To the Graduate Council:

I am submitting herewith a thesis written by James A. Tevepaugh entitled "Improvement of Film Boiling Heat Transfer by Means of Artificial Surface Projections." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

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IMPROVEMENT OF FILM BOILING HEAT TRANSFER BY MEANS OF ARTIFICIAL SURFACE PROJECTIONS

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ABSTRACT

The film boiling of small drops (0.5 to 2.0 milliliter) of water, freon-11 and freon-114 was investigated by comparing the total vaporization times of the fluids on a smooth steel disk with those on steel disks containing different artificial (as opposed to those occurring routinely from machining processes) surface projections. The surface projections included concentric grooves of varying depth and cylindrical pins with varying pin spacing. Vaporization times were measured over a range of boiling surface temperatures for all fluids on the surfaces with groove depths of .010 and .020 inch. Vaporization times for freon-11 and freon-114 boiling from surfaces with .050 inch high, .062 inch diameter cylindrical pins were measured with the pins positioned in a square array and spaced at various center-to-center distances.

Improved heat transfer was observed for the surfaces with artificial projections. One of the mechanisms responsible for the observed improvement was postulated to be intermittent direct contact between the liquid drops and the surface projections. Experimental measurements of the liquid-boiling surface contact were made for water film boiling on the smooth surface and the surfaces with concentric grooves. Contact was observed to occur in a continual

intermittent fashion on the surfaces with concentric grooves. No contact was observed on the smooth surface except at the instant of liquid deposition on the boiling surface.

Correlation of total vaporization time data from the surfaces with artificial surface projections with data from the smooth surface was attempted. Total vaporization times were partially correlated in terms of the increased area provided by the surface projections. Contact between the film boiling water and the surfaces with concentric grooves appeared to result in increased heat transfer on these surfaces.

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LIST OF SYMBOLS

A	curve fit coefficient
B	curve fit coefficient
C_p	specific heat at constant pressure
g	gravitational acceleration
g_c	conversion factor
k	thermal conductivity of vapor
L	drop thickness
N	number of cylindrical pins covered by liquid
r	drop radius
t	total vaporization time
t^*	dimensionless total vaporization time
T	temperature
ΔT	$T_{wall}-T_{sat}$
V	drop volume
V^*	dimensionless drop volume
δ	vapor layer thickness
λ	latent heat of vaporization
λ^*	modified latent heat of vaporization
λ_D	most dangerous wavelength
μ	viscosity of vapor
ρ	density
σ	surface tension

Subscripts

ℓ	liquid
sat	evaluated at saturation conditions
v	vapor
wall	wall

CHAPTER I

INTRODUCTION

Film boiling was first studied in 1756 by J. G. Leidenfrost (1), a German doctor, who observed water droplets on a glowing hot iron spoon. Leidenfrost noted that the vaporization time of the droplets was much longer when the spoon was glowing hot than when the spoon had cooled somewhat.

Film boiling occurs when a boiling liquid is completely separated from the heating surface by a film of the liquid's own vapor. Heat is transferred to the liquid by conduction across the vapor film and by thermal radiation from the heating surface.

Heat may be transferred to a liquid on a heated surface by several mechanisms. The region for which a given mechanism is dominant is related to the difference in temperature of the heated surface and the saturation temperature of the liquid. Figure 1 is a "boiling curve" with the various regions delineated. In region I the liquid is in contact with the heating surface and heat is transferred to the liquid by natural convection. Nucleate boiling is the dominant mechanism in region II. Heat transfer to the liquid is enhanced by the generation of vapor bubbles at nucleation sites on the heating surface. More nucleation sites are activated as the temperature of the heating surface

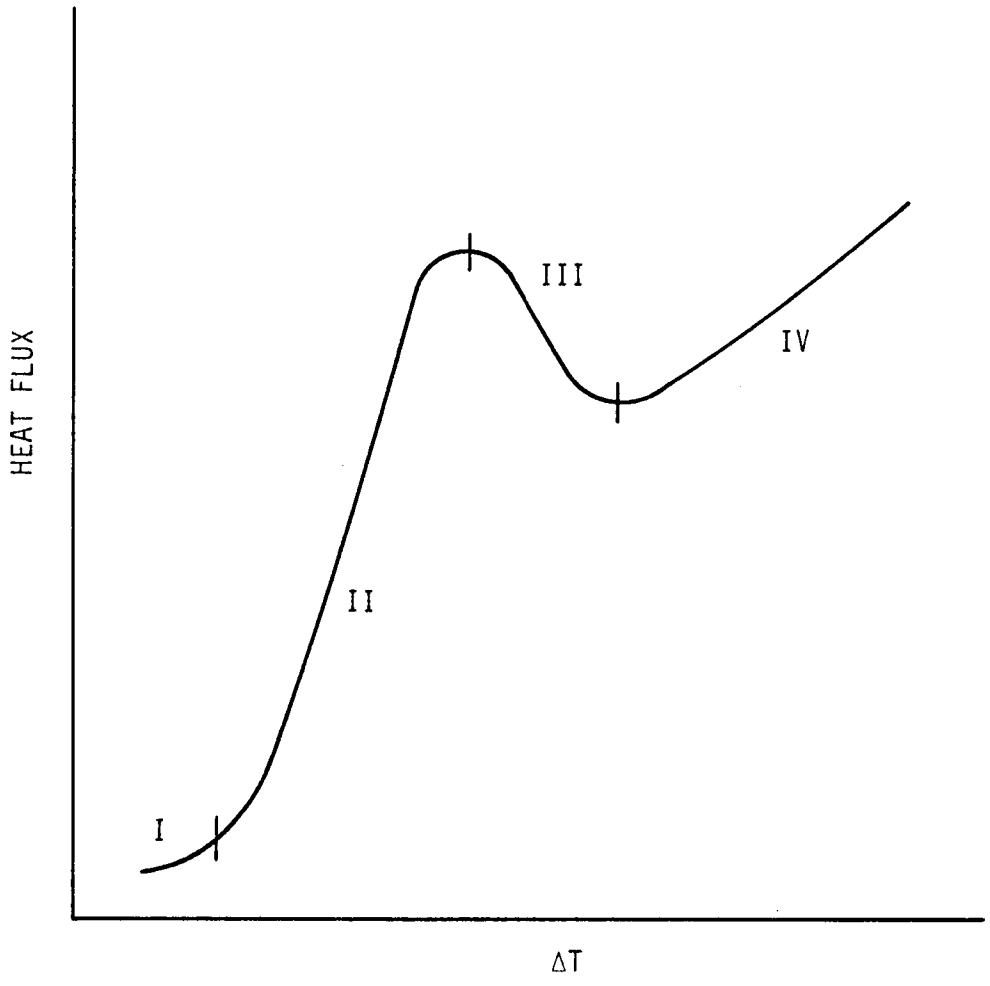


Figure 1. Boiling curve.

is increased. As indicated by the slope of the curve, relatively small increases in temperature result in substantial increases in heat transfer in region II. As the temperature is increased, more vapor is generated until vapor is formed in sufficient quantities to partially insulate the liquid from the heating surface. Further increases in temperature beyond this point of maximum heat transfer result in a decrease in heat transfer in region III. This region is characterized by transition boiling and may be obtained in practice only by using a temperature controlled surface. Sufficient vapor is formed at these temperatures to partially insulate the liquid from the heating surface but the quantity is not sufficient to support the liquid mass. Thus the vapor layer is unstable and the liquid makes frequent contact with the surface. In region III the liquid exhibits characteristics of both nucleate and film boiling.

If the temperature is increased further, a minimum point on the boiling curve is reached where vapor generation is sufficient to support the liquid mass above the heating surface. This point of minimum heat flux is termed the Leidenfrost point and marks the onset of stable film boiling. In region IV heat is transferred to the liquid by conduction across the stable vapor film. At higher temperatures heat transfer to the liquid is enhanced by thermal radiation. Since the dominant heat transfer mechanism in this region is

conduction through a vapor of relatively low thermal conductivity, the heat transfer rate is low and larger increases in heating surface temperature are required to produce increases in heat transfer comparable to nucleate boiling.

In application the characteristics of the boiling curve are of great importance. Liquid cooled surfaces such as the fuel elements of a nuclear reactor are heat flux controlled. If the heat flux supplied to the surface is increased beyond the maximum heat flux on the boiling curve (critical heat flux), the liquid coolant will proceed directly from the nucleate boiling region II to the film boiling region IV without moving through the transition boiling region. The resulting temperature may be above the melting point for the surface material and "burn out" would occur. Thus increasing the heat transfer rate to the film boiling liquid and/or increasing the Leidenfrost temperature is of great practical significance.

The objective of the present study is to investigate the improvement in film boiling heat transfer and increase in the Leidenfrost temperature with the addition of artificial projections to heating surfaces. Contact between the film boiling liquid and the heating surface is examined as one potential mechanism that may produce increased rates of heat transfer.

CHAPTER II

LITERATURE SURVEY

Numerous experimental and analytical efforts have been directed at the study of Leidenfrost film boiling. Film boiling heat transfer coefficients and the Leidenfrost temperature have been determined for various fluids on smooth boiling surfaces.

Lee (2) measured total vaporization times of small droplets (.001 to .03 milliliter initial volume) of water, carbon tetrachloride, ethyl alcohol, benzene and n-octane from a smooth stainless steel plate. He found that vaporization time of the droplets was a function of physical properties of the fluid, initial droplet volume and temperature of the boiling surface. The Leidenfrost temperature was observed to be independent of droplet volume. Lee developed an analytical model to calculate droplet vaporization rate and total vaporization time for small film boiling droplets approximately spherical in shape.

The work of Lee was extended by Patel (3) to include boiling of large liquid masses (.05 to 10 milliliter) of water, carbon tetrachloride, benzene and ethanol from a smooth stainless steel plate. Patel measured the vaporization time for a range of temperatures and determined the Leidenfrost temperature for each fluid. He observed that

all of the vapor generated between the liquid drop and boiling surface was unable to escape at the liquid periphery of the larger liquid masses. Vapor broke through the liquid drop in the form of symmetrical vapor bubbles. Vapor bubble breakthrough was observed for volumes greater than 2.7 milliliter of water and 1.2 milliliter of ethanol, benzene and carbon tetrachloride.

Baumeister (4) developed a dimensionless correlation for the vaporization times of discrete liquid masses undergoing Leidenfrost film boiling from smooth surfaces. Baumeister's correlation included the physical properties of the fluid and its vapor, the temperature of the boiling surface and the initial volume of liquid deposited on the boiling surface. The correlation was presented as a single curve relating a dimensionless vaporization time to a dimensionless initial liquid volume. The correlation was shown to work reasonably well for experimental data available in the literature at that time representing a wide range of initial liquid volumes.

There have been considerable differences in the literature for the numerical value of the Leidenfrost temperature for a given fluid. Baumeister (5) determined the Leidenfrost temperature for a group of fluids with widely varying physical properties boiling from surfaces fabricated of different material. The fluids investigated included the liquid metals, potassium and sodium, water, pentane and

freon-113 among others. Smooth boiling surfaces were fabricated of aluminum, copper, stainless steel and glass among others. Baumeister developed a correlating parameter that successfully predicted the Leidenfrost temperature of the various fluids on the different boiling surfaces. This successful correlation demonstrated that a number of quantities were responsible for the variation in previously reported values of Leidenfrost temperature. The quantities were critical temperature of the fluid, solid-liquid surface energy ratio and the density, specific heat and thermal conductivity of the boiling surface material.

Keshock (6) and (7) measured the vaporization rates and total vaporization times of liquid nitrogen film boiling from a smooth aluminum surface. Initial liquid volumes of .161 to 10.55 milliliter were investigated. Values of total vaporization time differed significantly, however, from the theoretical values predicted by the Baumeister correlation, particularly for large liquid volumes experiencing vapor bubble breakthrough. Corrections to the analytical model to account for bubble breakthrough produced improved agreement between the experimental data and the analytical predictions. Keshock studied the vapor breakthrough dynamics photographically and found the center-to-center distance between coincident vapor breakthroughs to lie between the most dangerous wavelength at low ΔT values and the critical wavelength at high ΔT values.

Obviously, numerous experimental and analytical studies have been conducted of the Leidenfrost phenomenon on smooth boiling surfaces. The investigators have viewed boiling surface roughness or projections primarily as an impediment to obtaining an accurate determination of the Leidenfrost temperature or film boiling heat transfer coefficient. Few investigators have examined the influence on film boiling of artificial (as opposed to those occurring routinely from machining processes) surface features.

Cash (8) developed optimum fin design criteria for fins used in boiling applications. The criteria were developed to improve boiling heat transfer from fins of circular cross section with temperature profiles such that nucleate, transition and film boiling occur simultaneously at adjacent positions on the fin. The resulting turnip shaped fins provided a 5-70 percent improvement in peak heat duty in a boiling application. However, the size of the fins was characteristic of those used for convective heat transfer improvement and not specifically suited for improving film boiling heat transfer.

Knoebel and Yeh (9) measured the total vaporization times and determined film boiling heat transfer coefficients for one, two and five milliliter volumes of water, ethanol and freon-11 boiling from brass plates with different artificial surface projections. Three different plates with

pins were investigated. One plate was fitted with .015 inch diameter stainless steel pins arranged in a square array on .125 inch centers with pin heights of .04 and .02 inch respectively. Another plate was fitted with .0393 inch diameter stainless steel pins arranged in a square array on .125 inch centers with pin heights of .04, .02 and .008 inch respectively. A third type of plate was supplied with tetrahedral pins of .031, .02 and .008 inch height by machining perpendicular grooves in a brass plate. A brass plate with concentric grooves was fabricated in three stages with heat transfer coefficients measured at each stage. The grooves were .023 inch center-to-center. The groove depth was increased at each stage from .006 inch initially to .012 inch and finally .020 inch with surface flats between the grooves of .013, .007 and 0.0 inch respectively. Heat transfer coefficients for a smooth brass plate were compared with coefficients from the surfaces with projections. A pin height of .008 inch had no effect on heat transfer coefficients for water although increases of 15-25 percent were determined for ethanol and freon-11. For pin heights of .04 inch and groove depth of .02 inch, heat transfer coefficients for ethanol and freon-11 increased 150 and 230 percent respectively. Pin heights and groove depth of .02 inch increased the film boiling heat transfer coefficient for water by 120 percent. Knoebel and Yeh observed

significant nucleate boiling on the surfaces with .04 inch pins.

Knoebel and Yeh obtained data on surfaces with concentric grooves of different groove depth. However, the cross sectional profile of the grooves was not constant so that it was not known if the improved heat transfer was the result of changes in groove profile or changes in groove depth. The present research employed surfaces with concentric grooves of constant profile but different groove depth so that the relationship between heat transfer improvement and groove depth could be established.

Data were obtained by Knoebel and Yeh on several surfaces with cylindrical pins of different diameter and height. However, the pin spacing was constant. Spacing of surface projections is suspected of influencing the spacing and frequency of bubble breakthrough in film boiling liquids of larger volumes. Keshock (6) demonstrated that vapor bubble breakthrough is an important mechanism in heat transfer to film boiling liquid masses. The present research investigated film boiling from surfaces with cylindrical pins of constant diameter and height spaced at various center-to-center distances so that the influence of pin spacing on film boiling heat transfer could also be evaluated.

Contact between the film boiling liquid and the boiling surface with nucleate boiling and consequently higher heat transfer rates at the contact site(s) was postulated as one

mechanism responsible for the observed improvement in film boiling heat transfer on surfaces with projections. Bradfield (10) performed an experimental study of possible liquid-solid contact for water boiling on a smooth copper surface and a roughened aluminum surface with an r.m.s. surface roughness of approximately 70 microinches. A voltage of 50 volts was applied between film boiling water drops and the boiling surfaces. An oscilloscope was used to measure and display changes in capacitance of the vapor layer as contact between the liquid and the boiling surface occurred. Bradfield reported no contact on the smooth copper surface but significant contact (amount of contact depending on ΔT) on the roughened aluminum surface. He concluded that contact may be periodic or quasicontinuous depending on the surface roughness and boiling surface temperature.

Recently, Nishio and Hirata (11) investigated contact between water drops undergoing Leidenfrost film boiling on a polished brass plate. A chromel probe maintained a direct current voltage of 2.5 volts between the drop and brass plate. Current flowing in the circuit due to liquid-solid contact passed through a standard resistance. The voltage drop across the resistance was displayed on a chart recorder. Nishio reported liquid-solid contact at the instant of liquid deposition on the boiling surface whose temperature ranged from the Leidenfrost point to 601 C. The period of contact

at deposition increased with decreasing boiling surface temperature until continual periodic contact was measured for surface temperatures less than 212 C. The Leidenfrost temperature reported by various researchers for water film boiling on various smooth surfaces is typically 250-325 C. Continual periodic liquid-solid contact measured by Nishio could very well have been the result of a transition boiling mode, in which case the result for a smooth surface is not surprising.

CHAPTER III

EXPERIMENTAL APPARATUS

Three fluids, water, freon-11 and freon-114 were chosen for the experimental investigation to provide a range of physical properties. Distilled water and commercial grade freons (98.5 percent purity) were used. The saturation temperatures of the three fluids corrected to an altitude of 950 feet above sea level (12) are listed in Table 1. Only freon-114 had a saturation temperature sufficiently low (36.5 F) to require special handling as discussed in Chapter IV. Also presented in Table 1 are the surface tension and density of the fluids at their respective saturation temperatures. Properties of the fluid vapors as functions of temperature were obtained from E. I. Dupont (13) and are included in a subroutine of the computer code discussed in Chapter VI.

Two different equipment configurations were required to obtain the desired experimental data. A block diagram of the experimental apparatus is presented in Figure 2 with the dashed lines representing additional hardware required for the second configuration.

Boiling surfaces used in this investigation were circular disks 3.5 inches in diameter and 0.4 inch thick excluding the retaining rim (Figure 3). The disks were

TABLE 1

FLUID PROPERTIES*

Fluid	T_{sat} (F)	ρ_ℓ (lb/ft^3)	σ (lb_f/ft)
Water	210	59.8	.00403
Freon-11	72.5	91.6	.00123
Freon-114	36.5	90.9	.00075

*At atmospheric pressure.

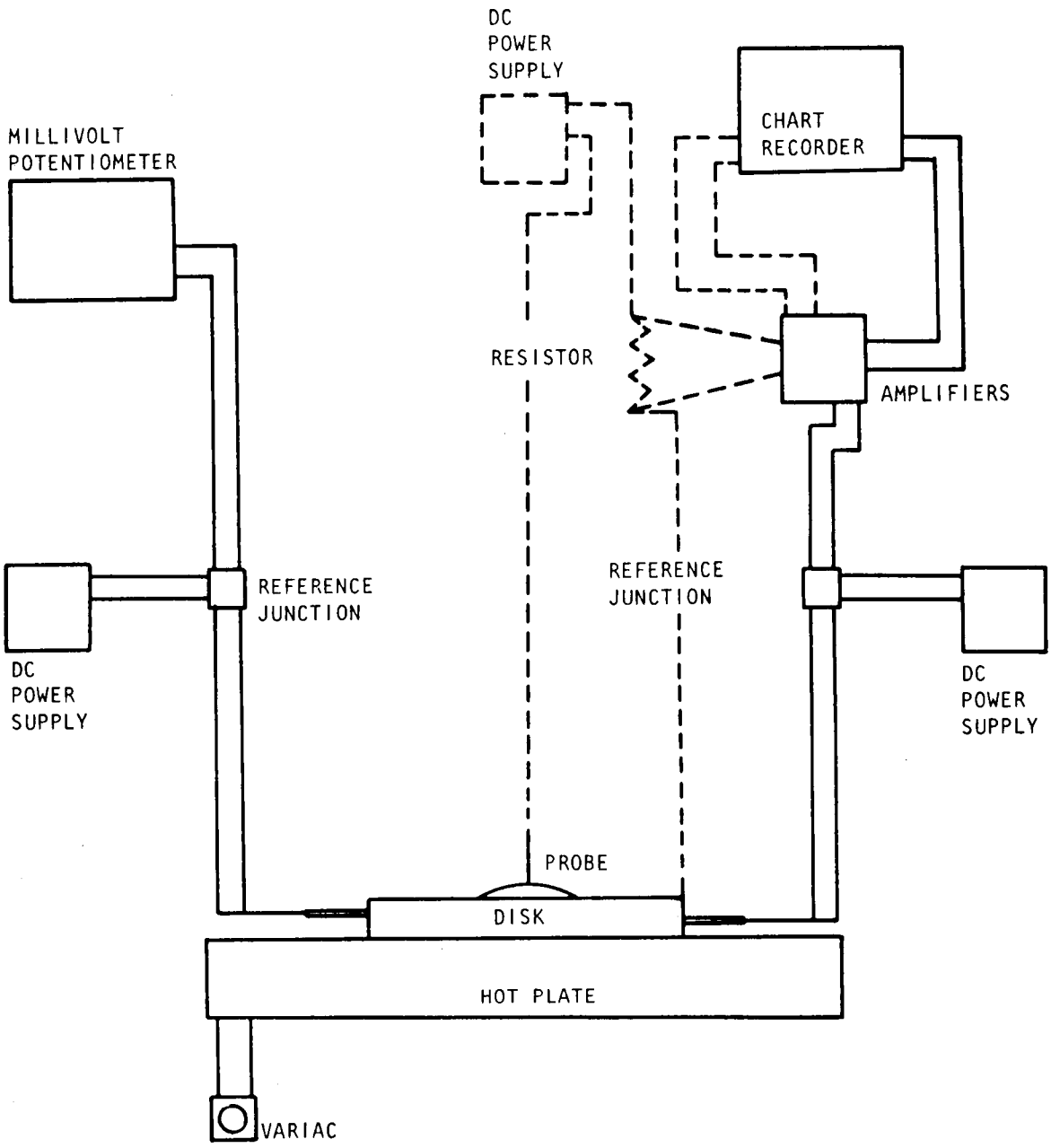


Figure 2. Experimental apparatus.

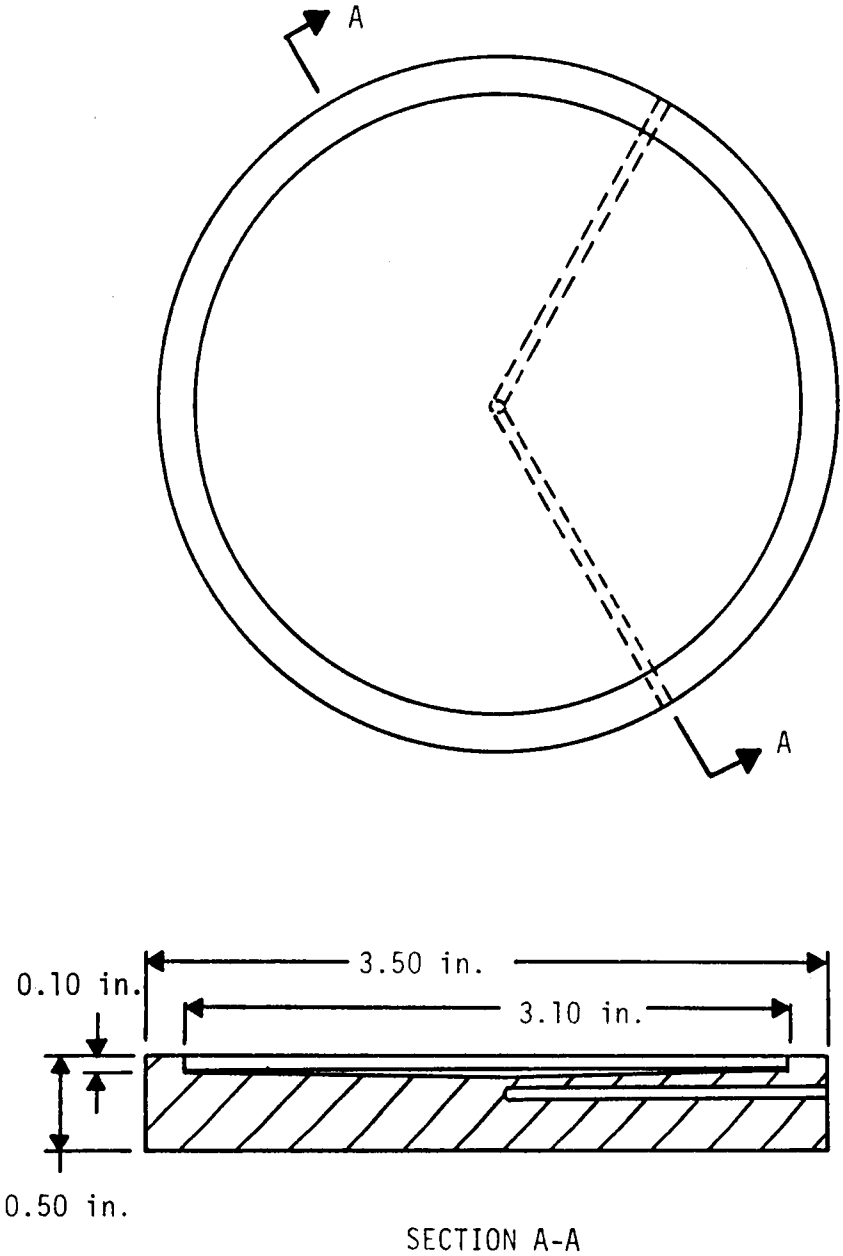


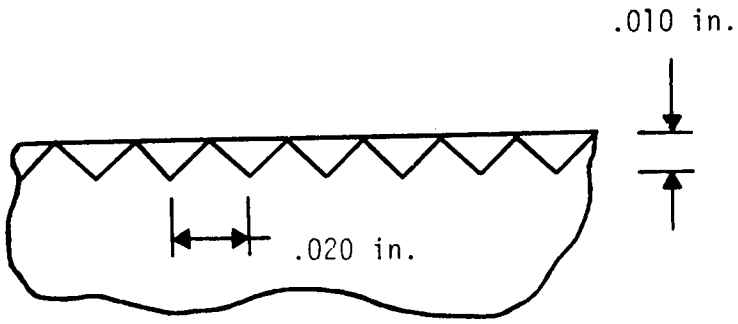
Figure 3. Disk with smooth boiling surface.

fabricated from carbon steel and were slightly dished (one degree slope) to position the liquid drops in the center of the disk. The boiling surface of one disk was polished to a mirror finish and electroplated with a .002 inch layer of nickel to inhibit corrosion. The resulting surface had an r.m.s. surface roughness of 5-10 microinches when measured with a profilometer. Film boiling data on this surface served as smooth surface reference data.

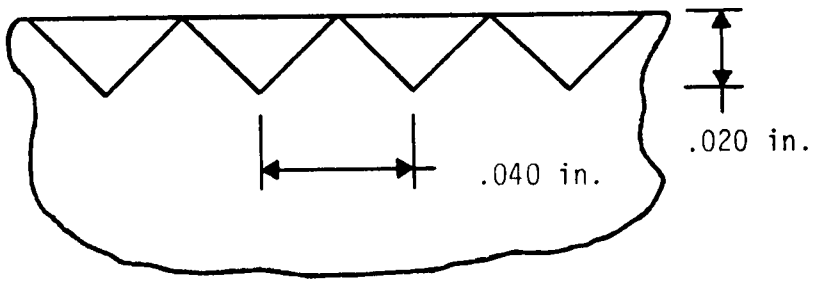
Surfaces with concentric grooves and cylindrical pins were chosen to be the surfaces modified by artificial projections. The height of the pins and depths of the grooves were chosen to be of approximately the same order of magnitude as the thickness of the vapor layer separating the liquid drops from the boiling surface.

The boiling surfaces of two disks were machined with concentric grooves with groove depths of .010 inch and .020 inch respectively. Geometric details of the groove profiles of the two surfaces are presented in Figure 4. These disks were electroplated with a .002 inch layer of nickel to inhibit corrosion.

Magnetic pins were used to provide an easy method of reconfiguring the smooth surface to surfaces with pins. One hundred cylindrical pins .050 inch in length and .062 inch in diameter were fabricated from ALNICO magnet material with the magnetic field parallel to the major axis of the



.010 INCH GROOVES



.020 INCH GROOVES

Figure 4. Concentric groove profiles.

cylinder. By weight the ALNICO material is 12 percent aluminum, 22 percent nickel, 5 percent cobalt and 61 percent iron. These magnetic pins could be arranged on the smooth surface in different configurations to provide a variety of boiling surfaces. The pins were positioned with a template in a square matrix. Center-to-center spacing between the pins was varied to create different surface configurations.

The interface between a film boiling liquid and the vapor layer is typically wavy in response to disturbances in the liquid or vapor. The wavelength at which the disturbances begin to grow in amplitude (rather than damping out) is called the "critical wavelength" (14). The wavelength for which disturbances grow most rapidly in amplitude is the "most dangerous wavelength." The "most dangerous wavelength," λ_D, was the criterion used for spacing the cylindrical pins. It is given by the expression,

$$\lambda_D = 2\pi \sqrt{\frac{3\sigma}{g(\rho_\ell - \rho_v)}}$$

The parameter, λ_D, is an indicator of the spacing of vapor bubble breakthrough in the film boiling of extended liquid masses (Patel (3) and Keshock (6)). Keshock (6) demonstrated that bubble breakthrough is possibly an important mechanism in film boiling heat transfer. Values of λ_D for the fluids investigated are presented in Table 2. The values of liquid

density, ρ_ℓ, and surface tension, σ, were evaluated at the saturation temperature of the liquid and atmospheric pressure. The vapor density was evaluated for the range of film temperatures encountered in the investigation. The film temperature is the mean temperature in the vapor layer and is taken as the average of the boiling surface temperature and the saturation temperature of the liquid. Although the vapor density is a function of film temperature, its magnitude is very small in comparison to that of the liquid density such that the value of λ_D is insensitive to film temperature. The change in λ_D over the temperature range investigated was negligible for the three fluids.

TABLE 2

MOST DANGEROUS WAVELENGTH

Fluid	λ_D (inch)
Water	1.02
Freon-11	0.48
Freon-114	0.37

Pin spacings of $\lambda_D/2$ and $\lambda_D/4$ were selected for the experimental study after observing the size of the liquid mass of the various fluid volumes film boiling on the smooth surface. Center-to-center pin spacings greater than $\lambda_D/2$

would have resulted in pin spacings on the same order as the initial liquid drop diameters and consequently little contact would have occurred between the film boiling drops and the pins. Pin spacings less than $\lambda_D/4$ were not investigated because adjacent pins would nearly be making contact for smaller separation distances.

The heights of the selected surface profiles were compared with the approximate thickness of the vapor layer for the three fluids. A relationship developed by Baumeister (15) was used to predict the vapor layer thickness, δ,

$$\delta = \left(\frac{3\pi k \Delta T \mu r^4}{2\rho_v \rho_\ell g \lambda V} \right)^{1/4}$$

Results of the calculations are summarized in Table 3 for water, freon-11 and freon-114 film boiling at ΔT = 500 F. The height of the cylindrical pins was 5-10 times the thickness of the vapor layer for the various fluids and so should extend into the film boiling drops. The drop thicknesses for the fluids were approximated by the Baumeister dimensionless drop thickness correlation (4) and also presented in Table 3. A concentric groove depth of .020 inch was 2-4 times the vapor layer thicknesses. Vapor layer thicknesses for drops of freon-11 and freon-114 were approximately the same as the concentric groove depth of .010 inch. For the smooth surface, the vertical surface

features associated with a surface roughness of 5-10 microinches are several orders of magnitude less than the smallest vapor layer thickness.

TABLE 3

VAPOR LAYER AND DROP THICKNESSES

Fluid	Volume (ML)	Vapor Layer Thickness (inch)	Drop Thickness (inch)
Water	0.5	.0057	.140
	1.0	.0064	.157
Freon-11	1.0	.0083	.081
	2.0	.0099	.081
Freon-114	1.0	.010	.064
	2.0	.011	.064

The disks were heated to the desired temperature by a 2000 watt CHROMALOX (model ROPH-201) hot plate. The temperature of the carbon steel disks was set by varying the voltage input to the hot plate using a Variac. The Variac was a General Radio Company 20 ampere model with 115 volt AC input and a 0-115 volt AC output.

The disks were instrumented with two chromel-alumel thermocouples located at the center of the disks at depths of .14 and .22 inch. Except for the junction bead, the thermocouples were encased in a stainless steel sleeve which was slip fit into the disks.

The temperature indicated by the output of the thermocouple nearest to the boiling surface was taken as the surface temperature. The output of this thermocouple was measured with a Leeds and Northrup model 8686 millivolt potentiometer. A reference voltage for the potentiometer corresponding to 32 F was supplied by a DC reference junction (Consolidated Ohmic Devices model JR366A-11). Constant DC voltage (eight volts DC) was supplied to the reference junction by a voltage regulated power supply, LAMBDA model LL-903. During preliminary investigations, the variation of disk temperature with time was measured by routing the output of the second thermocouple to the DC reference junction and then to a DC amplifier, ACCUDATA model 122. The amplified signal was used to drive one channel of a chart recorder, Brush Instruments model Mark II. The variation of disk temperature with time was measured for each fluid over a range of temperatures. For a fluid at a given temperature these data were to a large degree repetitive. After these data were obtained for the three fluids over a range of disk temperatures, collection of this information was discontinued.

For the purpose of measuring possible liquid-boiling surface contact, the apparatus indicated by the dashed lines in Figure 2, page 15, was used. The wire probe inserted into the boiling liquid drop consisted of one

six inch strand of copper filament from a segment of number 22 stranded wire. Voltage was supplied to the indicated circuit by another LAMBDA regulated DC power supply. For a film boiling liquid drop not in contact with the boiling surface, the low electrical conductivity of the vapor layer would prevent any measurable current flow through the circuit. There would be no voltage drop across the 100 kilohm resistor (1 percent tolerance) and thus no deflection of the chart recorder pen. If the liquid drop directly contacted the boiling surface at some contact site, the higher electrical conductivity of a conducting liquid would permit flow of current in the circuit with the resulting voltage drop across the resistor producing a deflection of the chart recorder pen. The voltage drop across the resistor was input to another ACCUDATA DC amplifier and this processed signal used to drive the second channel of the Brush chart recorder. This arrangement provided a time history of any liquid-boiling surface contact during the lifetime of the liquid drop.

Water volumes of 0.5 and 1.0 milliliter were deposited on the boiling surfaces with a precision syringe (Manostat model 71-500-040). The syringe had a capacity of 4.0 milliliter with graduated markings every 0.05 milliliter. Manufacturer's specifications indicated an accuracy for repeated delivery of ±0.5 percent. Because of their low

surface tensions the freons could not be deposited with the syringe. It was not possible to pull the freon liquids through the plastic delivery tube to the body of the syringe. A 10 milliliter graduated cylinder was used to deposit 1.0 and 2.0 milliliter volumes of freon-11 and freon-114 on the boiling surfaces. The cylinder was graduated in 0.2 milliliter increments.

Volumes delivered by the syringe and the graduated cylinder were compared by discharging 1.0 and 2.0 milliliter volumes of water from the syringe into the graduated cylinder. There was no discernable difference in the volume indicated by the graduated cylinder and the volume delivered by the syringe.

Vaporization times of the various liquid volumes were measured with a precision stopwatch graduated in 0.2 second intervals.

CHAPTER IV

EXPERIMENTAL PROCEDURE

A disk with the desired boiling surface was selected, instrumented with thermocouples and placed on the hot plate. With the hot plate dial setting on HIGH, the Variac was adjusted to provide the desired disk temperature using the plot of disk temperature versus Variac setting in Figure 5. This information was obtained by operating the Variac and hot plate over a series of Variac settings and measuring the resulting equilibrium temperature of the smooth disk. Using Figure 5, disk temperatures within ten degrees of the desired temperature were typically obtainable. The disk was allowed from one to one and one-half hours to reach the desired equilibrium temperature. Equilibrium was identified by periodically checking the disk surface temperature until there was no appreciable difference between consecutive measurements.

A quantity of the fluid being investigated on the boiling surface was placed in a 100 milliliter beaker. With water the beaker was secured on a ring stand with the syringe and the delivery tube of the syringe submerged in the beaker. With the freons the fluids were discharged from 30 pound pressurized tanks. Because of its low saturation temperature (36.5 F), freon-114 required special handling. The

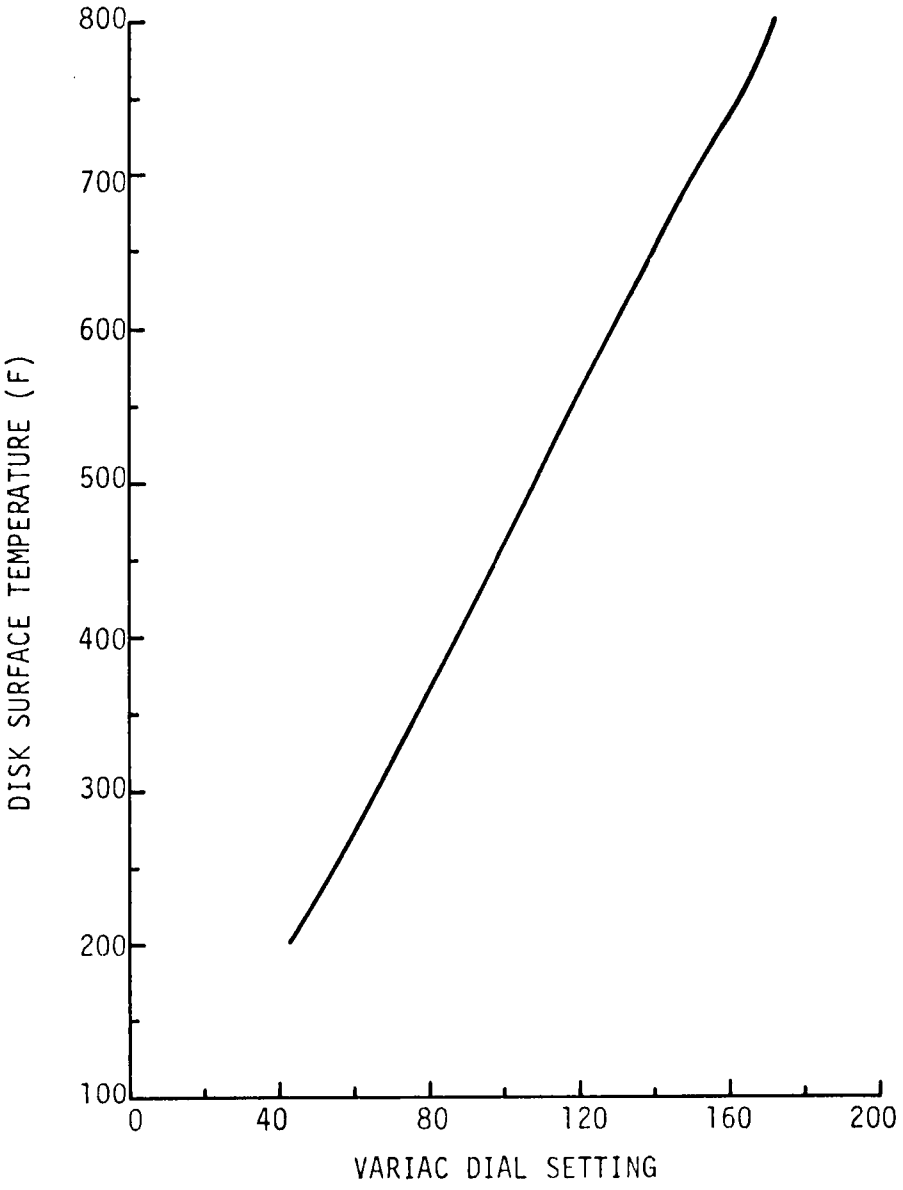


Figure 5. Disk surface temperature as a function of Variac dial setting.

pressurized tank of freon-114 was packed in ice in a six gallon container and allowed to cool for fifteen minutes. The 100 milliliter beaker and the graduated cylinder were also packed in ice for fifteen minutes to lower their temperature sufficiently to prevent boiling of the freon-114 prior to deposition on the boiling surface. After cooling, the pressurized tank of freon-114 was removed from the ice pack and placed on its side. Liquid freon-114 was dispensed to the cooled 100 milliliter beaker from this position. The beaker containing freon-114 was quickly returned to the ice pack. When preparations for a test point were complete, the beaker and graduated cylinder were removed from the ice pack and the required volume of liquid dispensed from the beaker to the graduated cylinder. The liquid was quickly deposited on the boiling surface before boiling of the freon-114 could occur in the graduated cylinder.

The 1.0 and 2.0 milliliter volumes of the liquid freons were poured onto the boiling surfaces in three seconds or less. The 0.5 and 1.0 milliliter volumes of water were deposited from the syringe in five seconds or less. Water was discharged to the boiling surfaces with the syringe positioned at an angle of approximately 45 degrees from the vertical. This delivery angle was found to produce the least disruptive boiling behavior. A finite deposition time was required to avoid splashing of the liquid from the disk.

For measuring total vaporization time, the stopwatch was activated when approximately one-half of the liquid had been deposited. This compromise was instituted to account for the vaporization which occurs during deposition of the liquid on the surface. Timing was terminated upon complete vaporization of the liquid.

Prior to deposition of liquid on the boiling surface the surface temperature of the disk was recorded. After deposition of the liquid, the surface temperature was monitored by frequent readings of the millivolt potentiometer. As indicated by chart recordings, the surface temperature was observed to quickly reach a minimum value and then proceed to return to its equilibrium value prior to deposition of the liquid as illustrated in Figure 6. The excursion in surface temperature ranged from a maximum of 10-20 F for 1.0 milliliter of water to only 3-6 F for 1.0 milliliter volumes of freon-11 and freon-114. The boiling surface temperature returned to its equilibrium value within five minutes following deposition of the freons and within ten minutes following deposition of water.

After the boiling surface reached equilibrium, the test procedure was repeated. If the first two consecutive measurements of total vaporization time were within 10 percent, no further data points for the particular fluid at that ΔT were taken. At least two data points at

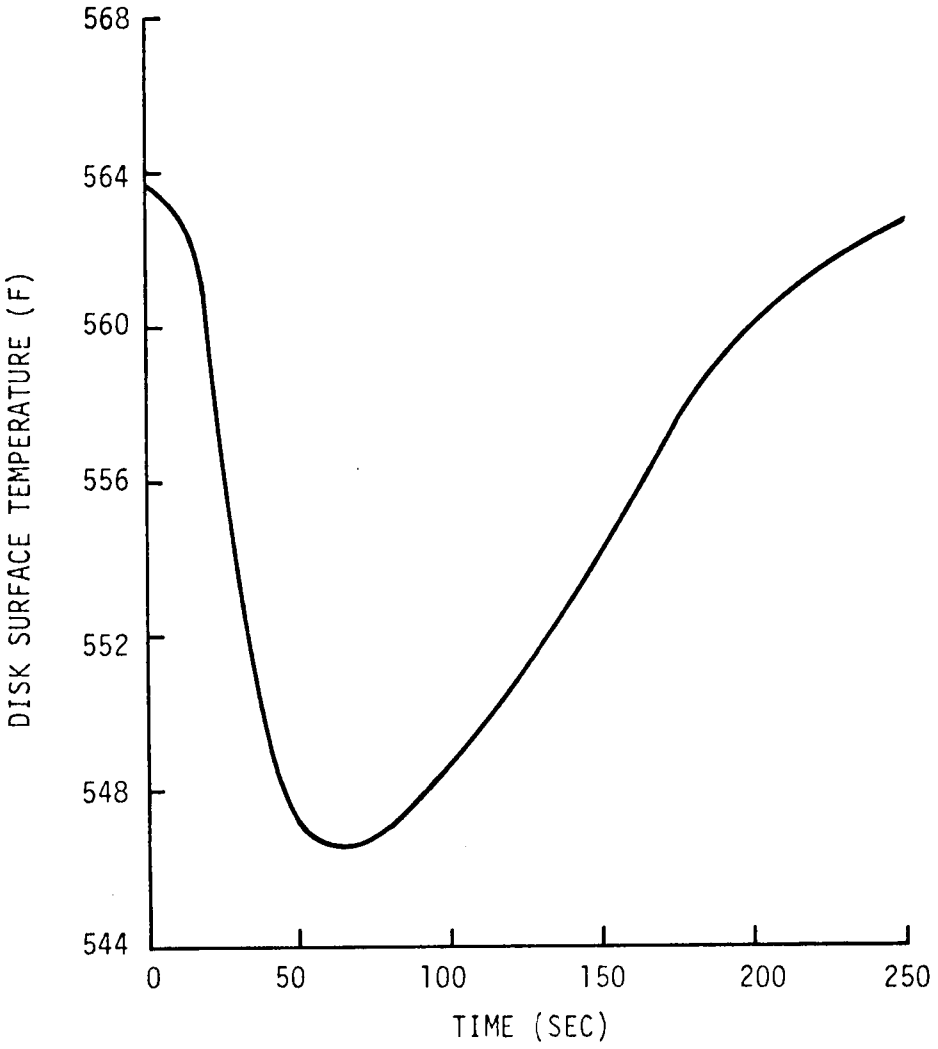


Figure 6. Typical disk surface temperature transient for 1.0 ML of water.

approximately the same ΔT were considered necessary to validate the value of total vaporization times for the given ΔT. If the first two vaporization times were not within 10 percent, three or more data points were obtained at approximately the same ΔT to establish the correct value of vaporization time. The freons typically exhibited excellent repeatability at a given value of ΔT and frequently only two data points at each ΔT were required. Vaporization times for water were more scattered and numerous data points near the same ΔT were frequently required. For each fluid and fluid volume measurements of total vaporization time were made at ΔT intervals decreasing from a value near $\Delta T = 700$ F to values in the nucleate boiling region.

Early in the experimental effort it was observed that the measured vaporization times for the liquid water were greater with the wire probe inserted in the liquid drops. Thus the data investigating possible liquid-boiling surface contact was obtained separately from data points in which total vaporization times were measured. A potential difference of 12 volts DC was applied across the film boiling water and the boiling surfaces investigated. The chart recorder was operated at a chart speed of five millimeters per second and a sensitivity of 0.5 volts per chart division scale. The ACCUDATA DC amplifier was operated with an

amplification factor of 0.5 to restrict maximum excursions of the chart pen to the chart scale.

The circuit providing a voltage potential between the liquid drop and boiling surface and the chart recorder was activated. A 0.5 milliliter volume of water was deposited on the surface. The liquid drop was penetrated by the copper wire probe which had been lowered to within .05 inch of the boiling surface. Measurement of the voltage drop across the 100 kilohm resistor was continued until the remaining liquid water siphoned up the wire probe due to surface tension. Measurement of possible liquid-boiling surface contact was attempted for three values of ΔT on each surface, at a value of ΔT near the Leidenfrost point for the particular surface, at a high ΔT near $\Delta T = 700$ F and at a value of ΔT between the previous two.

CHAPTER V

EXPERIMENTAL RESULTS

Discussion of the experimental results is divided into two sections; (1) a discussion of total vaporization time measurements and (2) a discussion of the measurement of liquid-boiling surface contact.

Total Vaporization Time Measurements

Experimental data were presented in plots of total vaporization time as a function of ΔT. As the surface temperature of the boiling surface decreased, the data points formed the anticipated boiling curve typified by Figures 7-9 for water, freon-11 and freon-114 respectively. The remainder of the vaporization time data is included in Figures A-1 to A-10 of Appendix A. Total vaporization time increased with decreasing ΔT until a maximum value was reached. This maximum in vaporization time corresponds to the minimum heat flux or the Leidenfrost point. Below this value of ΔT vaporization times diminished rapidly with decreasing ΔT to values characteristic of nucleate boiling.

The computer code to be discussed in detail in Chapter VI and listed in Appendix B was used to calculate least squares curve fits for the film boiling data for

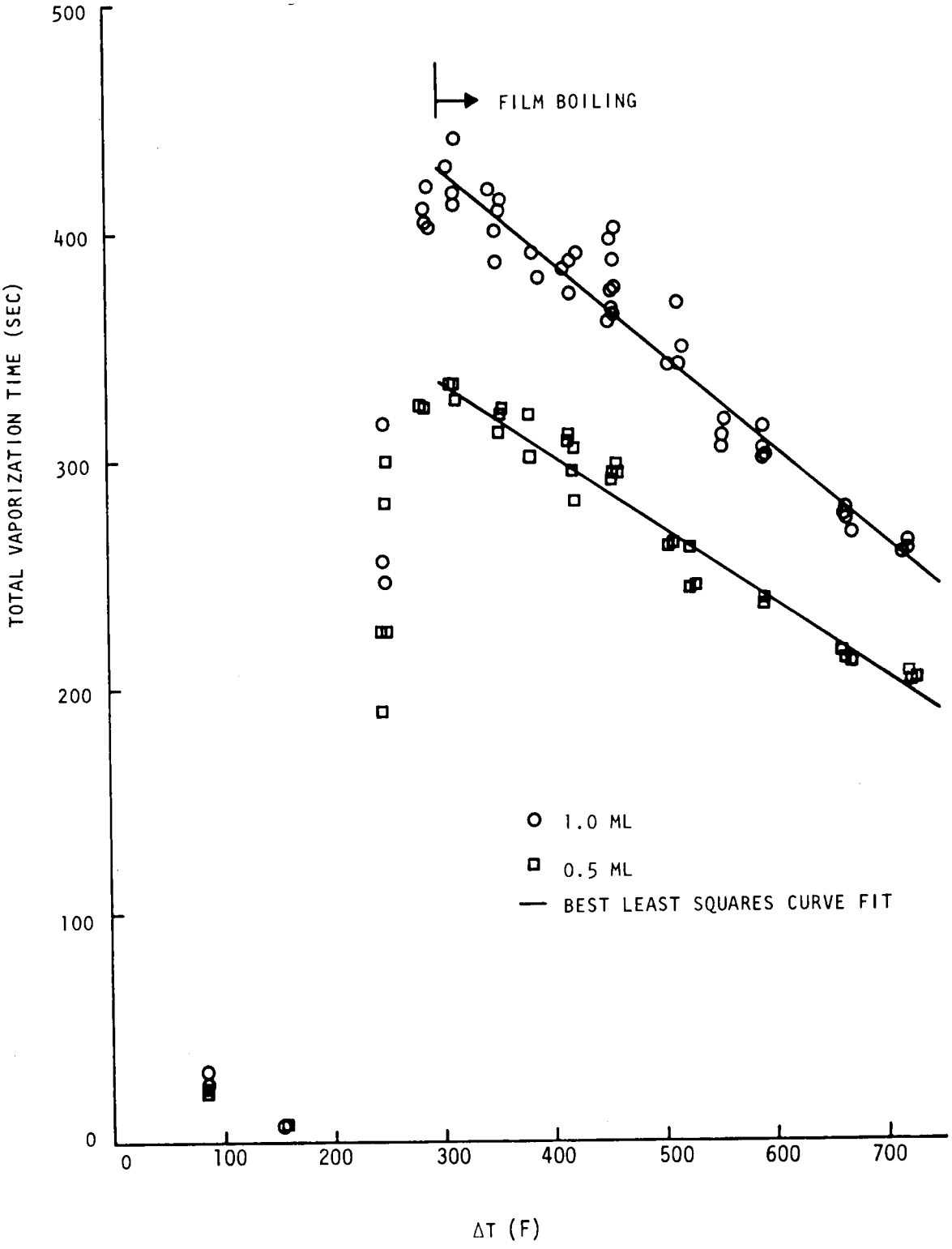


Figure 7. Total vaporization time as a function of ΔT for water boiling from a smooth surface.

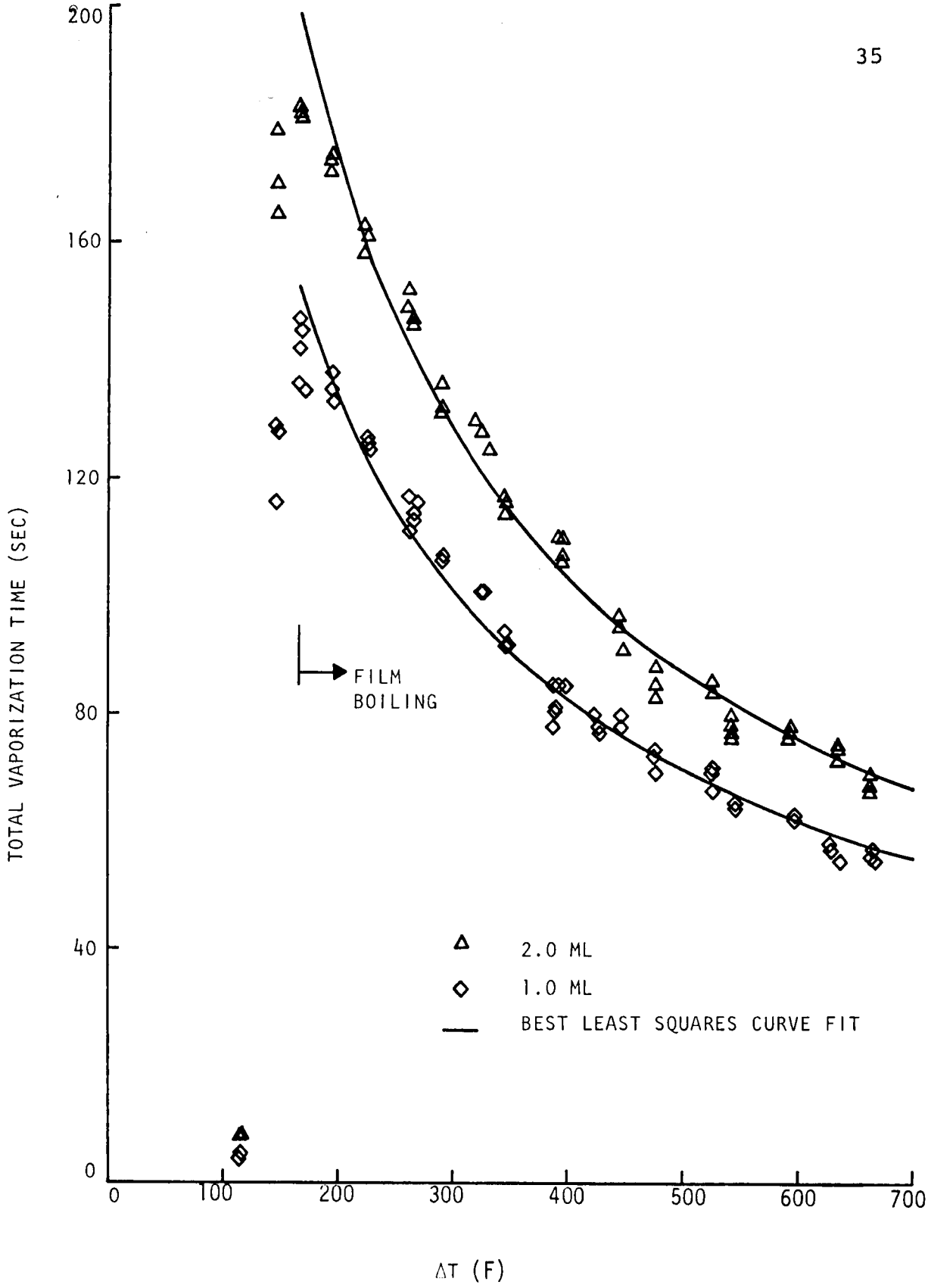


Figure 8. Total vaporization time as a function of ΔT for freon-11 boiling from a smooth surface.

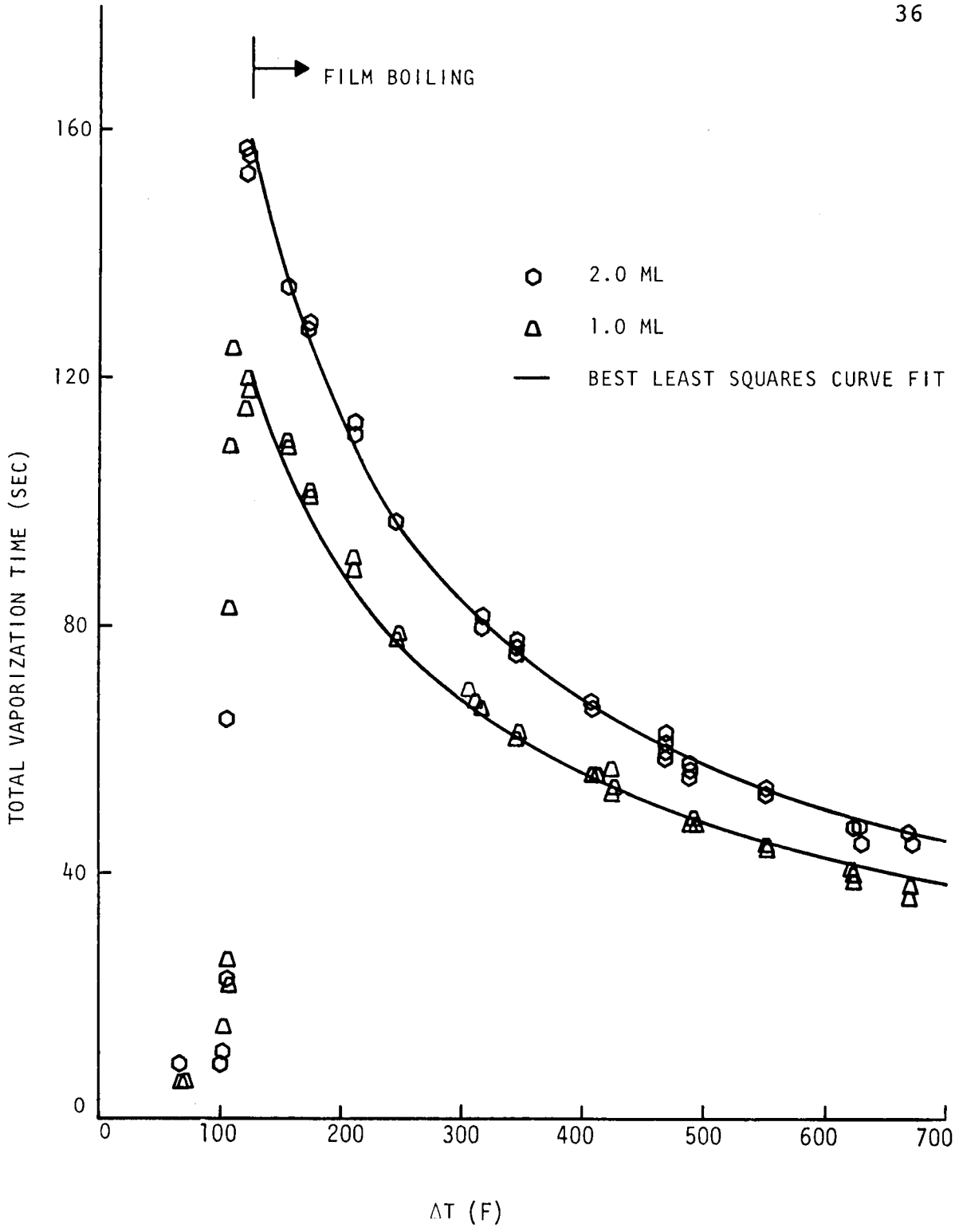


Figure 9. Total vaporization time as a function of ΔT for freon-114 boiling from a smooth surface.

each surface, fluid and fluid volume. Linear curve fits of the form,

$$t = A(\Delta T) + B$$

and power curve fits of the form,

$$t = A(\Delta T)^{B}$$

were calculated for each group of data. As indicated in Figures 8 and 9, power curve fits were excellent approximations of the freon-11 and freon-114 film boiling data and Figure 7 illustrates that a linear curve fit provided a good approximation of the water film boiling data. Correlation coefficients greater than 0.95 were obtained for all freon film boiling curve fits. Correlation coefficients greater than 0.85 were obtained for the water film boiling curve fits except for the surface with .010 inch concentric grooves. In subsequent discussions, least squares curve fits will be used in illustrative figures rather than the experimental data of Appendix A.

For each fluid, curves of total vaporization time as a function of ΔT for each type of modified surface were compared with the smooth surface curve. In discussing the results to follow, the phrase "heat transfer enhancement" refers to an increase in the heat transfer rate as reflected by a decrease in the total vaporization time of a given drop

volume over that obtained for boiling from the smooth surface. Typical variation of total vaporization time with initial liquid drop volume is presented in Figure 10. Results are shown for 1.0 and 2.0 milliliter of freon-114 film boiling from the smooth surface and the smooth surface with cylindrical pins spaced at $\lambda_D/2$ and $\lambda_D/4$. The difference in vaporization time between curves representing different drop volumes is greatest for the drops film boiling from the smooth surface. The difference in vaporization time between curves representing different initial drop volumes decreases with increasing ΔT.

As evidenced by the comparison of total vaporization time in Figure 10 for freon-114 and Figure 11 for freon-11, film boiling heat transfer rates are significantly greater for the surfaces with cylindrical pins. Also, film boiling heat transfer on the surfaces with cylindrical pins is observed to improve with decreasing pin spacing.

In Figures 10 and 11 the Leidenfrost temperature (temperature of minimum heat flux) is observed to increase with the addition of pins to the smooth surface and to increase with decreasing pin spacing. Decreasing the pin spacing from $\lambda_D/2$ to $\lambda_D/4$ increased the Leidenfrost temperature 25 F for the freon-11 and 40 F for freon-114. Increasing the Leidenfrost temperature is of practical significance in that the range of temperatures for nucleate

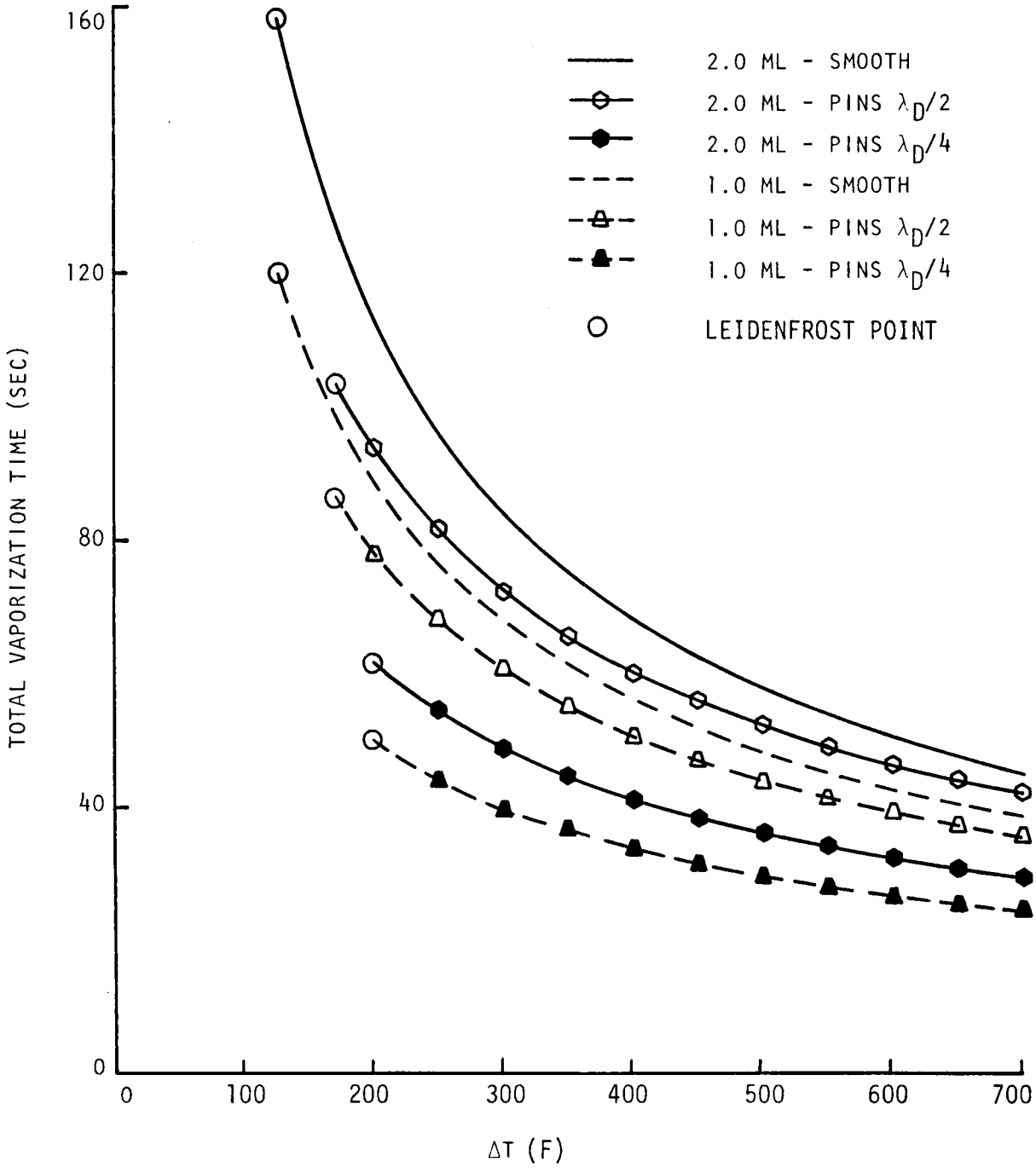


Figure 10. Total vaporization time as a function of ΔT for freon-114 film boiling from a smooth surface and surfaces with cylindrical pins.

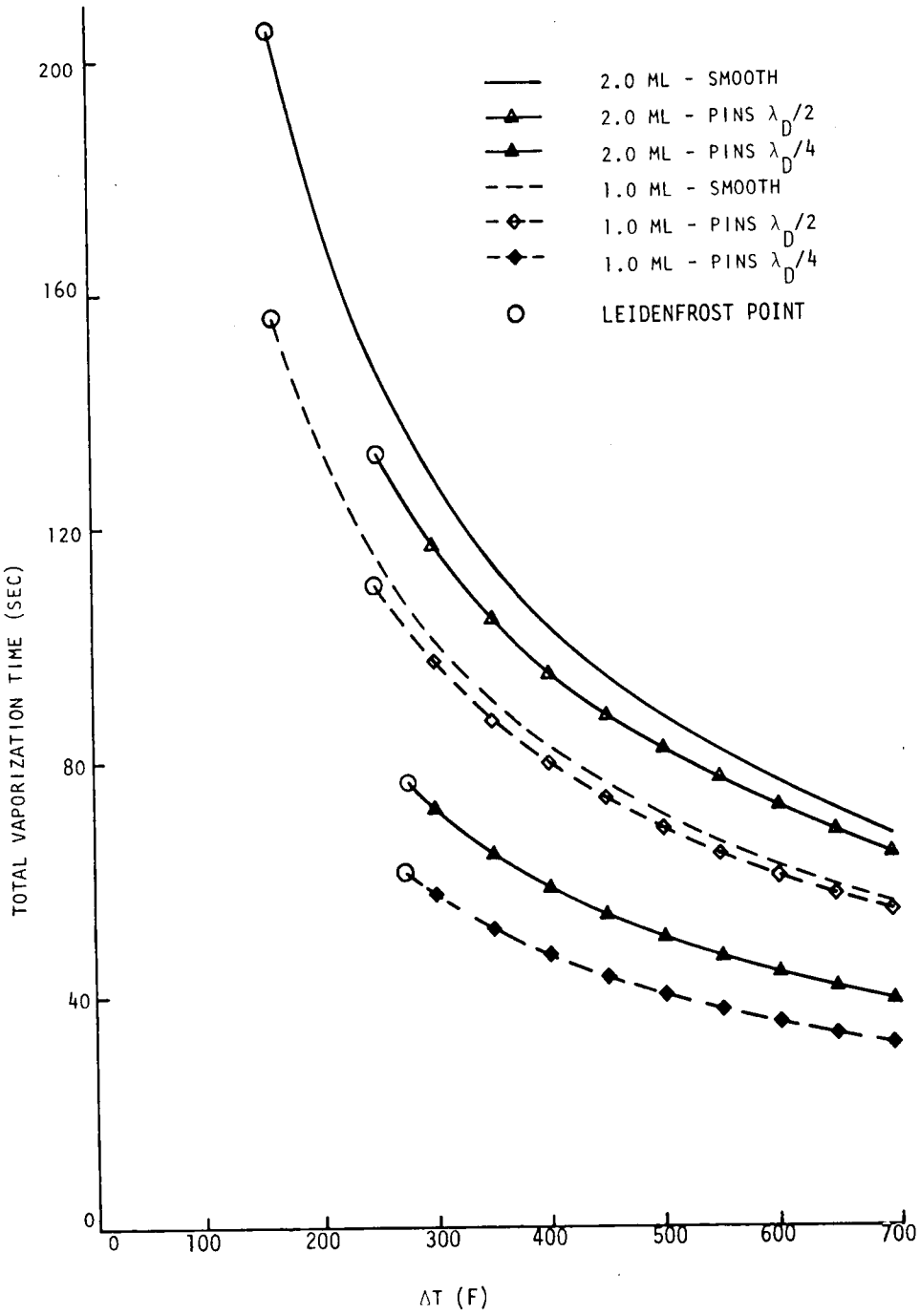


Figure 11. Total vaporization time as a function of ΔT for freon-11 film boiling from a smooth surface and surfaces with cylindrical pins.

boiling with its high heat transfer rate is extended. The onset of film boiling with its low heat transfer rate occurs at higher temperatures.

Boiling data for water was not obtained on surfaces with cylindrical pins spaced at $\lambda_D/2$ and $\lambda_D/4$. Film boiling of water was not attainable on these surfaces even at ΔT = 700 F. The water drops exhibited violent boiling behavior over the entire temperature range. Pin spacings greater than $\lambda_D/2$ were not tested for water because the center-to-center pin spacing would have been greater than the initial water drop diameter.

Pin tip temperature much lower than the boiling surface temperature was examined as a possible cause of the difficulty. The only physical variable changed between the configuration with the pins at $\lambda_D/2$ and at $\lambda_D/4$ was pin spacing. Changing pin spacing would have a negligible effect on pin tip temperature (the convective heat transfer environment of a pin would change slightly as adjacent pins were moved further away). If the pin tip temperature was significantly lower than the boiling surface temperature, nucleate boiling would occur at the pin tip for the same value of ΔT (regardless of pin spacing) for a given fluid. This would fix the value of the Leidenfrost temperature which would be the same for a given fluid on both surfaces with pins. However, examination of the data in Figures 10 and 11 reveals that the Leidenfrost temperature for the surfaces

with pins spaced at $\lambda_D/2$ and $\lambda_D/4$ are significantly different for both freon-11 and freon-114. Thus the pin tip temperature was not significantly different than the boiling surface temperature.

Figures 12 and 13 illustrate the improvement in heat transfer, in the sense of shorter total vaporization times, for surfaces with concentric grooves for 1.0 and 2.0 milliliter volumes of freon-11 and freon-114 respectively. Figure 14 illustrates the improvement in heat transfer for surfaces with concentric grooves for 0.5 and 1.0 milliliter or water. It is observed that the relative improvement in heat transfer for the freons film boiling from both the surfaces with concentric grooves is nearly identical and similar for water film boiling from the same two surfaces. This was a surprising result in view of the fact that the groove depth of one surface was twice the groove depth of the other surface.

To explain this result, it should be reiterated that both surfaces were fabricated with a "sawtooth" groove profile. Decreasing the groove depth from .010 to .020 inch increased the number of grooves per radial inch and consequently the effective heat transfer area per unit of plan area was nearly identical for the two surfaces. For example, the effective heat transfer area seen by a 1.0 milliliter volume of freon-11 on the surface with

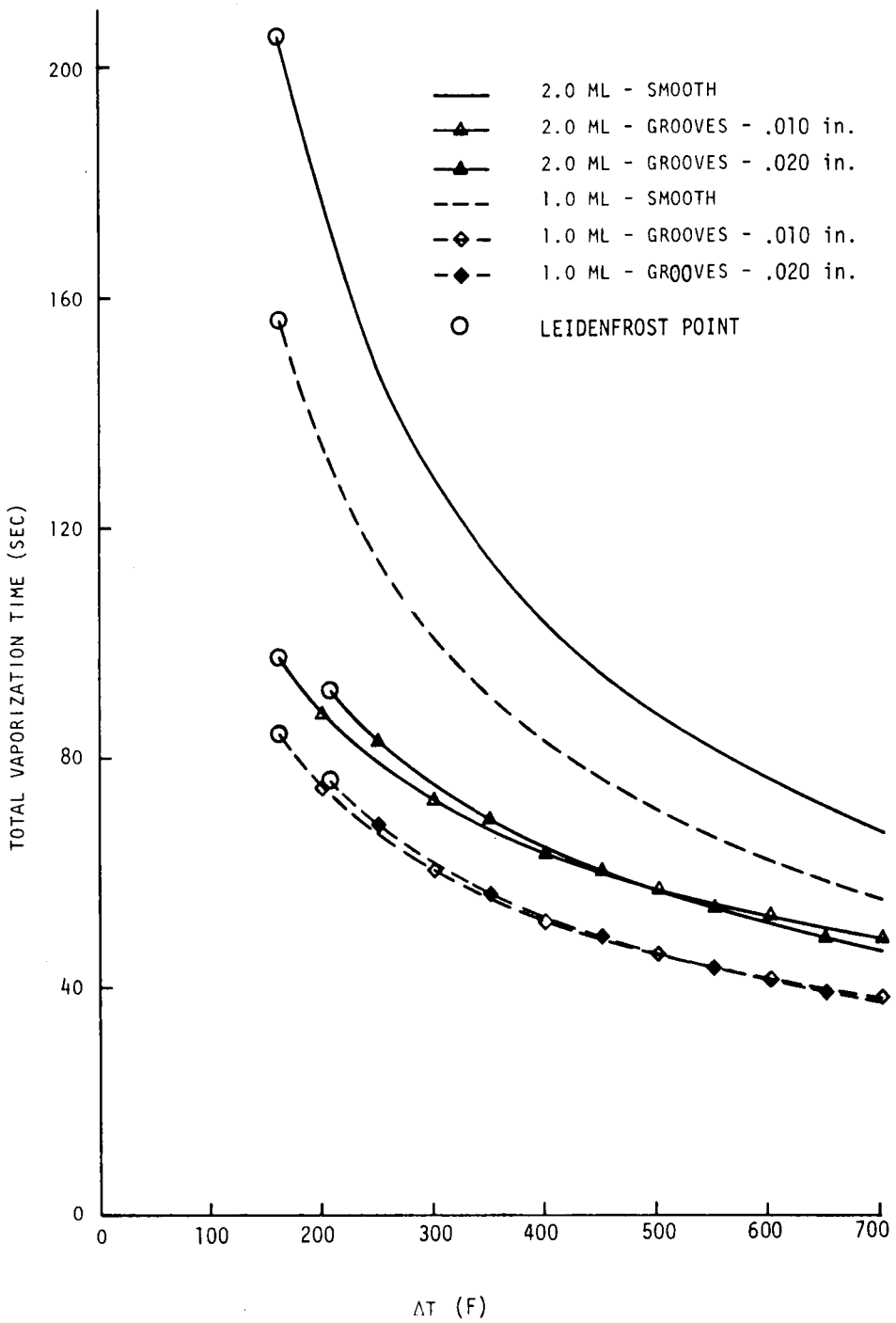


Figure 12. Total vaporization time as a function of ΔT for freon-11 film boiling from a smooth surface and surfaces with concentric grooves.

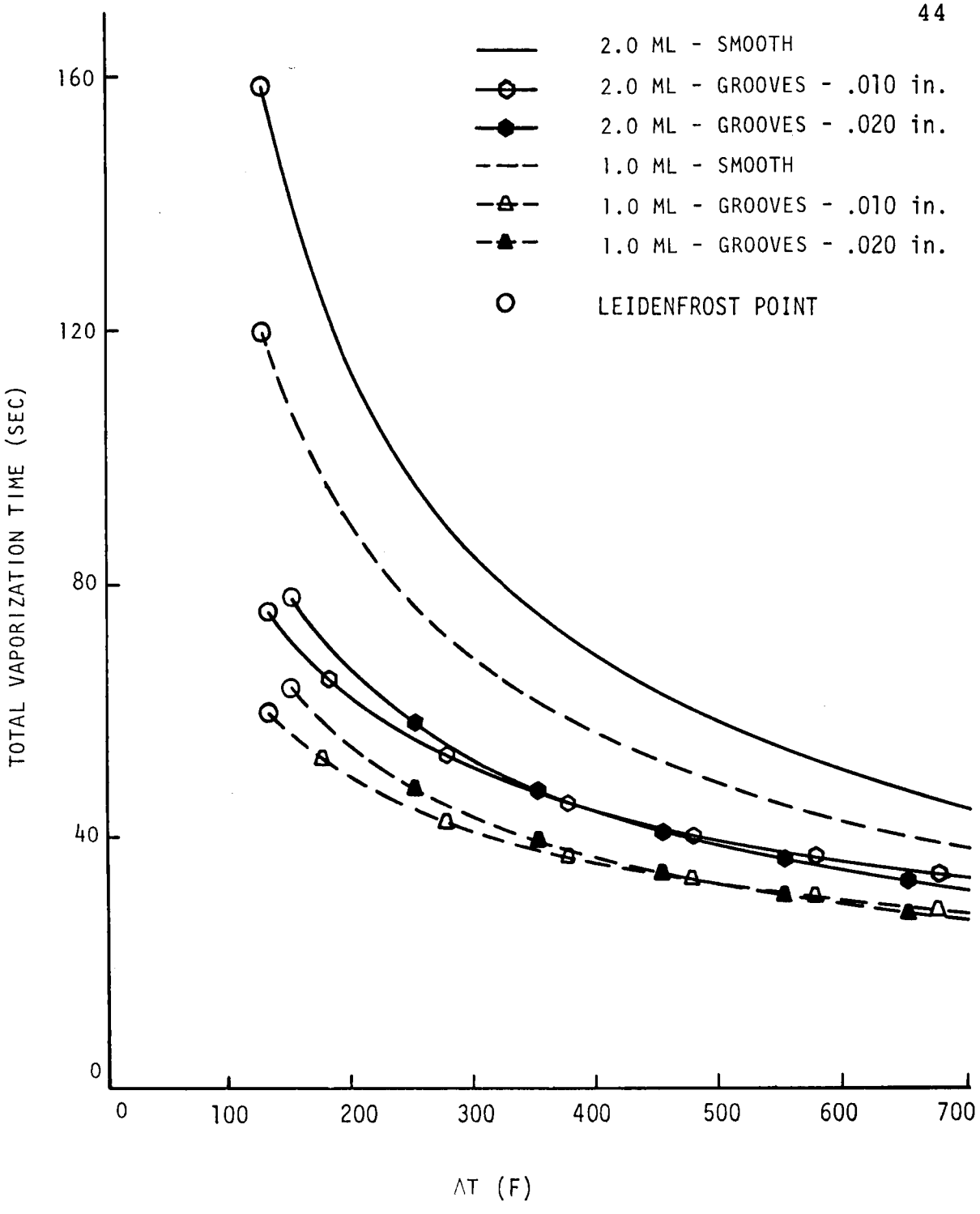


Figure 13. Total vaporization time as a function of ΔT for freon-114 film boiling from a smooth surface and surfaces with concentric grooves.

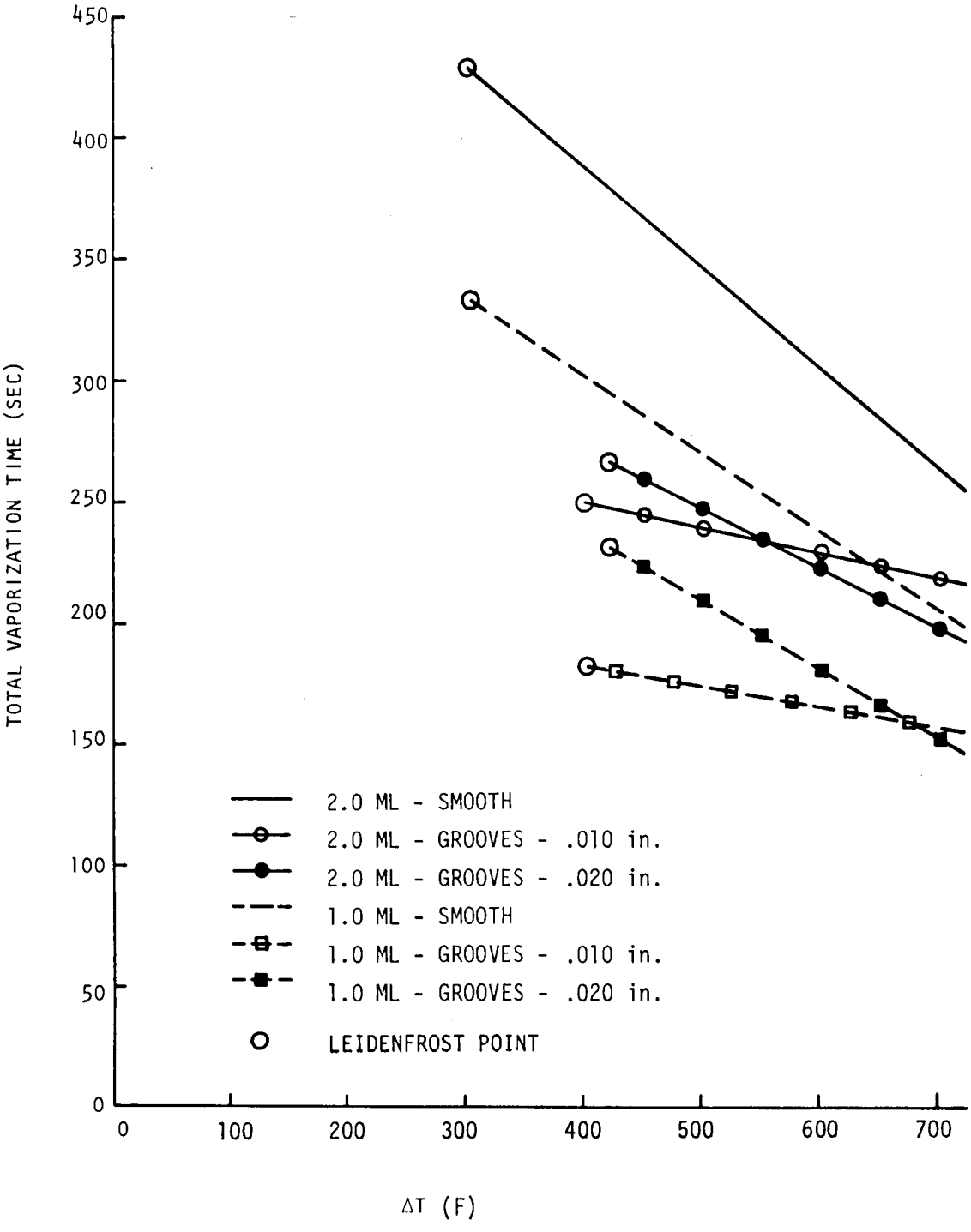


Figure 14. Total vaporization time as a function of ΔT for water film boiling from a smooth surface and surfaces with concentric grooves.

.010 inch concentric grooves was 1.02 square inch and on the surface with .020 inch grooves 1.08 square inch. Effective heat transfer area would thus appear to be one quantity controlling drop vaporization time under film boiling conditions.

Enhancement of film boiling heat transfer was compared for the five surfaces investigated. Total vaporization times as a function of ΔT for 2.0 milliliter of freon-11 and freon-114 film boiling from the five surfaces are presented in Figures 15 and 16 respectively. The power curve fits plotted as straight lines on the log-log scale. Results for the 1.0 milliliter volumes were identical with the exception of lower overall vaporization times due to the smaller volume, therefore the result for only one volume was presented in this fashion.

In each case the surface with cylindrical pins spaced at $\lambda_D/2$ provided only minimal heat transfer enhancement over the smooth surface. This surface did produce a significant increase in the Leidenfrost temperature of 50 to 90 F. Decreasing the center-to-center pin spacing from $\lambda_D/2$ to $\lambda_D/4$ significantly improved the film boiling heat transfer as indicated by the 30-35 percent reduction in total vaporization time for freon-11 and freon-114. The slopes of the curves for the two surfaces were nearly the same, indicating a uniform increase in film boiling heat transfer

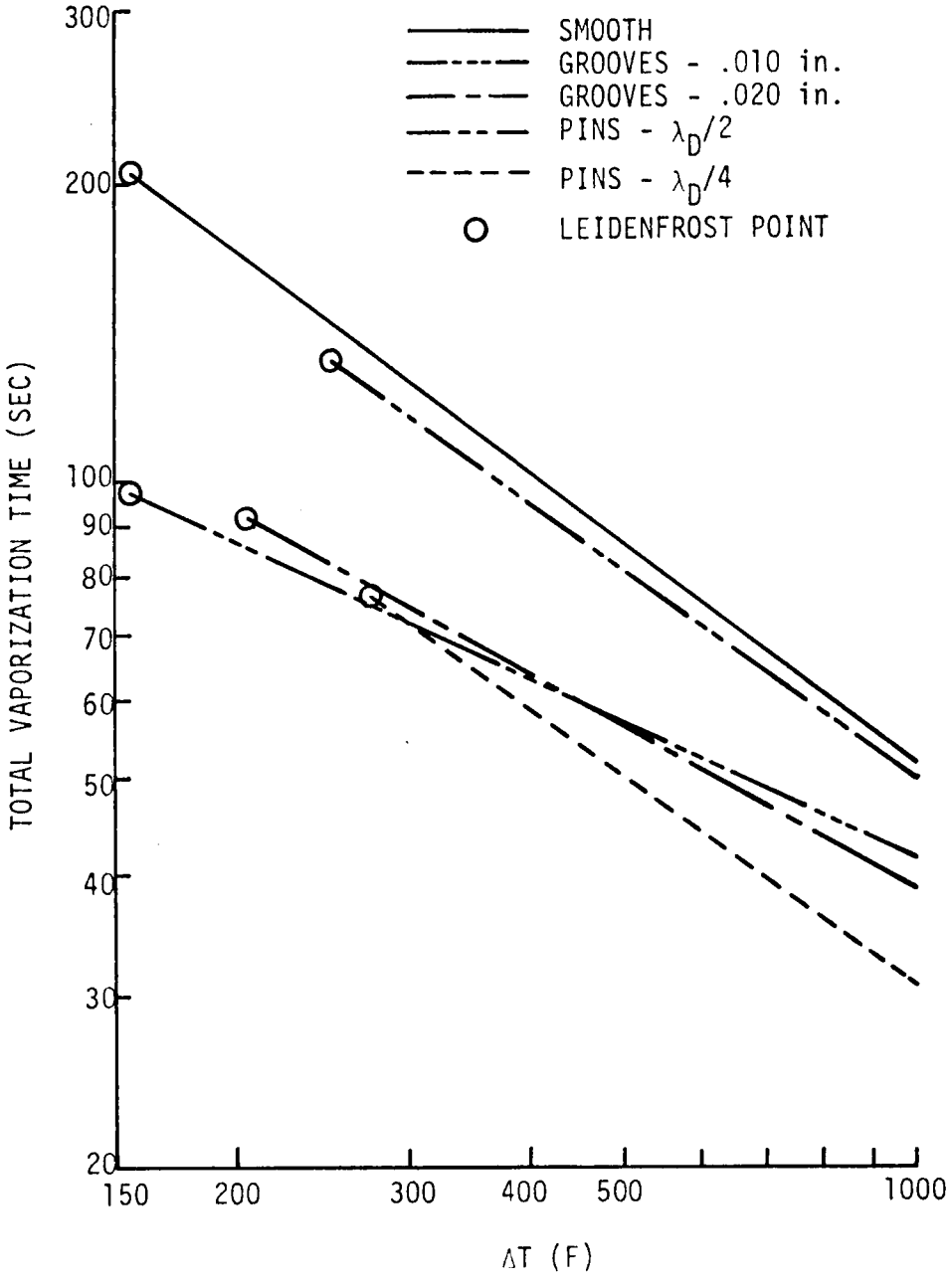


Figure 15. Total vaporization time as a function of ΔT for 2.0 ML of freon-11 film boiling from various surfaces.

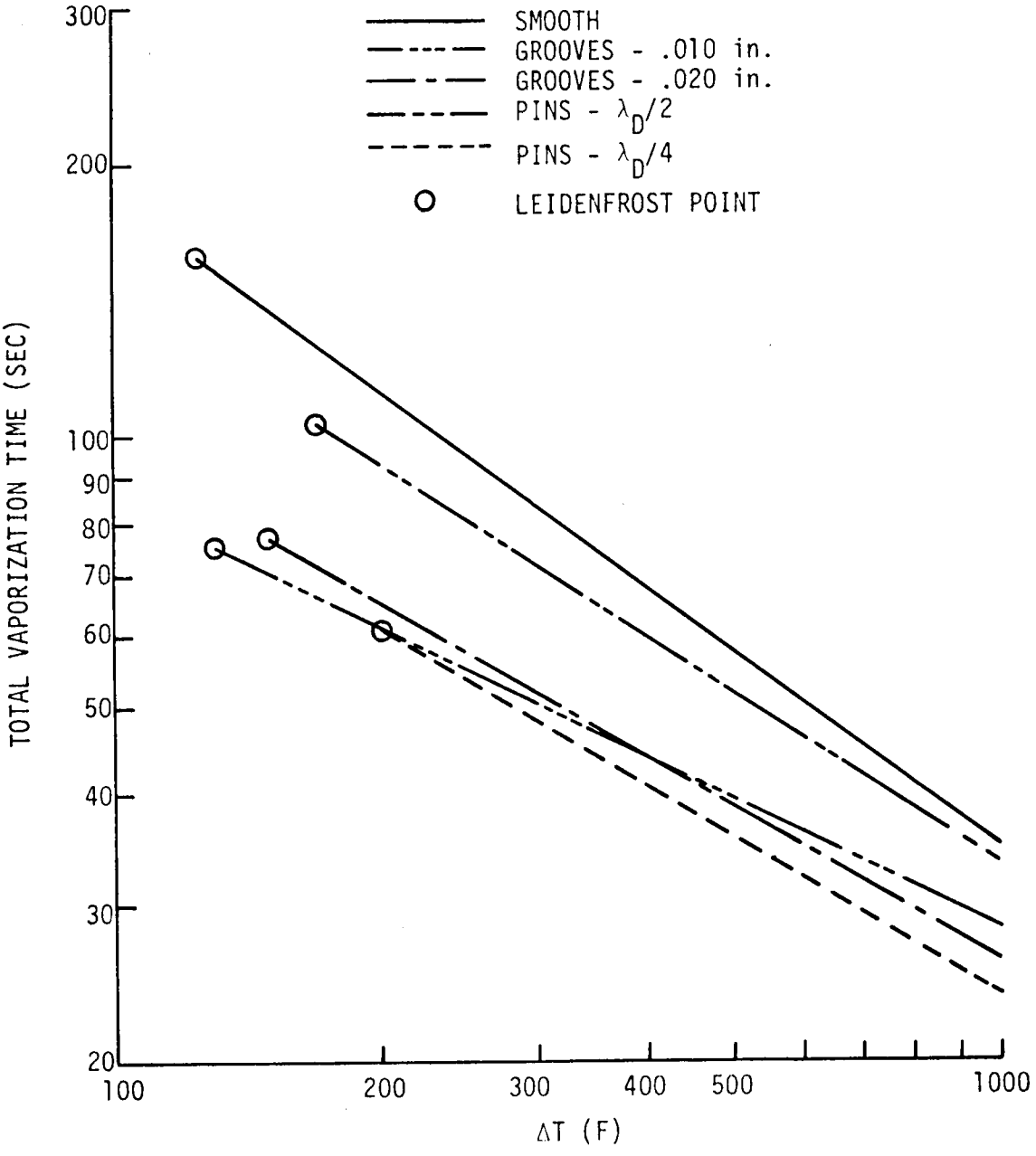


Figure 16. Total vaporization time as a function of ΔT for 2.0 ML of freon-114 film boiling from various surfaces.

with decreasing pin spacing over the range of temperatures investigated.

The surfaces with concentric grooves of both depths produced a significant improvement in film boiling heat transfer over the smooth surface. Improvement in heat transfer for the grooved surfaces is observed to be approximately the same at lower values of ΔT as the improvement obtained for the surface with cylindrical pins spaced at $\lambda_D/4$. At higher values of ΔT, however, the grooved surfaces produced less heat transfer enhancement than the surface with cylindrical pins spaced at $\lambda_D/4$. The Leidenfrost temperature of the freons was increased only 5-25 F on the surfaces with concentric grooves. Referring to Figure 14 on page 45, the Leidenfrost temperature of water was increased 100-120 F on the surfaces with concentric grooves. The Leidenfrost temperatures determined for the three fluids boiling on the various surfaces are summarized in Table 4.

TABLE 4

LEIDENFROST ΔT (F)

Surface	Water	Freon-11	Freon-114
Smooth	300	160	125
Grooves - .010 in.	400	160	130
Grooves - .020 in.	420	205	150
Pins - $\lambda_D/2$	---	250	170
Pins - $\lambda_D/4$	---	275	200

Liquid-Boiling Surface Contact

The possibility of the liquid drops contacting the boiling surface during film boiling was monitored using the technique described earlier in Chapter III. These observations were conducted for water over a range of film boiling temperatures on the smooth surface and the surfaces with concentric grooves. Film boiling of water could not be achieved on the surfaces with cylindrical pins, thus, liquid-boiling surface contact was not monitored on these surfaces. Liquid-boiling surface contact data was not obtainable for the nonconducting freons.

A representative portion of the chart recorder trace is presented in Figure 17 for water film boiling from the smooth surface. For a potential difference of 12 volts DC between the drop and boiling surface, no liquid-boiling surface contact was recorded for any value of ΔT above the Leidenfrost point on the smooth surface except at the instant of liquid deposition on the surface. This result agrees with the results of Nishio and Hirata (11) in the temperature range investigated. To increase the sensitivity of the system, the potential difference was increased to 40 volts DC. No liquid-boiling surface contact was measured on the smooth surface at this higher potential. Potential difference greater than 40 volts DC produced visible

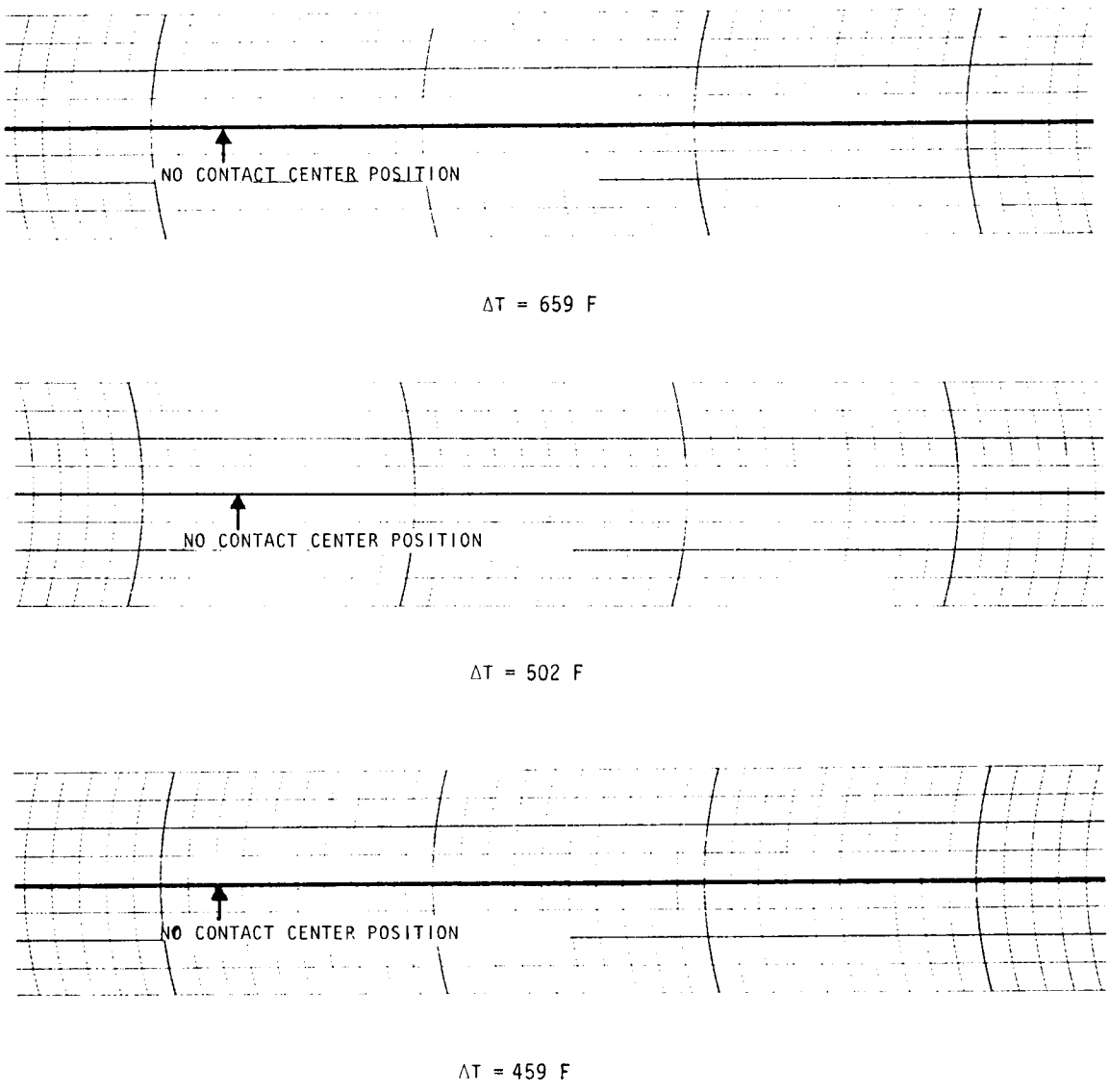
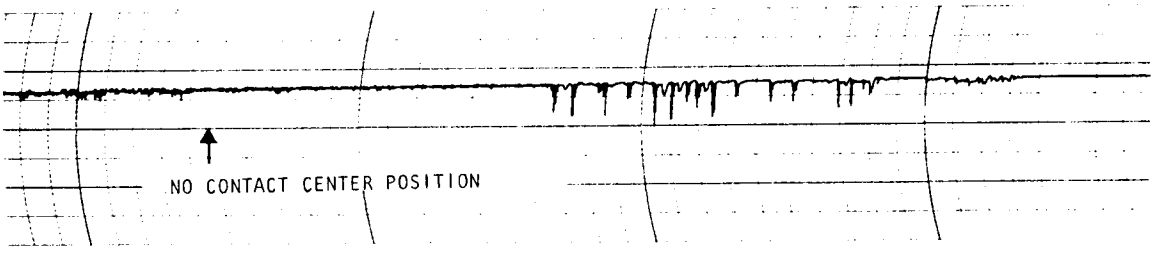


Figure 17. Time history of contact between film boiling water droplet and smooth surface for several values of ΔT.

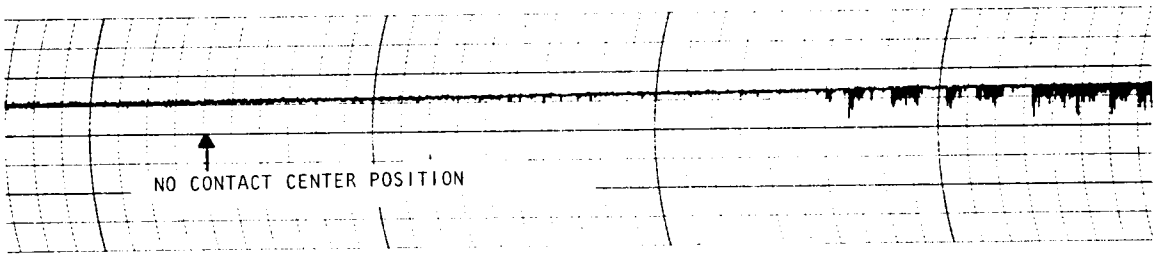
vibrations of the water drops. Data collection at potential differences greater than 40 volts DC was not attempted.

In Figures 18 and 19 representative portions of chart recorder traces are presented for water film boiling from the surfaces with .010 inch and .020 inch concentric grooves respectively. Nearly continual contact between the film boiling drops and the boiling surface was recorded on these surfaces. At the instant the liquid was deposited on the boiling surfaces, a voltage was recorded as indicated by the displacement of the recording pen from the center position. Side to side movements, vertical oscillations and drop vibration produced sporadic breaking of contact and thus the oscillating chart recorder trace. The downward pen movements in Figures 18 and 19 indicate breaking of contact and upward pen movements indicate restoration of contact. The ease with which small drop movements produced breaking of contact suggests liquid-boiling surface contact at small sites rather than over large areas. Lack of visible evidence of nucleate boiling characteristic of liquid-boiling surface contact on a larger scale also suggests contact at relatively small sites.

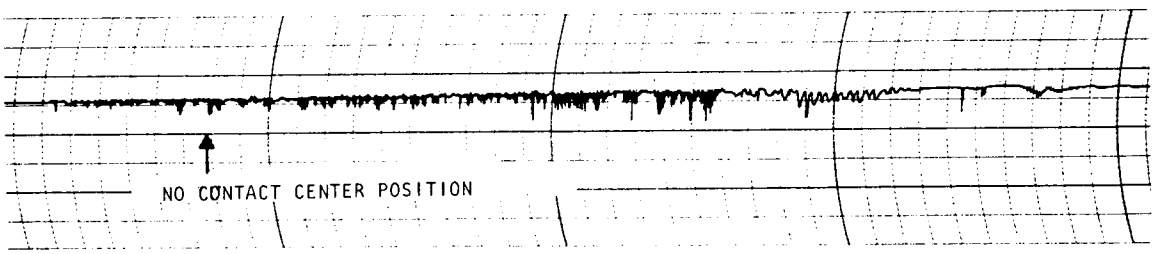
Liquid-boiling surface contact is observed to be similar for both surfaces with concentric grooves. There are no consistent distinguishable differences in contact characteristics (such as persistence of contact and



ΔT = 630 F

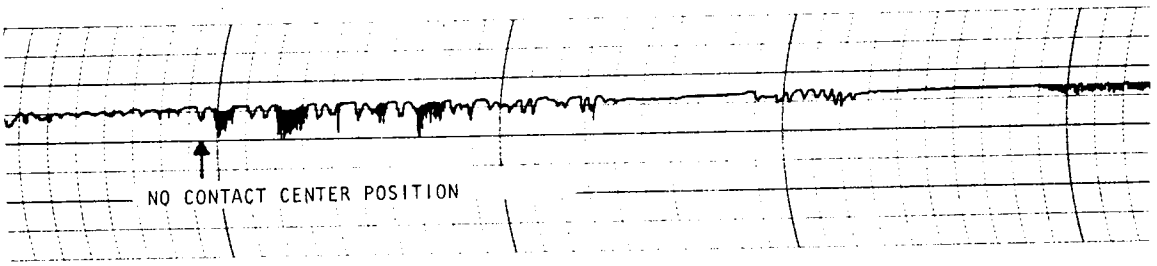


ΔT = 549 F

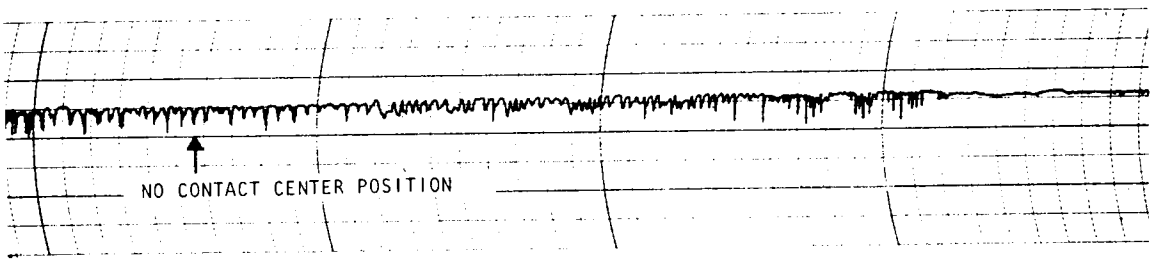


ΔT = 448 F

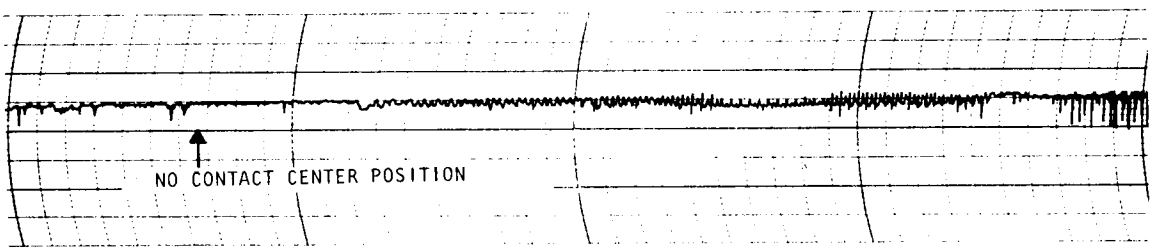
Figure 18. Time history of contact between film boiling water droplet and surface with .010 inch concentric grooves for several values of ΔT.



ΔT = 607 F



ΔT = 545 F



ΔT = 423 F

Figure 19. Time history of contact between film boiling water droplet and surface with .020 inch concentric grooves for several values of ΔT.

frequency of contact breaking and restoration) for the surfaces with different groove depths.

CHAPTER VI

ANALYSIS

An analysis was conducted to determine the dominant variable(s) responsible for the observed experimental results. The analysis consisted of a computer aided attempt at correlating the vaporization time data for all the fluids film boiling from the various surfaces with dimensionless parameters which reflect the relevant physical mechanisms.

A computer code was written to manipulate the large quantity of experimental data, to calculate physical characteristics such as vapor layer and drop thicknesses, drop radius and effective heat transfer area, and to permit rapid evaluation of candidate correlating parameters. The code was written in FORTRAN IV for use with the G level compiler of an IBM 360 multiprocessing system. Appendix B contains a listing of the code.

The code consists of five routines, MAIN, CURVE, CORR, DMLESS, and VALUE. MAIN reads the input run control parameters from cards and the experimental data (film boiling vaporization time as a function of disk surface temperature) from a disk file. It prints the input data if desired by the user and routes the program flow to the appropriate subroutines determined by the user defined run

control parameters. MAIN identifies the fluid used in each group of experimental data and by subtracting the corresponding saturation temperature converts the input experimental data to vaporization time as a function of ΔT. Subroutine CURVE calculates linear and power curve fit coefficients by the method of least squares for the vaporization time as a function of ΔT data of each combination of fluid, fluid volume and boiling surface. Control is returned to MAIN where the results of the curve fit calculations are printed. If specified by the user, the computer run is terminated at this point. If not, subroutine CORR is called for calculation of physical characteristics and dimensionless parameters. CORR controls the calculation of dimensionless parameters and prints the results. For a given film boiling curve, the curve fit with the highest correlation coefficient is selected and the corresponding curve fit equation is used to calculate the experimental vaporization time for values of ΔT beginning near the Leidenfrost point and increasing in 50 F increments to ΔT = 700 F. For each value of ΔT, subroutine DMLESS is called where the dimensionless parameters and physical characteristics are calculated. Subroutine VALUE is called from DMLESS and performs a table look-up for fluid vapor properties as a function of temperature as required by calculations in DMLESS. A linear interpolation scheme is

used in the table look-up procedure. Vapor density, thermal conductivity, viscosity and specific heat as functions of temperature for each fluid are contained in data statements in DMLESS. Fluid vapor properties are evaluated in VALUE for the film temperature (mean temperature in the vapor layer). Output of the computer code is contained in Appendix C.

The starting point for development of nondimensional correlating parameters was the work of Baumeister presented in reference (4). Baumeister has developed dimensionless time and liquid volume parameters that successfully correlate (15) drop vaporization time with drop volume for fluids film boiling from smooth surfaces. Figure 20 obtained from reference (15) illustrates the success of the correlation for a variety of data from the literature. Baumeister's dimensionless vaporization time is,

$$t^* = \frac{t}{\left[\frac{\rho_\ell^{1/2}\mu\lambda^4\sigma^{5/2}g_c^{5/2}}{k^3 g^{7/2}\lambda^*\rho_v\Delta T^3}\right]^{1/4}}$$

where,

$$\lambda^* = \lambda\left[1.0 + \frac{7}{20}\frac{C_p\Delta T}{\lambda}\right]^{-3}$$

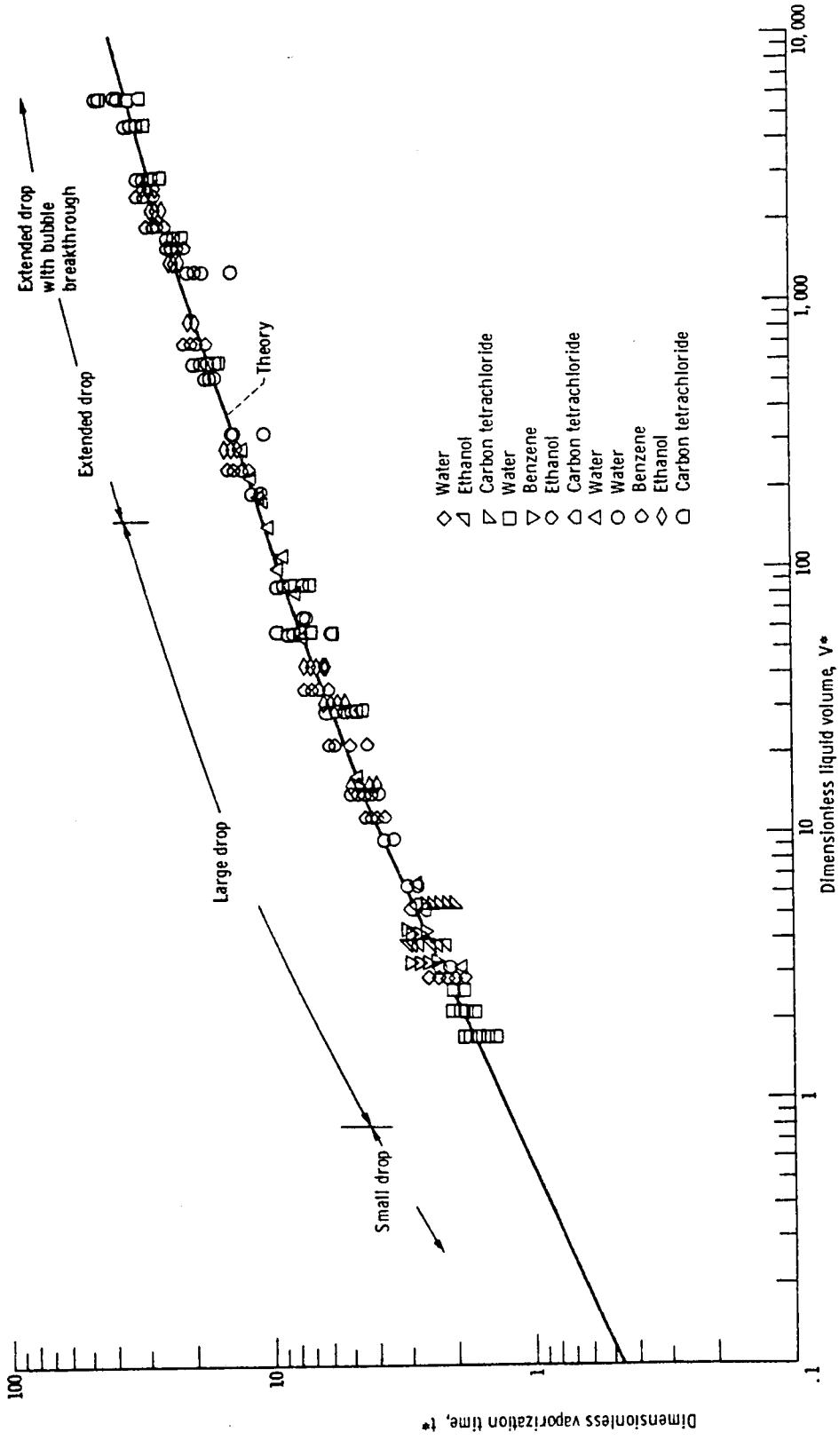


Figure 20. Universal total vaporization time curve.

The dimensionless drop volume is,

$$V^* = \frac{V}{\left[\frac{\sigma g_c}{\rho_\ell g}\right]^{3/2}}$$

These dimensionless parameters successfully predict the relationship between the vaporization time of film boiling liquid drops and the physical properties of the liquid and its vapor (comprising the vapor layer between the liquid drop and boiling surface). The parameters do not contain variables that reflect boiling surface properties such as surface roughness or projections.

Equations necessary to calculate t* and V* were incorporated in subroutine DMLESS of the computer code. Experimental vaporization time data for the five surfaces and three fluids were evaluated using the Baumeister correlation. Values of t* for a given film boiling curve (and thus one value of V*) calculated for the incremental values of ΔT were averaged. The resulting values of t* for the three fluids are scattered when plotted as a function of V* in Figure 21. For example, at a value of V* approximately equal to thirty-two, the value of t* ranges from 3.4 for data on the surface with .020 inch concentric grooves to 5.0 for data on the smooth surface. In order to illustrate the variation in the t*-V* relationship for the various surfaces, exactly the same data are plotted in

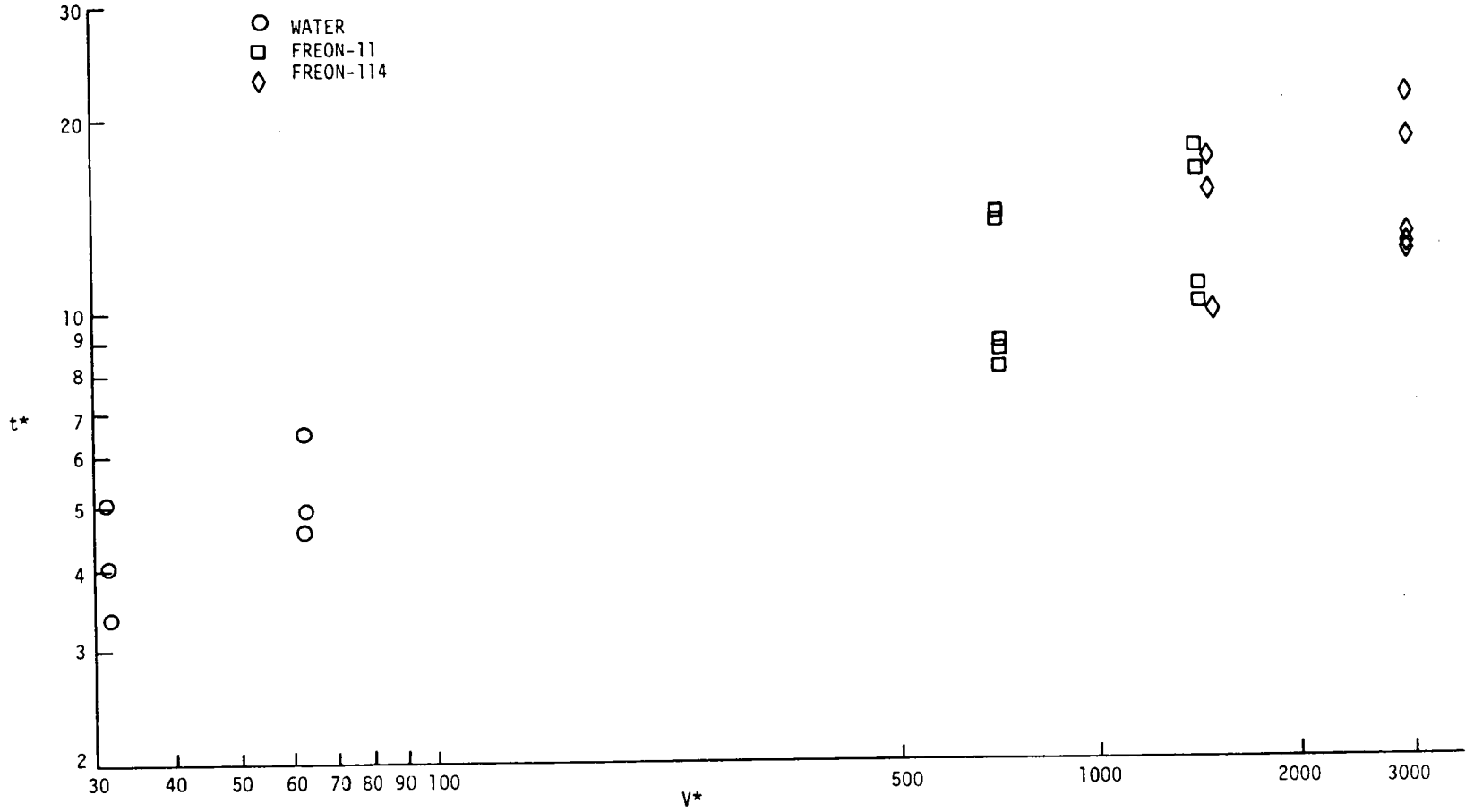


Figure 21. Dimensionless vaporization time as a function of dimensionless droplet volume for the fluids investigated.

Figure 22 with different symbols representing different surfaces. Curves could be faired through the data for each boiling surface. Thus the Baumeister correlation produced a single well behaved curve for the film boiling data for each surface but curves for the surfaces with projections deviated considerably from the smooth surface curve. Parameters influencing drop vaporization time, such as fluid properties and ΔT, appeared to be adequately correlated by the Baumeister relationship on the surfaces with projections as well as the smooth surface. However, the t*-V* relationship does not contain variables to reflect the differences in the boiling surfaces and thus does not correlate the data from the surfaces with projections with the smooth surface data.

A number of factors related to the geometry of the surfaces and physical characteristics of the film boiling drops were investigated as candidate correlating parameters. Dimensionless groups of variables were multiplied by t* to obtain correlating parameters that were plotted as functions of V*.

The Bond number is a ratio of gravity forces to surface tension forces and for a liquid drop on a smooth surface is,

$$\text{Bond number} = \frac{4r^2 g(\rho_\ell - \rho_v)}{g_c \sigma}$$

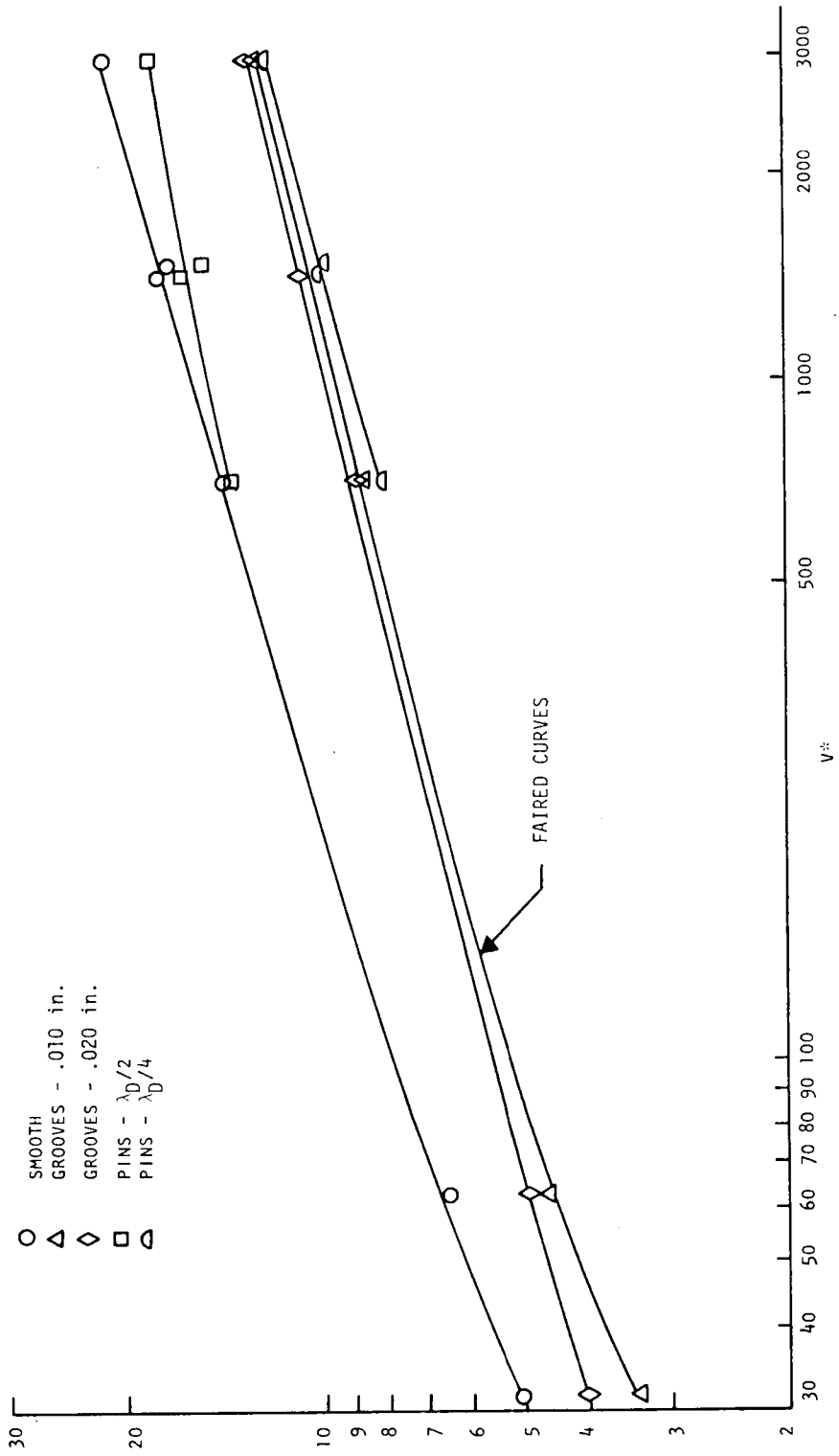


Figure 22. Dimensionless vaporization time as a function of dimensionless droplet volume.

The Bond number for the surfaces with cylindrical pins (.062 inch diameter) was determined to be,

$$\text{Bond number} = \frac{2r^2L(\rho_\ell - \rho_v)g}{.0025N\sigma g_c}$$

For the surfaces with concentric grooves, the smooth surface Bond number was used. The Bond number was calculated for the different fluids and surfaces, raised to several powers between 0.2 and 0.7, multiplied by t* and plotted as a function of V*. These parameters were unsuccessful in correlating the data from the surfaces with projections with the smooth surface data.

The ratio of vapor layer thickness plus the projection height (or depth) to the projection height was multiplied by t* and plotted as a function of V*. This parameter was also unsuccessful in correlating the data.

The only successful parameter was an area correction used to modify Baumesiter's dimensionless vaporization time, t*. That is, when the corresponding values of t* were multiplied by the ratio of projection surface area to the surface area of the smooth disk and plotted as a function of V*, the data for the five surfaces are reasonably correlated as in Figure 23. For the surfaces with pins, projection surface area is the exposed smooth surface area plus the surface area of the pins. For the surfaces with

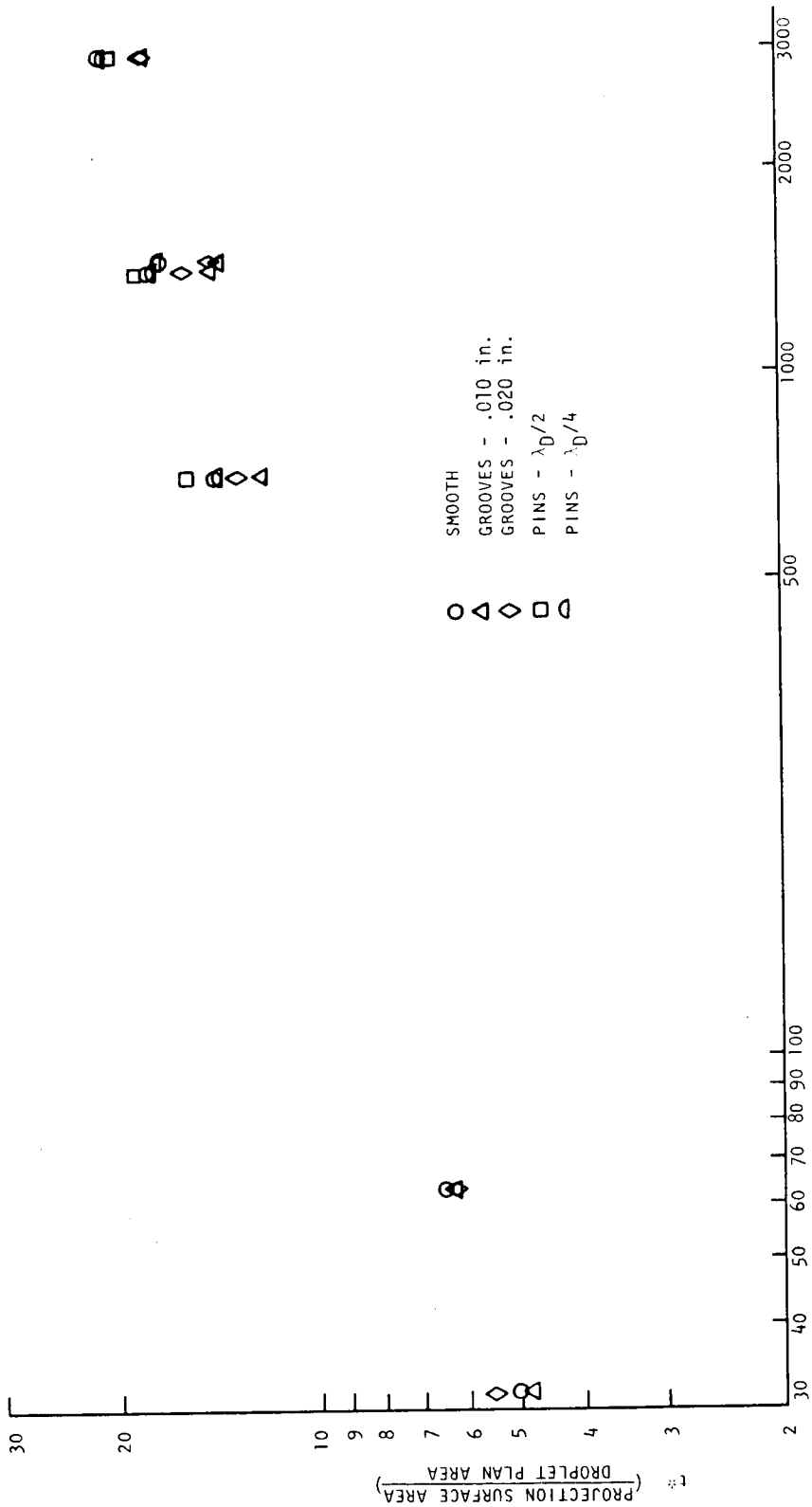


Figure 23. Modified dimensionless vaporization time as a function of dimensionless droplet volume.

concentric grooves, projection surface area is the exposed area of the grooves. The area correction factor is essentially the ratio of effective heat transfer area on a surface with artificial surface projections to the effective heat transfer area on a smooth surface.

The area correction factor provides an improved correlation of the data for the surfaces investigated, however, the data for surfaces with concentric grooves lie below the smooth surface data for V* greater than 100. Thus the area correction factor does not entirely compensate for the decrease in total vaporization time measured on the surfaces with concentric grooves.

Direct contact between a liquid and a boiling surface at film boiling temperatures would result in high heat transfer nucleate boiling at the site of contact. Nucleate boiling at sites of contact would reduce the total vaporization time of the liquid drop thus contributing to an improvement in heat transfer. As discussed in Chapter V, liquid-boiling surface contact was measured for water film boiling from the surfaces with concentric grooves. This observed contact could be responsible for the additional improvement in heat transfer evident in Figure 23 for the surfaces with concentric grooves and V* greater than 100. The contribution to heat transfer improvement of liquid-boiling surface contact could not be quantified in the form

of a dimensionless parameter with the data available from the present experimental investigation.

CHAPTER VII

CONCLUSIONS

The following conclusions were deduced from the previous discussions:

1. Addition of cylindrical pins or concentric grooves to a smooth surface increases the heat transfer rate to liquid drops film boiling on the surface.
2. Heat transfer to film boiling liquid drops on surfaces with cylindrical pins increases with decreasing pin spacing.
3. Improvement of film boiling heat transfer on surfaces with cylindrical pins and concentric grooves is a function of effective heat transfer area.
4. The Leidenfrost temperature of water, freon-11 and freon-114 is increased significantly by the addition of cylindrical pins to a smooth surface.
5. The Leidenfrost temperature of water is increased significantly by the addition of concentric grooves to a smooth surface but the Leidenfrost temperature of freon-11 and freon-114 is increased only slightly.
6. On a smooth surface (5-10 microinches r.m.s.) there is no contact between a film boiling liquid

drop and the boiling surface except at the instant of liquid deposition on the boiling surface.

7. On surfaces with concentric grooves there is continual intermittent contact between a film boiling liquid drop and the boiling surface.
8. Contact between the film boiling liquid drop and the boiling surface appears to result in improved heat transfer on surfaces with concentric grooves.

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REFERENCES

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APPENDIXES

APPENDIX A

EXPERIMENTAL VAPORIZATION TIME AS A FUNCTION OF ΔT

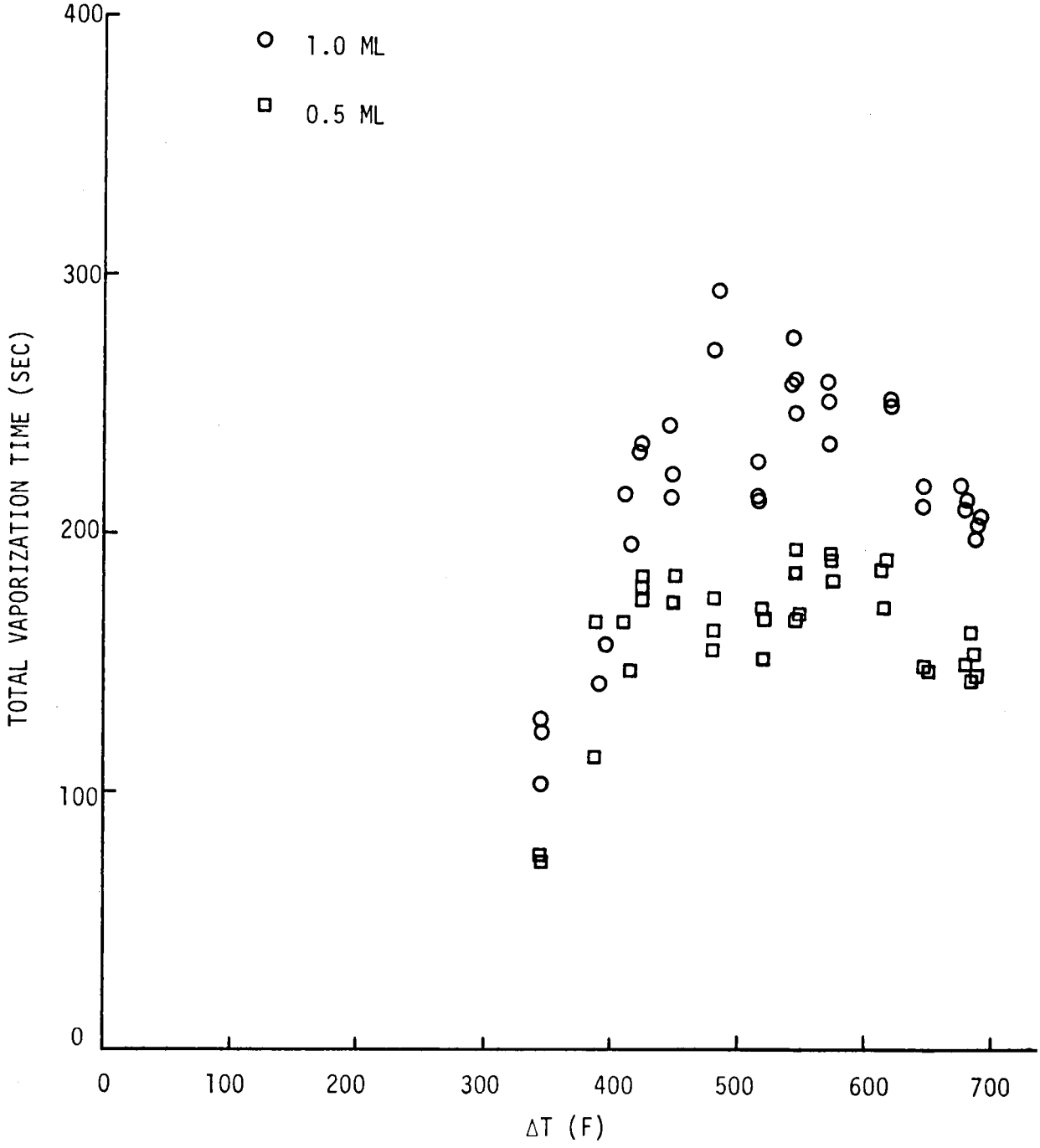


Figure A-1. Water boiling on surface with .010 inch concentric grooves.

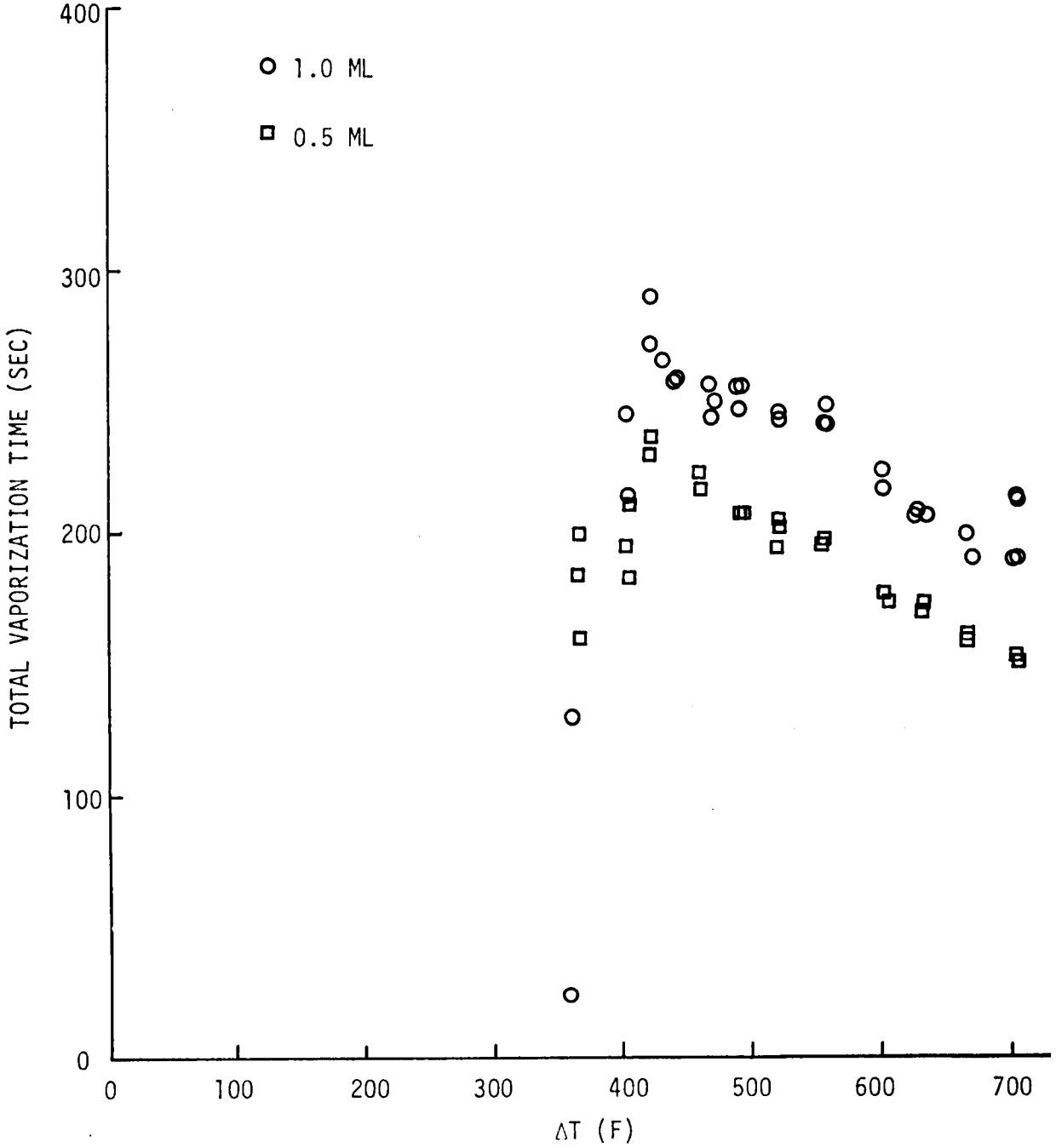


Figure A-2. Water boiling on surface with .020 inch concentric grooves.

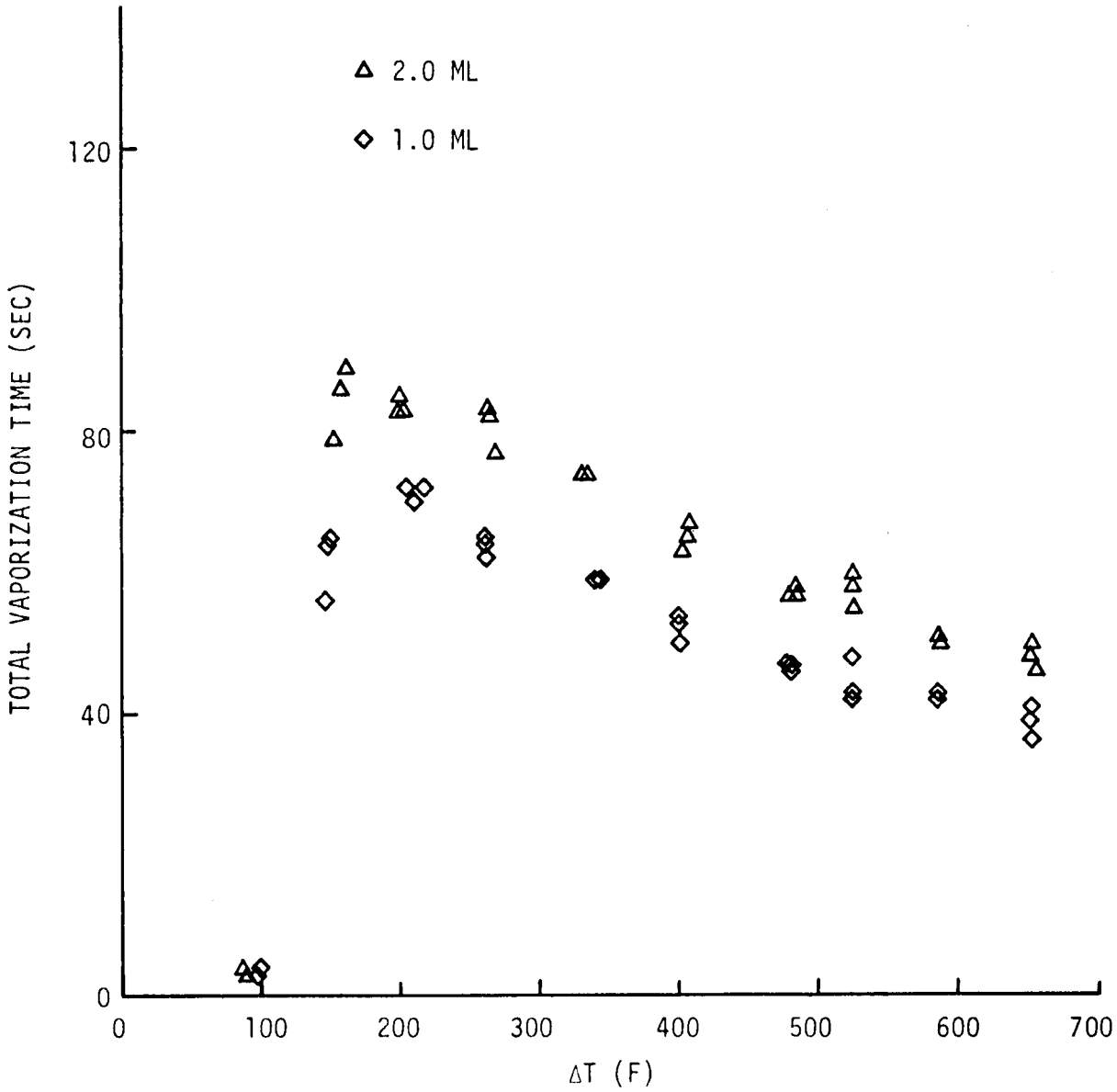


Figure A-3. Freon-11 boiling on surface with .010 inch concentric grooves.

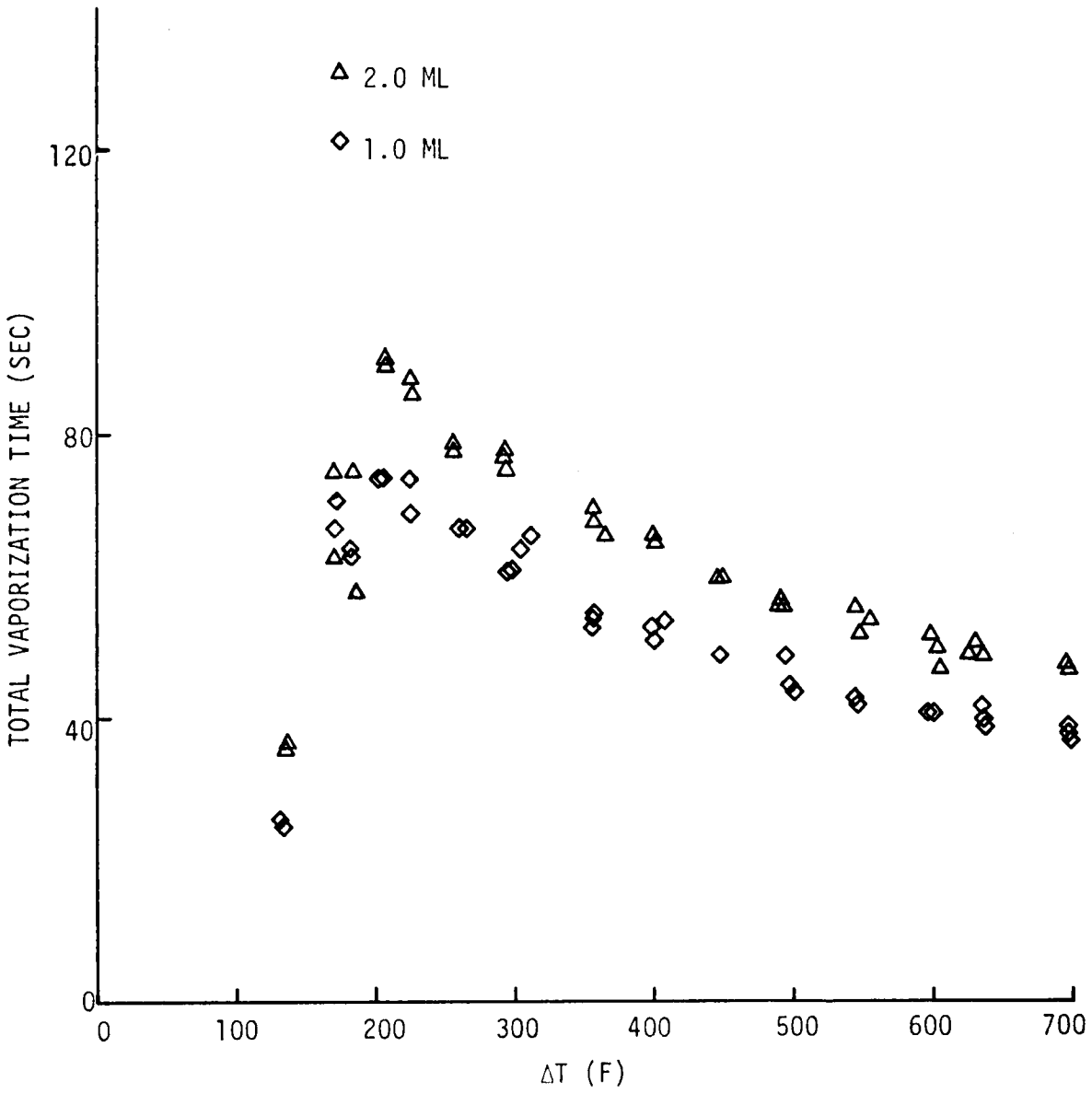


Figure A-4. Freon-11 boiling on surface with .020 inch concentric grooves.

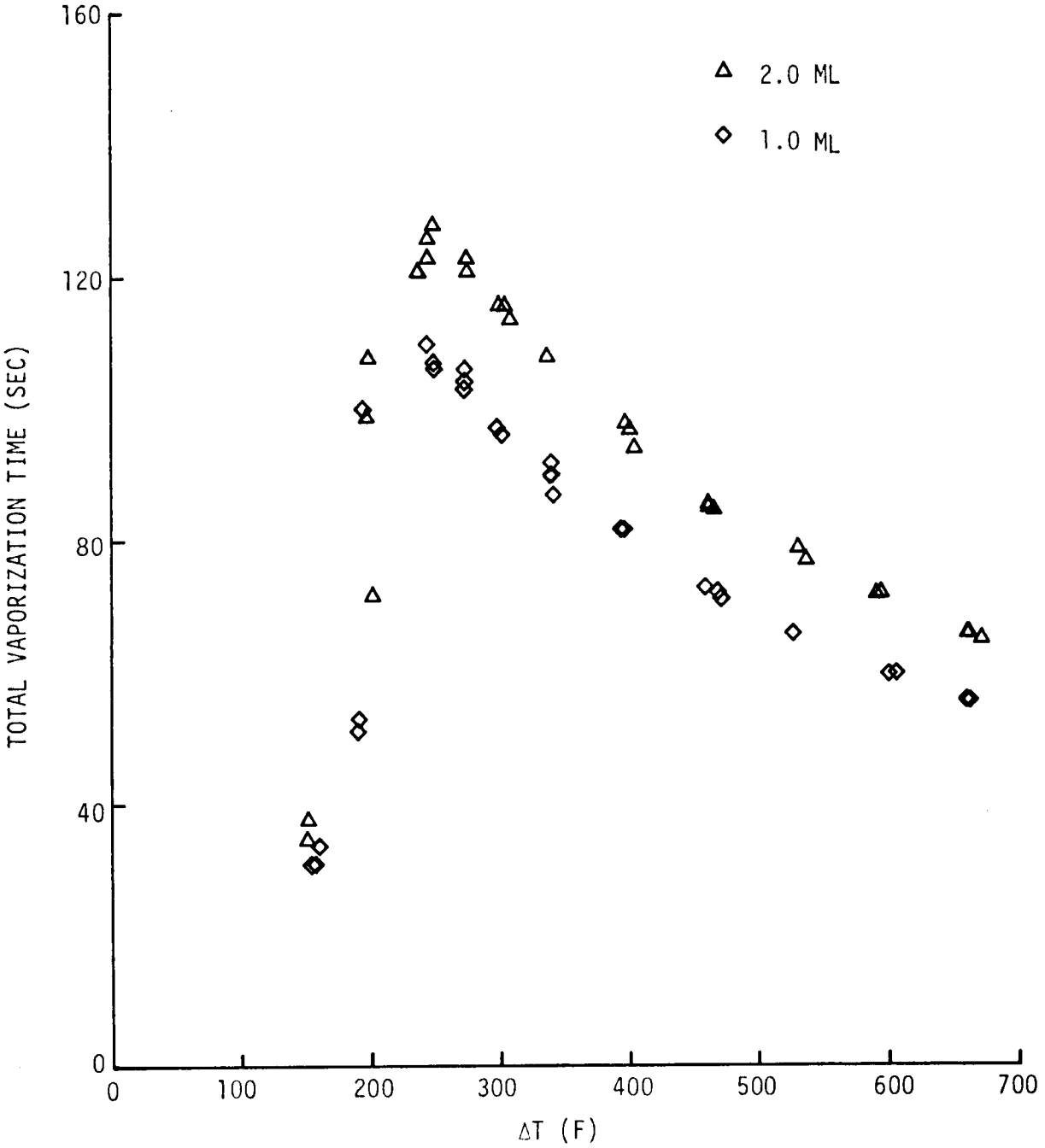


Figure A-5. Freon-11 boiling on surface with cylindrical pins at $\lambda_D/2$.

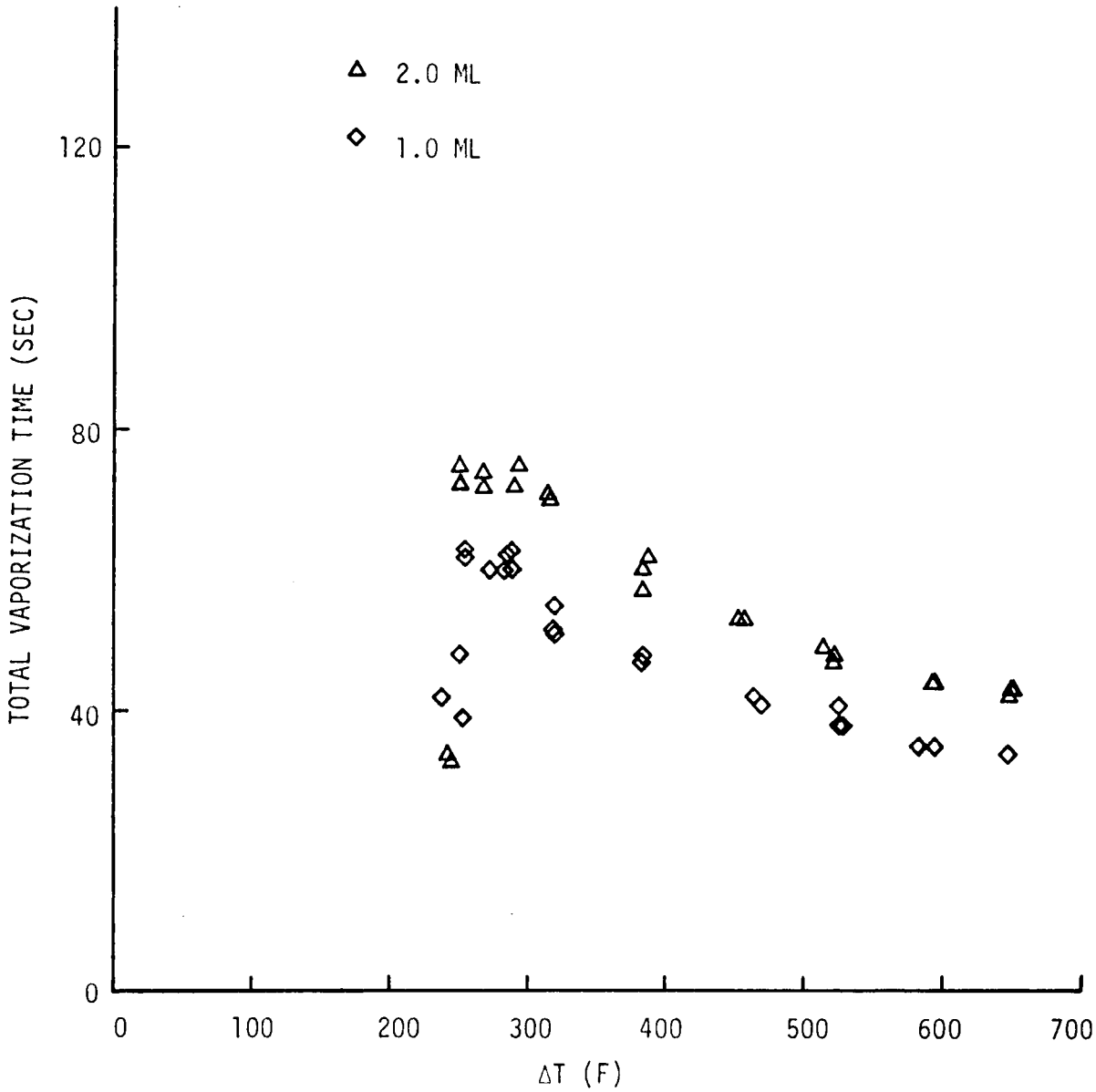


Figure A-6. Freon-11 boiling on surface with cylindrical pins at $\lambda_D/4$.

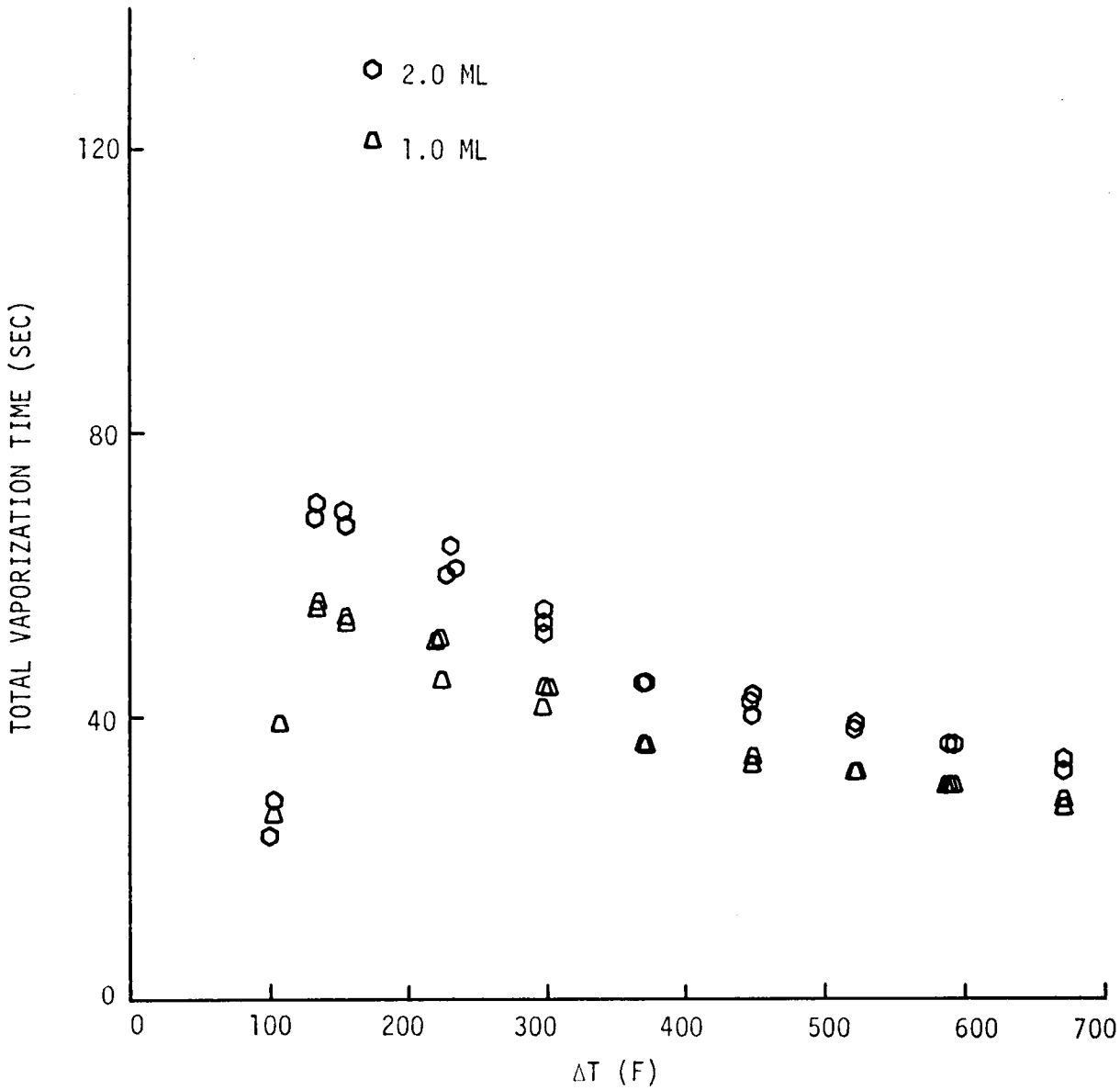


Figure A-7. Freon-114 boiling on surface with .010 inch concentric grooves.

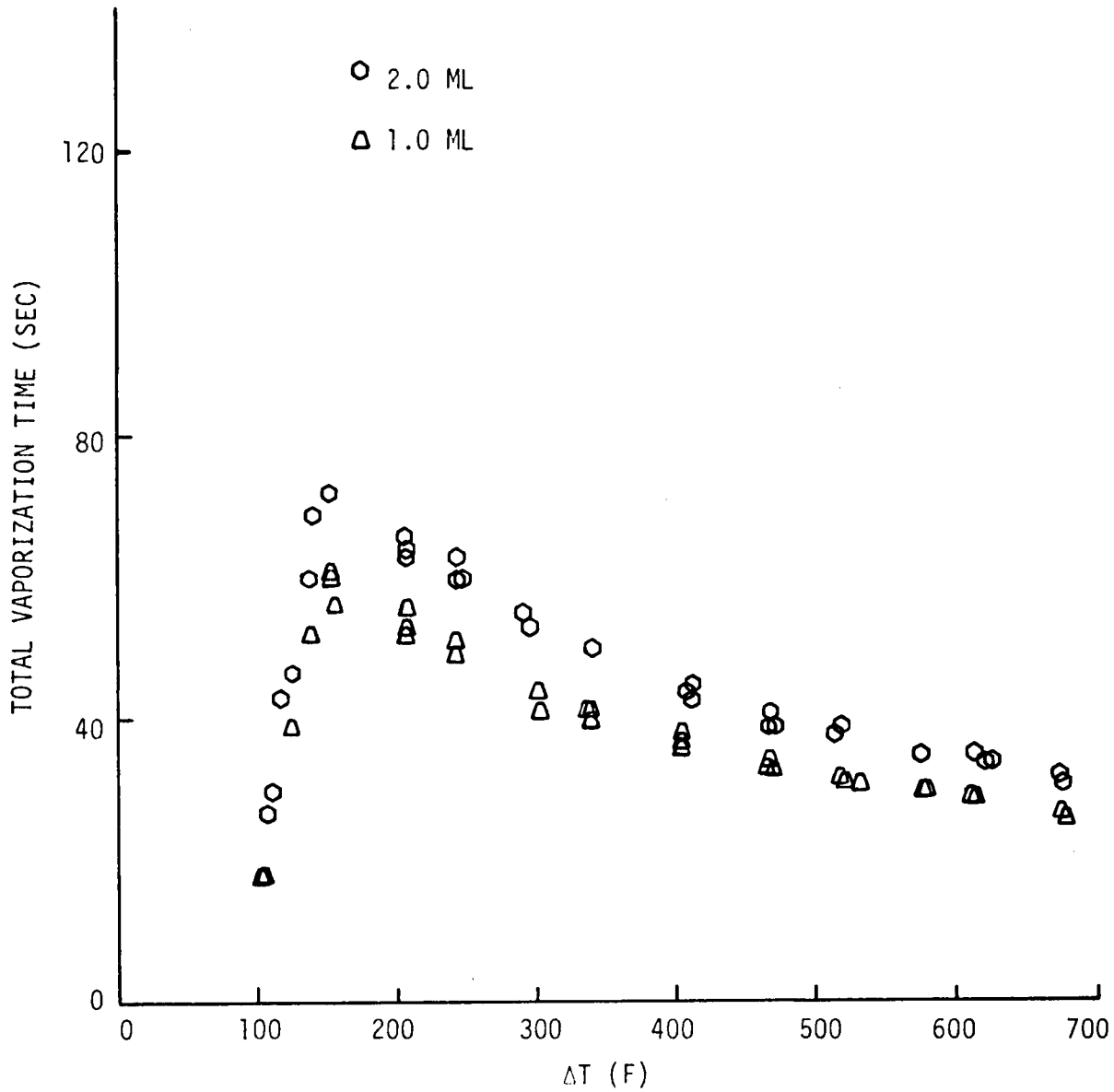


Figure A-8. Freon-114 boiling on surface with .020 inch concentric grooves.

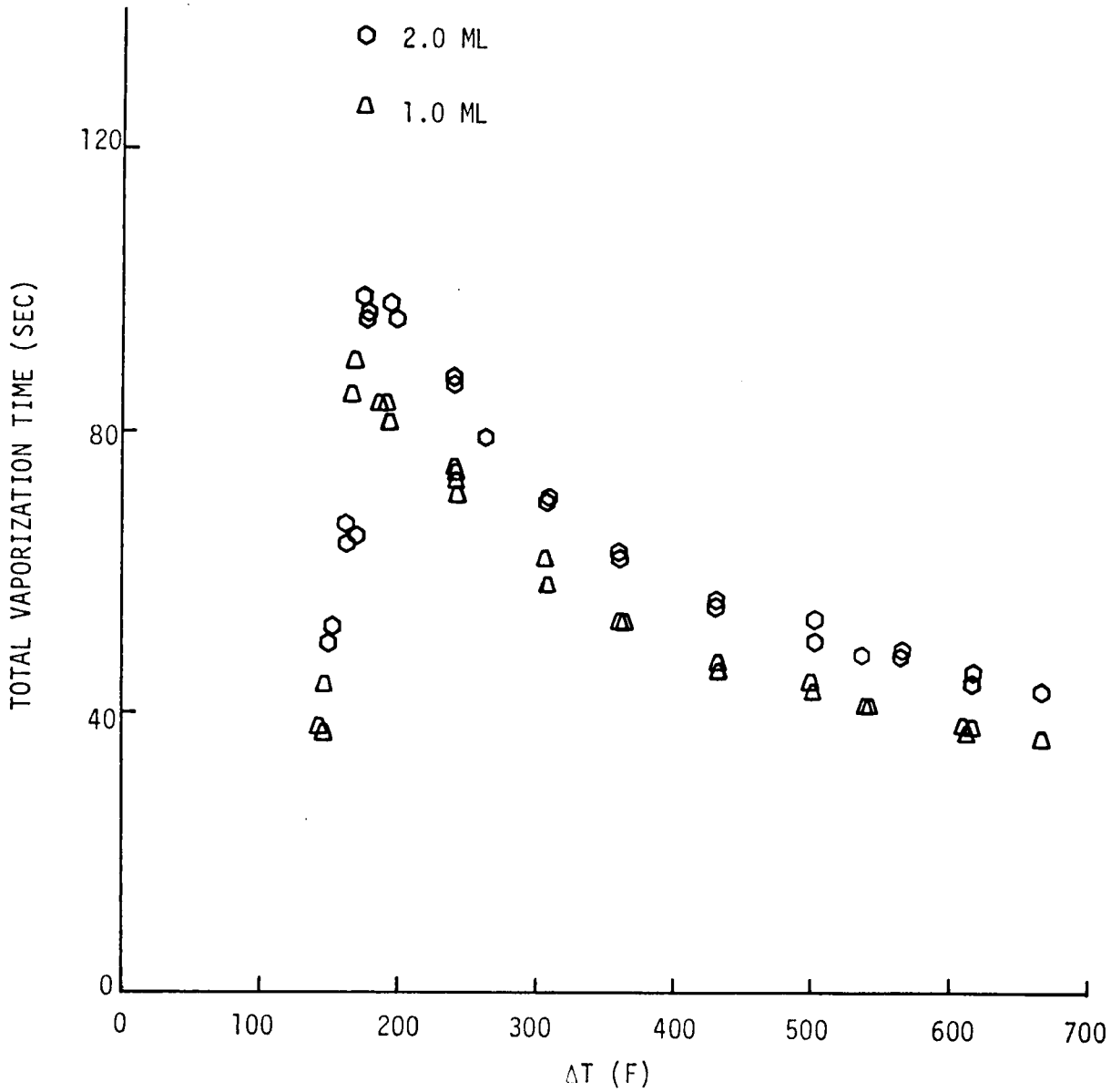


Figure A-9. Freon-114 boiling on surface with cylindrical pins at $\lambda_D/2$.

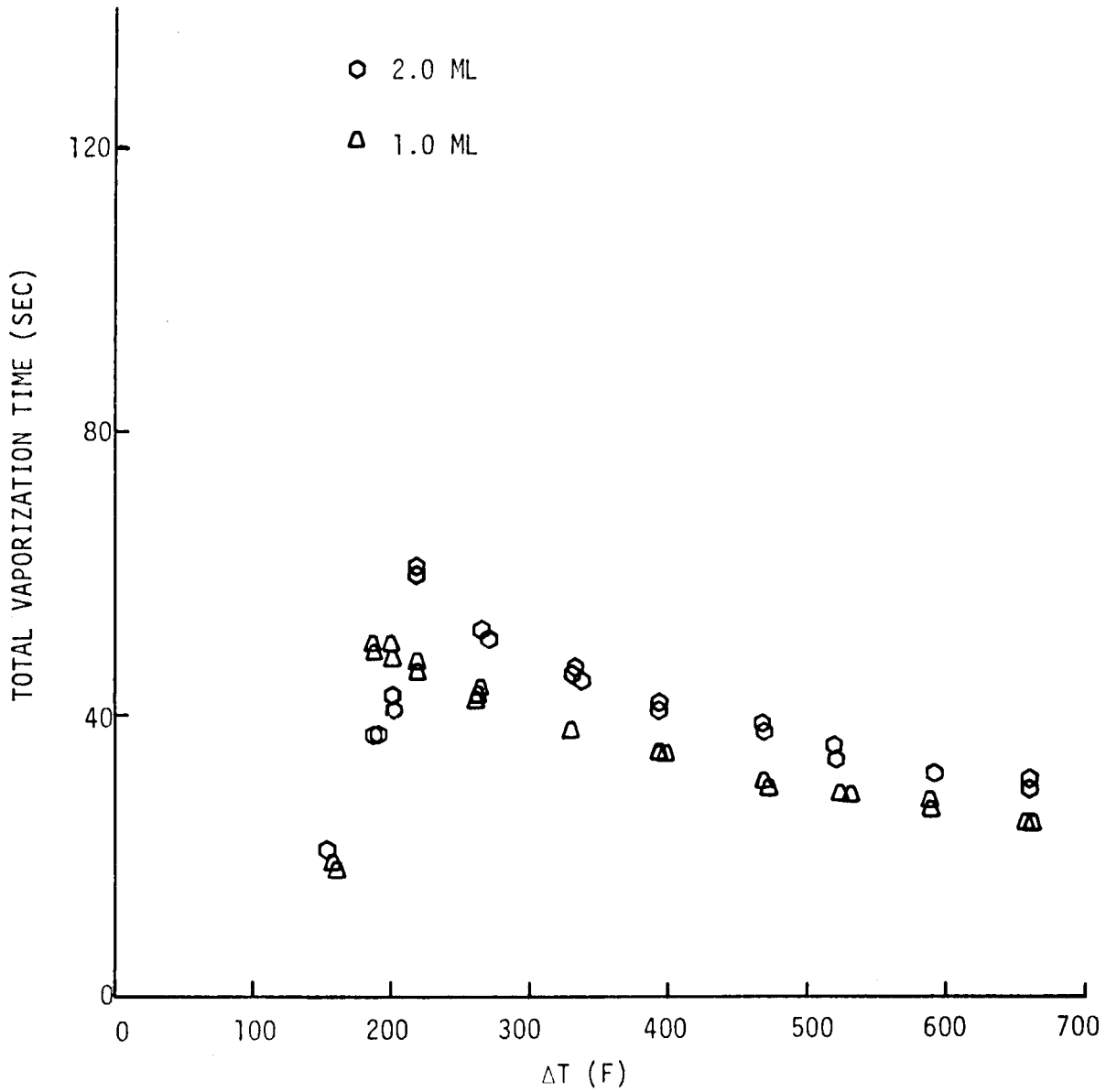


Figure A-10. Freon-114 boiling on surface with cylindrical pins at $\lambda_D/4$.

APPENDIX B

COMPUTER CODE LISTING

```
C***  THIS CODE READS EXPERIMENTAL FILM BOILING DATA (VAPORIZATION
C     TIME AS A FUNCTION OF DELTA T ) CALCULATES LINEAR AND POWER
C     CURVE FIT COEFFICIENTS, CALCULATES DIMENSIONLESS DROP VOLUME
C     AND DIMENSIONLESS VAPORIZATION TIME, CALCULATES PARAMETERS TO
C     CORRELATE DATA FROM DIFFERENT BOILING SURFACES
C
      COMMON/DATAIN/SURF(36),          VOL(36),DELT(36,100),TIME(36,100)
     1,TMIN(36,100),M(36),N,FLUID(36,3),TLF(36),SPH(36)
      COMMON/DATOUT/AO(36),A1(36),RL(36),A(36),B(36),RP(36),
     1TWALL(36,100),DELTS(36,100),IPCODE(36)
      COMMON/PROP/TSAT(36),PSA,THTA,TEFF,RADIUS
C
C     IPCODE(I)=1,SMOOTH SURFACE
C     IPCODE(I)=11,SURFACE WITH CYLINDRICAL PINS AT (MOST DANGEROUS
C                  WAVELENGTH) FOR FREON 11
C     IPCODE(I)=12,SURFACE WITH CYLINDRICAL PINS AT (MOST DANGEROUS
C                  WAVELENGTH)/2 FOR FREON 11
C     IPCODE(I)=13,SURFACE WITH CYLINDRICAL PINS AT (MOST DANGEROUS
C                  WAVELENGTH)/3 FOR FREON 11
C     IPCODE(I)=14,SURFACE WITH CYLINDRICAL PINS AT (MOST DANGEROUS
C                  WAVELENGTH)/4 FOR FREON 11
C     IPCODE(I)=2,SURFACE WITH CONCENTRIC GROOVES
C
C***  READ RUN CONTROL PARAMETERS (N=NO. SURFACE/FLUID/VOLUME
C     COMBINATIONS , M=NO. DATA POINTS FOR EACH COMBINATION
C     ICURVE=1 CURVE FIT DATA, ICURR=1 CALCULATE CORRELATION
C     PARAMETERS AND DIMENSIONLESS DROP VOLUME AND VAPORIZATION TIME)
C
      READ(5,10)N,ICURVE,IDLESS,ICURR,IDATA
      WRITE(6,40)N,ICURVE,IDLESS,ICURR,IDATA
      WRITE(6,41)
C
C     READ SURFACE/FLUID/VOLUME COMBINATIONS AND DATA POINTS FOR
C     EACH COMBINATION
C
      DO 100 I=1,N
      READ(1,20)SURF(I),(FLUID(I,J),J=1,3),VOL(I),TSAT(I),M(I),TLF(I),
     1SPH(I),IPCODE(I)
      K=M(I)
      DO 100 J=1,K
      READ(1,30)DELT(I,J),TIME(I,J),TMIN(I,J)
      TWALL(I,J)=DELT(I,J)+TSAT(I)
      DELTS(I,J)=TWALL(I,J)-TMIN(I,J)
  100 CONTINUE
      IF(IDATA.EQ.0)GOTO151
      DO 150 I=1,N
      WRITE(6,50)SURF(I),(FLUID(I,J),J=1,3),M(I)
      WRITE(6,60)
      K=M(I)
      DO 150 J=1,K
      WRITE(6,70)VOL(I),TWALL(I,J),DELT(I,J),TMIN(I,J),DELTS(I,J),
     1TIME(I,J)
  150 CONTINUE
  151 CONTINUE
C
C***  CALL CURVE FOR CALCULATION OF CURVE FIT COEFFICIENTS
      IF(ICURVE.EQ.0)GO TO200
```

```
      CALL CURVE
      WRITE(6,79)
      WRITE(6,80)
      WRITE(6,81)(SURF(I),(FLUID(I,J),J=1,3),VOL(I),A0(I),A1(I),RL(I),I=
     11,N)
      WRITE(6,79)
      WRITE(6,82)
      WRITE(6,81)(SURF(I),(FLUID(I,J),J=1,3),VOL(I),A(I),B(I),RP(I),I=1,
     1N)
  200 CONTINUE
C
C     CALL CORR FOR CALCULATION OF CORRELATION PARAMETERS AND
C     DIMENSIONLESS  DROP VOLUME AND VAPORIZATION TIME
      IF(ICORR.EQ.0)GOTO300
      CALL CORR
  300 CONTINUE
   10 FORMAT(5I5)
   20 FORMAT(A4,3A4,4X,2E10.6,I5,5X,E10.6,E10.6,I5)
   30 FORMAT(3E10.6)
   40 FORMAT(1H1,50X,22HRUN CONTROL PARAMETERS,/,46X,1HN,4X,6HCURVE,4X,
     16HIDLESS,4X,5HICORR,4X,5HIDATA,/,43X,I5,2X,I5,5X,I5,4X,I5,4X,I5)
   41 FORMAT(///,48X,29HKEY TO SURFACE CONFIGURATIONS,/,53X,12HS      SMO
     1OTH,/,53X,33HCG01  CONCENTRIC GROOVES-.010 IN.,/,53X,33HCG02  CONC
     2ENTRIC GROOVES-.020 IN.,/,53X,31HCP52  CYLINDRICAL PINS-LAMBDA/2,
     3/,53X,31HCP54  CYLINDRICAL PINS-LAMBDA/4)
   50 FORMAT(/,50X,7HSURFACE,4X,5HFLUID,4X,11HDATA POINTS,/,51X,A4,3X,
     13A4,3X,I5)
   60 FORMAT(/,12X,13HLIQUID VOLUME,8X,5HTWALL,8X,10HTWALL-TSAT,8X,13HTW
     1ALL MINIMUM,8X,11HDELTA TWALL,8X,17HVAPORIZATION TIME,/,16X,5H(CM3
     2),13X,3H(F),12X,3H(F),16X,3H(F),18X,3H(F),19X,5H(SEC),/)
   70 FORMAT(13X,F10.6,7X,F10.6,6X,F10.6,9X,F10.6,10X,F10.6,12X,F10.6)
   79 FORMAT(1H1)
   80 FORMAT(//,40X,51HLINEAR CURVE FIT COEFFICIENTS OF THE FORM  Y=A0+A
     11X,/,30X,7HSURFACE,8X,5HFLUID,8X,6HVOLUME,8X,2HA0,8X,2HA1,8X,23HCO
     2EFF. OF DETERMINATION)
   81 FORMAT(/,32X,A4,5X,3A4,3X,F6.2,5X,F10.3,3X,F6.4,10X,F6.4)
   82 FORMAT(//,40X,49HPOWER CURVE FIT COEFFICIENTS OF THE FORM  Y=AX**B
     1,/,30X,7HSURFACE,8X,5HFLUID,8X,6HVOLUME,8X,2HA ,8X,2HB ,8X,23HCOEF
     2F. OF DETERMINATION)
  400 CONTINUE
      STOP
      END
```

```
      SUBROUTINE CURVE
C***  THIS SUBROUTINE CALCULATES LINEAR AND POWER CURVE FIT COEFFICIENTS
C     USING THE METHOD OF LEAST SQUARES
C
      COMMON/DATAIN/SURF(36),          VOL(36),DELT(36,100),TIME(36,100)
     1,TMIN(36,100),M(36),N,FLUID(36,3),TLF(36),SPH(36)
      COMMON/DATOUT/AO(36),AL(36),RL(36),A(36),B(36),RP(36),
     1TWALL(36,100),DELTS(36,100),IPCODE(36)
C
C***  CALCULATE LINEAR CURVE FIT COEFFICIENTS
C
      DO 100 I=1,N
      K=M(I)
      RK=K
      SUMX=0.
      SUMY=0.
      SUMXY=0.
      SUMX2=0.
      SUMY2=0.
      DO 200 J=1,K
      SUMX=SUMX+DELT(I,J)
      SUMY=SUMY+TIME(I,J)
      SUMXY=SUMXY+(TIME(I,J)*DELT(I,J))
      SUMX2=SUMX2+DELT(I,J)**2
      SUMY2=SUMY2+TIME(I,J)**2
  200 CONTINUE
      XBAR=SUMX/RK
      YBAR=SUMY/RK
      C1=SUMX*SUMY/RK
      C2=SUMX**2/RK
      C3=SUMY**2/RK
      AL(I)=(SUMXY-C1)/(SUMX2-C2)
      AO(I)=YBAR-AL(I)*XBAR
      RL(I)=(SUMXY-C1)**2/((SUMX2-C2)*(SUMY2-C3))
  100 CONTINUE
C
C***  CALCULATE POWER CURVE FIT COEFFICIENTS
C
      DO 300 I=1,N
      K=M(I)
      RK=K
      SUMX=0.
      SUMY=0.
      SUMXY=0.
      SUMX2=0.
      SUMY2=0.
      DO 400 J=1,K
      SUMX=SUMX+ALOG(DELT(I,J))
      SUMY=SUMY+ALOG(TIME(I,J))
      SUMXY=SUMXY+ALOG(DELT(I,J))*ALOG(TIME(I,J))
      SUMX2=SUMX2+ALOG(DELT(I,J))**2
      SUMY2=SUMY2+ALOG(TIME(I,J))**2
  400 CONTINUE
      C1=SUMX*SUMY/RK
      C2=SUMX**2/RK
      C3=SUMY**2/RK
      B(I)=(SUMXY-C1)/(SUMX2-C2)
```

```
      A(I)=EXP(SUMY/RK-B(I)*SUMX/RK)
      RP(I)=(SUMXY-C1)*2/((SUMX2-C2)*(SUMY2-C3))
300   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CORR
      COMMON/DATAIN/SURF(36),          VOL(36),DELT(36,100),TIME(36,100)
     1,TMIN(36,100),M(36),N,FLUID(36,3),TLF(36),SPH(36)
      COMMON/DATOUT/A0(36),A1(36),EL(36),A(36),B(36),RP(36),
     1TWALL(36,100),DELTS(36,100),IPCODE(36)
      COMMON /CORLAT/HTAREA,DROPTH,DROPRD,VLTH,HTC,BOND
      COMMON/PROP/TSAT(36),PSA,THTA,TEFF,RADIUS
      DIMENSION COR1(36,50),COR2(36,50),COR3(36,50)
      DIMENSION VTIME(36,50)
C
C     INITIALIZE PARAMETERS
C
      TEMP=0.0
      DELTAT=50.0
      WRITE(6,96)
      WRITE(6,98)
      WRITE(6,97)
      DO 70 I=1,N
      PSA=0.0
      K=0
      IDML=I
      SPHP=SPH(I)
      IF(SPHP.EQ.1.0)SPHP=0.0
      WRITE(6,96)
      WRITE(6,99)SURF(I),(FLUID(I,J),J=1,3),VOL(I),TLF(I),SPHP
      WRITE(6,100)
      WRITE(6,101)
      WRITE(6,102)
      IF(TLF(I).LT.500.0)TEMP=450.0
      IF(TLF(I).LT.400.0)TEMP=350.0
      IF(TLF(I).LT.300.0)TEMP=250.0
      IF(TLF(I).LT.200.0)TEMP=150.
 20   CONTINUE
      K=K+1
      MNR=0
C***  CALCULATE THE VAPORIZATION TIME FOR TEMP FROM BEST
C     CURVE FIT COEFFICIENTS
      IF(RP(I).GT.RL(I))GOTO30
      VTIME(I,K)=A0(I)+A1(I)*TEMP
      DTIME=VTIME(I,K)
      GOTO40
 30   VTIME(I,K)=A(I)*TEMP**B(I)
      DTIME=VTIME(I,K)
 40   CONTINUE
      CALL DMLESS(DTIME,IDML,VSTAR,TSTAR,TEMP,DELCC,DELCB)
      COR1(I,K)=TEFF
      COR2(I,K)=TSTAR*(1.+DELCB/SPH(I))
      COR3(I,K)=TSTAR*(1.0+PSA/HTAREA)
      IF(IPCODE(I).EQ.2)COR3(I,K)=TSTAR*(1.0+PSA/(3.14159*RADIUS**2.0))
      HFLUX=HTC*TEMP
      WRITE(6,103)TEMP,DTIME,TSTAR,VSTAR,COR1(I,K),BOND      ,COR3(I,K),
     1 VLTH
      TEMP=TEMP+DELTAT
      IF(TEMP.LT.750.)GOTO20
      WRITE(6,104)PSA,THTA,DROPRD,DROPTH,MNR
 70   CONTINUE
 96   FORMAT(1H1)
```

```
 97   FORMAT(//,30X,70HCORRELATION PARAMETER,COR1=(DIMENSIONLESS VAPORIZ
     1ATION TIME)*(1.+RATIO,/,58X,44HOF VAPOR LAYER THICKNESS TO SURFACE
     2          ,/,58X,18HPROJECTION HEIGHT),/,30X,70HCORRELATION PARAMET
     3ER,COR2=(DIMENSIONLESS VAPORIZATION TIME)*(1.+RATIO,/,58X,46HOF BE
     4RENSON'S CRITICAL FILM THICKNESS TO SURFACE,/,58X,18HPROJECTION HE
     5IGHT)/,30X,72HCORRELATION PARAMETER,COR3=(DIMENSIONLESS VAPORIZATI
     6ON TIME) MODIFIED BY,/,58X,23HPROJECTION SURFACE AREA)
 98   FORMAT(////,20X,76HDIMENSIONLESS VAPORIZATION TIMES AND DROP VOLUM
     1ES AND CORRELATION PARAMETERS)
 99   FORMAT(//,10X,7HSURFACE,8X,5HFLUID,8X,6HVOLUME,8X,17HLEIDENFROST T
     1EMPS,8X,25HSURFACE PROJECTION HEIGHT,/,39X,5H(CM3),15X,3H(F),25X,
     24H(FT),/,12X,A4,8X,3A4,3X,F5.2,10X,F10.2,20X,F10.6)
100   FORMAT(/,10X,10HWALL-SAT,4X,12HVAPORIZATION,4X,13HDIMENSIONLESS,
     14X,13HDIMENSIONLESS,6X,4HCOR1,7X,4HBOND,8X,4HCOR3,4X,11HVAPOR LAYE
     2R)
101   FORMAT(28X,4HTIME,8X,12HVAPORIZATION,5X,11HDROP VOLUME,19X,3HNO.,2
     11X,4H(FT))
102   FORMAT(28X,5H(SEC),12X,4HTIME)
103   FORMAT(/,10X,F10.3,4X,F10.3,6X,F10.3,6X,F10.3,4X,F10.3,2X,F10.3,
     12X,F10.3,2X,F10.6,5X,F10.3)
104   FORMAT(///,10X,24HPROJECTION SURFACE AREA=,E15.6,2X,3HFT2,/,10X,
     119HHEAT TRANSFER AREA=,E15.6,2X,3HFT2,/,10X,12HDROP RADIUS=,E15.6,
     22X,2HFT,/,10X,15HDROP THICKNESS=,E15.6,2X,2HFT,/,10X,
     323HNO. CONCENTRIC GROOVES=,I5)
      RETURN
      END
```

```
      SUBROUTINE DMLESS(TIME,I,VSTAR,TSTAR,TEMP,DELCC,DELCB)
C     DIMENSIONLESS VAPORIZATION TIME VS DIMENSIONLESS VOLUME
C     TOTAL VAPORIZATION TIMES UNCORRECTED FOR RADIATION OR CONVECTION
C     LIQUID VOLUMES CALCULATED FROM BAUMEISTER APPROXIMATIONS
C     DENSITY(LBM/FT3)-CP(BTU/LBM.R)-HEAT OF VAPORIZATION(BTU/LBM)
C     SURFACE TENSION(LBF/FT)-VISCOSITY(LBM/FT.SEC)-
C     THERMAL CONDUCTIVITY(BTU/SEC.FT.R)-GC(FT.LBM/LBF.SEC2)
C     GRAV(FT/SEC2)
      COMMON/DATAIN/SURF(36),          VOL(36),DEL1(36,100),TDUM(36,100)
     1,TMIN(36,100),M(36),N,FLUID(36,3),TLF(36),SPH(36)
      COMMON/DATOUT/AO(36),AL(36),RL(36),AP(36),BP(36),EP(36),
     1TWALL(36,100),DELTS(36,100),IPCODE(36)
      COMMON/PROP/TSAT(36),PSA,THTA,TEFF,RADIUS
      COMMON /GEOPLAT/HTAREA,DROPTH,DROPRD,VLTH,HTC,BOIL
      DIMENSION CDVW(20),RHOVW(20),VISW(20),CPW(20),TPROP(20)
      DIMENSION CDVF1(20),RHOVF1(20),VISF1(20),CPF1(20),TPROP1(20)
      DIMENSION CDVF4(20),RHOVF4(20),VISF4(20),CPF4(20),TPROP4(20)
C***  WATER-DENSITY AND SPECIFIC HEAT AS FUNCTIONS OF TEMPERATURE
      DATA RHOVW/.0506,.0481,.0459,.0438,.0419,.0402,.0386
     1,.0372,.0358,.0345,.0334,.0323,.0312,.0303,.0294,.0285,.0277,
     2.0269,.0262,.0255/,CPW/.4561,.4513,.4478,.4454,.4439,
     3.443,.4428,.4431,.4438,.4449,.4463,.4479,.4498,.4518,.454,
     4.4563,.4587,.4611,.4637,.4663/
C***  WATER-THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE
      DATA CDVW/2.305E-06,2.472E-06,2.666E-06,2.805E-06,2.972E-06,
     13.166E-06,3.333E-06,3.5E-06,3.694E-06,3.861E-06,4.027E-06,
     24.222E-06,4.416E-06,4.555E-06,4.777E-06,4.972E-06,5.166E-06,
     35.389E-06,5.611E-06,5.833E-06/
C***  WATER-VISCOSITY AS A FUNCTION OF TEMPERATURE
      DATA VISW/8.618E-06,8.618E-06,8.618E-06,8.618E-06,
     28.618E-06,8.618E-06,8.618E-06,8.618E-06,8.618E-06,8.972E-06,
     39.327E-06,9.682E-06,1.003E-05,1.039E-05,1.074E-05,1.11E-05,
     41.146E-05,1.182E-05,1.218E-05,1.254E-05/
C***  FREON 11-DENSITY AS A FUNCTION OF TEMPERATURE
      DATA RHOVF1/.3858,.3608,.3497,.334,.3197,.3066,.2945,.2833,
     1.273,.2634,.2544,.246,.2382,.2308,.2239,.2174,.2112,.2054,.1999,
     2.1947/
C***  FREON 11-SPECIFIC HEAT AS A FUNCTOON OF TEMPERATURE
      DATA CPF1/.134,.137,.139,.141,.143,.144,.146,.148,.149,.151,
     1.152,.153,.155,.156,.157,.158,.1585,.159,.1595,.160/
C***  FREON 11-THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE
      DATA CDVF1/1.222E-06,1.278E-06,1.333E-06,1.416E-06,1.5E-06,
     11.583E-06,1.666E-06,1.778E-06,1.861E-06,1.944E-06,2.0E-06,
     22.111E-06,2.194E-06,2.305E-06,2.416E-06,2.528E-06,2.722E-06,
     32.916E-06,3.264E-06,3.611E-06/
C***  FREON 11-VISCOSITY AS A FUNCTION OF TEMPERATURE
      DATA VISF1/6.611E-06,7.361E-06,7.889E-06,8.25E-06,8.528E-06,
     18.722E-06,8.861E-06,9.0E-06,9.194E-06,9.444E-06,9.833E-06,
     21.036E-05,1.108E-05,1.208E-05,1.333E-05,1.472E-05,1.569E-05,
     31.666E-05,1.958E-05,2.25E-05/
C***  FREON 114-DENSITY AS A FUNCTION OF TEMPERATURE
      DATA RHOVF4/.48,.4364,.435,.4156,.3815,.366,.3525,
     1.3396,.3277,.3165,.3061,.2963,.2872,.2785,.2704,.2628,.2556,
     2.2487,.2422/
C***  FREON 114-SPECIFIC HEAT AS A FUNCTION OF TEMPERATURE
      DATA CPF4/.161,.166,.171,.175,.179,.184,.19,.197,.207,.218,
     1.233,.256,.275,.302,.336,.361,.385,.385,.385,.385/
```

```
C***  FREON 114-VISCOSITY AS A FUNCTION OF TEMPERATURE
      DATA VISF4/8.805E-06,7.222E-06,7.503E-06,7.801E-06,8.111E-06,
     18.361E-06,8.639E-06,8.972E-06,9.361E-06,9.861E-06,1.055E-05,
     21.139E-05,1.166E-05,1.222E-05,1.278E-05,1.305E-05,1.333E-05,
     31.444E-05,1.555E-05,2.083E-05/
C***  FREON 114-THERMAL CONDUCTIVITY AS A FUNCTION OF TEMPERATURE
      DATA CDVF4/1.52E-06,1.6E-06,1.68E-06,1.76E-06,1.85E-06,
     11.94E-06,2.02E-06,2.11E-06,2.2E-06,2.29E-06,2.38E-06,2.47E-06,
     22.52E-06,2.56E-06,2.61E-06,2.64E-06,2.66E-06,2.68E-06,
     32.7E-06,2.73E-06/
C***  CORRESPONDING TEMPERATURES FOR WATER DATA AND FREON 11, FREON 114
C     DENSITY DATA
      DATA TPROP/484.,509.,534.,559.,584.,609.,634.,659.,684.,709.,734.,
     1759.,784.,809.,834.,859.,884.,909.,934.,959./
C***  FREON 11-CORRESPONDING TEMPERATURES FOR SPECIFIC HEAT,VISCOSITY,
C     THERMAL CONDUCTIVITY
      DATA TPROP1/520.,540.,560.,580.,600.,620.,640.,660.,680.,
     1700.,720.,740.,760.,780.,800.,820.,830.,840.,844.,848./
C***  FREON 114-CORRESPONDING TEMPERATURES FOR SPECIFIC HEAT,VISCOSITY,
C     THERMAL CONDUCTIVITY
      DATA TPROP4/480.,500.,520.,540.,560.,580.,600.,620.,640.,660.,
     1680.,700.,710.,720.,730.,735.,740.,745.,750.,754./
      ICONDV=20
      ICP=20
      IRHOV=20
      IVIS=20
      GC=32.174
      GRAV=32.174
      I=1.0
      TSATR=TSAT(I)+459.
      TFILM=(TEMP+2.0*TSATR)/2.0
      IF(TSAT(I).EQ.210.0)GO TO 10
      IF(TSAT(I).EQ.72.5)GOTO20
      RHOL=90.895
      SIGMA=0.000747
      ALAM=58.52
      IFL=3
      CALL VALUE(TPROP4,CPF4,ICP,TFILM,CPA)
      CALL VALUE(TPROP ,RHOVF4,IRHOV,TFILM,RHOVA)
      CALL VALUE(TPROP4,VISF4,IVIS,TFILM,VISA)
      CALL VALUE(TPROP4,CDVF4,ICONDV,TFILM,CONDVA)
      IF(TFILM.GT.TPROP4(20))WRITE(6,100)TFILM
      GOTO30
 10   RHOL=59.8297
      SIGMA=0.00403
      ALAM=970.3
      IFL=1
      CALL VALUE(TPROP,CPW,ICP,TFILM,CPA)
      CALL VALUE(TPROP ,RHOVW,IRHOV,TFILM,RHOVA)
      CALL VALUE(TPROP,VISW,IVIS,TFILM,VISA)
      CALL VALUE(TPROP,CDVW,ICONDV,TFILM,CONDVA)
      IF(TFILM.GT.TPROP(20))WRITE(6,100)TFILM
      GOTO30
 20   RHOL=91.581
      SIGMA=0.00123
      ALAM=77.59
      IFL=2
```

```
      CALL VALUE(TPROP1,CPFI,ICP,TFILM,CPA)
      CALL VALUE(TEMP ,RHOVFI,IRHOV,TFILM,RHOVA)
      CALL VALUE(TPROP1,VISFI,IVIS,TFILM,VISA)
      CALL VALUE(TPROP1,CONVFI,ICONDV,TFILM,CONDVA)
      IF(TFILM.GT.TPROP1(20))WRITE(6,100)TFILM
   30 CONTINUE
C
C     CALCULATE DIMENSIONLESS DROP VOLUME AND VAPORIZATION TIME
C
      VOLUME=VOL(I)*0.3531E-04
      STLAM=(ALAM)/(1.+(0.35)*(CPA)*(TEMP)/(ALAM))**3.0
      A=(GC**2.5)*(RHOL**.5)*VISA*(ALAM**4.)*(SIGMA**2.5)
      B=(CONDVA**3.)*(GRAV**3.5)*STLAM*RHOVA*(TEMP**3.0)
      TSTAR=TIME/(E*(A/B)**.25)
      VSTAR=VOLUME/((GC*SIGMA)/(RHOL*GRAV))**1.5
C
C     CALCULATE CRITICAL VAPOR FILM THICKNESS FOR WAVE INSTABILITY
C
C     MODEL OF CHANG
      DELRHO=RHOL-RHOVA
      ALPHAC=(CONDVA*TEMP)/(2.0*ALAM*RHOVA)
      PISQ=3.14159**2.0
      DELCC=((8.0*PISQ*VISA*ALPHAC)/(GC*DELRHO))**0.333
C     MODEL OF BERENSON
      SQROOT=((SIGMA*GC)/(GC*DELRHO))**0.5
      DELCB=2.35*((VISA*CONDVA*TEMP*SQROOT)/(ALAM*RHOVA*GC*DELRHO))**.25
C
C     CALCULATE AVG, DROP THICKNESS, EFFECTIVE HEAT TRANSFER
C     AREA AND HEAT TRANSFER COEFFICIENT
C
      FACTOR=((GC*SIGMA)/(RHOL*GRAV))*929.03
      IF(VSTAR.GT.155.)GOTO50
      IF(VSTAR.GT.0.8.AND.VSTAR.LT.155.)GOTO40
C
C     SMALL DROP DOMAIN
      DROPTH=0.83*VOL(I)**0.333
      HTAREA=1.5*VOL(I)**0.666*(3.*SQRT(3.14159)/4.)**0.666
      FNUM=STLAM*GC*RHOL*RHOVA*CONDVA**3.0
      FDENOM=TEMP*VISA*VOLUME**0.33
      HTC=1.1*(FNUM/FDENOM)**0.25
      GOTO60
C
C     LARGE DROP DOMAIN
   40 CONTINUE
      DROPTH=0.8*VOL(I)**0.1666*FACTOR**0.25
      HTAREA=1.25*VOL(I)**0.8333/FACTOR**0.25
      FNUM=STLAM*SQRT(GRAV)*SQRT(RHOL)*SQRT(RHOVA)*SQRT(SIGMA)*
     1SQRT(GC)*CONDVA**3.0
      FDENOM=TEMP*VISA*VOLUME**0.666
      HTC=1.075*(FNUM/FDENOM)**0.25
      GOTO60
C
C     EXTENDED DROP DOMAIN
   50 CONTINUE
      DROPTH=1.85*FACTOR**0.5
      HTAREA=0.54*VOL(I)/FACTOR**0.5
      FNUM=STLAM*RHOVA*SIGMA*GC*CONDVA**3.0
```

```
      FDENOM=TEMP*VISA*VOLUME
      HTC=1.64*(FNUM/FDENOM)**0.25
   60 CONTINUE
      DROPTH=DROPTH/30.48
      HTAREA=HTAREA/929.03
      DROPRD=SQRT(VOLUME/(3.14159*DROPTH))
C
C     CALCULATE VAPOR LAYER THICKNESS
C
      FNUM=3.0*3.14159*CONDVA*TEMP*VISA*DROPRD**4.0
      FDENOM=2.0*RHOVA*RHOL*GC*STEAM*VOLUME
      VLTH=(FNUM/FDENOM)**0.25
      HTC=HTC*3600.0
C
C     CALCULATE BOND NO. BASED ON DROP DIAMETER
C
C     SMOOTH SURFACE
      DIAM=2.0*DROPRD
      BOND=(DIAM*DIAM)*GRAV*(RHOL-RHOVA)/(GC*SIGMA)
      IF(IPCODE(I).EQ.1)GOTO61
C     SURFACE WITH CYLINDRICAL PINS- CALCULATE PARAMETER
C     TO BE USED IN CORR TO CALCULATE BOND NUMBER
      BOND=(RHOL*DIAM*DIAM*GRAV*DROPTH)/(SIGMA*GC)
   61 CONTINUE
      PDIA=0.062/12.0
      PLA=3.14159*(.125)**2.0
      HTA=HTAREA
C
C     CALCULATE PROJECTION SURFACE AREA
C
      DAREA=3.14159*DROPRD**2
      IF(IPCODE(I).EQ.1)GOTO90
      IF(IPCODE(I).EQ.2)GOTO80
C     SURFACE WITH CYLINDRICAL PINS
      IF(IPCODE(I).EQ.11)PIN=44.0
      IF(IPCODE(I).EQ.12)PIN=88.0
      IF(IPCODE(I).EQ.13)PIN=236.0
      IF(IPCODE(I).EQ.14)PIN=526.0
      PINA=PIN*(2.0*3.14159*(PDIA/2.0)*SPH(I)+3.14159*(PDIA/2.0)**2.0)
      PSA= DAREA*PINA/PLA
      HTA= DAREA+PSA-(3.14159*(PDIA/2.0)**2.0)*PIN* DAREA/PLA
      PRAD=PDIA/2.0
      PINNUM=PSA/(2.0*3.14159*PRAD*SPH(I)+3.14159*PRAD**2.0)
      BOND=BOND/(2.0*PRAD*PINNUM)
      GOTO90
C     SURFACE WITH CONCENTRIC GROOVES
   80 CONTINUE
      RADIUS=.025/12.0
      SQR2=SQRT(2.0)
      SQR3=SQRT(3.0)
      DELRAD=2.0*SPH(I)
      PSA=3.14159*(RADIUS)**2.0
      PIN=RADIUS
      RADIUS=RADIUS+SPH(I)
      RSLOPE=(PIN+RADIUS)/2.0
      PSA=PSA+(2.0*3.14159*RSLOPE)*2.0*SQR2*SPH(I)
      NRING=(DROPRD-RADIUS)/DELRAD
```

```
      MNR=NRING
      MNR=MNR+1
      DO 85 J=2,MNR
      RIN=RADIUS*SPH(I)
      RADIUS=RADIUS+DELRAD
      RSLOPE=(RIN+RADIUS)/2.0
 85   PSA=PSA+4.0*3.14159*SPH(I)*SQR2*RSLOPE
      THEA=PSA
 90   CONTINUE
C
C     MODIFIED TSTAR (TEFF) BASED ON INCREASED H.T. AREA
C
      IF(IPCODE(I).EQ.2.OR.IPCODE(I).EQ.1)GOTO64
      C5=3.14159*(PIN/PLA)*(PDIA/2.0)**2.0
      DENOM=1.0-C5+(PINA/PLA)
      IF(VSTAR.GT.155.)GOTO63
      IF(VSTAR.GT.0.8.AND.VSTAR.LT.155.)GOTO62
C
C     SMALL DROP DOMAIN
      TEFF=TSTAR*DENOM
      GOTO64
 62   CONTINUE
C
C     LARGE DROP DOMAIN
C
      TEFF=TSTAR*DENOM
      GOTO64
 63   CONTINUE
C
C     EXTENDED DROP DOMAIN
      TEFF=TSTAR*DENOM
 64   CONTINUE
      IF(IPCODE(I).EQ.1)TEFF=1.0
      IF(IPCODE(I).EQ.2)TEFF=TSTAR*PSA/DAREA
 100  FORMAT(5X,5H*****,E15.6,2X,1HR,3X,29HOUTSIDE RANGE OF KNOWN VALUES
     1)
 200  RETURN
      END
```

```
      SUBROUTINE VALUE(X,G,IG,XA,GA)
      DIMENSION G(20),X(20)
      XX1=XA-X(1)
      IF(XX1.NE.0.0)GOTO100
      GA=G(1)
      GOTO102
100   DO 105 K=2,IG
      XX2=XA-X(K)
      IF(XX2.LT.0.0)GOTO106
      GOTO105
106   I=K
      IF(XX2.EQ.0.0)GOTO104
      GOTO103
105   CONTINUE
      GA=G(IG)
      RETURN
104   GA=G(I)
      GOTO102
103   SLPE=(G(I)-G(I-1))/(X(I)-X(I-1))
      GA=SLPE*(XA-X(I-1))+G(I-1)
102   RETURN
      END
```

APPENDIX C

COMPUTER CODE OUTPUT

RUN CONTROL PARAMETERS

N	ICURVE	IDLESS	ICORR	IDATA
26	1	0	1	0

KEY TO SURFACE CONFIGURATIONS

S	SMOOTH
CG01	CONCENTRIC GROOVES-.010 IN.
CG02	CONCENTRIC GROOVES-.020 IN.
CP52	CYLINDRICAL PINS-LAMBDA/2
CP54	CYLINDRICAL PINS-LAMBDA/4

SURFACE	FLUID	VOLUME	LINEAR CURVE FIT COEFFICIENTS OF THE FORM Y=A0+A1X A0	A1	COEFF. OF DETERMINATION
S	WATER	1.00	550.088	-.4077	0.9281
CG01	WATER	1.00	291.871	-.1029	0.1486
CG02	WATER	1.00	370.277	-.2457	0.8452
S	WATER	0.50	430.064	-.3196	0.9560
CG01	WATER	0.50	216.478	-.0831	0.2141
CG02	WATER	0.50	350.557	-.2830	0.9803
S	FREON 11	2.00	206.422	-.2282	0.9396
CG01	FREON 11	2.00	101.239	-.0845	0.9702
CG02	FREON 11	2.00	102.470	-.0868	0.9429
CP52	FREON 11	2.00	158.706	-.1464	0.9682
CP54	FREON 11	2.00	95.013	-.0854	0.9305
S	FREON 11	1.00	160.983	-.1747	0.9341
CG01	FREON 11	1.00	83.569	-.0723	0.9497
CG02	FREON 11	1.00	84.287	-.0719	0.9245
CP52	FREON 11	1.00	136.473	-.1291	0.9654
CP54	FREON 11	1.00	78.461	-.0733	0.9116
S	FREON 114	2.00	158.376	-.1978	0.8814
CG01	FREON 114	2.00	76.482	-.0711	0.9437
CG02	FREON 114	2.00	78.983	-.0759	0.9478
CP52	FREON 114	2.00	108.006	-.1047	0.9410
CP54	FREON 114	2.00	64.425	-.0544	0.9612
S	FREON 114	1.00	125.649	-.1524	0.9066
CG01	FREON 114	1.00	60.242	-.0534	0.9293
CG02	FREON 114	1.00	64.764	-.0619	0.9321
CP52	FREON 114	1.00	89.815	-.0871	0.9557
CP54	FREON 114	1.00	56.776	-.0516	0.9567

SURFACE	POWER CURVE FIT COEFFICIENTS OF THE FORM Y=AX**B FLUID	VOLUME	A	B	COEFF. OF DETERMINATION
S	WATER	1.00	7668.781	-.5039	0.8565
CG01	WATER	1.00	954.466	-.2283	0.1318
CG02	WATER	1.00	9368.090	-.5865	0.8393
S	WATER	0.50	9031.629	-.5702	0.9174
CG01	WATER	0.50	930.816	-.2699	0.2082
CG02	WATER	0.50	35372.535	-.8272	0.9719
S	FREON 11	2.00	9379.629	-.7528	0.9794
CG01	FREON 11	2.00	1047.679	-.4682	0.9372
CG02	FREON 11	2.00	1696.538	-.5477	0.9870
CP52	FREON 11	2.00	6402.809	-.7025	0.9958
CP54	FREON 11	2.00	3955.279	-.7028	0.9845
S	FREON 11	1.00	5356.582	-.6966	0.9779
CG01	FREON 11	1.00	1261.793	-.5338	0.9619
CG02	FREON 11	1.00	1591.306	-.5705	0.9773
CP52	FREON 11	1.00	4674.773	-.6794	0.9935
CP54	FREON 11	1.00	3063.296	-.6991	0.9684
S	FREON 114	2.00	5215.398	-.7240	0.9962
CG01	FREON 114	2.00	795.941	-.4829	0.9627
CG02	FREON 114	2.00	1357.782	-.5723	0.9844
CP52	FREON 114	2.00	2662.452	-.6325	0.9931
CP54	FREON 114	2.00	1392.325	-.5980	0.9848
S	FREON 114	1.00	2374.334	-.6572	0.9830
CG01	FREON 114	1.00	536.893	-.4517	0.9645
CG02	FREON 114	1.00	1309.162	-.5533	0.9848
CP52	FREON 114	1.00	2117.106	-.6238	0.9910
CP54	FREON 114	1.00	963.362	-.5592	0.9888

DIMENSIONLESS VAPORIZATION TIMES AND DROP VOLUMES AND CORRELATION PARAMETERS

CORRELATION PARAMETER,COR1=(DIMENSIONLESS VAPORIZATION TIME)*(1.+RATIO
OF VAPOR LAYER THICKNESS TO SURFACE
PROJECTION HEIGHT)
CORRELATION PARAMETER,COR2=(DIMENSIONLESS VAPORIZATION TIME)*(1.+RATIO
OF BERENSON'S CRITICAL FILM THICKNESS TO SURFACE
PROJECTION HEIGHT)
CORRELATION PARAMETER,COR3=(DIMENSIONLESS VAPORIZATION TIME) MULTIPLIED BY
PROJECTION SURFACE AREA

SURFACE S	FLUID WATER	VOLUME (CM3) 1.00	LEIDENFROST IN-FS (FT) 300.00	SURFACE PROJECTION HEIGHT (FT) 0.0			
WALL-TEMP	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CORR	BOND NO.	CAP	VAPOR LAYER (FT)
350.000	407.405	6.058	63.873	1.000	50.819	6.058	0.000486
400.000	387.021	6.411	63.873	1.000	50.820	6.411	0.000476
450.000	366.638	6.693	63.873	1.000	50.821	6.693	0.000505
500.000	346.254	6.912	63.873	1.000	50.822	6.912	0.000535
550.000	325.871	7.055	63.873	1.000	50.822	7.055	0.000565
***** 0.950000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
600.000	305.488	7.080	63.873	1.000	50.822	7.080	0.000589
***** 0.999000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
650.000	285.104	6.977	63.873	1.000	50.822	6.977	0.000614
***** 0.1019 0E 04	R OUTSIDE RANGE OF KNOWN VALUES						
700.000	264.721	6.809	63.873	1.000	50.822	6.819	0.000619

PROJECTION SURFACE AREA= 0.0 FT2
HEAT TRANSFER AREA= 0.269018E-02 FT2
DROP RADIUS= 0.292607E-01 FT
DROP THICKNESS= 0.131274E-01 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TW-TS (F)	SURFACE PROJECTION HEIGHT (FT)
C601	WATER	1.00	400.00	0.000833

	TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CDR1	BOND NO.	CDR3	VAPOR LAYER (FT)
	450.000	245.559	4.483	63.873	5.942	0.667	11.015	0.000535
	500.000	240.413	4.799	63.873	6.361	0.667	11.793	0.000535
	550.000	235.267	5.093	63.873	6.751	0.667	12.515	0.000565
*****	0.990000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
	600.000	230.122	5.333	63.873	7.069	0.667	13.105	0.000589
*****	0.994000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
	650.000	224.976	5.505	63.873	7.297	0.667	13.528	0.000604
*****	0.199000E 04	R OUTSIDE RANGE OF KNOWN VALUES						
	700.000	219.830	5.655	63.873	7.495	0.667	13.895	0.000619

PROJECTION SURFACE AREA= 0.356528E-02 FT2
HEAT TRANSFER AREA= 0.356528E-02 FT2
DROP RADIUS= 0.292607E-01 FT
DROP THICKNESS= 0.131274E-01 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TWALS (F)	SURFACE PROJECTION HEIGHT (FT)			
CU2	WATER	1.00	420.00	0.031667			

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
450.000	259.714	4.741	63.873	6.117	0.667	11.879	0.000505
500.000	247.429	4.939	63.873	6.373	0.667	12.375	0.000535
550.000	235.144	5.091	63.873	6.568	0.667	12.754	0.000565
***** 0.969000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
600.000	222.859	5.165	63.873	6.664	0.667	12.941	0.000589
***** 0.999000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
650.000	210.575	5.153	63.873	6.648	0.667	12.910	0.000614
** * 0.101900E 04	R OUTSIDE RANGE OF KNOWN VALUES						
700.000	198.290	5.101	63.873	6.561	0.667	12.779	0.000619

PROJECTION SURFACE AREA= 0.347049E-02 FT2
HEAT TRANSFER AREA= 0.347049E-02 FT2
DROP RADIUS= 0.292607E-01 FT
DROP THICKNESS= 0.131274E-01 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TW-TS (F)	SURFACE PROJECTION HEIGHT (FT)
S	WATER	0.50	300.00	0.0

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
350.000	318.208	4.732	31.936	1.000	28.520	4.732	0.000397
400.000	302.229	5.007	31.936	1.000	28.521	5.007	0.000424
450.000	286.249	5.226	31.936	1.000	28.521	5.226	0.000450
500.000	270.270	5.395	31.936	1.000	28.521	5.395	0.000477
550.000	254.291	5.505	31.936	1.000	28.522	5.505	0.000503
0.969000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
600.000	238.311	5.523	31.936	1.000	28.522	5.523	0.000525
0.994000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
650.000	222.332	5.440	31.936	1.000	28.522	5.440	0.000538
0.101000E 04	R OUTSIDE RANGE OF KNOWN VALUES						
700.000	206.353	5.308	31.936	1.000	28.522	5.308	0.000552

PROJECTION SURFACE AREA= 0.0 FT2
HEAT TRANSFER AREA= 0.150963E-02 FT2
DROP RADIUS= 0.219202E-01 FT
DROP THICKNESS= 0.116957E-01 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TW-TS (F)	SURFACE PROJECTION HEIGHT (FT)
COPPER	WATER	0.50	400.00	0.000833

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CCR1	BOND NO.	CCR3	VAPOR LAYER (FT)
450.000	179.097	3.269	31.936	4.517	0.334	8.079	0.000450
500.000	174.944	3.493	31.936	4.825	0.334	8.630	0.000477
550.000	170.790	3.697	31.936	5.108	0.334	9.137	0.000503
***** 0.965000E 03	F OUTSIDE RANGE OF KNOWN VALUES						
600.000	166.637	3.862	31.936	5.336	0.334	9.544	0.000525
***** 0.974000E 03	F OUTSIDE RANGE OF KNOWN VALUES						
650.000	162.483	3.976	31.936	5.493	0.334	9.825	0.000538
***** 0.101700E 04	F OUTSIDE RANGE OF KNOWN VALUES						
700.000	158.330	4.073	31.936	5.627	0.334	10.064	0.000552

PROJECTION SURFACE AREA= 0.208546E-02 FT2
HEAT TRANSFER AREA= 0.208546E-02 FT2
DROP RADIUS= 0.219202E-01 FT
DROP THICKNESS= 0.116957E-01 FT
OF CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TEMP (F)	SURFACE PROJECTION HEIGHT (FT)
COPPER	WATER	0.50	420.00	0.001667

WALL-TEMP	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CURV	BOND NO.	CURV	VAPOR LAYER (FT)
450.000	223.196	4.074	31.936	5.435	0.334	10.337	0.000453
500.000	209.044	4.173	31.936	5.567	0.334	10.587	0.000477
550.000	194.893	4.219	31.936	5.628	0.334	10.704	0.000503
***** 0.969000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
600.000	180.742	4.169	31.936	5.568	0.334	10.628	0.000525
***** 0.994000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
650.000	166.591	4.076	31.936	5.438	0.334	10.343	0.000538
***** 0.101900E 04	R OUTSIDE RANGE OF KNOWN VALUES						
700.000	152.439	3.921	31.936	5.231	0.334	9.948	0.000552

PROJECTED SURFACE AREA= 0.201365E-02 FT2
HEAT TRANSFER AREA= 0.201365E-02 FT2
DROP RADIUS= 0.219202E-01 FT
DROP THICKNESS= 0.116957E-01 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CU.FT)	LEIDENFROST TEMPS (F)	SURFACE PROJECTION HEIGHT (FT)			
S	FREON 11	2.00	160.00	0.0			
WALL-SAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CORI	BOND NO.	CORJ	VAPOR LAYER (FT)
150.000	215.812	17.602	1434.738	1.000	984.134	17.602	0.000406
200.000	173.790	17.770	1434.738	1.000	984.265	17.770	0.000461
250.000	145.918	18.094	1434.738	1.000	984.387	18.094	0.000516
300.000	126.076	18.209	1434.738	1.000	984.499	18.209	0.000569
350.000	114.044	18.127	1434.738	1.000	984.603	18.127	0.000624
400.000	103.138	17.995	1434.738	1.000	984.701	17.995	0.000683
450.000	94.387	17.823	1434.738	1.000	984.792	17.823	0.000751
500.000	87.190	17.629	1434.738	1.000	984.877	17.629	0.000826
550.000	81.153	17.333	1434.738	1.000	984.957	17.333	0.000912
600.000	76.008	17.735	1434.738	1.000	985.032	17.735	0.001022
***** 0.85050E 03 R OUTSIDE RANGE OF KNOWN VALUES							
650.000	71.563	19.364	1434.738	1.000	985.103	19.364	0.001253
***** 0.86150E 03 R OUTSIDE RANGE OF KNOWN VALUES							
700.000	67.680	18.874	1434.738	1.000	985.170	18.874	0.001309

PROJECTION SURFACE AREA= 0.0 FT2
HEAT TRANSFER AREA= 0.1040712-01 FT2
DROP RADIUS= 0.5758098-01 FT
DROP THICKNESS= 0.6779878-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST (W-I'S (F)	SURFACE PROJECTION HEIGHT (FT)
COPPER	FREON 11	2.00	160.00	0.033853

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
150.000	68.569	7.224	1434.738	9.888	6.695	17.593	0.000416
200.000	84.346	8.624	1434.738	11.804	6.695	21.003	0.000461
250.000	80.122	9.868	1434.738	13.506	6.695	24.031	0.000516
300.000	75.899	10.791	1434.738	14.769	6.695	26.279	0.000569
350.000	71.676	11.393	1434.738	15.593	6.695	27.745	0.000624
400.000	67.452	11.769	1434.738	16.108	6.695	28.662	0.000683
450.000	63.229	11.939	1434.738	16.342	6.695	29.077	0.000750
500.000	59.006	11.930	1434.738	16.329	6.695	29.054	0.000826
550.000	54.782	11.701	1434.738	16.015	6.695	28.495	0.000912
600.000	50.559	11.797	1434.738	16.147	6.695	28.730	0.001022
***** 0.6553000E 03 R OUTSIDE RANGE OF KNOWN VALUES							
650.000	46.336	12.538	1434.738	17.161	6.695	30.534	0.001253
*** 0.8815000E 03 R OUTSIDE RANGE OF KNOWN VALUES							
700.000	42.112	11.744	1434.738	16.074	6.695	28.600	0.001309

PROJECTION SURFACE AREA= 0.142568E-01 FT2
HEAT TRANSFER AREA= 0.142568E-01 FT2
DROP RADIUS= 0.575809E-01 FT
DROP THICKNESS= 0.677987E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST Tw-Ts (F)	SURFACE PROJECTION HEIGHT (FT)			
C602	FREON 11	2.00	205.00	0.001667			
TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CGR1	BOND NO.	CGR3	VAPOR LAYER (FT)
250.000	82.469	10.157	1434.738	14.544	6.695	24.949	0.000516
300.000	74.632	10.610	1434.738	15.194	6.695	26.064	0.000569
350.000	68.590	10.902	1434.738	15.611	6.695	26.780	0.000624
400.000	63.753	11.123	1434.738	15.928	6.695	27.324	0.000683
450.000	59.770	11.286	1434.738	16.161	6.695	27.724	0.000750
500.000	56.419	11.407	1434.738	16.335	6.695	28.021	0.000826
550.000	53.549	11.497	1434.738	16.377	6.695	28.095	0.000912
600.000	51.057	11.913	1434.738	17.059	6.695	29.264	0.001022
**** 0.856500E 03 P OUTSIDE RANGE OF KNOWN VALUES							
650.000	48.868	13.223	1434.738	18.935	6.695	32.482	0.001253
**** 0.361500E 03 P OUTSIDE RANGE OF KNOWN VALUES							
700.000	46.924	13.085	1434.738	18.738	6.695	32.144	0.001309

PROJECTED SURFACE AREA= 0.149153E-01 FT2
HEAT TRANSFER AREA= 0.149153E-01 FT2
DROP RADIUS= 0.575809E-01 FT
DROP THICKNESS= 0.677987E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TWTS (F)	SURFACE PROJECTION HEIGHT (FT)			
COS2	FREON 11	2.00	250.00	0.004167			

SMALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
250.000	132.362	16.301	1434.738	18.278	69.392	18.893	0.000516
300.000	116.449	16.556	1434.738	18.563	69.392	19.188	0.000569
350.000	104.497	16.809	1434.738	18.623	69.392	19.250	0.000624
400.000	95.140	16.809	1434.738	16.613	69.392	19.239	0.000683
450.000	87.385	16.938	1434.738	18.544	69.392	19.167	0.000751
500.000	81.336	16.445	1434.738	16.439	69.392	19.060	0.000826
550.000	76.068	16.247	1434.738	18.217	69.392	18.830	0.000912
600.000	71.558	16.697	1434.738	18.721	69.392	19.351	0.001022
***** 0.656500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
650.000	67.645	16.304	1434.738	20.523	69.392	21.214	0.001253
***** 0.681500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
700.000	64.213	17.907	1434.738	20.078	69.392	20.754	0.001309

PROJECTION SURFACE AREA= 0.165445E-02 FT2
HEAT TRANSFER AREA= 0.116791E-01 FT2
DROP RADIUS= 0.575809E-01 FT
DROP THICKNESS= 0.677987E-02 FT
NO. CHARACTERISTIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TWALS (F)	SURFACE PROJECTION HEIGHT (FT)			
CPS+	FREON 11	2.00	275.00	0.004166			
TWALL-TEST	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CCM1	BOND NO.	CCR3	VAPOR LAYER (FT)
250.000	81.623	10.052	1434.738	17.364	11.565	19.639	0.000516
300.000	71.806	10.209	1434.738	17.634	11.565	19.945	0.000569
350.000	64.433	10.241	1434.738	17.690	11.565	20.008	0.000624
400.000	58.661	10.235	1434.738	17.680	11.565	19.996	0.000683
450.000	54.001	10.197	1434.738	17.613	11.565	19.921	0.000750
500.000	50.146	10.139	1434.738	17.514	11.565	19.808	0.000826
550.000	46.897	10.016	1434.738	17.302	11.565	19.569	0.000912
600.000	44.115	10.293	1434.738	17.780	11.565	20.110	0.001022
*****	0.856990E 03 R OUTSIDE RANGE OF KNOWN VALUES						
650.000	41.702	11.284	1434.738	19.491	11.565	22.045	0.001253
*****	0.861500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
700.000	39.585	11.039	1434.738	19.068	11.565	21.567	0.001309

PROJECTION SURFACE AREA= 0.992514E-02 FT2
HEAT TRANSFER AREA= 0.179923E-01 FT2
DROP RADIUS= 0.575809E-01 FT
DROP THICKNESS= 0.677987E-02 FT
NO. SCREENING GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TW-TS (F)	SURFACE PROJECTION HEIGHT (FT)			
S	FREON 11	1.00	160.00	0.0			
TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
150.000	163.353	13.324	717.369	1.000	492.067	13.324	0.000341
200.000	133.690	13.669	717.369	1.000	492.133	13.669	0.000387
250.000	114.445	14.095	717.369	1.000	492.193	14.095	0.000434
300.000	100.796	14.330	717.369	1.000	492.249	14.330	0.000479
350.000	90.534	14.390	717.369	1.000	492.302	14.390	0.000525
400.000	82.493	14.393	717.369	1.000	492.350	14.393	0.000575
450.000	75.995	14.350	717.369	1.000	492.396	14.350	0.000631
500.000	70.618	14.278	717.369	1.000	492.438	14.278	0.000695
550.000	66.082	14.114	717.369	1.000	492.479	14.114	0.000767
600.000	62.196	14.512	717.369	1.000	492.516	14.512	0.000859
*****	0.8369D0E 03	R OUTSIDE RANGE OF KNOWN VALUES					
650.000	58.823	15.917	717.369	1.000	492.551	15.917	0.001054
*** *	0.6815D0E 03	R OUTSIDE RANGE OF KNOWN VALUES					
700.000	55.863	15.578	717.369	1.000	492.585	15.578	0.001101

PRODUCTION SURFACE AREA= 0.0 FT2
HEAT TRANSFER AREA= 0.5203535E-02 FT2
DROP RADIUS= 0.4071586-01 FT
DROP THICKNESS= 0.6779876-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TW-TS (F)	SURFACE PROJECTION HEIGHT (FT)			
COOL	FREON 11	1.00	160.00	0.000833			

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COP1	BOND NO.	COP3	VAPOR LAYER (FT)
150.000	86.953	7.092	717.369	9.675	3.347	17.336	0.000341
200.000	74.574	7.625	717.369	10.401	3.347	18.639	0.000387
250.000	66.199	8.153	717.369	11.122	3.347	19.929	0.000434
300.000	60.059	8.539	717.369	11.648	3.347	20.872	0.000479
350.000	55.315	8.792	717.369	11.994	3.347	21.491	0.000525
400.000	51.509	8.987	717.369	12.260	3.347	21.968	0.000575
450.000	48.370	9.133	717.369	12.459	3.347	22.326	0.000621
500.000	45.724	9.245	717.369	12.611	3.347	22.598	0.000665
550.000	43.456	9.281	717.369	12.661	3.347	22.688	0.000767
600.000	41.484	9.679	717.369	13.204	3.347	23.660	0.000859
*****	0.6565D0E 03	R OUTSIDE RANGE OF KNOWN VALUES					
650.000	39.748	10.755	717.369	14.672	3.347	26.291	0.001054
*****	0.3815D0E 03	R OUTSIDE RANGE OF KNOWN VALUES					
700.000	38.206	10.654	717.369	14.534	3.347	26.044	0.001101

PROJECTION SURFACE AREA= 0.710446E-02 FT2
HEAT TRANSFER AREA= 0.710446E-02 FT2
DROP RADIUS= 0.407158E-01 FT
DROP THICKNESS= 0.677987E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE: COPPER | FLUID: FREON 11 | VOLUME (CM3): 1.00 | LEIDENFROST TEMPS (F): 205.00 | SURFACE PROJECTION HEIGHT (FT): 0.001667

	WALL TEMP	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CORI	BOND NO.	CORJ	VAPOR LAYER (FT)
	250.000	68.209	8.400	717.369	12.209	3.347	20.786	0.000434
	300.000	61.472	8.739	717.369	12.702	3.347	21.625	0.000479
	350.000	56.297	8.948	717.369	13.005	3.347	22.142	0.000525
	400.000	52.168	9.102	717.369	13.229	3.347	22.523	0.000575
	450.000	48.778	9.211	717.369	13.387	3.347	22.791	0.000631
	500.000	45.932	9.267	717.369	13.498	3.347	22.980	0.000695
	550.000	43.502	9.291	717.369	13.504	3.347	22.990	0.000767
	600.000	41.395	9.059	717.369	14.038	3.347	23.901	0.000859
*****	0.856300E 03	R OUTSIDE RANGE OF KNOWN VALUES						
	650.000	39.548	10.701	717.369	15.553	3.347	26.479	0.001054
*****	0.831500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
	700.000	37.911	10.572	717.369	15.365	3.347	26.160	0.001101

PROJECTED SURFACE AREA= 0.756938E-02 FT2
HEAT TRANSFER AREA= 0.756938E-02 FT2
DROP RADIUS= 0.407156E-01 FT
DROP THICKNESS= 0.677987E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TW-TS (F)	SURFACE PROJECTION HEIGHT (FT)
COP2	FREON 11	1.00	250.00	0.004167

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
250.000	109.806	13.523	717.369	15.163	69.392	15.673	0.000434
300.000	97.013	13.792	717.369	15.465	69.392	15.985	0.000479
350.000	87.367	13.987	717.369	15.570	69.392	16.094	0.000525
400.000	79.790	13.922	717.369	15.610	69.392	16.135	0.000575
450.000	73.654	13.908	717.369	15.594	69.392	16.119	0.000631
500.000	68.566	13.863	717.369	15.544	69.392	16.067	0.000695
550.000	64.267	13.726	717.369	15.391	69.392	15.908	0.000767
600.000	60.578	14.135	717.369	15.849	69.392	16.382	0.000859
*****	0.856500E 03 F OUTSIDE RANGE OF KNOWN VALUES						
650.000	57.372	15.524	717.369	17.406	69.392	17.992	0.001054
*****	0.881500E 03 F OUTSIDE RANGE OF KNOWN VALUES						
700.000	54.555	15.213	717.369	17.058	69.392	17.632	0.001101

PROJECTION SURFACE AREA= 0.827246E-03 FT2
HEAT TRANSFER AREA= 0.583950E-02 FT2
DROP RADIUS= 0.407158E-01 FT
DROP THICKNESS= 0.677987E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TEMPS (F)	SURFACE PROJECTION HEIGHT (FT)
CP54	FREON 11	1.00	275.00	0.004166

WALL-TEMP	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CCR1	BOND NO.	CCR3	VAPOR LAYER (FT)
500.000	64.950	7.999	717.369	13.817	11.565	15.628	0.000434
500.000	57.177	8.129	717.369	14.042	11.565	15.881	0.000479
550.000	51.336	8.160	717.369	14.094	11.565	15.941	0.000525
400.000	46.760	8.159	717.369	14.093	11.565	15.939	0.000575
450.000	43.064	8.132	717.369	14.046	11.565	15.887	0.000631
600.000	40.006	8.089	717.369	13.972	11.565	15.803	0.000695
550.000	37.427	7.994	717.369	13.808	11.565	15.617	0.000767
600.000	35.218	8.217	717.369	14.194	11.565	16.054	0.000859
0.850500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
650.000	33.302	9.011	717.369	15.565	11.565	17.605	0.001054
0.881500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
700.000	31.620	8.818	717.369	15.231	11.565	17.227	0.001101

PROJECTION SURFACE AREA= 0.496257E-02 FT2
HEAT TRANSFER AREA= 0.899614E-02 FT2
DROP RADIUS= 0.407158E-01 FT
DROP THICKNESS= 0.677987E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TW-TS (F)	SURFACE PROJECTION HEIGHT (FT)
S	FREON 114	2.00	125.00	0.0

SWELL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CORI	BOND NO.	COR3	VAPOR LAYER (FT)
150.000	138.584	23.198	2997.468	1.000	2053.906	23.198	0.000514
200.000	112.526	22.785	2997.468	1.000	2054.482	22.785	0.000586
250.000	95.738	22.408	2997.468	1.000	2054.812	22.408	0.000669
300.000	83.899	21.836	2997.468	1.000	2055.117	21.836	0.000769
350.000	75.038	21.042	2997.468	1.000	2055.399	21.042	0.000885
400.000	68.123	19.914	2997.468	1.000	2055.662	19.914	0.000994
450.000	62.554	18.206	2997.468	1.000	2055.908	18.206	0.001175
500.000	57.960	15.815	2997.468	1.000	2056.137	15.815	0.001457
***** 0.770500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
550.000	54.095	14.012	2997.468	1.000	2056.353	14.012	0.001719
***** 0.795000E 03	R OUTSIDE RANGE OF KNOWN VALUES						
600.000	50.792	13.427	2997.468	1.000	2056.555	13.427	0.001837
***** 0.820500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
650.000	47.932	12.889	2997.468	1.000	2056.746	12.889	0.001957
***** 0.845500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
700.000	45.428	12.395	2997.468	1.000	2056.925	12.395	0.002077

PROJECTION SURFACE AREA= 0.0 FT2
HEAT TRANSFER AREA= 0.133042E-01 FT2
DROP RADIUS= 0.651041E-01 FT
DROP THICKNESS= 0.530349E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TW-TS (F)	SURFACE PROJECTION HEIGHT (FT)
COPPER	FREON 114	2.00	130.00	0.000833

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
150.000	70.810	11.853	2997.468	16.697	10.941	28.934	0.000504
200.000	61.626	12.479	2997.468	17.579	10.941	30.356	0.000536
250.000	55.331	12.951	2997.468	18.244	10.941	31.504	0.000669
300.000	50.668	13.187	2997.468	18.577	10.941	32.080	0.000760
350.000	47.033	13.185	2997.468	18.579	10.941	32.084	0.000863
400.000	44.096	12.891	2997.468	18.159	10.941	31.358	0.000994
450.000	41.658	12.124	2997.468	17.079	10.941	29.494	0.001175
500.000	39.592	10.803	2997.468	15.218	10.941	26.279	0.001457
*****	0.776590E 03 R OUTSIDE RANGE OF KNOWN VALUES						
550.000	37.811	9.794	2997.468	13.797	10.941	23.826	0.001719
*****	0.795500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
600.000	36.255	9.584	2997.468	13.502	10.941	23.315	0.001837
*****	0.820300E 03 R OUTSIDE RANGE OF KNOWN VALUES						
650.000	34.881	9.380	2997.468	13.213	10.941	22.818	0.001957
*****	0.845500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
700.000	33.655	9.182	2997.468	12.935	10.941	22.337	0.002077

PROJECTION SURFACE AREA= 0.187578E-01 FT2
HEAT TRANSFER AREA= 0.187578E-01 FT2
DROP RADIUS= 0.651041E-01 FT
DROP THICKNESS= 0.530349E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST (W-TS (F)	SURFACE PROJECTION HEIGHT (FT)
COO2	FREON 114	2.00	150.00	0.001667

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
150.000	77.158	12.915	2997.468	17.908	10.941	31.668	0.000504
200.000	65.444	13.252	2997.468	18.456	10.941	32.493	0.000586
250.000	57.598	13.481	2997.468	18.776	10.941	33.055	0.000669
300.000	51.891	13.506	2997.468	18.810	10.941	33.115	0.000760
350.000	47.509	13.322	2997.468	18.554	10.941	32.666	0.000865
400.000	44.013	12.806	2997.468	17.919	10.941	31.548	0.000994
450.000	41.144	11.975	2997.468	16.677	10.941	29.361	0.001175
500.000	38.736	10.869	2997.468	14.720	10.941	25.916	0.001457
*****	0.7705000E 03 R OUTSIDE RANGE OF KNOWN VALUES						
550.000	36.680	9.501	2997.468	13.233	10.941	23.297	0.001719
*****	0.7955000E 03 R OUTSIDE RANGE OF KNOWN VALUES						
600.000	34.858	9.226	2997.468	12.849	10.941	22.621	0.001837
*****	0.8205000E 03 R OUTSIDE RANGE OF KNOWN VALUES						
650.000	33.335	8.964	2997.468	12.485	10.941	21.980	0.001957
*****	0.8455000E 03 R OUTSIDE RANGE OF KNOWN VALUES						
700.000	31.951	8.717	2997.468	12.141	10.941	21.375	0.002077

PROJECTION SURFACE AREA= 0.185451E-01 FT2
HEAT TRANSFER AREA= 0.185451E-01 FT2
DROP RADIUS= 0.651041E-01 FT
DROP THICKNESS= 0.530349E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	DIMENSIONLESS TIMES (F)	SURFACE PROJECTION HEIGHT (FT)			
CO52	PRESENT	2.00	170.00	0.004166			

	WELL-HEAD	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CORI	BOND NO.	FOR3	VAPOR LAYER (FT)
	100.000	111.920	16.754	2997.463	21.005	88.709	21.712	0.000504
	200.000	93.301	16.842	2997.464	21.183	88.709	21.895	0.000586
	250.000	81.019	16.963	2997.468	21.262	88.709	21.977	0.000669
	300.000	72.195	16.770	2997.463	21.068	88.709	21.777	0.000750
	350.000	65.488	16.364	2997.469	20.590	88.709	21.283	0.000865
	400.000	61.184	17.594	2997.463	19.726	88.709	20.390	0.000994
	450.000	55.864	16.259	2997.468	16.230	88.709	16.843	0.001175
	500.000	52.262	14.260	2997.468	15.989	88.709	16.527	0.001457
***	0.770500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
	550.000	49.205	12.746	2997.468	14.291	88.709	14.772	0.001719
****	0.795500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
	600.000	46.570	12.311	2997.469	13.804	88.709	14.268	0.001837
*****	0.820500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
	650.000	44.271	11.905	2997.468	13.348	88.709	13.797	0.001957
******	0.845500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
	700.000	42.244	11.526	2997.468	12.923	88.709	13.358	0.002077

PROJECTION SURFACE AREA= 0.211468E-02 FT2
HEAT TRANSFER AREA= 0.149299E-01 FT2
DROP RADIUS= 0.651041E-01 FT
DROP THICKNESS= 0.530349E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TEMPS (F)	SURFACE PROJECTION HEIGHT (FT)
OFHC	FREON 114	2.00	200.00	0.004160

WALL-TEMP	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
250.000	54.180	12.681	2997.468	21.905	14.785	24.775	0.000669
300.000	46.672	12.668	2997.468	21.882	14.785	24.749	0.000760
350.000	44.455	12.466	2997.468	21.533	14.785	24.355	0.000865
400.000	41.098	12.014	2997.468	20.753	14.785	23.472	0.000994
450.000	38.348	11.161	2997.468	19.279	14.785	21.805	0.001175
500.000	36.045	9.835	2997.468	16.988	14.785	19.214	0.001457
***** 0.770500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
550.000	34.080	8.828	2997.468	15.249	14.785	17.247	0.001719
***** 0.795500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
600.000	32.381	8.507	2997.468	14.706	14.785	16.724	0.001837
***** 0.820500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
650.000	30.892	8.307	2997.468	14.349	14.785	16.230	0.001957
***** 0.845500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
700.000	29.575	8.069	2997.468	13.938	14.785	15.765	0.002077

PROJECTION SURFACE AREA= 0.126881E-01 FT2
HEAT TRANSFER AREA= 0.231009E-01 FT2
DROP RADIUS= 0.651041E-01 FT
DROP THICKNESS= 0.530349E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TM-TS (F)	SURFACE PROJECTION HEIGHT (FT)
S	FREON 114	1.00	125.00	0.0

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CORI	BOND NO.	CDRG	VAPOR LAYER (FT)
150.000	106.748	17.869	1498.734	1.000	1026.953	17.869	0.000424
200.000	88.359	17.892	1498.734	1.000	1027.240	17.892	0.000493
250.000	76.306	17.860	1498.734	1.000	1027.405	17.860	0.000563
300.000	67.689	17.618	1498.734	1.000	1027.558	17.618	0.000639
350.000	61.167	17.152	1498.734	1.000	1027.699	17.152	0.000727
400.000	56.028	16.379	1498.734	1.000	1027.831	16.379	0.000836
450.000	51.855	15.092	1498.734	1.000	1027.953	15.092	0.000988
500.000	48.385	13.202	1498.734	1.000	1028.068	13.202	0.001226
***** 0.776500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
550.000	45.447	11.772	1498.734	1.000	1028.176	11.772	0.001445
***** 0.795500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
600.000	42.921	11.347	1498.734	1.000	1028.277	11.347	0.001545
***** 0.820500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
650.000	40.722	10.951	1498.734	1.000	1028.373	10.951	0.001646
***** 0.845500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
700.000	38.780	10.582	1498.734	1.000	1028.462	10.582	0.001747

PROJECTION SURFACE AREA= 0.0 FT2
HEAT TRANSFER AREA= 0.665210E-02 FT2
DROP RADIUS= 0.463356E-01 FT
DROP THICKNESS= 0.530349E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TW-TS (F)	SURFACE PROJECTION HEIGHT (FT)			
COPPER	FREON 114	1.00	130.00	0.000833			

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CORI	BOND NO.	CORJ	VAPOR LAYER (FT)
150.000	56.838	9.347	1498.734	12.622	5.470	22.815	0.000424
200.000	49.034	9.929	1498.734	13.408	5.470	24.236	0.000493
250.000	44.332	10.376	1498.734	14.013	5.470	25.328	0.000563
300.000	40.827	10.626	1498.734	14.350	5.470	25.938	0.000639
350.000	38.081	10.679	1498.734	14.421	5.470	26.066	0.000727
400.000	35.852	10.481	1498.734	14.154	5.470	25.583	0.000836
450.000	33.995	9.894	1498.734	13.361	5.470	24.150	0.000988
500.000	32.415	8.844	1498.734	11.944	5.470	21.589	0.001226
***** 0.770500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
550.000	31.049	8.043	1498.734	10.861	5.470	19.632	0.001445
***** 0.795500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
600.000	29.852	7.892	1498.734	10.657	5.470	19.263	0.001545
***** 0.820500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
650.000	28.792	7.742	1498.734	10.456	5.470	18.899	0.001646
***** 0.845500E 03 R OUTSIDE RANGE OF KNOWN VALUES							
700.000	27.844	7.597	1498.734	10.259	5.470	18.544	0.001747

PROJECTION SURFACE AREA= 0.899122E-02 FT2
HEAT TRANSFER AREA= 0.899122E-02 FT2
DROP RADIUS= 0.460356E-01 FT
DROP THICKNESS= 0.530349E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TEMPS (F)	SURFACE PROJECTION HEIGHT (FT)
C602	FREON 114	1.00	150.00	0.001667

TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
150.000	63.083	10.559	1498.734	14.022	5.470	26.079	0.000424
200.000	53.800	10.894	1498.734	14.466	5.470	26.905	0.000493
250.000	47.551	11.130	1498.734	14.779	5.470	27.487	0.000563
300.000	42.988	11.189	1498.734	14.857	5.470	27.633	0.000639
350.000	39.473	11.069	1498.734	14.699	5.470	27.338	0.000727
400.000	36.662	10.717	1498.734	14.232	5.470	26.469	0.000836
450.000	34.349	9.997	1498.734	13.275	5.470	24.690	0.000998
500.000	32.404	8.841	1498.734	11.741	5.470	21.836	0.001226
*****	0.770500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
550.000	30.739	7.962	1498.734	10.573	5.470	19.665	0.001445
*****	0.795500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
600.000	29.294	7.744	1498.734	10.284	5.470	19.126	0.001545
*****	0.820500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
650.000	28.025	7.536	1498.734	10.007	5.470	18.612	0.001646
*****	0.845500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
700.000	26.899	7.339	1498.734	9.746	5.470	18.126	0.001747

PROJECTION SURFACE AREA= 0.884103E-02 FT2
HEAT TRANSFER AREA= 0.884103E-02 FT2
DROP RADIUS= 0.460356E-01 FT
DROP THICKNESS= 0.530349E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TWALLS (F)	SURFACE PROJECTION HEIGHT (FT)			
CF52	FREON 114	1.00	170.00	0.004166			
TWALL-TSAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	CDR1	BOND NO.	CDR3	VAPOR LAYER (FT)
150.000	92.970	15.562	1498.734	17.449	88.709	18.036	0.000424
200.000	77.698	15.733	1498.734	17.640	88.709	18.234	0.000493
250.000	67.602	15.823	1498.734	17.741	88.709	18.338	0.000563
300.000	60.339	15.703	1498.734	17.607	88.709	18.199	0.000639
350.000	54.803	15.368	1498.734	17.231	88.709	17.811	0.000727
400.000	50.423	14.740	1498.734	16.527	88.709	17.083	0.000836
450.000	46.852	13.836	1498.734	15.289	88.709	15.803	0.000988
500.000	43.871	11.970	1498.734	13.422	88.709	13.873	0.001226
*****	0.775500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
550.000	41.339	10.708	1498.734	12.006	88.709	12.410	0.001445
*****	0.795500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
600.000	39.155	10.351	1498.734	11.606	88.709	11.996	0.001545
*****	0.820500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
650.000	37.248	10.016	1498.734	11.231	88.709	11.609	0.001646
*****	0.845500E 03 R OUTSIDE RANGE OF KNOWN VALUES						
700.000	35.566	9.704	1498.734	10.880	88.709	11.246	0.001747

PROJECTED SURFACE AREA= 0.105734E-02 FT2
HEAT TRANSFER AREA= 0.746498E-02 FT2
DROP RADIUS= 0.460356E-01 FT
DROP THICKNESS= 0.530349E-02 FT
NO. CONCENTRIC GROOVES= 0

SURFACE	FLUID	VOLUME (CM3)	LEIDENFROST TM-TS (F)	SURFACE PROJECTION HEIGHT (FT)
CF54	FREON 114	1.00	200.00	0.004166

WALL-SAT	VAPORIZATION TIME (SEC)	DIMENSIONLESS VAPORIZATION TIME	DIMENSIONLESS DROP VOLUME	COR1	BOND NO.	COR3	VAPOR LAYER (FT)
250.000	43.929	10.282	1498.734	17.760	14.785	20.088	0.000563
300.000	39.670	10.325	1498.734	17.835	14.785	20.172	0.000639
350.000	36.394	10.206	1498.734	17.629	14.785	19.938	0.000727
400.000	33.775	9.873	1498.734	17.055	14.785	19.290	0.000836
450.000	31.622	9.203	1498.734	15.897	14.785	17.980	0.000988
500.000	29.813	8.134	1498.734	14.051	14.785	15.892	0.001226
***** 0.770500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
550.000	28.265	7.322	1498.734	12.647	14.785	14.304	0.001445
***** 0.795500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
600.000	26.923	7.117	1498.734	12.294	14.785	13.905	0.001545
***** 0.820500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
650.000	25.744	6.923	1498.734	11.958	14.785	13.525	0.001646
***** 0.845500E 03	R OUTSIDE RANGE OF KNOWN VALUES						
700.000	24.699	6.739	1498.734	11.640	14.785	13.166	0.001747

PROJECTED SURFACE AREA= 0.634405E-02 FT2
HEAT TRANSFER AREA= 0.115005E-01 FT2
DROP RADIUS= 0.460350E-01 FT
DROP THICKNESS= 0.530349E-02 FT
NO. CONCENTRIC GROOVES= 0

VITA

James Alton Tevepaugh, Jr., was born to James A. and Dorothy B. Tevepaugh in Statesville, North Carolina, on November 16, 1949. He attended elementary school in Charlotte, North Carolina, and was graduated from West Mecklenburg High School in June 1968. In September 1968 he entered North Carolina State University and in May 1973 received a Bachelor of Science degree in aerospace engineering. As a cooperative education student, he was employed by the National Aeronautics and Space Administration at Marshall Space Flight Center in Huntsville, Alabama.

Following graduation from North Carolina State University, he was employed by Lockheed Missiles and Space Company in Huntsville, Alabama. In September 1977 he entered the Graduate School of the University of Tennessee, Knoxville. He received the Master of Science degree in mechanical engineering in March 1979.

The author is a member of Phi Kappa Phi, Sigma Gamma Tau, American Institute of Aeronautics and Astronautics and the Amateur Radio Relay League.

He is married to Carol Whitt of Toney, Alabama.