

SURFACE TEMPERATURE TRANSIENTS
IN THE FILM BOILING REGIME

By

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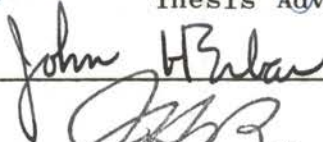
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Thesis Approved



Thesis Adviser




Dean of Graduate College

PREFACE

Surface temperature transients were obtained for liquids in film boiling using horizontal plates of different materials. The effect of different plate materials upon the Leidenfrost point and the total evaporation times of water and ethanol were studied. A mathematical model was developed to predict the temperature transients within the heating material.

I greatly appreciate the advice and guidance given by Dr. Kenneth J. Bell during my thesis work. I would like to express my gratitude to the members of my graduate committee and to the entire staff of the School of Chemical Engineering.

Financial support was gratefully received from the U. S. Army Research Office in Durham, North Carolina. The interest shown by the ARO advisors was inspiring.

I am deeply indebted to my family for their financial and moral support throughout my entire college career. Without their support, my graduate studies would not have been possible.

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CHAPTER I

INTRODUCTION

Film boiling occurs when a boiling liquid is completely masked from the heating surface by a film of its own vapor. All heat transfer to the liquid is by conduction and radiation. Since a vapor ordinarily has a much lower thermal conductivity than the liquid, the film insulates the liquid causing the low heat transfer coefficients usually associated with film boiling.

In 1756, Johann G. Leidenfrost, a German doctor, studied the boiling of small liquid masses on a hot surface. His observations are the first known study in the field of boiling. The process in which small liquid masses exist in film boiling on a hot surface is called the Leidenfrost Phenomenon, in his honor.

Film boiling is only one mechanism of heat transfer from a hot surface to a pool of liquid. Three other mechanisms exist: nonboiling convection, nucleate boiling, and transition boiling. These processes are illustrated by the boiling curve in Figure 1.

Region AB represents the nonboiling convection process. Heat is transferred to the liquid in contact with the heating surface by natural convection. No change in phase occurs at the solid-liquid interface. The temperature difference between

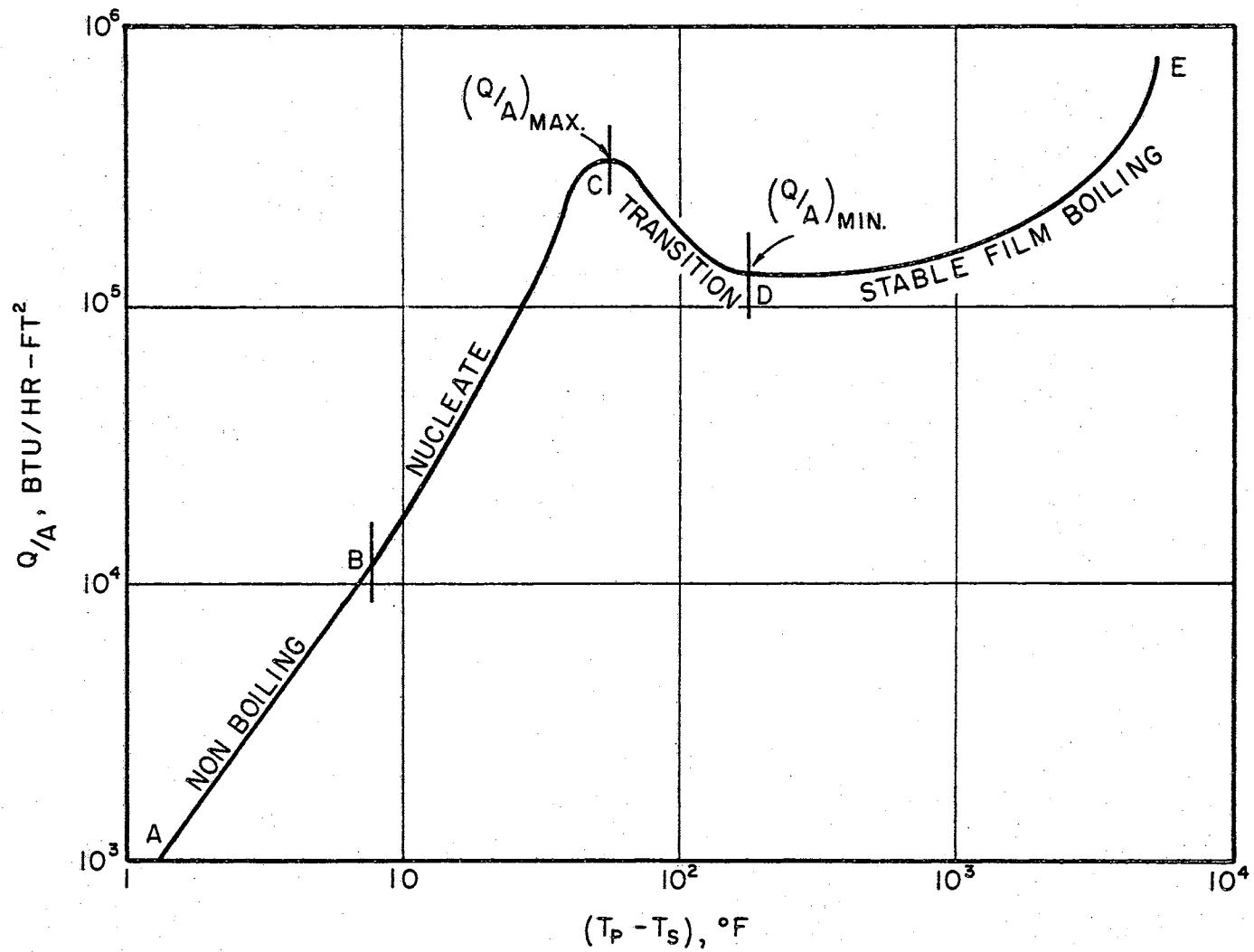


FIGURE 1. TYPICAL BOILING CURVE.

the heating surface and the liquid is less than 10°F . With an increase in surface temperature bubbles form at favored sites on the heating surface. This is the nucleate boiling regime - Region BC on the boiling curve. As the rate of bubble production increases, the stream of bubbles moving up through the liquid increases the velocity of the circulation currents in the mass of liquid, and the coefficient of heat transfer becomes greater than that in undisturbed natural convection. This increasing coefficient, multiplied by the increasing temperature difference, results in an even more rapid increase in the total heat transferred per unit area.

During nucleate boiling, the bubbles occupy but a small portion of the heat transfer surface at a time, and most of the heating surface is in direct contact with the liquid. However, if the temperature of the surface is continually increased, a point is found where the heat transfer coefficient reaches a maximum. At point C, an increase in the temperature difference usually results in a decrease in the heat flux. At this critical temperature difference, the bubbles coalesce into a locally continuous film of vapor that insulates the liquid from the heating surface. Region CD, the transition regime, is a combination of nucleate boiling occurring with an unstable vapor film partially covering the heating surface.

A further increase in the temperature difference causes the vapor film to completely shield the liquid from the heating surface. The heat flux falls to a minimum and this point is called the Leidenfrost point. Stable film boiling, represented

by Region DE, begins at the minimum heat flux. In this region any increase in the temperature difference causes a corresponding increase in the heat flux until the heating surface burns out. Only with very high surface temperature (incandescent, electrically heated wires) can the high heat fluxes obtainable in nucleate boiling be reached.

The object of this work was to study the effect of a liquid in film boiling upon the material of the heating surface. The major questions to be investigated may be stated as:

- (1) What happens to the surface temperature when a liquid mass is placed on the heating surface?
- (2) Does the material of the heating surface have an effect on the Leidenfrost point of the liquid?
- (3) Does the material of the heating surface have an effect on the total evaporation time of the liquid?
- (4) Can a mathematical model be developed to predict the effect a liquid in film boiling has on the surface temperature?

CHAPTER II

LITERATURE SURVEY

J. G. Leidenfrost's study using a well polished iron spoon heated over hot coals was the first detailed investigation of the once-called "spheroidal-state" film boiling regime-now called the Leidenfrost Phenomenon. Several studies of droplets and extended masses in film boiling were made by the Russians. Pleteneva and Rebinder (13) determined the total evaporation times of water and some organic liquids using a stainless steel plate exposed to the air and heated electrically. They found that at a plate temperature of 250°C, water droplets first began to show characteristics of the Leidenfrost Phenomenon and at 275°C the total evaporation time reached a maximum. The evaporation time decreased as the plate temperature increased above this point. The organic liquids were found to behave similarly, but the plate temperature which gave the maximum evaporation time for each organic liquid was found to be proportional to its normal boiling point in absolute temperature units.

Borishansky (2) studied small droplets of water, benzene, ethanol, and carbon tetrachloride at 600°C on plates of copper, brass, and stainless steel. His study of extended masses of water, however, was of more interest to this investigation. He determined the total evaporation times for water volumes of 1 to

5 ml on a brass plate at temperatures of 275°C and 350°C. He observed that for the larger masses, the liquid tends to flatten and approach a constant thickness. He reported this thickness to be about 7 mm.

In the attempt to measure coefficients for heat transfer to droplets from the heating surface, Gorton (4) used plates of stainless steel and platinum. He concluded that the type of heating surface affected only the contribution due to radiation caused by the different metal emissivities. Because his photographic measurements of the thickness of the film separating the liquid from the plate were in error, he was unable to make a definite statement concerning the effect of the plate material on the conduction through the vapor film.

Gottfried (5) studied stable film boiling for small droplets of water, carbon tetrachloride, ethanol, and benzene. He developed an analytical model which predicted the total evaporation times for small droplets with a maximum error of 25 percent. He initiated possibly the first completely analytical approach to the study of the Leidenfrost Phenomenon for small droplets.

The analytical model proposed by Gottfried was modified and extended by C. J. Lee (9). He attempted to determine experimentally the point of minimum heat flux, or Leidenfrost point, for water and various organic liquids using a stainless steel plate. Lee found the Leidenfrost point for the organic droplets at a well defined plate temperature, while the initiation of stable film boiling for the water droplets occurred at a

plate temperature between 250°C to 310°C.

A large aluminum plate, 8 in. by 8 in., was used by Hosler and Westwater (6) to study film boiling for water and Freon-11. The horizontal surface was covered with liquid to a depth of approximately 1/2 inch. The minimum heat flux for water occurred at 258°C plate temperature, according to the authors. From their published plots of experimental heat flux data for water, however, the minimum was in the range of 250°C to 270°C plate temperature.

In his Ph.D. thesis, B. M. Patel (12) had difficulty in pinpointing the Leidenfrost point for extended masses of water. For liquid volumes of 0.05 to 10 ml, he observed the beginning of fully developed film boiling at about 307°C plate temperature. Patel compared his experimental data with the work of Borishansky and found good agreement for total evaporation times of water masses at a plate temperature of 350°C. At the lower plate temperature of 275°C, however, the total evaporation times of Patel were significantly less than the times of Borishansky. The experimental work of Borishansky seemed to indicate that the water masses were in film boiling, while Patel's own data appeared to be in the transition boiling regime at 275°C.

Patel offered the explanation that possibly the thermal behavior of the plate itself was responsible for the disagreement. He noticed that during the evaporation of larger water masses, the temperature of the plate dropped. He recorded this cooling and constructed a plot of the transient temperatures within the plate. The plate cooled about 15°C for a 10 ml water sample. Patel used a stainless steel plate with a thermal

diffusivity of $0.0534 \text{ cm}^2/\text{sec}$ for the temperature range investigated, while the brass plate of Borishansky had a thermal diffusivity of $0.162 \text{ cm}^2/\text{sec}$. The thermal diffusivity of a metal is the thermal conductivity divided by the product of the specific heat and density.

In 1964, Baumeister (1) studied the film boiling of small water droplets to determine heat transfer coefficients and the thickness of the supporting vapor film. He used stainless steel and graphite plates in measuring evaporation times and found their different surface conditions did not noticeably affect the evaporation times. Baumeister briefly mentioned having difficulty placing the water masses on the plate at the lower temperatures. He attributed this to local cooling of the plate surface.

CHAPTER III

EXPERIMENTAL APPARATUS

Two 304 stainless steel plates of different dimensions and one solid silver plate were used as test surfaces in this investigation. The experimental apparatus is shown schematically in Figure 2.

The small stainless steel plate was four inches in diameter and 1/4 inch thick. Five chromel-alumel thermocouples were installed in the plate as shown in Figure 3. Figure 4 shows the eight-inch diameter stainless steel plate and the placement of twelve similar thermocouples. Completing the plate descriptions, Figure 5 shows the small silver plate and the arrangement of four thermocouples.

After polishing the surfaces to a mirror finish, the stainless steel plates required no further preparation except to be heated to operating temperature for about 24 hours. This metal formed a smooth and very stable oxide film. The silver plate, however, formed a powdery white oxide which interfered with the experiment. To prevent this oxide from forming, the silver plate was flashed with copper to provide a bonding agent. Then the plate was electroplated with an approximate 0.002 inch nickel coating. After heating for several hours, the plate developed a dark gold color and presented no more difficulty.

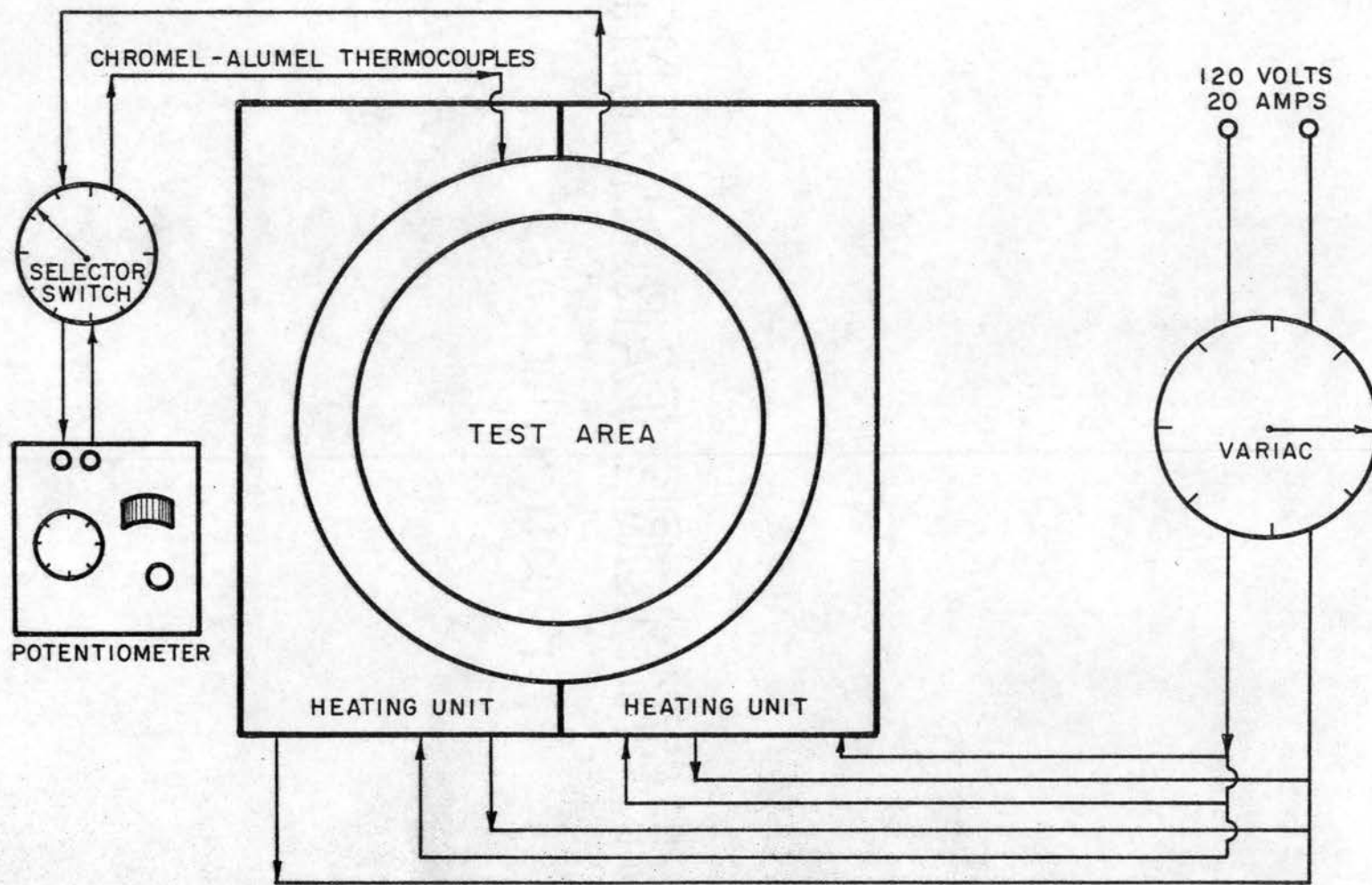


Figure 2. SCHEMATIC DRAWING OF APPARATUS.

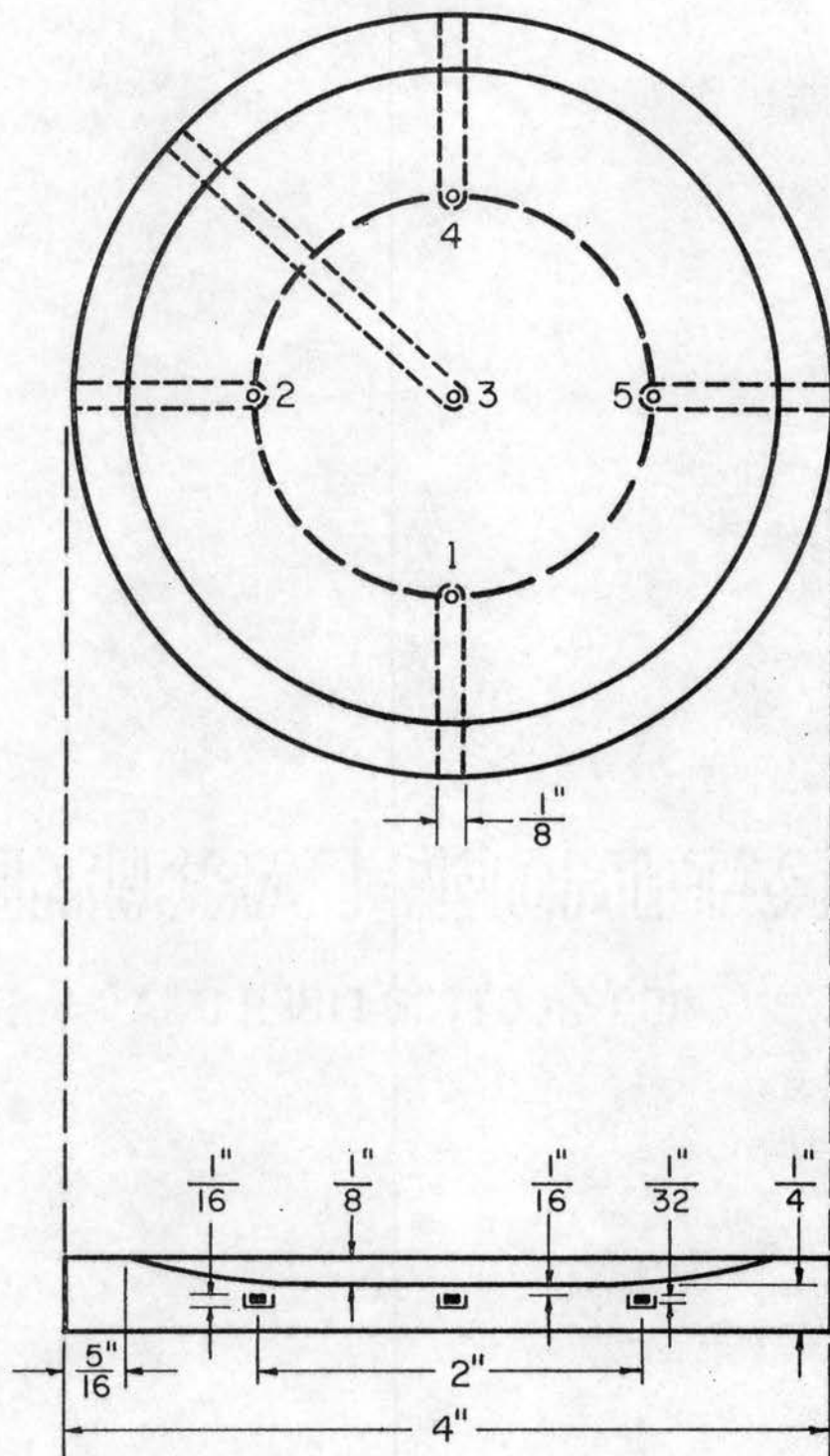


Figure 3. SMALL STAINLESS STEEL TEST PLATE.

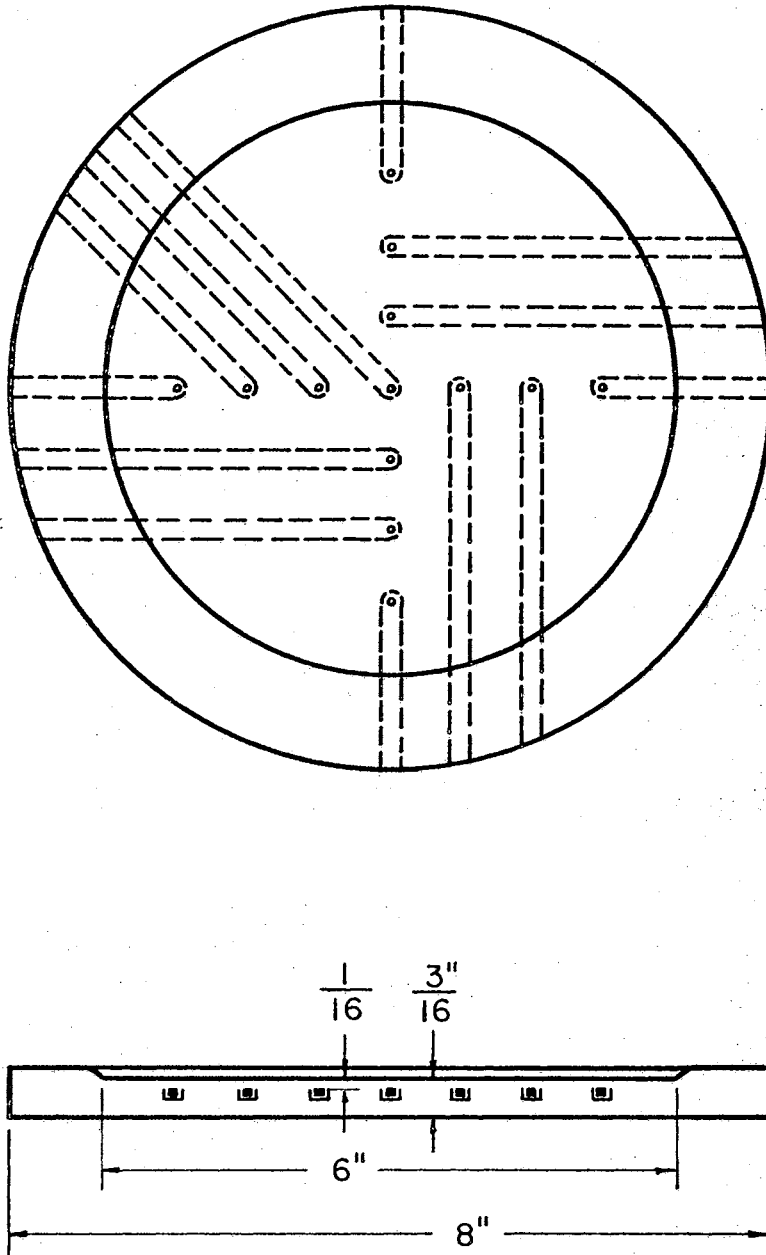


Figure 4. LARGE STAINLESS STEEL TEST PLATE.

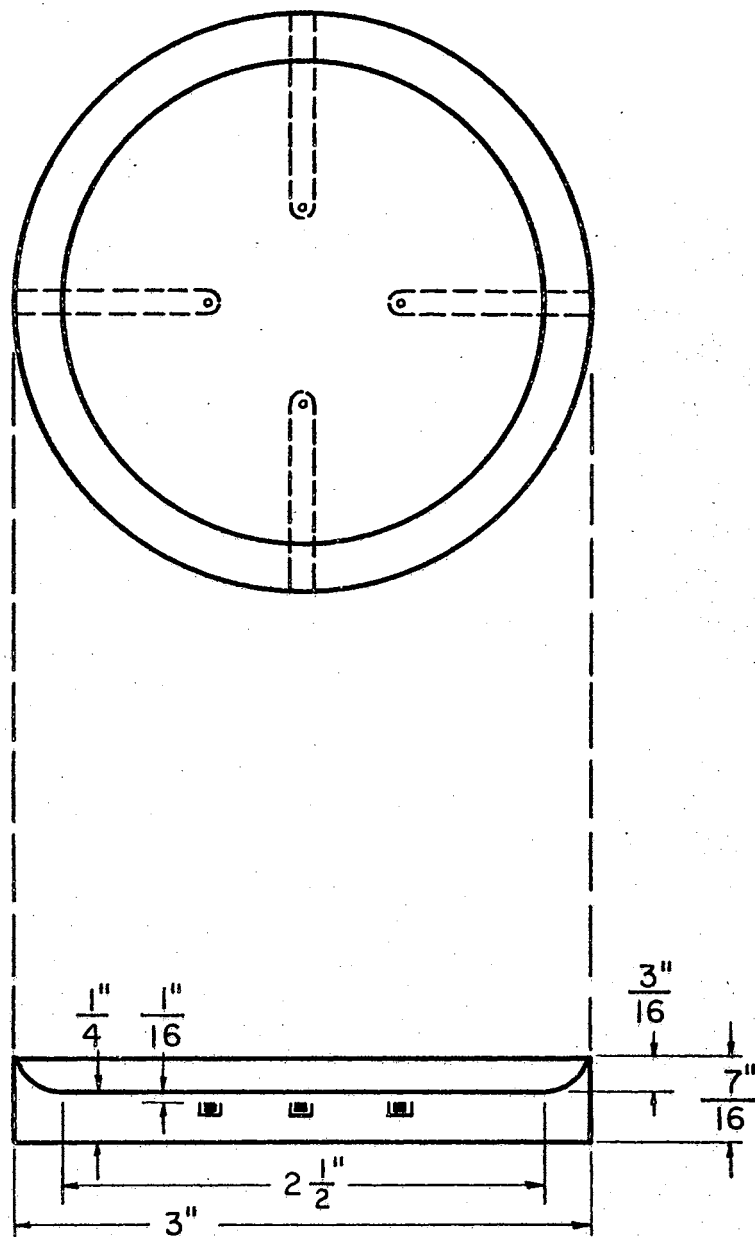


Figure 5. SILVER TEST PLATE.

Chromel-alumel thermocouples were chosen for the temperature measurements because of their high voltage differential per degree and their stability over the temperature range involved. The thermocouples were fastened to the plates using high-temperature saureisen cement. The thermocouple junctions were prevented from contacting the bare metal of the plate by a thin coating of insulation. The thermocouples were calibrated at 25°C and 100°C and were found to deviate less than 0.1°C from the standard values. Details of the calibrations may be found in Appendix A. The thermocouple e.m.f. was measured on a No. 8690 Leeds and Northrup millivolt potentiometer using an ice bath as the reference junction.

Each small plate was centered upon a Hevi-Duty #56-TS, flat electric heating unit, while the large plate rested on two Hevi-Duty #54-KSS flat heating units. Each Hevi-Duty #56-TS unit was connected to a 10 ampere, 120 volt Variac. The Hevi-Duty #54-KSS units were connected to a 20 ampere, 120 volt Variac. The Variacs were in turn connected to a 120 volt 60 cycle line.

Calibrated pipettes were used to produce liquid volumes of 0.5, 1, 3, 5, 8, and 10 ml. Three pipettes (10 ml, 5 ml, and 1 ml) were used to cover this range.

Each plate and its heating surface were supported by a series of asbestos insulating plates, each of which were separated by an inch of air space. The asbestos plates were constructed with adjustable legs for horizontal leveling. The plate was leveled horizontally, then slightly canted so that the test liquid would preferentially move over an area directly above a thermocouple.

To keep the liquid mass centered over a thermocouple required a needle support. This was a ringstand which supported a needle that barely touched the surface of the liquid. Surface tension kept the mass from breaking away from the needle; thus the liquid remained in a certain area. The needle support was removed after the plate began to reheat and before the volume of liquid dropped to 0.3 ml, so that the small droplet evaporation rates was not affected.

CHAPTER IV

EXPERIMENTAL PROCEDURE

The stainless steel plates were cleaned with No. 0 emery paper before they were allowed to heat. The cleaning was necessary because the final evaporation of a liquid sample left a residue adhering to the surface. This residue was difficult to remove from the stainless plates, but adhered only weakly to the silver plate. Thus a small amount of water, in film boiling, loosened and removed the residue from the surface of the silver plate. The water was then blown from the plate. This prevented chipping or scratching of the thin nickel coating on the silver plate.

After initial heating began, the plates reached steady state in about two hours. At this time, the temperature was recorded and the proper volume of liquid was drawn into the pipette. With a stopwatch in one hand and the pipette in the other hand, the liquid was allowed to flow onto the plate surface. Because a finite amount of time was necessary to drain the pipette, the stopwatch was started when one half of the sample volume left the pipette. As quickly as possible, transient temperature readings and the times of the readings were recorded. A transient reading was achieved by setting a temperature reading on the potentiometer slightly below the actual

temperature of the plate, and then noting the time when the plate cooled to that specific reading. The time and millivolt reading were recorded and the process was repeated.

Distilled water was the primary liquid investigated. A lesser volume of data was recorded for ethanol to insure that similar temperature transients existed for other liquids. The test liquids were initially at 25°C before they were placed onto the test surfaces during the majority of the test runs. The effect of using water initially near its saturation temperature was also investigated. A large volume of water was heated in a flask to its saturation temperature. The heat to the flask was then regulated until the water barely boiled. Water was drawn into the pipette and discharged several times until the pipette was heated. The desired volume of water was then drawn into the pipette and quickly placed on the plate.

An effort was made to pinpoint the Leidenfrost point of water by a transient method. The test plate was heated to a temperature above the Leidenfrost point; then the surface was covered by water. After the rapid initial cooling of the plate in the first few seconds, the temperature declined gradually. Water was intermittently added to keep the surface covered. The water stayed in film boiling as the temperature declined until suddenly the entire mass went into apparent nucleate boiling. The temperature immediately prior to this was recorded as the point of minimum heat flux.

CHAPTER V

MATHEMATICAL MODEL

When the fact was established that the heating surface cooled significantly following deposition of liquid, a method was desired to predict the transient temperature effects in the plate itself. A mathematical model was built by subdividing a section of the plate into small volumes with a reference number assigned to central nodal points (Figure 6). A time-iteration procedure was adopted so that instantaneous temperatures were calculated for successive time intervals. The general methods for time-iteration procedures outlined by Dusenberre (3) were used.

The heating surface was a short cylindrical plate. The plate was divided into pie-shaped wedges. Heat was assumed to flow in the axial and radial directions, but not in the angular direction. Thus the plate was axi-symmetric, and a wedge of 1 radian represented the entire plate. Assuming a semi-infinite cylinder, heat was transferred to the air from the top surface and to the bottom of the plate by heaters. The plate was assumed infinite in the radial direction, thus no heat was lost or gained from the sides.

A heat balance was made for each nodal point. For example, consider the nodal point 2.

Heat in - Heat out = Accumulation of heat in element

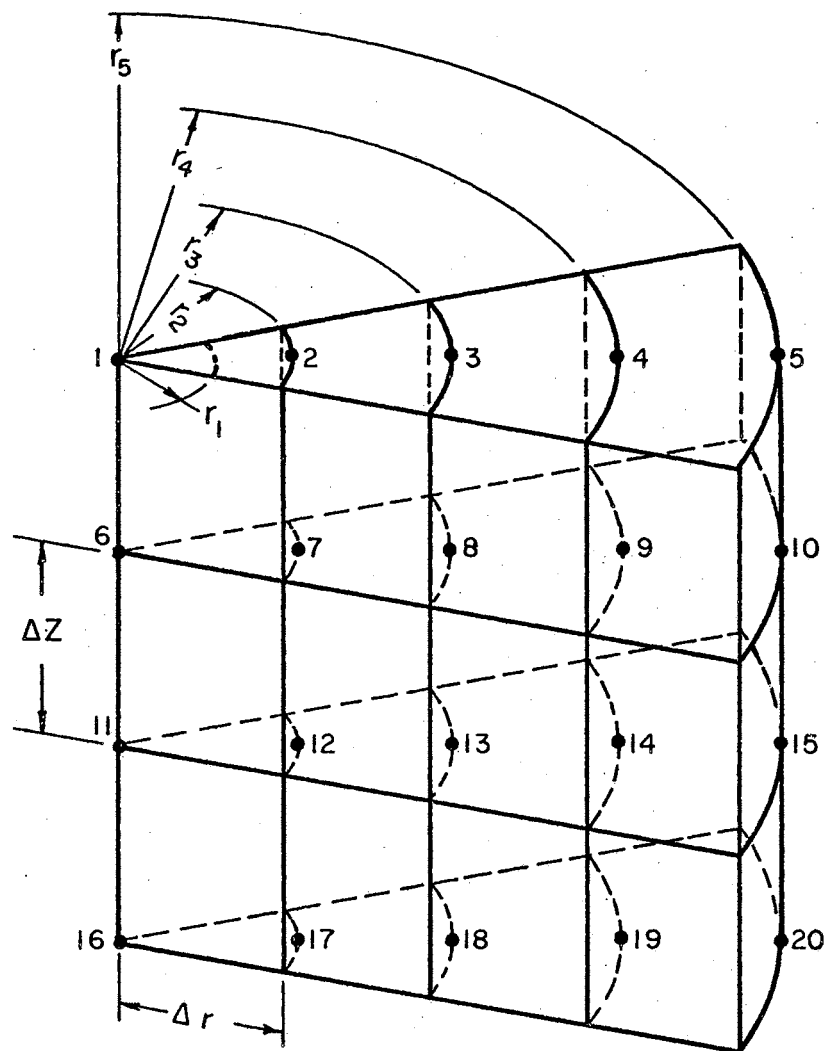


FIGURE 6. MATHEMATICAL MODEL WITH LATTICE POINTS.

Point 2

$$Q_{3-2} + Q_{7-2} - Q_{2-1} - Q_{2-s} = W_2 C \frac{\Delta T_2}{\Delta t} \quad (1-1)$$

$$\left(\frac{k}{\Delta r}\right)(2\pi r_2)\left(\frac{\theta}{2\pi}\right)\left(\frac{\Delta Z}{2}\right)(T_3 - T_2) + \left(\frac{2k}{\Delta Z}\right)\pi(r_2^2 - r_1^2)\left(\frac{\theta}{2\pi}\right) -$$

$$\left(\frac{k}{\Delta r}\right)(2\pi r_1)\left(\frac{\theta}{2\pi}\right)(T_2 - T_1) - h_A \pi(r_2^2 - r_1^2)\left(\frac{\theta}{2\pi}\right)(T_2 - T_s)$$

$$= \pi(r_2^2 - r_1^2)\left(\frac{\theta}{2\pi}\right)\frac{\Delta Z}{2} \rho C \frac{\Delta T_2}{\Delta t} \quad (1-2)$$

where, $\Delta T_2 = T_{2n} - T_2$

T_{2n} = Temperature of point 2 at the end of Δt .

Δt = Time interval

T_i = Temperature of point i at start of Δt .

ρ = Density of plate

C = Specific heat of plate

h_A = Heat transfer coefficient to air.

T_s = Temperature of air.

k = Thermal conductivity of plate.

A similar equation was obtained for each of the nodal points.

These twenty equations provided the basis of the mathematical model.

The use of the twenty equations required initial starting values for the temperatures of the nodal points. The plate was assumed to be in steady state. A temperature for one of the nodal points and a corresponding heat transfer coefficient to the surrounding air were chosen. By using this nodal temperature and air coefficient, the heat flux to the plate necessary to maintain steady state was calculated. During steady state, temperatures of nodal points differed due to conduction within the plate in

the axial direction only. Thus initial temperatures were determined for all nodal points.

Heat transfer coefficients to the air for various plate temperatures were initially calculated using empirical correlations by McAdams (11). It was later decided to try and obtain experimental values for the coefficients. The following procedure was used. The plate was heated to the maximum temperature obtainable. The heaters were then shut off. As the plate cooled, the temperature of the plate was recorded as a function of the time required to cool (Figure 7). By assuming 1) the plate is isothermal during this process, 2) all heat is lost through the surface and, 3) changes in physical properties of air are negligible, a coefficient can be computed based on cooling time of the plate.

$$\text{FOR CONVECTION TO AIR} \quad q = h_a A_p (T_a - T_p) \quad (1-3)$$

$$\text{FOR COOLING OF PLATE} \quad q = W_p C_p \frac{dT_p}{dt} \quad (1-4)$$

By equating the equations, separating variables, and integrating, the final result is:

$$h_a = \left(\frac{W_p C_p}{A_p} \right) \frac{\ln \left(\frac{T_a - T_{p1}}{T_a - T_{p2}} \right)}{(t_2 - t_1)} \quad (1-5)$$

At a plate temperature of 380°C, the heat transfer coefficient calculated from the experimental method was 0.000362 cal/cm²-sec-°C. McAdams' correlations gave a coefficient of 0.00094 cal/cm²-sec-°C for the same plate temperature.

Steady state in the plate was disrupted experimentally by introducing a mass of liquid onto the plate's surface. This was simulated in the mathematical model by changing the heat transfer

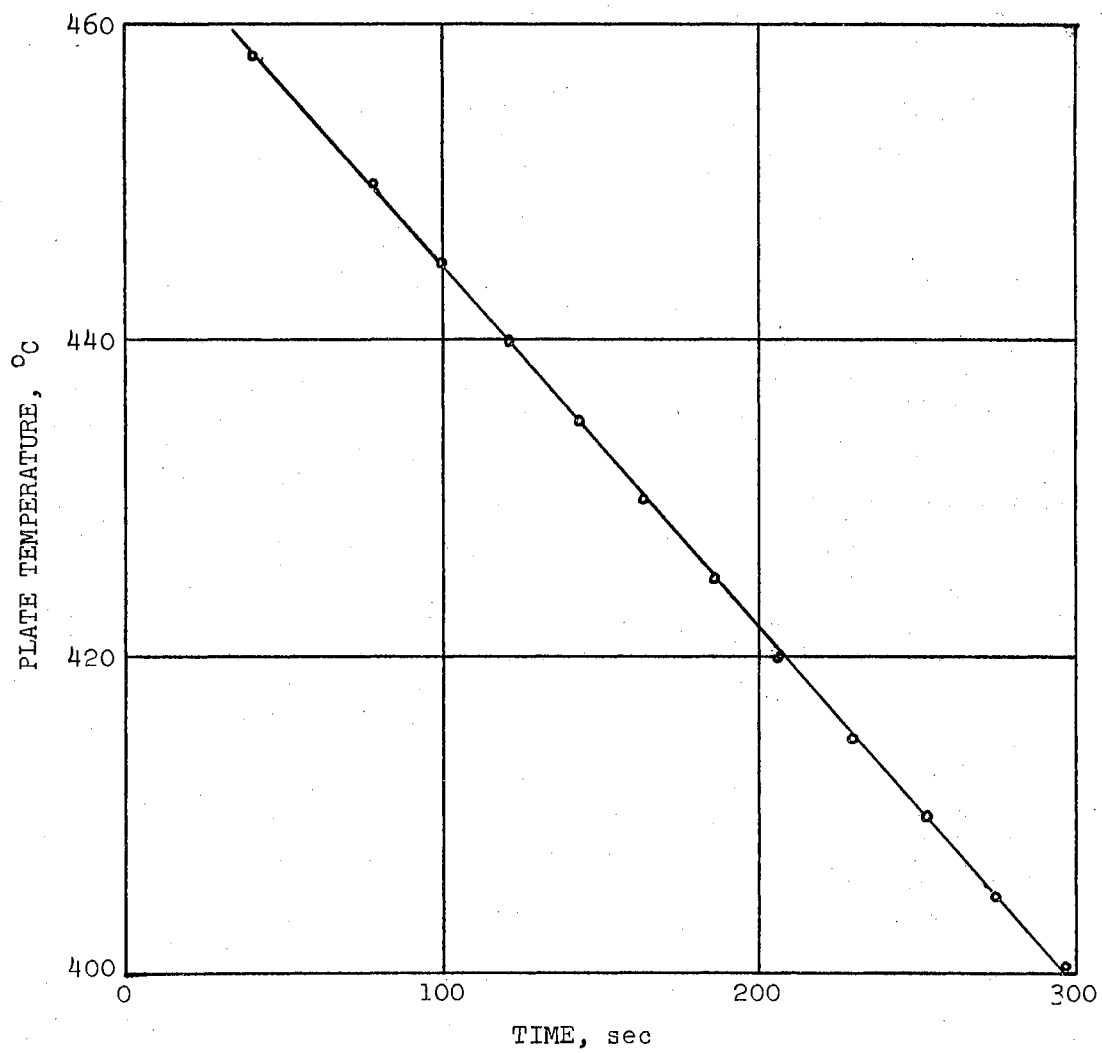


Figure 7. Cooling Rate of Small Stainless Plate

coefficient to the surroundings over a portion of the plate. Patel (12) determined experimentally the thickness of a liquid mass as a function of its volume for various plate temperatures (Figure 8). The liquid was assumed to be cylindrical until the volume was very small. Thus for a given volume of liquid, the radius was known. With the assumption that both liquid center and plate center coincided, it was known how much of the plate was covered by the liquid. The portion of the plate covered by the liquid saw a different heat transfer coefficient than the rest of the plate.

The liquid was slowly evaporated from the plate by using the following equation.

$$\frac{dM}{dt} = q A_1 h_1 (T_p - T_l) \quad (1-6)$$

where $\frac{dM}{dt}$ = Liquid evaporation rate
 q = Heat flux to the plate
 A_1 = Projected liquid area on plate
 h_1 = Heat transfer coefficient to liquid
 T_p = Temperature of plate
 T_l = Temperature of liquid

Heat transfer coefficients to the liquid were calculated from experimental total evaporation times using the equation:

$$h_1 = \frac{(V_i - V_f) \rho_L (1/2C_v T' + L)}{A_1 \Delta T (t_i - t_f)} \quad (1-7)$$

where $1/2C_v T' + L = C_v \left(\frac{T_p - T_s}{2} - T_s \right) + L$

V_i = Initial volume of liquid sample

V_f = Final volume of liquid sample

C_v = Vapor heat capacity

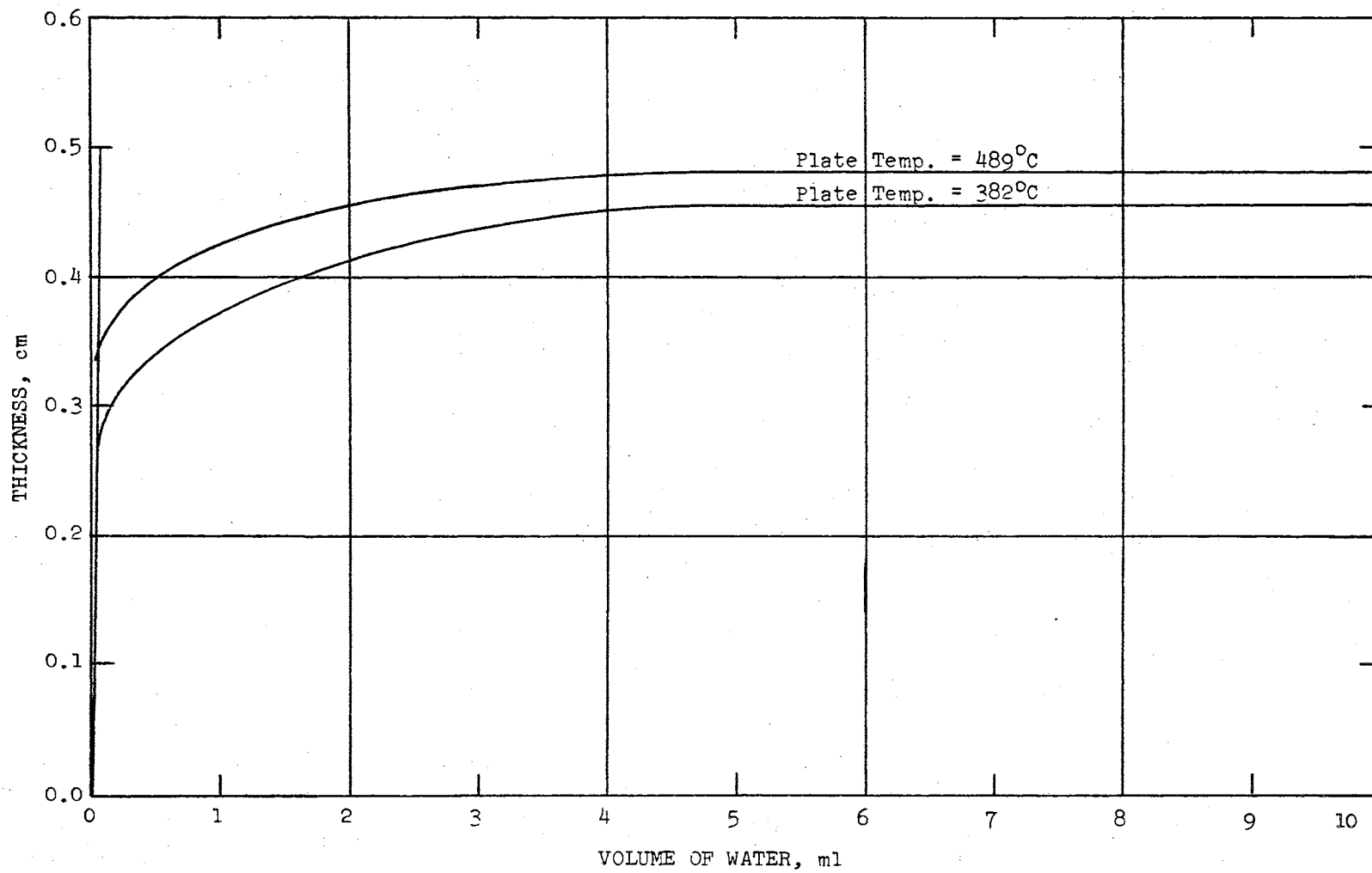


Figure 8. Thickness of Water Masses as a Function of Volume

L = Latent heat of vaporization

t_i = Initial time

t_f = Final time

Boundary conditions of the plate complicated the transient heat conduction problem. The lower boundary condition was a constant heat flux to the bottom of the plate. At the surface, the heat transfer coefficient varied with time and radial distance from the center of the plate. Because of the complexity of this transient heat conduction problem, the only feasible method of solution was to employ a digital computer and numerical techniques. Numerical solutions to heat flow problems are classed as either implicit or explicit. Implicit methods have the property that computations of temperatures at a given time level requires solution of a simultaneous system of algebraic equations. On the other hand, explicit method yield the temperature at a given time level directly from previously computed temperatures. Explicit methods generally do not have the advantage of the stability properties of implicit methods. An explicit method was chosen because of the simplicity.

A single equation, like equation 1-2, of the set of m differential equations may be written as

$$C_q \frac{dT_q}{dt} = \sum_{j=1}^P K_{j,q} (T_j - T_q) + P_q \quad (1-8)$$

for $q = 1, 2, 3 \dots m$

One such computing method for solving this set of equations is the modified Euler method.

$$T_{q,n+1} = T_{q,n} + \frac{\Delta t}{C_q} \sum_{j=1}^P K_{j,q} (T_{j,n} - T_{q,n}) + hP_q/C_q \quad (1-9)$$

This method of solution could not be used practically because of its demand for stability. Stability for the Euler method required

$$\Delta t \leq C_q / \sum_{j=1}^P K_{j,q}$$

for all q .

For this particular problem, the thickness of the plate was the determining factor for the size of the time interval. To insure stability using the modified Euler method, a time interval of less than 0.3 second was required. The use of such a small time interval was not feasible since calculations had to be made until a total time of 900 seconds had elapsed. This required too much computer time.

A method called exponential approximation was selected for its stability and simplicity. The general equation has the form

$$T_{q,n+1} = Z T_{q,n} + \frac{(1-Z) \left\{ \sum_{j=1}^P K_{j,q} T_{j,n} + P_{q,n} \right\}}{\sum_{j=1}^P K_{j,q}} \quad (1-10)$$

where $Z = \exp\left(\frac{-\Delta t}{C_q} \sum_{j=1}^P K_{j,q}\right)$

Larkin (8) states that for any $\Delta t > 0$ the method is unconditionally stable. Truncation error for the exponential method is the same as for the modified Euler method. The error at any time in any temperature is proportional to Δt .

Even with an unconditionally stable method, the time interval

had to be small to keep the truncation error as small as possible. A half second interval was used until the initial cooling rate was less than 0.5 degree Centigrade per increment. The interval was then increased to one second until 200 seconds had elapsed, at which time the experimental results had already reached the maximum temperature drop. The time interval was again increased to 5 seconds. The increases in the time intervals were made solely to conserve computing time. For each interval, a set of 20 exponential equations had to be solved which required considerable computer time. A larger time interval was used for comparison. Starting with an initial interval of 0.5 second, the interval was doubled each time the cooling rate dropped to less than 0.5°C per interval until the time interval became greater than 10 seconds. At this time, the interval was changed to 10 seconds and remained constant throughout the rest of the computations.

CHAPTER VI

DISCUSSION OF RESULTS

The cooling effect of extended masses in film boiling was found to be quite extensive, especially for the surface area directly beneath the liquid. Figures 9, 10, 11, and 12 show the change in the initial plate temperature for various volumes of water and ethanol. The surface temperature of the plate dropped rapidly after the liquid was placed on the surface. More than half of the total temperature drop for water occurred in the first twenty seconds. The maximum temperature drop was reached in less than one-third of the total evaporation time. From that point, the plate began to reheat. The rapid initial cooling and slow reheating of the plate caused the average surface temperature beneath the liquid during evaporation to be lower than the arithmetic average of the initial and minimum temperature. The average surface temperature was actually between 60 to 75 percent of the maximum temperature drop below the initial temperature.

Several factors influenced the extent of cooling in the plates. They are 1) the amount of liquid, 2) the kind of liquid, 3) the initial plate temperature, 4) the dimensions of the plate, and 5) the plate material.

Small droplets caused an insignificant and less than a degree temperature drop of the plate surface. Extended masses, however,

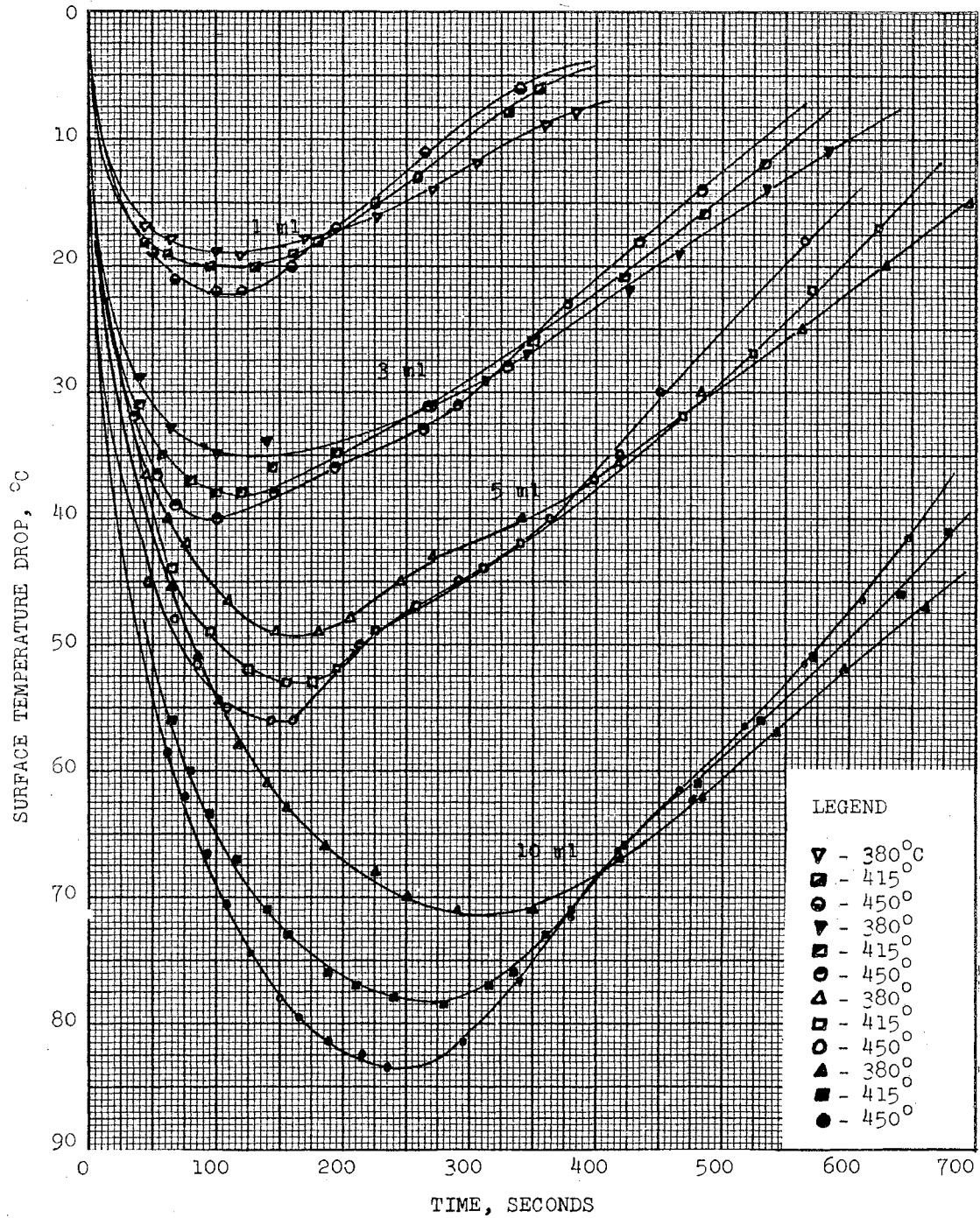


Figure 9. Surface Temperature Transients of Small Stainless Plate for Water

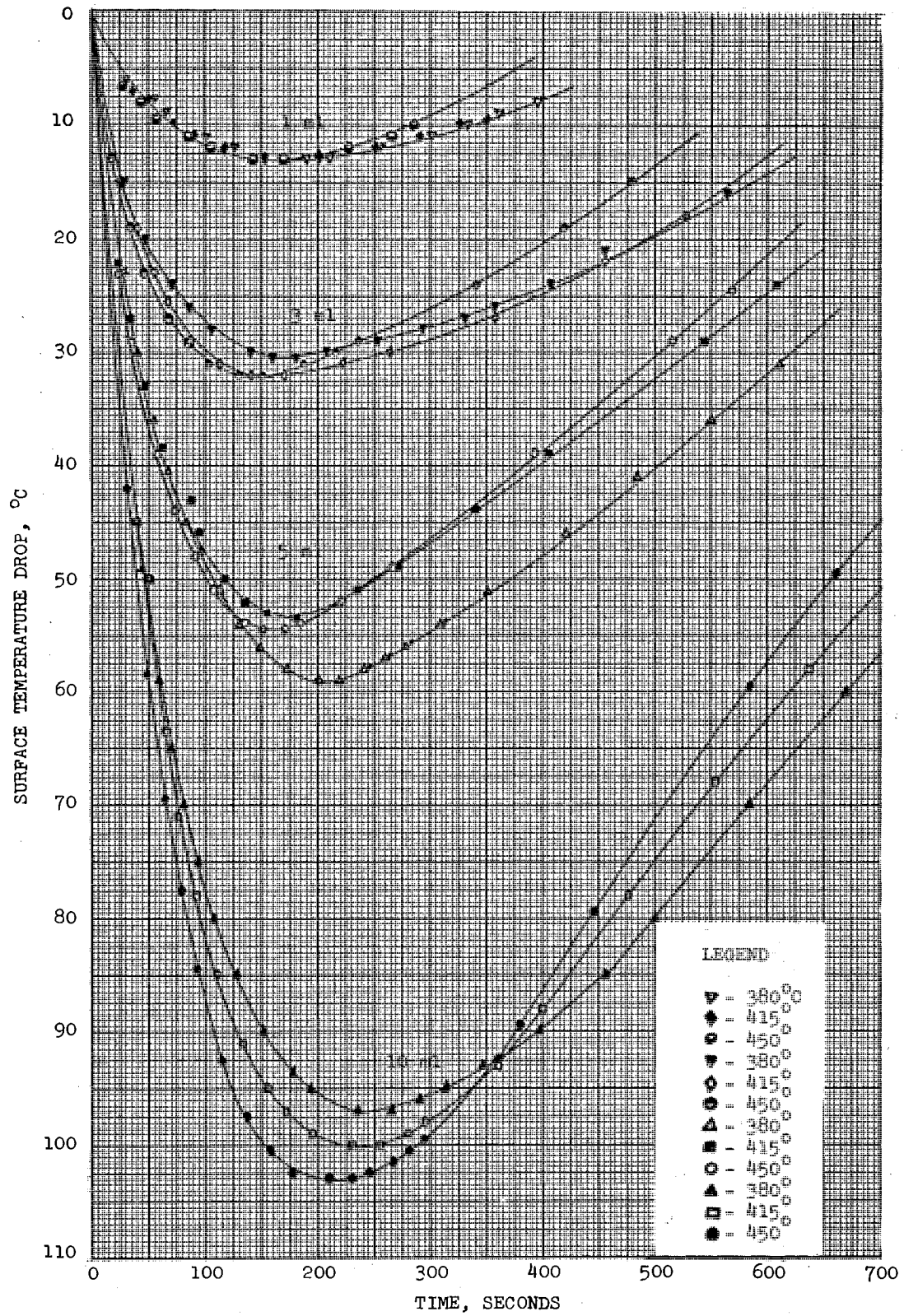


Figure 10. Surface Temperature Transients of Silver Plate for Water

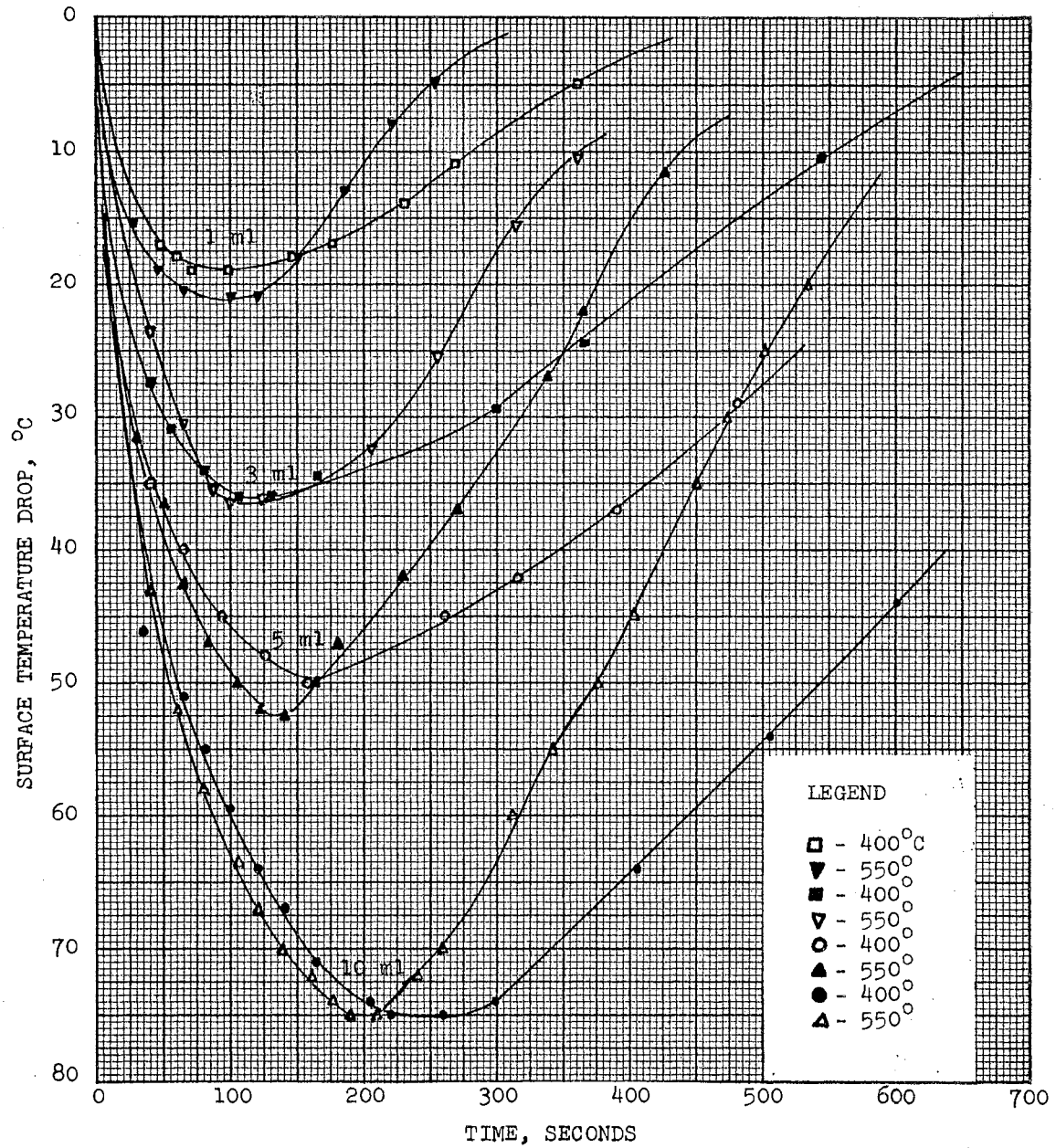


Figure 11. Surface Temperature Transients of Large Stainless Plate for Water

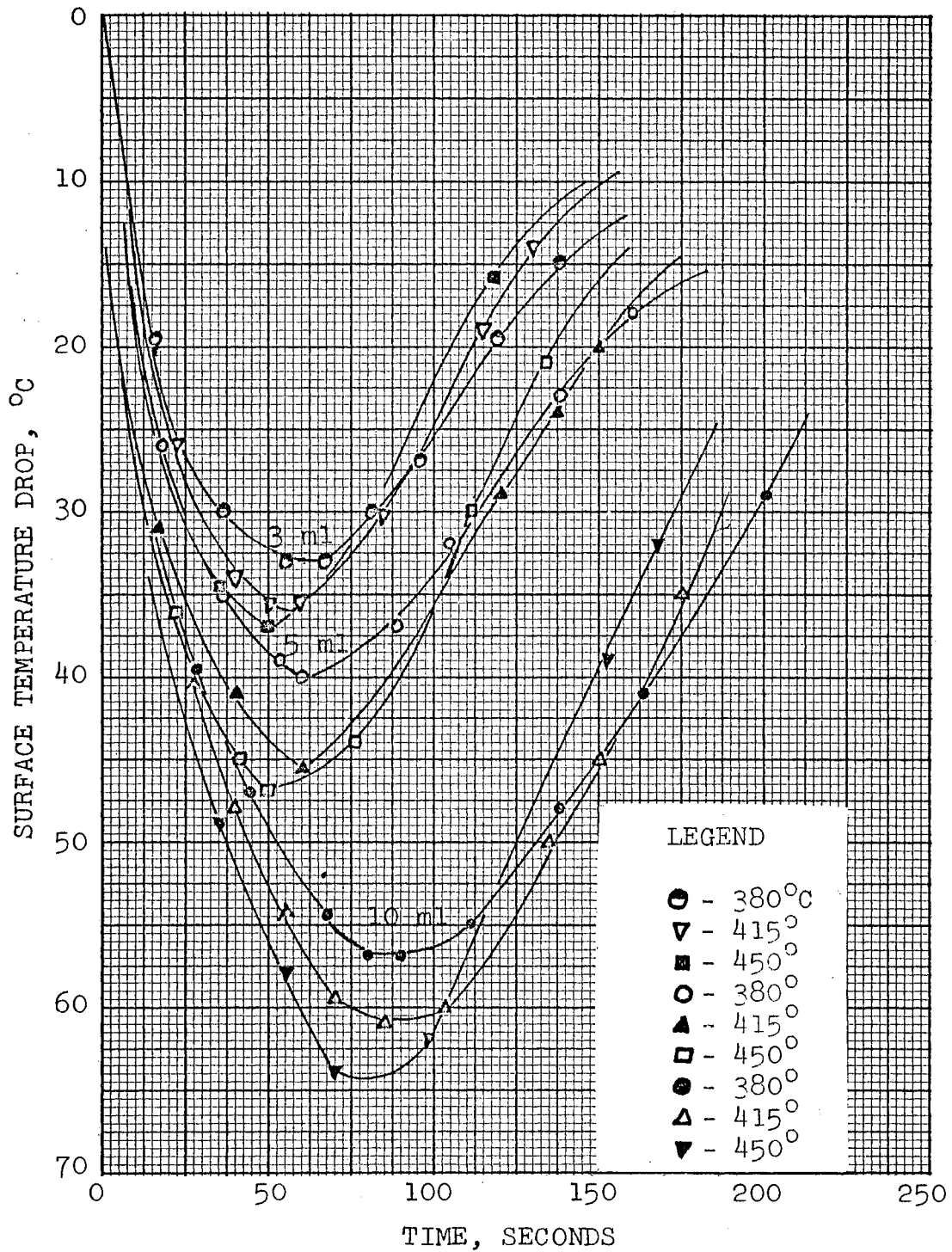


Figure 12. Surface Temperature Transients of Small Stainless Plate with Ethanol

had a pronounced cooling effect on the plates. The transient temperature curves in Figure 9, for instance, show how the volume of water influenced the cooling of the plate. Figure 12 shows the effect of various volumes of ethanol. The kind of liquid influences the degree of cooling also. At an initial surface temperature of 380°C , 10 ml of water cooled the small stainless steel plate 72°C , and 10 ml of ethanol cooled the plate 55°C . For 5 ml, water lowered the temperature 49°C and ethanol lowered it 40°C .

Figure 9 clearly shows the effect of initial surface temperature for a given volume of water on the maximum temperature drop. The maximum surface temperature drop on the small stainless plate with 10 ml of water and the corresponding initial temperature was 72°C for 390°C , 78°C for 415°C , and 84°C for 450°C . For all water volumes used except 0.5 ml, sufficient data were obtained to give a smooth curve of the cooling of the plate. The slow evaporation rate of water allowed ample time to record transient temperatures at close intervals.

The effects of plate dimensions and physical properties upon the extent of cooling are closely related. This may be explained by considering the cooling that occurred in the small stainless steel plate and the silver plate during the film boiling of water masses. The surface temperature under the liquid for the silver plate fell less than for the stainless for volumes of water up to and including 3 ml. For 5 ml and larger volumes, the silver surface cooled more. In order to understand the reason for this, both the dimensions and physical properties of the two plates must be considered.

A simplified model is developed as seen in Figure 13. The plate is divided into two sections; the area of the plate covered by the liquid, and the area exposed to the air. The mean temperature of the section covered by liquid is T_{pl} . The mean temperature representing the section exposed to air is T_{pa} . A difference in T_{pl} and T_{pa} results in a flow of heat from one section to the other. This flow of heat is represented by Q and is assumed to move from the air section to the liquid section of the plate. The heat flux, q , to the bottom of the plate is constant.

The equations for the accumulation of heat in each section are:

SECTION UNDER LIQUID

$$A_l \times \rho_p C_p \frac{dT_{pl}}{dt} = qA_l - h_l A_l (T_{pl} - T_l) + Q \quad (1-11)$$

SECTION EXPOSED TO AIR

$$A_a \times \rho_p C_p \frac{dT_{pa}}{dt} = qA_a - h_a A_a (T_{pa} - T_a) - Q \quad (1-12)$$

The equations, as presented give the instantaneous cooling rate of each section, dT_{pl}/dt and dT_{pa}/dt . In order to compare the cooling in silver and stainless steel plates, average cooling rates for the total temperature drop in each plate are needed. The cooling rates are thus changed to $\Delta T_{pl}/\Delta t$ and $\Delta T_{pa}/\Delta t$ to represent the temperature drop in each section during a certain time. Since the area of the liquid, A_l , is held constant, an average area must be used to represent the liquid during the evaporation time, Δt , considered. The heat transfer coefficients

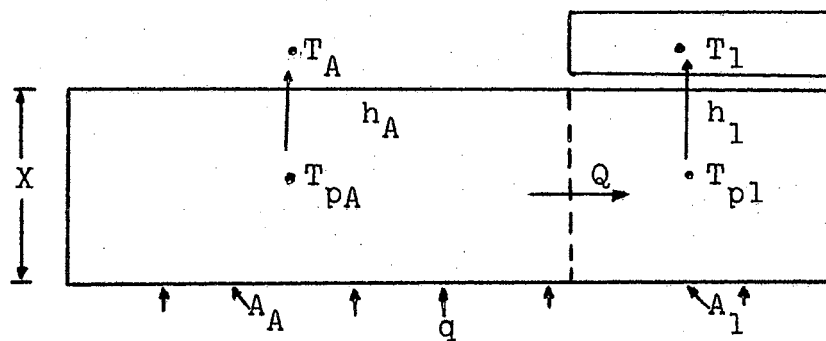


Figure 13. Simplified Plate Model

to the air and to the liquid, h_a and h_l , are also held constant during Δt .

Experimental data are available for $\Delta T_{pl}/\Delta t$ and $\Delta T_{pa}/\Delta t$ during the evaporation of 5 and 3 ml volumes of water. Using this experimental data, equation 1-11 is solved for Q . The value found for Q is then used in equation 1-12, and ΔT_{pa} is calculated and compared to the experimental value of ΔT_{pa} . Table I contains the calculated values for each group in equations 1-11 and 1-12, and gives the comparison of plate cooling in the air section, ΔT_{pa} . The relative magnitudes of each group are the main objectives for solving the equations. The values given in Table I show that the heat transfer to the liquid group is the significant term in equation 1-11. The accumulation term, $A_a X_p C_p \Delta T_{pa}/\Delta t$, is the most significant term in equation 1-12. The heat to the bottom of the plate and the heat transfer to the air almost cancel the effect of each other in equation 1-12, as they would do at steady state with no liquid on the plate. The key group which shows the effect of both dimensions and physical properties of the plate is the accumulation in equation 1-12.

The low thermal conductivity of stainless steel, 12 Btu/hr-ft²-°F, requires the average temperature drop in the air section, ΔT_{pa} , to be small. Silver's high conductivity, 242 Btu/hr-ft²-°F, allows ΔT_{pa} to be only slightly less than ΔT_{pl} . For a given volume of water, ΔT_{pl} can be greater for silver than for stainless steel only if A_a for the silver plate is sufficiently smaller than A_a for the stainless steel plate to compensate for the difference in their thermal conductivities.

TABLE I

CALCULATED VALUES OF TERMS IN EQUATIONS 1-11 AND 1-12

	$A_1 X C_p \frac{\Delta T_{p1}}{\Delta t}$	qA_1	$h_1 A_1 (T_{p1} - T_1)$	Q	$A_A X C_p \frac{\Delta T_{pA}}{\Delta t}$	qA_A	$h_A A_A (T_{pA} - T_A)$	A_A	$\frac{\Delta T_{pA}}{\Delta t}$
	cal/sec		cal/sec		cal/sec		cal/sec	ft ²	°C/sec
<u>5 ml</u>									
SILVER	-1.30	1.16	-8.85	6.30	-5.25	4.77	-3.72	36.7	-0.53
STEEL	-1.80	1.16	-9.03	6.07	-5.98	9.38	-9.29	72.1	-0.19
<u>3 ml</u>									
SILVER	-0.682	0.635	-5.27	3.95	-3.05	5.30	-4.40	40.7	-0.25
STEEL	-0.846	0.635	-5.16	3.68	-3.58	9.89	-9.79	76.1	-0.09

Since the thickness is the same for both plates, only the relative areas exposed to air are a factor here. With plates of different thickness, the relative volumes of the air sections would have to be considered. From experimental data, the surface temperature, initially at 380°C, dropped 49°C for the stainless plate and 59°C for the silver plate during the evaporation of 5 ml of water. Three ml of water cooled the surface beneath the liquid 35°C for the stainless steel and 30°C for the silver plate. Equations 1-11 and 1-12 suggest that if the area of the silver plate were the same as the area of the stainless plate, 5 ml of water would cool the surface of the silver only 35°C.

Borishansky mentions the effect of plate dimensions in his work. He used two brass plates of different thickness, 2 mm and 8 mm, to determine the temperature for the cessation of nucleate boiling, t_{cp1} , and the temperature for the start of film boiling, t_{cp2} , for water. He noted that for the 2 mm plate, t_{cp1} was 25°C higher than for the 8 mm plate. A smaller effect, approximately 5°C, was noted for t_{cp2} . Borishansky stated that the difference in the critical temperatures was apparently due to deeper local cooling of the heating surface.

Borishansky also noted a difference in t_{cp1} and t_{cp2} using a 5 mm copper plate and a 2 mm brass plate. He made no comment on the results other than to say his experiments show the material of the heating surface does affect the values of t_{cp1} and t_{cp2} . A plot of this effect presented in his paper appears confusing. From an evaluation of his previous data on the 2 mm brass plate, however, the plot can be interpreted as showing t_{cp1}

and t_{cp2} for the brass plate were $20^{\circ} - 25^{\circ}\text{C}$ higher than t_{cp1} and t_{cp2} for the copper plate.

The thermal conductivity of the heating surface does seem to have an effect on the Leidenfrost point. The surfaces of both the silver and stainless plates were covered with water at a plate temperature of 350°C . More water was added occasionally to keep the surfaces covered. After the large initial temperature drop, the plates cooled slowly until the water fell out of film boiling. Nucleate boiling was initiated on the stainless steel plate from a small area and spread until all the water dropped out of film boiling. The onset of nucleate boiling occurred at a plate temperature of 273°C for the stainless steel plate. The uniform cooling of the silver plate allowed the water to stay in film boiling until at 236°C the entire water mass began nucleate boiling at the same time. Borishansky reported the beginning of film boiling occurred at 245°C for small water droplets on a brass plate. If the interpretation of his plot is right, he found that film boiling began at 220°C for a copper plate.

It is reasonable to assume, then, that stable film boiling begins at a lower plate temperature for a material of high thermal conductivity than for a material of low conductivity. The damping of severe local cooling in the plates of high thermal conductivities is responsible for the lower threshold of film boiling.

Total evaporation times for the entire range of water masses studied are presented in Table II. Comparisons of evaporation times

TABLE II

TOTAL EVAPORATION TIMES FOR WATER ON DIFFERENT PLATES

Plate	seconds					
	0.5 ml	1 ml	3 ml	5 ml	8.8 ml	10.8 ml
PLATE TEMPERATURE 380°C						
STAINLESS STEEL	284	381	583	685	844	929
SILVER	276	385	563	706	836	916
PLATE TEMPERATURE 415°C						
STAINLESS STEEL	270	358	531	625	-	811
SILVER	265	348	526	616	-	815
PLATE TEMPERATURE 450°C						
STAINLESS STEEL	251	343	483	564	688	722
SILVER	241	320	478	569	-	768

for the silver plate and the small stainless steel plate show little difference. The thermal diffusivity is $1.65 \text{ cm}^2/\text{sec}$ for silver and $0.0534 \text{ cm}^2/\text{sec}$ for stainless steel. This indicates that the thermal diffusivity of the heating surface has no appreciable effect on the total evaporation times of liquids in film boiling.

For his studies of film boiling for water volumes up to 5 ml, Baumeister did not report any temperature drops within his plates. He only mentioned local cooling of the plate surface when the water flowed from a pipette onto the plate in a fine jet. He noted that at a low plate temperature, 320°C , the cooling effect of the jet initiated nucleate boiling at the point of contact. By directing the jet against a nonwetting surface which drained onto the plate, the initiation of nucleate boiling was avoided.

Two of the plates Baumeister used were machined flat and allowed the water droplets to move across the entire plate surface. To keep the droplets from colliding with the barrier walls of the plates, a stainless steel plate was machined with a 1 degree apex angle. This slight dip kept the droplets confined to the center of the plate. Even with this arrangement, Baumeister did not state whether he observed any cooling under the water. This could possibly be explained by the thickness of the plate and the location of thermocouples. The slightly dished plate had a thickness of $1-1/8$ inches and the nearest thermocouple to the droplets was $3/4$ -inch below the surface.

The mathematical model developed during this thesis study was adjusted to describe the plate of Baumeister, and the transient

temperatures beneath the water droplets were computed. The model predicted a 27°C surface temperature drop for a 5 ml water droplet and 23°C for a 3 ml droplet with an initial plate temperature of 380°C . However, at the thermocouple position the temperature fell a maximum of 11°C and 8°C for 5 ml and 3 ml volumes respectively. Thus Baumeister only saw a small temperature change for the largest droplets he investigated.

Although Patel noticed extended masses in film boiling caused a decline in plate temperature, he did not realize the magnitude of the cooling effect. For determination of total evaporation times, Patel wanted the liquid masses to be free from any support other than their own vapor. By keeping an 8-inch diameter plate level, the masses moved randomly across the surface. Thermocouples were installed $1/16$ -inch below the surface to give the temperature profile across the plate. The random movement of the liquid required the recording of temperatures at all sections of the plate. Patel then averaged these temperatures to obtain the transient behavior within the plate.

The low thermal conductivity of stainless steel restricted the cooling of the plate to the area immediately under the liquid mass. The wandering of the liquid, however, allowed the major portion of the plate surface to be cooled, preventing any area from being exposed to the full cooling effect. Local cooling as observed by Patel was thus dampened by the movement of the liquid over a large surface area.

Figure 14 shows the temperature drop in the small stainless steel plate approximately one inch from the center of the liquid

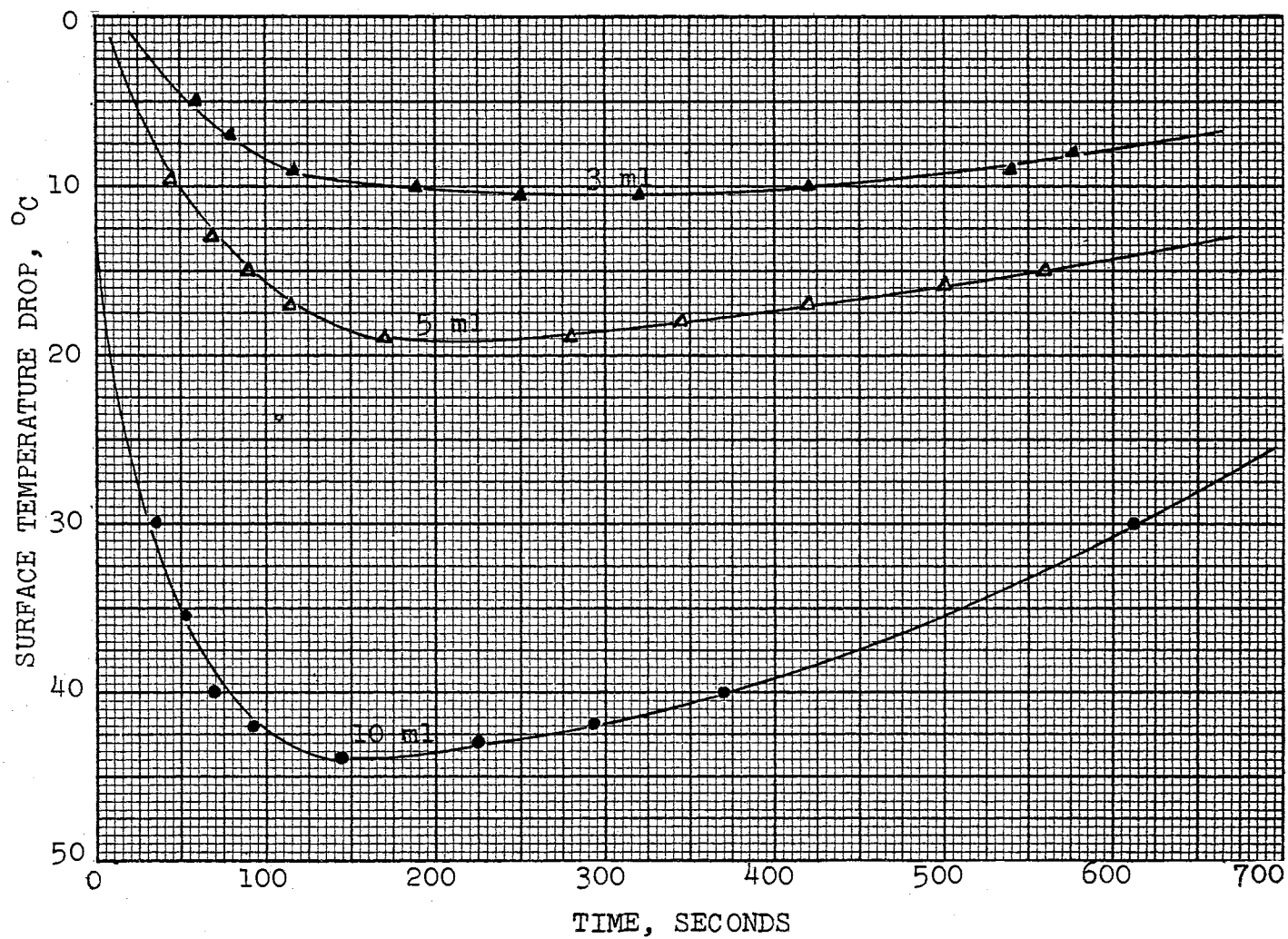


Figure 14. Temperature Transients One Inch from Liquid Center

mass and 1/16-inch below the surface. The curves show that the plate cools significantly only in the area directly under the liquid. The thermocouple registered a 44°C temperature drop for 10 ml since it was under the edge of the water mass. The mathematical model predicted temperature drops of 15.5°C and 30°C for 5 ml and 10 ml water volumes as compared to experimental readings of 18°C and 44°C for the stainless plate.

Although the analytical study was not a complete success, valuable insight was gained about the physical problem. By using heat transfer coefficients obtained from experimental total evaporation times, the maximum drop of the surface temperature could be predicted. This calculated temperature compared favorably with the experimental results (Table III). The predictions of the temperature drop on the surface one inch from the center of the water droplet by the model agreed reasonably well with the experimental results. The mathematical model was able to predict the total temperature drop, but it was unable to match the experimental transient curves. Figure 15 shows experimental results as compared to the curve predicted numerically. The model poorly represented the actual reheating of the plate. The initial cooling as calculated by the model followed the experimental curve fairly well until the maximum temperature drop was approached. The deviation became significant at this point.

Part of the blame for the deviation can be placed on the difficulty in describing the physical problem mathematically. The heat transfer coefficients to the liquid were rough average values obtained from the differences between the total evaporation

TABLE III

COMPARISON OF MAXIMUM SURFACE TEMPERATURE DROP

INITIAL PLATE TEMPERATURE 380°C

<u>Liquid Volume</u>	<u>Experimental</u>	<u>Computed</u>
DIRECTLY UNDER LIQUID CENTER		
5 ml	51°C	53°C
10 ml	71.5°C	69°C
ONE INCH FROM LIQUID CENTER		
5 ml	18°C	16°C
10 ml	44°C	30°C

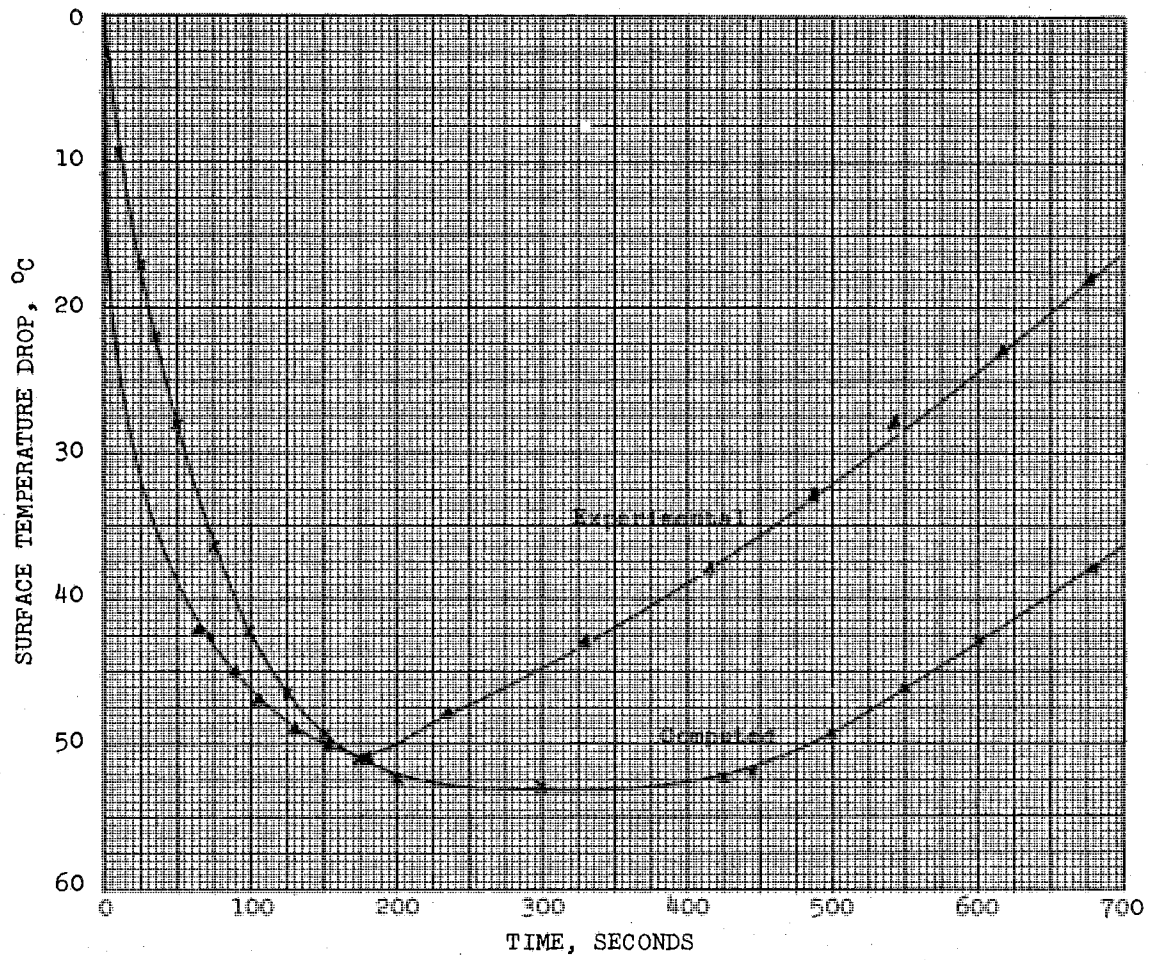


Figure 15. Comparison of Experimental and Computed Temperature Transients for 5 ml of Water

times for various volumes. Coefficients were calculated for evaporation between 10-8 ml, 8-5 ml, 5-3 ml, 3-1 ml, 1-0.5 ml, and 0.50-0.0 ml. A better representation of the actual heat transfer coefficient might be obtained by experimental determining total evaporation times from 1 ml to the range desired in 0.5 ml increments. A plot could be constructed to get a curve representing the mass evaporation rate as a function of the volume. An instantaneous coefficient could be calculated from this curve with the aid of the thickness of the liquid mass as a function of volume curve.

The present method of calculating the heat lost from a nodal point when its area was exposed partially to the liquid and partially to the air needs to be examined. The method now calculates the heat loss that occurs when the entire area over the nodal point is exposed to the air and when the entire area is exposed to the liquid. The temperature drop for the partially covered area is a weighted averaged of the drop predicted for no liquid and completely covered by liquid. The temperature drop is the sum of the drop with no liquid plus the product of the fraction of the total area covered by the liquid times the difference between the drop predicted for no liquid and the drop predicted for all liquid. A more sophisticated method for subdividing the nodal area to compensate for the evaporation liquid needs to be employed.

One of the major problems involved in the calculation of the temperature transients with this model was the time interval. The thickness of the actual plate demanded that a time interval

of less than 0.2 second be used to insure stability if a modified Euler numerical method of calculation were used. The exponential approximation method was used for the numerical solution of the problem because it was unconditionally stable for any time interval. Truncation error, however, became the limiting factor. Results obtained using two different time intervals as explained in Chapter V show the effect of truncation error. Using the larger time interval, the model predicted a 32°C temperature drop occurring at a time of 414 seconds for a 5 ml water volume at an initial plate temperature of 380°C. For the same conditions, the model predicted a 53°C temperature drop occurring at 310 seconds with the smaller interval. Experimental results show a 51°C drop at a time of 210 seconds. Using a 0.5 second interval until total evaporation occurred or even a small interval until the maximum temperature drop is reached would probably give a little better result. Until the problems with the heat transfer coefficients are solved, however, the added results obtained by using a small time increment throughout the entire calculations do not justify the additional cost or use of valuable computer time.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The following significant conclusions may be drawn from the previous discussions:

- (1) The heating surface is cooled significantly when extended liquid masses are placed on the plate.
- (2) Local cooling of the surface is more severe for a plate of low thermal conductivity.
- (3) The thermal diffusivity of a plate has no noticeable effect on the total evaporation time of a liquid in film boiling at the same initial plate temperature.
- (4) Disagreements for the Leidenfrost point of water are probably due to the different degrees of local cooling, controlled by the thermal conductivities of the different plates.
- (5) Size and thermal conductivity of a plate both affect the extent of the cooling. A large, thick plate of high thermal conductivity should have the smallest temperature transients.
- (6) The Leidenfrost point for water at one atmosphere using a completely submerged plate is 236°C for silver and 273°C for stainless steel.

- (7) Other liquids have noticeable cooling effects on the heating surface though not as severe as for water.
- (8) The mathematical model will successfully predict the maximum temperature drop in the plate.
- (9) The model can not presently match the experimental transient temperature curves.

The following recommendations are made in view of the results of this study.

- (1) A large diameter, thick plate of high thermal conductivity should be used for any further studies of film boiling on a horizontal surface.
- (2) A silver or copper plate may be nickel plated to provide a smooth and stable protective coating.
- (3) A smooth curve representing heat transfer coefficients as a function of liquid volume needs to be determined.
- (4) A better method of representing the changing volume of a liquid mass over the heating surface should be developed and built into the mathematical model.

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APPENDIX A

CALIBRATION OF THERMOCOUPLES FOR SILVER PLATE

Five chromel-alumel thermocouples with 3-foot leads were used for temperature measurements in the silver plate. The thermocouples had a diameter of 0.015 inch. These particular metals were selected for their high thermal emf output per degree of temperature difference and stability over the temperature range anticipated.

The thermocouples were calibrated in the Leidenfrost Phenomenon Laboratory at Stillwater, utilizing water at atmospheric pressure. Data were taken with the same potentiometer which was used to take the test data, with the temperature of melting ice as reference point.

A total immersion, calibrated thermometer with the range -1° to $+101^{\circ}\text{C}$ in 0.1°C increments was used to check the thermocouples. Corrections for the emergent stem was made as specified by the National Bureau of Standards Certificate, No. NBS186c, Test No. 171285.

Thermocouples for the stainless steel plates were calibrated by Patel (12) and Lee (9).

Thermocouple No.	Reading mv	Temperature °C
1	4.00	97.75
2	4.00	97.75
3	4.00	97.75
4	4.00	97.75

Corrected Thermometer Reading $97.7^{\circ}\text{C} \pm 0.1^{\circ}$

Thermocouple No.	Reading mv	Temperature °C
1	0.91	22.75
2	0.91	22.75
3	0.91	22.75
4	0.91	22.75

Corrected Thermometer Reading $22.80^{\circ}\text{C} \pm 0.02^{\circ}$

APPENDIX A

CALIBRATION OF PIPETTES WITH WATER AT 23°C

Liquid Volume ml	Liquid Mass gm	Deviation From Mean percent	Liquid Volume ml	Liquid Mass gm	Deviation From Mean percent	Liquid Volume ml	Liquid Mass gm	Deviation From Mean percent
10 ml	10.7610	-0.2610	8 ml	8.8182	-0.2090	5 ml	4.9977	-0.0880
	10.7950	+0.0540		8.8511	+0.1630		5.0067	+0.0920
	10.7897	+0.0050		8.8098	-0.3040		5.0079	+0.1160
	10.7975	+0.0770		8.8416	+0.0550		5.0044	+0.0460
	10.7570	-0.2980		8.8380	+0.0120		5.0032	+0.0220
	10.7936	+0.0410		8.8324	-0.0490		5.0020	-0.0020
	10.7864	-0.0260		8.8523	+0.1760		5.0047	+0.0520
	10.8048	+0.1440		8.8482	+0.1300		4.9992	-0.0580
	10.7917	+0.0230		8.8383	+0.0180		4.9995	-0.0540
	<u>10.8151</u>	<u>+0.2400</u>		<u>8.8369</u>	<u>+0.0020</u>		<u>4.9955</u>	<u>-0.1320</u>
10.7892	±0.1170	8.8367	±0.1120	5.0021	±0.0662			
3 ml	2.9878	-0.0301	1 ml	1.0231	0.0000	0.5 ml	0.5141	-0.4068
	2.9909	+0.0736		1.0242	+0.1075		0.5160	-0.0387
	2.9859	-0.0937		1.0209	-0.2150		0.5161	-0.0194
	2.9924	+0.1238		1.0265	+0.3323		0.5167	+0.0969
	2.9794	-0.3112		1.0187	-0.4301		0.5185	+0.4456
	2.9883	-0.0167		1.0270	+0.3812		0.5192	+0.5812
	2.9899	+0.0402		1.0222	-0.0880		0.5157	-0.0969
	2.9894	+0.0234		1.0257	+0.2541		0.5150	-0.2325
	2.9878	-0.0301		1.0223	-0.0782		0.5142	-0.3874
	<u>2.9956</u>	<u>+0.2309</u>		<u>1.0205</u>	<u>-0.2541</u>		<u>0.5169</u>	<u>+0.1356</u>
2.9887	±0.0974	1.0231	±0.2140	0.5162	±0.2441			

APPENDIX B
TRANSIENT TEMPERATURE DATA

TABLE IB

TRANSIENT DATA FOR SMALL S.S. PLATE, INITIALLY 380°C, USING WATER

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C
0	0	0	0	0	0	0	0	0	0
64	45.5	45	36.5	39	29	44	17	40	11
85	51	61	40	63	33	65	18	67	12
101	54.5	76	42	100	35	100	19	120	12
118	57.5	109	46.5	139	34	120	19	150	11
140	61	148	49	270	31	170	18	174	10
160	63	180	49	312	29	227	16	198	9
185	66	205	48	346	27	270	14	246	7
225	68	245	45	425	22	306	12	282	5
250	70	272	43	466	19	360	9	287	4
290	71	341	40	535	14	383	8		
350	71	417	35	583	11				
418	67	482	30						
483	62	562	25						
543	57	628	20						
596	52	694	15						
658	47								
718	42								
830	32								
927	23								

TABLE IIB

TRANSIENT DATA FOR SMALL S.S. PLATE, INITIALLY 415°C, USING WATER

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME	TEMP DROP	TIME	TEMP DROP	TIME	TEMP DROP	TIME	TEMP DROP	TIME	TEMP DROP
SEC	°C	SEC	°C	SEC	°C	SEC	°C	SEC	°C
0	0	0	0	0	0	0	0	0	0
64	56	67	44	39	31	45	18	32	13
80	60	95	49	57	35	63	19	50	14
95	63.5	125	52	80	37	96	20	80	14
116	67	155	53	100	38	130	20	103	13
140	71	175	53	120	38	160	19	137	11
158	73	195	52	145	36	181	18	171	9
188	76	226	49	195	35	225	15	233	6
210	77	258	47	268	31	258	13	271	4
240	78	310	44	350	26	330	8		
280	78.5	338	42	422	21	355	6		
315	77	398	37	485	16				
335	76	468	32	532	12				
360	73	523	27						
379	71	570	22						
422	66	623	17						
480	61								
530	56								
572	51								
640	46								
678	41								
722	36								
779	31								
869	27								

TABLE IIIB

TRANSIENT DATA FOR SMALL S.S. PLATE, INITIALLY 450°C, USING WATER

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C
0	0	0	0	0	0	0	0	0	0
63	58.5	46.5	45	35	32	50	19	23	14
75	62	67	48	52	36.5	68.5	21	50	16
93	66.5	85	51.5	68	39	100	22	80	16
109	70.5	109	55	100	40	120	22	100	15
127	74.5	144	56	145	38	160	20	120	14
150	77.5	160	56	192	36	194	17	155	11
164	79.5	212	50	262	33	265	12	177	9
188	81.5	292	45	290	31	265	12	249	2
217	82.5	364	40	329	28	340	6		
235	83.5	419	35	378	23				
295	81.5	450	30	434	18				
339	76.5	565	18	482	14				
380	71.5								
417	66.5								
468	61.5								
518	56.5								
565	51.5								
610	46.5								
648	41.5								
739	-								

TABLE IVB

TRANSIENT DATA FOR SILVER PLATE, INITIALLY 380°C, USING WATER

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP °C	TIME SEC	TEMP °C	TIME SEC	TEMP °C	TIME SEC	TEMP °C	TIME SEC	TEMP °C
0	0	0	0	0	0	0	0	0	0
46	49	25	23	28.5	15	30	6	33	4
60	59	39	30	48	20	51	8	47	5
70	65	54	36	69	24	65	9	64	6
81	70	67	40.5	85	26	101	11	104	7
94	75	82	45	105	28	128	12	130	7.5
108	80	94	47.5	140	30	190	13	160	7.5
127.5	85	112	51	160	30.5	210	13	200	7
151	90	130	54	180	30.5	256	12	245	6
178	93.5	148	56	208	30	300	11	272.5	5
193	95	173	58	253	29	332	10		
235	97	200	59	293	28	360	9		
265	97	220	59	330	27	390	8		
290	96	241	58	357	26				
314	95	260	57	407	24				
348	93	276.5	56						
398	90	308	54						
454	85	350	51						
500	80	421	46						
585	70	485	41						
669	60	550	36						
713	55	612	31						
759	50	714	23						
805	45								
856	40								
916.5	35								

TABLE VB

TRANSIENT DATA FOR SILVER PLATE, INITIALLY 415°C, USING WATER

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP °C	TIME SEC	TEMP °C	TIME SEC	TEMP °C	TIME SEC	TEMP °C	TIME SEC	TEMP °C
0	0	0	0	0	0	0	0	0	0
39	45	24	22	25	15	36	7	35	4
51	50	34	27	40	19.5	48	8	46	5
64	63.5	47	33	53	23.5	71	10	66	6
76.5	71	62	38.5	67	26.5	87	11	110	7
92	78	88.5	43	87	29.5	118	12	160	7
111	85	93	46	112	31.5	150	13	222	6
133.5	91	118	50	140	32.5	200	13	259	5
155	95	136	52	170	32.5	250	12	265	-
171.5	97	154	53	223	31.5	290	11		
195	99	180	53.5	263	30.5	325	10		
230	100	234	51	357	27.5	347.4	9.5		
255	100	265	49	454	22.5				
279	99	340	44	526	18.5				
296.5	98	406	39						
312	97	543	29						
359	93	608	24						
400	88	615.6	-						
477	78								
552	68								
637	58								
725	48								
825	37								

TABLE VIB

TRANSIENT DATA FOR SILVER PLATE, INITIALLY 450°C, USING WATER

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C
0	0	0	0	0	0	0	0	0	0
31	42	24	23	18	13	27	6.5	30	4
49	58.5	34.5	29	33	19	42.5	8	44	5
64	69.5	58	39	46.5	23	57	9.5	61	6
77	77.5	74	44	66	27	85	11	80	7
93	84.5	91	48	87	29	104	12	90	7
115	92.5	108	51	102	31	143	13	150	7
137.5	97.5	134	54	130	32	170	13	202	6
157	100.5	150	54.5	150	32	228	12	241	5
177	102.5	170	54.5	187	31	265	11		
210	103	187	54	215	30	286	10		
230	103	221	52	237	29	319.2	-		
246	102.5	266	49	340	24				
267	101.5	393	39	419	19				
282	100.5	514	29	478	15				
295	99.5	568.6	24.5						
360	92.5								
380	89.5								
447	79.5								
584	59.5								
661	49.5								
747	39.5								
768.6	37.5								

TABLE VIIB

TRANSIENT DATA FOR LARGE S.S. PLATE, INITIALLY 400°C, USING WATER

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C
0	0	0	0	0	0	0	0	0	0
34.5	46	41	35	40	27.5	48	17	26	12
65	51	66	40	57	31	60	18	50	14
81	55	93	45	81	34	70	19	80	14
99	59.5	125	48	106	36	100	19	130	12
121	64	160	50	130	36	147	18	278	2
140	67	261	45	163	34.5	176	17		
164	71	316	42	298	29.5	230	14		
203	74	390	37	365	24.5	268	11		
221	75	480	29	543	10.5	362	5		
260	75	651	-						
298	74								
406	64								
504	54								
601	44								
833	-								

TABLE VIII B

TRANSIENT DATA FOR LARGE S.S. PLATE, INITIALLY 490°C, USING WATER

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C
0	0	0	0	0	0	0	0	0	0
46	45.5	31	34	37	23.5	32.5	15	30	11
62	51	43	37	51	26.5	49.5	18.5	40	11.5
79.5	57	57	39.5	76	29.5	76	20.5	60	11.5
98	62	76	43	108	31	90	21	113	10
118	66.5	91.5	45	140	33	142	15	155	7
140	69.5	115	47	206	30	166	13	196	3
169	72	140	47.5	230	28	192	11		
190	73	184	45	261	24	225	8		
210	73	213	43	283	22	297	3.5		
255	71	254	40	329	18				
328	61	308	35	368	15				
410	51	357.5	30	418	12				
487	41	400	25						
616	20.5	499	13						

TABLE IXB

TRANSIENT DATA FOR LARGE S.S. PLATE, INITIALLY 550°C, USING WATER

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C
0	0	0	0	0	0	0	0	0	0
41	43	31	31.5	39	23.5	26	15.5	25	12
61	52	51	36.5	66	30.5	44	19	60	14.5
79	58	66	42.5	87	35.5	65	20.5	75	15
104	63.5	82	47	100	36.5	100	21	137	9
120	67	104	50	124	35.5	120	21	188	4
138	70	124	52	205	32.5	150	18	195	-
160	72	140	52.5	259	25.5	186	13		
177	74	162	50	314	15.5	220	8		
190	75	180	47	360	10.5	253	5		
210	75	229	42						
241	72	270	37						
260	70	337	27						
311	60	363	22						
343	55	426	21.5						
375	50								
402	45								
450	35								
474	30								
502	25								
533	20								

TABLE XB

TRANSIENT DATA FOR SMALL S.S. PLATE, INITIALLY 380°C, USING ETHANOL

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C
0	0	0	0	0	0	0	0	0	0
28	39.5	19	26	16	19.5	30	19.5	30	13.5
45	47	37	34.5	37	30	40	19.5	84.1	-
68	54	53	39	55	33	102.8	-		
80	57	60	40	65	33				
90	57	89	37	80.5	30				
111	55	105	32	96.5	27				
138	48	139	23	119	19.5				
163	41	160.7	18	138	15				
200.9	29			144.9	-				

TABLE XIB

TRANSIENT DATA FOR SMALL S.S. PLATE, INITIALLY 415°C, USING ETHANOL

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C
0	0	0	0	0	0	0	0	0	0
27	40.5	21.5	31	22	26	40	20	36	14.5
40	48	41	41	40	34	95.3	7	77	5
54	54	60	45.5	50	35.5				
70	59.5	86	41	60	35.5				
85	61	120	29	81	30				
103	60	137	24	114	19				
136	50	150	20	130	14				
150	45								
175	35								
186	-								

TABLE XIIB

TRANSIENT DATA FOR SMALL S.S. PLATE, INITIALLY 450°C, USING ETHANOL

10 ml		5 ml		3 ml		1 ml		0.5 ml	
TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C
0	0	0	0	0	0	0	0	0	0
36	49	23.5	36	36.5	34.5	38	22	33	15.5
54.5	58	41.5	45	50	37	86.2	8	70.6	5
70	64	50	47	119	16				
98	62	76	44						
152	39	111	30						
167.6	32	134.1	21						

TABLE XIII B

TRANSIENT DATA 1 INCH FROM LIQUID CENTER, USING WATER ON SMALL S.S. PLATE AT 380°C

10 ml		5 ml		5 ml		3 ml		1 ml	
TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C	TIME SEC	TEMP DROP °C
0	0	0	0	0	0	0	0	0	0
36	30	59	10	46	9.5	59	5	75	2
52	35.5	81	13	68	13	79	7	130	3
70	40	101	15	90	15	118	9	160	3.5
93	42	135	17	114	17	190	10	383	3.5
143	44	170	18	170	19	250	10.5		
225	43	260	18	280	19	320	10.5		
293	42	345	17	420	17	420	10		
370	40	430	16	560	15	540	9		
612	30	500	15	694.2	-	576.8	8		
858	21	565	14						
891	20	608	13						
902.4	-	691.6	12						

TABLE XIVB

TRANSIENT DATA FOR WATER NEAR SATURATION TEMPERATURE

SMALL S.S. PLATE - 380°C

SILVER PLATE - 415°C

10 ml		5 ml		10 ml	
TIME	TEMP DROP	TIME	TEMP DROP	TIME	TEMP DROP
SEC	°C	SEC	°C	SEC	°C
0	0	0	0	0	0
33	32	27.5	27	24.5	36
41	35	47	32	41	50
56	40.5	57	35	60	63
63	46	61	38.5	80	74
92	51	97.5	43	96	81
116	56	120	45	119.5	85
149	61	133	46	125	89
167	63	150	47	143	93
190	65	180	47	156	95
215	66	223	46	190	98
222	67	243	45	215	99
243	68	279	43	240	99
290	69	388	38	270	98
320	69	524	28	291	97
340	68	632	18	306	96
368	67	665	16	333	94
393	65			354	92
437	61			396	87
479	58			470	77
719	38			542	67
820	28			626	57
890.6	22			713	47
				815.7	35

APPENDIX C
COOLING RATES OF TEST PLATES

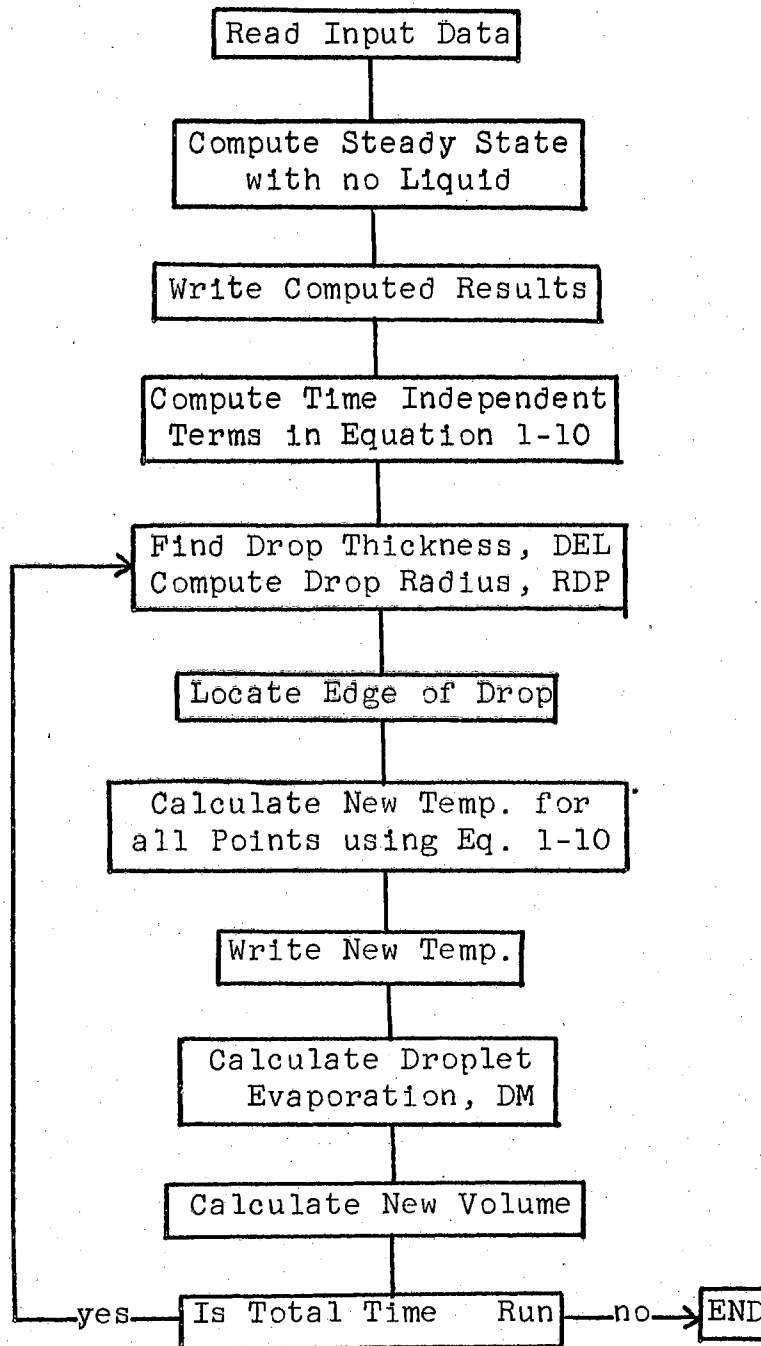
APPENDIX C

COOLING TIME OF PLATES IN AIR

Small Stainless		Large Stainless		Silver	
Time sec	Temp. °C	Time sec	Temp. °C	Time sec	Temp. °C
0	465	0	535	0	559
40	458	27	530	37	555
78	450	47	525	69	545
100	445	67	520	82.5	540
121	440	87	515	120	525
143	435	105	510	144	515
164	430	122	505	193	495
186	425	140	500	218	485
208	420	157	495	245	475
230	415	193	485	272	465
253	410	230	475	286	460
275	405	249	470	316	450
297	400	286	460	331	445
347	390	325	450	346	440
373	385	366	440	378	430
398	380	409	430	412	420
425	375	454	420	447	410
450	370	498	410	484	400
477	365	548	400	522	390
505	360	597	390	564	380
535	355	652	380	606	370
563	350	707	370	652	360
592	345	767	360	701	350
622	340	828	350	751	340
653	335	892	340	806	330
686	330	957	330	863	320
719	325	1027	320	954.5	305
753	320	1102	310	987	300
787	315	1180	300	1056	290
821	310	1264	290	1131	280
859	305			1209	270
896	300			1293	260
933	295			1386	250
974	290			1479	240
				1584	230

APPENDIX D
COMPUTER PROGRAM

BLOCK DIAGRAM




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1001 FORMAT(41X,46H FILM BOILING SURFACE TEMPERATURE TRANSIENTS )
1002 FORMAT(1X,115H LIQ. COEF HL AIR COEF HA DENSITY PLATE SPECIF
11C HEAT PLATE PLATE CONDUCTIVITY TIME INTERVAL POWER INPUT )
1003 FORMAT(1X,112H CAL/(CM)*(CM)*(SEC)(DEG.C) GMS/CU.CM. CAL/(GM
1)(DEG.C) CAL/(CM)(SEC)(DEG.C) SECONDS CAL/SEC SQCM)
1004 FORMAT(F10.7,5X,F10.7,5X,F10.7,5X,F10.7,10X,F10.7,5X,F10.7,5X,
1F12.9)
2001 FORMAT(6F10.7)
2002 FORMAT(7F10.7)
2003 FORMAT ( 3F10.5)
2004 FORMAT(4F10.6)
1006 FORMAT( 5X,7HTIME = ,F7.3,5X,16H SECONDS T1 = ,F7.3, 5X,6HT2 = ,
1 F7.3, 5X,6HT3 = ,F7.3, 5X,6HT4 = ,F7.3,5X,6HT5 = ,F7.3)
1007 FORMAT(30X,5HT6 = ,F7.3, 5X,6HT7 = ,F7.3, 5X,6HT8 = ,F7.3, 5X,
1 6HT9 = ,F7.3,5X,6HT10 = ,F7.3)
1008 FORMAT(5X,9HVOLUME = ,F8.5,3X,2HML,3X,5HT11= ,F7.3, 5X,6HT12 = ,
1F7.3, 5X,6HT13 = ,F7.3,5X,6HT14 = ,F7.3,5X,6HT15 = ,F7.3)
1009 FORMAT(30X,5HT16= ,F7.3, 5X,6HT17 = ,F7.3, 5X,6HT18 = ,F7.3, 5X,
1 6HT19 = ,F7.3,5X,6HT20 = ,F7.3)
3001 FORMAT (1HJ)
3002 FORMAT (1HK)
200 READ(1,2001) HL, HA, RHO, C, BK, DT
READ(1,2002) DR, R1, R2, R3, R4,R5,DZ
READ(1,2003) TTC, TL, TA
READ(1,2004)V,DEN,ALAM,RUN
U = 1.0/ (1.0/HA + DZ/BK )
QOA = U * (TTC-TA)
P = QOA /(RHO*DZ*C)
T6 = TTC
T7 = T6
T8 = T6
T9 = T6
T10 = T6
T1 = T6 - QOA*DZ/BK
T2 = T1
T3 = T1
T4 = T1
T5 = T1
T11 = T6 + QOA*DZ/BK
T12 = T11
T13 = T11
T14 = T11
T15 = T11
T16 = T11 + QOA*DZ/BK
T18 = T16
T17 = T18
T19 = T16
T20 = T16
TIME = 0.0
WRITE(3,3001)
WRITE(3,3002)
WRITE(3,1001)
WRITE(3,3001)
WRITE(3,3002)
WRITE(3,1002)
WRITE(3,3001)
WRITE(3,1003)
WRITE(3,3001)
WRITE(3,1004) HL, HA, RHO, C, BK, DT, QOA
WRITE(3,3002)
WRITE(3,2002) DR, R1, R2, R3, R4,R5,DZ
WRITE(3,3002)

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```

WRITE(3,2004) V,DEN,ALAM,RUN
WRITE(3,3002)
WRITE(3,1006) TIME,T1,T2,T3,T4,T5
WRITE(3,1007) T6, T7, T8, T9,T10
WRITE(3,1008)V,T11,T12,T13,T14,T15
WRITE(3,1009)T16, T17, T18, T19, T20
R11 = R1*R1
R22 = R2*R2
R33 = R3*R3
R44 = R4*R4
R55 = R5*R5
Y1 = BK*R1*DZ/(2.0*DR)
Y2 = BK* R11/(DZ* 2.0 )
CQ1 = R11*DZ*RHO*C/4.0
Y4 = BK*R2*DZ/(2.0*DR)
Y5 = BK*(R22-R11)/(2.0*DZ)
CQ2 = DZ*RHO*C*(R22-R11)/4.0
Y7 = BK*DZ*R3/(2.0*DR)
Y8 = BK*(R33-R22)/(2.0*DZ)
CQ3 = (R33-R22)*DZ*RHO*C/4.0
Y10 = BK*R4*DZ/(2.0*DR)
Y11 = BK*(R44-R33)/(2.0*DZ)
CQ4 = (R44-R33)*DZ*RHO*C/4.0
Y13 = BK*(R55-R44)/(2.0*DZ)
CQ5 = DZ*(R55-R44)*RHO*C/4.0
CQ6 = 2.0*CQ1
SUMK6 = 2.0*Y1+ 2.0*Y2
CQ7 = 2.0*CQ2
SUMK7 = 2.0*Y4+ 2.0*Y5+ 2.0*Y1
CQ8 = 2.0*CQ3
SUMK8 = 2.0*(Y7+ Y8+ Y4)
CQ9 = 2.0*CQ4
SUMK9 = 2.0*(Y10+Y11+Y7)
CQ10 = 2.0*CQ5
SUM10 = 2.0*(Y10+Y13)
SUM16 = Y1+Y2
P1 = R11*QOA/2.0
SUM17 = Y4+Y1+Y5
P2 = (R22-R11)*QOA/2.0
SUM18 = Y7+Y4+Y8
P3 = (R33-R22)*QOA/2.0
SUM19 = Y10+Y7+Y11
P4 = (R44-R33)*QOA/2.0
SUM20 = Y10+Y13
P5 = (R55-R44)*QOA/2.0
100 DEL=0.27476272+0.13077056*V-0.03681354*V*V+0.00357793*V*V*V
IF(DEL.GT.0.455) DEL = 0.455
IF(V.LE.5.0) HL = 0.00423
IF(V.GT.0.025) GO TO 101
DEL = (6.0*V/ 3.14159)**0.333333
RDP = DEL/2.0
GO TO 102
101 RDP = (V/(3.14159*DEL))**0.50
102 DE = DT
IF(RDP.GT.R5) GO TO 400
IF(RDP.LT.R4) GO TO 40
H1 = HL
H2 = HL
H3 = HL
H4 = HL
H5 = HL
S1 = TL

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```

S2 = TL
S3 = TL
S4 = TL
S5 = TL
Y14 = HA*(R55-R44)/2.0
SUMK5 = Y13 + Y10+ Y14
Z5 = EXP(-1.0*DE*SUMK5/CQ5)
T5K = Z5*T5 + (1.0-Z5)*(Y13*T10+ Y10*T4+ Y14*TA)/SUMK5
GO TO 80
40 IF (RDP.LT.R3) GO TO 50
H1 = HL
H2 = HL
H3 = HL
H4 = HL
H5 = HA
S1 = TL
S2 = TL
S3 = TL
S4 = TL
S5 = TA
Y12 = HA*(R44-R33)/2.0
SUMK4 = Y10+ Y11+ Y7+ Y12
Z4 = EXP(-1.0*DE*SUMK4/CQ4)
T4K = Z4*T4+ (1.0-Z4)*(Y10*T5+ Y11*T9+ Y7*T3+ Y12*TA)/SUMK4
GO TO 80
50 IF(RDP.LT.R2) GO TO 60
H1 = HL
H2 = HL
H3 = HL
H4 = HA
H5 = HA
S1 = TL
S2 = TL
S3 = TL
S4 = TA
S5 = TA
Y9 = HA*(R33-R22)/2.0
SUMK3 = Y7+ Y8+ Y4+ Y9
Z3 = EXP(-1.0*DE*SUMK3/CQ3)
T3K = Z3*T3 + (1.0-Z3)*(Y7*T4+ Y8*T8+ Y4*T2+ Y9*TA)/SUMK3
GO TO 80
60 IF(RDP.LT.R1) GO TO 70
H1 = HL
H2 = HL
H3 = HA
H4 = HA
H5 = HA
S1 = TL
S2 = TL
S3 = TA
S4 = TA
S5 = TA
Y6 = HA*(R22-R11)/2.0
SUMK2 = Y4+Y5+Y1+Y6
Z2 = EXP(-1.0*DE*SUMK2/CQ2)
T2K = Z2*T2 + (1.0-Z2)*(Y4*T3+Y5*T7+ Y1*T1 +Y6*TA)/SUMK2
GO TO 80
70 H1 = HL
H2 = HA
H3 = HA
H4 = HA
H5 = HA

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```

S1 = TL
S2 = TA
S3 = TA
S4 = TA
S5 = TA
Y3 = HA*R11/2.0
SUMK1 = Y1 +Y2+Y3
Z1 = EXP(-1.0*DE*SUMK1/CQ1)
T1K = Z1*T1 +(1.0-Z1) *(Y1*T2 +Y2*T6 + Y3*TA)/SUMK1
80 Y3 = H1*R11/2.0
Y6 = H2*(R22-R11)/2.0
Y9 = H3*(R33-R22)/2.0
Y12 = H4*(R44-R33)/2.0
Y14 = H5*(R55-R44)/2.0
SUMK1 = Y1 +Y2+Y3
SUMK2 = Y4+Y5+Y1+Y6
SUMK3 = Y7+ Y8+ Y4+ Y9
SUMK4 = Y10+ Y11+ Y7+ Y12
SUMK5 = Y13+ Y10+ Y14
Z1 = EXP(-1.0*DE*SUMK1/CQ1)
T1N = Z1*T1 +(1.0-Z1) *(Y1*T2 +Y2*T6 + Y3*S1)/SUMK1
Z2 = EXP(-1.0*DE*SUMK2/CQ2)
T2N = Z2*T2 + (1.0-Z2)*(Y4*T3+Y5*T7+ Y1*T1 +Y6*S2)/SUMK2
Z3 = EXP(-1.0*DE*SUMK3/CQ3)
T3N = Z3*T3 + (1.0-Z3)*(Y7*T4+ Y8*T8+ Y4*T2+ Y9*S3)/SUMK3
Z4 = EXP(-1.0*DE*SUMK4/CQ4)
T4N = Z4*T4+ (1.0-Z4)*(Y10*T5+ Y11*T9+ Y7*T3+ Y12*S4)/SUMK4
Z5 = EXP(-1.0*DE*SUMK5/CQ5)
T5N = Z5*T5 +(1.0-Z5)*(Y13*T10+ Y10*T4+ Y14*S5 )/SUMK5
Z6 = EXP(-1.0*DE*SUMK6/CQ6)
T6N = Z6*T6+ (1.0-Z6)*(Y2*T11+2.0*Y1*T7+ Y2*T1)/SUMK6
Z7 = EXP(-1.0*DE*SUMK7/CQ7)
T7N = Z7*T7+ (1.0-Z7)*(2.0*Y4*T8+ Y5*T12+ 2.0*Y1*T6+Y5*T2)/SUMK7
Z8 = EXP(-1.0*DE*SUMK8/CQ8)
T8N = Z8*T8+ (1.0-Z8)*(2.0*Y7*T9+Y8*T13+2.0*Y4*T7+Y8*T3)/SUMK8
Z9 = EXP(-1.0*DE*SUMK9/CQ9)
T9N = Z9*T9+ (1.0-Z9)*(2.0*Y10*T10+Y11*T14+2.0*Y7*T8+Y11*T4)/SUMK9
Z10 = EXP(-1.0*DE*SUM10/CQ10)
T10N = Z10*T10+ (1.0-Z10)*(Y13*T15+ 2.0*Y10*T9+Y13*T5)/SUM10
T11N = Z6*T11+ (1.0-Z6)*(Y2*T16+2.0*Y1*T12+Y2*T6)/SUMK6
T12N = Z7*T12+ (1.0-Z7)*(2.0*Y4*T13+Y5*T17+2.0*Y1*T11+Y5*T7)/SUMK7
T13N = Z8*T13+(1.0-Z8)*(2.0*Y7*T14+Y8*T18+2.0*Y4*T12+Y8*T8)/SUMK8
T14N = Z9*T14+(1.0-Z9)*(2.0*Y10*T15+Y11*T19+2.0*Y7*T13+Y11*T9)/SUMK9
T15N = Z10*T15+(1.0-Z10)*(Y13*T20+2.0*Y10*T14+Y13*T10)/SUM10
Z16 = EXP(-1.0*DE*SUM16/CQ1)
T16N = Z16*T16+ (1.0-Z16)*(Y1*T17+Y2*T11+P1)/SUM16
Z17 = EXP(-1.0*DE*SUM17/CQ2)
T17N = Z17*T17+(1.0-Z17)*(Y4*T18+Y1*T16+Y5*T12+P2)/SUM17
Z18 = EXP(-1.0*DE*SUM18/CQ3)
T18N = Z18*T18+(1.0-Z18)*(Y7*T19+Y4*T17+Y8*T13+P3)/SUM18
Z19 = EXP(-1.0*DE*SUM19/CQ4)
T19N = Z19*T19+(1.0-Z19)*(Y10*T20+Y7*T18+Y11*T14+P4)/SUM19
Z20 = EXP(-1.0*DE*SUM20/CQ5)
T20N = Z20*T20+(1.0-Z20)*(Y10*T19+Y13*T15+P5)/SUM20
IF(RDP.LT.R4) GO TO 110
T5M = T5K + RDP*RDP*(T5N-T5K)/R55
T5N = T5M
GO TO 150
110 IF(RDP.LT.R3) GO TO 120
T4M = T4K + RDP*RDP*(T4N-T4K)/R44
T4N = T4M
GO TO 150

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120 IF(RDP.LT.R2) GO TO 130
    T3M = T3K + RDP*RDP*(T3N-T3K)/R33
    T3N = T3M
    GO TO 150
130 IF(RDP.LT.R1) GO TO 140
    T2M = T2K + RDP*RDP*(T2N-T2K)/R22
    T2N = T2M
    GO TO 150
140 T1M = T1K + RDP*RDP*(T1N-T1K)/R11
    T1N = T1M
150 TIME = TIME + DT
    IF(ABS(T1-T1N).LT.0.5) DT = 1.0
    IF(TIME.GE.300.0) DT = 5.0
160 QOA = HL*(T1-TL)
    IF(V.LT.2.0) QOA = (0.99+ 1.5*EXP(-1.35*V))*QOA
    T1 = T1N
    T2=T2N
    T3=T3N
    T4=T4N
    T5= T5N
    T6=T6N
    T7=T7N
    T8= T8N
    T9=T9N
    T10=T10N
    T11=T11N
    T12= T12N
    T13 = T13N
    T14 = T14N
    T15 = T15N
    T16 = T16N
    T17 = T17N
    T18 = T18N
    T19 = T19N
    T20 = T20N
    IF(V.GE.0.025) GO TO 300
    DM = DE*QOA*2.0*3.14159*RDP*RDP/ALAM
    GO TO 310
300 DM = DE*QOA*3.14159*RDP*RDP/ALAM
310 V = V - DM/DEN
    IF(V.LT. 0.0) V = 0.0
    WRITE(3,3002)
    WRITE(3,1006) TIME,T1,T2,T3,T4,T5
    WRITE(3,1007) T6, T7, T8, T9,T10
    WRITE(3,1008)V,T11,T12,T13,T14,T15
    WRITE(3,1009) T16, T17, T18, T19, T20
    IF(TIME.LT.RUN) GO TO 100
    GO TO 200
400 STOP
    END

```

TYPICAL INPUT DATA

.00423	.000362	8.017009	.12	.0417486	.5	
1.27	.635	1.905	3.175	4.445	5.08	.9525
380.	100.	21.				
3.0	.95838	538.7	600.0			

VITA

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Candidate for the Degree of
Master of Science

Thesis: SURFACE TEMPERATURE TRANSIENTS IN FILM BOILING

Major Field: Chemical Engineering

Biographical:

Personal Data: Born in Paragould, Arkansas, December 17, 1941, the son of Albert J. and Keturah Batten.

Education: Attended elementary and high school in Paragould, Arkansas; graduate from Paragould High School in 1959; attended Arkansas State College for two years, then transferred to University of Arkansas in September, 1961; received a Bachelor of Science degree in Chemical Engineering, in May, 1964; completed requirements for Master of Science degree at Oklahoma State University in May, 1966. Membership in scholarly or professional societies includes Omega Chi Epsilon, Tau Beta Pi, and American Institute of Chemical Engineers.

Professional experience: Summer employment in the Kansas City, Kansas refinery of Phillips Petroleum Company in 1963; employed as a Junior Engineer in the Reservoir Analysis Group, Production Department of Humble Oil and Refining Co. at Houston, Texas, summer of 1964. Presently employed as an Exploitation Engineer in the Production Department of Shell Oil Company in Houston, Texas.