A study of the nucleate boiling of liquid nitrogen, liquid argon, and liquid carbon monoxide from atmospheric to near the critical pressure

Craig Bauer Johler

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A STUDY OF THE
NUCLEATE BOILING OF LIQUID NITROGEN,
LIQUID ARGON, AND LIQUID CARBON MONOXIDE
FROM ATMOSPHERIC TO NEAR THE CRITICAL PRESSURE

BY
CRAIG BAUER JOHLER

A
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Approved by
(advisor)
ABSTRACT

The nucleate boiling curves of three corresponding states liquids (nitrogen, argon, and carbon monoxide) were analyzed. Each liquid was studied at pressures ranging from atmospheric pressure to near the critical pressure. Saturated liquid boiling was conducted from cylindrical heaters in the horizontal position having diameters of 0.75 inches and lengths of three inches. Liquid nitrogen was boiled from four different gold heat transfer surfaces; argon and carbon monoxide were boiled from the same gold surface.

The critical heat flux correlation of Cobb and Park (8) was further verified by agreement with the experimental critical heat flux ratios obtained in this investigation. It was demonstrated that the critical heat flux is a function of the heat transfer surface; and that this dependence on surface conditions should be provided for in maximum heat flux correlations. Nucleate boiling curves obtained for liquid nitrogen illustrated that a change in boiling heat transfer surface affects both the slope and shape of nucleate boiling curves. The nucleate boiling of carbon monoxide was observed to show partial film boiling along with low critical heat fluxes.

Measured over a wide range of reduced pressures, the liquid argon critical heat fluxes were approximately 24 percent higher than liquid nitrogen critical heat fluxes for a given surface. When compared to the critical heat fluxes of liquid carbon monoxide, the critical heat fluxes of liquid argon and liquid nitrogen averaged 176 and 130 percent larger in magnitude respectively.
ACKNOWLEDGEMENTS

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I. INTRODUCTION

When heat is supplied to a saturated liquid, vapor begins to form at the free surface above the liquid; and convective currents start to circulate the heated liquid. A further increase in heat flux causes vapor bubbles to form at specific locations on the heated surface. These discrete bubbles are intermittently released from the heated surface and rise to the vapor-liquid interface. The vapor bubbles are formed on surface anomalies called nuclei, and this phenomenon is known as nucleate boiling.

The nucleate boiling region is of great importance to the engineer because in this region large quantities of heat can be removed with relatively low temperature difference. Nucleate boiling has been widely used in the power industry, in refrigeration, and in reactor cooling.

To date, there is no general correlation which will predict nucleate boiling behavior. It is known that increased bubble production increases the heat flux greatly, while the temperature difference between the boiling surface and the saturated liquid remains relatively small. At higher temperature differences the bubble population increases to such an extent that the bubbles coalesce and completely cover the surrounding surface with an unstable vapor film. This added film resistance greatly decreases the heat transfer rate. The maximum heat flux attained before the onset of this film boiling is known as the critical heat flux (burnout point) because the decreased heat transfer rate characteristic of film boiling may cause the metal-surface temperature to suddenly rise well above the melting point.
It is this dangerous situation that has caused wide interest in an accurate prediction of the critical heat flux.

Nukiyama (31) summarized the relationship between heat flux and temperature difference by separation of the boiling curve into four distinct heat transfer regions: 1) convective, 2) nucleate boiling, 3) unstable film boiling, and 4) film boiling. The four regions are graphically illustrated in Figure 1.
Figure 1  A Typical Boiling Heat Transfer Curve
II. REVIEW OF LITERATURE

In order to provide a background in the field of nucleate boiling, the principle areas of study in this field have been reviewed. Emphasis has been given to the study of the critical heat flux, but developments in the areas of nucleation sites, bubble dynamics, mechanisms of boiling heat transfer, and surface effects have also been examined.

It is known that bubbles originating from nucleation sites are a distinguishing feature of boiling heat transfer. Jacob (19) pointed out that the boiling liquid is always slightly superheated at the liquid-vapor interface. It is this small temperature difference between the two phases that causes evaporation at the interface. By using the analogy of a capillary tube, Jacob (19) showed that boiling would not start unless finite curvatures (nucleation sites) were present.

Bankoff (2) stated that in practically all cases the appearance of bubbles is controlled by minute quantities of gas, usually entrapped on the solid heat transfer surface. Theoretical arguments by Bankoff (1,2) specify the activity of nucleation sites on the basis of cavity geometry and liquid solid-contact angle. By studying nucleation from a single cavity, Griffith and Wallis (16) determined the importance of cavity geometry. The cavity mouth diameters defined the superheat needed to initiate boiling and the cavity shape determined stability once boiling had begun. Studying nucleation from artificial cavities, Donny (11) concluded that steep-walled cavities with a depth-to-diameter ratio greater than one were the most active
nucleation centers. Kosky (22) proposed three mechanisms which could drive a liquid plug into a vapor nucleation site, causing the site to be de-activated.

Clark, Strange, and Westwater (6) boiled ether and pentane from zinc and aluminum alloys. They presented photographic evidence identifying nucleation sites and found these sites to be pits with diameters of 0.0003 to 0.003 inches. Experimental techniques involving scale deposits by Heled and Orell (17) facilitated the identification and location of active sites. By use of nickel salts, Gaertner and Westwater (14) counted active nucleation sites, and a maximum of 1130 sites per square inch was counted for sub-maximum heat fluxes. Wei and Preckshot (40) showed detailed evidence of bubble growth from glass capillary tubes with the capillaries serving as artificial cavities.

Extensive study has been devoted to vapor bubbles and their relation to the high heat transfer coefficients found in nucleate boiling transfer. As stated, nucleation sites give rise to the development of bubbles. Jacob (19) found that the product of bubble detachment diameter and frequency of bubble departure was essentially constant. Boiling with carbon tetrachloride, Denny (11) discovered that bubble departure diameter increased significantly with increasing temperature, while frequency remained practically constant. More recently Ivey (18) showed that no single expression could correlate frequency and bubble departure diameter and developed correlations for three nucleate boiling regions: hydrodynamic region, transition region, and thermodynamic region. Using a vibrating wire as a heating surface, Nangia and Chon (30) reported shorter generating periods
for bubbles and smaller bubble diameters at breakoff.

Johnson, de la Pena, and Mesler (21) concluded that bubbles of spherical shape have little contact area, small size, slow rate of growth, and little or no delay time; while hemispherical bubbles have large contact area, large size, fast rate of growth, and long delay time. A change in surface position, from horizontal to vertical, was found by Williams and Mesler (41) to affect the delay time of bubbles from an artificial site.

Various nucleate boiling heat transfer mechanisms have been postulated as the result of previous studies concerning nucleation sites and bubble dynamics. These theories are outlined by Cobb (7) and Forster and Grief (13). Both studies dismissed the theories of microconvection in the sublayer and latent heat transport by bubbles. Forster and Grief favored the vapor-liquid exchange mechanism, however Cobb considered the mechanism of mass transfer through the bubble as presented by Moore and Mesler (29) to be the correct mechanism.

By substituting inert gas bubbles for bubbles produced in boiling, Bard and Leonard (3) indicated that heat transfer was most intensive during the time the bubble detaches from the surface. In contrast, Chang and Snyder (4) reported that the high heat flux in nucleate boiling was caused by agitation due to bubble growth and not bubble detachment.

Since nucleation sites have been found to play an important role in boiling heat transfer, great attention has been directed toward the condition of the heat transfer surface. Corty and Foust (9) discovered that for a roughened surface a significantly lower temperature difference was required for a given heat flux when compared to
highly polished surfaces. It was also shown that heat transfer coefficients varied with the immediate past history of boiling. Corty and Foust reported that with increase in flux, active nuclei became centers of patches on which boiling occurred violently. The theory that surface roughness affects both the position and shape of the nucleate boiling curve was confirmed by Kurihara and Meyers (24), who found that surface aging in the liquid to be boiled was essential for reproducible runs.

Boiling from a grooved copper surface, Jacob and Fritz (20) showed that the surface contained absorbed air and gave initially much higher coefficients which decreased with continued boiling. McAdams (28) concluded that difficulties in correlating boiling data were due to three experimental variables: the amount of gas dissolved in the liquid and absorbed on the heat transfer surface, impurities and contamination on the surface, and difference in experimental technique.

Enhancement of nucleation due to suspended solids was reported by Elrod and Clark (12). It was believed that the suspended solids triggered additional nucleation sites, either in the superheated boundary layer above the heat transfer surface or on the surface itself.

The maximum heat flux point of the nucleate boiling curve has proven to be an area of great interest. Many attempts have been made to develop a correlating equation for predicting the maximum heat flux, but such equations have been used with only limited success.

By defining a universal bubble departure velocity near the critical heat flux, Rohsenow and Griffith (35) developed equation 1.
$$\frac{(Q/A)_{\text{MAX}}}{\rho_v L} = 143 \frac{\rho_L - \rho_v}{\rho_v^{0.6}}$$  \hspace{1cm} (1)$$

Where:  $L$ is the latent heat of vaporization  
$\rho_v$ is the vapor density  
$\rho_L$ is the liquid density

Kutateladze (25) derived a similar equation independently by use of dimensional analysis. It was pointed out by Zuber, Tribus, and Westwater (45) that both of the previously mentioned equations have the same form as the equation for flooding in a bubble-cap column. This correspondence is to be expected because of the similarity between burnout in heat transfer and flooding in mass transfer.

Zuber (43) presented equation 2, based on Helmholtz's instability for two phase flow involving liquid and vapor.

$$\frac{(Q/A)_{\text{MAX}}}{\rho_v L} = \frac{\pi}{24} \left( \sigma g \frac{\rho_L - \rho_v}{\rho_v} g_c \right)^{\frac{1}{4}} \left[ \frac{\rho_L}{\rho_L + \rho_v} \right]^{\frac{1}{2}}$$  \hspace{1cm} (2)$$

Where: $\sigma$ is the surface tension  
$g$ is the acceleration of gravity

Using experimental data from many organic liquids, Cichelli and Bonilla (5) empirically developed equation 3.

$$\frac{(Q/A)_{\text{MAX}}}{P_r} = \alpha f (P_r)$$  \hspace{1cm} (3)$$

Where: $P_r$ is the reduced pressure  
$\alpha$ is equal to 1 for clean surfaces  
$\alpha$ is equal to 1.15 for "dirty" surfaces

Applying thermodynamic similarity and the Clausius Clapeyron equation, Lienhard and Schrock (26) obtained an equation similar to equation 3, involving the definition of a parachor.
Zuber (43) predicted a random scatter of ±14 percent for critical heat fluxes based on the hydrodynamic instability theory of unstable liquid wavelengths. It is interesting to note that Leinhard and Schrock (26) reported a ±14 percent uncertainty in burnout heat flux data, which they attributed to the inherent uncertainty in such data as shown by Zuber (43). Gambill (15) likewise found a characteristic randomness in critical heat fluxes which approximated that predicted by the hydrodynamic instability theory.

Contrary to these findings, Kosky (23), boiling with cryogenic liquids, discovered peak nucleate boiling fluxes to be reproducible to ±1 percent about the mean critical flux. It was reported that a dependence of the critical flux on the heat transfer surface shifted fluxes 15 percent. The report suggested that inherent uncertainty in predicting critical fluxes was in reality due only to surface variability. Sterman and Vilenma (37) also reproduced critical heat fluxes to ±2.5 percent using diphenyl.

By use of surface deposits, Costello and Frea (10) noted that increasing the wettability of the heat transfer surface reduced the base radius of the departing surface bubbles, the deposits enabled more liquid to reach the heater and in turn increased the critical heat flux.

As discussed by Park (33) and Cobb (7), Frederking used a thermodynamic approach to predict the temperature difference at burnout. He defined the degree of metastability as,

\[ \epsilon = \frac{\Delta T_{bo}}{\Delta T_{vdw}} \]

where the theoretical temperature difference at burnout might be approached in an ultraclean system.
Since the burnout temperature difference changes radically with change in the microroughness of the surface, Park (33) extended Frederking's work and established a reference value for each surface. Equation 5 was obtained by limiting his work to corresponding states liquids.

\[
\frac{\Delta T_{bo}}{\Delta T_{bo \text{ reference}}} = 2.3 (1-T_r)^{0.64} \tag{5}
\]

Where: \( T_r \) is the reduced temperature.

As the critical heat flux has likewise been found to vary with the microroughness of the surface, Cobb and Park (8) established the reference value at a reduced pressure of one tenth and included it in the correlation for the maximum heat flux. They made use of the Clausius-Clapeyron equation and the assumption that the critical heat flux is a function of the heat of vaporization which led to the development of equation 6.

\[
\frac{(Q/A)_{\text{MAX}}}{(Q/A)_{\text{MAX} \text{ reference}}} = 1.70 - 3.90 T_r - 0.048 T_r^2 + 2.81 T_r^3 + 2.48 T_r^4 \tag{6}
\]

This correlation is a least squares fit of experimental nucleate boiling results from various heat transfer surfaces and geometrics using several corresponding states fluids. The average deviation of the correlation was reported to be 12.6 percent.

The results of studies in the areas of nucleation sites, bubble dynamics, mechanisms of boiling heat transfer, and the critical heat flux all point to the importance of the heat transfer surface associated with nucleate boiling. Attempts to develop a general nucleate boiling heat transfer correlation have failed due to neglect of the
role of the heat transfer surface or to improper characterization of this surface. Cobb and Park (8) have eliminated the effect of the heat transfer surface in their correlation of maximum heat flux ratios.

The purpose of this investigation is to further verify and extend the Cobb and Park correlation by studying the nucleate boiling behavior of the following corresponding states fluids: liquid nitrogen, liquid argon, and liquid carbon monoxide. Specific attention will be given to the role of the heat transfer surface on the critical heat fluxes of these liquids. Several heat transfer surfaces will be employed in the investigation to emphasize the importance of the heat transfer surface on the nucleate boiling curves of the previously mentioned cryogenic liquids.
III. EXPERIMENTAL EQUIPMENT

The experimental equipment was composed of four components: 1) pressure and condensing system (Figure 2), 2) heating element (Figure 3), 3) electrical system, and 4) the temperature measuring system.

The pressure and condensing system used was similar to those described by Sciance (36) and Cobb (7). A one gallon autoclave, manufactured by Autoclave Engineers, Inc., contained the heating element and liquid pool. The vessel had a depth of twelve inches and an inside diameter of five inches.

Pressure in the closed vessel was controlled by the amount of vapor condensed outside the internal condenser as shown in Figure 2. The condenser coolant, liquid nitrogen, was supplied at 235 pounds per square inch gage from Linde LS-110B and LS-156 dewars. A Heise Bourdon tube gauge with a 16 inch dial graduated from 0 to 1000 pounds per square inch measured the pressure of the system. The system was protected from dangerously high pressures by a Black, Sivalls, and Bryson rupture disc, rated at 960 pounds per square inch gage at 72°F. All connections shown in Figure 2 were made of 316 stainless steel. The tubing was 0.25 inch outside diameter with a 0.065 inch wall thickness, and the valves were Whitey No. 1 Series 0.25 inch valves number IRS4-316.

Figure 3 shows the assembled heating element. Tungsten wire (0.020 inches in diameter) wound on a 0.40 inch lava core with 18 threads per inch provided the heat source. This core was insulated from the copper cylinder by Sauereisen Electrical Resistor Cement No. 7 paste. The copper cylinder measured 0.750 inches in outside diameter, 0.55 inches inside diameter, and 3.00 inches in length. Temperature distribution
Figure 2. Pressure and Condensing System - Schematic Diagram
Figure 3. Heat Transfer Element
in the heating element was measured with three copper constantan thermocouples. These thermocouples were silver soldered into 1/16 inch holes drilled axially into the heater wall. Positioning of the thermocouples is clearly shown in Figure 3. A coating of metallic gold was electroplated onto the outer copper surface of the heater, and this gold coating served as the heat transfer surface.

Direct current power was provided by a Sorensen D.C. Power Source, Model DCR 60-40A. The power source had an output voltage range of 0-60 volts with a current range of 0-40 amperes.

Voltage drop across the heating element was measured to ± 0.2 percent of the full scale reading of a Digitec Voltmeter, Model 201, multiple range (000.0 - 100.0 V.). Current input to the heating element was measured to ± 0.25 percent of the full scale reading of a Weston Model 1 (class 50), 50 ampere meter in series with the heating element.

Three thermocouples measured the temperature distribution within the heating element as shown in Figure 3. A fourth thermocouple measured the pool saturation temperature and was located several inches from the heater in the liquid pool. The thermocouples were made of constantan wire and copper wire (Honeywell - Type T - Model No. 9BIC - 30 A.W.G. - with fiber glass coating).

The three thermocouples leading from the heating element were each attached to the female end of a thermocouple plug made by Marlin Mfg. Corp. This plug arrangement allowed for easy removal of the heater from the autoclave. Each wire from the male end of the three thermocouple plugs and the pool thermocouple wire were passed out of the vessel through a Conax MM-062-A16-T gland with teflon sealant to a
liquid nitrogen reference junction on the outside of the autoclave. From the reference junction, the thermocouple wires were connected to a Leeds and Northrup rotary thermocouple switch which was used in conjunction with a Digitec Voltmeter, Model 451, single range (00.00 - 10.00 M.V.). The Digitec Voltmeter measured to ± 0.1 percent of the full scale reading.

The combined product errors of current and voltage for measuring heat fluxes are ± 0.125 percent, which is approximately equal to ± 50 Btu/hr. ft.² for the large heat fluxes obtained in this investigation. Temperature could be read to ± 0.001 millivolts; equivalent to a temperature accuracy of ± 0.1°F. However, Figure 4 shows a typical reproduction of a previous liquid nitrogen nucleate boiling curve on the same heat transfer surface. Temperature differences deviate by an average of less than 1°F. for corresponding heat fluxes. Errors of measurement in this work are thoroughly discussed in appendix B.
Heat Flux, BTU/hr. Ft. \( \frac{2}{(10)^{\frac{1}{4}}} \)
IV. EXPERIMENTAL PROCEDURE

Before filling the autoclave, liquid nitrogen was allowed to circulate through the internal condenser to aid in cooling the vessel (see Figure 2). If the autoclave were to be filled with nitrogen, liquid nitrogen was charged through the fill line and into the vessel and was vented to the atmosphere. Carbon monoxide and argon were available in the gaseous state and were condensed inside the autoclave by regulating the gas flow through the fill line and into the vessel. Continued circulation of liquid nitrogen through the internal condenser caused the gas to condense, until the required liquid level was reached within the autoclave.

When the liquid level was approximately seven inches, the vessel was closed to the atmosphere; and the system pressure controlled by monitoring the nitrogen flow through the internal condenser. When the desired pressure was reached, power was supplied to the heating element. To achieve proper aging of the heat transfer surface, power was increased until the heater passed into the film boiling region. The power was then turned off, and the heater allowed to cool to saturation temperature. This procedure of entering the film boiling region was repeated each time the heater was exposed to the atmosphere.

With the liquid pool at the desired saturation temperature, power was once again supplied to the heating element. Temperature, amperage and voltage were recorded after steady state was achieved by adjusting the nitrogen flow rate in the internal condenser, the power level was raised and the next nucleate boiling point was recorded. Intermittently
between points, the thermocouple recording the pool temperature was checked to observe any change in the saturation temperature. This procedure was continued until the burnout point was attained. Once a pressure run had been completed, the power was turned off and the pressure was adjusted to a new value. The previous steps were repeated at each pressure, until all of the desired nucleate boiling curves for the specific liquid were recorded.

To check for reproducible results, the boiling curve at a reduced pressure of one tenth was always the first and last boiling curve to be studied for a given liquid. The reduced pressure of one tenth was chosen because of the desire to carefully examine the correlation developed by Cobb and Park (8).

The critical heat flux was defined by a rapid increase in \( \Delta T \). This rapidly rising \( \Delta T \) was observed, for most runs, to occur as soon as the power was increased from the previous setting. Only in a few instances was the \( \Delta T \) found to rise suddenly after the power setting had remained constant for several minutes. In the latter case the last power setting was recorded as the critical heat flux; for the former case the critical heat flux was recorded as an average of the last two power settings.
V. RESULTS

During the course of taking experimental boiling heat transfer data, four different heat transfer surfaces were used. Table I is a summary of the various gold heat transfer surfaces employed. Two heaters were necessary because of the failure of the heating element within heater number 1. An entirely new heater and heating surface were introduced after this failure; however, both heaters were of the same design.

A total of thirty-eight nucleate boiling runs were made while boiling with liquid nitrogen, liquid argon, and liquid carbon monoxide over a wide range of reduced pressures. Four heating surfaces were used in taking the twenty-two liquid nitrogen boiling runs, but only one surface (surface number 2) was employed for the sixteen liquid argon and liquid carbon monoxide boiling runs. Thirteen of the thirty-eight nucleate boiling runs were duplications of previous runs at various reduced pressures.

Figures 5 through 8 present a number of the nucleate boiling curves at several reduced pressures for individual boiling surfaces. The boiling curves for liquid nitrogen and liquid argon followed the same general pattern. The slopes of the boiling curves became larger with increasing pressure, and the critical heat fluxes had their greatest values at reduced pressures ranging from three to five tenths. In contrast, the nucleate boiling curves obtained with liquid carbon monoxide (Figure 8) were characterized by abbreviated nucleate boiling regions and low critical heat fluxes. Surface number 2 yielded S-shaped boiling curves when boiling with liquid nitrogen, liquid argon and liquid carbon monoxide.
TABLE I

HEAT TRANSFER SURFACES

<table>
<thead>
<tr>
<th>Surface number</th>
<th>Heater number</th>
<th>Characteristics of the surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>electroplated with gold - unaltered</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>electroplated with gold - unaltered</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Surface number 2 - boiled in tap water for 24 hours</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>Surface number 3 - polished with a soft cloth wheel</td>
</tr>
</tbody>
</table>
Figure 5: Nucleate Boiling Curves for Liquid Nitrogen
Figure 7. Evaporative Boiling Curves for Liquid Argon on Heat Transfer Surface 2

Heat Flux, BTU/ft²·hr (10)

Temperature Difference, °F

\( \text{Pr} = 0.10 \)
\( \text{Pr} = 0.30 \)
\( \text{Pr} = 0.50 \)
\( \text{Pr} = 0.80 \)
\( \text{Pr} = 0.95 \)
Figure 8. Nucleate Boiling Curves for Liquid Carbon Monoxide on Heat Transfer Surface Number 2
VI. DISCUSSION

This study was made with the purpose of extending the knowledge of boiling heat transfer in three areas. The first area involves the prediction of the critical heat flux and maximum temperature difference for both liquid nitrogen and liquid argon. The effects of the heat transfer surface on nucleate boiling are covered in the second area. The third phase of study deals with nucleate boiling of liquid carbon monoxide.

CRITICAL HEAT FLUX AND MAXIMUM TEMPERATURE DIFFERENCE CORRELATIONS

All critical flux data for nitrogen and argon was correlated by using the Cobb and Park (8) maximum heat flux correlation. By using the reduced pressure of one tenth as a reference value, the correlation eliminates the effect of heat transfer surface on the critical heat flux throughout a series of pressure runs. It must be emphasized that the heat transfer surface should remain constant during a series of pressure runs for the correlation to be utilized.

An average error of 6.18 percent with a standard deviation of 18.2 percent was obtained when sixteen liquid nitrogen and liquid argon critical heat fluxes were compared to the Cobb and Park equation in Figure 9.

The series of nitrogen runs with heating surface number 1 deviates noticeably from the Cobb and Park equation at reduced pressure of three tenths and five tenths. This deviation can probably be attributed to a change in the heat transfer surface during boiling. Although care was taken to properly age the heating surface before a series of runs,
Figure 9. Cobb and Park Maximum Heat Flux Correlation

\[ \left( \frac{q}{h} \right)_{\text{max}} / \left( \frac{q}{h} \right)_{\text{max}} P_r = 0.1 \]

\[ \frac{\left( q / h \right)_{\text{max}}}{(q/h)_{\text{max}}} P_r = 0.1 \]

- \( \circ \) \( \text{N}_2 \) Surface 1
- \( \triangledown \) \( \text{N}_2 \) Surface 2
- \( \triangle \) \( \text{N}_2 \) Surface 3
- \( \square \) \( \text{Ar} \) Surface 2

Reduced Temperature, \( T_r \)
a change in surface conditions could have occurred after or during the first nitrogen pressure run which was made at a reduced pressure of one tenth. A premature burnout at this particular pressure would cause the high deviation from the Cobb and Park equation. An attempt to prove this argument, by reproducing the one tenth reduced pressure run at a later date, was unsuccessful because of the failure of heater number 1.

Figure 10 shows the accuracy of Zuber's (43) critical heat flux correlation for liquid nitrogen, having an average experimental error of -10 percent; however, the Kutateladze (25) curve is shifted upward from the data. The correlations of Cichelli and Bonilla (5), Lienhard and Schrock (26), and Rohsenow and Griffith (35) yield results which are in error by several hundred percent.

The complete failure of the five previously mentioned correlations to predict maximum heat fluxes corresponding to the experimental results obtained using liquid argon is presented in Figure 11. The Zuber and Kutateladze correlations fail to fit the argon data while they provide a close approximation to the nitrogen data because the surface tension of argon is approximately ten times larger than the surface tension of nitrogen, (see equation 2). The experimental heat flux data yields a mean error of 11.9 percent with a standard deviation of 26.0 percent when compared to the Cobb and Park equation.

For a given surface (surface number 2), the liquid argon critical heat fluxes were approximately 24 percent higher than the liquid nitrogen critical heat fluxes. This percentage is based on nucleate boiling runs made at reduced pressures ranging from one tenth to eight
tenths. Cobb (7) found the maximum heat flux to be 10 to 30 percent higher with liquid argon than liquid nitrogen.

The data of this investigation confirms Park's (33) maximum temperature difference correlation, equation 5. The scattering of the data (Figure 12) can be attributed to the following sources: 1) Determination of the exact temperature difference at the burnout point is difficult because of heater instability and 2) The magnitude of the temperature difference is much smaller than that of the heat flux.
Figure 10. Maximum Heat Flux Correlations for Liquid Nitrogen
Figure 11. Maximum Heat Flux Correlations for Liquid Argon
Figure 12, Generalized Maximum Temperature Difference Correlation

Reduced Temperature, $T_r$

$\Delta T$ Critical/\$T$ Critical $F_r = 0.1$

- $\bigcirc$ N$_2$ Surface 1
- $\square$ N$_2$ Surface 2
- $\triangle$ N$_2$ Surface 3
- $\triangledown$ Ar Surface 2
HEAT TRANSFER SURFACE EFFECTS ON NUCLEATE BOILING

Four different heat transfer surfaces were utilized during the experimental nucleate boiling runs, as indicated in Table I. Figure 13 illustrates the effect of the condition of the heat transfer surface on the shape and slope of liquid nitrogen nucleate boiling curves. Relatively smooth nucleate boiling curves are associated with surfaces 1 and 4, but the slope of the surface 1 boiling curve is approximately twice the slope of the boiling curve exhibited by surface 4. The boiling curve obtained from surface 3 is also of greater slope than the surface 4 curve; as stated in Table I, surface 4 is highly polished and smoother than surface 3. Surface 2 and 3 boiling curves initially have similar slopes, but their shapes and slopes differ greatly as the critical heat flux is approached.

The boiling curves derived from these surfaces confirm the conclusions reached by Carty and Foust (9); that $\Delta T$ in nucleate boiling decreases with increased roughness and that the positions and slopes of the boiling curves vary with roughness.

The S-shaped curve associated with surface 2 is particularly unusual. S-shaped curves have been reported by several authors: Tang and Rotem (38), Rallis and Jawurck (34), Van Stralen (39), and Zuber (44); however, the observation of such curves is relatively infrequent. Orell (32) gives further insight into the S-shaped curve by relating its appearance to a sudden increase in the nucleation site density.

Many authors - Gambill (15), Costello and Frea (10), Stermen and Vilemas (37), Kosky (23), and Young and Hummel (42) - have indicated the importance of the state of the heat transfer surface on the critical heat flux. As mentioned, different pressure runs were reproduced
Figure 13. Nucleate Boiling Curves for Liquid Nitrogen on Different Jettisons Surfaces at 0.1 P

- Surface 1 - electroplated with gold
- Surface 2 - electroplated with gold
- Surface 3 - Surface 2 boiled in tap water for 24 hours
- Surface 4 - Surface 3 polished with a soft cloth wheel

Heat Flux, BTU/hr. ft.² (10⁻¹⁴)

Temperature Difference, °F
to be sure that the heating surface had not changed during boiling. Eight boiling curves were duplicated at various pressures on unaltered heat transfer surfaces. Reproduction of the critical heat flux never deviated by more than 7 percent; and the average deviation for the eight critical fluxes reproduced was 3 percent. An inherent error of 3 percent was calculated for this heater arrangement.

In contrast, the five nitrogen reduced pressure runs duplicated on surfaces 1 and 2 produced an average deviation of 17.6 percent among corresponding maximum heat fluxes. Similarly, a deviation of 24.0 percent was found between atmospheric critical heat fluxes on surfaces 1 and 3; while the maximum heat flux was decreased by 16.4 percent by polishing surface number 3.

Of the eight boiling curves duplicated on unaltered surfaces, five were not exposed to the atmosphere between checks for reproducibility and three were exposed. This exposure did not affect duplication of the maximum heat flux but did affect the reproducibility of the maximum temperature difference. The reproducibility of the maximum $\Delta T$ on the five unexposed surfaces never deviated by more than 7.2 percent, with an average deviation of 4.6 percent. The maximum $\Delta T$ on the three exposed surfaces varied with an average deviation of 19.9 percent. Frederking (27) explains this deviation by noting that in different experiments the temperature difference may vary by a factor of two, due to the amount of vapor or foreign gas trapped in surface cavities.
NUCLEATE BOILING OF CARBON MONOXIDE

Nucleate boiling of liquid carbon monoxide gave unusual results when compared to the experimental data of nitrogen and argon.

Three boiling curves were duplicated at a reduced pressure of one tenth, and the average critical heat flux deviation was 11.3 percent for the same boiling surface. This high deviation might be accounted for by change in the heat transfer surface caused by carbon monoxide or by the unique behavior of the carbon monoxide critical heat flux as discussed below.

The critical heat fluxes of liquid argon and liquid nitrogen were defined by a sudden rise in surface temperature signaling the beginning of film boiling. In contrast, the pressure runs of liquid carbon monoxide, above the reduced pressure of one tenth, entered partial film boiling at relatively low heat fluxes. This partial film boiling was characterized by a slow increase in temperature difference with time at a constant heat flux. After several minutes had elapsed, the last \( \Delta T \) was recorded before a rapid increase in surface temperature marked the initiation of fully developed film boiling. The last \( \Delta T \) recorded varied randomly in the range of 20 to 50\(^{\circ}\)F with different pressure runs.

Boiling from a platinum surface with liquid oxygen, Lyon, Kosky, and Harman (27) experienced this same phenomena of partial film boiling at higher pressures. They attributed this behavior to a small section of the test element entering film boiling. It is apparent that the variation of pressure causes a change in the normal mechanisms of nucleate boiling for liquid oxygen and liquid carbon monoxide;
adsorption of the oxygen molecule on the boiling surface at higher pressures may be an explanation.

The carbon monoxide nucleate boiling runs were all obtained while boiling from heat transfer surface number 2. This is the same surface that exhibited the S-shaped boiling curves for liquid nitrogen and liquid argon. It may be possible that surface effects other than oxygen adsorption caused the premature film boiling observed with liquid carbon monoxide, and that these same unknown surface effects are the source of the unique S-shaped boiling curves. Nucleate boiling of carbon monoxide from different heat transfer surfaces should provide a definite answer to this question.

The carbon monoxide nucleate boiling curve associated with the reduced pressure of three tenths has a very definite S-shaped appearance. This curve may represent the effects of an unstable transition between the larger slope of the one tenth reduced pressure boiling curves and the smaller sloped boiling curves at reduced pressures of five tenths and higher.

The heat flux that initiated partial film boiling was defined as the critical heat flux for carbon monoxide. Figure 14 is an enlargement of Figure 8, and both figures show the low critical heat fluxes of carbon monoxide coupled with the gradual disappearance of the nucleate boiling region with increasing pressure.

A family of nucleate boiling pressure runs was made on surface number 2 for liquid nitrogen, liquid argon, and liquid carbon monoxide. Comparison of the critical heat fluxes for these liquids shows that the argon and nitrogen critical heat fluxes average 176 and 130 percent larger in magnitude respectively, when compared to the critical heat fluxes of liquid carbon monoxide.
Figure 14. Nucleate Boiling Curves for Liquid Carbon Monoxide on Heat Transfer Surface Number 2

Heat Flux, W/ft²

Temperature Difference, °F

Symbols:
△ Pr 0.10
○ Pr 0.30
□ Pr 0.50
▼ Pr 0.80
● Pr 0.90
▲ Pr 0.95
VII. CONCLUSIONS

1. Of the critical heat flux correlations tested, the Cobb and Park (8) equation is the most accurate for the prediction of the critical heat fluxes of liquid nitrogen and liquid argon.

2. Measured over a wide range of reduced pressures, the liquid argon critical heat fluxes are approximately 24 percent higher than liquid nitrogen critical heat fluxes for a given surface.

3. Each boiling heat transfer surface has its own characteristic boiling curve with respect to both shape and slope.

4. For a given surface, the critical heat flux can be reproduced to within 3 percent at various reduced pressures; however, it may vary as much as 25 percent among different heat transfer surfaces.

5. Exposure of the heat transfer surface to the atmosphere does not affect the critical heat flux, but does alter the maximum temperature difference by an average of 20 percent.

6. In contrast to liquid nitrogen and liquid argon, the critical heat fluxes of liquid carbon monoxide are defined by the appearance of partial film boiling at reduced pressures ranging from three tenths to near the critical pressure.

7. When compared to the critical heat fluxes of liquid carbon monoxide over a wide range of reduced pressures and for a given surface, the critical heat fluxes of liquid argon and liquid nitrogen average 176 and 130 percent larger in magnitude respectively.
NOMENCLATURE

A = Area, ft.\(^2\)
\(g\) = Acceleration due to gravity, ft./sec.\(^2\)
\(g_c\) = Conversion factor in Newton's law of motion, lb.m ft./lb.f sec.\(^2\)
P = Pressure, P.S.I.
Q = Rate of heat transfer, B.T.U./hr.
T = Temperature, °R or °F
\(\Delta T\) = Temperature difference, \((T_{\text{surface}} - T_{\text{liquid}})\)

Greek Symbols

e = Degree of metastability, defined by Equation 8
\(\sigma\) = Surface tension, lb.\(_f\)/ft.
\(\rho\) = Density, lb./ft.\(^3\)

Subscripts

L = Refers to the liquid
r = Refers to reduced property
v = Refers to the vapor
\(\max\) = Refers to the point where the maximum heat flux occurs
BIBLIOGRAPHY


APPENDIX A
CALCULATED DATA

TABLE A-I   NUCLEATE BOILING NITROGEN DATA SURFACE NUMBER 1
TABLE A-II  NUCLEATE BOILING NITROGEN DATA SURFACE NUMBER 2
TABLE A-III NUCLEATE BOILING NITROGEN DATA SURFACE NUMBER 3
TABLE A-IV  NUCLEATE BOILING NITROGEN DATA SURFACE NUMBER 4
TABLE A-V   NUCLEATE BOILING ARGON DATA SURFACE NUMBER 2
TABLE A-VI  NUCLEATE BOILING CARBON MONOXIDE DATA SURFACE NUMBER 2
TABLE A-I

NUCLEATE BOILING NITROGEN DATA ON SURFACE NUMBER 1

Date - 6-27-67
Saturation Temperature 138.7°R
Saturation Pressure 14.2 P.S.I.A.

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<th>ΔT °F</th>
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Date - 4-18-68
Saturation Temperature 160.7°R
Saturation Pressure 49 P.S.I.A.

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**Saturation Pressure 148 P.S.I.A.**

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### Date - 6-6-68

**Saturation Temperature 187.2°R**

**Saturation Pressure 148 P.S.I.A.**

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TABLE A-I continued

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TABLE A-I continued

Date - 6-6-68
Saturation Temperature 202.9°F
Saturation Pressure 246 P.S.I.A.

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Saturation Pressure 423 P.S.I.A.

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**TABLE A-II**

NUCLEATE BOILING NITROGEN DATA ON SURFACE NUMBER 2

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Saturation Temperature 160.7°R
Saturation Pressure 49 P.S.I.A.

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Burnout Point

Date - 8-8-68
Saturation Temperature 160.7°R
Saturation Pressure 49 P.S.I.A.

<table>
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<th>Q/A (10)^-4</th>
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<td>1.605</td>
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Burnout Point
TABLE A-II continued

Date - 8-8-68
Saturation Temperature 187.2°R
Saturation Pressure 148 P.S.I.A.

<table>
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<tbody>
<tr>
<td>0.203</td>
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Date - 8-8-68
Saturation Temperature 202.9°R
Saturation Pressure 246 P.S.I.A.

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</thead>
<tbody>
<tr>
<td>0.146</td>
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</tr>
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<td>0.545</td>
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</tr>
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<td>2.500</td>
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</tr>
<tr>
<td>3.420</td>
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<tr>
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<td>9.6</td>
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<tr>
<td>3.930</td>
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</table>
### TABLE A-II continued

**Date - 8-8-68**

Saturation Temperature 218.9°R  
Saturation Pressure 394 P.S.I.A.

<table>
<thead>
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<td>B.t.u./hr. ft.²</td>
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<tr>
<td>0.078</td>
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<tr>
<td>0.288</td>
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<td>1.510</td>
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<td>2.200</td>
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</table>

**Date - 8-8-68**

Saturation Temperature 221.4°R  
Saturation Pressure 423 P.S.I.A.

<table>
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<tr>
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<td>0.281</td>
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<tr>
<td>1.915</td>
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</table>
## TABLE A-III

NUCLEATE BOILING NITROGEN DATA ON SURFACE NUMBER 3

**Date - 8-31-68**

Saturation Temperature 138.7°R
Saturation Pressure 14.2 P.S.I.A.

<table>
<thead>
<tr>
<th>$Q/A \times 10^{-4}$</th>
<th>$\Delta T$</th>
<th>$\text{B.t.u./hr. ft.}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.127</td>
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<td>0.508</td>
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<tr>
<td>1.320</td>
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<td>2.160</td>
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<td></td>
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<tr>
<td>2.460</td>
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<tr>
<td>2.570</td>
<td>13.0</td>
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<tr>
<td>2.640</td>
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</tbody>
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**Date - 9-4-68**

Saturation Temperature 138.7°R
Saturation Pressure 14.2 P.S.I.A.

<table>
<thead>
<tr>
<th>$Q/A \times 10^{-4}$</th>
<th>$\Delta T$</th>
<th>$\text{B.t.u./hr. ft.}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.279</td>
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<td>0.763</td>
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</tr>
<tr>
<td>1.210</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>1.760</td>
<td>12.2</td>
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<tr>
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</tr>
<tr>
<td>2.340</td>
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<tr>
<td>2.490</td>
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</tbody>
</table>
### TABLE A-III continued

Date - 9-5-68  
Saturation Temperature 160.7°F  
Saturation Pressure 49 P.S.I.A.

<table>
<thead>
<tr>
<th>Q/A (10)^{-4}</th>
<th>B.t.u./hr. ft.^2</th>
<th>ΔT (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.149</td>
<td>0.188</td>
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<tr>
<td>0.485</td>
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<td>6.8</td>
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<td>1.050</td>
<td>8.0</td>
</tr>
<tr>
<td>1.995</td>
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<td>2.590</td>
<td>2.500</td>
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<tr>
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<td>12.5</td>
</tr>
<tr>
<td>3.520</td>
<td>3.430</td>
<td>13.7</td>
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<tr>
<td>3.760</td>
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<tr>
<td>3.700</td>
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</table>

*Burnout Point*
### TABLE A-IV

NUCLEATE BOILING NITROGEN DATA ON SURFACE NUMBER 4

Date - 9-5-68
Saturation Temperature 160.7°R
Saturation Pressure 49 P.S.I.A.

<table>
<thead>
<tr>
<th>Q/A $(10)^{-4}$</th>
<th>$\Delta T$ °F</th>
<th>B.t.u./hr. ft.$^2$</th>
</tr>
</thead>
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<td>0.219</td>
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<tr>
<td>1.200</td>
<td>9.8</td>
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</tr>
<tr>
<td>1.970</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>2.520</td>
<td>14.2</td>
<td></td>
</tr>
<tr>
<td>2.780</td>
<td>16.4</td>
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</tr>
<tr>
<td>2.770</td>
<td>16.2</td>
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</tr>
<tr>
<td>2.870</td>
<td>16.6</td>
<td></td>
</tr>
<tr>
<td>2.940</td>
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<td>3.030</td>
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<td>3.140</td>
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</table>

Date - 9-5-68
Saturation Temperature 160.7°R
Saturation Pressure 49 P.S.I.A.

<table>
<thead>
<tr>
<th>Q/A $(10)^{-4}$</th>
<th>$\Delta T$ °F</th>
<th>B.t.u./hr. ft.$^2$</th>
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</thead>
<tbody>
<tr>
<td>0.410</td>
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<td>2.540</td>
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<tr>
<td>2.780</td>
<td>16.5</td>
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<tr>
<td>2.940</td>
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<tr>
<td>3.030</td>
<td>17.4</td>
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### TABLE A-V

NUCLEATE BOILING ARGON DATA ON SURFACE NUMBER 2

Date - 7-6-68  
Saturation Temperature 192.0°F  
Saturation Pressure 71 P.S.I.A.

<table>
<thead>
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<th>Q/A (10)^{-4} B.t.u./hr. ft.²</th>
<th>ΔT °F</th>
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</thead>
<tbody>
<tr>
<td>0.339</td>
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<tr>
<td>1.059</td>
<td>8.6</td>
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<tr>
<td>2.660</td>
<td>12.7</td>
</tr>
<tr>
<td>3.440</td>
<td>16.9</td>
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<tr>
<td>4.210</td>
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<td>4.670</td>
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<tr>
<td>5.350</td>
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Burnout Point

Date - 8-1-68  
Saturation Temperature 192.0°F  
Saturation Pressure 71 P.S.I.A.

<table>
<thead>
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<th>Q/A (10)^{-4} B.t.u./hr. ft.²</th>
<th>ΔT °F</th>
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<tbody>
<tr>
<td>0.348</td>
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<td>2.460</td>
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<td>4.100</td>
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<td>4.350</td>
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<td>4.560</td>
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<tr>
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Burnout Point
TABLE A-V continued

Date - 8-1-68
Saturation Temperature 192.0°F
Saturation Pressure 71 P.S.I.A.

<table>
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<th>Q/A (10)^-4</th>
<th>ΔT</th>
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</thead>
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<td>4.650</td>
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Date - 7-6-68
Saturation Temperature 225.0°F
Saturation Pressure 212 P.S.I.A.

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<td>2.770</td>
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<td>3.560</td>
<td>6.9</td>
</tr>
<tr>
<td>4.230</td>
<td>7.3</td>
</tr>
<tr>
<td>4.780</td>
<td>6.4</td>
</tr>
<tr>
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</table>
### TABLE A-V continued

**Date - 7-6-68**

Saturation Temperature 243.0°F
Saturation Pressure 352 P.S.I.A.

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<td>5.9</td>
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<td>8.6</td>
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<td>4.150</td>
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</table>

**Date - 8-1-68**

Saturation Temperature 262.0°F
Saturation Pressure 564 P.S.I.A.

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TABLE A-V continued

<table>
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<th>Q/A (10)^{-4}</th>
<th>B.t.u./hr. ft.²</th>
<th>ΔT</th>
<th>°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.214</td>
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<tr>
<td>0.354</td>
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<td></td>
</tr>
<tr>
<td>0.615</td>
<td></td>
<td>1.8</td>
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</tr>
<tr>
<td>0.915</td>
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</tr>
<tr>
<td>1.123</td>
<td></td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>1.309</td>
<td></td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>1.372</td>
<td></td>
<td>2.1</td>
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</tr>
<tr>
<td>1.681</td>
<td></td>
<td>2.2</td>
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</tr>
<tr>
<td>1.810</td>
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<td>2.2</td>
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</tr>
<tr>
<td>1.900</td>
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<td>Burnout Point</td>
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Date - 8-1-68
Saturated Temperature 268.0°F
Saturated Pressure 634 P.S.I.A.

Date - 8-1-68
Saturated Temperature 270.0°F
Saturated Pressure 670 P.S.I.A.

<table>
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<th>°F</th>
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<tbody>
<tr>
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</tr>
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<td>0.444</td>
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<td>1.6</td>
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<tr>
<td>0.710</td>
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<td>1.5</td>
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<tr>
<td>0.840</td>
<td></td>
<td>1.7</td>
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<tr>
<td>0.925</td>
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<td>Burnout Point</td>
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</table>
# TABLE A-VI

**NUCLEATE BOILING OF CARBON MONOXIDE DATA**  
**SURFACE NUMBER 2**

Date - 8-1-68  
Saturation Temperature 175.5°R  
Saturation Pressure 51 P.S.I.A.

<table>
<thead>
<tr>
<th>Q/A (10)^-4</th>
<th>ΔT</th>
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<tbody>
<tr>
<td>B.t.u./hr. ft.²</td>
<td>°F</td>
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<tr>
<td>0.342</td>
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<tr>
<td>1.170</td>
<td>8.3</td>
</tr>
<tr>
<td>1.948</td>
<td>10.1</td>
</tr>
<tr>
<td>2.930</td>
<td>10.9</td>
</tr>
<tr>
<td>3.700</td>
<td>12.2</td>
</tr>
<tr>
<td>4.500</td>
<td>12.4</td>
</tr>
<tr>
<td>5.080</td>
<td>11.9 Burnout Point</td>
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Date - 8-8-68  
Saturation Temperature 175.5°R  
Saturation Pressure 51 P.S.I.A.

<table>
<thead>
<tr>
<th>Q/A (10)^-4</th>
<th>ΔT</th>
</tr>
</thead>
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<tr>
<td>B.t.u./hr. ft.²</td>
<td>°F</td>
</tr>
<tr>
<td>0.117</td>
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<tr>
<td>3.660</td>
<td>11.8</td>
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<tr>
<td>3.780</td>
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<tr>
<td>3.850</td>
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<tr>
<td>3.950</td>
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<tr>
<td>4.050</td>
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</table>
TABLE A-VI continued

Date - 8-8-68
Saturation Temperature 175.5°R
Saturation Pressure 51 P.S.I.A.

<table>
<thead>
<tr>
<th>Q/A (10)^-4</th>
<th>B.t.u./hr. ft.²</th>
<th>ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.124</td>
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<td>6.6</td>
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Date - 8-8-68
Saturation Temperature 202.9°R
Saturation Pressure 152 P.S.I.A.

<table>
<thead>
<tr>
<th>Q/A (10)^-4</th>
<th>B.t.u./hr. ft.²</th>
<th>ΔT</th>
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<tbody>
<tr>
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<tr>
<td>0.170</td>
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<tr>
<td>0.330</td>
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<td>4.1</td>
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<tr>
<td>0.733</td>
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<td>4.7</td>
</tr>
<tr>
<td>0.990</td>
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<td>5.0</td>
</tr>
<tr>
<td>1.328</td>
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<tr>
<td>1.590</td>
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<tr>
<td>1.858</td>
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<td>4.9</td>
</tr>
<tr>
<td>2.100</td>
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<td>6.0  Partial Film</td>
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</table>
**TABLE A-VI continued**

Date - 8-8-68  
Saturation Temperature 218.7°F  
Saturation Pressure 254 P.S.I.A.

<table>
<thead>
<tr>
<th>Q/A (10)^{-4}</th>
<th>B.t.u./hr. ft.²</th>
<th>(\Delta T)</th>
<th>°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.072</td>
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<td>1.5</td>
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</tr>
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<td></td>
<td>2.0</td>
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</tr>
<tr>
<td>0.438</td>
<td></td>
<td>2.8</td>
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<td>0.695</td>
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<td>3.7</td>
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</tr>
<tr>
<td>0.928</td>
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<td>1.261</td>
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<td>1.511</td>
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<td>9.1 Partial Film</td>
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</tr>
</tbody>
</table>

Date - 8-8-68  
Saturation Temperature 237.2°F  
Saturation Pressure 407 P.S.I.A.

<table>
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<tr>
<th>Q/A (10)^{-4}</th>
<th>B.t.u./hr. ft.²</th>
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<th>°F</th>
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<tbody>
<tr>
<td>0.065</td>
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<tr>
<td>0.124</td>
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<td>1.7</td>
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<td>0.746</td>
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<td>7.9 Partial Film</td>
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</table>
### TABLE A-VI continued

**Date - 8-2-68**  
Saturation Temperature 239.4°R  
Saturation Pressure 461 P.S.I.A.

<table>
<thead>
<tr>
<th>Q/A (10)^{-4}</th>
<th>$\Delta T$ °F</th>
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<tbody>
<tr>
<td>0.053</td>
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<tr>
<td>0.141</td>
<td>1.3</td>
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<tr>
<td>0.270</td>
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<tr>
<td>0.488</td>
<td>2.6 Partial Film</td>
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</table>

**Date - 8-2-68**  
Saturation Temperature 240.8°R  
Saturation Pressure 482 P.S.I.A.

<table>
<thead>
<tr>
<th>Q/A (10)^{-4}</th>
<th>$\Delta T$ °F</th>
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<tbody>
<tr>
<td>0.009</td>
<td>0.4</td>
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<tr>
<td>0.039</td>
<td>0.6</td>
</tr>
<tr>
<td>0.077</td>
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<tr>
<td>0.146</td>
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</tr>
<tr>
<td>0.246</td>
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<td>0.376</td>
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<tr>
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<td>0.685</td>
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<tr>
<td>0.765</td>
<td>Burnout Point</td>
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</table>
APPENDIX B

EXPERIMENTAL ERRORS
As noted, the equipment and apparatus discussed in this study are very similar to that used by Park (33) and Cobb (7). The error analysis developed in these references should be referred to for detailed study of errors.

Current and voltage could be read to within ± 0.125 amperes and ± 0.01 volts respectively. The combined product errors are ± 0.125 percent. Temperature could be read to ± 0.001 millivolts which is equivalent to a temperature accuracy of ± 0.1°F.

Both pool thermocouple and heater thermocouples were checked for calibration, when no heat flux was applied, by using vapor pressure data. Due to the resistance of the thermocouple plug and wires, an inherent positive error of approximately 1°F was noticed. This error was subtracted from thermocouple readings at each heat flux; and the ΔT was then unaffected by this error, since the error was due to resistance outside of the heating system and was eliminated by subtraction. During boiling, the three thermocouples within the heater differed from 1 to 2°F depending on the intensity of the heat flux.

Pressures were measured accurately to ± 1 pound per square inch.
VITA

Craig Bauer Johler, the son of Mr. and Mrs. Walter W. Johler, was born August 12, 1945, in Alton, Illinois.

He attended both elementary and secondary schools in the Roxana, Illinois, school system. After graduation from Roxana Community High School in June of 1963, he entered the University of Missouri School of Mines and Metallurgy in the fall of 1963. He received his Bachelor of Science in chemical engineering in June, 1967; and enrolled in the graduate school of the University of Missouri - Rolla in the fall of 1967.