10}$	"	5.49×10^{-6}	3.35×10^{17}	2.58×10^{-6}

Table 12
Constant Enthalpy - 1450
$T_{Liq} = 164\,^{\circ}R$

r-cm	v_i-ft^3	ΔP-psia	P_g-psia	T_g-°R	V-ft^3/lb.	H-chart	$nm = v_i/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec
10^{-7}	1.479×10^{-25}	1.736×10^{3}	1.751×10^{3}	314	0.0334	1450	4.43×10^{-24}	4.33×10^{1}	8.09×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	1.883×10^{2}	202	0.320	"	4.62×10^{-22}	4.51×10^{3}	" $\times 10^{-24}$
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.206×10^{1}	171	1.930	"	7.66×10^{-20}	7.48×10^{5}	" $\times 10^{-24}$
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.643×10^{1}	169	3.54	"	4.18×10^{-17}	3.98×10^{8}	" $\times 10^{-24}$
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.487×10^{1}	168	4.20	"	3.52×10^{-14}	3.44×10^{11}	" $\times 10^{-24}$
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	"	4.31	"	3.43×10^{-11}	3.35×10^{14}	" $\times 10^{-24}$
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	" $\times 10^{-24}$

Ave energy Gas molec.	Surface area bubble	Number surf molec	Extra surf energy	Ave. energy surf molec	Total energy surf + Gas	Total molec. Surf + Gas	Energy of equal liq.
1.64×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.87×10^{-22}	12.23×10^{-24}	1.56×10^{-21}	1.13×10^{2}	9.14×10^{-22}
"	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.59×10^{-19}	1.14×10^{4}	9.22×10^{-20}
"	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.08×10^{-17}	1.44×10^{6}	1.16×10^{-17}
"	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.37×10^{-15}	4.67×10^{8}	3.78×10^{-15}
"	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	5.72×10^{-12}	3.51×10^{11}	2.84×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.50×10^{-9}	3.36×10^{14}	2.72×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.49×10^{-6}	3.35×10^{17}	2.71×10^{-6}

Table 13
Constant Entropy - 17.0
$T_{Liq} = 140\,°R$

r - cm	v_1 - ft³	ΔP - psi	P_g - psia	T_g - °R	V - ft³/lb	H-chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq molec.
10^{-7}	1.479×10^{-26}	2.56×10^{3}	2.57×10^{3}	614	0.103	3075	1.436×10^{-24}	1.40×10^{1}	6.93×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.71×10^{2}	337	0.446	2030	3.316×10^{-22}	3.24×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	4.03×10^{1}	185	1.64	1510	9.02×10^{-20}	8.81×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.73×10^{1}	140	3.03	1345	4.88×10^{-17}	4.77×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.50×10^{1}	135	3.29	1320	4.50×10^{-14}	4.39×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.47×10^{1}	134	3.43	1315	4.31×10^{-11}	4.21×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	4.21×10^{17}	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec.	Extra surf energy	Ave. energy surf. molec.	Total energy Surf + Gas	Total molec. Surf + Gas	Energy of equal Liq.
2.705×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.13×10^{-22}	11.45×10^{-24}	1.17×10^{-21}	8.33×10^{1}	5.77×10^{-22}
2.02×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.48×10^{-19}	1.02×10^{4}	7.07×10^{-20}
1.68×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.27×10^{-17}	1.57×10^{6}	1.09×10^{-17}
1.57×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	8.28×10^{-15}	5.46×10^{8}	3.78×10^{-15}
1.56×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.92×10^{-12}	4.46×10^{11}	3.09×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.58×10^{-9}	4.22×10^{14}	2.92×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.57×10^{-6}	4.21×10^{17}	2.91×10^{-6}

Table 14
Constant Entropy - 17.0
$T_{Liq.} = 148^{o}R$

r-cm	v_1-ft^3	ΔP-psi	P_g-psia	T_g-^oR	V-ft^3/lb	H-chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq molec.
10^{-7}	1.479×10^{-25}	2.252×10^{3}	2.277×10^{3}	598	0.1115	3010	1.326×10^{-24}	1.29×10^{1}	7.32×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.399×10^{2}	324	0.486	1995	3.043×10^{-22}	2.97×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.722×10^{1}	181	1.77	1487	8.356×10^{-20}	8.16×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.695×10^{1}	140	3.09	1335	4.786×10^{-17}	4.67×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.493×10^{1}	135	3.31	1320	4.468×10^{-14}	4.36×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	134	3.43	1315	4.312×10^{-11}	4.21×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	"	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surface mol.	Extra surf energy	Ave energy surf. molec.	Total energy surf + Gas	Total molec surf + Gas	Energy of equal Liq.
2.66×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.03×10^{-22}	11.69×10^{-24}	1.15×10^{-21}	8.22×10^{1}	6.02×10^{-22}
2.00×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.40×10^{-19}	9.90×10^{3}	7.25×10^{-20}
1.67×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.17×10^{-17}	1.51×10^{6}	1.11×10^{-17}
1.57×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	8.14×10^{-15}	5.36×10^{8}	3.92×10^{-15}
1.56×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.88×10^{-12}	4.43×10^{11}	3.24×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.58×10^{-9}	4.22×10^{14}	3.09×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.57×10^{-6}	4.21×10^{17}	3.08×10^{-6}

Table 15
Constant Entropy - 17.0
T_{Liq} = 156 °R

r-cm	v_1 - ft³	ΔP-psi	P_g - psia	T_g - °R	V-ft³/lb.	H-chart	nm = v_1/V	n = nm/m	Ave energy Liq molec.
10^{-7}	1.479×10^{-25}	1.985×10^{3}	2.000×10^{3}	577	0.123	2930	1.20×10^{-24}	1.17×10^{1}	7.71×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.132×10^{2}	311	0.530	1955	2.79×10^{-22}	2.72×10^{3}	"
10^{-5}	" $\times 10^{-20}$	" $\times 10^{1}$	3.455×10^{1}	176	1.835	1470	8.05×10^{-20}	7.87×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.668×10^{1}	139	3.14	1330	4.69×10^{-17}	4.56×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.490×10^{1}	135	3.34	1320	4.43×10^{-14}	4.33×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	134	3.43	1315	4.312×10^{-11}	4.21×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec	Surface area bubble	Number surf-molec.	Extra surf energy	Ave energy surf. molec.	Total energy surf+Gas	Total molec. Surf+Gas	Energy of equal liq.
2.61×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.94×10^{-22}	11.95×10^{-24}	1.13×10^{-21}	8.10×10^{1}	6.25×10^{-22}
1.97×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.36×10^{-19}	9.65×10^{3}	7.44×10^{-20}
1.65×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.13×10^{-17}	1.48×10^{6}	1.14×10^{-17}
1.56×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.94×10^{-15}	5.25×10^{8}	4.05×10^{-15}
1.55×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.79×10^{-12}	4.40×10^{11}	3.39×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.54×10^{-9}	4.22×10^{14}	3.25×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.53×10^{-6}	4.21×10^{17}	3.24×10^{-6}

Table 16
Constant Entropy - 17.0
$T_{Liq} = 164\ °R$

r-cm	v_1 - ft³	ΔP - psi	P_g - psia	T_g - °R	V - ft³/lb.	H-chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	1.763×10^{3}	1.751×10^{3}	564	0.131	2865	1.13×10^{-24}	1.10×10^{1}	8.09×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	1.883×10^{2}	301	0.580	1915	2.66×10^{-23}	2.49×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.206×10^{1}	172	1.974	1455	7.62×10^{-20}	7.44×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.643×10^{1}	138	3.14	1345	4.71×10^{-17}	4.60×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.487×10^{1}	134	3.36	1315	4.40×10^{-14}	4.30×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	"	3.43	"	4.012×10^{-11}	4.21×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	"	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec.	Extra surf. energy	Ave energy surf. molec.	Total energy surf. + Gas	Total molec. surf. + Gas	Energy of equal Liq.
2.57×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.84×10^{-22}	12.23×10^{-24}	1.13×10^{-21}	8.03×10^{1}	5.60×10^{-22}
1.95×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.33×10^{-19}	9.42×10^{3}	7.62×10^{-20}
1.65×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.08×10^{-17}	1.45×10^{6}	1.17×10^{-17}
1.57×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	8.07×10^{-16}	6.23×10^{8}	4.23×10^{-15}
1.56×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.95×10^{-12}	4.37×10^{11}	3.54×10^{-12}
"	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.58×10^{-9}	4.22×10^{14}	3.41×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.57×10^{-6}	4.21×10^{17}	3.40×10^{-6}

Table 17
Constant Entropy - 17.3
$T_{Liq} = 140\,^\circ R$

r - cm	v_1 - ft³	ΔP - psi	P_g - psia	T_g - °R	V - ft³/lb.	H-chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	2.56×10^{3}	2.57×10^{3}	630	0.105	3170	1.409×10^{-24}	1.38×10^{1}	6.93×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.71×10^{2}	350	0.468	2095	3.16×10^{-22}	3.09×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	4.03×10^{1}	193	1.714	1530	8.63×10^{-20}	8.43×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.73×10^{1}	147.5	3.24	1365	4.56×10^{-17}	4.45×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.50×10^{1}	142	3.50	1340	4.23×10^{-14}	4.13×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.47×10^{1}	140	3.59	1330	4.12×10^{-11}	4.02×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	"	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surface mol.	Extra surf. energy	Ave energy surf. molec.	Total energy surf + Gas	Total molec surf + Gas	Energy of equal Liq.
2.77×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.13×10^{-22}	11.45×10^{-24}	1.18×10^{-21}	8.31×10^{1}	5.76×10^{-22}
2.06×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.43×10^{-19}	1.01×10^{4}	7.00×10^{-20}
1.69×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.22×10^{-17}	1.54×10^{6}	1.07×10^{-17}
1.59×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.87×10^{-15}	5.08×10^{8}	3.52×10^{-15}
1.57×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.56×10^{-12}	4.20×10^{11}	2.91×10^{-12}
1.56×10^{-23}	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.28×10^{-9}	4.03×10^{14}	2.79×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.27×10^{-6}	4.02×10^{17}	" $\times 10^{-6}$

Table 18
Constant Entropy - 17.3
$T_{Liq} = 148\ ^\circ R$

r - cm	v, in ft³	ΔP - psi	P_g - psia	T_g - °R	V - ft³/lb	H - chart	$nm = v/V$	$n = \frac{nm}{m}$	Ave energy Liq molec
10^{-7}	1.479×10^{-26}	2.252×10^{3}	2.277×10^{3}	616	0.1142	3100	1.295×10^{-24}	1.265×10^{1}	7.32×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.399×10^{2}	338	0.513	2055	2.88×10^{-22}	2.81×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.722×10^{1}	188	1.825	1520	8.10×10^{-20}	7.91×10^{6}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.695×10^{1}	147	3.214	1362	4.60×10^{-17}	4.49×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.493×10^{1}	142	3.50	1340	4.23×10^{-14}	4.13×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	140	3.59	1330	4.12×10^{-11}	4.02×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	"	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec	Surface area bubble	Number surf. molec.	Extra surf. energy	Ave energy surf. molec	Total energy surf + Gas	Total molec surf + Gas	Energy of equal liq.
2.72×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.03×10^{-22}	11.69×10^{-24}	1.15×10^{-21}	8.20×10^{1}	6.00×10^{-22}
2.04×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.38×10^{-19}	9.74×10^{3}	7.13×10^{-20}
1.69×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.15×10^{-17}	1.48×10^{6}	1.09×10^{-17}
1.58×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.90×10^{-15}	5.18×10^{8}	3.79×10^{-15}
1.57×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.56×10^{-12}	4.20×10^{11}	3.07×10^{-12}
1.56×10^{-23}	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.28×10^{-9}	4.03×10^{14}	2.95×10^{-9}
"	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.27×10^{-6}	4.02×10^{17}	2.94×10^{-6}

Table 19
Constant Entropy - 17.3
$T_{Liq} = 156\,^\circ R$

r-cm	v_1 - ft^3	ΔP-psi	P_g-psia	T_g-°R	V-ft^3/lb.	H-chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	1.985×10^{3}	2.000×10^{3}	600	0.1285	3020	1.151×10^{-24}	1.124×10^{1}	7.71×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.132×10^{2}	327	0.554	2010	2.67×10^{-22}	2.61×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.455×10^{1}	184	1.915	1500	7.72×10^{-20}	7.54×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.668×10^{1}	147	3.26	1360	4.54×10^{-17}	4.43×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.490×10^{1}	142	3.52	1340	4.20×10^{-14}	4.10×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	140	3.59	1330	4.12×10^{-11}	4.02×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	"	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec.	Extra surf. energy	Ave energy surf. molec.	Total energy surf.+Gas	Total molec. surf.+Gas	Energy of equal Liq.
2.67×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.94×10^{-22}	11.95×10^{-24}	1.13×10^{-21}	8.05×10^{1}	6.21×10^{-22}
2.01×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.35×10^{-19}	9.54×10^{3}	7.35×10^{-20}
1.67×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.09×10^{-17}	1.46×10^{6}	1.12×10^{-17}
1.58×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.83×10^{-16}	5.12×10^{8}	3.95×10^{-16}
1.57×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.51×10^{-12}	4.17×10^{11}	3.22×10^{-12}
1.56×10^{-23}	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.28×10^{-9}	4.03×10^{14}	3.11×10^{-9}
" $\times 10^{-23}$	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.27×10^{-6}	4.02×10^{17}	3.10×10^{-6}

Table 20
Constant Entropy - 17.3
$T_{Liq} = 164\,°R$

r - cm	v_1 - ft³	ΔP - psi	P_g - psia	T_g - °R	V - ft³/lb	H - chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq molec.
10^{-7}	1.479×10^{-25}	1.736×10^{3}	1.751×10^{3}	585	0.1372	2945	1.078×10^{-24}	1.05×10^{1}	8.09×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	1.883×10^{2}	312	0.641	1970	2.31×10^{-22}	2.26×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.206×10^{1}	180	2.11	1485	9.01×10^{-20}	6.86×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.643×10^{1}	146	3.29	1360	4.50×10^{-17}	4.39×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.487×10^{1}	141	3.52	1335	4.20×10^{-14}	4.10×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	140	3.59	1330	4.12×10^{-11}	4.02×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec	Extra Surf. energy	Ave energy Surf molec	Total energy surf + Gas	Total molec surf + Gas	Energy of equal Liq.
2.62×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.84×10^{-22}	12.23×10^{-24}	1.12×10^{-21}	7.98×10^{1}	6.46×10^{-22}
1.98×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.30×10^{-19}	9.19×10^{3}	7.43×10^{-20}
1.67×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	1.99×10^{-17}	1.38×10^{6}	1.12×10^{-17}
1.58×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.78×10^{-15}	5.08×10^{8}	4.11×10^{-15}
1.57×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.52×10^{-12}	4.17×10^{11}	3.37×10^{-12}
1.56×10^{-23}	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	6.28×10^{-9}	4.03×10^{14}	3.26×10^{-9}
" $\times 10^{-23}$	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	6.27×10^{-6}	4.02×10^{17}	3.25×10^{-6}

Table 21
Constant Entropy -18.0
$T_{Liq.} = 140\,°R$

r-cm	v_1 - ft³	ΔP-psi	P_g - psia	T-°R	V-ft³/lb.	H-chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec
10^{-7}	1.479×10^{-25}	2.56×10^{3}	2.57×10^{3}	702	0.111	3475	1.33×10^{-24}	1.30×10^{1}	6.93×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.71×10^{2}	383	0.523	2235	2.83×10^{-22}	2.76×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	4.03×10^{1}	212	1.905	1615	7.76×10^{-20}	7.58×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.73×10^{1}	163	3.49	1425	4.24×10^{-17}	4.14×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.50×10^{1}	158	3.85	1400	3.84×10^{-14}	3.75×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.47×10^{1}	156	3.93	1396	3.76×10^{-11}	3.67×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	"	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec.	Extra surf. energy	Ave energy surf. molec.	Total energy surf + Gas	Total molec. surf + Gas	Energy of equal Liq.
2.97×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.13×10^{-22}	11.45×10^{-24}	1.18×10^{-21}	8.23×10^{1}	5.70×10^{-22}
2.16×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.39×10^{-19}	9.69×10^{3}	6.71×10^{-20}
1.76×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.12×10^{-17}	1.45×10^{6}	1.00×10^{-17}
1.63×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.54×10^{-15}	4.83×10^{8}	3.35×10^{-15}
1.61×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.12×10^{-12}	3.82×10^{11}	2.65×10^{-12}
1.60×10^{-23}	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.88×10^{-9}	3.68×10^{14}	2.55×10^{-9}
" $\times 10^{-23}$	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.87×10^{-6}	3.67×10^{17}	2.54×10^{-6}

Table 22
Constant Entropy - 18.0
$T_{Liq} = 148\,^\circ R$

r-cm	v_1 - ft^3	ΔP-psi	P_g-psia	T_g-°R	v-ft^3/lb.	H-chart	$nm = \frac{v_1}{V}$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	2.252×10^{3}	2.277×10^{3}	680	0.1223	3380	1.209×10^{-24}	1.18×10^{1}	7.32×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.399×10^{2}	371	0.567	2185	2.608×10^{-22}	2.55×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.722×10^{1}	209	2.02	1590	7.32×10^{-20}	7.15×10^{6}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.696×10^{1}	161	3.54	1420	4.18×10^{-17}	4.08×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.493×10^{1}	157	3.86	1400	3.83×10^{-14}	3.74×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	156	3.93	1395	3.76×10^{-11}	3.67×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec.	Extra surf. energy	Ave energy surf. molec.	Total energy surf. + Gas	Total molec surf. + Gas	Energy of equal Liq.
2.91×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.03×10^{-22}	11.69×10^{-24}	1.15×10^{-21}	8.11×10^{1}	5.94×10^{-22}
2.12×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.35×10^{-19}	9.48×10^{3}	6.94×10^{-20}
1.68×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	2.01×10^{-17}	1.41×10^{6}	1.03×10^{-17}
1.62×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.42×10^{-15}	4.77×10^{8}	3.49×10^{-15}
1.61×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.10×10^{-12}	3.81×10^{11}	2.79×10^{-12}
" $\times 10^{-23}$	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.92×10^{-9}	3.68×10^{14}	2.69×10^{-9}
" $\times 10^{-23}$	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.91×10^{-6}	3.67×10^{17}	" $\times 10^{-6}$

Table 23
Constant Entropy -180
$T_{Liq} = 156\ °R$

r-cm	v_i - ft³	ΔP-psia	P_g-psia	T_g-°R	V-ft³/lb.	H-chart	$nm = v_i/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	1.985×10^{3}	2.000×10^{3}	658	0.1345	3390	1.10×10^{-24}	1.09×10^{1}	7.71×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.132×10^{2}	366	0.569	2135	2.60×10^{-22}	2.64×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.455×10^{1}	202	2.13	1575	6.94×10^{-20}	6.78×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.668×10^{1}	160	3.60	1420	4.11×10^{-17}	4.01×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.490×10^{1}	157	3.91	1400	3.79×10^{-14}	3.70×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	156	3.93	1395	3.76×10^{-11}	3.69×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec	Surf area bubble	Number surf. molec.	Extra surf energy	Ave energy surf. molec.	Total energy surf. + Gas	Total molec. surf. + Gas	Energy of equal Liq.
2.91×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.94×10^{-22}	11.95×10^{-24}	1.14×10^{-21}	8.00×10^{1}	6.17×10^{-22}
2.09×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.36×10^{-19}	9.47×10^{3}	7.30×10^{-20}
1.72×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	1.99×10^{-17}	1.39×10^{6}	1.06×10^{-17}
1.62×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.32×10^{-15}	4.70×10^{8}	3.62×10^{-15}
1.61×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	6.04×10^{-12}	3.74×10^{11}	2.91×10^{-12}
1.60×10^{-23}	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.88×10^{-9}	3.68×10^{14}	2.84×10^{-9}
" $\times 10^{-23}$	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.87×10^{-6}	3.67×10^{17}	2.83×10^{-6}

Table 24
Constant Entropy - 18.0
$T_{Liq} = 164\,°R$

r - cm	v_1 - ft³	ΔP - psi	P_g - psia	T_g - °R	V - ft³/lb.	H-chart	nm = v_1/V	n = $\frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	1.736×10^{3}	1.751×10^{3}	635	0.149	3210	1.006×10^{-26}	9.82×10^{0}	8.09×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	1.883×10^{2}	345	0.760	2090	1.946×10^{-22}	1.90×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.206×10^{1}	196	2.24	1555	6.60×10^{-20}	6.44×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.643×10^{0}	159	3.62	1415	4.08×10^{-17}	3.98×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.483×10^{1}	159	3.92	1395	3.77×10^{-14}	3.68×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	156	3.93	"	3.76×10^{-11}	3.67×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec.	Extra surf. energy	Ave energy surf. molec.	Total energy surf. + Gas	Total molec. Surf. + Gas	Energy of equal Liq.
2.79×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.84×10^{-22}	12.23×10^{-24}	1.12×10^{-21}	7.91×10^{1}	6.40×10^{-22}
2.06×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.24×10^{-19}	8.83×10^{3}	7.14×10^{-20}
1.71×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	1.96×10^{-17}	1.34×10^{6}	1.08×10^{-17}
1.62×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	7.30×10^{-16}	4.67×10^{8}	3.78×10^{-15}
1.60×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	5.97×10^{-12}	3.75×10^{11}	3.03×10^{-12}
" $\times 10^{-23}$	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.88×10^{-9}	3.68×10^{14}	2.98×10^{-9}
" $\times 10^{-23}$	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.87×10^{-6}	3.67×10^{17}	2.97×10^{-6}

Table 25
Constant Entropy - 19.0
$T_{liq.}$ = 140 °R

r - cm	v_1 - ft³	ΔP - psi	P_g - psia	T_g - °R	V - ft³/lb.	H-chart	nm = v/V	n = nM/M	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	2.56×10^{3}	2.59×10^{3}	819	0.113	3970	1.309×10^{-24}	1.28×10^{1}	6.93×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.71×10^{2}	437	0.606	2460	2.44×10^{-22}	2.38×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	4.03×10^{1}	243	2.23	1730	6.63×10^{-20}	6.47×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.73×10^{1}	186	4.04	1525	3.66×10^{-17}	3.57×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.50×10^{1}	179	4.45	1495	3.32×10^{-14}	3.24×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.47×10^{1}	177	4.54	1485	3.26×10^{-11}	3.18×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec.	Extra surf. energy	Ave energy surf. molec.	Total energy Surf + Gas	Total molec. Surf + Gas	Energy equal Liquid.
3.29×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.13×10^{-22}	11.45×10^{-24}	1.21×10^{-21}	8.21×10^{1}	5.69×10^{-22}
2.30×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.34×10^{-19}	9.31×10^{3}	6.45×10^{-20}
1.82×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	1.99×10^{-17}	1.34×10^{6}	9.29×10^{-18}
1.69×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	6.82×10^{-16}	4.26×10^{8}	2.95×10^{-15}
1.67×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	5.49×10^{-12}	3.31×10^{11}	2.29×10^{-12}
1.67×10^{-23}	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.32×10^{-9}	3.19×10^{14}	2.21×10^{-9}
" $\times 10^{-23}$	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.31×10^{-6}	3.18×10^{17}	2.20×10^{-6}

Table 26
Constant Entropy - 19.0
$T_{Liq} = 148\ ^\circ R$

r-cm	v_1 - ft^3	ΔP-psi	P_g-psia	T_g-°R	V-ft^3/lb.	H-chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	2.252×10^{3}	2.277×10^{3}	792	0.123	3,870	1.20×10^{-24}	1.17×10^{1}	7.32×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.399×10^{2}	423	0.658	2400	2.25×10^{-22}	2.20×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.722×10^{1}	238	2.39	1715	6.19×10^{-20}	6.04×10^{5}	"
10^{-4}	" $\times 10^{-17}$	" $\times 10^{0}$	1.695×10^{1}	185	4.11	1520	3.60×10^{-17}	3.52×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.493×10^{1}	179	4.47	1495	3.31×10^{-14}	3.23×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	177	4.54	1485	3.26×10^{-11}	3.18×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number surf. molec.	Extra surf. energy	Ave energy surf. molec.	Total energy surf + Gas	Total molec. surf + Gas	Energy of equal Liq.
3.23×10^{-23}	1.35×10^{-16}	6.93×10^{1}	3.03×10^{-22}	11.69×10^{-24}	1.19×10^{-21}	8.10×10^{1}	5.93×10^{-22}
2.26×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.31×10^{-19}	9.13×10^{3}	6.68×10^{-20}
1.82×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	1.91×10^{-17}	1.30×10^{6}	9.52×10^{-18}
1.69×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	6.76×10^{-15}	4.21×10^{8}	3.08×10^{-15}
1.67×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	5.47×10^{-12}	3.30×10^{11}	2.42×10^{-12}
" $\times 10^{-23}$	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.32×10^{-9}	3.19×10^{14}	2.33×10^{-9}
" $\times 10^{-23}$	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.31×10^{-6}	3.18×10^{17}	" $\times 10^{-6}$

Table 27
Constant Entropy - 19.0
$T_{Liq.} = 156\,^{\circ}R$

r - cm	v_1 - ft³	ΔP - psi	P_g - psia	T_g - °R	V - ft³/lb.	H - chart	$nm = v_1/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	2.262×10^{3}	2.000×10^{3}	761	0.143	3750	1.034×10^{-24}	1.01×10^{1}	7.71×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	2.132×10^{2}	409	0.714	2345	2.07×10^{-22}	2.02×10^{3}	"
10^{-5}	" $\times 10^{-20}$	" $\times 10^{1}$	3.455×10^{1}	232	2.51	1690	5.89×10^{-20}	6.75×10^{5}	"
10^{-4}	" $\times 10^{-17}$	" $\times 10^{0}$	1.668×10^{1}	184	4.18	1515	3.54×10^{-17}	3.46×10^{8}	"
10^{-3}	" $\times 10^{-15}$	" $\times 10^{-1}$	1.490×10^{1}	178	4.49	1490	3.29×10^{-14}	3.21×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	177	4.54	1485	3.26×10^{-11}	3.18×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area. bubble	Number surf. molec.	Extra surf. energy	Ave energy surf molec.	Total energy surf.+gas.	Total molec. surf.+Gas	Energy of equal Liq.
3.15×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.94×10^{-22}	11.95×10^{-24}	1.15×10^{-21}	7.94×10^{1}	6.12×10^{-22}
2.23×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.28×10^{-19}	8.95×10^{3}	6.90×10^{-20}
1.80×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	1.86×10^{-17}	1.27×10^{6}	9.79×10^{-18}
1.68×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	6.64×10^{-15}	4.15×10^{8}	3.20×10^{-15}
1.67×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	5.44×10^{-12}	3.28×10^{11}	2.53×10^{-12}
" $\times 10^{-23}$	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.32×10^{-9}	3.19×10^{14}	2.46×10^{-9}
" $\times 10^{-23}$	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.31×10^{-6}	3.18×10^{17}	2.45×10^{-6}

Table 28
Constant Entropy - 19.0
$T_{Liq} = 164\ ^{\circ}R$

r-cm	v_i - ft³	ΔP-psi	P_g-psia	T_g-°R	V-ft³/lb.	H-chart	$nm = v_i/V$	$n = \frac{nm}{m}$	Ave energy Liq. molec.
10^{-7}	1.479×10^{-25}	1.736×10^{3}	1.751×10^{3}	720	0.154	3640	9.60×10^{-26}	9.38×10^{0}	8.09×10^{-24}
10^{-6}	" $\times 10^{-22}$	" $\times 10^{2}$	1.883×10^{2}	392	0.780	2285	1.90×10^{-23}	1.85×10^{3}	"
10^{-5}	" $\times 10^{-19}$	" $\times 10^{1}$	3.206×10^{1}	227	2.65	1675	5.58×10^{-20}	5.45×10^{5}	"
10^{-4}	" $\times 10^{-16}$	" $\times 10^{0}$	1.643×10^{1}	184	4.20	1510	3.52×10^{-17}	3.44×10^{8}	"
10^{-3}	" $\times 10^{-13}$	" $\times 10^{-1}$	1.487×10^{1}	178	4.50	1490	3.29×10^{-14}	3.21×10^{11}	"
10^{-2}	" $\times 10^{-10}$	" $\times 10^{-2}$	1.470×10^{1}	177	4.54	1485	3.26×10^{-11}	3.18×10^{14}	"
10^{-1}	" $\times 10^{-7}$	" $\times 10^{-3}$	" $\times 10^{1}$	"	"	"	" $\times 10^{-8}$	" $\times 10^{17}$	"

Ave energy Gas molec.	Surface area bubble	Number of Surf. molec.	Extra surf. energy	Ave energy surf. molec.	Total energy surf + gas	Total molec. surf + Gas	Energy of equal Liq.
3.08×10^{-23}	1.35×10^{-16}	6.93×10^{1}	2.87×10^{-22}	12.23×10^{-24}	1.14×10^{-21}	7.74×10^{1}	6.26×10^{-22}
2.19×10^{-23}	" $\times 10^{-14}$	" $\times 10^{3}$	" $\times 10^{-20}$	"	1.25×10^{-19}	8.78×10^{3}	7.10×10^{-20}
1.79×10^{-23}	" $\times 10^{-12}$	" $\times 10^{5}$	" $\times 10^{-18}$	"	1.82×10^{-17}	1.24×10^{6}	1.00×10^{-17}
1.68×10^{-23}	" $\times 10^{-10}$	" $\times 10^{7}$	" $\times 10^{-16}$	"	6.63×10^{-15}	4.07×10^{8}	3.29×10^{-15}
1.67×10^{-23}	" $\times 10^{-8}$	" $\times 10^{9}$	" $\times 10^{-14}$	"	5.44×10^{-12}	3.28×10^{11}	2.65×10^{-12}
" $\times 10^{-23}$	" $\times 10^{-6}$	" $\times 10^{11}$	" $\times 10^{-12}$	"	5.32×10^{-9}	3.19×10^{14}	2.58×10^{-9}
" $\times 10^{-23}$	" $\times 10^{-4}$	" $\times 10^{13}$	" $\times 10^{-10}$	"	5.31×10^{-6}	3.18×10^{17}	2.57×10^{-6}

APPENDIX 3

DERIVATION OF THE MAXWELL-BOLTZMAN DISTRIBUTION FOR DIATOMICS

The equipartition theorem proposes that each degree of freedom of a molecule should be as capable of receiving energy as any other, and that in the steady state the average energy of each degree of freedom will be the same. Of course this will only be true if the average is taken over a large number of molecules, say 10^4. It could be true for a small number, say 10, also; but it would be difficult to be sure. A nitrogen molecule might thus be expected to have energy associated with it in the following ways.

a. Translation along the x axis = E_x

b. Translation along the y axis = E_y

c. Translation along the z axis = E_z

d. Rotation about the x axis = E_θ

e. Rotation about the y axis = E_ϕ

f. Rotation about the z axis = E_ψ

g. Vibration of normal modes = E_v

h. Electrons in excited states = E_e

Fortunately the quantum theory eliminates some of these in the range of temperatures which are of interest in this problem. It also shows that the classical theory is substantially correct in its interpetation of the energy associated with the remaining degrees of freedom. Let us see which of a-h above are of significance and which can be eliminated. The three of translation (a,b,c) may be kept but one of the rotational axes will be inactive. This is the axis which passes thru both molecules. Let us say the Z axis. The quantum theory then shows that there will be no vibration as long as the assembly is below some characteristic temperature $\theta_{vib.}$ which for nitrogen is $3380^{\circ}K.$[26] Electronic excitation occurs at an even higher temperature so it need not be considered. Consequently

$$E \text{ total} = E_x + E_y + E_z + E_\theta + E_\Phi$$

And

$$E_x = E_y = E_z = E_\theta = E_\psi \quad \text{where E denotes energy.}$$

Now following Slater[26] whose treatment is most lucid, one writes the expression for the momentum of all the molecules between P and P + dP

$$\iiiint\!\!\int \exp^{-\left(\frac{P_x^2}{2mkT} + \frac{P_y^2}{2mkT} + \frac{P_z^2}{2mkT} + \frac{P_\theta^2}{2IkT} + \frac{P_\Phi^2}{2IkT}\right)} dP_x\, dP_y\, dP_z\, dP_\theta\, dP_\Phi$$

where P is momentum, m is the mass of the molecule, I is the moment of inertia, k is the Boltzman constant, and T is the absolute temperature. Let n be the fraction of the total energy contained in $E_x + E_y + E_z$. Consequently $E_\theta + E_\Phi$ will contain the fraction 1-n. Or

$$E_x + E_y + E_z = n\, E_T \text{ and } E_\theta + E_\Phi = (1-n)\, E_T$$

But by definition

$$E_x = \frac{P_x^2}{2m}, \quad E_\theta = \frac{P_\theta^2}{2I} \text{ etc.}$$

So substituting above

$$\iiiint\!\!\int \exp^{-\left(\frac{E_x}{kT} + \frac{E_y}{kT} + \frac{E_z}{kT} + \frac{E_\theta}{kT} + \frac{E_\Phi}{kT}\right)} dP_x\, dP_y\, dP_z\, dP_\theta\, dP_\Phi$$

$$\iiiint\!\!\int \exp^{-\frac{E_T}{kT}} dP_x\, dP_y\, dP_z\, dP_\theta\, dP_\Phi$$

Now $dP_x\, dP_y\, dP_z$ represents the volume of a spherical shell for which the corresponding velocity vectors have magnitude between v and v + dv

Thus

$$dP_x\, dP_y\, dP_z = [\tfrac{4}{3}\pi\, (mv + mdv)^3 - \tfrac{4}{3}\pi\, (mv)^3] = 4\pi m^2 v^2 dV$$

Now since $n\, E_T = \frac{1}{2} m\, (V_x{}^2 + V_y{}^2 + V_z{}^2) = \frac{1}{2} mv^2$ the expression for

$dP_x\, dP_y\, dP_z = 4\sqrt{2}\, \pi\, m^{3/2}\, n^{3/2}\, E_T{}^{1/2}\, dE_T$

In like fashion $dP_\theta\, dP_\Phi$ as an annular region for which the corresponding velocity vectors lie between ω and $\cdot\omega d\omega$.

Thus

$$dP_\theta dP_\Phi = [\pi\, (I\omega + Id\omega)^2 - \pi(I\omega)^2] = 2\pi I^2\, \omega d\omega$$

And since $(1-n)\, E_T = \frac{1}{2} I\, (\omega_\theta{}^2 + \omega_\Phi{}^2) = \frac{1}{2} I\, \omega^2$ the expression for

$dP_\theta\, dP_\Phi$ becomes by substitution for

$$dP_\theta\, dP_\Phi = 2\pi I(1-n)\, dE_T$$

Putting the value for $dP_x\, dP_y\, dP_z\, dP_\theta\, dP_\Phi$ in the integral changes it from an integration of values of momentum to an integration of values of kinetic energy. The integral becomes:

$$\int [8\, 2^{1/2}\, \pi^2\, I\, m^{3/2}\, n^{3/2}\, (n-1)]\, E_T{}^{1/2}\, \exp^{-\frac{E}{kT}}\, dE_T$$

Replacing $[8\, 2^{1/2}\, \pi^2\, I\, m^{3/2}\, n^{3/2}\, (n-1)]$ by K and E_T by E

$$K \int E^{1/2} \exp^{-\frac{E}{kT}}\, dE$$

It is interesting to note at this point that except for the value of the constant K this is exactly the integral which is found by considering translation only and in the expression used the K's cancel.

What we are really concerned with here is the fraction of all molecules which have energy greater than or less than some particular value $E_1 > 0$. If the last expression is integrated between the limits of zero and ∞ this will give a value for the total energy of the assembly. Likewise if the integration is from zero to E_1 this should be the energy $\leq E_1$. The fraction of the total energy which is less than E_1 is thus given by

$$\text{Fraction} = \frac{K \int_0^{E_1} E^{1/2} \exp^{-\frac{E}{kT}}\, dE}{K \int_0^{\infty} E^{1/2} \exp^{-\frac{E}{kT}}\, dE}$$

The integration by parts may be made after a change of variables letting $E/kT = x^2$. The fraction becomes

$$\text{Fraction} = \frac{-2^{1/2} \left(\frac{kT}{m}\right)^{3/2} \int_0^{E_1 = kT\, x_1{}^2} 2x^2 \exp^{-x^2}\, dx}{-2^{1/2} \left(\frac{kT}{m}\right)^{3/2} \int_0^{\infty} 2x^2 \exp^{-x^2}\, dx}$$

$$= \frac{x \exp^{-x^2} - (\frac{\pi}{4})^{1/2} \text{Erf } x \Big|_0^{x = E^{1/2}/kT}}{x \exp^{-x^2} - (\frac{\pi}{4})^{1\ 2} \text{Erf } x \Big|_0^{\infty}}$$

where Erf is the error function.

$$= \frac{[-(\frac{E_1}{kT})^{1/2} \exp^{-\frac{E_1}{kT}} - (\frac{\pi}{4})^{1/2} \text{Erf } (\frac{E}{kT})^{1/2}] - [0 - (\frac{\pi}{4})^{1/2} \text{Erf } 0]}{[0 - (\frac{\pi}{4})^{1/2} \text{Erf } \infty] - [0 - (\frac{\pi}{4})^{1/2} \text{Erf } 0]}$$

$$= \text{Erf } (\frac{E_1}{kT})^{1/2} - \frac{2}{(\pi)^{1|2}} (\frac{E_1}{kT})^{1/2} \exp^{-\frac{E_1}{kT}}$$

APPENDIX 4

EXPERIMENTAL DATA, CALCULATIONS

AND THE RESULTING CURVES

FOR LIQUID HELIUM

APPENDIX 4

SAMPLE CALCULATIONS - LIQUID HELIUM

The last row of Table 8 - H_e will be used as an example.

Exp - volts (64760.0×10^{-7}) Observed data

Std - volts (55635.7×10^{-6}) Observed data

R - ohm $$R = \frac{64760.0 \times 10^{-7} \times 0.01}{55635.7 \times 10^{-6}} = 0.8600 \times 10^{-3} \text{ ohm}$$

EI - watts $$EI = \frac{64760.0 \times 10^{-7} \times 55635 \times 10^{-6}}{0.01} = 4.876 \times 10^{-2}$$

BTU/ft^2 hr BTU/ft^2 hr $= EI \cdot 2.383 \times 10^4 = 1.16 \times 10^3$

Res Res = 133.4 ohm. Observed data

T_b - ^oK From Figure 26

T_w - ^oK From Figure 28

0.01 Ω std.

Table 1 - He.
Ice Point Calibration

Wire 1
0.004"

Exp-volts	Std-volts	R_0-Ohm
54791.3 $\times 10^{-7}$	1132.0 $\times 10^{-7}$	4.8355 $\times 10^{-1}$
54794.95	1133.3	4.8350
54805.6	1132.8	4.8380
96629.0	1998.3	4.8356
96631.5	1998.5	4.8352

Average $R_0 = 4.8363 \times 10^{-1}$ Ω

0.01 Ω std.

Table 2 - He.
Down Run

Wire 1
0.004"

Exp-volts	Std-volts	R-ohm	EI-watts	BTU/ft²hr	Res	T_b-°K	T_w-°K	ΔT-°C	ΔT-°F
14146.7×10^{-6}	46973.3×10^{-6}	3.0116×10^{-3}	6.645×10^{-2}	1.70×10^{3}	131.6	4.21	Film boiling		—
11324.0	40429.4	2.8009	4.578	1.17	131.5	4.22	5.99	1.77	3.18
10180.0	36360.8	2.8000	3.702	9.46×10^{2}	131.4	4.23	5.96	1.74	3.13
90368.0×10^{-7}	32289.9	2.7987	2.918	7.45	131.2	4.23	5.91	1.68	3.02
77523.7	27708.2	2.7979	2.148	5.49	131.1	4.23	5.87	1.64	2.95
69973.1	25009.7	2.7978	1.750	4.47	131.1	4.23	5.87	1.64	2.95
55855.2	19963.7	2.7978	1.115	2.85	130.7	4.24	5.87	1.63	2.93
46340.0	16566.3	2.7973	7.677×10^{-3}	1.96	130.5	4.25	5.85	1.60	2.88
36883.0	13186.1	2.7971	4.863	1.24	130.5	"	5.84	1.59	2.86
28203.0	10084.1	2.7968	2.844	7.27×10^{1}	130.3	"	5.83	1.58	2.84
22847.3	81692.0×10^{-7}	2.7968	1.866	4.79	130.3	"	5.83	1.58	2.84
16971.6	60696.3	2.7961	1.030	2.63	130.2	"	5.81	1.58	2.8[illegible]
1.2561.9	44935.3	2.7956	5.645×10^{-4}	1.44	130.2	"	5.78	1.52	2.75
69235.0×10^{-8}	24808.4	2.7908	1.718	4.39×10^{0}	130.1	"	5.57	1.52	2.38
49279.5	17674.0	2.7882	8.710×10^{-5}	2.25	130.2	"	5.44	1.32	2.14
31227.2	11217.3	2.7838	3.503	8.95×10^{-1}	130.2	"	5.20	1.19	1.71

0.01 Ω std.

Table 3 - He.
Up Run

Wire 1
0.004″

Exp-volts	std-volts	R-ohm	EI-watts	BTU/ft²hr	Res	T_b-°K	T_w-°K	ΔT-°C	ΔT-°F
3326.2 × 10^{-8}	12377.6 × 10^{-7}	2.6873 × 10^{-3}	4.117 × 10^{-5}	1.05 × 10^{0}	132.7	4.20	5.41	1.21	2.18
3743.5	13924.5	2.6884	5.213	1.33	132.7	″	5.49	1.27	2.29
4226.9	15711.2	2.6904	6.641	1.70	132.6	″	5.57	1.37	2.47
4852.8	18025.8	2.6922	8.748	2.23	132.6	″	5.66	1.46	2.63
5692.5	21130.1	2.6940	1.203 × 10^{-4}	3.07	132.5	4.21	5.74	1.53	2.75
6878.0	25520.7	2.6951	1.755	4.48	132.4	″	5.78	1.57	2.83
8687.5	32218.9	2.6964	2.799	7.16	132.2	″	5.84	1.63	2.93
11782.1 × 10^{-7}	43675.1	2.6977	5.146	1.31 × 10^{1}	132.1	″	5.89	1.68	3.02
15070.3	55851.5	2.6983	8.417	2.15	132.0	″	5.91	1.70	3.06
20371.1	75484.2	2.6987	1.538 × 10^{-3}	3.93	131.9	4.22	5.93	1.71	3.08
28538.6	10570.5 × 10^{-6}	2.6998	3.017	7.71	131.8	″	5.97	1.75	3.15
35879.5	13290.4	2.6997	4.769	1.22 × 10^{2}	131.7	″	5.97	1.75	3.15
44376.8	16436.3	2.6999	7.294	1.86	131.6	″	5.97	1.75	3.15
54943.2	20346.5	2.7004	1.118 × 10^{-2}	2.86	131.5	4.23	5.99	1.76	3.17
69764.5	25833.0	2.7006	1.802	4.60	131.3	″	6.00	1.77	3.19

0.01 Ω Std

Table 4 - He
Down Run

Wire 1
0.004"

Exp-volts	Std-volts	R-ohm	EI-watts	BTU/ft²hr	Res	T_b-°K	T_w-°K	ΔT-°C	ΔT-°F
12500.0×10^{-6}	49301.0×10^{-6}	2.5354×10^{-3}	6.163×10^{-2}	1.57×10^{3}	130.9	4.24	–	–	720
10294.3	43838.0	2.3482	4.513	1.15	"	"	6.04	1.80	3.24
95029.0	40472.9	2.3480	3.846	9.82×10^{2}	"	"	6.03	1.79	3.22
85623.7	36474.0	2.3475	2.449	7.98	"	"	6.01	1.77	3.19
75843.9	32294.8	2.3485	1.050×10^{-4}	6.26	"	"	6.04	1.80	3.24
49526.0	21197.9×10^{-7}	2.3364	7.627×10^{-5}	2.68×10^{0}	130.6	"	5.54	1.30	2.34
42204.5	18070.9	2.3355	6.032	1.95	"	"	5.50	1.26	2.27
37540.0	16068.4	2.3363	4.561	1.54	"	"	5.54	1.30	2.34
32953.0	14114.1	2.3348	4.561	1.19	"	"	5.46	1.22	2.20
26766.0	11473.1	2.3329	3.071	7.84×10^{-1}	130.5	"	5.35	1.11	2.00
20897.0	89683.0×10^{-8}	2.3301	1.874	4.79	130.6	"	5.19	0.95	1.71
13777.3	59324.0	2.3224	8.193×10^{-6}	2.08	130.8	"	4.65	0.41	0.74

0.01 Ω std

Table 5 - He
Up Run

Wire 1
0.004"

Exp-volts	Std.-volts	R-ohm	EI-watts	BTU/ft²hr	Res	T_b-°K	T_w-°K	ΔT-°C	ΔT-°F
15163.0 $\times 10^{-8}$	65205.5 $\times 10^{-8}$	2.3256 $\times 10^{-3}$	9.887 $\times 10^{-6}$	2.53 $\times 10^{-1}$	131.4	4.23	4.68	0.45	0.81
19319.0	82893.5	2.3306	1.601 $\times 10^{-5}$	4.09	131.2	"	5.04	0.81	1.46
23072.3	98889.5	2.3333	2.282	5.83	131.2	"	5.21	0.98	1.76
28255.3	120992.6 $\times 10^{-7}$	2.3366	3.417	8.73	130.9	4.24	5.39	1.15	2.07
32943.3	14098.6	2.3366	4.645	1.19 $\times 10^{0}$	130.8	"	5.39	1.15	2.07
37760.7	16152.5	2.3378	6.099	1.56	130.7	"	5.45	1.21	2.18
43480.7	18591.1	2.3388	8.084	2.07	130.6	"	5.51	1.27	2.29
51297.7	21923.0	2.3399	1.125 $\times 10^{-4}$	2.87	130.4	4.25	5.57	1.32	2.38
58730.0	25083.9	2.3414	1.473	3.76	129.4	4.27	5.63	1.36	2.45

0.01 Ω std. Table 6 - He Up Run Wire 2 0.004"

Exp-volts	Std-volts	R-ohm	EI-watts	BTU/ft²hr	Reo	T_w-°K	T_b-°K	ΔT-°C	ΔT-°F
50000.0 $\times 10^{-9}$	59616.0 $\times 10^{-8}$	0.8387 $\times 10^{-3}$	2.981 $\times 10^{-6}$	7.10 $\times 10^{-2}$	131.7	4.87	4.24	0.63	1.13
65796.7	66231.0	0.8425	3.696	8.81	"	5.13	"	0.89	1.60
73213.3	86456.0	0.8468	6.330	1.51 $\times 10^{-1}$	"	5.36	"	1.12	2.02
81380.0	95979.0	0.8479	7.810	1.86	"	5.41	"	1.17	2.11
88320.0	10404.9 $\times 10^{-7}$	0.8488	9.190	2.19	"	5.45	"	1.21	2.18
99063.3	11661.6	0.8495	1.155 $\times 10^{-5}$	2.75	"	5.49	"	1.25	2.25
11014.0 $\times 10^{-8}$	12947.6	0.8507	1.426	3.40	"	5.54	"	1.30	2.34
12334.0	14485.1	0.8515	1.786	4.26	"	5.58	"	1.34	2.41
14009.0	16437.7	0.8523	2.303	5.49	132.1	5.61	4.22	1.39	2.50
16201.3	18999.7	0.8529	3.078	7.34	"	5.63	"	1.41	2.54
18197.5	21321.9	0.8535	3.888	9.27	"	5.66	"	1.44	2.59
21187.5	24809.8	0.8540	5.275	1.25 $\times 10^{0}$	"	5.68	"	1.46	2.63
26643.5	31163.1	0.8550	8.303	1.98	132.5	5.72	4.21	1.51	2.72
35839.5	41870.1	0.8560	1.501 $\times 10^{-4}$	3.58	"	5.76	"	1.55	2.79
45107.0	52663.9	0.8565	2.376	5.66	"	5.78	"	1.57	2.83
66072.0	77088.2	0.8571	5.093	1.21 $\times 10^{1}$	"	5.81	"	1.60	2.88
92285.0	10761.1 $\times 10^{-6}$	0.8576	9.931	2.37	"	5.83	"	1.62	2.92
134427.4 $\times 10^{-7}$	15673.7	0.8580	2.108 $\times 10^{-3}$	5.02	"	5.84	"	1.63	2.93
17899.0	20839.5	0.8589	3.730	8.89	"	5.88	"	1.67	3.00
22756.5	26495.4	0.8589	6.029	1.44 $\times 10^{2}$	"	5.88	"	1.67	3.00
26073.4	30354.8	0.8590	7.915	1.89	"	5.88	"	1.67	3.01
29998.0	34914.2	0.8592	1.047 $\times 10^{-2}$	2.50	"	5.89	"	1.68	3.02
34274.0	39877.4	0.8595	1.367	3.26	"	5.90	"	1.69	3.04
38518.5	44795.5	0.8599	1.729	4.11	"	5.91	"	1.70	3.06
42888.5	49876.2	0.8599	2.139	5.10	"	5.91	"	1.70	3.06
48356.0	56194.0	0.8605	2.717	6.48	"	5.94	"	1.70	3.11

Table 6 - contd

Exp-volts	Std-volts	R-ohm	EI-watts	BTU/ft^{2}hr	Res	T_b-°K	T_w-°K	ΔT-°C	ΔT-°F
52681.0 $\times 10^{-7}$	61208.7 $\times 10^{-6}$	0.8607 $\times 10^{-3}$	3.225 $\times 10^{-3}$	7.69 $\times 10^{2}$	132.9	4.20	5.95	1.75	3.15
56395.0	65391.0	0.8624	3.688	8.79	"	"	6.02	1.82	3.28
59124.5	68656.7	0.8612	4.059	9.67	"	"	5.99	1.77	3.13
62380.0	72060.0	0.8657	4.495	1.07 $\times 10^{3}$	"	"	6.14	1.94	3.49

0.01 Ω std

Table 7 - He.
Up Run

Wire 2
0.004"

Exp-volts	Std-volts	R-ohm	EI-watts	BTU/ft²hr	Res	T_w °K	T_b -°K	ΔT-°C	ΔT-°F
49105.0 $\times 10^{-9}$	58667.0 $\times 10^{-8}$	0.8370 $\times 10^{-3}$	2.881 $\times 10^{-6}$	6.87 $\times 10^{-2}$	133.3	4.76	4.22	0.54	0.97
57685.0	68730.3	0.8393	3.965	9.45	"	4.92	"	0.70	1.26
65240.0	77505.7	0.8417	5.056	1.21 $\times 10^{-1}$	"	5.07	"	0.85	1.53
75020.0	88842.2	0.8444	6.665	1.59	"	5.24	"	1.02	1.84
82220.0	97249.0	0.8454	7.996	1.91	"	5.29	"	1.07	1.93
89450.0	10571.6 $\times 10^{-7}$	0.8461	9.456	2.25	133.4	5.32	"	1.10	1.98
97720.0	11536.0	0.8471	1.127 $\times 10^{-5}$	2.69	"	5.37	"	1.15	2.07
10924.5 $\times 10^{-8}$	12947.7	0.8446	1.414	3.37	"	5.25	"	1.03	1.85
12234.3	14477.1	0.8449	1.771	4.22	"	5.27	"	1.05	1.89
16112.5	19013.1	0.8474	3.063	7.30	"	5.39	"	1.17	2.11
19130.2	22568.3	0.8485	4.317	1.03 $\times 10^{0}$	"	5.44	"	1.22	2.20
22493.8	26488.7	0.8491	5.958	1.42	"	5.47	"	1.25	2.25
28030.2	32959.6	0.8504	9.239	2.20	"	5.53	"	1.31	2.36

0.01 Ω std.

Table 8 - He
Up Run

Wire 2
0.004"

Exp-volts	Std-volts	R-ohm	EI-watts	BTU/ft^{2}hr	Res	T_b-°K	T_w-°K	ΔT-°C	ΔT-°F
48947.5 $\times 10^{-9}$	58683.2 $\times 10^{-8}$	0.8341 $\times 10^{-3}$	2.872 $\times 10^{-6}$	6.84 $\times 10^{-2}$	133.0	4.23	4.54	0.31	0.56
57657.5	68753.8	0.8386	3.964	9.45	"	"	4.87	0.65	1.17
66922.5	79548.3	0.8413	5.342	1.29 $\times 10^{-1}$	"	"	5.05	0.82	1.48
77200.0	91532.7	0.8434	7.066	1.68	"	"	5.17	0.94	1.69
91012.5	10762.5 $\times 10^{-7}$	0.8457	9.795	2.33	"	"	5.30	1.07	1.93
10263.2 $\times 10^{-8}$	12115.1	0.8471	1.243 $\times 10^{-5}$	2.96	"	"	5.38	1.15	2.07
11866.5	13983.6	0.8486	1.659	3.95	"	"	5.45	1.22	2.20
13430.0	15802.2	0.8499	2.122	5.06	"	"	5.51	1.28	2.30
15374.7	18161.4	0.8466	2.792	6.65	"	"	5.36	1.13	2.03
18119.7	21360.6	0.8483	3.870	9.22	"	"	5.43	1.20	2.16
22039.5	25922.3	0.8502	5.713	1.36 $\times 10^{0}$	"	"	5.52	1.29	2.32
28081.7	32960.4	0.8522	9.253	2.20	138.4	4.22	5.61	1.39	2.50
39224.7	45918.0	0.8542	1.801 $\times 10^{-4}$	4.29	"	"	5.69	1.47	2.65
46994.5	54972.3	0.8549	2.583	6.16	"	"	5.72	1.50	2.70
56485.0	66011.2	0.8557	3.728	8.88	"	"	5.75	1.53	2.75
64937.0	75851.7	0.8561	4.926	1.17 $\times 10^{1}$	"	"	5.77	1.55	2.79
83919.0	97953.3	0.8567	8.220	1.96	"	"	5.79	1.57	2.83
10574.0 $\times 10^{-7}$	12332.1 $\times 10^{-6}$	0.8574	1.304 $\times 10^{-3}$	3.11	"	"	5.82	1.60	2.88
13702.2	15968.0	0.8581	2.188	5.21	"	"	5.86	1.63	2.93
17337.5	20193.8	0.8586	3.501	8.34	"	"	5.87	1.65	2.97
21793.5	25370.7	0.8590	5.529	1.32 $\times 10^{2}$	"	"	5.88	1.66	2.99
26260.0	30558.6	0.8593	8.025	1.91	"	"	5.89	1.67	3.02
30793.5	35822.0	0.8596	1.103 $\times 10^{-2}$	2.63	"	"	5.90	1.68	3.04
35111.5	40810.9	0.8598	1.433	3.42	"	"	5.93	1.69	3.08
39571.0	46003.7	0.8602	1.820	4.34	"	"	5.93	1.71	3.08
43272.0	50297.3	0.8603	2.176	5.19	"	"	5.94	1.71	3.08

Table 8 - Contd.

Exp-volts	Std-volts	R-ohm	EI-watts	BTU/ft^{2}hr	Res	T_b-°K	T_w-°K	ΔT-°C	ΔT-°F
47869.5 x 10^{-7}	55635.7 x 10^{-6}	0.8604 x 10^{-3}	2.663 x 10^{-2}	6.35 x 10^{2}	133.4	4.22	5.94	1.72	3.10
52209.0	60656.3	0.8607	3.167	7.55	"	"	5.95	1.73	3.11
57250.5	71398.3	0.8609	4.390	9.07	"	"	5.96	1.74	3.13
61486.5	66497.0	0.8612	3.807	1.05 x 10^{3}	"	"	5.97	1.75	3.15
64760.0	75300.0	0.8600	4.876	1.16	"	"	5.92	1.70	3.06

Could not reach 8 amps. Maximum $q/a < 1.30$ BTU/ft^{2}hr.

LITERATURE CITED

1. Drew, T. B. and Mueller, A. C., Trans. Am. Inst. Chem. Engrs. Vol 33 449-471 (1937).

2. Nukiyama, Shiro, J. Soc. Mech. Engrs. (Japan) Vol 37 367-74 and 553-54 (1934).

3. Buck, D. A., Proc. Inst. Radio Engrs. Vol. 44 482-493 (1956).

4. McAdams, W. H., Addoms, N. J., Rinaldo, P. M. and Day, R. S. Chem. Engr. Prog. Vol. 44 Number 8 639-646 (1948).

5. National Research Council of the United States of America, "International Critical Tables" McGraw-Hill, New York Volume 6 130-131 (1929).

6. American Institute of Physics, "Temperature, Its Measurement and Control in Science and Industry" Reinhold, New York Vol 1 159-161 (1941).

7. I. C. T. Vol 1 P. 53 (see ref. 5).

8. Reference 6, PP. 173-175.

9. Bromley, LeRoy A., Chem. Engr. Prog. Vol 46 Number 5 221-227 (1950).

10. Westwater, J. W., Scientific American Vol 190 Number 6 64-68 (1954)

11. Jakob, M., Research Pub. Ill. Inst. Tech. Vol 2 Number 3 (1942).

12. Larson, R. F., Ind. and Eng. Chem. Vol 37 Number 10 1004-1016 (1945).

13. Keenan, J. H., "Thermodynamics" pp. 431-435, John Wiley and Sons, New York (1941).

14. McAdams, W. H., "Heat Transmission" 3rd ed. Chapter 14, McGraw-Hill Book Co., New York (1954).

15. Ellion, M E., "A Study of the Mechanism of Boiling Heat Transfer" Jet Propulsion Laboratory Memorandum 20-88. California Institute of Technology, March 1954.

16. I. C. T., Vol 3, p. 309 (see ref. 5).

17. Forster, K. E. and Greif, R., Am. Soc. Mech. Engrs., Paper No. 58-HT-11, 29 West 39th Street N.Y. (18), New York (1958).

18. Frenkel, J., "Kinetic Theory of Liquids", Chapter 7, Oxford University Press, London, (1946).

19. Miller, R. W., and Sullivan, J. D., U. S. Bureau of Mines Technical Paper 424 (1928).

20. I. C. T., Vol 3, p. 17 (see ref. 5).

21. I. C. T., Vol 5, p. 82 (see ref. 5).

22. Adam, N. K., "Physics and Chemistry of Surfaces", 3rd ed., Chapter 1, Oxford University Press, London, (1941).

23. Chapman, S. and Cowling, T. G., "The Mathematical Theory of Non-Uniform Gases" McMillan, London (1939).

24. "Tables of the Error Function and its Derivative" National Bureau of Standards, Applied Mathematics Series 41. For sale by the Superintendent of Documents, USGPO. Washington 25, D. C.

25. Slater, J. C., "Introduction to Chemical Physics" First Ed. McGraw-Hill, New York (1939).

26. Blake, C., Chase, C. E. and Maxwell, B., Review of Scientific Instruments, Vol 29 No. 8 (1958).

27. Edwards, J. L., Private communication.

28. Langmuir, I., Phys. Rev. Vol 34 p. 401 (1912).

29. Westwater, A. W., Am. Scientist, Vol 47 no. 3 (1959).