THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

BOILING HEAT TRANSFER WITH CRYOGENIC FLUIDS AT STANDARD, FRACTIONAL AND NEAR-ZERO GRAVITY

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NOMENCLATURE

a	Local acceleration - ft/hr^2
A	Area - ft^2
C_p	Specific heat - BTU/lbm-°F
D	Dia. - ft.
g	Acceleration due to standard (terrestrial) gravity $32.2\ ft/sec^2 = 4.16 \times 10^8\ ft/hr^2$.
g_o	Mass-force conversion constant = $4.16 \times 10^8\ lbm/lb_f\ ft/hr^2$
h	Enthalpy - BTU/lbm-°F
$\overline{h}$	Heat transfer coefficient - BTU/hr-ft^2-°F
h_{fg}	Latent heat of vaporization - BTU/lbm
k	Thermal conductivity - BTU/hr-ft-°F
M	Mass - lbm
Pr	Prandtl number
q	Heat transfer rate - BTU/hr
t	Temperature - °F
T	Temperature - °R
V	Volume - ft^3
Δp	Saturation pressure difference corresponding to heater surface superheat - lb_f/ft^2.
Δt_{cr}	Temperature difference at maximum heat flux - °F
Δt_{sat}	Heater surface superheat - °F
θ	Time - hrs
ρ	Density - lbm/ft^3
σ	Surface tension - lb_f/ft
μ	Viscosity - lbm/hr-ft

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Subscripts

s	Sphere
sat	Saturation
f	Film temperature
l	liquid
v	vapor

INTRODUCTION

This paper presents results of an experimental study of boiling heat transfer to a cryogenic fluid, liquid nitrogen, at standard, fractional and near-zero gravity in the nucleate, maximum, transitional, minimum and film boiling regions. Comparison is made with results predicted by various correlations for the maximum and minimum heat flux and film boiling regions.

One motivation for this study arose from previous work by the authors[1] with high force fields. Prior to this work studies of boiling heat transfer had not considered the gravitational field to be a variable, and it was considered that further understanding may be gained by conducting this study.

Initial research at high gravities includes a/g up to 40[1,2] for pool boiling of saturated water, and a/g up to 20[3] for pool boiling of saturated liquid nitrogen, both at atmospheric pressure. It was found that significant changes in the $q/A - \Delta t_{sat}$ relationship were not observed except at low values of heat flux where the relative contribution of non-boiling natural convection was appreciable. This appeared to indicate that the buoyant forces acting on the bubbles were not a significant factor in promoting the large rates of heat transfer associated with nucleate boiling.

In view of these circumstances it was desirable to extend the work to determine if similar effects occurred in cases where the gravity field is less than standard. In this connection a Froude number criterion for distinguishing the limits of a buoyant force dominated process, has

been presented[4] based on the results of Adelberg and Forster[6] and Forster and Zuber.[7] This will be discussed later.

Another purpose for this study is the current problem, generated by the global interest in space flight and exploration, of predicting the behavior of fluid systems under adiabatic and diabatic conditions in environments where the force fields will be low. It may be anticipated that, for the sake of compactness, boiling heat transfer will continue as an important mechanism for power generation and energy dissipation for some time to come.

A drop tower is used to achieve fractional and near-zero gravities. Inherent in this method is the short time of exposure of the test system to reduced gravities. In experimental studies of pool boiling the primary parameters of heat flux and temperature difference are usually measured under steady-state conditions. A steady-state is convenient for the determination of heat flux under those conditions where it is undesirable to correct the data for the thermal lag of the heater surface. In those cases where the heater surface is sufficiently small that its thermal capacity can be neglected, scaling effects may be significant.

In view of the short test period available for these measurements, no attempts were made to obtain steady-state conditions. Instead, a transient technique was used, in which the heating surface serves as a dynamic calorimeter. The surface heat flux is determined from the rate of change of enthalpy of the heating surface as found from the measurement of its temperature change with time. In addition, the corresponding temperature difference may be obtained by this method.

This technique is not new, and has been used by the authors for a number of years in the laboratory to demonstrate the behavior of lumped-parameter systems to undergraduate students in heat transfer. Metallurgists have made these types of measurements in the study of heat treatment of metals. Kays, et al.[27] reports an application of this method for the determination of heat transfer from tubes. Several references with this method are given by Stolz.[11] It is believed, however, that this method has not been fully exploited to obtain boiling heat transfer data. The same simple test device permits measurements in the film, transition, maximum and nucleate boiling regions. Ruzicka[12] has presented boiling data for liquid nitrogen with a hollow vertical cylinder as a transient calorimeter.

Several studies of transient boiling have been conducted[13,14] wherein power pulsations were imposed on small wires. The degree to which a transient process represents one at the steady-state depends upon the ratio of the characteristic times of the system and the particular process. In the present application, the residence time of the bubble is small compared to the inverse time-constant of the calorimeter. Hence, the results may be considered as essentially steady-state whenever this condition prevails. Furthermore, it will be seen that comparison of the transient data with those from steady-state measurements validates this supposition.

EXPERIMENTAL APPARATUS

A cross section of the drop tower facility is shown in Figure 1. The free fall distance of 32 feet gives 1.4 seconds of approximately zero gravity. A special design hydraulic buffer topped by an automotive-type coil spring and foam rubber brings the test platform, having a total mass of 120 pounds, to rest in 2-1/2 feet with a deceleration no greater than approximately 30 g's.

The test platform, Figure 2, consists of an aluminum I-Beam weldment on which the insulated test vessel is mounted. Because of close clearances in the drop area, guide wires are installed. The test vessel is a five liter stainless steel beaker surrounded by three inches of styrofoam, open to the atmosphere. A loosely fitting hinged cover minimizes contamination of the pure liquid nitrogen (99.9+%) by condensed oxygen from the atmosphere.

Prior to release for free-fall the test platform is suspended from a 17 gage resistance wire. Release is achieved by melting the wire with A.C. electrical current. The opening of the A.C. circuit furnishes an accurate measurement of the instant of release.

A Kistler Model 303S Servo-Accelerometer ($\pm$ 1.0 g range) is installed to monitor the local gravitational force field during drop. Measurements under free fall conditions indicate that the force field lies in the range $0.01 < a/g < 0.03$, due to air drag and guide wire friction. True zero gravity is not possible with the present test system because of air drag and guide wire friction. Modifications are underway to achieve lower gravity fields by the use of a double-package drop system, the outer vessel acting as an air screen.

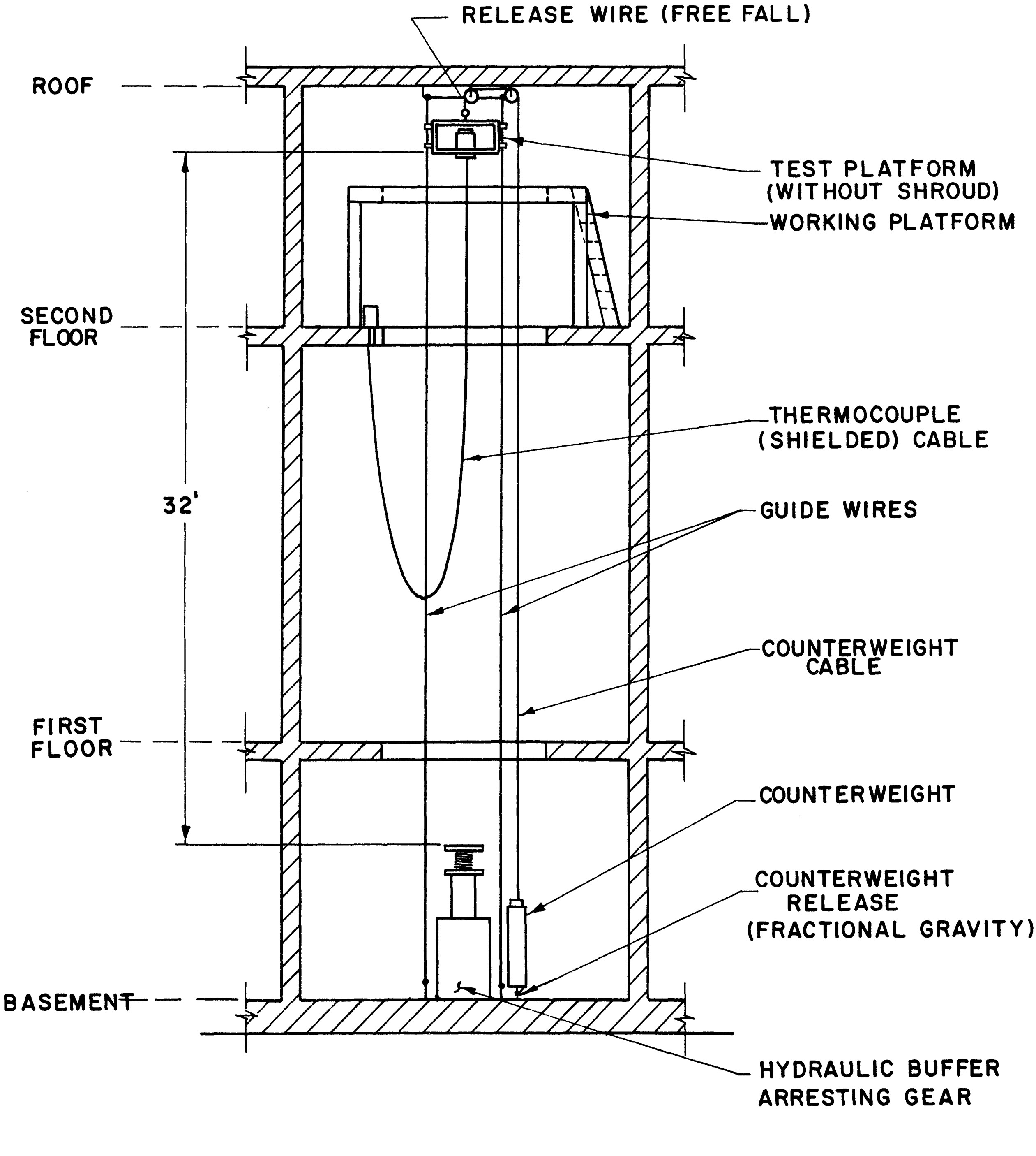


Figure 1. Drop Tower Facility.

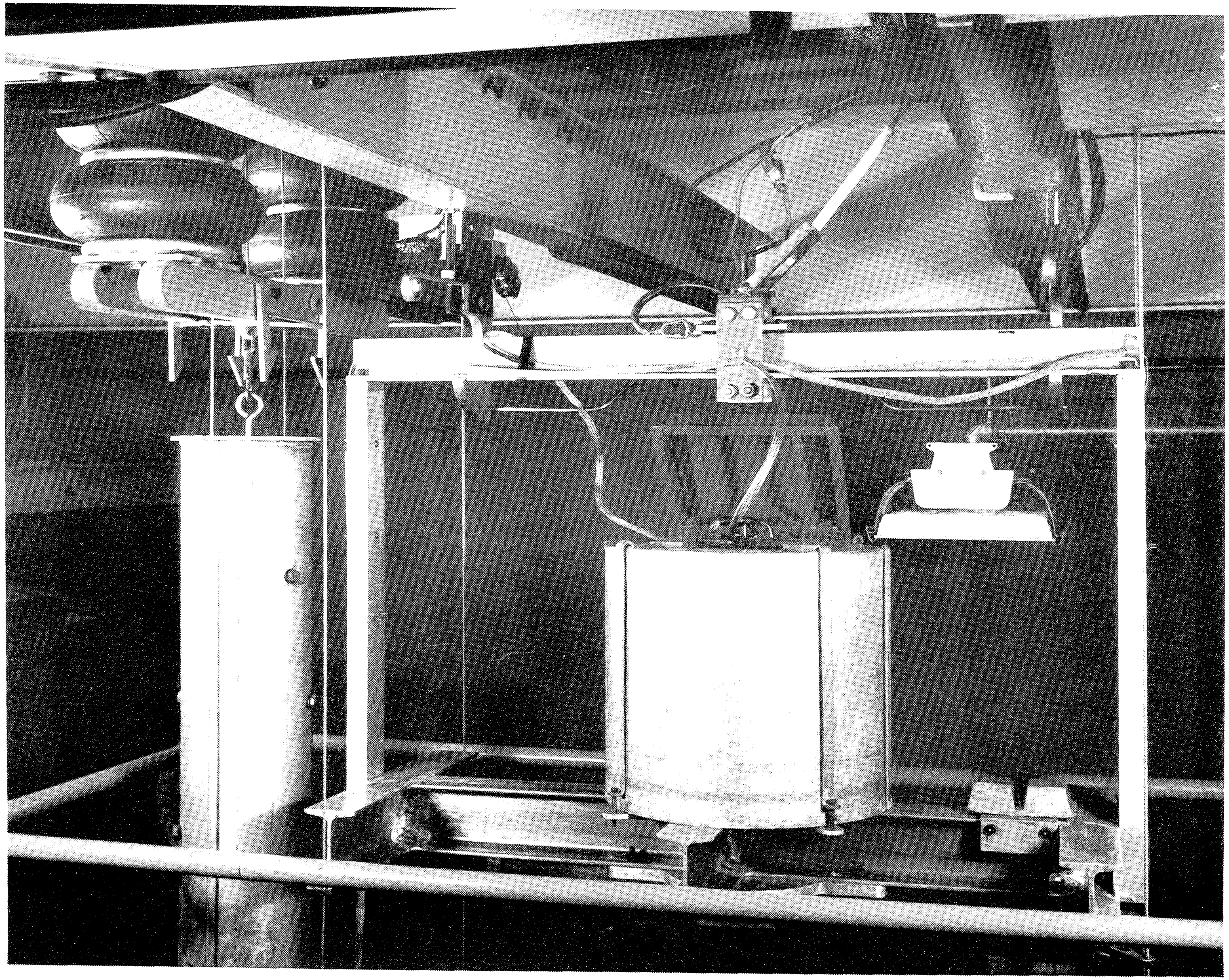


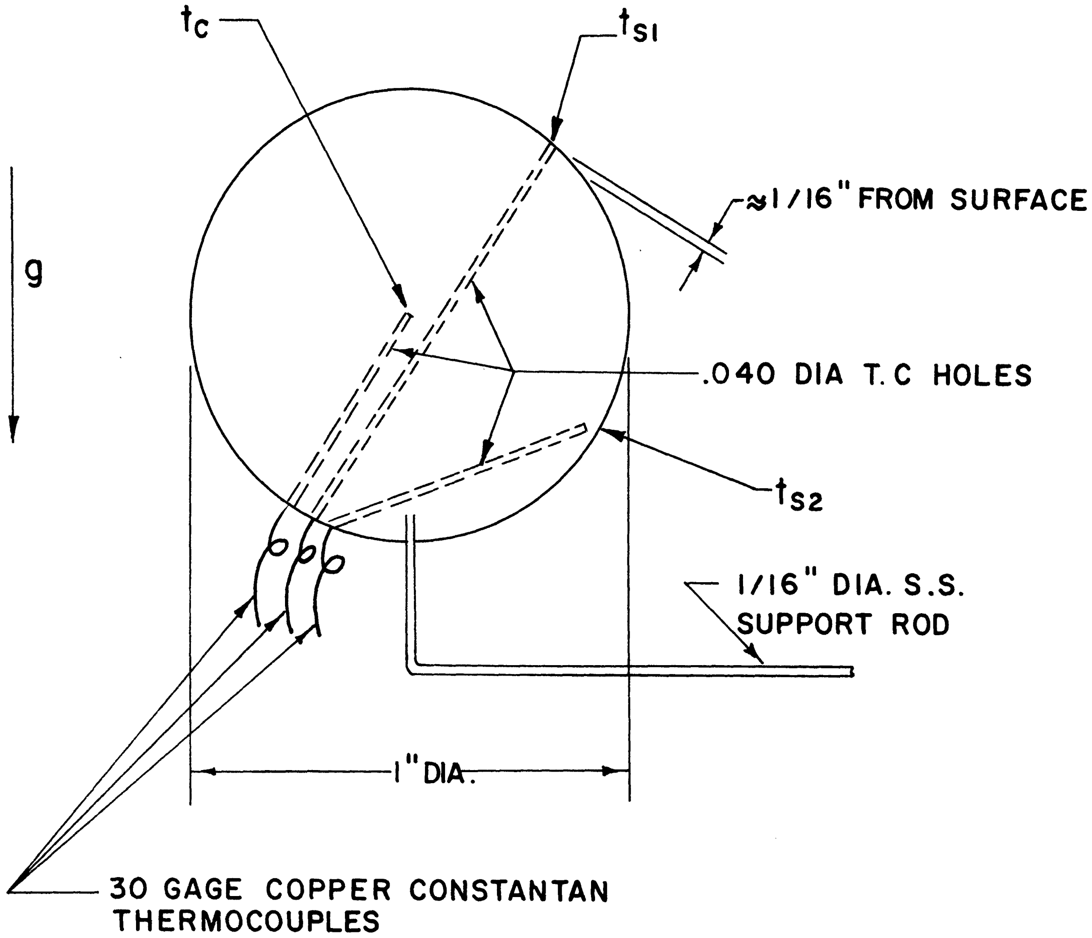
Figure 2. View of Insulated Test Vessel Mounted on Test Platform.

For fractional gravity a counterweight is used. This consists of a six inch O.D., five foot long, closed aluminum tube filled with variable quantities of lead shot, and may be seen in Figure 2. The counterweight is attached to the test platform via a 1/8 inch diameter flexible cable with light weight ball bearing pulleys. The counterweight impact is absorbed with two automotive-type air springs venting through adjustable orifices, Figure 2.

It was found that oscillations existed in the test platform during fractional gravity operation as a consequence of the dynamics initiated upon release. The test platform, counterweight and counterweight cable acted as a two-mass-spring system. The maximum amplitude of the oscillations ranged from $\pm$ 0.15 to $\pm$ 0.05 for a/g of 0.60 and 0.20, respectively. The corresponding frequencies were approximately 10 and 20 cps. The oscillations were of a greater amplitude when the drop was initiated by releasing the counterweight than when the test platform was directly supported and then released. It is felt that the results can be considered representative for the mean value of a/g.

The heat transfer surface geometry for the results presented here is a one inch diameter sphere of electrolytic copper. A sphere was selected for symmetry and ease of instrumentation. Copper was chosen because its heat capacity is a well known function of temperature and its high thermal diffusivity results in a close approximation to a lumped parameter system. By suitable design other geometries can readily be adapted.

Figure 3 shows the thermocouple locations in one of the test spheres. The temperature at point t_{s1} was measured using a 30 gage



MEASUREMENTS :

t_{S1} - WITH RESPECT TO ICE POINT

$(t_C - t_{S1})$-DIFFERENTIAL

$(t_C - t_{S2})$-DIFFERENTIAL

Figure 3. Copper Sphere Used as Calorimeter.

cu-constantan thermocouple having a spark welded junction and soft soldered at the bottom of the drilled hole with a minute amount of solder. The temperature differentials $t_c - t_{s1}$ and $t_c - t_{s2}$ were obtained by soldering separate single constantan wires in the holes, using the copper sphere as the intermediate metal. The differentials were installed to determine if the results were influenced by the orientation of the measuring junction t_{s1}. No significant effect was observed. To prevent heat conduction from the junctions to the liquid nitrogen through the wire itself, a polyethylene sleeve is placed over the wires external to the sphere and sealed to the sphere. The sphere is supported by a 1/16 inch dia. stainless rod attached with a press fit. In some cases a 1/2 inch dia. sphere was used, in which case it was possible to install only a single thermocouple at the center.

The thermocouple wire was calibrated with a nitrogen vapor-pressure cryostat and at the CO_2, mercury freezing and steam points.

The thermocouple emf were recorded on a Sanborn 150 series recorder through approximately 50 feet of shielded cable which falls free with the test platform. To take advantage of the high sensitivity of the recorder (10 μv/mm) it was found necessary to calibrate it against a precision potentiometer immediately prior to and after each test run. It is estimated that the accuracy of the level of temperature measurement is $\pm$ 0.5°F while the accuracy of relative temperature measurement is better than $\pm$ 0.2°F. Relative temperature measurement is considered with respect to changes taking place during a particular test.

The sphere is highly polished, and the only treatment given to the surface is to cleanse with reagent-grade acetone prior to each test to remove any oil films deposited by handling.

DATA REDUCTION

Figure 4 shows a representative curve for the cooling of the sphere from ambient to liquid nitrogen temperature. In the film boiling range the temperature difference between the center and surface of the sphere is negligible, as might be expected since the corresponding Biot number is approximately 0.004. The heat flux can be computed from the direct measurement of the temperature-time slope from the cooling data and using the specific heat corresponding to the instantaneous temperature. Hence, from the first law of thermodynamics the heat flux is related to the time rate of enthalpy change of the sphere as

$$q/A_s = \frac{m_s}{A_s} (dh/d\theta) = \frac{\rho_s V_s}{A_s} \; Cp_s \; (t_s) \frac{dt_s}{d\theta} \qquad (1)$$

For measurements of film boiling under fractional gravity the millivolt and time scales on the Sanborn recorder are expanded and the test platform released when the sphere reaches the desired temperature level. Normally the sphere is inserted in the liquid nitrogen at room temperature to cool to the desired level, taking as long as 2-1/2 minutes in some cases. To determine if the liquid motion in the container induced by the film boiling influences the results during free fall, a number of tests were conducted by pre-cooling the sphere in the vapor space above the liquid nitrogen, plunging the sphere in the nitrogen and releasing the platform within several seconds. No effect of residual liquid motion could be detected, with both one inch dia. and 1/2 inch dia. spheres.

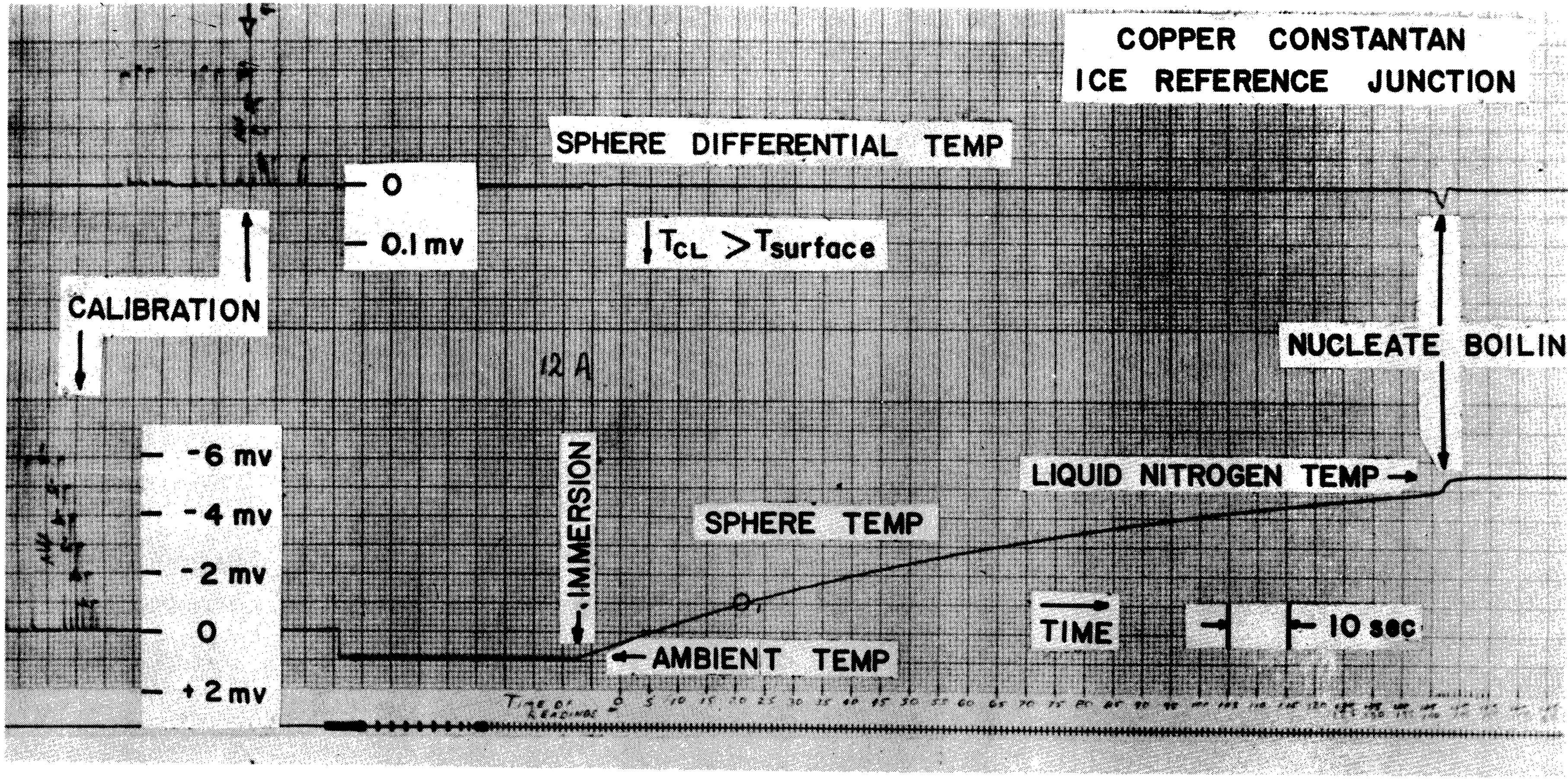


Figure 4. Typical Oscillographic Record of Temperature within One Inch Dia. Copper Sphere with Film Boiling of Liquid Nitrogen. a/g = 1.

In Figure 5 representative measurements in the transition-nucleate region at $a/g = 1$ are given. The correspondence between the point of maximum slope and the largest temperature difference within the sphere (approximately 2°F) is to be noted. For data under fractional gravity or free-fall conditions in this region the test platform is again released at the desired temperature level, as illustrated in Figure 6.

Until recently, the experimental data in the transition-nucleate region were reduced with Equation (1) by assuming the system to be thermally lumped. As with film boiling the cooling rate $(dt_s/d\theta)$ was determined by replotting the original data as temperature vs. time, the slope being computed manually with at least two independent checks. Stolz[11] has suggested that where the Biot number for the sphere $\bar{h}\, r_o/k < 0.4$ the results of the lumped system approximation will be accurate within 1%. The maximum Biot number with liquid nitrogen is 0.35.

While this method of data reduction has proven to be satisfactory, it was time consuming and had an element of subjectivity which was desirable to eliminate. This has been accomplished by finite-difference computations carried out using the IBM 7090 digital computer. The program accepts the original temperature-time data as input and computes the local temperatures at 10 spacial points within the sphere at time intervals of 0.001 seconds. From these the instantaneous spacial average enthalpy of the sphere and then the time rate of change of spacial average enthalpy is computed, which is related to the instantaneous

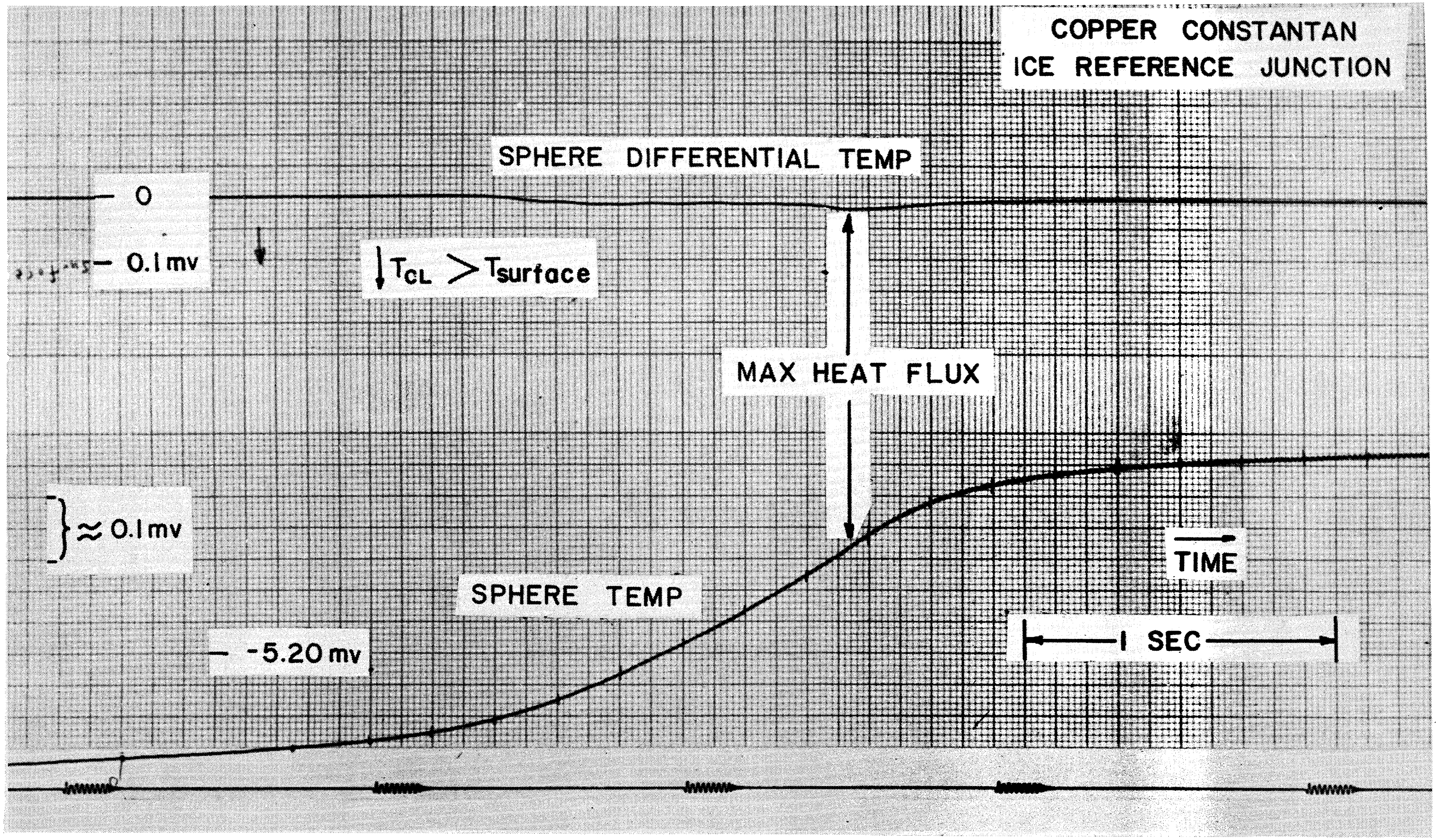


Figure 5. Typical Oscillographic Record with Transition and Nucleate Boiling. a/g = 1.

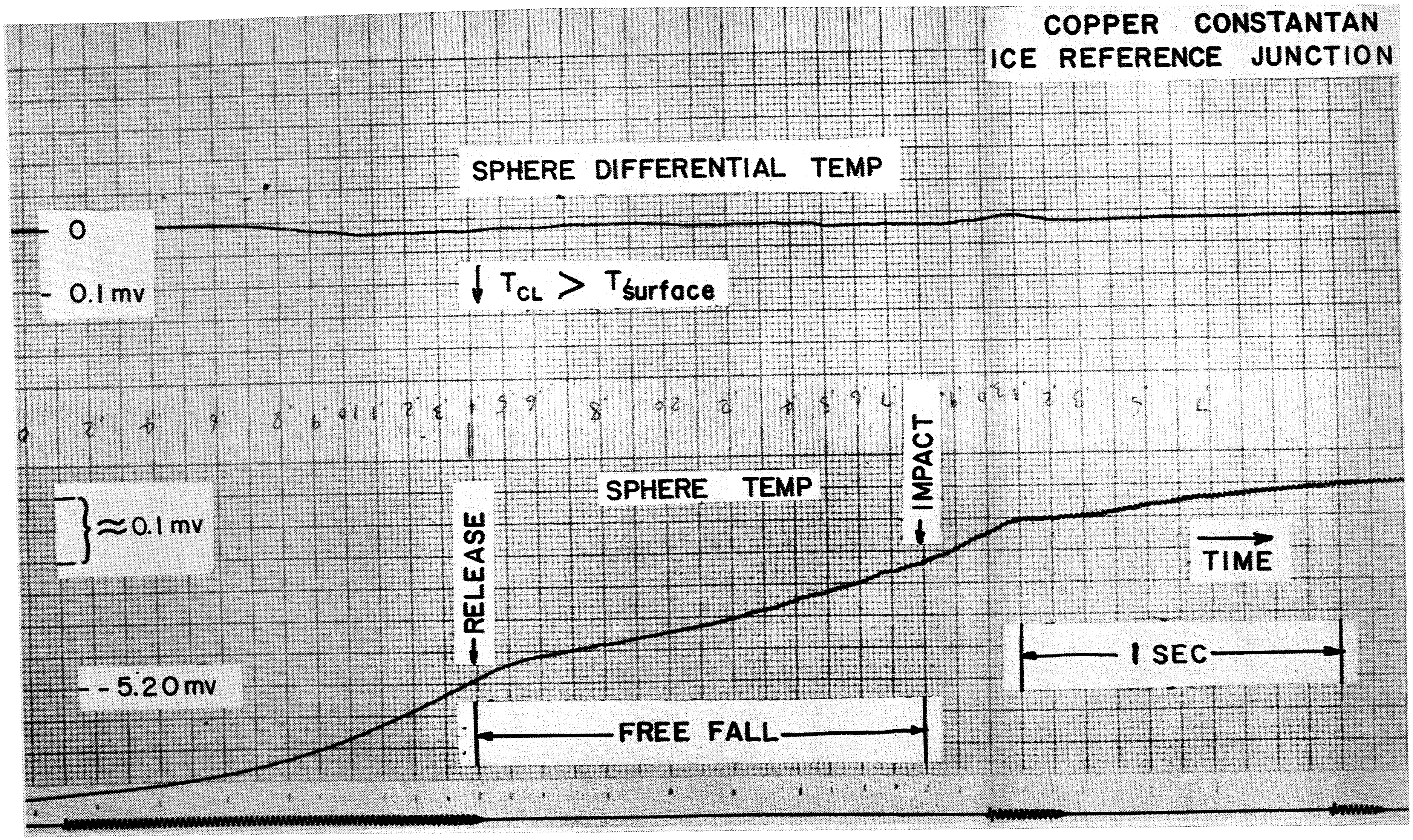


Figure 6. Typical Oscillographic Record During Free Fall with Nucleate and Transition Boiling. a/g 0.

heat flux. The heat flux, surface-fluid temperature difference, and internal temperature difference are outputs of the program.

Favorable comparisons between the carefully performed manual computations and the digital computer results are indicated in Figure 7. These results are modified somewhat in subsequent tests by the use of liquid nitrogen having a higher degree of purity.

For the computer program input the temperatures measured near the surface are taken as the surface temperatures, an acceptable approximation in this case. In circumstances where the maximum heat flux is considerably greater than for liquid nitrogen, an improved approximation for temperature would be required. The inverse method as is given by Stolz[11] also might be used in this case.

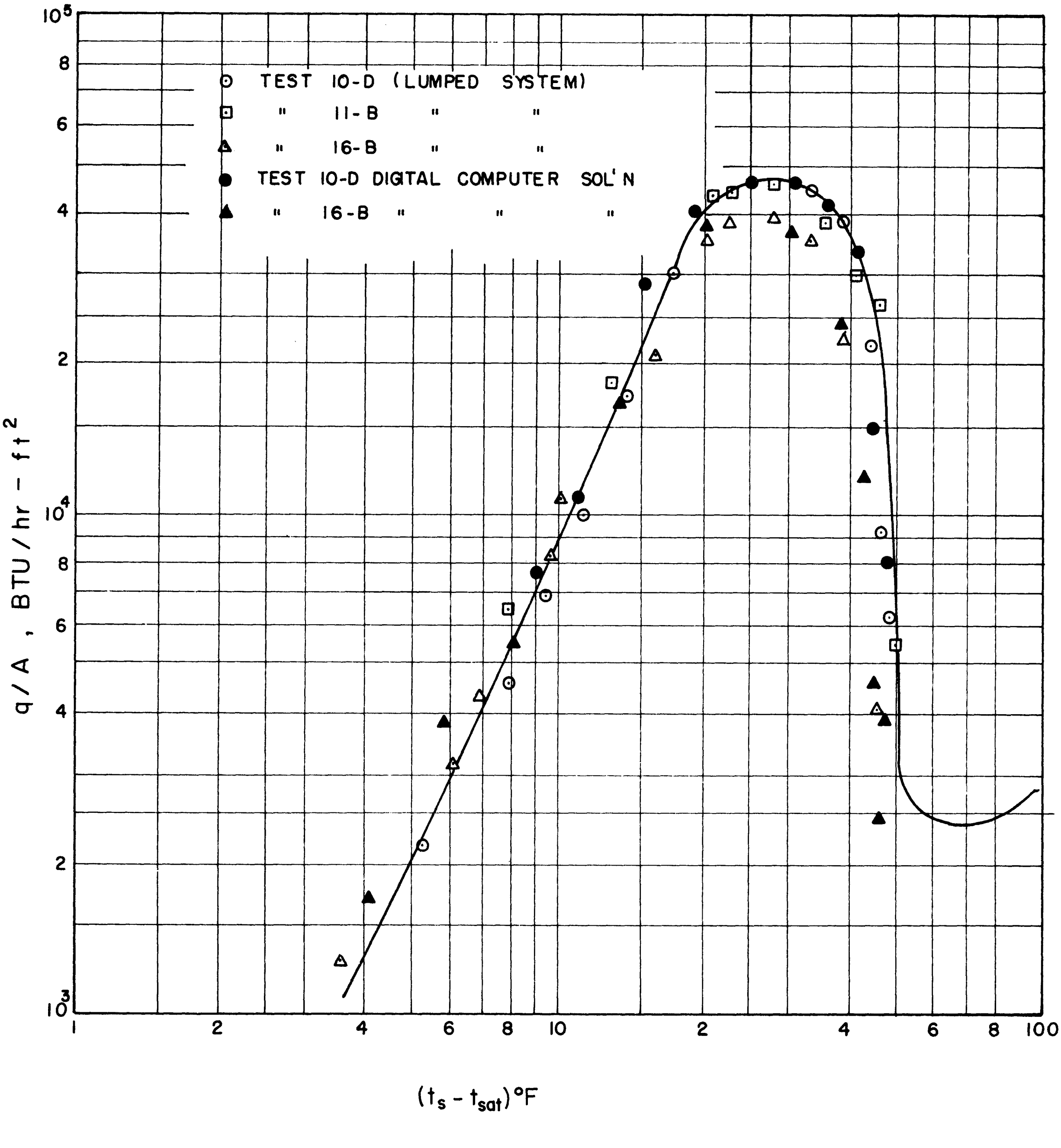


Figure 7. Comparison of Results Reduced Manually and by Digital Computer. a/g = 1.

RESULTS

For convenience and clarity the experimental results are presented according to the sub-groups listed below.

(a) Film Boiling Region

On the right hand side of Figure 8 the results for film boiling at standard gravity, several fractional gravities and free fall are plotted. The scatter in the data for free fall are considered the consequence of large relative variations in the local effective gravity which can occur with minute variation in guide-wire friction.

No effect of a change in size of the sphere from one inch dia. to 1/2 inch dia. could be detected, and comparison is made with the data of Bromley[15] for an electrically heated horizontal tube in the steady-state. Although the raw data agree well with the present work the correlation of Bromley does not represent the behavior at $a/g = 1$ nor at fractional gravities. This probably results from the fact that Bromley's correlation is for laminar conditions which do not exist in these experiments. Bromley's correlation is:

$$\frac{\bar{h}D_o}{k_{vf}} = 0.62\left[\frac{D_o^3\rho_{vf}(\rho_\ell-\rho_{vf})g}{\mu_{vf}^2}\left(\frac{C_p\mu}{k}\right)_{vf}\left(\frac{h_{fg}}{C_p\Delta t} + 0.4\right)\left(\frac{a}{g}\right)\right]^{1/4} \qquad (2)$$

A number of other workers,[20,25,26] have obtained film boiling relationships for horizontal and vertical surfaces similar to the above under saturation conditions, also for laminar flow.

Frederking, et al.[17] analyzed film boiling about a sphere for laminar flow, and the resulting equation included a 1/4 exponent on the modified Rayleigh number. It was noted that experimental results

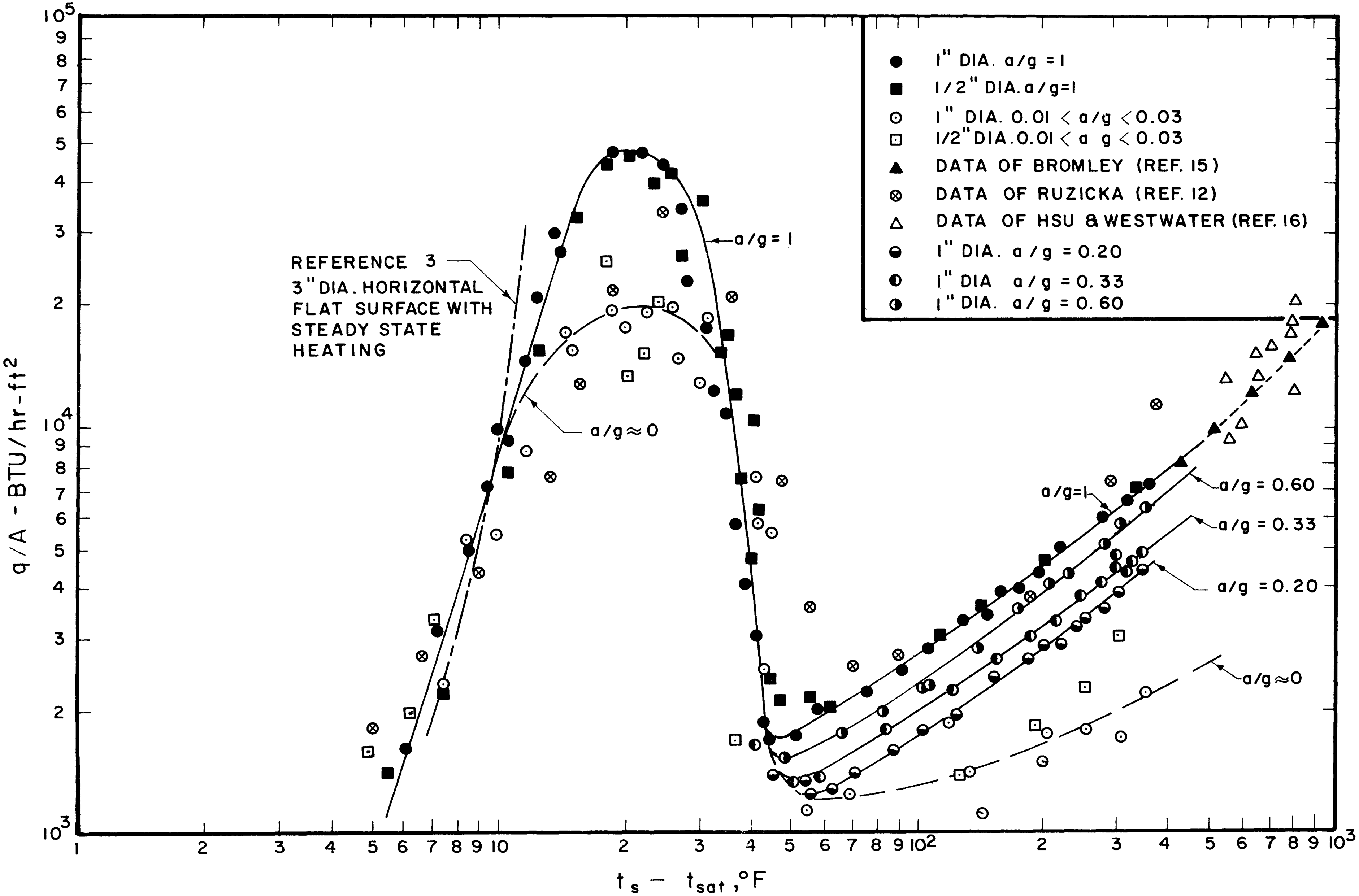


Figure 8. Film Boiling Under Standard and Fractional Gravity and Nucleate Boiling at Standard Gravity and Free Fall. Liquid Nitrogen.

for vertical surfaces,[12] horizontal tubes and spheres give essentially the same results, and thus concluded that film boiling in these regions is independent of geometry, a characteristic of turbulent free convection. Accordingly, the exponent on the modified Rayleigh number was changed to 1/3 and the results given as:

$$\frac{\bar{h}D_o}{k_{vf}} = 0.15\left[\frac{D_o^3 \rho_{vf}(\rho_\ell - \rho_{vf})g}{\mu_{vf}^2}\left(\frac{C_p\mu}{k}\right)_{vf}\left(\frac{h_{fg}}{C_p\Delta t} + 0.5\right)\left(\frac{a}{g}\right)\right]^{1/3} \quad (3)$$

Figure 9 shows that Equation (3) predicts the film boiling behavior under fractional gravity reasonably well. Bromley's correlation[15] also is included using his definition of the modified Rayleigh number. This result suggests that a transition from laminar to turbulent film boiling appears to occur at a modified Rayleigh number. This result suggests that a transition from laminar to turbulent film boiling appears to occur at a modified Rayleigh number of about 5×10^7.

(b) Transition and Nucleate Boiling Region

Experimental results in the transitional and nucleate boiling regions also are placed on Figure 8 for both standard gravity and free fall conditions. It will be noted that no difference exists in the behavior of the 1/2 inch dia. and one inch dia. spheres. Furthermore, it also appears that transitional and nucleate boiling are quite insensitive to the two orders of magnitude range in gravity covered.

This is consistent with the results of Sherley.[9] In this work nucleate boiling of liquid hydrogen was obtained from an electrically heated flat surface at standard gravity, under free-fall conditions in a drop tower and in a KC-135 aircraft. It was found that zero-gravity

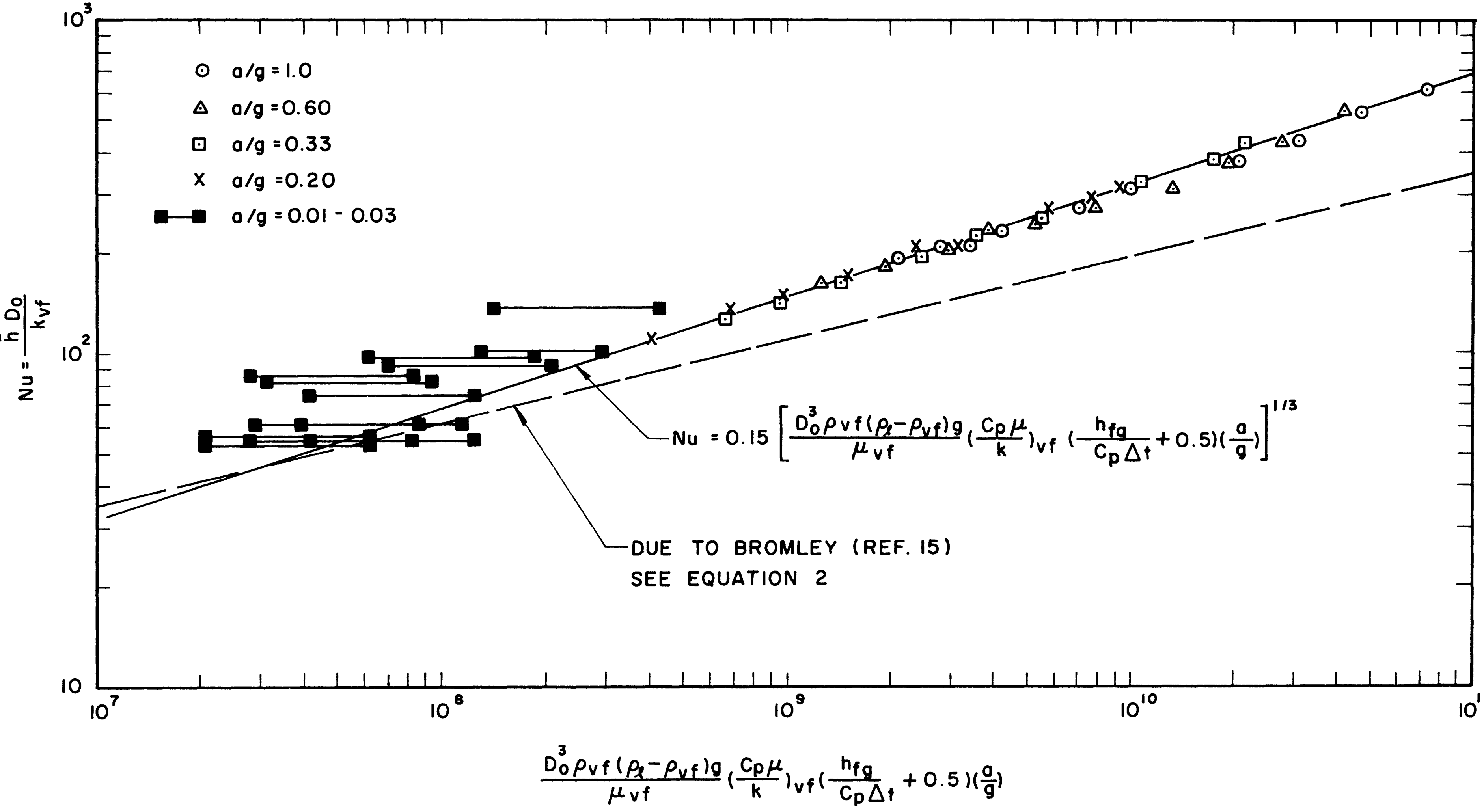


Figure 9. Comparison of Fractional Gravity Film Boiling Data for Liquid Nitrogen with Correlations by Frederking and Clark(17) and Bromley.(15)

tests produced the same results as those at standard gravity. From these somewhat unexpected results it might then be concluded that the dynamic or inertial force present in bubble growths, even with saturated boiling, is the controlling factor in nucleate boiling rather than buoyant forces. A ratio of the bubble growth inertial force to the buoyant force, having the nature of a Froude number, was defined(4) using the bubble growth equation of Forster and Zuber.(7) With representative values of bubble size and heater surface superheat the Froude number varied from 452 for liquid nitrogen to 14,000 for water at $a/g = 1$.

In the region of the maximum heat flux the heat transfer rates are sensitive to the effective gravity, as is evident from the scatter of the data under free fall. Figures 9 and 10 show the complete data for a number of tests in the nucleate-transition region for $a/g = 1$ and including the fractional gravities of $a/g = 0.20$ and $a/g = 0.33$. It is noted again that the behavior in the transition and nucleate region is not significantly altered by gravity whereas the peak heat flux is decreased.

Slight shifts in the transition and nucleate region have occurred from day to day, as may be noted by comparing Figures 9 and 10. No explanation has yet been found for this behavior.

(c) Maximum Heat Flux Region

A number of correlations for the maximum heat flux with pool boiling have been presented in the literature. In most cases a dependence on effective gravity is given as $(a/g)^{1/4}$. Burnout measurements with a platinum wire in water(5) under various fractional gravities have

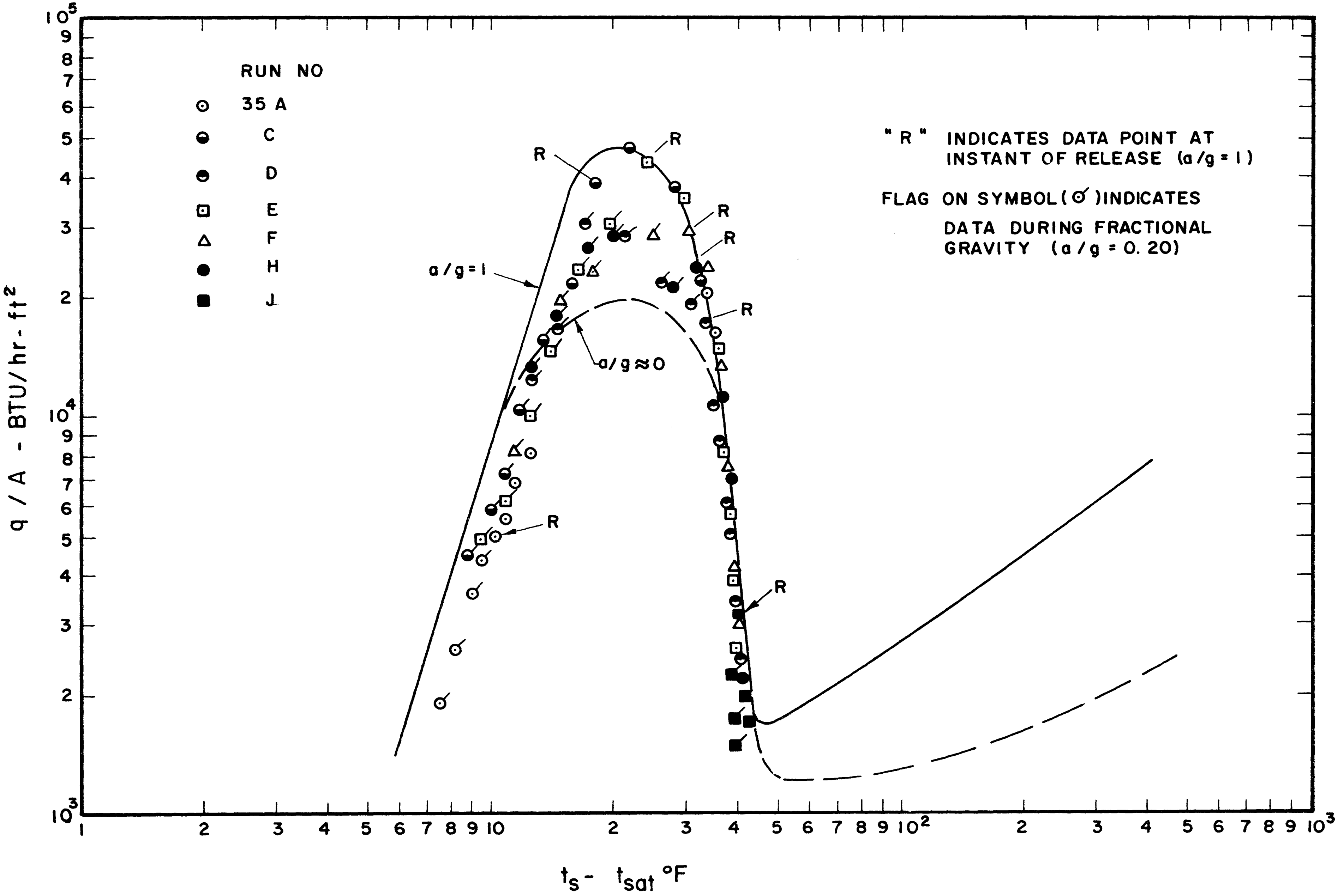


Figure 10. Nucleate Boiling of Liquid Nitrogen from Sphere During Fractional Gravity. a/g = 0.20.

shown this trend. The data in Figures 8, 10, and 11 furnish further opportunity for verification.

In Figure 12 the maximum heat flux is plotted against the local acceleration ratio. The correlation of Noyes,[18] which includes an effect of Prandtl number, gives the best comparison with the data presented here. Some of the recent correlations for the maximum heat flux are listed below for reference, and the values predicted for saturated liquid nitrogen at atmospheric pressure are given in Table I.

Noyes:[18]

$$(q/A)_{max} = 0.144\ h_{fg}\rho_v^{1/2}\left[\frac{(\rho_\ell-\rho_v)^2}{\rho_\ell}\ gg_o\sigma\right]^{1/4}\ P_r^{-0.245}\left(\frac{a}{g}\right)^{1/4} \quad (4)$$

Chang and Snyder:[19]

$$(q/A)_{max} = 0.145\ h_{fg}\rho_v^{1/2}[gg_o\sigma(\rho_\ell-\rho_v)]^{1/4}\left(\frac{a}{g}\right)^{1/4} \quad (5)$$

Zuber - Discussion in Reference 20:

$$(q/A)_{max} = C_1 h_{fg}\rho_v^{1/2}[gg_o\sigma(\rho_\ell-\rho_v)]^{1/4}\left(\frac{a}{g}\right)^{1/4} \quad (6)$$

where

$$.120 \leq C_1 \leq .157$$

Borishanskii:[22]

$$(q/A)_{max} = K_2 h_{fg}\rho_v^{1/2}[gg_o\sigma(\rho_\ell-\rho_v)]^{1/4}\left(\frac{a}{g}\right)^{1/4} \quad (7)$$

where

$$K_2 = 0.13 + 4N^{-0.4}$$

and

$$N = \frac{\rho_\ell\sigma^{3/2}}{\mu^2[g(\rho_\ell-\rho_v)]^{1/2}}\left(\frac{a}{g}\right)^{-1/2}$$

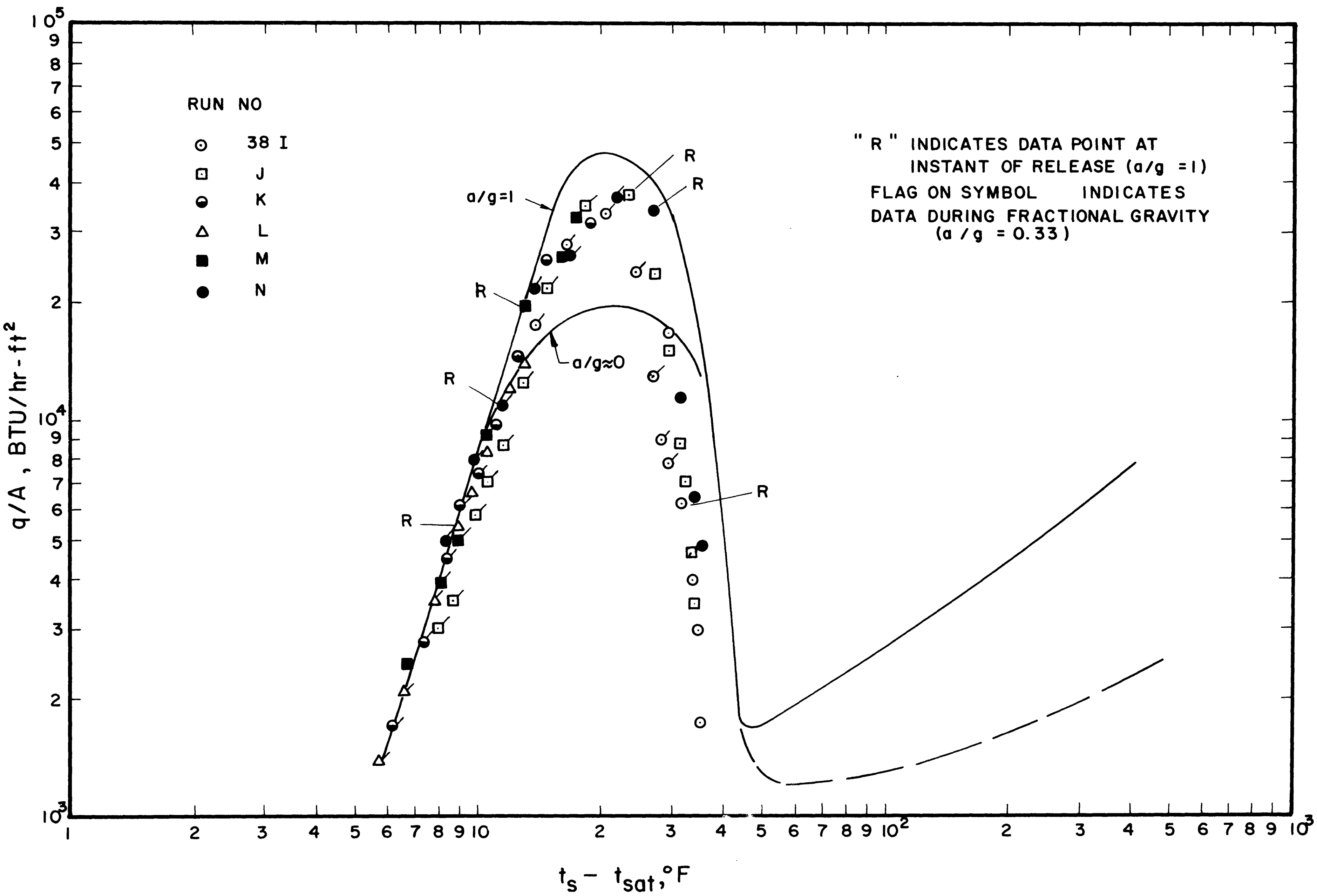


Figure 11. Nucleate Boiling of Liquid Nitrogen from Sphere During Fractional Gravity. a/g = 0.33.

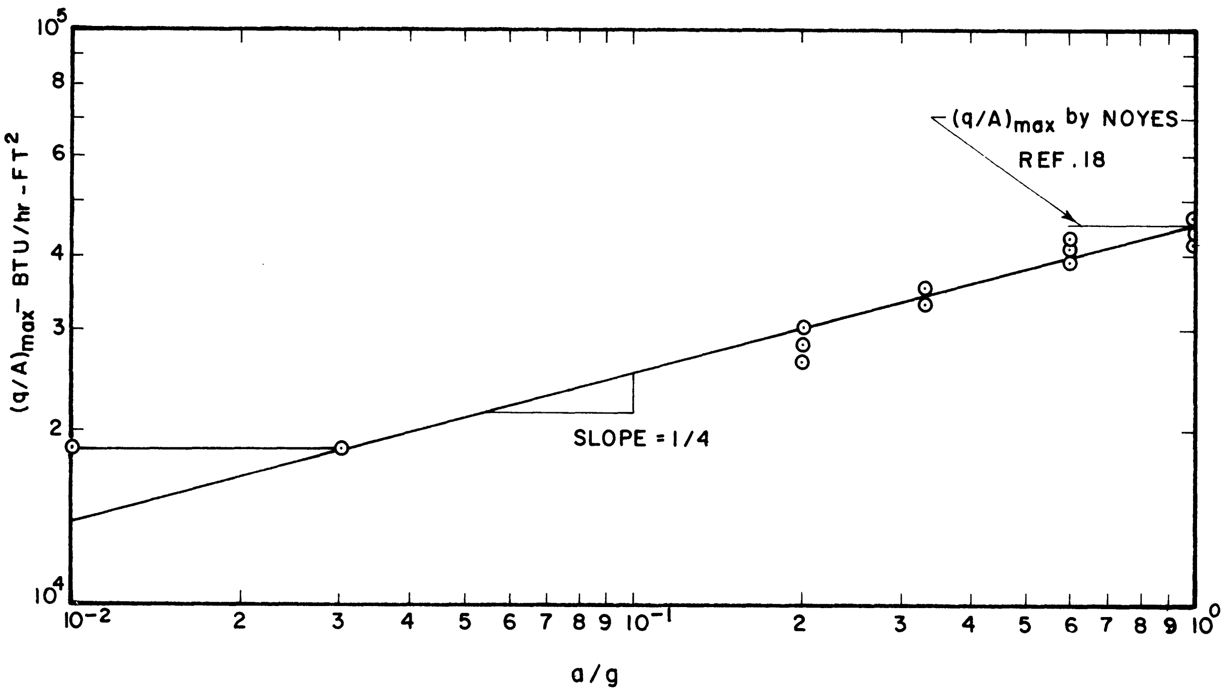


Figure 12. Maximum Heat Flux Data for Liquid Nitrogen from Sphere During Fractional Gravity.

Moissis and Berenson:[23]

$$(q/A)_{max} = C_2 h_{fg} \rho_v^{1/2} [g g_o \sigma (\rho_\ell - \rho_v)]^{1/4} (\frac{a}{g})^{1/4} \qquad (8)$$

where

$$C_2 = 0.18 \frac{(\frac{\rho_\ell + \rho_v}{\rho_v})^{1/2}}{1 + 2 (\frac{\rho_v}{\rho_\ell})^{1/2} + (\frac{\rho_v}{\rho_\ell})}$$

TABLE I

COMPARISON OF $(q/A)_{max}$ CORRELATIONS FOR SATURATED LIQUID NITROGEN AT ATMOSPHERIC PRESSURE AND $a/g = 1$

Source	Equation	$(q/A)_{max}$ BTU/hr-ft^2
Noyes (18)	(4)	45,000
Chang & Snyder (19)	(5)	56,500
Zuber (20)	(6)	46,000 - 61,000
Borishanskii (22)	(7)	61,000
Moissis & Berenson (23)	(8)	65,000
Experimental	Present authors	47,000

The experimental values of the maximum heat flux are plotted in Figure 13 to indicate the corresponding temperature differences.

Chang and Snyder[19] derived an expression for Δt_{cr} by equating the maximum heat flux, Equation (5), to the product of the Δt_{cr} and their correlation for $\bar{h}$ in nucleate boiling, resulting in:

$$\Delta t_{cr} = \frac{0.725}{1.450} \times 10^3 \frac{(h_{fg}\rho_v)^{9/5} \sigma [g g_o \sigma (\rho_\ell - \rho_v)]^{1/4}}{\rho_v^{1/2} k_\ell [C_p T_s (\rho_\ell - \rho_v)]^{2/5} \Delta P^{7/5}} (\frac{a}{g})^{1/4} \qquad (9)$$

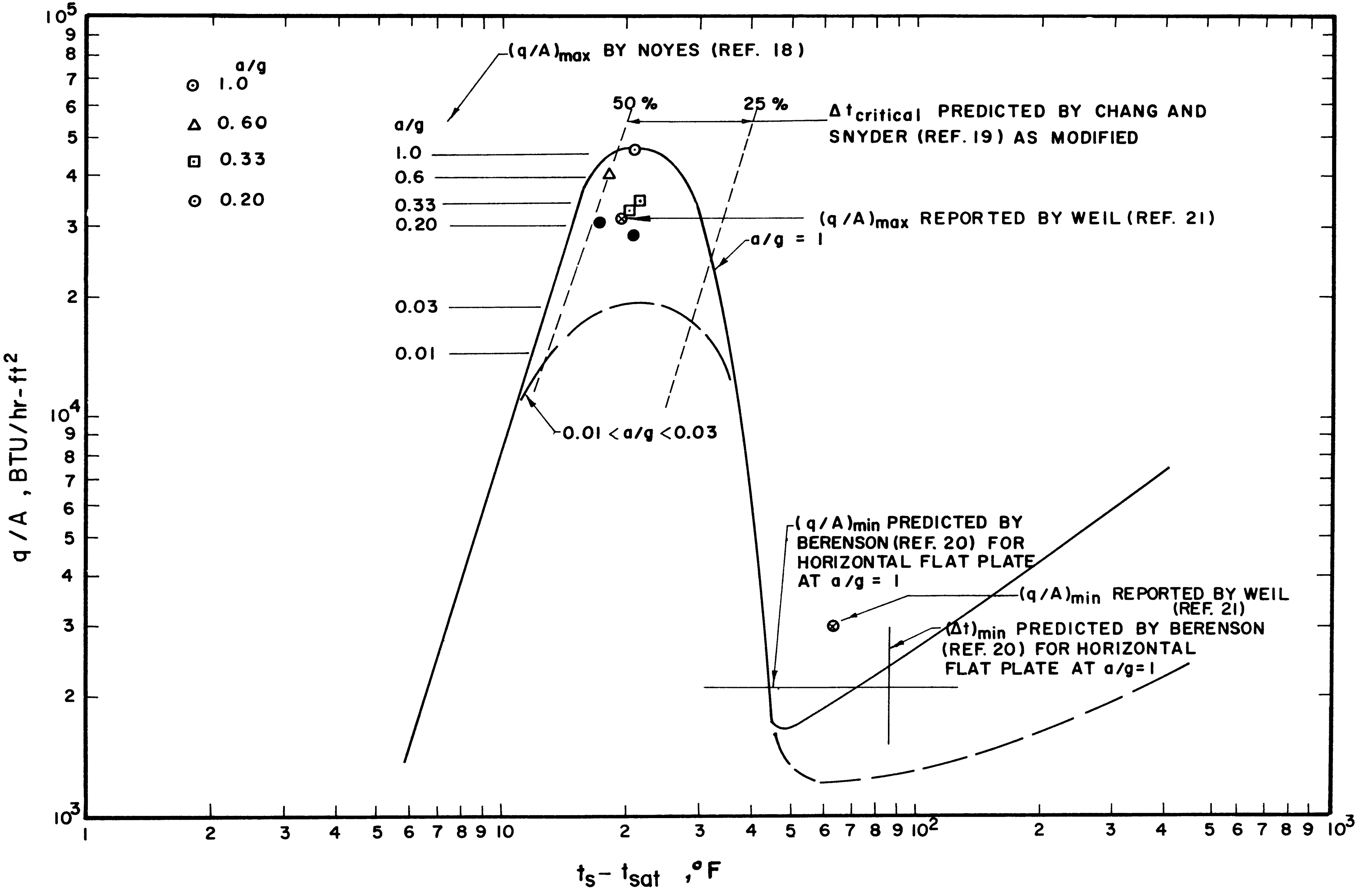


Figure 13. Comparison of Data with Maximum and Minimum Correlations.

The range in the constant arises from the assumption of from 25% to 50% coverage of the heater surface by the bubbles at the maximum heat flux. For liquid nitrogen Equation (9) predicts values in the range $26°F < \Delta t_{cr} < 50°F$ at $a/g = 1$.

In the original equation for $\bar{h}$ used in deriving Equation (9) an empirical constant equal to 0.363 is determined from nucleate boiling data for water. When this constant is redetermined for liquid nitrogen nucleate boiling it is found to be 0.60 and the corresponding constant in Equation (9) ranges from 0.26 to 0.52. The resulting values of Δt_{cr} for the various a/g are shown in Figure 13. The experimental results fall within the range predicted.

(d) Minimum Heat Flux Region

Based on the analysis of Zuber,[24] Berenson[20] had determined the following relation for the minimum heat flux with film boiling,

$$(q/A)_{min} = 0.09\, h_{fg}\rho_{vf}\left[\frac{gg_o\sigma(\rho_\ell-\rho_v)}{(\rho_\ell+\rho_v)^2}\right]^{1/4}\left(\frac{a}{g}\right)^{1/4} \tag{10}$$

This value for liquid nitrogen is indicated on Figure 13 for $a/g = 1$.

The data of Figure 8 furnish approximate experimental values of $(q/A)_{min}$ at the various fractional gravities, and these are compared with the predicted values of Equation (10) in Table II. Although the predicted values were specified as applying to horizontal surfaces, the similarity with the experimental results from a sphere is interesting.

An equation for Δt_{min} was derived by Berenson[20] by equating the minimum heat flux, Equation (10), to $\bar{h} \times \Delta t_{min}$ using his correlation

for film boiling, resulting in:

$$\Delta t_{min} = 0.127 \frac{\rho_{vf} h_{fg}}{k_{vf}} \left[\frac{g(\rho_\ell - \rho_v)\mu_f}{(\rho_\ell + \rho_v)^2}\right]^{1/3} \left[\frac{g_o \sigma}{g(\rho_\ell - \rho_v)}\right]^{1/2} \left(\frac{a}{g}\right)^{-1/6} \quad (11)$$

This result for liquid nitrogen at $a/g = 1$ is also indicated on Figure 13.

TABLE II

COMPARISON OF EXPERIMENTAL AND PREDICTED VALUES OF $(q/A)_{min}$, EQUATION (10)

a/g	$(q/A)_{min}$-predicted	$(q/A)_{min}$-experimental
1	2100	1700 - 2100
.6	1850	1550
.33	1590	1300 - 1400
.20	1400	1300
.03	875	870 - 1100
.01	666	

CONCLUSIONS

1. For film boiling from spheres, the heat flux and the Nusselt number have been found to be proportional to $(a/g)^{1/3}$ within the range of gravities examined, $0.01 < a/g < 1$. Although these results were achieved with a transient technique over a short time interval, it is believed that steady-state measurements would yield the same results. With saturated liquid, steady-state film boiling is not possible at zero gravity unless the vapor formed can be removed from the vicinity of the heating surface by means other than gravitational buoyant forces. In this case the rate of heat transfer will be a function of the vapor-removing mechanism.

2. The nucleate and transition boiling regions appear to be insensitive to gravity within the range covered for saturated liquids. This may be expected to be the case with pool boiling of a subcooled liquids as well.

   Any comparison between nucleate boiling under short term and long term zero gravity will depend on the motion of the vapor as it is generated. If it remains in the vicinity of the heating surface then nucleate boiling as such can no longer continue. Subcooled liquid at the heating surface would be difficult to maintain with no gross convection.

3. The maximum and minimum heat flux with pool boiling appear to follow a dependence of gravity according to $(a/g)^{1/4}$.

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