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THE EFFECT OF SUPERATMOSPHERIC PRESSURES ON  
NUCLEATE BOILING OF ORGANIC LIQUIDS

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THE EFFECT OF SUPERATMOSPHERIC PRESSURES ON  
NUCLEATE BOILING OF ORGANIC LIQUIDS

Of all the variables known to influence nucleate boiling the one single variable which exerts the most marked effect is pressure. This fact was perhaps first pointed out by Cichelli and Bonilla in 1945 (7). As an example of the pronounced effect, these investigators showed that raising the pressure on benzene from atmospheric up to 645 lbs/sq in. abs decreased the temperature difference from 63 to 3°F at a heat flux of 50,000 Btu/(hr)(sq ft).

Despite this large effect of pressure, pressure has not been recognized as a significant independent variable in itself. Instead the effect of pressure has been thought of in terms of its effect on other liquid or vapor properties which were changed by an increase in pressure.

The most prominent characteristic of nucleate boiling is that once a certain temperature is exceeded a large increase in the number of bubbles is brought about by only a slight increase in the surface temperature. This behavior at once suggests that a certain temperature is necessary to allow bubble growth. However, the logical criterion for bubble growth is the difference in pressure between the vapor pressure of the liquid at the temperature of the surface and the pressure of the system.

One might well expect that at different system pressures roughly the same pressure difference would be necessary for the bubbles to form rapidly. However, the temperature difference corresponding to a particular difference in vapor pressure is a very sensitive function of the pressure and the vapor pressure-temperature equilibrium. Thus, just as the pressure determines the boiling temperature it also determines the temperature difference necessary to give a particular difference in vapor pressure.

Assume that for bubble growth at different pressures it is necessary to exceed the same pressure difference between the vapor pressure of the liquid at the heating surface and the pressure of the system. Then, by picturing the increasing slope of the vapor pressure curve, it is easy to see how the temperature difference for bubble growth decreases rapidly with increasing pressure.

Perhaps the reason that pressure has not been considered a primary variable in boiling is that the first studies and correlations were made either entirely at or close to atmospheric pressure (2, 5, 9, 10, 13, 14, 15, 19). Jakob's 1935 correlation based on data at atmospheric pressure failed to show the improved heat transfer at higher pressures. In 1938 he modified it for this reason. Later, when dimensionless correlations were proposed to include the effect of pressure this effect was included either superficially or only in so far as it affected the physical properties which had been used to correlate boiling data.

It has been universal practice to use dimensional analysis to arrive at boiling correlations. However, dimensional analysis, as it



has been used, requires that the data fit an equation of the type  $q/A = \Delta T^n$ . To evaluate  $n$  the data are plotted on a  $\log q/A$  vs  $\log \Delta T$  plot. Plotting the data in this way does not show clearly the sudden way the heat flux rises as the temperature difference becomes large enough to support nucleate boiling.

Two other related experimental facts support this idea that a certain pressure difference is necessary to support nucleate boiling. One is that in subcooled boiling it is the temperature of saturated vapor and not the bulk temperature of the liquid which correlates the data. The other is a special case of the first. With mercury, where the density is high, there is an appreciable effect of small liquid heads above the heating surface when the pressure is near atmospheric (4). Measurements show that the temperature of the mercury above the heating surface is uniform and close to the equilibrium temperature corresponding to the pressure over the mercury.

An examination of the published data lends support to the idea that the pressure difference remained relatively the same for the same liquid at different pressures. It is apparent that more data are required. One important fact that is apparent is that water is an exception. The decrease in the temperature difference with pressure is not as great for water as it is for organic liquids. That water should not behave as an organic liquid in this respect is to be expected in view of its other unique behavior. Its maximum heat flux is three to five times as great as for organic liquids. Its temperature differences in nucleate boiling at atmospheric pressure are about half the normal temperature differences of organic liquids. Its physical properties,

such as its thermal conductivity, surface tension, specific heat, and critical pressure, are outside the ranges of those for organic liquids.

#### DESCRIPTION OF EQUIPMENT

The apparatus consisted principally of a pressure vessel containing the boiling surface. A general view of the apparatus is shown in Figure 1.

The boiling surface was the outside surface of a type 304 stainless steel tube. The outside diameter of the tube was 0.0643 in. and the wall thickness 0.0082 in. The tube was suspended in the pressure vessel by two electrodes which also supplied the electrical current with which the tube was heated. A thermocouple was located inside the tube midway between the supporting electrodes.

The pressure vessel was constructed of stainless steel, and with its windows was pressure tested to 750 lbs/sq in. Two windows in the vessel allowed viewing the boiling tube from either side.

A three-phase full-wave rectifier was used to supply direct current to heat the tube. The rectifier was supplied from a variable-voltage transformer which furnished the means of varying the heat generated in the tube.

The vessel was insulated with Fiberglas which was placed between the vessel and its angle-iron support structure. Additional insulation was placed on top of the vessel.

The pressure was controlled by two external heaters which supplied heat to the vessel. One was a high-power heater and the other a low-power heater.

### Pressure Vessel and Auxiliary Equipment

The details of construction of the pressure vessel are shown in Figure 2. The vessel was constructed of a 12 in. length of seamless, type 302 stainless steel, schedule 40 pipe. A spherical cap was welded to the bottom. A bolting flange was welded to the outside of the pipe 1/2 inch below the top. Just above the bottom weld and on opposite sides of the vessel were welded two 2 in. stainless steel, welding neck flanges. These served as windows for visual observation of the boiling tube.

A 1 in. circular cover plate was used to close the top of the vessel. This cover was tightened to the bolting flange of the vessel with ten 3/8 in. cap screws. Between the vessel and the cover plate was a 1 in. connector ring. It admitted electrodes and thermocouple tubes into the vessel. The seal between the ring and electrodes or thermocouple tubes was effected by using Teflon cylinders in screw-tightened stuffing boxes.

Either aluminum or chromium-plated copper gaskets were used above and below the connector ring. V-shaped grooves were machined on the bottom of the cover plate, on both sides of the connector ring, and on the top of the pipe section of the vessel. These grooves were used to seat the gaskets.

An early experiment demonstrated the rapid attack of aluminum by absolute ethanol at higher temperatures. Consequently, chromium-plated copper gaskets were used when ethanol was in the system.

The connector ring held the thermocouple tubes, the electrodes supporting the boiling section, and a valve to vent air from the system. The whole assembly could be removed intact from the vessel.

The thermocouple tubes were held in place by a small piece of Teflon attached to one of the electrodes. The vapor thermocouple tube extended three inches below the connector ring; the liquid thermocouple ten inches. The tube enclosing the liquid thermocouple was connected to the far end of the boiling tubing with a small copper wire so that the voltages across the boiling tube could be measured.

Each window contained two disks of 1/2 in. pyrex glass. A carbon steel, 600 lb, welding neck flange held the glass disks against the flange welded to the side of the vessel.

#### Power Supply

A rectifier supplied d-c current to heat the boiling tube. The rectifier was a Udylite, three-phase, full-wave rectifier. It was supplied from a 206 v three-phase Superior Powerstat (Figure 3).

A circuit diagram for the heaters is shown in Figure 4. The low-power heater was supplied from a 10 amp Adjustavolt transformer. The heater consisted of two coils of Chromel A wire wrapped around the vessel just above and below the window. They were insulated from the vessel with Sauereisen cement. They could be connected separately or in parallel and were each rated at 300 watts. An ammeter and voltmeter monitored the power to the heaters.

The higher power heater consisted of Chromel A wire coiled in three blocks molded of Alundum cement. These were placed against the sides and bottom of the vessel below the liquid level. They were wired in series to a 206 volt circuit. Together they were rated at 2 kw.

#### Instrumentation

The routine instrumentation consisted of a potentiometer, thermocouples, a recorder, a thermocouple selector switch, an ice bath,

ammeter shunts, a d-c voltmeter, a volt-box, an a-c voltmeter and ammeter, and two pressure gauges.

### Thermocouples

The thermocouples used were 30 ga copper-constantan made from one lot of wire. The hot junctions were welded in an electric arc while the cold junctions were soldered. Each thermocouple had its own cold junction. Sauereisen cement was used to electrically insulate the junctions from the tube wall. Lengths of the 0.065 in. OD tubing were used to contain all thermocouple junctions. One end was silver-soldered shut and the thermocouple threaded into the tube from the other end. Plastic tubing was used to protect the wires outside the metal tubing. Electrical leads were taken from the copper wire. A diagram of the thermocouple circuit is shown in Figure 5. The first set of thermocouples was calibrated against NBS calibrated, mercury in glass thermometers. Later thermocouples were checked only in water vapor.

### Tube Measurements

The outside diameter of the boiling tube was measured to 0.0001 in. with the use of a Pratt and Whitney supermicrometer. It was found to be uniform to within 0.0002 in. The length of the boiling section was measured to 0.0005 in. using a caliper and a 2- to 3-in. micrometer.

The wall thickness was calculated as 0.0082 in. by weighing measured lengths of tubing. A number of samples were mounted in plastic and polished in order to examine the cross section. Examination of the cross section with a projection microscope at approximately 100 diameters magnification revealed variations in the tube wall of only 2 percent.

Values of the electrical resistance were used to determine if differences existed between boiling sections.

## EXPERIMENTAL METHODS AND PROCEDURES

### Discussion of Liquids

The liquids that were boiled were acetone, benzene, ethanol, and Freon 113 (1, 1, 2-trichlorotrifluoroethane).

Several factors furnished the basis of selection. Each liquid was chosen as representing a different family of compounds. The boiling point had to be greater than room temperature to allow for cooling without refrigeration. The temperature at the highest pressure could not exceed 475°F, as limited by the use of Teflon. The liquid had to be available in commercial quantities and at reasonable cost. The liquid had to be non-toxic and non-explosive. An unstable liquid would have added needless complications. The physical properties should cover as great a range as possible and should be known at higher temperatures. Availability of physical properties was too stringent a requirement and was relaxed somewhat.

### Preparation for Boiling

To prepare for a run the vessel was disassembled, cleaned with the liquid to be boiled, and dried. The boiling tube was polished in as reproducible a manner as possible. Crocus cloth was brought back and forth along the length of tube. The distance between electrode holders was measured. The boiling tube and thermocouples were then replaced in the vessel. A liquid volume of 1500 ml was added. This allowed 3 in. submergence of the tube.

The cover plate was bolted in place and the pressure gauge connection was made. The high-power heater was turned on. In five to fifteen minutes vapor began to escape through the valve on the connector ring. The high-power heater was turned off and the low-power heater turned on. The vapor vented was condensed and the condensate was collected and measured. When 25 to 50 ml had been collected the valve was closed. A similar amount of condensate was collected from a valve located by the pressure gauges and then it was closed.

In the heating process the high-power heater caused violent boiling in the vessel. This boiling was allowed to subside before the tube current was turned on. The tube current was gradually increased. Before a heat flux of 25,000 Btu/(hr)(sq ft) was exceeded an observation was made to make sure boiling began. This was done to avoid any possibility of film boiling occurring. If the boiling initiated during the heating period was allowed to die away completely, it sometimes required as much as 30 minutes before the tube would begin to boil. Although the boiling would begin at some one point, it would quickly spread along the tube.

#### Initial Atmospheric Runs

The heat flux was raised to 50- to 60,000 Btu/(hr)(sq ft) except in the case of Freon 113 where it was limited to 30,000. These heat fluxes were chosen to give high values of the heat flux but still avoid the complication of film boiling. Preliminary readings were taken. After half an hour or longer a complete set of data at atmospheric pressure and various heat fluxes was taken.

A set of data at constant pressure consisted of readings at ten or more values of the heat flux. Half of these were taken as the

heat flux was decreased and half as it was increased. At each heat flux readings were taken of the tube current, the tube thermocouple voltage, the vapor and liquid thermocouple voltages, and the pressure. A visual observation was made of the boiling. Then the Powerstat was turned to give a new value of the heat flux. About 2 minutes were required to take the readings at each heat flux. Either before or after the run the voltage across the tube, the shunt voltage and the tube current were measured.

If the liquid thermocouple voltage indicated a change the current through the low-power heater was altered accordingly. When an adjustment was made, the new value of either the voltage or current was recorded. In this manner the liquid temperature was maintained constant to within 2°F, usually within 1°F.

By removing the insulation from around the vessel it was possible to dissipate all of the heat generated in the boiling tube even when boiling Freon 113 at 117°F. At 450°F with all the insulation in place it was necessary to add about 400 watts to maintain the temperature.

The lowest value of the heat flux at which readings were taken was usually 8,000 to 12,000 Btu/(hr)(sq ft). At this heat flux the tube was still boiling, and at the lower pressures it was possible to count the number of bubble columns. In no case was the heat flux lowered to such a value that boiling ceased during a set of measurements at constant pressure.

Normally the tube was allowed to boil overnight and the atmospheric run repeated before measurements were taken at higher pressures.



### Pressure Runs

The pressures to be run were selected on the basis of giving approximately equal reductions in the value of the difference between the surface and the liquid-saturation temperatures. From preliminary measurements the pressures were chosen as 15, 25, 40, 65, 115, 265, and 515 lbs/sq in. absolute. For benzene and Freon 113 the two highest pressures were chosen as 215 and 365 lbs sq in. absolute. This was done for Freon 113 so as to not exceed the 495 lbs/sq in. critical pressure and for benzene so as to not exceed the 482°F limitation of the Teflon.

A complete set of pressures was run at one time to give as consistent data as possible. Consecutively higher pressures were used because it was easier to heat than to cool the vessel.

The high-power heater was used to increase the pressure. Between 15 to 30 minutes were required to increase the pressure one step. The tube current was turned off during the heating because of the violent boiling caused by the high-power heater. Because radiation accounted for the transfer of heat from the high-power heater to the vessel, there was some time lag in the heating. After the heater was turned off the boiling was allowed to subside before the tube current was turned on.

When the tube current was turned on it was increased in steps to approximately the same maximum value as at atmospheric pressure. Preliminary readings were taken while the low-power heaters were being adjusted to give the desired liquid temperature. The tube was allowed to boil 15 to 20 minutes while this was being done, and before a run was made.

The liquid level was not maintained constant for various pressures but was allowed to increase as the density decreased. The level at the highest pressure was calculated to be 3 to 4 inches higher than at atmospheric pressure for the various liquids. Preliminary data indicated that changes in level at atmospheric pressure showed no significant effect on the boiling.

#### Final Atmospheric Run

When the run at the highest pressure was completed all heat to the vessel was turned off and the vessel was allowed to cool. A day or so later the vessel was heated and another run was made at atmospheric pressure. In most instances air had leaked back into the vessel, probably because of differential contraction on cooling. It was necessary to again purge the vessel. During the pressure runs some vapor generally escaped through unnoticeable leaks but never was the amount greater than 400 ml. This always left the tube submerged at least one inch in liquid.

After the atmospheric run the vessel was allowed to cool. The cover plate and the connector ring were removed and the liquid level was measured. The appearance of the tube was noted.

#### Ripple Voltages

The rms ripple voltage across the boiling tube was measured and found to be 5.5 percent of the d-c voltage. Thus, the ripple voltage accounted for only 0.3 percent of the power dissipated by the direct current. It was neglected in computing the heat flux.

#### Boiling Tubes

One boiling tube was used to obtain the data on ethanol, benzene, and acetone and another to obtain the data on Freon 113. Two tubes were ruined in attempts to boil Freon 113 at too high heat fluxes.

In film boiling the tube acquired a dark adherent coating which could not be removed by polishing with crocus cloth.

### Treatment of the Data

The heat flux was computed from the measurements of the outside diameter of the tube, the length of the boiling section, the resistance of the boiling section, the calibration of the shunt millivolt meter with its leads, and the reading of the shunt millivolt meter.

The temperature drop across the tube wall was calculated with the following assumptions:

1. Heat generation is uniform in the wall of the tube.
2. The cross section of the tube is uniform.
3. The temperature of the outside surface of the tube is constant.
4. No heat flows to the interior of the tube.

The resulting relationship is

$$T_i - T_o = \frac{q/A_o}{2k} r_o \left( 1 - \frac{\ln (r_o/r_i)^2}{(r_o/r_i)^2 - 1} \right) \quad (1)$$

where

T denotes temperature,

r denotes radius,

q/A denotes heat flux, and

k denotes thermal conductivity.

The subscripts i and o refer to the inside and outside of the tube wall.

The thermal conductivity of stainless steel varies only 5 percent per 100°F according to Kreith and Summerfield (16). The thermal conductivity

was taken at 212°F and the temperature drop across the tube wall became simply:

$$T_i - T_o = 3.78 \times 10^{-5} q/A \quad (2)$$

#### Experimental Accuracy

The temperatures are probably accurate to 0.2°F and the heat flux to about 2.6 percent at 50,000 Btu/(hr)(sq ft) and 5 percent at 10,000. The accuracy of the calculated temperature drop across the tube wall is probably accurate to better than 15 percent.

### RESULTS

#### Plots of Data

Plots of heat flux versus temperature difference at various pressures for acetone, benzene, ethanol and Freon 113 are given in Figures 6, 7, 8, and 9. The results are also tabulated in Table I. Plots for atmospheric pressure are also given separately to show the shifts in the curves before, during, and after a sequence of super-atmospheric pressure runs. These are shown in Figures 10 and 16. In all the plots the temperature difference is the difference between the vapor thermocouple temperature and the boiling tube thermocouple temperature; the difference corrected for temperature drop across the tube. The vapor temperature was used because it is believed to be a better measure of the liquid saturation temperature. In no instance did the liquid and vapor thermocouple temperatures differ by more than two degrees F and usually less.

The data were taken with both increasing and decreasing heat fluxes. The readings were not different except in a very few cases. Therefore, the two sets of readings are not distinguished on the plots.

Two independent series of pressure runs were made with acetone. The agreement is good although a 7°F difference exists between two of the atmospheric runs. Both series were preceded by boiling overnight. The temperature difference increased in one case and decreased in the other after the pressure runs.

Two series of pressure runs were also made with benzene. The liquid was the same but the surface was polished between runs. The atmospheric temperature difference decreased about 7° before the pressure run in the second set. Both series showed a 5°F difference in the temperature difference between just before and after the pressure runs.

For ethanol at atmospheric pressure the temperature difference increased 3° overnight before the pressure run, and then decreased the same amount after the run.

Freon 113 gave experimental difficulties. It film boiled twice, once at 42,000 Btu/(hr)(sq ft) and once at 60,000. Subsequently the heat flux was limited to about 30,000 but the bubbles were smaller than usual, the temperature differences low, and the surface quickly fouled. This may have been due to small particles dispersed in the liquid. The first three samples taken from the shipping cylinder were cloudy. Finally, the vessel was given an especially good cleaning, all copper was replated with chromium, and clear liquid was charged in. The clear liquid was then boiled, and although it still gave a low temperature difference, it gave a normal boiling appearance. A pressure run was made and on boiling again at atmospheric pressure the temperature difference had increased 13°. Then another pressure run was made and a subsequent atmospheric test showed the temperature difference was

unchanged. Tube temperature fluctuations at atmospheric pressures were larger for Freon 113 than for other liquids.

Figures 11, 12, 13, and 14 compare the data of this investigation with that of Cichelli and Bonilla (7) for benzene and ethanol. Figure 14 also shows the data of Perry (21) for ethanol. For the data of Cichelli and Bonilla the steeper slopes do not occur until somewhat higher heat fluxes. Also, their data show more scatter and do not cover the range of this investigation as well as do the data of this investigation. These latter points are some of the reasons for this experimentation. Although the exact values of the two sets of data differ slightly, as would be expected, both sets of data show the same effect of pressure.

In comparing the atmospheric results of this investigation with other data at atmospheric pressure it should be pointed out that the atmospheric results of this investigation were taken with the tube temperatures fluctuating. These fluctuations are discussed later.

Figure 15 compares the data of Perry for acetone at atmospheric pressure with those of this investigation.

Figure 16 compares the atmospheric results of Corty for Freon 113 with those of this investigation. Corty boiled Freon 113 on both a highly polished copper surface and a highly polished nickel-plated surface. Corty offered no explanation of the shift to lower temperature differences on subsequent days for the data from the nickel surface.

#### Surface Temperature Fluctuations

With nucleate boiling at atmospheric pressure the surface thermocouple did not show a constant temperature as it did at higher

pressures. The fluctuations were rapid and changed in less than a second at times. A plot of the thermocouple voltage against time made with a recorder showed a random behavior. The fluctuations were more prominent at lower heat fluxes in the nucleate boiling region. Similar fluctuations have been reported in the literature (6).

With the tube in purely convective heat transfer the temperature varied over much larger values but more slowly. This was interpreted to mean that the tube temperature was a function of the circulation in the vessel and the tube was acting like a hot wire anemometer.

Tests were made to determine if the temperature difference in nucleate boiling was also a function of circulation. Varying the heat input into the vessel which would give more violent agitation did not affect the nucleate boiling temperature difference. This is in agreement with an observation by Addoms (1), and Robinson and Katz (22).

When the surface thermocouple voltage was measured an average value was taken and the violence of the fluctuations noted. The actual temperature fluctuation of the surface would be greater than that indicated by the thermocouple for other than the slowest fluctuations.

At pressures above atmospheric no fluctuations were noted. Because of the fluctuations at low pressures, no data were taken at pressures below atmospheric. Because of the more violent fluctuations at low heat fluxes, data were not taken in the convection or transitional regions.

#### Visual Observations

The effect of pressure was to make the bubbles rising from the tube smaller until at the highest pressures the bubbles appeared like a fog rising above the tube. At pressures up to 50 to 100 lbs/sq in.

gauge a heat flux of 5,000 to 10,000 Btu/(hr)(sq ft) gave 10 to 30 bubble columns along the 2 inch length of tube. At higher pressures the bubbles were too small to count in individual columns. The number of columns at the same heat flux increased with pressure.

At low heat fluxes and low pressures bubbles originated almost entirely at the top of the tube. With higher heat fluxes bubbles appeared at the bottom of the tube, and at the highest heat fluxes bubbles almost completely covered the surface of the tube. At the highest heat fluxes bubbles coalesced above the tube to form large volumes of vapor. When film boiling was encountered, the vapor surrounded the tube, and large volumes of vapor would break off and rise to the surface.

When first boiling Freon 113 the number of vapor columns rising from the tube was far greater and the bubbles smaller than for the other liquids. As mentioned previously, later runs showed the normal behavior.

The appearance of the surface after a series of pressure runs varied. In every case the surface still had a shine, but was colored brown or tan of various intensities. The discoloration was easily removed by wiping with tissue. The discoloration was not even and showed numerous pockmarks or small dark rings.

#### DISCUSSION OF RESULTS

This discussion attempts to explain some of the aspects of boiling covered by this investigation. Also, the results are treated in such a fashion that a correlation is developed which should predict



the effect of superatmospheric pressure on the nucleate boiling of many other organic liquids. Comparisons are made with recent correlations which attempt to predict the effect of pressure on nucleate boiling.

#### Discussion of the Boiling Curves

When examining the plots of heat flux versus the difference between the surface and the saturated-liquid temperatures, the most striking feature is the steepness of the curve in the nucleate boiling region. Furthermore, the curve appears to be quite linear in this region. The effect of higher pressures is to displace the steep portion of the curve in a parallel manner towards lower temperature differences.

To examine this further, the available data were plotted and lines were drawn through the data at the higher heat fluxes so as to represent the data as well as possible. The reciprocal slopes of these lines were computed and are tabulated in Table II.

The reciprocal slopes were examined rather than the slopes because it is less misleading to consider the heat flux as the independent variable. This is because the nucleate boiling region covers only a small range of temperature differences while the range of heat fluxes is not so limited. The reciprocal slopes are conveniently treated in terms of the increase in the temperature per 100,000 Btu/(hr)(sq ft).

The reciprocal slopes were gathered from the data of Corty (8), Cichelli and Bonilla (7), Perry (21), Kaulakis and Sherman (15, 2), and this investigation. However, only the reciprocal slopes from Cichelli and Bonilla and this investigation apply to superatmospheric pressures.

The reciprocal slopes do not show a consistent decrease with pressure. Some sets do show a slight decrease but in no case is the decrease as great as the temperature difference. Other sets remain relatively constant while still others show a random variation. The large variability of the reciprocal slopes for the atmospheric data of this investigation is due to the fluctuations of the tube temperature. These fluctuations are discussed under Results.

The data of Kaulakis and Sherman, and of Perry show exceptionally high values for the reciprocal slopes. These values are as high as  $40^{\circ}\text{F}$  per  $100,000 \text{ Btu}/(\text{hr})(\text{sq ft})$ . However, Perry's own data show more values of 10 to 18 for the same liquids. If these extremely high values, as well as the zero values from this investigation, are excluded as not representative, the range of values is from 5 to 20. An average value is about 10.

In surveying Table II it should be kept in mind that the slopes calculated from the data of Cichelli and Bonilla are based on very few points and are thus subject to error.

Table II gives the range of heat fluxes over which the data fall near the straight lines drawn through the data. If this range was limited by the range of the data that fact is noted by an asterisk. The linearity of the steep portion of the curve extends above the range investigated here, and appears from the data of Kaulakis and Sherman (15, 2), Perry (21), and Cichelli and Bonilla (7) to extend to almost the maximum heat flux.

Return now to a consideration of the shifts with pressure of the heat flux versus temperature difference curves. Since a principal characteristic of the nucleate boiling region is the necessity of

slightly exceeding a certain temperature, it is not difficult to reason that this temperature is required to permit the bubble growth and evolution associated with nucleate boiling. The most appropriate driving force for bubble growth is a pressure difference. More particularly, the pressure difference would be the difference in pressure between the vapor pressure of liquid at the temperature of the surface and the pressure of the system. For the data obtained in this investigation this difference was calculated corresponding to the temperature differences at a constant heat flux of 50,000 Btu/(hr)(sq ft) or 25,000 in the case of Freon 113. The results are tabulated in Table III. This pressure difference for each set of data varies by no more than a factor of 2 while the temperature difference varies by a factor of 8 to 10.

Whether the pressure difference is evaluated for the temperature difference at a heat flux of 50,000 or at some lower heat flux does not appreciably alter its value except at the higher pressures. At the higher pressures the slope of the curve exerts a large effect on the pressure difference. To eliminate this effect one can consider the temperature difference obtained by extrapolating the steep linear portion of the curve back to zero heat flux. The pressure differences calculated from these temperature differences are also shown in Table III and are plotted in Figure 17 against log pressure. In addition, the pressure difference divided by its average value in the relatively constant region for the respective liquid is plotted against log pressure in Figure 18. The pressure difference was normalized by dividing by an average value to take advantage of the decreased variance of an average compared to a single value.

This last plot brings all the data to a common curve except for one point at the highest pressure for acetone. An examination of the highest pressure  $\Delta T$  versus  $q/A$  curve for acetone reveals an abnormal behavior, but the reason for this behavior is not known.

The behavior of the pressure difference is to increase about 20 percent with an increase in pressure from atmospheric to about 100 lbs/sq in. Above 100 lbs/sq in. the pressure difference decreases apparently toward zero at the critical pressure. Detailed analysis of the behavior of the pressure differences at pressures of 365 lbs/sq in. and above is complicated by the decrease in accuracy of the data and of the extrapolation to zero heat flux. At these pressures the temperature differences are less than 7.5°F.

Because the common curve of  $\Delta P/P_{ave}$  versus log pressure represents data from four distinctly different organic liquids, it should apply for a wide range of other organic liquids. With the use of the curve, the vapor pressure of the liquid, the average slope of the boiling curve, and one nucleate boiling temperature difference, the nucleate boiling curve at any pressure between atmospheric and about two-thirds of the critical can be predicted. As an example of this prediction the nucleate boiling data for n-pentane were predicted and compared with the data of Cichelli and Bonilla (7). The comparison is shown in Figure 19. The prediction agrees with the data to within about 2°F. The prediction was made on the basis of  $\Delta T = 50^\circ$  at  $q/A = 50,000$  for nucleate boiling at 22 lbs sq in. absolute.

The nucleate boiling curves for an organic liquid can be estimated without any boiling data for the liquid. A value of 50°F estimates to within 50 percent the value of the temperature difference

at a heat flux of 50,000 Btu/(hr)(sq ft) for atmospheric boiling of various organic liquids. This is seen by examining Table IV which lists data from the literature. With this value of 50°F the superatmospheric behavior can be predicted.

### Theory

A theory has been proposed by Corty (8) and others (11) to account for the phenomenon encountered in nucleate boiling. It is reasoned that as a bubble leaves a surface it leaves behind a much smaller bubble with a radius of the order of magnitude of 10 microinches. The size of the bubble left behind is the all-important factor. It is its size that determines what specific temperature the surface temperature must exceed to maintain nucleate boiling. Perhaps several small bubbles are left behind by the departing vapor bubble and only the largest one is able to grow and form another departing bubble. According to capillary theory the excess pressure inside a spherical bubble is:

$$\Delta P = \frac{2\sigma}{r} \quad (3)$$

Of course this pressure difference must be exceeded to cause growth of the bubble.

An important fact which supports this theory is that the surface temperature can exceed the temperature usually giving nucleate boiling for a time without the occurrence of boiling. This commonly occurs with increasing heat flux before boiling has started. Then some portion of the surface starts to boil and the boiling quickly spreads across the surface. Such behavior was observed in this investigation and by others (3, 8).

Still another fact which supports the theory is the way in which bubbles rise from particular points on the surface. The behavior is as if a departing bubble left behind a smaller bubble from which the next departing bubble could grow.

Assuming a spherical bubble, the equilibrium radii corresponding to the pressure differences shown in Figure 17 were calculated. These are shown in Figure 20. At atmospheric pressure the radii range from 7 to 12 microinches. This is the same variation that Corty obtained (n-pentane, 13.5 microinches; diethyl ether, 7.5; Freon 113, 6.9 and 5.0).

A decrease in radius with pressure is shown for all four liquids. At the highest pressure the radii for acetone and Freon 113 are much smaller than those for benzene and ethanol. This may not be significant because accuracy of the data is poor at high pressures.

The radii always decrease with increasing pressure. The pressure difference from which these radii were calculated first increased with pressure from atmospheric to 100 lbs/sq in. and then decreased with further increase in pressure.

#### Bubble Size

The bubbles from the boiling surface were much smaller at higher pressures, particularly at pressures over 200 lbs/sq in.

Recent work of Van Wijk, Vos and Van Stralen (25) showed that for binary mixtures certain compositions gave much smaller bubble sizes than others. They also found that the compositions which gave the smallest bubbles also gave the highest burn-out heat fluxes.

Data of Cichelli show that the burn-out heat flux increases with pressure up to close to the critical temperature but then decreases.

These observations seem to give a clue to the better understanding of burn-out heat flux.

### Recent Correlations

Two correlations have been proposed recently which claim to predict the effect of pressure on nucleate boiling. Rohsenow (23) published the following correlation in 1952:

$$\frac{h}{k_L} \sqrt{\frac{g_c \sigma}{g(\rho_L - \rho_V)}} = \frac{1}{C_{sf}} \left[ \frac{q/A}{\mu_L \lambda} \sqrt{\frac{g_c \sigma}{g(\rho_L - \rho_V)}} \right]^{0.667} \left[ \frac{C_L \mu_L}{k_L} \right]^{-0.7} \quad (4)$$

McNelly (17) published his equation in 1953:

$$\frac{hD}{k_L} = 0.225 \left[ \frac{Dq/A}{\lambda \mu_L} \right]^{0.69} \left[ \frac{PD}{\sigma} \right]^{0.31} \left[ \frac{\rho_L}{\rho_V} - 1 \right]^{0.33} \left[ \frac{C_L \mu_L}{k_L} \right]^{0.69} \quad (5)$$

In these two equations  $h$  is the heat transfer coefficient,  $k$  the thermal conductivity,  $D$  is a length which is arbitrary since it cancels out,  $g_c$  is the conversion factor in Newton's law of motion,  $g$  is the acceleration of gravity,  $\sigma$  is the surface tension,  $\rho$  is the density,  $q/A$  is the heat flux,  $\mu$  is the viscosity,  $\lambda$  is the latent heat of vaporization,  $C$  is the heat capacity and  $P$  is the absolute pressure.  $C_{sf}$  is a constant depending upon both the liquid and the surface. The subscripts  $L$  and  $V$  refer to the liquid and vapor respectively.

Forster and Zuber (12, 24) published an equation which they derived to correlate nucleate boiling data and which they tested only at maximum heat flux. Perkins and Westwater (20) compared boiling data predicted from the Forster and Zuber equation with experimental data they obtained for nucleate boiling of methanol at atmospheric pressure. The Forster and Zuber equation is:

$$\left[ \frac{C_L \rho_L \sqrt{\pi \alpha_L} q/A}{k_L \lambda \rho_V} \right] \left[ \frac{2\sigma}{\Delta P} \right]^{1/2} \left[ \frac{\rho_L}{g_c \Delta P} \right]^{1/4}$$

$$= 0.0015 \left[ \frac{P_L}{\mu_L} \left( \frac{C_L \rho_L \Delta T \pi \alpha_L}{\lambda \rho_V} \right)^2 \right]^{0.62} \left[ \frac{C_L \mu_L}{k_L} \right]^{0.33} \quad (6)$$

Here the  $\Delta T$  is the temperature difference between the surface and the liquid saturation temperature,  $\alpha$  is the thermal diffusivity, and  $\Delta P$  is the pressure difference between the equilibrium vapor pressures corresponding to the temperatures in  $\Delta T$ .

To compare these correlations with data obtained here a plot of the temperature differences at a heat flux of 50,000 Btu/(hr)(sq ft) versus log pressure was made. Figure 21 shows the plot for benzene and Figure 22 for ethanol. Also plotted are interpolated values from the data of Cichelli and Bonilla. The physical properties to evaluate the equations were taken from Mesler (18).

Rohsenow's equation shows the best agreement. To use Rohsenow's equation the value of  $C_{sf}$  must be evaluated experimentally. Values of  $C_{sf}$  proposed by Rohsenow to fit the data of Cichelli and Bonilla were used for Figures 21 and 22. Values of  $C_{sf}$  proposed by Rohsenow have a 5.5-fold variation which he attributes to undeterminable surface factors.

Both Rohsenow's and McNelly's correlations at constant pressure are of the form

$$\Delta T = \text{constant} \times (q/A)^n \quad (7)$$

where  $n$  is 0.333 for Rohsenow's and 0.31 for McNelly's correlation. Accordingly, the quantity  $\frac{d(\Delta T)}{d(q/A)}$  at constant heat flux varies as  $\Delta T$



whereas for the data of this investigation the quantity was shown to be almost independent of  $\Delta T$ .

The predicted value of the reciprocal slope at a heat flux of 50,000 Btu/(hr)(sq ft) decreases from 33.3°F per 100,000 Btu/(hr)(sq ft) at  $\Delta T = 50^\circ\text{F}$  to 6.7 at  $\Delta T = 10^\circ\text{F}$ .

### CONCLUSIONS

The results of this investigation substantiate the fact that higher pressures always reduce the difference between the surface and the liquid-saturation temperatures at a constant heat flux in nucleate boiling.

In this study it was determined that the nucleate boiling data for organic liquids are well represented by straight lines on a linear plot of heat flux versus the temperature difference. This observation is verified by data in the literature as well as by data of this investigation. In the transitional region between the convection and nucleate boiling regions the temperature differences increase more rapidly with increasing heat fluxes than in the nucleate boiling region. Also, close to the maximum heat flux the increase is more rapid.

The reciprocal slopes of the lines representing nucleate boiling data are in the range of from 5 to 20°F per 100,000 Btu/(hr)(sq ft). An average value is about 10. They are, at least to a first approximation, independent of pressure.

The effect of pressure is to shift the lines representing nucleate boiling to lower temperature differences. By extrapolating the nucleate boiling lines to zero heat flux it is possible to consider

separately the effect of pressure and the effect of heat flux on the temperature difference.

The pressure difference between the pressure of the system and the vapor pressure of the liquid at the surface temperature, extrapolated to zero heat flux, behaves in a regular manner. This pressure difference increases about 20 percent between atmospheric pressure and about 100 lbs/sq in., and then apparently tends to zero at the critical pressure. The behavior is shown in Figure 18. Water does not show this behavior.

Corty (8) suggested that a pressure difference such as is defined here would behave somewhat as it does on the basis of a theory which he formulated. His theory supposes that departing vapor bubbles leave behind much smaller bubbles attached to the surface. The temperature of the surface must be high enough so that the vapor pressure is great enough to permit the small attached bubbles to grow.

By taking the reciprocal slopes of the lines representing the nucleate boiling data as  $10^{\circ}\text{F}$  per 100,000 Btu/(hr)(sq ft) and by using the above behavior of the pressure difference it is possible to predict the temperature differences in nucleate boiling at pressures from atmospheric to about two-thirds the critical pressure. The prediction requires either a knowledge or an assumption of a nucleate boiling temperature difference at some pressure and heat flux. A value of  $50^{\circ}\text{F}$  estimates to within 50 percent the atmospheric nucleate boiling temperature difference at a heat flux of 50,000 Btu/(hr)(sq ft) for organic liquids.

This prediction does not require a knowledge of any of the physical properties except vapor pressure.

Rohsenow's (23) equation adequately predicts the effect of pressure on the nucleate boiling of the organic liquids studied in this investigation for which the physical property data are available at superatmospheric pressures. McNelly's (17) and Forster and Zuber's (12) equations give poorer predictions particularly in underestimating temperature differences at lower pressures and overestimating temperature differences at higher pressures.

The effect of superatmospheric pressure on the appearance of nucleate boiling is to make the bubbles smaller. At 350 to 500 lbs/sq in. in the bubbles are almost too small to be seen individually.

Experimental results obtained showed the importance of repeating boiling runs and of being able to take the data in a time short compared to the time over which random variations are obtained.

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TABLE I

EXPERIMENTAL DATA

Table I is not reproduced here because of its length and because the data are well represented by the figures. Copies of Table I are available from Engineering Research Institute and the authors.

TABLE II

VALUES OF RECIPROCAL SLOPES AND TEMPERATURE DIFFERENCES

Temp °F	Pressure $\frac{\text{lbs}}{\text{in}^2}$ abs	$\frac{d(\Delta T)}{d(q/A)} 10^5$	$\frac{\Delta T}{q/A=50,000}$ °F	Range of Heat Flux (q/A)(10 <sup>-3</sup> )
Acetone (3/19/55)				
418	515	3.8	8.4	15 to 60*
345	265	7.0	10.4	15 to 60*
270	115	6.0	18.7	15 to 60*
236	65	7.7	27.0	15 to 60*
191	40	5.4	33.9	15 to 60*
162	25	0	41.6	15 to 60*
134	15	0	47.6	15 to 60*
	15	2.2**		
Acetone (3/26/55)				
418	515	3.2	8.8	15 to 60*
345	265	7.2	10.7	15 to 60*
270	115	3.4	19.0	15 to 60*
191	40	6.1	32.8	15 to 60*
162	25	4.7	40.5	15 to 60*
134	15	1.7	50.2	15 to 60*
	15	3.8**		
Benzene (2/21/55 and 3/2/55)				
460	365	10	9.2	25 to 50*
397	215	10	13.2	25 to 50*
331	115	8.4	20.0	25 to 50*
280	65	9.0	28.5	25 to 50*
242	40	10.4	35.8	25 to 50*
209	25	10.4	43.7	25 to 50*
177	15	15.6	55.3	25 to 50*
	15	19.8	5.4	
	15	18.8	7.6	
	15	14.6	0	
Benzene; Cichelli and Bonilla (7)				
538	645	---	2.2	30* to 50*
491	465	5.2	7.1	20 to 120*
418	265	7.5	14.0	20 to 140*
331	115	9.0	30.5	40 to 150*
256	50	12.0	38.5	40 to 120*
177	14.7	15.8	63.0	40 to 70*

\* Upper or lower limit of the data, see text.

\*\* Repeat runs where results were not reproducible.

TABLE II (continued)

VALUES OF RECIPROCAL SLOPES AND TEMPERATURE DIFFERENCES

Temp °F	Pressure $\frac{\text{lbs}}{\text{in}^2}$ abs	$\frac{d(\Delta T)}{d(q/A)} 10^5$	$\frac{\Delta T}{q/A=50,000}$ °F	Range of Heat Flux $(q/A)(10^{-3})$
Ethanol				
409	515	4.0	4.3	10 to 60*
350	265	4.0	9.9	20 to 60*
286	115	6.4	18.6	10 to 60*
250	65	6.0	25.8	10 to 60*
223	40	5.0	33.2	15 to 60*
199	25	2.5	41.6	20 to 60*
175	15	0	46.5	20 to 60*
		7.5**		
Ethanol; Cichelli and Bonilla (7)				
449	765	5.7	--	70* to 130*
409	515	7.5	3.9	45* to 150*
350	265	9.9	9.0	40* to 140*
286	115	9.3	17.2	25 to 200*
239	55	9.6	25.2	30 to 150*
173	14.7	9.3	50.2	45 to 150*
Freon 113			q/A=25,000	
376	365	17.0	8.0	10 to 30*
318	215	20.8	14.2	10 to 30*
259	115	17.0	19.9	10 to 30*
213	65	17.8	25.4	10 to 25*
179	40	20.0	33.0	10 to 25*
148	25	14.0	40.3	10 to 25*
119	15	15.4	50.0	10 to 30*
		0**		
Freon 113; Corty (8)			q/A=30,000	
Atmospheric pressure		36.6	68.5	15 to 35*
Successive days		26.4	65.0	15 to 35*
		22.4	59.0	15 to 35*
		15.6	57.0	15 to 35*

\* Upper or lower limit of the data, see text.

\*\* Repeat runs where results were not reproducible.



TABLE II (continued)

VALUES OF RECIPROCAL SLOPES AND TEMPERATURE DIFFERENCES

Temp °F	Pressure $\frac{\text{lbs}}{\text{in}^2}$ abs	$\frac{d(\Delta T)}{d(q/A)} \cdot 10^5$	$\Delta T$ °F q/A=50,000	Range of Heat Flux (q/A)(10 <sup>-3</sup> )
n-Pentane; Cichelli and Bonilla (7)				
368	415	7.8	5.7	12 to 46*
336	315	11.7	9.3	20 to 90*
295	215	10.2	13.5	10 to 130*
247	115	8.5	23.7	30 to 110*
185	60	11.5	33.5	35 to 130*
117	22	15.2	50.0	30 to 90*
n-Pentane; Corty (8)				
Atmospheric Pressure		q/A=25,000		
Surfaces	( 3 Ni	11.0	23.0	5 to 25*
	( 1 Ni	7.6	25.5	5 to 35*
	( 0 Ni	4.8	26.8	5 to 35*
	( 2/0 Ni	7.0	32.3	5 to 35*
	( 4/0 Ni	19.0	36.7	10 to 35*
	( 4/0 Cu	7.2	30.3	10 to 35*
( 4/0 Cu	10.0	38.0	10 to 25*	
Kaulakis and Sherman (15)				
Atmospheric Pressure		q/A=100,000		
Water, run I	10.0	24.5	80 to 360*	
Water, run IV	7.2	22	80* to 370*	
		q/A=50,000		
iso-Butanol	34.0	50	30* to 110*	
iso-Propanol	40.0	42	20 to 90	
n-Butanol	32.5	38.5	30* to 100*	
Perry (21)				
Atmospheric Pressure				
Acetone	11.8	30	15 to 130*	
Butanol	25.0	45	20 to 130*	
Ethanol	10.3	47	35 to 140*	
	11.4	44	35 to 140*	
	31.6	42	20 to 130*	
	16.7	47	30 to 140*	
	33.0	43	30 to 140*	

\* Upper or lower limit of the data, see text.

TABLE III  
VALUES OF THE PRESSURE AND TEMPERATURE DIFFERENCES

Pressure $\frac{\text{lbs}}{\text{in}^2}$ abs	q/A = 50,000				extrapolated to q/A = 0		
	$\Delta T$ °F	$\Delta P$ $\frac{\text{lbs}}{\text{in}^2}$	$\Delta T$ °F	$\Delta P$ $\frac{\text{lbs}}{\text{in}^2}$	$\Delta T$ °F	$\frac{\text{lbs}}{\text{in}^2}$	$\frac{\Delta P}{\Delta P_{\text{ave}}}$
Acetone	3/18/55		3/26/55				
515	8.4	37.5	8.8	39.5	6.3	28	1.32
265	10.4	28.6	10.7	29.4	5.8	15.5	.74
115	18.7	28.5	19.0	29.0	15.5	23.3	1.10
65	27.0	27.0			23	22.5	1.06
40	33.9	25.5	32.8	24.5	30.5	22.5	1.06
25	41.6	23.1	40.5	22.4	39	20.2	.95
					37.5	21.2	1.0
15	47.6	18.6	50.2	20.1	47.5	18.6	.88
					50	19.9	.94
Benzene	2/21/55		3/2/55				
365	8.8	25.6	9.6	27.9	4.5	13.1	.68
215	13.0	26.0	13.3	26.6	9.2	17.8	.93
					10	19.6	
115	19.9	25.5	20.1	25.8	15.7	19.8	1.03
65	28.5	25.1	28.5	25.1	24.3	21.4	1.11
40	35.8	23.4	35.8	23.4	30.7	19.8	1.03
25	43.8	21.2	43.6	21.1	38.5	18.7	.97
15	55.6	20.7	55.0	20.4	46.6	16.7	.87
					53.0	19.8	1.03
Ethanol							
515	4.3	23.3			2.2	11.8	.43
265	9.9	33.2			7.7	25.4	.93
115	18.6	35.3			15.2	28.3	1.03
65	25.8	33.4			23.0	29.3	1.07
40	33.2	31.5			31.0	28.9	1.06
25	41.6	29.6			40.0	28.0	1.02
15	46.2	24.6			48.0	24.6	.90
Freon 113	q/A = 25,000						
365	8.0	23.5			3.6	10.6	.54
215	14.2	29.8			8.8	18.1	.92
115	19.9	27.7			15.6	21.4	1.09
65	25.4	24.3			22.0	20.7	1.06
40	33.0	23.4			28.0	19.3	.98
25	40.3	21.6			36.7	19.2	.98
15	49	19.6			45.9	17.9	.91
	50.6	20.6					

TABLE IV

VALUES OF NUCLEATE BOILING TEMPERATURE  
DIFFERENCES AT ATMOSPHERIC PRESSURE

	q/A = 25,000 Btu/(hr)(sq ft) $\Delta T, ^\circ F$	q/A = 50,000 Btu/(hr)(sq ft) $\Delta T, ^\circ F$
This Investigation		
Acetone		46 to 54
Benzene		49 to 62
Ethanol		44 to 48
Freon 113	48 to 51	
Cicchelli and Bonilla (7)		
Benzene		61 to 67
n-Pentane (22 lbs/sq in.)		49 to 51
n-Heptane		38 to 48
Ethanol		50 to 53
Kaulakis and Sherman (15)		
Water		17 to 19
iso-Butanol		50
iso-Propanol		45
n-Butanol		38
Banchero, Barker and Boll (3)		
Oxygen		23 to 29
Corty (8)		
Freon 113	38 to 66	
n-Pentane	23 to 39	
Ether	36 to 50	
Perry (21)		
Acetone		32
Butanol		46
Ethanol		39 to 49
Water		21 to 25

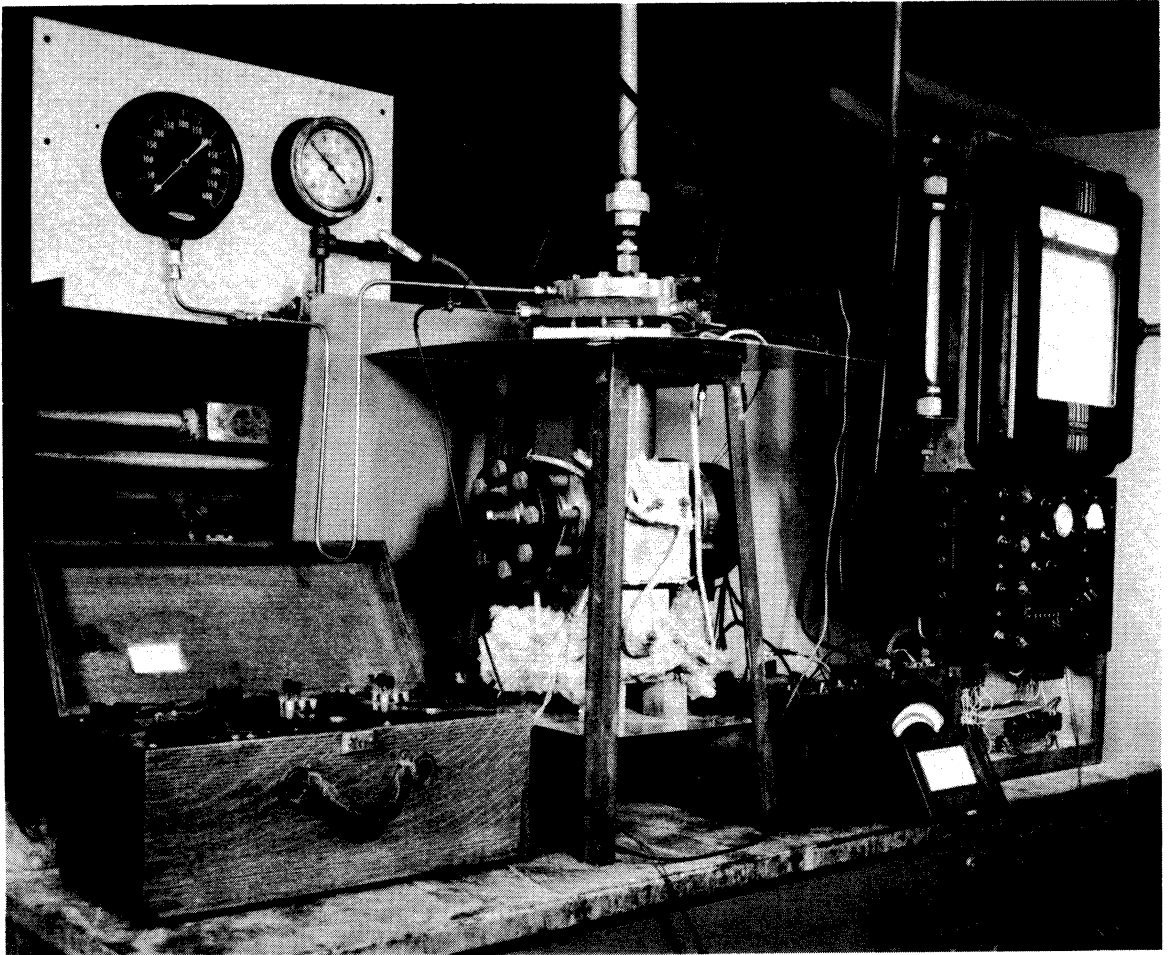


FIG. 1 GENERAL VIEW OF THE APPARATUS

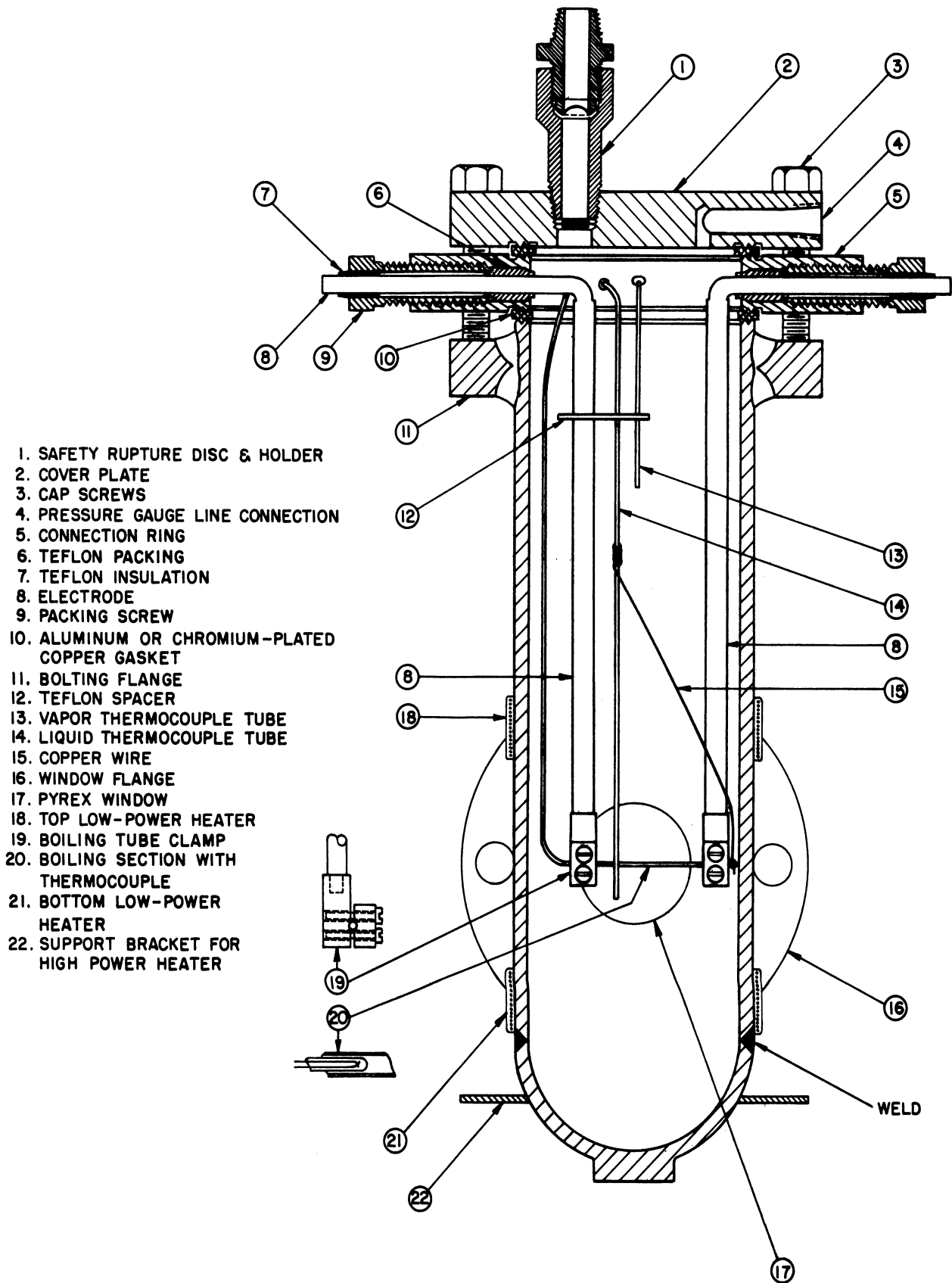


FIG. 2. SECTIONAL VIEW OF THE PRESSURE VESSEL.

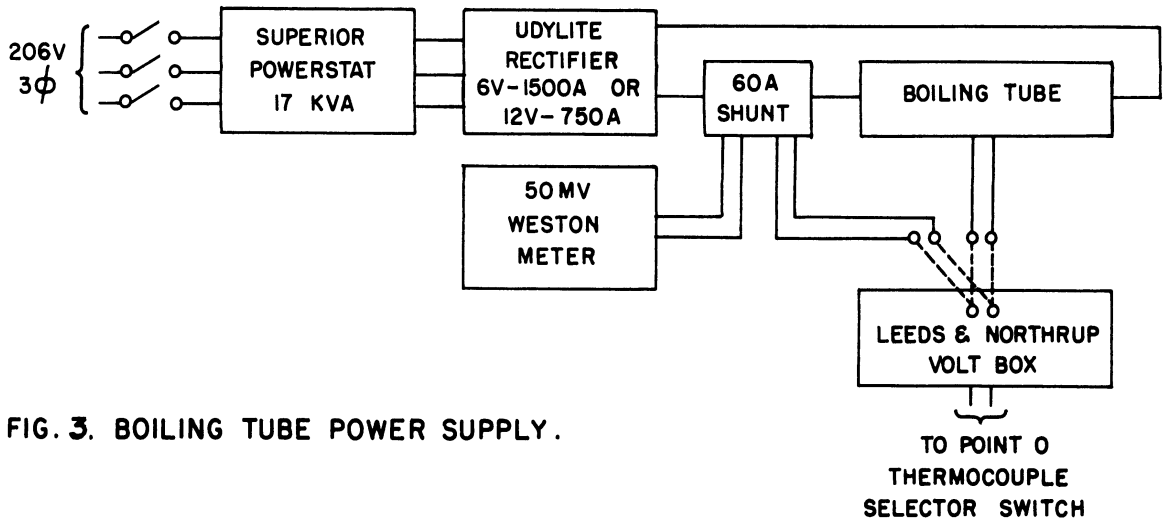


FIG. 3. BOILING TUBE POWER SUPPLY.

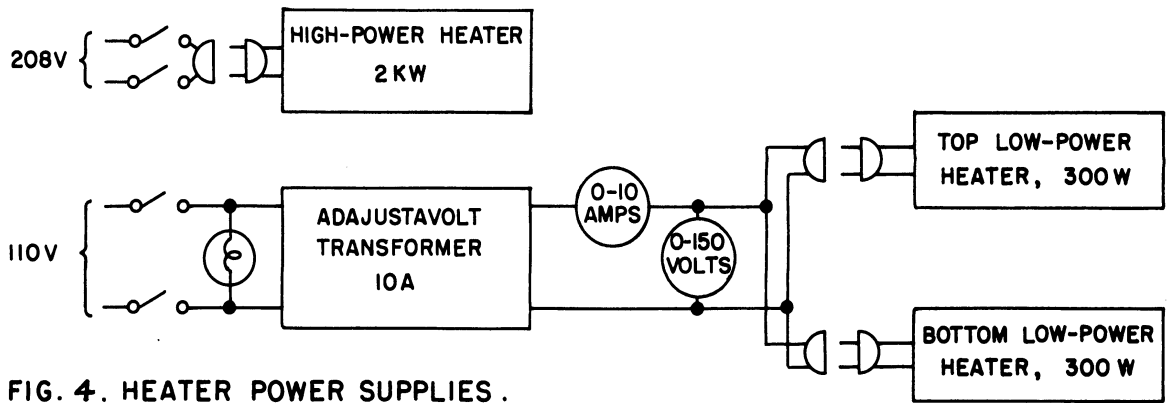


FIG. 4. HEATER POWER SUPPLIES.

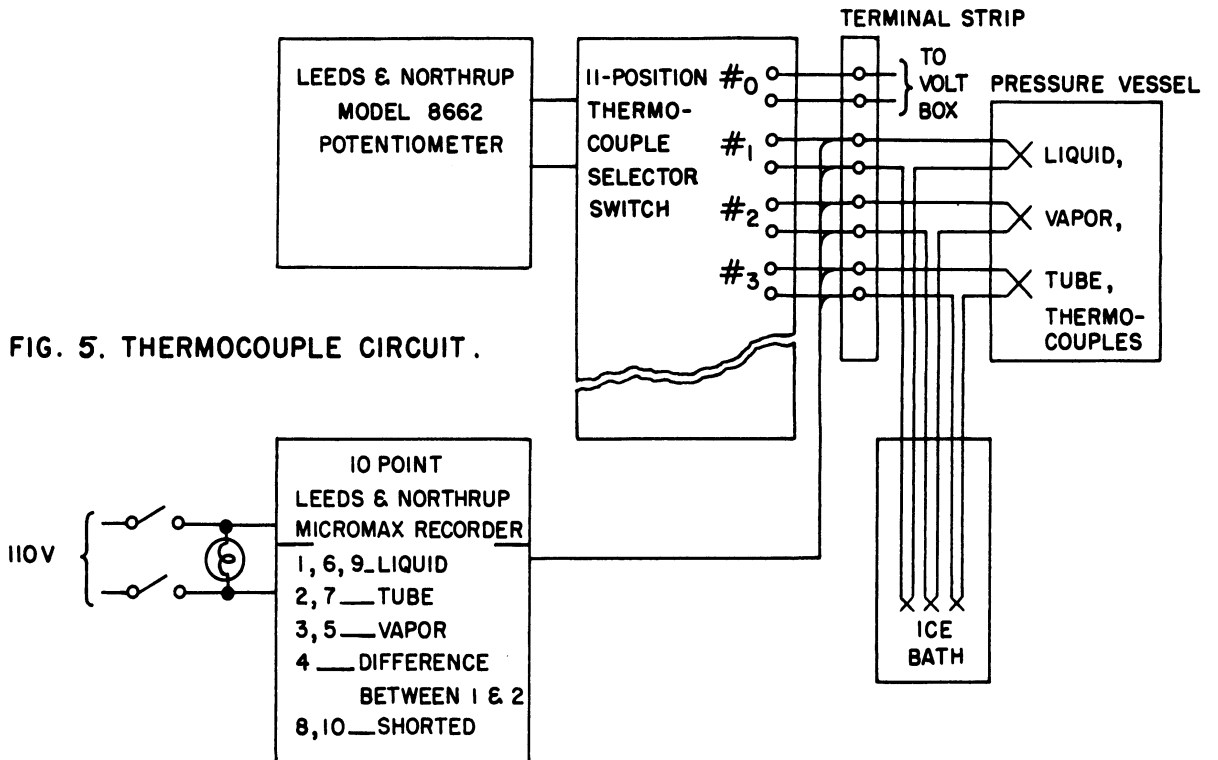


FIG. 5. THERMOCOUPLE CIRCUIT.

(O, Δ DATA OF 3-18-55 & ●, ▲ DATA OF 3-26-55)

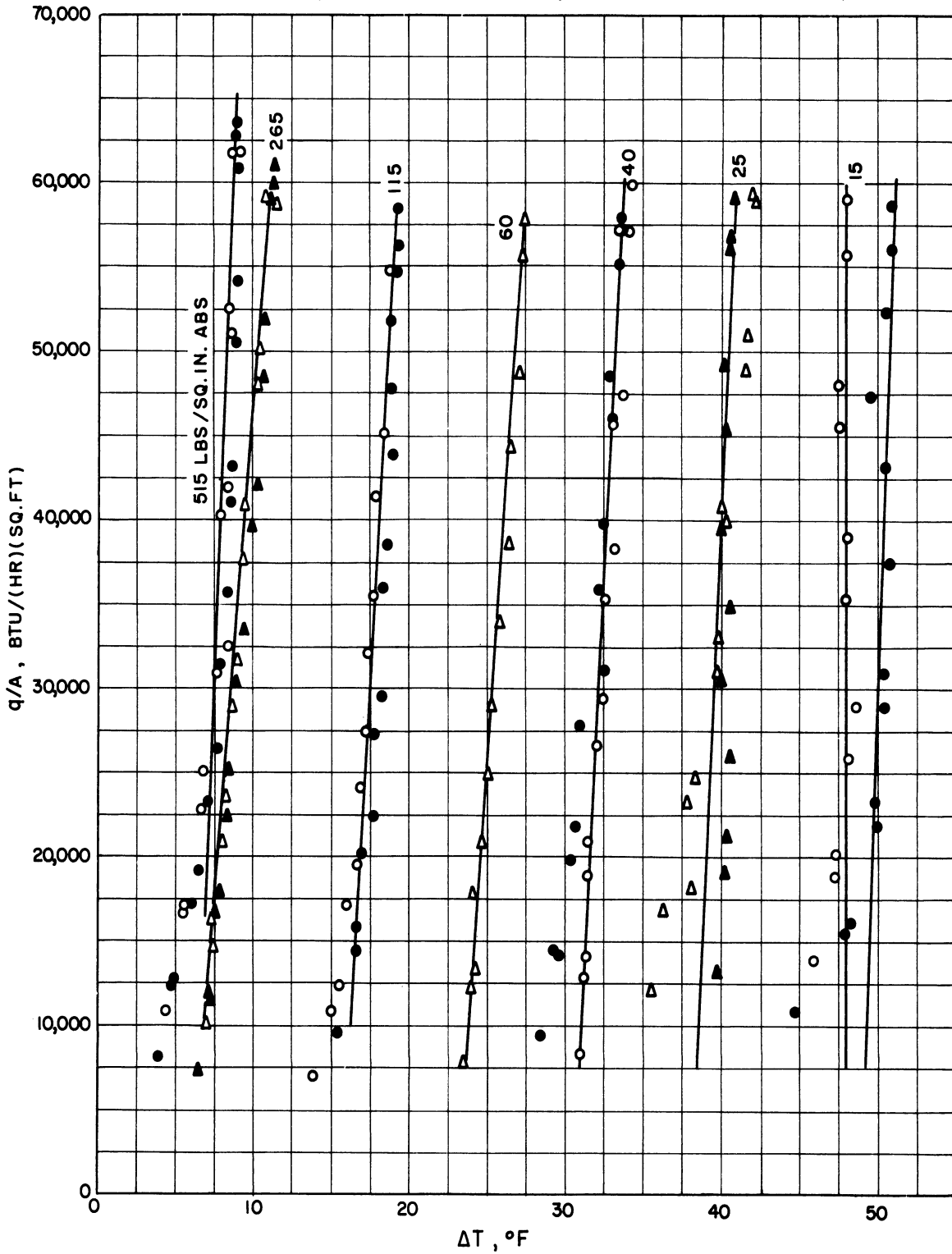


FIG. 6 . SUPERATMOSPHERIC BOILING DATA FOR ACETONE .

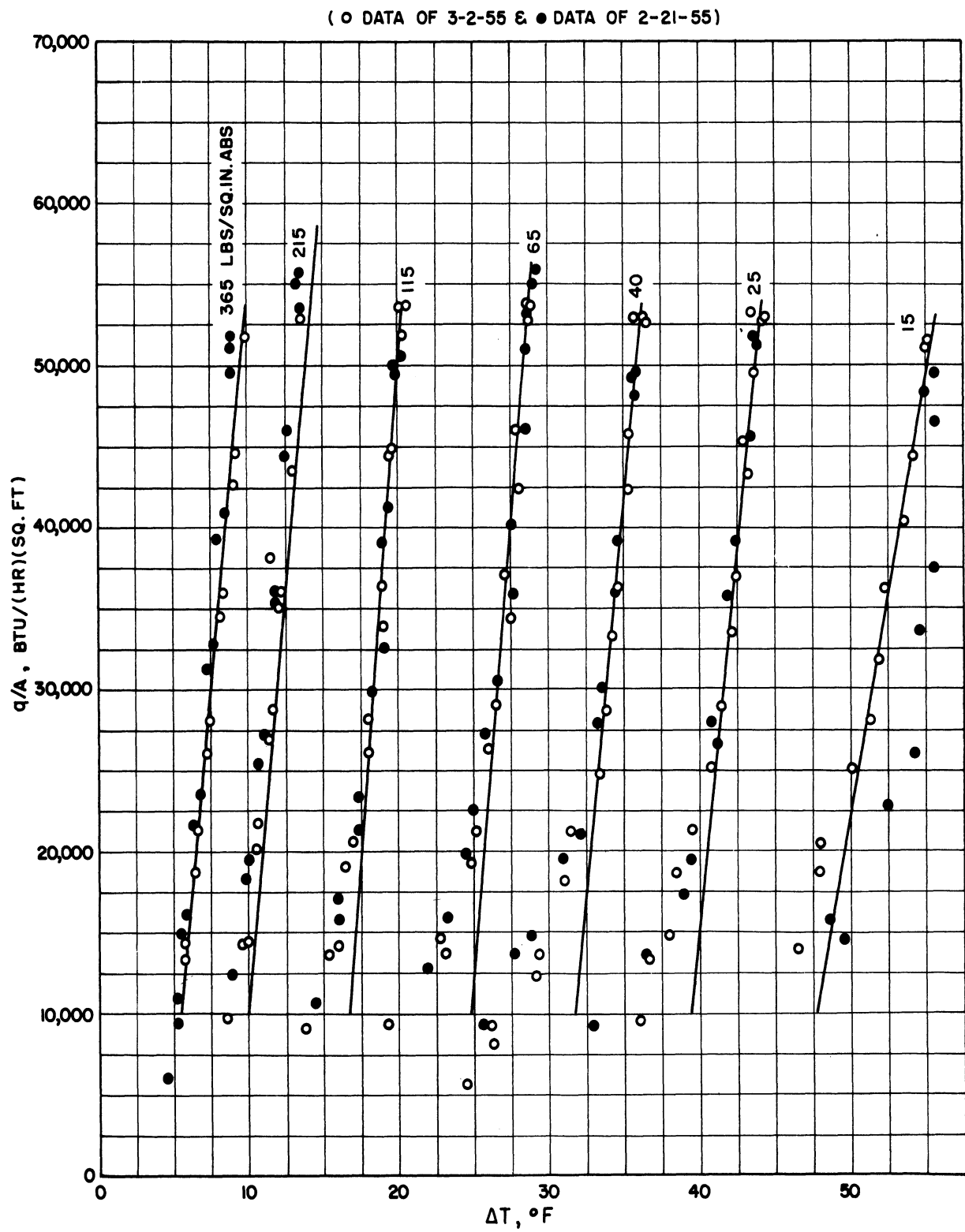


FIG. 7. SUPERATMOSPHERIC BOILING DATA FOR BENZENE .



( DATA OF 3-12-55 )

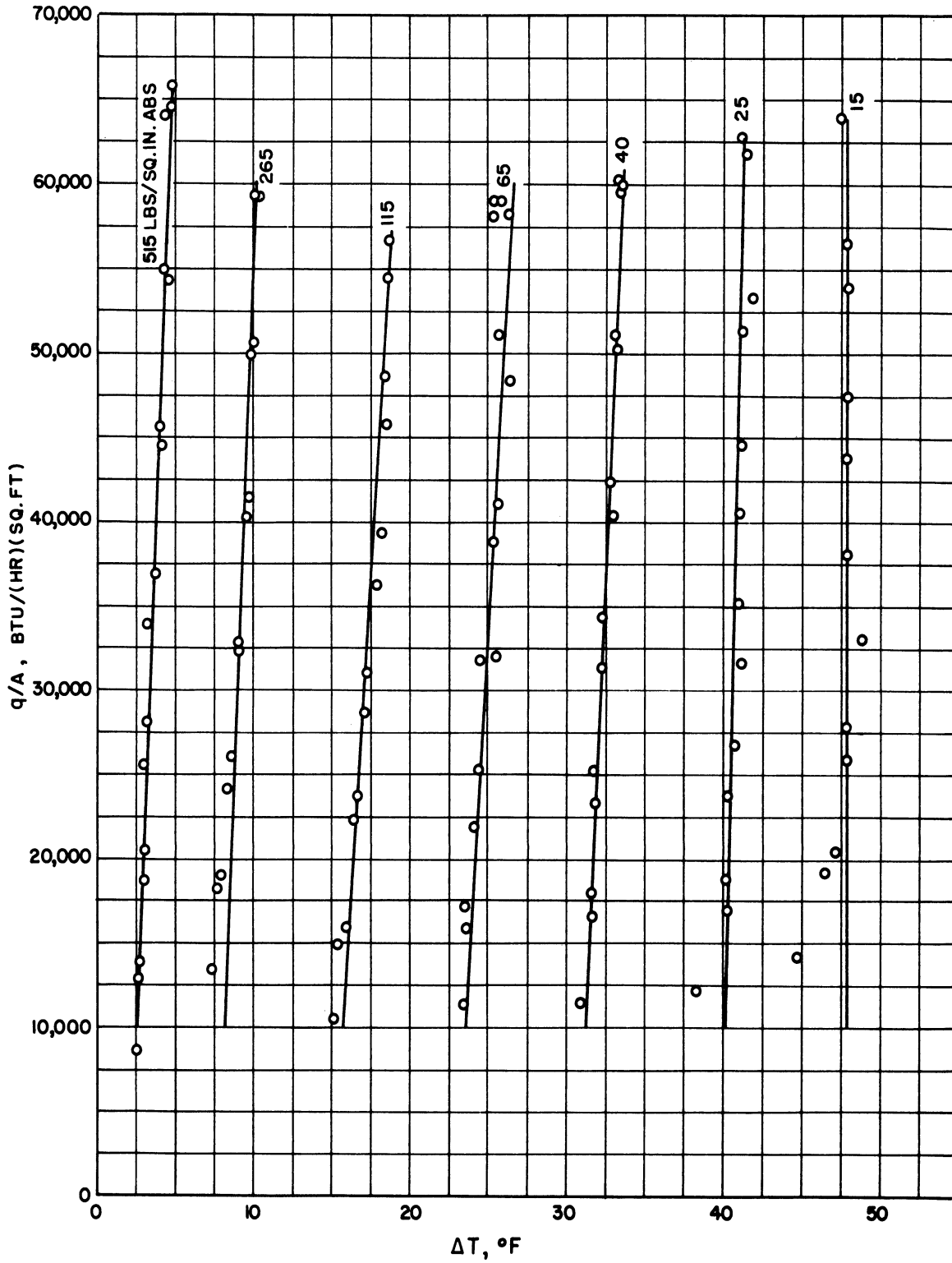


FIG. 8. SUPERATMOSPHERIC BOILING DATA FOR ETHANOL.

( DATA OF 4-26-55 )

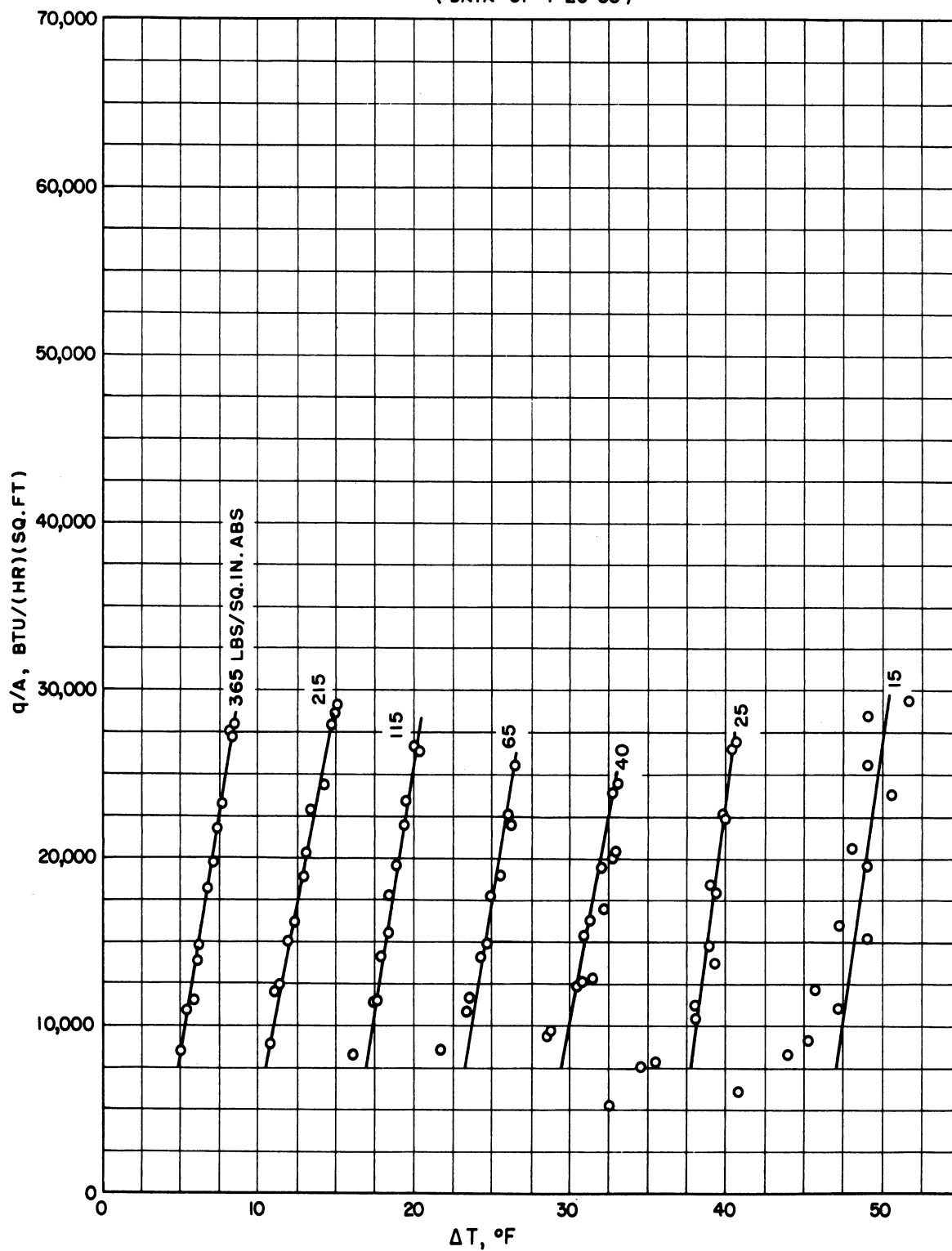


FIG. 9. SUPERATMOSPHERIC BOILING DATA FOR FREON 113.

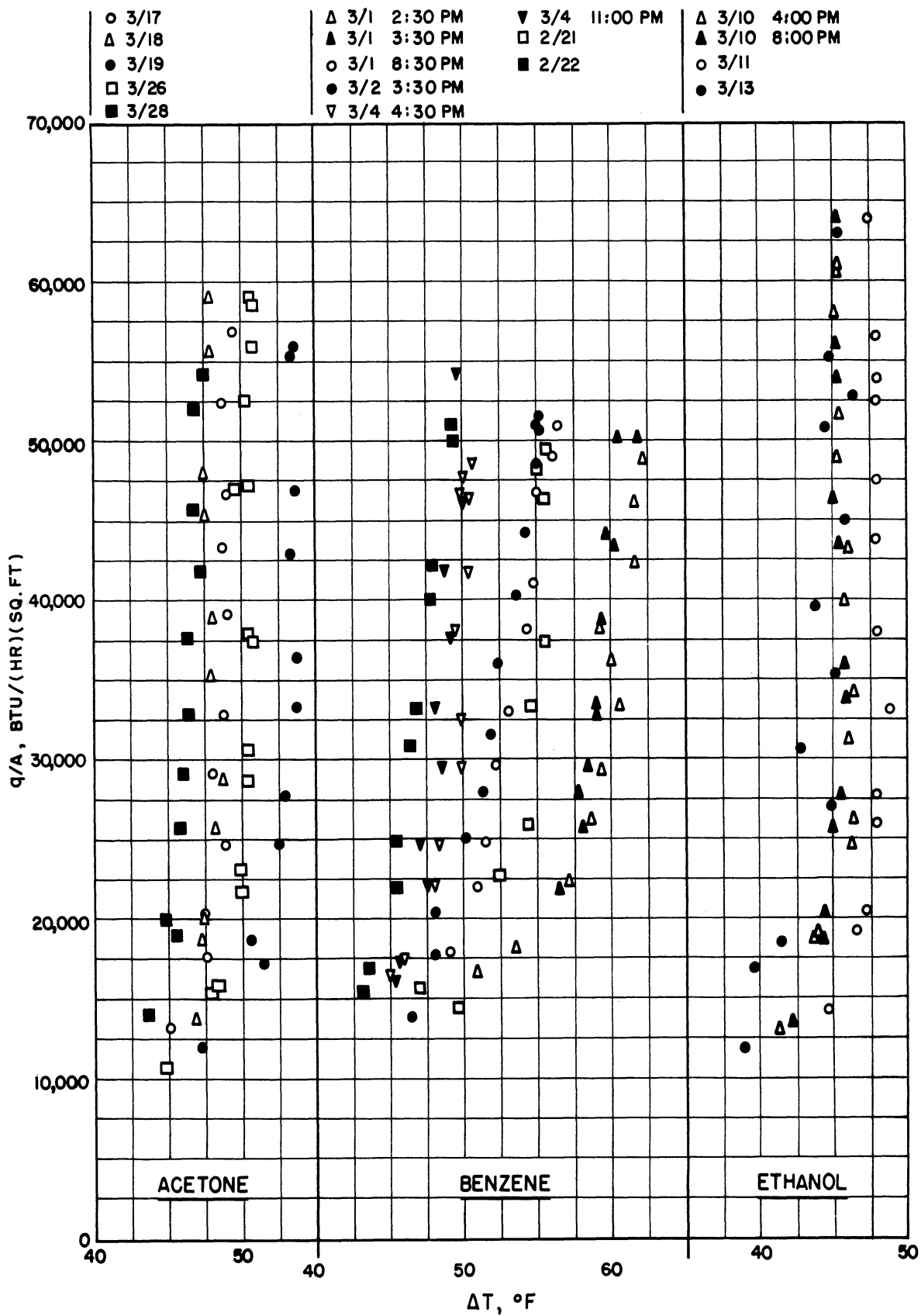


FIG. 10. ATMOSPHERIC BOILING DATA FOR ACETONE, BENZENE AND ETHANOL.

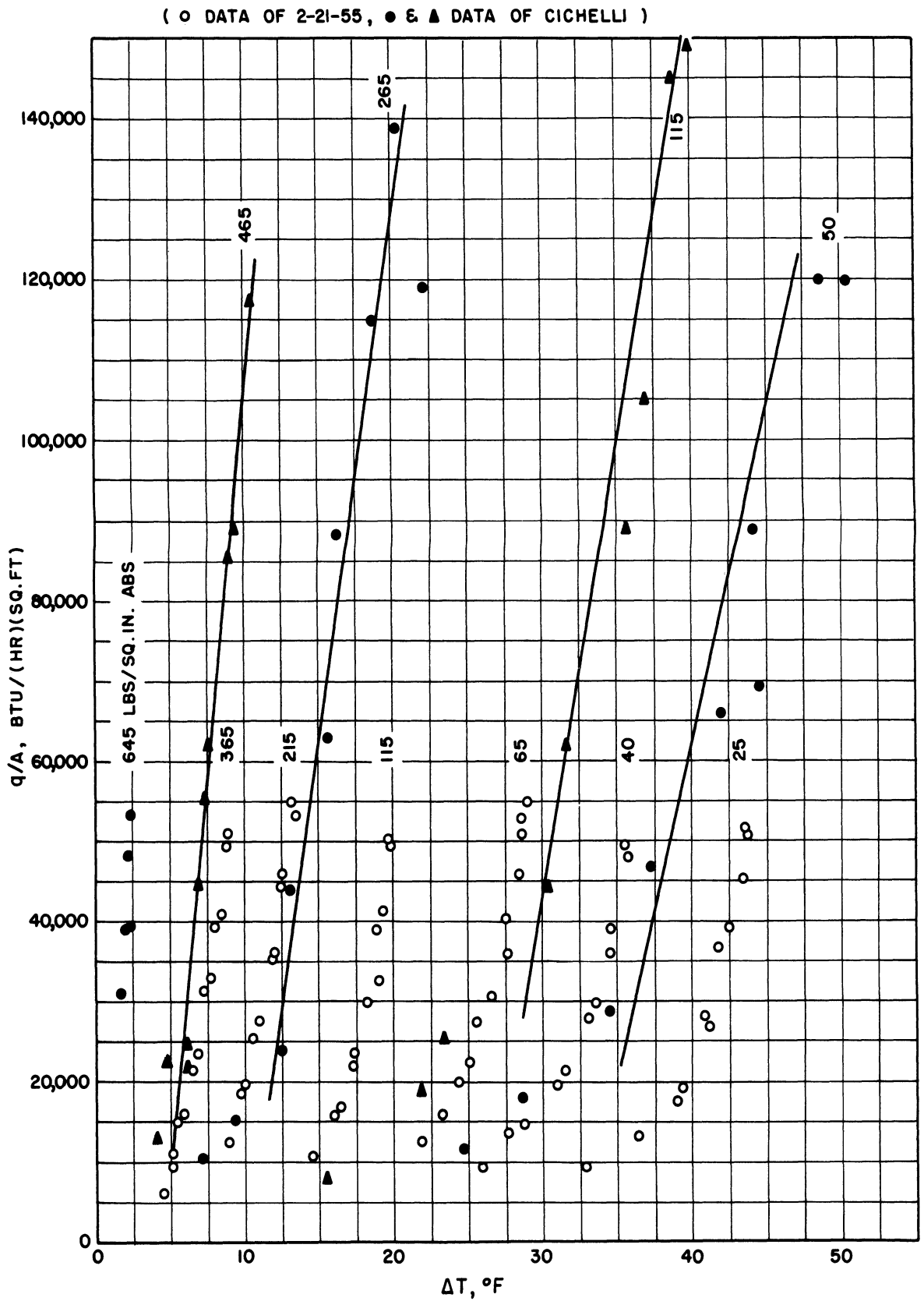


FIG. 11 . SUPERATMOSPHERIC BOILING DATA FOR BENZENE COMPARED WITH DATA OF CICHELLI AND BONILLA (7) .

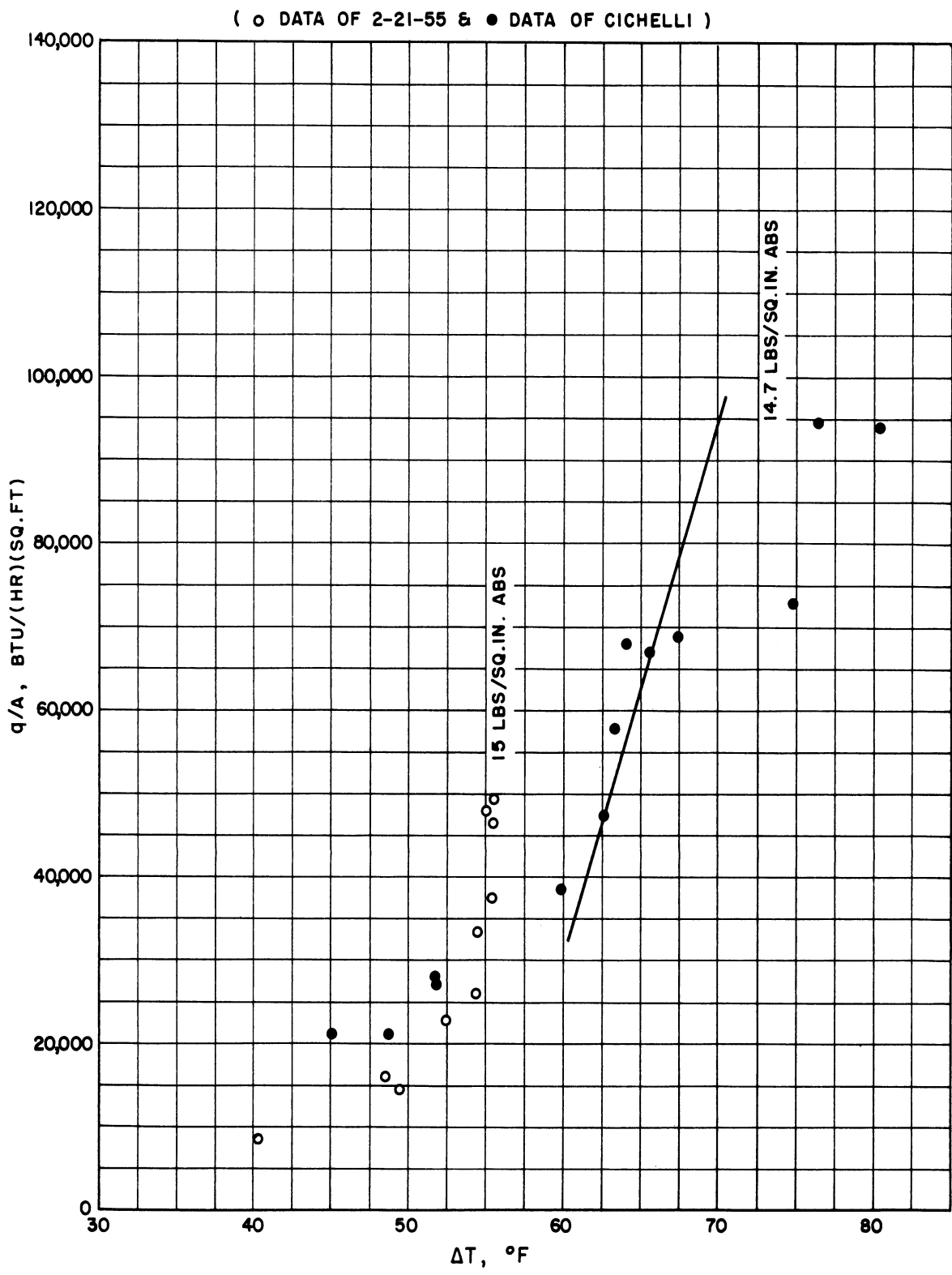


FIG. 12. ATMOSPHERIC BOILING DATA FOR BENZENE COMPARED WITH DATA OF CICHELLI AND BONILLA (7).

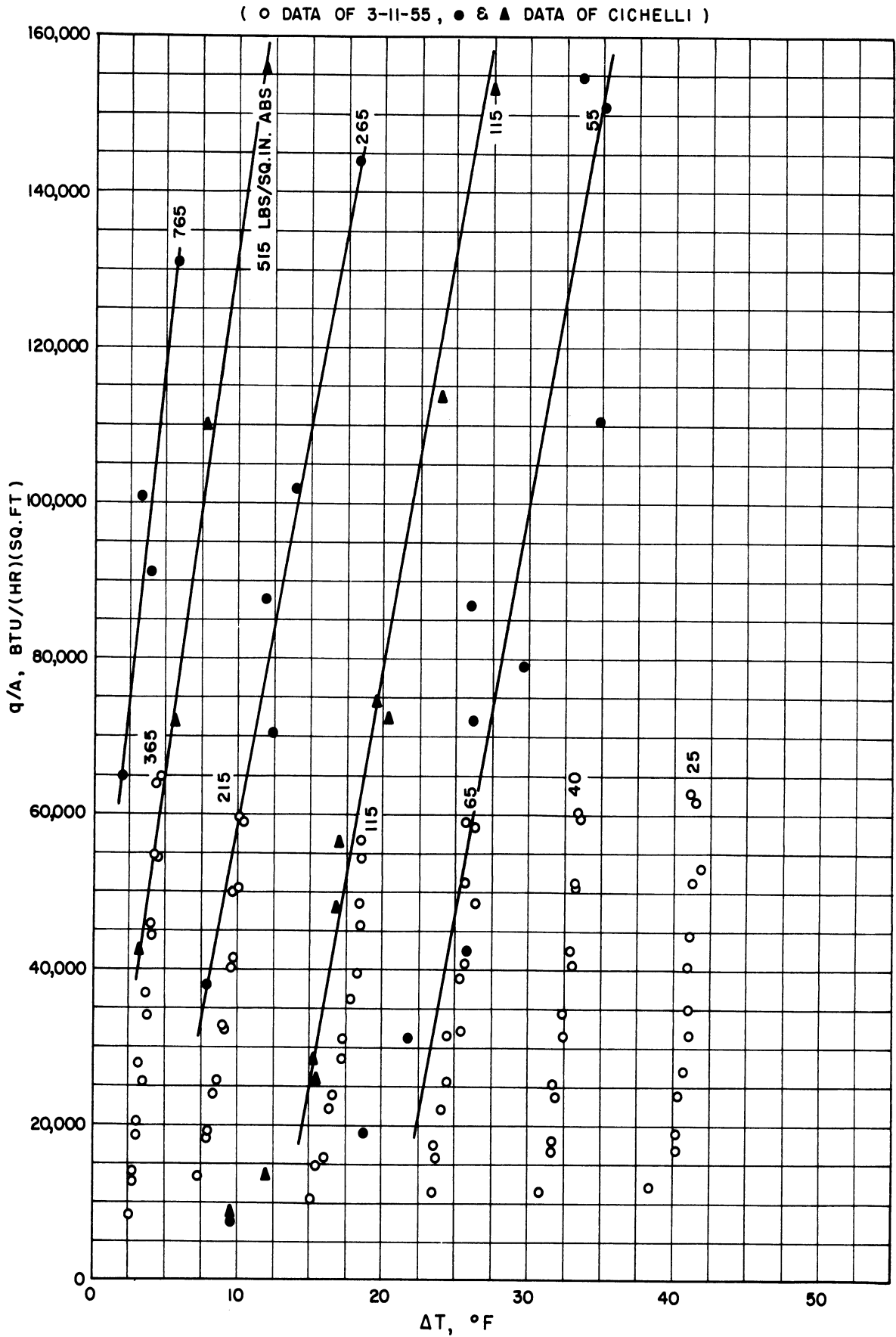


FIG. 13. SUPERATMOSPHERIC BOILING DATA FOR ETHANOL COMPARED WITH DATA OF CICHELLI AND BONILLA (7).

( ● DATA OF 3-11-55, ■ DATA OF CICHELLI & ○, △, ▽, □ DATA OF PERRY )

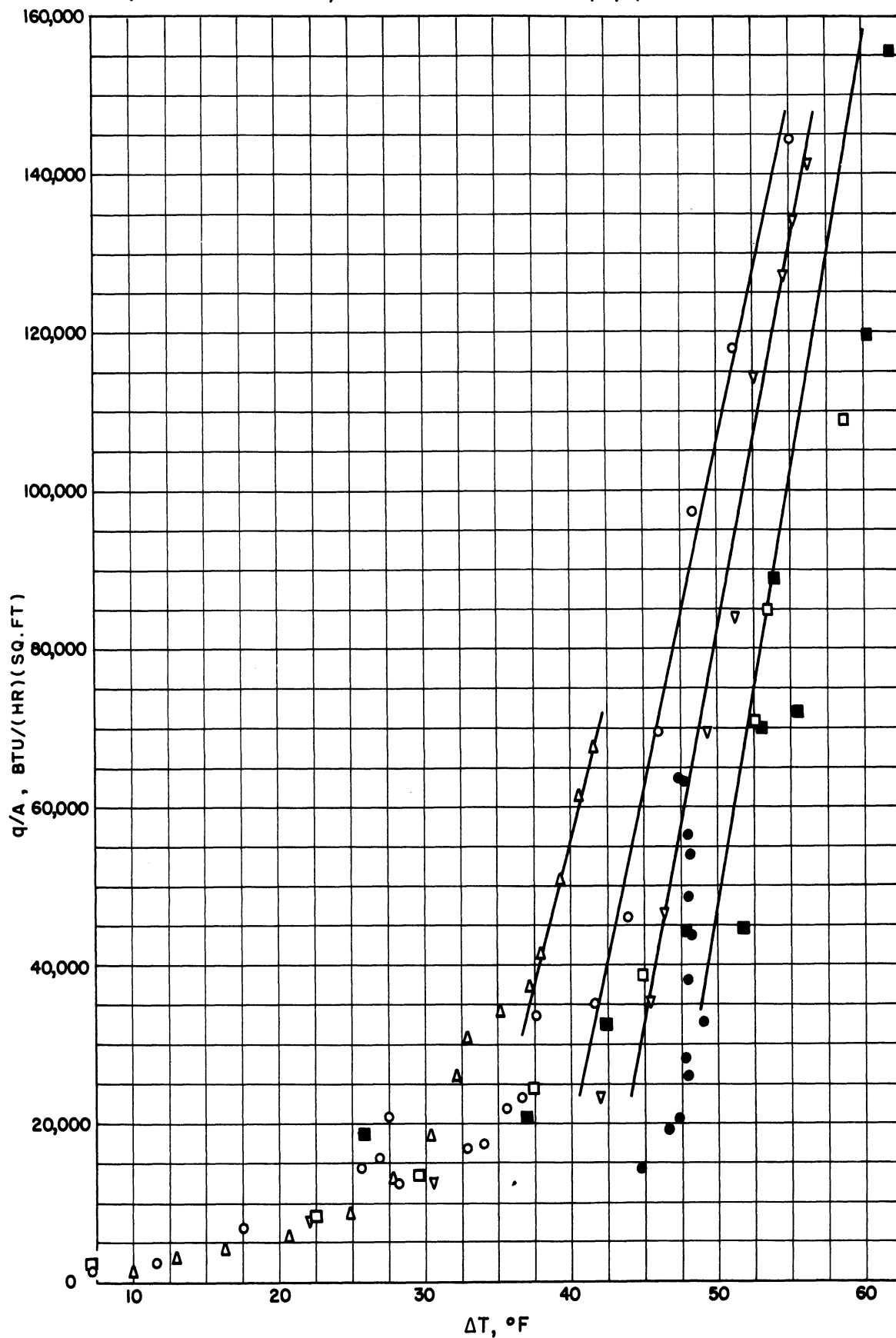


FIG. 14. ATMOSPHERIC BOILING DATA FOR ETHANOL COMPARED WITH DATA OF CICHELLI AND BONILLA (7), AND OF PERRY (21).

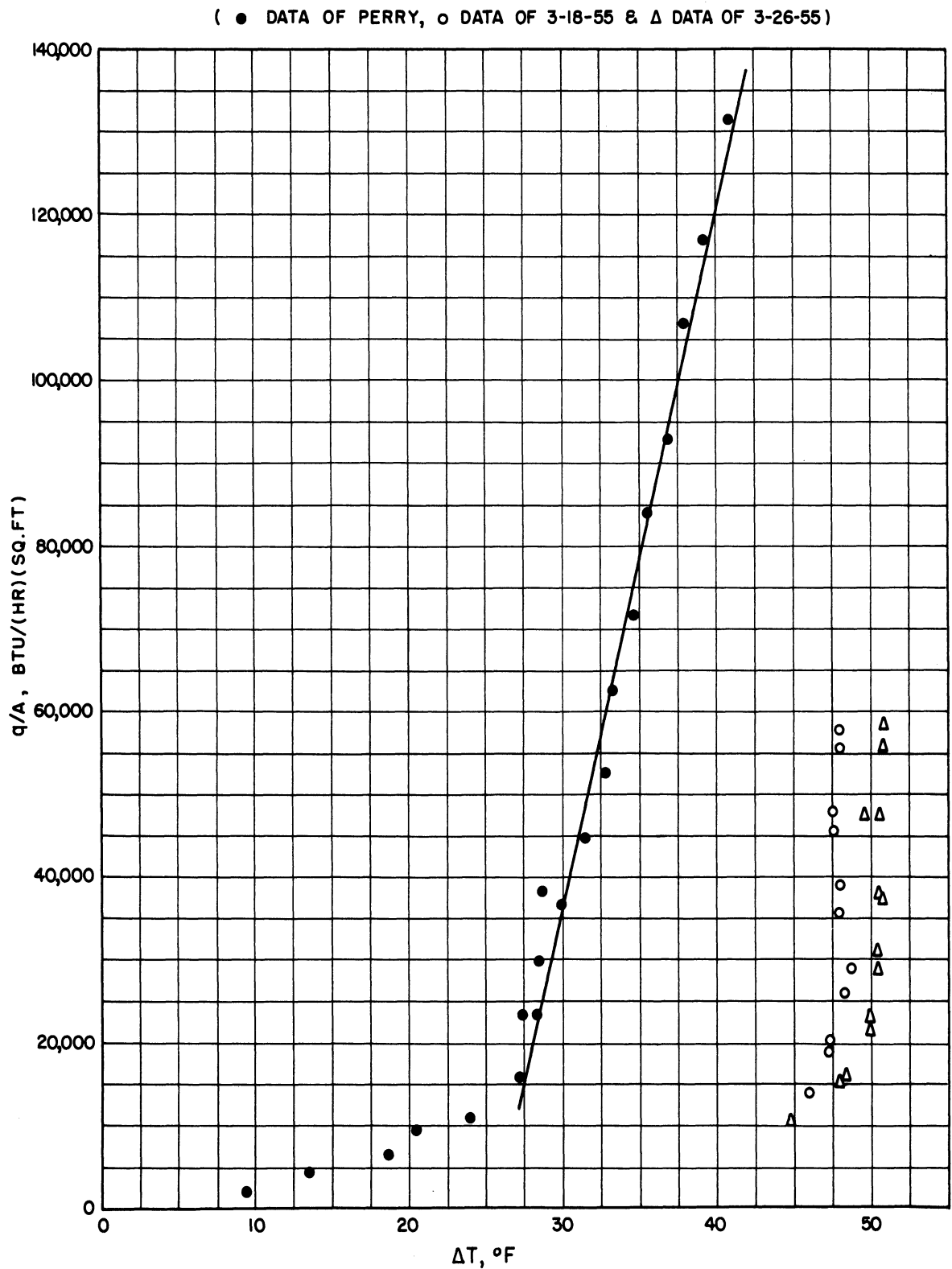


FIG. 15. ATMOSPHERIC BOILING DATA FOR ACETONE COMPARED WITH DATA OF PERRY (21).



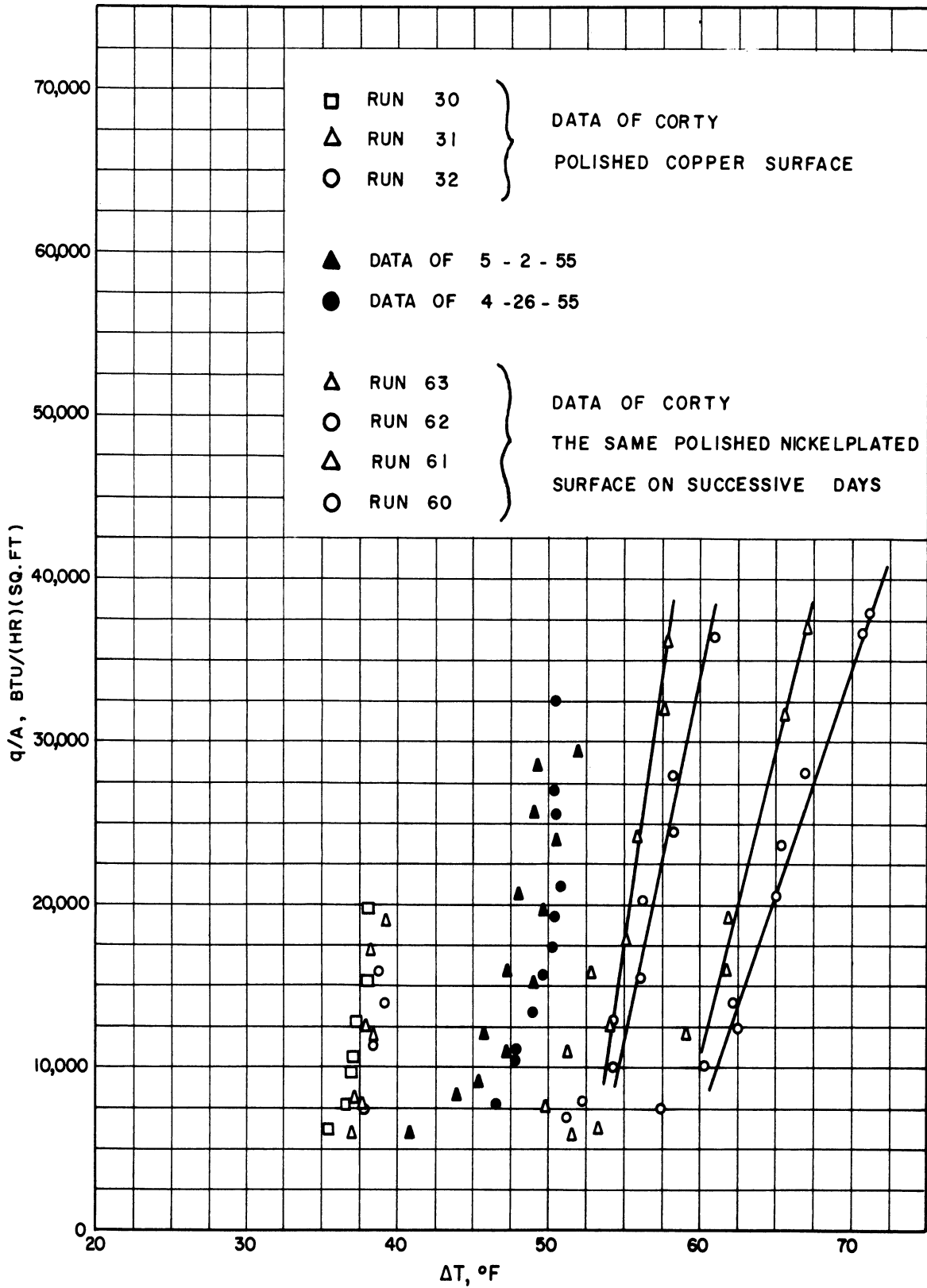


FIG. 16 . ATMOSPHERIC BOILING DATA FOR FREON 113 COMPARED WITH DATA OF CORTY (8) .

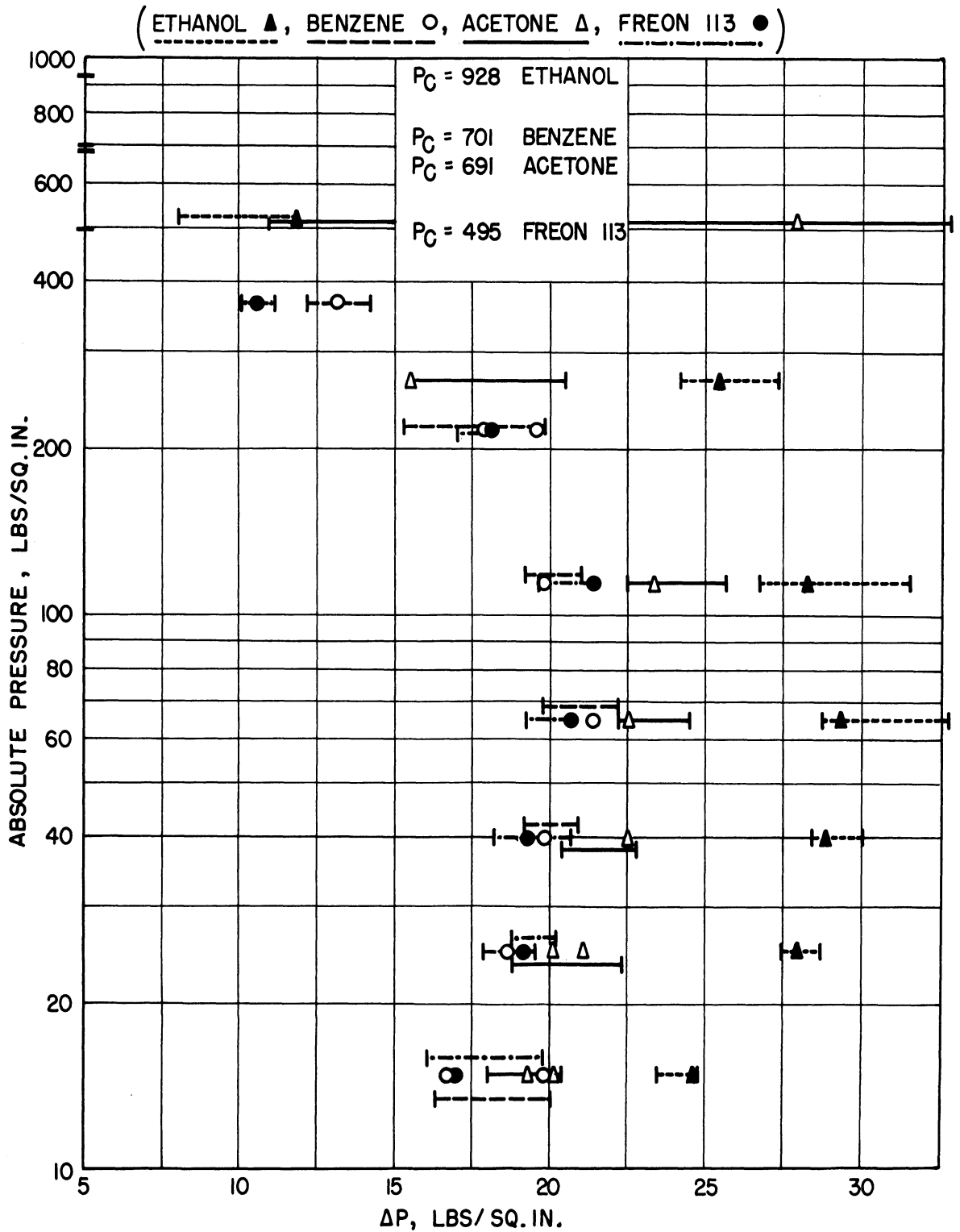


FIG. 17. THE DIFFERENCE BETWEEN THE PRESSURE AND THE VAPOR PRESSURE OF THE LIQUID EVALUATED AT EXTREME EXTRA-POLATED VALUES OF THE SURFACE TEMPERATURE AT ZERO HEAT FLUX - THE DIFFERENCE PLOTTED VS PRESSURE.

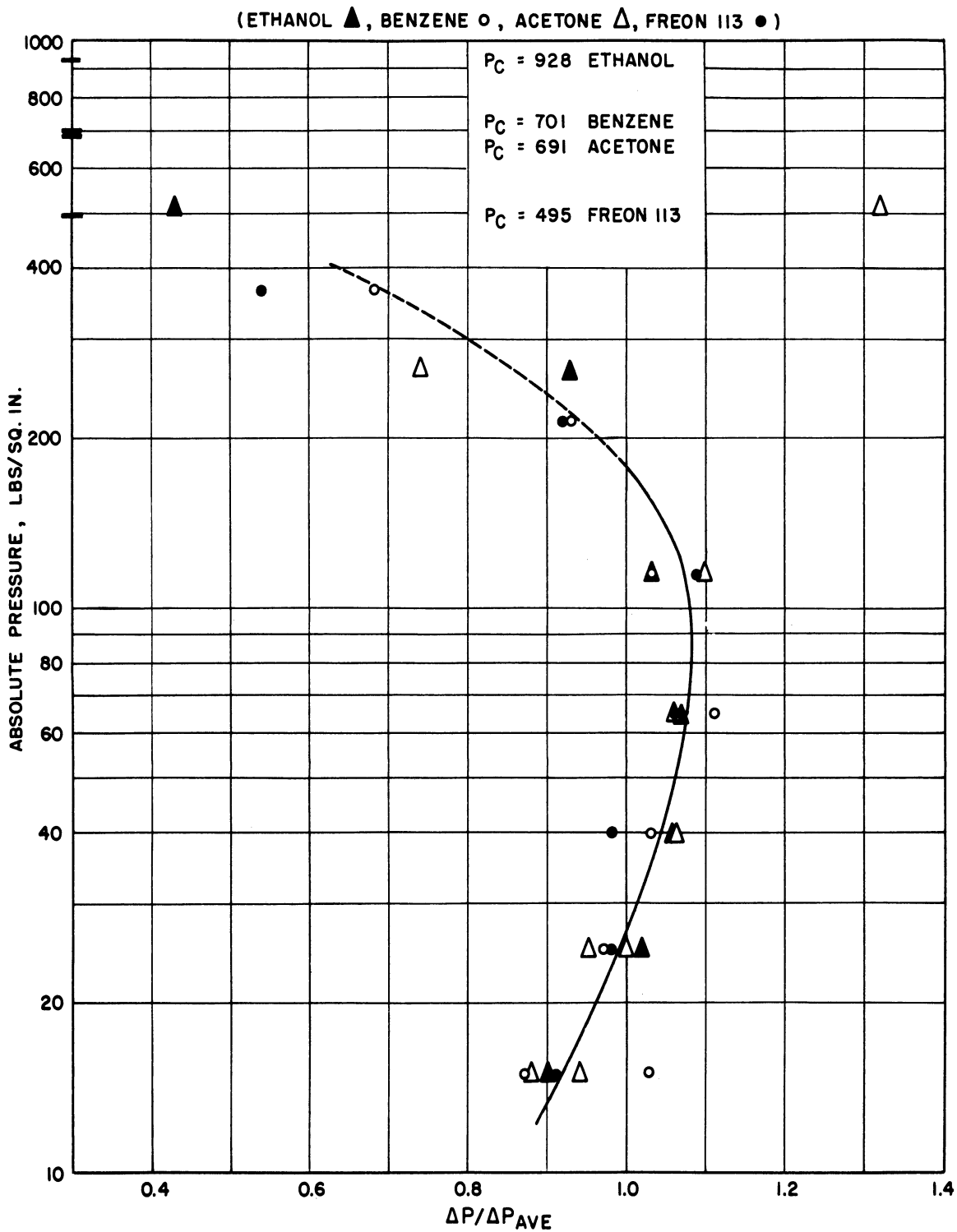


FIG. 18. VALUES AT VARIOUS PRESSURES OF THE NORMALIZED DIFFERENCE BETWEEN THE PRESSURE AND THE VAPOR PRESSURE OF THE LIQUID AT THE SURFACE TEMPERATURE EXTRAPOLATED TO ZERO HEAT FLUX.

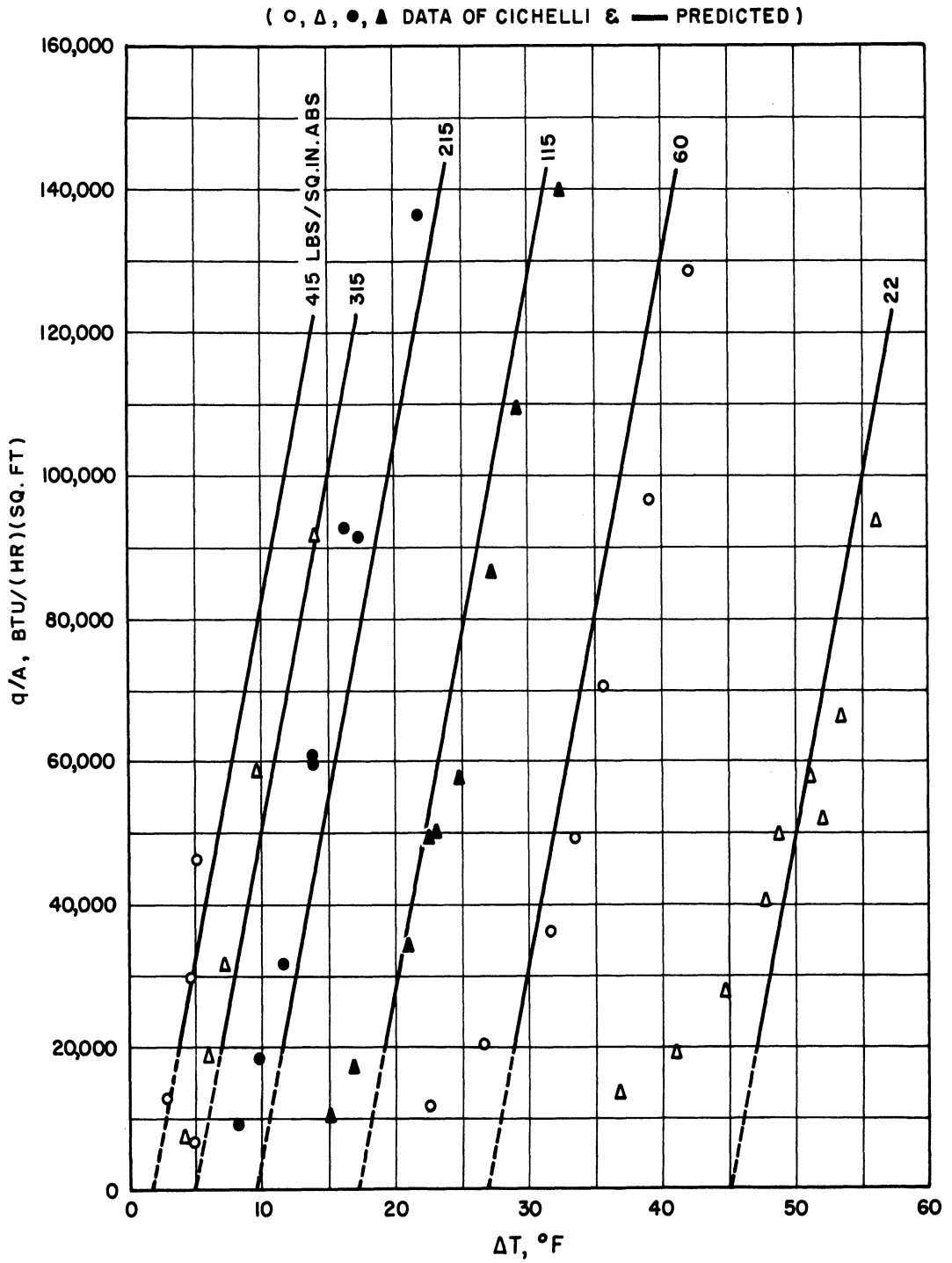


FIG. 19. COMPARISON OF THE PREDICTED SUPERATMOSPHERIC BOILING DATA FOR N-PENTANE WITH DATA OF CICHELLI AND BONILLA ( 7 ).

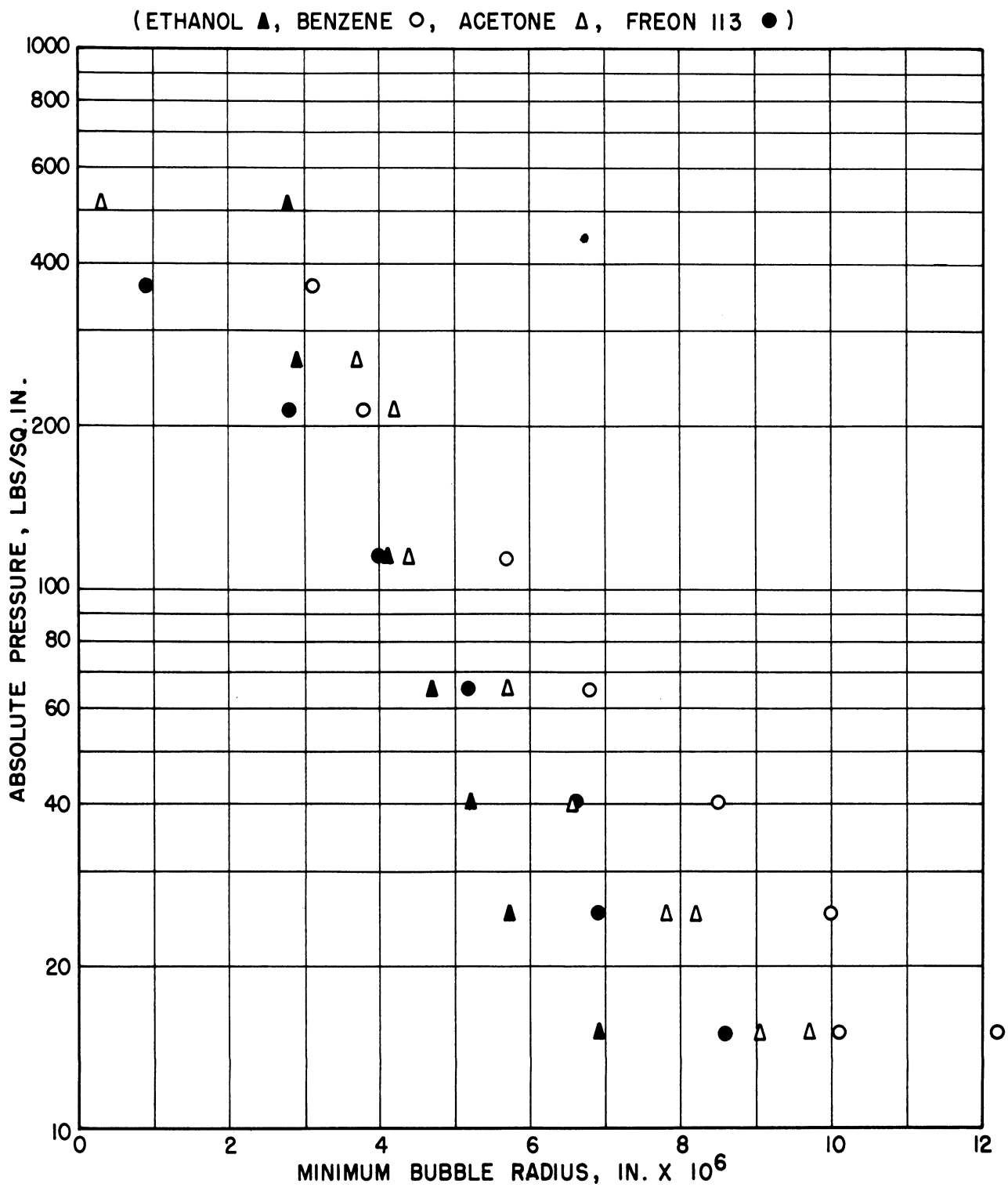


FIG. 20. MINIMUM RADII OF BUBBLES THAT ARE ABLE TO GROW UNDER THE PRESSURE DIFFERENCES SHOWN IN FIG. 17.

( ○ DATA OF 3-2-55, △ DATA OF 2-21-55 & ● DATA OF CICHELLI )

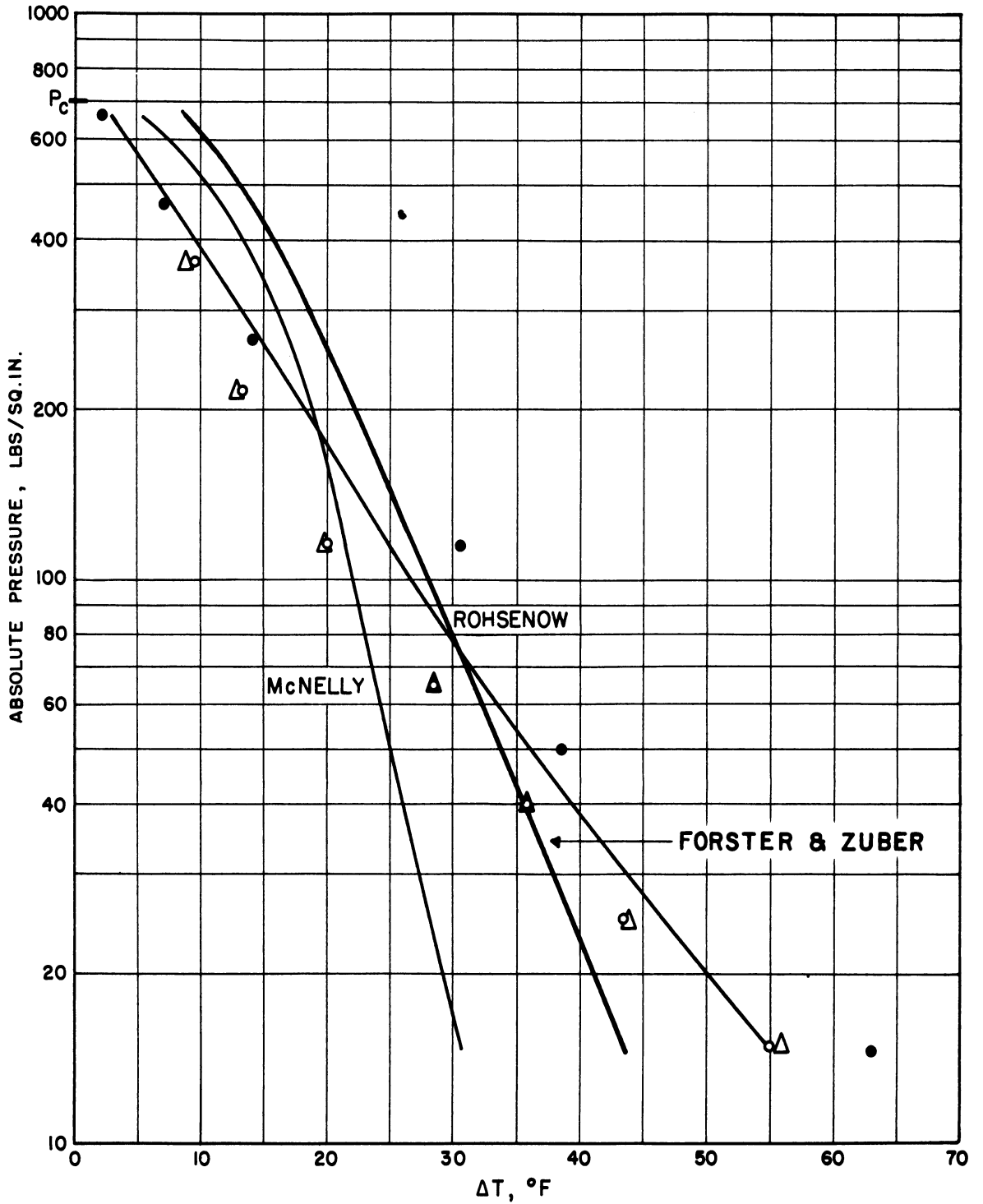


FIG. 21 . SUPERATMOSPHERIC TEMPERATURE DIFFERENCES AT  $q/A = 50,000$  BTU/(HR)(SQ. FT) FOR BENZENE COMPARED WITH ROHSENOW'S FORSTER & ZUBER'S AND McNELLY'S PREDICTION.

( ○ DATA OF 3-11-55 & ● DATA OF CICHELLI )

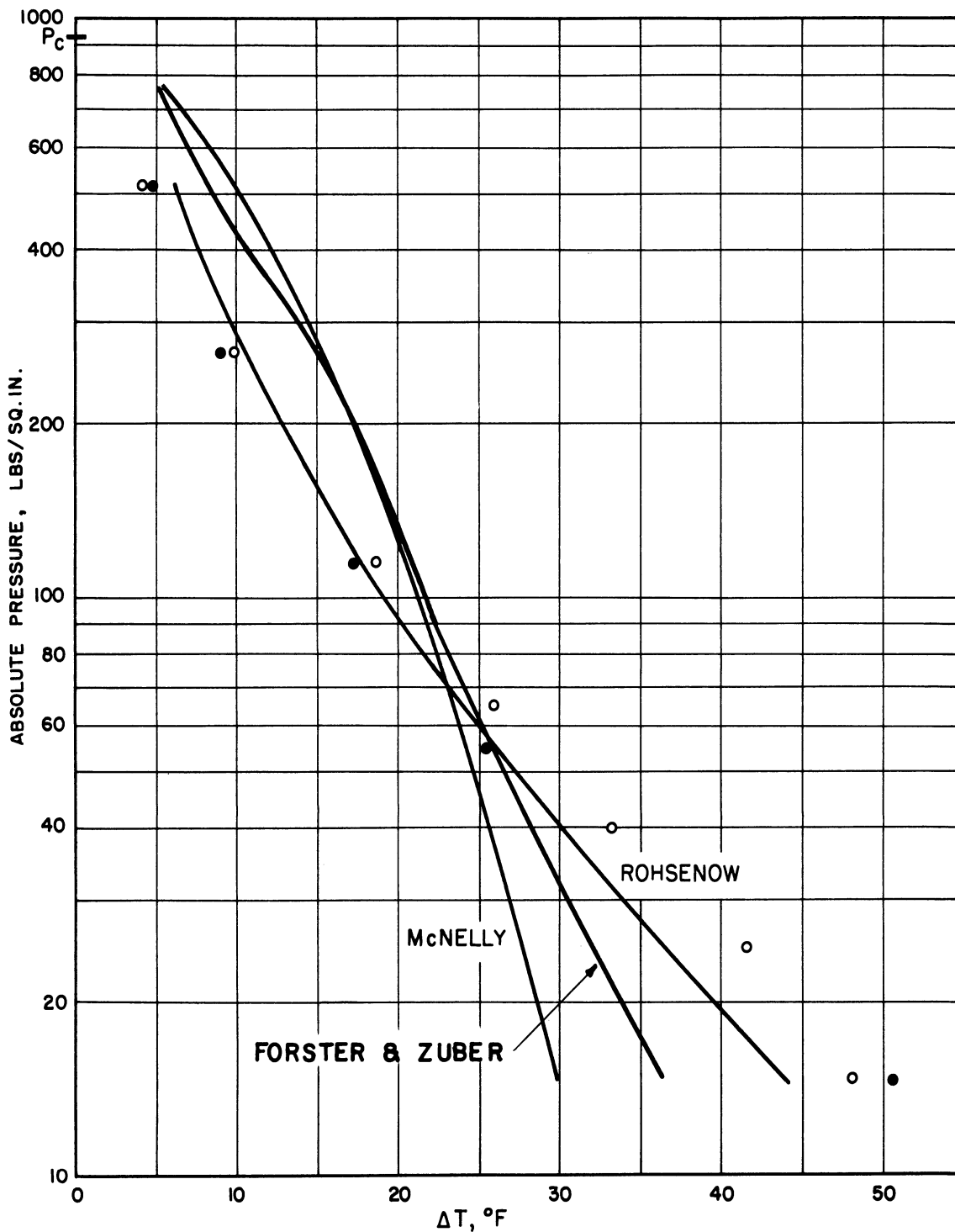


FIG. 22. SUPERATMOSPHERIC TEMPERATURE DIFFERENCES AT  $q/A = 50,000$  BTU/(HR)(SQ.FT) FOR ETHANOL COMPARED WITH ROHSENOW'S FORSTER & ZUBER'S AND McNELLY'S PREDICTION.

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