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ROLE OF THE SURFACE IN THE MEASUREMENT OF
THE LEIDENFROST TEMPERATURE

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ABSTRACT

Aluminum, brass, stainless steel, gold plated copper, and pyrex glass surfaces were used to investigate the effect of surface properties on the Leidenfrost temperature. The initial drop radius, heater surface characteristics, and liquid subcooling were related by a conduction model to the Leidenfrost point. The model indicated the important parameters effecting the Leidenfrost point. Using this model, most of the variation of Leidenfrost temperature reported in the literature could be delineated. Also, for practical purposes, experimental evidence indicates a possible equivalence between the Leidenfrost and the minimum temperature in a pool boiling system. Surface roughness and contamination, particularly for water, are shown to have extremely large effects on the Leidenfrost and minimum temperatures.

The Leidenfrost point, thus, is not a unique property of the fluid. Consequently, the nature of the surface must be considered when estimating the efficiency of boiling heat transfer in quenching operations or in spray cooled systems.

SYMBOLS

C	specific heat of heater plate
$\bar{h}$	time average heat transfer coefficient
k	thermal conductivity of heater surface
N_τ	dimensionless group, $\bar{h}^2 t_\infty / k\rho C$
q	heat flux
q_c	critical heat flux
q_{min}	heat flux at T_{min}
R_0	radius of drop, see Fig. 3
r	radius
T	plate temperature
T_L	liquid temperature
T_{Leid}	Leidenfrost temperature
$T_{Leid, iso}$	ideal isothermal value of T_{Leid}
$T_{Leid, meas}$	measured value of T_{Leid} associated with point B' in Fig. 2
T_{min}	surface temperature associated with point B in Fig. 1
$T_{min, iso}$	ideal isothermal value of T_{min}
T_0	initial plate temperature
T_p	surface temperature of plate
T_{sat}	saturation temperature
t	time
t^*	dimensionless time
t_{evap}	time for a liquid drop to completely evaporate
t_∞	characteristic time
v	velocity of drop normal to surface just before impact
We	Weber number ($We = \rho_L v^2 R_0 / \sigma$
z	axial direction perpendicular to plate
z^*	dimensionless z, $\bar{h}z/k$
α	thermal diffusivity, $(k/C\rho)$
β	$(\rho Ck)^{-1}$
η	dimensionless radius, $\bar{h}r/k$
η_0	dimensionless surface radius, $\bar{h}R_0/k$
θ	$(T - T_L)/(T_0 - T_L)$
ρ	plate density

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ρ_L drop density

σ drop surface tension

τ dimensionless time, $\bar{h}^2 t / k \rho C_p$

INTRODUCTION

In recent years, the familiar pool boiling curve, shown in Fig. 1, and the droplet evaporation curve[1-11] shown in Fig. 2, have been the object of intensive study. In particular, the prediction and experimental determination of the minimum temperature T_{min}, and the Leidenfrost temperature T_{Leid}, have received much attention. A knowledge of these temperatures is important for a basic understanding of boiling, as well as for quenching studies, cool down of cryogenic pumps, spray cooling, liquid droplet removal in mist section of boilers, and in the transition from nucleate to film boiling. The latter example is important in nuclear reactor safety considerations.

For spray cooling, the heat removal efficiency depends on whether the surface against which the drops impinge has a temperature above or below the Leidenfrost temperature. If the wall temperature is below the Leidenfrost temperature, high heat transfer rates associated with nucleate boiling occur, while if the surface temperature is above the Leidenfrost temperature, lower heat transfer rates associated with film boiling occur. It will be shown herein that the Leidenfrost point is not a unique property of the fluid. Consequently, the surface-fluid combination establishes the type of boiling (film or nucleate) which will occur. Thus, the heat transfer coefficient in these systems can be enhanced (or reduced) by an order of magnitude simply by changing the properties of the surface so as to increase or decrease the Leidenfrost temperature.

The Leidenfrost temperature is also important in constant q systems. In a constant q (heat flux) system, a question of stability must be considered if a small vapor patch of film boiling should occur. Will the vapor patch grow and engulf the whole coolant channel or will it collapse and disappear? Semeria and Martinet[12] predicted that stability would depend on the value of the minimum temperature squared. Simon et al[13, 14] pointed out that any error in the prediction of the minimum temperature will be greatly magnified in the squaring process. Thus, all the parameters which affect the minimum or the Leidenfrost temperature should be clearly delineated.

At the present time, however, there seems to be considerable uncertainty in the literature as to what is the Leidenfrost temperature or minimum temperature for a given fluid.

Table I displays a variety of Leidenfrost and minimum point data for a given fluid. Water, for example, gives evidence of wide scatter in the reported data.

Bell[1] states that at the present time there is no unique value of the Leidenfrost temperature for a given fluid, and that there is insufficient information available to predict the Leidenfrost temperature. He further states, "One must either guess from the most similar experimental cases available, or better still yet, test one's own case experimentally."

The purpose of the present paper is to explain why there are large variations in the Leidenfrost measurements and to delineate the important parameters involved in the measurement of the Leidenfrost temperature. Also, the present paper will consider under what conditions the minimum temperature T_{min} might be deduced from measurements of T_{Leid}. For if it is desired to measure the minimum temperature of a new fluid, the Leidenfrost technique would be preferred because of its simplicity.

There are a number of experimental factors that could account for the large variations in the measured values of the Leidenfrost temperature reported in Table I. For example:

1. How does the placement of the drop on the surface affect the Leidenfrost temperature?

2. How does the extremely short but very important temperature reduction beneath drop affect the Leidenfrost temperature? Here, the properties of the supporting plate as well as liquid properties and subcooling govern the magnitude of the temperature transient.

3. What effect will surface roughness, contamination (fouling) and chemical reactions have on the Leidenfrost temperature?

4. For a given heated surface, how does wettability – liquid contact angle – effect the Leidenfrost temperature? This report will deal with item 2 and 3 above.

First, an analytical conduction model will be constructed which will indicate the important dimensionless groups which affect the transient plate temperature beneath a liquid drop in a Leidenfrost boiling experiment. From consideration of these dimensionless groups, the effect of changes in surface properties, liquid subcooling and liquid volume on the Leidenfrost temperature can be seen.

Second, experiments will be presented to verify the predicted trends and to ascertain the effects of surface roughness and contamination on the Leidenfrost and minimum temperature.

SURFACE TEMPERATURE CRITERIA

Physical Situation

Consider a surface whose temperature is above the Leidenfrost temperature T_{Leid}. When a drop approaches and touches[20] this surface, a vapor layer will begin to form under the drop. The exact mechanism by which the heat is transferred to the drop to generate the vapor layer is unknown; however, a comprehensive discussion of the possible heat transfer mechanisms is given by Harvey.[20] Thus, upon impact of the drop, the surface temperature begins to decrease, because of the heat transferred to the drop.

If the surface temperature falls sufficiently, transition or nucleate boiling will occur and the drop will seemingly explode. On the other hand, if the initial plate temperature is greater than T_{Leid}, and if the fall in surface temperature is not too severe, the vapor generated beneath the drop will coalesce and form an insulating film. Here, the liquid no longer touches (wets) the surface, except possibly for small liquid spikes which can penetrate the vapor layer.[21] The drop will now evaporate slowly in the Leidenfrost boiling state where the vapor film supports the drop.

In measuring the Leidenfrost temperature, the experimenter sets a plate at an initial temperature T_0, ejects a liquid drop on to the surface, and measures the time it takes for the liquid drop to evaporate. Next he plots his vaporization time data against T_0 as shown in Fig. 2 and determines the Leidenfrost temperature, $T_{Leid,meas}$ from this curve. In this type of experiment, however, the experimenter generally does not measure the transient temperature directly beneath the drop at the plate surface, he only measures the initial temperature of the surface. But, as previously discussed, the initial surface temperature will fall when the liquid comes in contact with it. Thus, the "true" value of the Leidenfrost temperature is the real wall temperature that exists under the drop in the short period after the drop makes contact with the surface. In all cases the surface temperature will decrease; consequently, the actual Leidenfrost temperature will always be less than the initial plate temperature associated with point B in Fig. 2.

The Leidenfrost temperature, therefore, measured on a surface which does not experience any temperature drop, $T_{Leid,iso}$ (an isothermal surface) will be somewhat less than the measured Leidenfrost temperature on a real surface which experiences a temperature drop, assuming that both surfaces have the same surfaces finish and wetting characteristics. Thus,

$$T_{Leid,iso} < T_{Leid,meas}. \tag{1}$$

since the surface temperature is measured before the liquid is placed on the surface.

The parameters which affect a decrease in surface temperature beneath the drop can now be found by consideration of the transient conduction equation in the heated plate. It must be emphasized that the following considerations apply only to the very short time in which the initial transient has occurred, perhaps 100 msec. The end of this short initial transient is designated by time, t_∞. For times greater than t_∞, the drop enters a steady state of nucleate, transition, or film boiling. The transient time t_∞ is negligible compared to the evaporation time scale shown in Fig. 2. However, the thermodynamics which occurs during this short transient controls which of the boiling regimes in Fig. 2 the drop will enter.

Conduction Model

Consider a hot semi-infinite solid at initial temperature T_0, as shown in Fig. 3. A drop of liquid is now placed gently on the surface. If liquid is injected onto the surface with a sufficient velocity, mechanical breakup will occur and the present analysis will not apply. This will be discussed later. For simplicity, during the initial but very short transient period, the unknown time dependent heat transfer coefficient is represented by a time averaged heat transfer coefficient designated $\bar{h}$. For this simple model, liquid properties and liquid subcooling will affect the surface temperature through the parameter $\bar{h}$. At present, as Harvey[20] points out, we just do not understand what is happening during this extremely short complex transient process to be any more specific. We will, however, consider general effects that would result from a decrease or increase in $\bar{h}$.

Since the drop is symmetric about the origin, the governing energy equation in the solid material becomes

$$\frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \tag{2}$$

with the conditions

$$t = 0 \qquad z \geq 0 \qquad T = T_0 \tag{3}$$

$$\left. t > 0 \quad -k \frac{\partial T}{\partial z} \right|_{\substack{z=0 \\ r \leq R_0}} = \left. \bar{h}(T_L - T) \right|_{\substack{z=0 \\ r \leq R_0}}$$

$$\left. \frac{\partial T}{\partial z} \right|_{\substack{z=0 \\ r > R_0}} = 0 \tag{4}$$

$$t > 0 \quad \lim_{z \to \infty} T = T_0 \tag{5}$$

Introducing the following dimensionless variables

$$\theta = \frac{T - T_L}{T_0 - T_L} \tag{6}$$

$$\eta = \frac{\bar{h}r}{k} \tag{7}$$

$$\eta_0 = \frac{\bar{h}R_0}{k} \tag{8}$$

$$z^* = \frac{\bar{h}z}{k} \tag{9}$$

$$t^* = \frac{t}{t_\infty} \tag{10}$$

into Eq. (2) gives

$$\frac{\partial \theta}{\partial t^*} = N_T \left(\frac{\partial^2 \theta}{\partial \eta^2} + \frac{1}{\eta} \frac{\partial \theta}{\partial \eta} + \frac{\partial^2 \theta}{\partial z^{*2}} \right) \tag{11}$$

where

$$N_T = \frac{\bar{h}^2 t_\infty}{k \rho C} = \frac{\bar{h}^2 \alpha t_\infty}{k^2} \tag{12}$$

and t_∞ is a short characteristic time which is of sufficient length so either steady state nucleate or Leidenfrost boiling could be established. The initial conditions and boundary conditions become

$$t^* = 0 \qquad z^* \geq 0 \qquad \theta = 1 \tag{13}$$

$$t^* > 0 \quad \left. \frac{\partial \theta}{\partial z^*} \right|_{\substack{z^*=0 \\ \eta \leq \eta_o}} = \left. \theta \right|_{\substack{z^*=0 \\ \eta \leq \eta_o}}$$

$$\left. \frac{\partial \theta}{\partial z^*} \right|_{\substack{z^*=0 \\ \eta > \eta_o}} = 0 \tag{14}$$

$$t^* > 0 \quad \lim_{z^* \to \infty} \theta = 1 \tag{15}$$

The dimensionless number N_T tells us under what conditions the measured value of the Leidenfrost temperature $T_{Leid, meas}$ will be equal to the Leidenfrost temperature on an isothermal surface $T_{Leid, iso}$.

By inspection of Eq. (11), if N_T is large, the time dependent temperature gradient will be large and the temperature beneath the drop falls; the surface is nonisothermal. On the other hand, for small N_T the change in surface temperature will be very small; the surface is nearly isothermal.

We can better comprehend the above ideas and get a better physical feeling for the effect of the dimensionless parameter N_T by considering the solution of Eq. (11) for the case of an infinite drop ($\eta_o = \infty$). In this special case, Eq. (11) becomes

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial z^{*2}} \quad \text{for } \eta_o = \infty \tag{16}$$

where we have chosen the new dimensionless time τ to be of the form

$$\tau = t \; N_T = \frac{t}{t_\infty} N_T = \frac{\bar{h}^2 t}{k\rho C} \tag{17}$$

The solution to Eq. (16) with the conditions (14) and (15) is given in Ref. (22) (p. 71) and is shown in Fig. 4, as the curve marked η_∞. The temperature drop is smaller for finite η_o because of radial conduction effects.

Assuming the ratio of t/t_∞ is order 1,

$$\frac{t}{t_\infty} = 0(1) \tag{18}$$

that is, sufficient time has occurred for the drop to enter the nucleate or film boiling state, then the abscissa in Fig. 4 is equivalent to N_T.

As was previously stated, for small N_T drop in surface temperature will be quite small, and we label (arbitrarily) this region when $N_T < 0.01$ the "isothermal" region. For $N_T > 0.1$ the surface will be "nonisothermal." The region between these two regions is arbitrarily labeled the "intermediate" region in Fig. 4.

Any change in the system, therefore, which decreases N_T, such as increased k, ρ, C, or decreased $\bar{h}$ will make the surface more nearly isothermal. Furthermore, an increase in η_o will increase the temperature drop making the surface nonisothermal. However, this only occurs in the nonisothermal region where the η_o curves fan out. However, in the isothermal region the radius of the drop will have little effect, since a drop of infinite radius does not effectively lower the surface temperature.

Conduction Criteria

Consequently, after the liquid touches the surface, the surface temperature of the plate T_p will be equal to the initial surface temperature T_o when N_T approaches zero, that is,

$$\lim_{N_T \to 0} T_p = T_o \tag{19}$$

Under the condition of small N_T, the surface temperature will remain isothermal during the experiment. Therefore, when condition (19) holds, the measured value of the Leidenfrost temperature $T_{Leid, meas}$, will be equal to the isothermal value of the Leidenfrost temperature $T_{Leid, iso}$ under the conditions of the particular experiment. That is,

$$\lim_{N_T \to 0} T_{Leid, meas} = T_{Leid, iso} \tag{20}$$

As will be discussed later, $T_{Leid, iso}$ may not be solely a property of the fluid under consideration. Rather $T_{Leid, iso}$ is a complicated function of other system parameters, for example surface roughness and surface contamination.

In correlating the experimental data to be presented later, it is convenient to write N_T as the product $\bar{h}^2 t$ and β where

$$\beta = \frac{1}{k\rho C} \tag{21}$$

The parameter β contains the important surface material properties, while $\bar{h}^2 t_\infty$ implicitly contains the effects of liquid properties, subcooling and some surface roughness effects. These effects will be superimposed on the thermal property effects contained in β. Then as an approximation to Eq. (19), assume

$$\lim_{\beta \to 0} T_p = T_o \tag{22}$$

For finite value of the product $\bar{h}^2 t_\infty$, Eqs. (19) and (22) have the same limiting value. Equation (20) can also be written in the form

$$\lim_{\beta \to 0} T_{Leid, meas} = T_{Leid, iso} \tag{23}$$

The key property group $k\rho C$ has been observed to be an important parameters in drop impingement studies for large Weber number[23] and for T_{min} in flow film boiling.[24]

Measurement of T_{min}

In a pool boiling system, consider a hypothetical surface which remains at a fixed temperature even when liquid comes in contact with it. In principle, there should be

some minimum temperature T_{min} such that if the surface temperature is below T_{min} nucleate or transition boiling will occur. On the other hand, if the surface temperature is greater than T_{min} the vapor generated at the surface will coalesce and film boiling will occur.

At first glance, no criteria should be required for the steady state constant temperature pool boiling measurement of T_{min}, since by definition the surface is held at constant temperature. In reality, however, fluxations in the so-called steady state heat transfer coefficients will cause a time dependent surface temperature variation.

For example, in nucleate boiling, sites are alternately active and quiet.[25] In film boiling, vapor domes alternately shift positions as the liquid-vapor interface adjusts to the unstable body force.[26,27] Finally, in transition boiling, extremely large variations in the heat transfer coefficient occur along the surface, due to alternate wetting and dewetting.

To reduce the effect of the temperature fluctuations in the pool boiling experiment, the criteria given by Eqs. (19) and (22) is applicable. The equivalent form of Eqs. (20) and (23) becomes

$$\lim_{N_\tau \to 0} T_{min} = T_{min, iso} \qquad (24)$$

and

$$\lim_{\beta \to 0} T_{min} = T_{min, iso} \qquad (25)$$

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Stainless steel, brass, aluminum, gold plated copper, and pyrex glass heating surfaces approximately 12 cm in diameter and 1.5 cm thick were fabricated and instrumented for use in this study. The metal surfaces were polished to a glass-like finish. After a fine lathe cut, the surfaces were sanded with silicon paper (320, 400, 500, 600) in the order given. Then, the surfaces were hand and wheel buffed with Tripoli 3X abrasive powder and then (Simichrome) polished. Finally the surface was cleaned with a dry cloth. A roughness indicator gave a 3 to 4 rms μin. measurement of the surface. The pyrex glass had the same rms range.

An 1100-W hot plate was used to slowly bring each of the surfaces up to an equilibrium temperature. From two to four Chromel-Alumel thermocouples (24 gauge) positioned about 1/32 in. beneath the surface were used to measure the surface temperature.

The vaporization times of liquid drops placed on these surfaces were measured and vaporization time curves such as shown in Fig. 2 were plotted. The liquid was placed on the heated surface by the use of hypodermic syringes, a small calibrated glass beaker and a small metal ladle. A 0.032 milliliter (ml) distilled water drop and a 0.0125 ml ethanol drop were obtained with a calibrated syringe. A small marked glass beaker, which was used to scoop up boiling water, was calibrated to give a 6 ml drop. It was estimated that the standard deviation for the large drop was 0.5 ml.

In using the syringe, however, control of the bulk liquid temperature becomes difficult for runs other than

for room temperature. Therefore, the liquid drop from the syringe was sometimes placed in a metal ladle heated to about 550° C. The drop immediately went into the Leidenfrost state, consequently the liquid temperature was always very near saturation value. The ladle was immediately (within 1 sec) placed on the hot test surface and rotated. The drop skidded off a feather edge to the test surface. It fell about 0.02 cm, thereby minimizing the possibility of it entering a metastable state. For a 0.02 cm fall from the ladle to the surface, the Weber number (We = $\rho_L v^2 R_0/\sigma$) is of the order of 0.1. For large Weber numbers, the drops bounce and break up. Wachters[28] and Harvey[20] have experimentally investigated dynamic effects of falling drops impacting on heated surfaces for Weber numbers much greater than 1.

A conventional stop watch accurate to a tenth of a second was used to measure the vaporization time of the liquid drops on the hot surface.

DISCUSSION OF RESULTS

Vaporization Time Curves

The vaporization time curves for ethanol and water drops are shown in Figs. 5 to 7 for various surface materials, liquid temperatures, and drop volumes as indicated in the figures.

The Leidenfrost point occurs where the curves break sharply downward, corresponding to point B' in Fig. 2. For the pyrex glass surface, shown in Fig. 5, some of the nucleate boiling and natural convection range is seen. As seen in these figures, the Leidenfrost temperatures for the different surfaces are significantly different, as also seen in the tabulation of table II. The additional data in table II will be discussed shortly.

Surface Fouling or Contamination

Before investigating the effects of the surface properties, let's consider the effect of contamination of the surface by the liquids. For water, in Fig. 5, a large scattering of the data is seen in the plate temperature range from 150° to 275° C. In this range the drop bounces and vibrates on the surface. Godleski and Bell[3] discuss in detail the bouncing and swirling of drops which, we believe, accounts for much of the data scatter. But why do small drops vibrate in this temperature range? Hoffman[29] suggests that the formation of an oxide layer or perhaps partial wetting of the plate could account for the vibration.

A most interesting phenomean occurred when the very first drop was placed on a freshly polished aluminum surface at a plate temperature of 167° C, as shown in Fig. 5. The drop remained in quiescent film boiling at this temperature. No bouncing or swirling of the drop was seen. This point was always easily reproduced on a freshly polished surface.

A freshly polished aluminum (3 to 4 rms μin.) was heated to 167° C and held at this temperature for 60 minutes, see Fig. 8. Then a water drop was placed on the surface. It went into quiescent film boiling and reproduced the original first drop data point shown in Fig. 5. Thus, the additional amount of surface oxidation that occurred during the 60 minute heating did not affect the results.

As additional drops of liquid were placed on the surface, however, the vaporization time of the drops began to decrease and sputtering and vibration began to occur, see Fig. 8. The surface was apparently being contaminated. A large 6 ml drop was then vaporized on the surface to accelerate the contamination. After the 6 ml drop vaporized, the vaporization times of the small drop was one order of magnitude shorter than on the clean fresh surface.

Figure 9 shows the Leidenfrost temperature of water on freshly polished surfaces to be approximately 152° C, which is nearly 75° C lower than on the conventional contaminated surface (upper curve in fig. 9 will be discussed later). It should be pointed out, that the contaminated surface looks clean and highly polished to the naked eye.

When large 6 ml liquid drops were placed on a freshly polished surface no significant decrease was found from that in Fig. 6 (see table II). Apparently, the surface becomes contaminated upon liquid solid contact. For the small drops, however, the drop can move to an uncontaminated portion of the surface after the initial contact. This is not possible with large 6 ml drop. Double distilled water, as well as every possible precaution was used to keep the system clean, in this particular case.

At present, the contamination is believed by the authors to be brought on by the reaction of water with the fresh aluminum surface, or by deposits due to possible hardness in the water, or by deposits from dissolved salts.

To prevent surface reaction, a relatively inert gold plated copper surface was then used to measure the vaporization times of large double distilled water drops. The first drop was placed on the surface at a plate temperature of 189° C. The large drop went into conventional Leidenfrost film boiling. This point is shown in Fig. 9. The nature of surface changed after the drop evaporated. It would appear that very minute impurities were deposited on the surface. Perhaps, the water more easily wets a contaminated surface and prevent stable film boiling from occurring at the same temperature.

The vaporization time curves for ethanol are shown in Fig. 7 for various surface materials and liquid temperatures as indicated in the figure. The results were not strongly dependent on the surface contamination. Whether the surface was freshly polished or contaminated with water and ethanol drops, the vaporization times were nearly identical. In Fig. 7, the O' symbols indicates data taken on a freshly polished surface. As seen in Fig. 7, a small drop and a large 6 ml liquid drop have the same Leidenfrost temperature. From this the authors concluded that the Leidenfrost temperature for small or large drops are identical for an isothermal surface provided such factors as surface fouling do not enter the problem.

The new value of the Leidenfrost temperature of 152° C in Fig. 9 agrees quite well with the value of 155 reported in table I by Blaszkowska and Zakrzewka. The value in table I was found by merely observing the drops by eye. The authors, no doubt, assumed the drop to be in film boiling when a drop vibrated and bounced on the surface. This crude technique of judging may account for the low value of 142 degrees reported by Bovtingny.[18]

Effect of β Variations

The surface with the smallest value of β should give the best approximation for an isothermal surface and consequently the lowest value of the Leidenfrost temperature. Plotting the Leidenfrost points from Figs. 5 to 7 in Figs. 10 and 11, we see the expected decrease in the measured values of the Leidenfrost temperature for decreasing β.

As seen in Fig. 10, the measured values of the Leidenfrost temperatures are nearly the same for the aluminum and brass surface. Consequently, we could assume that both surfaces are for all practical purposes isothermal. From Fig. 10, for β less than 4×10^{-3} (hr ft^4 F^2/btu^2), the surface can be assumed to be isothermal.

Figure 12 gives further proof of this assumption. The temperature history of stainless steel and aluminum surfaces are illustrated for various initial surface and bulk fluid temperatures after a 6 ml water drop reaches the surface. As seen in the figure, a large temperature drop occurs in the stainless steel surface while little or no temperature drop occurs in the aluminum surface. The drop in temperature on the stainless steel surface most likely accounts for the shift upward of the stainless steel data to the dotted line shown in Fig. 6. Notice in Fig. 12, that the actual plate temperature which stainless steel begins to nucleate boil is 250° C. This is quite near the measured value for the aluminum and brass surface.

We believe that the relatively high value of β for stainless steel accounts for the higher values of Leidenfrost temperatures reported from measurements on stainless steel in table I as well as in the present data in table II.

Effect of η_0 Variations

Notice in Fig. 4, that the effect of the initial liquid radius η_0 has a very small effect on the temperature drop in the isothermal region. Since aluminum and brass fall into this region we might expect very little radius effect on the Leidenfrost point. This is confirmed in Figs. 10 and 11. As shown in those figures, the measured values of the Leidenfrost temperature were nearly independent of the initial drop volume. The water data is based on the conventional contaminated surface, while the ethanol data is independent of surface contamination.

On the other hand, stainless steel is not an isothermal surface as shown by the temperature plot in Fig. 12. Consequently, stainless steel falls into the intermediate region designated in Fig. 4. In this region, the constant η_0 lines begin to fan out. As a result, we can expect the Leidenfrost temperatures to be sensitive to the initial drop radius. Gottfried, Lee, and Bell[4] observed an effect of initial radius on the Leidenfrost temperature. In Ref. (4), for example, on a stainless steel surface, the Leidenfrost temperature for a 0.0154 ml water drop is approximately 25 degrees lower than for a 0.032 ml drop. Both drops were at room temperature. In the present study, as shown in Fig. 10, the larger drop (6 ml) has a Leidenfrost temperature approximately 20° C higher than the smaller drop. This is a relatively small change, and in fact data in Ref. (5) for water on a stainless steel surface did not show this result. This radius effect, however, should be even more pronounced on a surface with high β.

Subcooling Effects

During the initial experimentation, subcooled and saturated water drops were tested on both the aluminum and brass plates. In general, saturated and subcooled drops had the same Leidenfrost temperature. Consequently, most of the data taken to determine the Leidenfrost point on aluminum and brass were for subcooled conditions, as this was the easiest to do experimentally. Some early experimental results of Borishansky[6] confirm that the Leidenfrost temperature is independent of subcooling.

According to Bradfield,[30] however, subcooling has a large affect on T_{min} for a pool. The difference between pool and Leidenfrost boiling probably results from the fact that small subcooled liquid drops quickly heat to the saturation temperature.

For the highly nonisothermal glass surface, however, a large subcooling effect was seen. The increase in $\bar{h}$ for subcooling shifted the value of N_T further into the nonisothermal region. Here, for a fixed η_o, a much larger temperature drop would occur. As verified in Fig. 7, the Leidenfrost temperature for subcooled ethanol on glass is 100° C higher than the value for saturated ethanol. Room temperature water could not be made to Leidenfrost boil on glass, even after heating the upper surface of the glass with a propane torch.

Minimum Temperature

Berenson[31] working with a pool boiling apparatus measured the temperature at the minimum point for pentance on inconel, nickel, and copper surfaces under steady state constant temperature boiling conditions. The minimum temperature for his various materials has been replotted as a function of β in Fig. 13. The minimum temperature decreases as β decreases, in the similar manner as in the Leidenfrost experiments.

Surface Roughness and the Minimum Temperature

Hosler and Westwater[19] measured a steady state minimum temperature for water of 258° C on an aluminum surface (see table I) which was polished with "0 gauge" emery paper. This value was slightly higher than the measured Leidenfrost temperature for a 6 ml water drop on aluminum ($T_{Leid, meas} = 235^o$ C).

In the present study, however, the surface was highly polished. Therefore, the highly polished surface was roughened with 0 gauge emery paper in order to compare the measured value of $T_{Leid, meas}$ to the experimental value of T_{min} by Hosler and Westwater.

The experimental results for the roughened surface are shown in Fig. 14. As seen in this figure, the measured value of the Leidenfrost temperature is 265° C, which is, for all practical purposes, the same value as measured by Hosler and Westwater.

A recent paper by Cumo, Farello, and Ferrari[11] shows the same trend for increased surface roughness. A course sandblasted surface has a Leidenfrost temperature 70° C greater than a smooth lapped surface.

Because of the agreement with the present experimental results shown in Fig. 14 with those of Hosler and Westwater, we suspect an equivalence between T_{Leid} and

T_{min} under certain conditions. In fact, for large saturated drops with similar surface conditions, the two may be identical.

CONCLUSIONS

As seen in the present set of experimental data, surface contamination, k, ρ, C, drop volume, liquid subcooling, and surface roughness can account for the variations in the Leidenfrost and minimum temperatures reported in the literature.

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TABLE I. – COMPARISON OF LEIDENFROST AND MINIMUM TEMPERATURES MEASURED

(Degrees Centigrade)

Liquid	Boiling point	$T_{Leid,meas}$ (small drops)						$T_{Leid,meas}$ (large drop)		T_{min}
		Godleski Bell[3] [SS]	Gottfried, Lee, and Bell[4] [SS]	Tamura Tanasawa[10] [SS]	Kutateladze Borishanski[15] [?]	Blaszkowska Zakrzewka[17] [A-B]	Boutigny[18] [Ag]	Godleski Bell[3] [SS]	Patel Bell[5] [SS]	Hosler Westwater[19] [Al]
Water	100.0	320	280	302	250	157	142	264	300	258
Ethanol	78.4	175	178	185	170	112	----	175	183	----
Benzene	80.0	180	185	195	175	117	----	180	184	----

[SS] – Stainless steel
[A-B] – Aluminum-Bronze alloy
[Ag] – Silver
[Al] – Aluminum
[?] – Not given

TABLE II. – LEIDENFROST TEMPERATURES MEASURED IN PRESENT PAPER

(Degrees Centigrade)

Plate material	Water				Ethanol		
	0.032 ml drop		6 ml drop		0.0125 ml drop		6 ml drop
	T_L 100° C	T_L 26° C	T_L 100° C	T_L 26° C	T_L 78.5° C	T_L 26° C	T_L 26° C
Pyrex glass (3-4 rms)	515	>700	---	---	260	360	---
Stainless steel (3-4 rms)	305	305	325	325	190	190	---
Brass (3-4 rms)	---	230	235	235	---	---	---
Aluminum (3-4 rms)	---	230	235	235	155	155	157
Aluminum 0-gauge (25 rms)	---	---	265	---	---	---	---
Aluminum (fresh polish) (3-4 rms)	---	155	>200	---	---	157	157
Brass (fresh polish) (3-4 rms)	---	---	>200	---	---	---	---
Gold fresh polish (very smooth)	---	---	<184	---	---	---	---
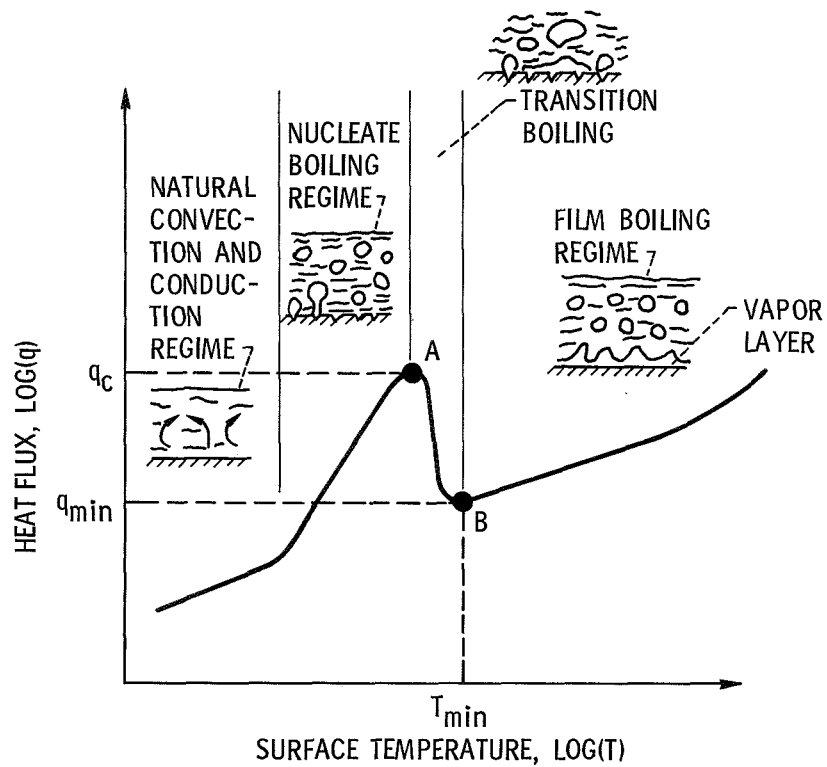
Figure 1. - Conventional pool boiling curve.
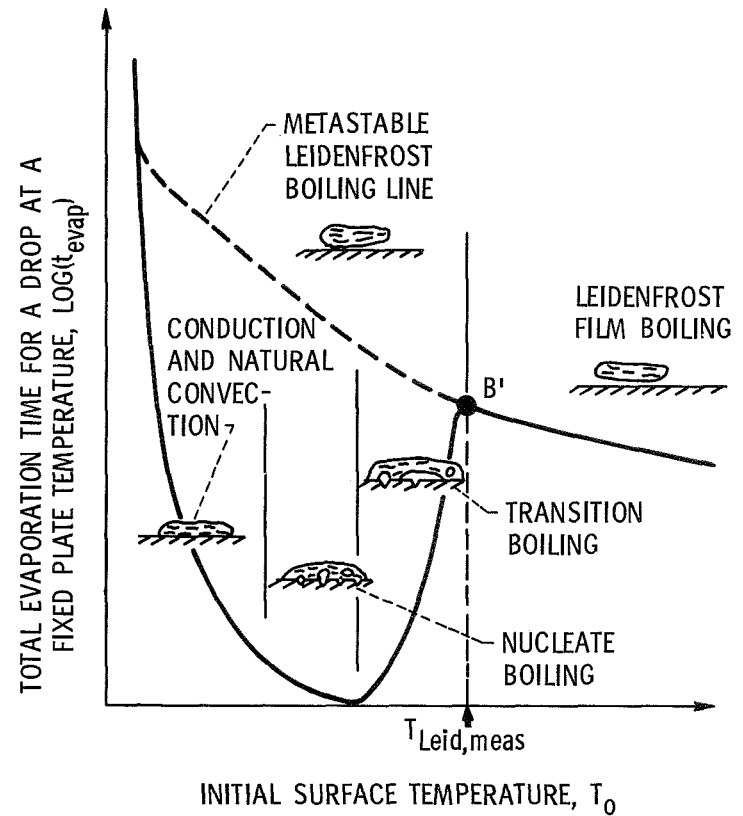
Figure 2. - Evaporation time curve of liquid drops in contact with hot surface for drops of equal volume and equal initial temperature.
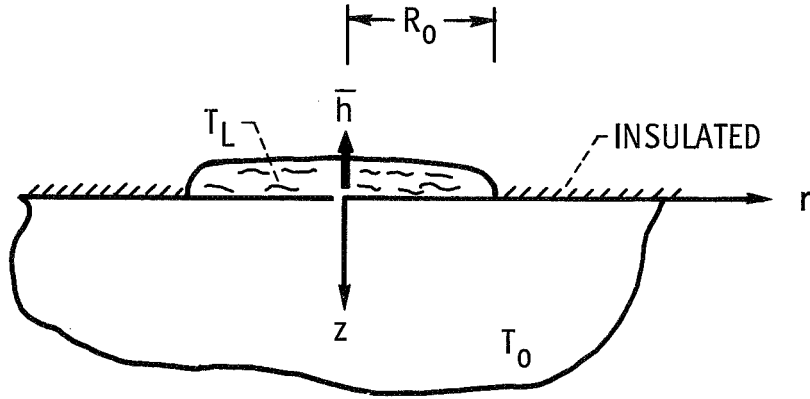
Figure 3. - Hot plate conduction model.
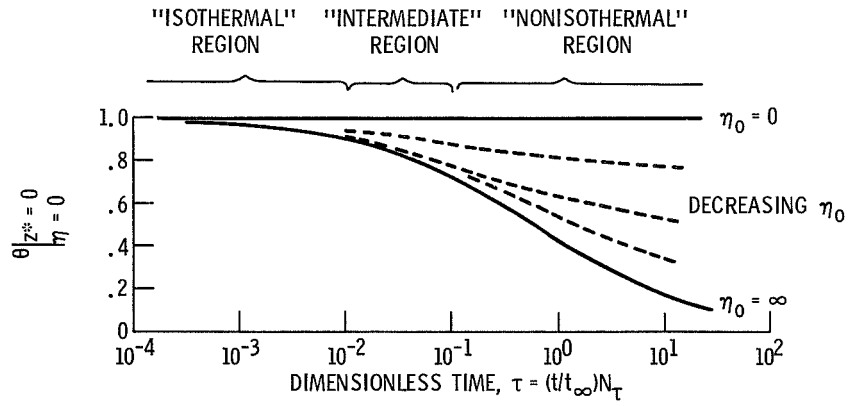
Figure 4. - Effect of N_τ on surface temperature.
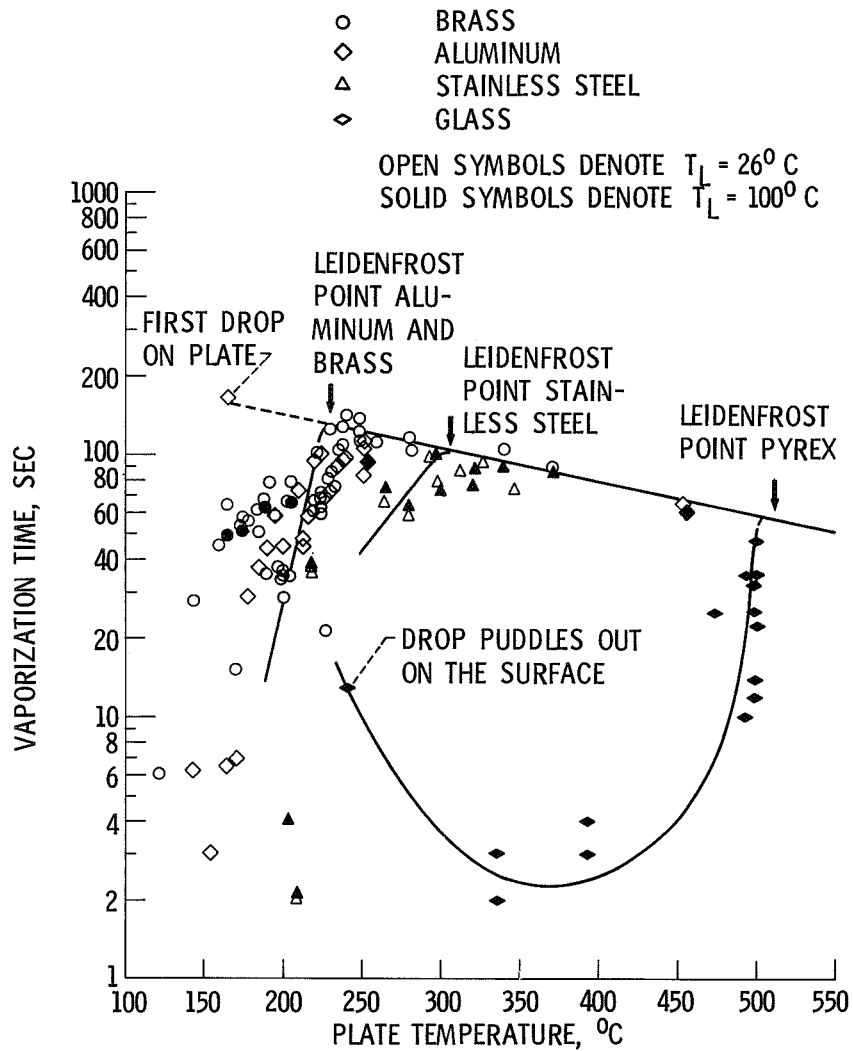
Figure 5. – Total vaporization time of 0.032 ml water drops on polished aluminum, glass, brass and stainless steel surfaces.
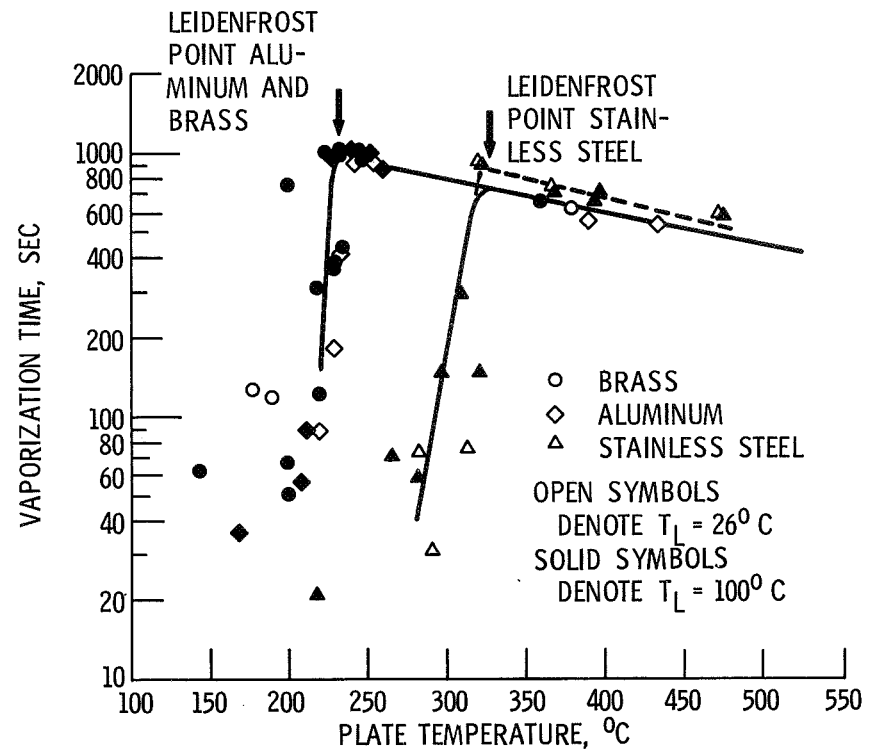
Figure 6. – Total vaporization time of 6 ml water drops on polished aluminum, brass, and steel surfaces.
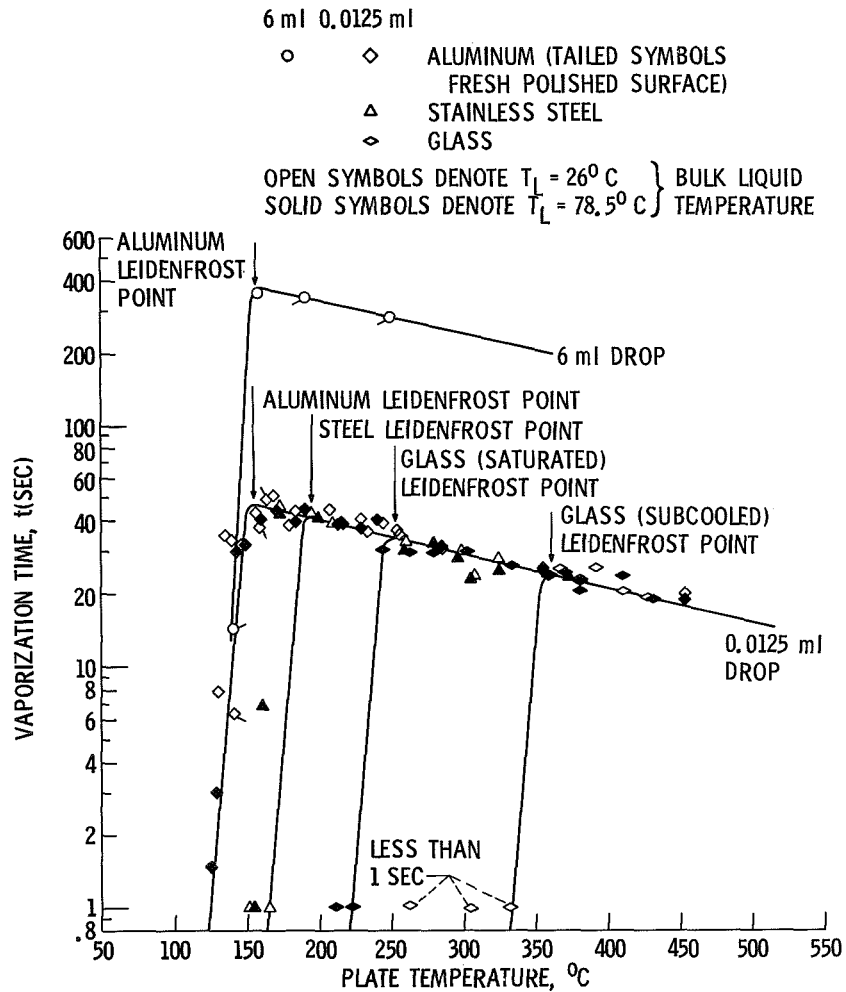
Figure 7. - Total vaporization time of ethanol drops on polished aluminum, stainless steel, and glass surfaces.
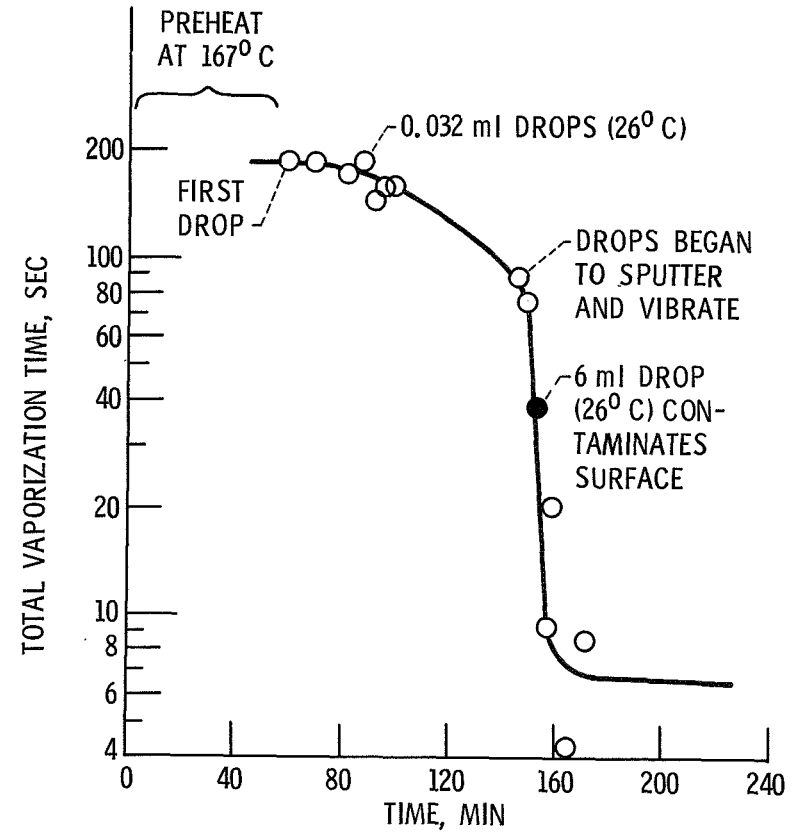
Figure 8. - Effect of increased surface contamination on vaporization time of a water drop on an aluminum surface at 167° C.
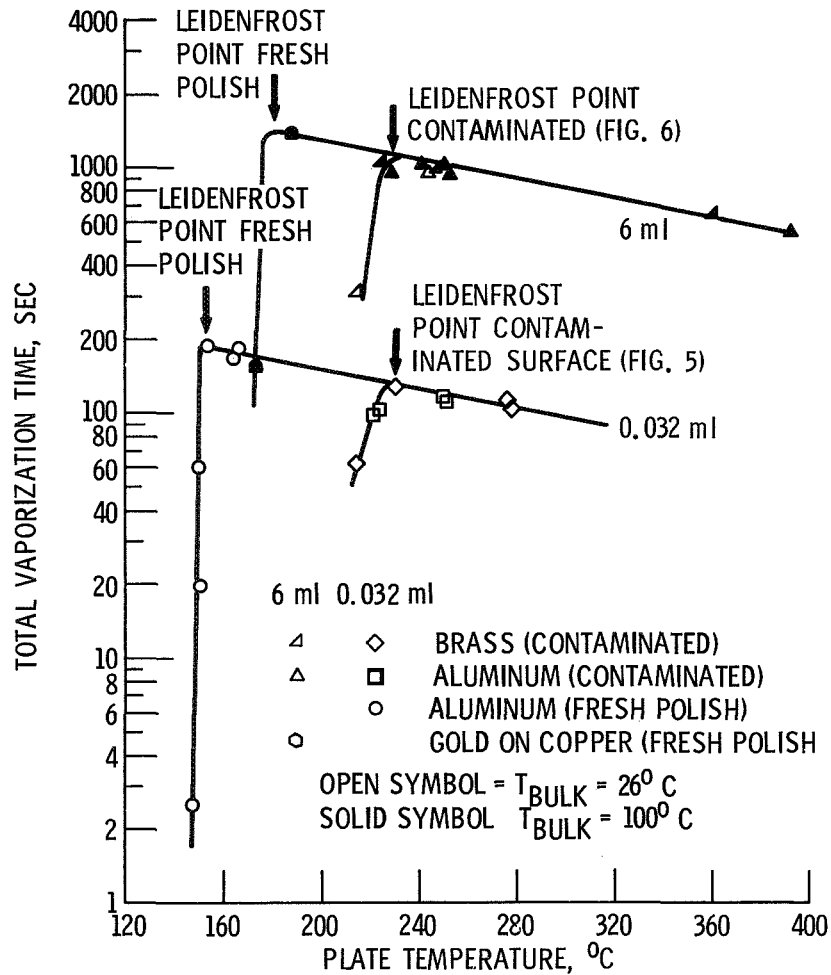
Figure 9. - Lowering of Leidenfrost temperature by measurement of vaporization time on freshly polished aluminum and inert gold surfaces.
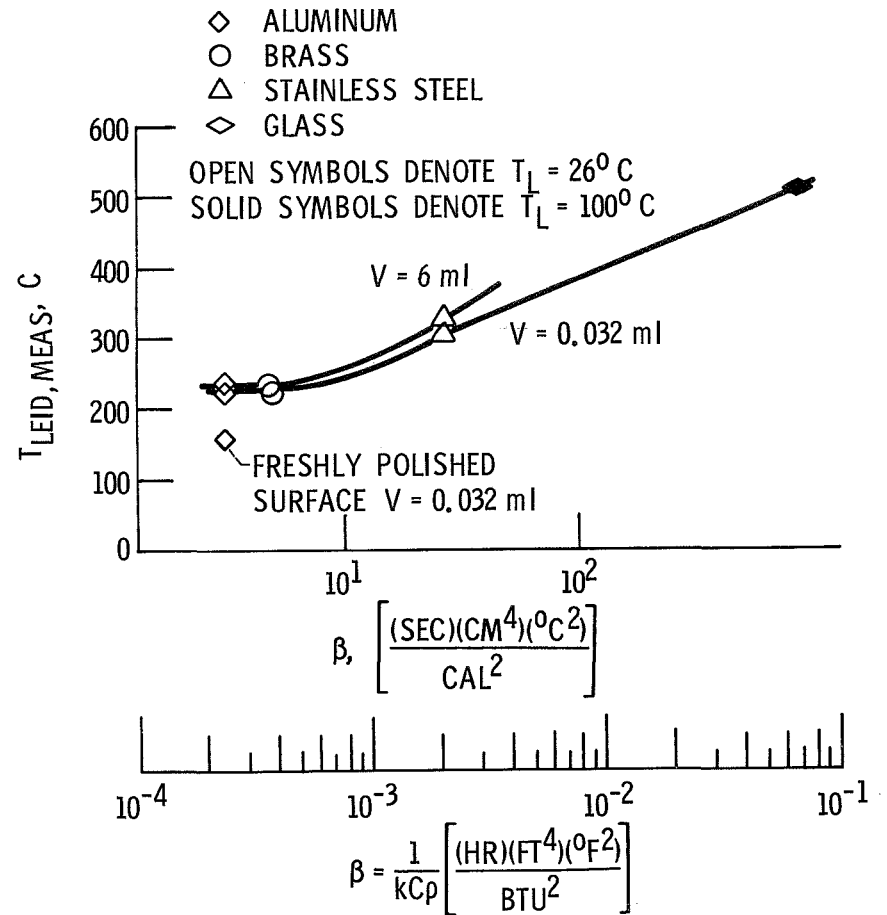
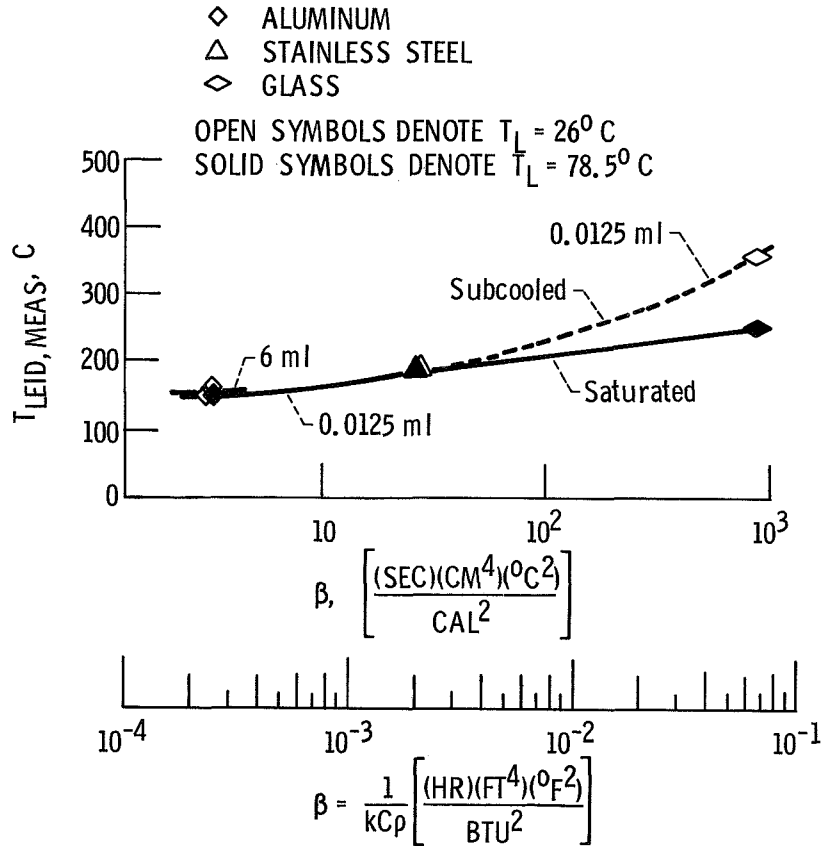Figure 10. - Effect of surface material and initial drop volume on the Leidenfrost temperature of water.

Figure 11. - Effect of surface material on the Leidenfrost temperature of ethanol.
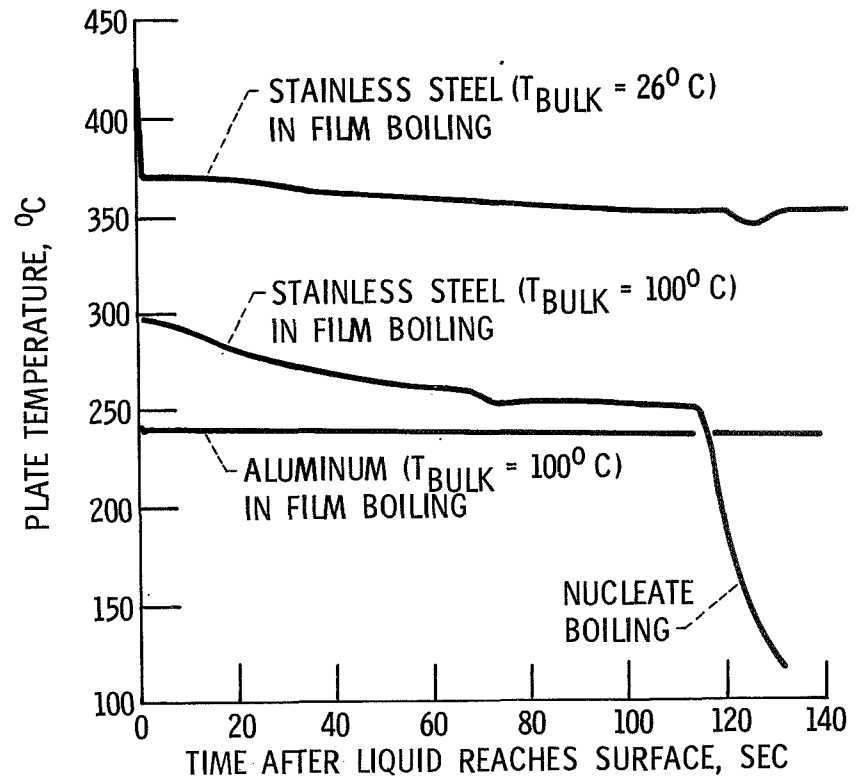

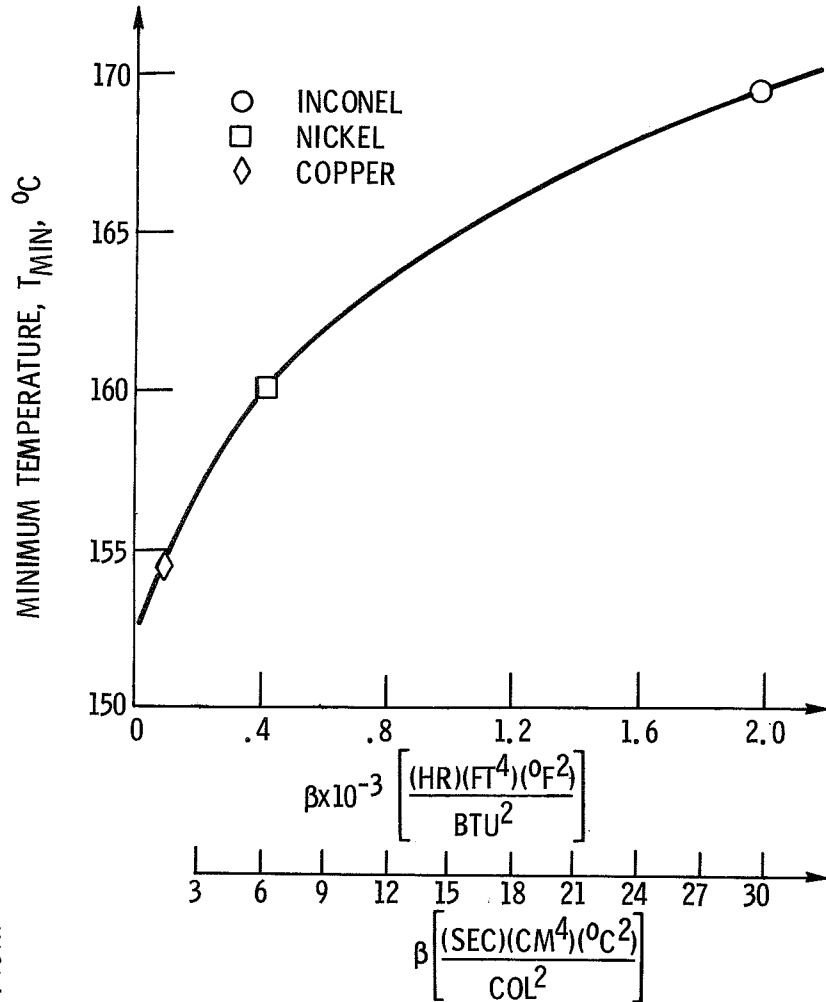Figure 12. - Temperature 1/32 inch beneath surface after 6 ml drop of water reaches the heating surface.

Figure 13. - Minimum temperature as a function of β for n-pentane (Data - Berenson, ref. 31).
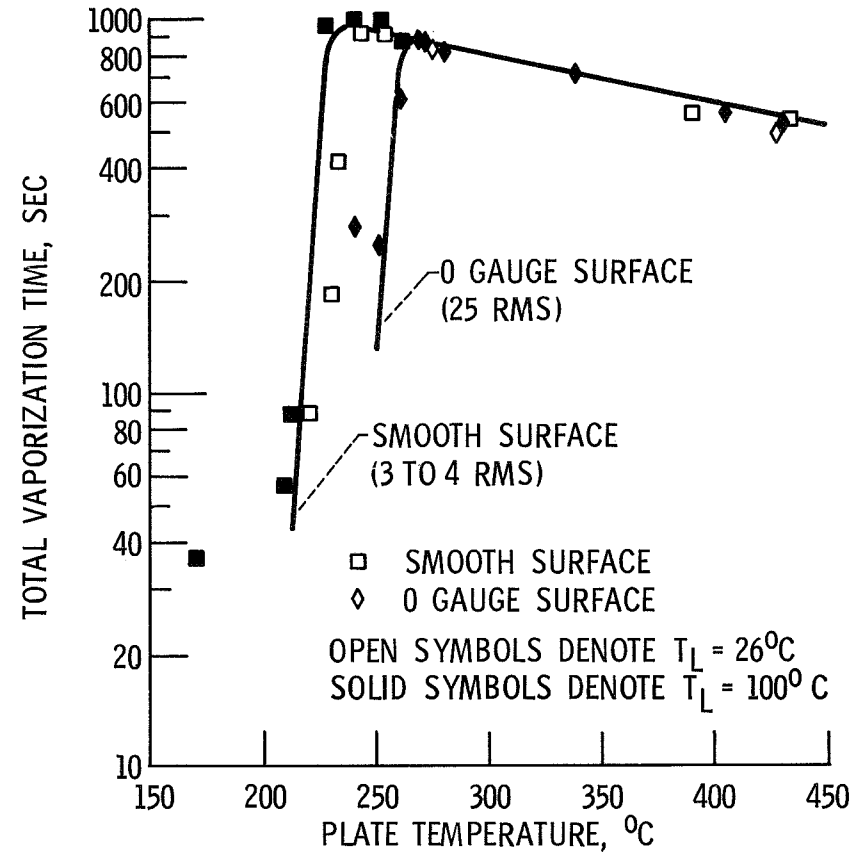

Figure 14. - Effect of surface roughness on the Leidenfrost temperature of 6 ml water drops on an aluminum surface.