THE UNIVERSITY OF MICHIGAN

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HEAT TRANSFER AT "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 = 4.17×10^8 ft/hr^2.
g_o	Mass-force conversion constant = 4.17×10^8 lbm/lb$_f$ ft/hr^2
h	Enthalpy - BTU/lbm-°F
$\bar{h}$	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
Ra'	Modified Rayleigh number - see Figure 9
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
$\lambda_c = 2\pi \left[\frac{g_c \sigma}{g(\rho_\ell - \rho_v)}\right]^{1/2}$	Critical wavelength - ft

Subscripts

s	Sphere
sat	Saturation
f	Film temperature
l	Liquid
v	Vapor

INTRODUCTION

A prior work(1) has been presented which deals with boiling heat transfer from a one-inch diameter sphere to saturated liquid nitrogen at atmospheric pressure under reduced gravity. The present paper considers the effects of a change in size (to one-quarter inch diameter) and an increase in pressure (to five atmospheres). Additional data are presented which were obtained under conditions more closely approaching the condition of zero gravity. These resulted from a modification to the test facility permitting an a/g ratio less than 0.002, as compared with the previous range from 0.01 to 0.03.

One motivation for this study arose from previous work(2) with high force fields. Previous 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 investigating the influence of this parameter.

Initial research includes the range of a/g up to 40(3) for nucleate pool boiling of saturated water, and a/g up to 20(4) for nucleate 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 whether similar effects occurred in cases where the force field is less than that corresponding to standard gravity. In this connection a Froude number criterion for distinguishing the limits of a bouyant force dominated process has been presented(5) based on the results of Adelberg and Forster(7) and Forster and Zuber.(8)

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.

A drop tower is used to achieve fractional and near-zero gravities. Inherent in this msthod 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 condition is probably the most convenient for this determination. For unsteady-state conditions it is necessary to include the effect of the thermal capacity of the heater surface.

In view of the short test period available for these measurements in a drop tower, 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. Simultaneously, the corresponding temperature difference is obtained.

This technique is not new and has been used for a number of years in this laboratory to demonstrate the behavior of lumped-parameter thermal 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.(9) reports an application of this method for the determination of heat transfer from tubes. Several references with this method are given by Stolz.(10) This method has been used to obtain boiling heat transfer data.(1,2,4,5) The same simple test device permits measurements in the film, transition, maximum and minimum, nucleate boiling and free convection regions. Ruzicka(11) has presented boiling data for liquid nitrogen with a hollow vertical cylinder as a transient calorimeter.

Several studies of transient boiling have been conducted(12,13) 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, comparison of the transient data with those from steady-state measurements validates this supposition.(1)

EXPERIMENTAL APPARATUS

A cross-section of the drop tower facility is shown in Figure 1. The free fall distance of 31 feet gives 1.4 seconds of approximately zero-gravity. A specially designed hydraulic buffer topped by an automotive-type coil spring and foam rubber brings the test package, having a total mass of 135 pounds, to rest in 2 1/2 feet with a maximum deceleration of approximately 30 g's. After the test package comes to a stop, it falls over a few degrees from the vertical until the top rests against one or two of the upright members which form an inverted conical enclosure around the base of the buffer.

A sketch of the test package is shown in Figure 2. The test vessel is a three liter stainless steel beaker surrounded by three inches of styrofoam. For "Zero-g" tests, the test vessel is suspended from the upper part of the outer package via three chains and a spring loaded pawl which is prevented from withdrawing by friction. The outer package is released by withdrawing a solenoid actuated yoke, and the weight of the inner vessel is then removed from the spring-loaded pawl, thereby releasing the inner vessel. The outer package thus acts as a wind screen, eliminating the effects of air disturbances and drag.

The upper end of the outer package has a welded flange and a removable cover so that the test vessel may be pressurized. The cover is equipped with a pressure transducer, a quick-disconnect pressure fitting, a pressure relief valve, and a release stud. A dial face pressure gauge was calibrated with a dead weight calibration fixture,

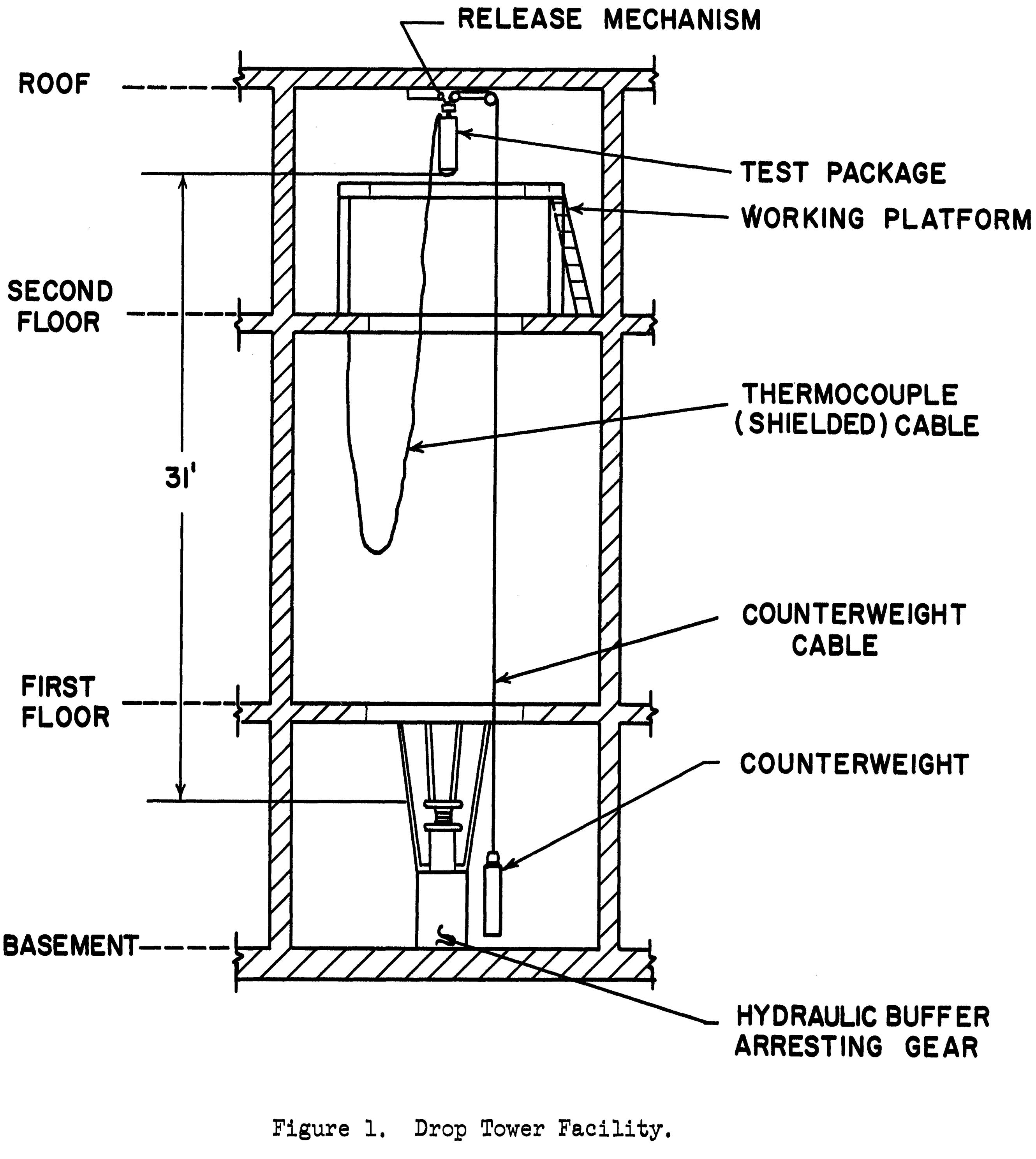


Figure 1. Drop Tower Facility.

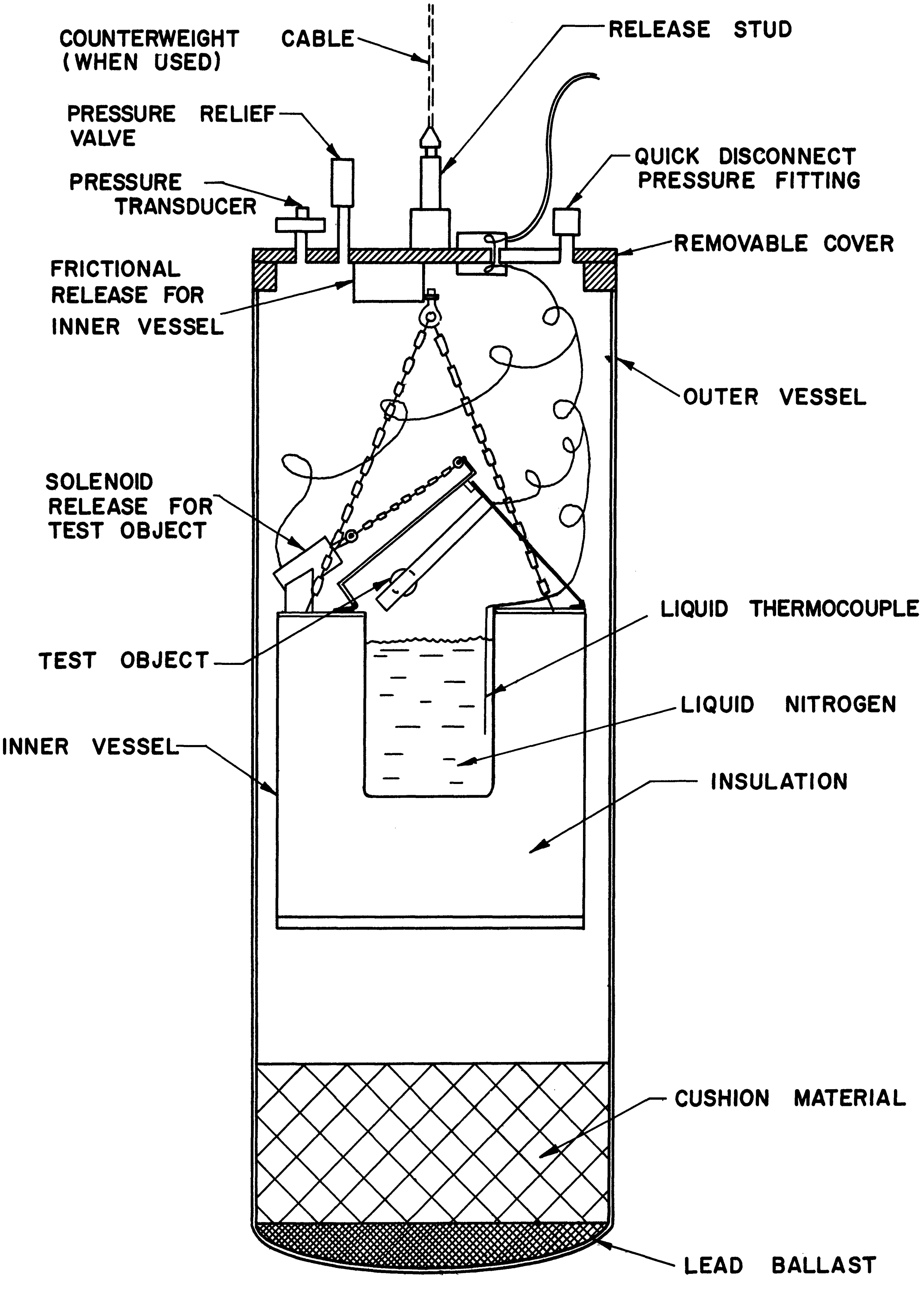


Figure 2. Test Package.

then used to calibrate the pressure transducer before each run. It is estimated that the accuracy of the pressure determination is ± 1%.

A Kistler Model 303 Servo-Accelerometer (± 1.0 g range) is installed to monitor the local gravitational force field of the inner vessel during drop. Measurements indicate that the effective force field with free fall is approximately 0.001 g . More accurate measurements of the force field than this are not practical because of background electrical noise level. The force field has been reduced to the level, it is believed, where the forces in the small electrical wires between the outer package and the inner test vessel are becoming influential.

For fractional gravity a counter-weight system is used. This consists of a six inch O.D., five foot long, counter-weight made of a closed aluminum tube filled with variable quantities of lead shot. The counter-weight is attached to the test package via a 1/8 inch diameter flexible steel cable with light weight ball bearing supported pulleys. The counter weight cable passes through the solenoid operated release mechanism. The counter-weight impact is absorbed with two automotive-type air springs venting through adjustable orifices.

The inner test vessel rests on the bottom of the outer package for fractional gravity tests.

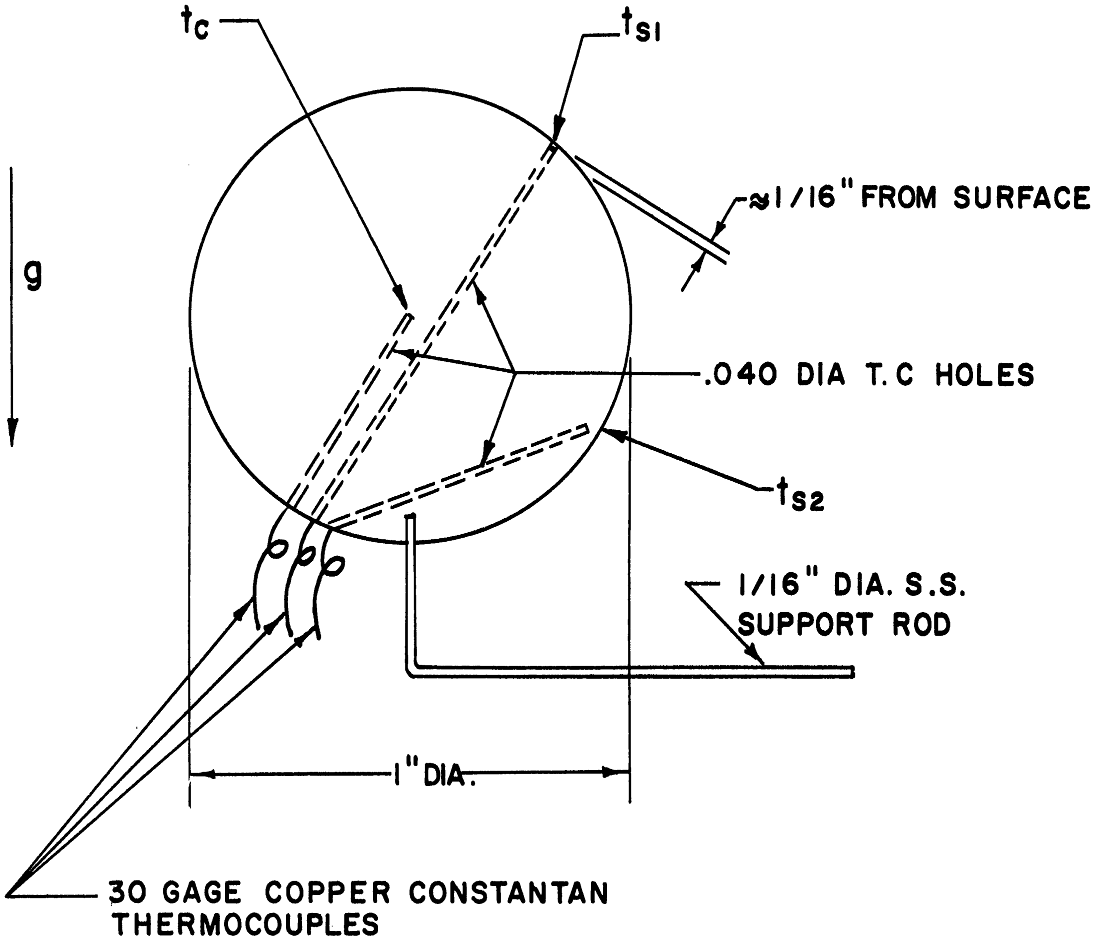
The outer package was pressurized with high purity dry nitrogen when performing saturated boiling tests at elevated pressures.

The heat transfer surface geometry for the results presented here is a sphere, selected for symmetry and ease of instrumentation.

Electrolytic copper was chosen as the sphere material 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.

Three test sphere diameters were used: one inch, one-half inch, and one-quarter inch. Figure 3 shows the thermocouple locations in the one-inch diameter test sphere. The temperature at point t_{s1} was measured using a 30-gage copper-constantan thermocouple having a spark welded junction and soldered at the bottom of the drilled hole with a minute amount of soft-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 thermocouples were installed to determine the influence of 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 one-inch and one-half inch diameter spheres are supported by 1/16 inch diameter stainless steel rods attached with press fits. The one-quarter inch diameter sphere is supported only by the thermocouple wires. It was possible to install a single thermocouples only at the centers of the one-half inch and one-quarter inch spheres.

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



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 for Boiling Heat Transfer Measurements.

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 (10μv/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 ± 0.5°F while the accuracy of relative temperature measurement is better than ± 0.2°F. Relative temperature measurement is considered with respect to changes taking place during a particular test.

The spheres are highly polished, and the only treatment given to the surface is to cleanse it with reagent-grade acetone prior to each test to remove any contamination deposited by handling.

DATA REDUCTION

Figure 4 shows a representative cooling curve for the sphere from the 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 temperature-time slope of the cooling data and using the specific heat corresponding to the instantaneous temperature. Hence, the time rate of enthalpy change of the sphere is

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

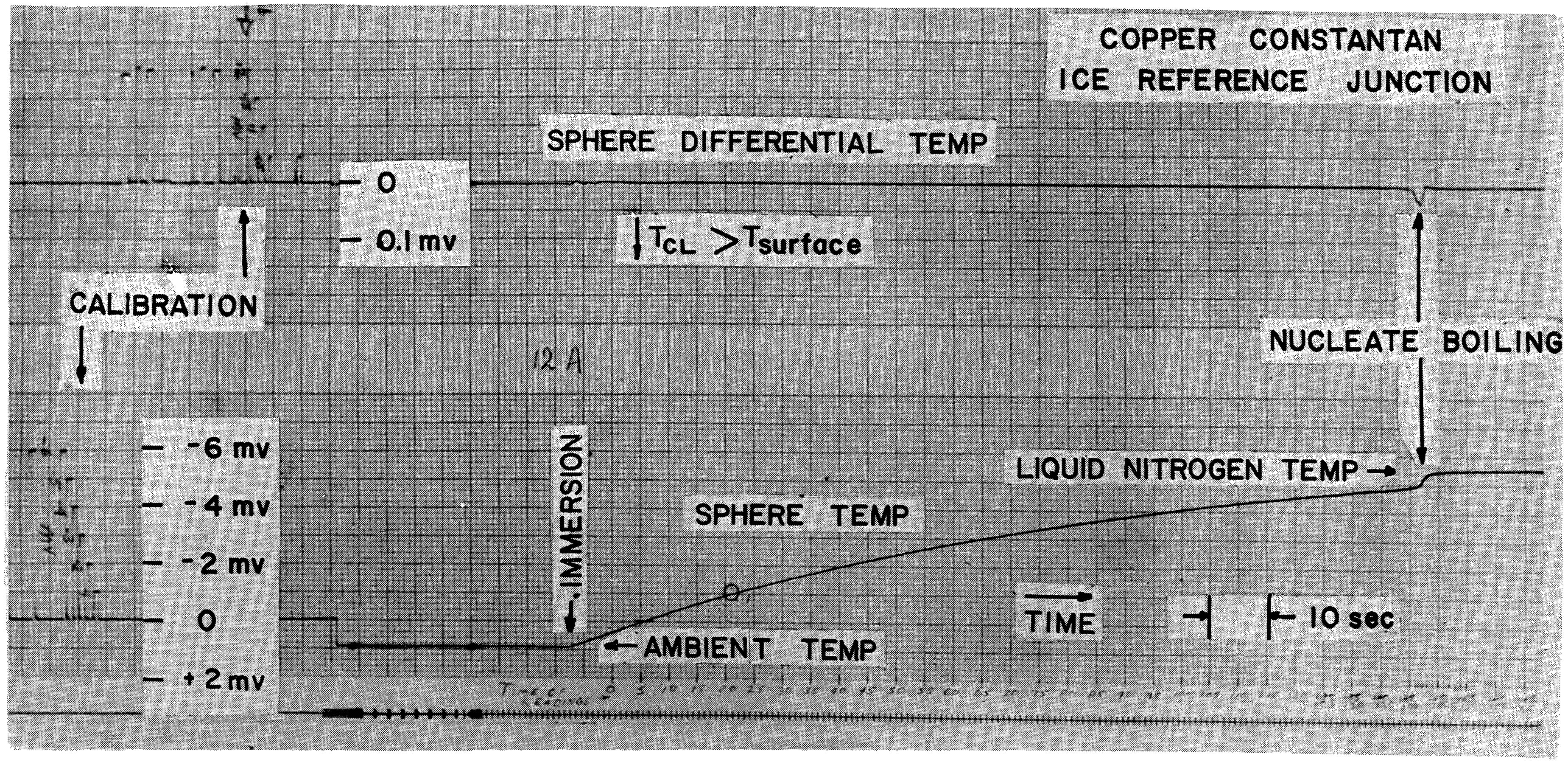


Figure 4. Typical Oscillographic Record of Temperatures Within One Inch Diameter Copper Sphere with Film Boiling of Liquid Nitrogen. a/g = 1

For measurements of film boiling under fractional gravity the millivolt and time scales on the Sanborn recorder are expanded and the test package 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, requiring as long as 2-1/2 minutes in some cases. To determine the influence or the liquid motion in the container induced by the film boiling on 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 package within several seconds. No effect of residual liquid motion could be detected, with both one-inch diameter and 1/2 inch diameter spheres.

In Figure 5 a representative result is shown in the transition-nucleate boiling region. The correspondence between the point of maximum slope and the largest temperature difference within the sphere (approximately 2°F) may be noted. For data under fractional gravity or free-fall conditions in this region the test package is released at the desired temperature level, as illustrated in Figure 5. A method for determining the heat flux in the transition-nucleate boiling region is described in Reference 1.

RESULTS

(a) The Effects of Pressure and Size on Boiling

Boiling data for the several sphere diameters and pressures investigated are presented in Figure 6 for the standard gravity case.

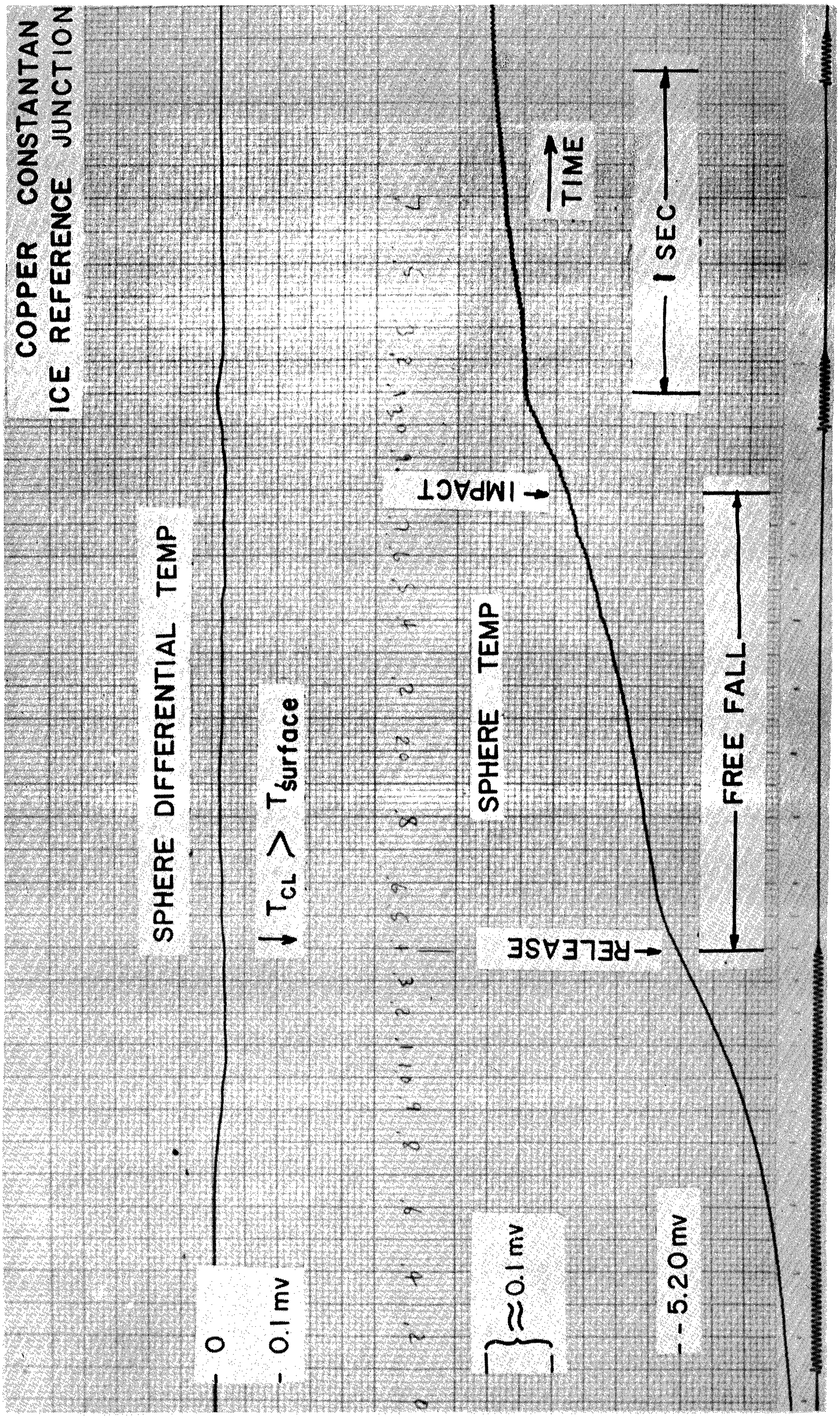


Figure 5. Typical Oscillographic Record During Free Fall with Nucleate and Transition Boiling. $a/g \approx 0$

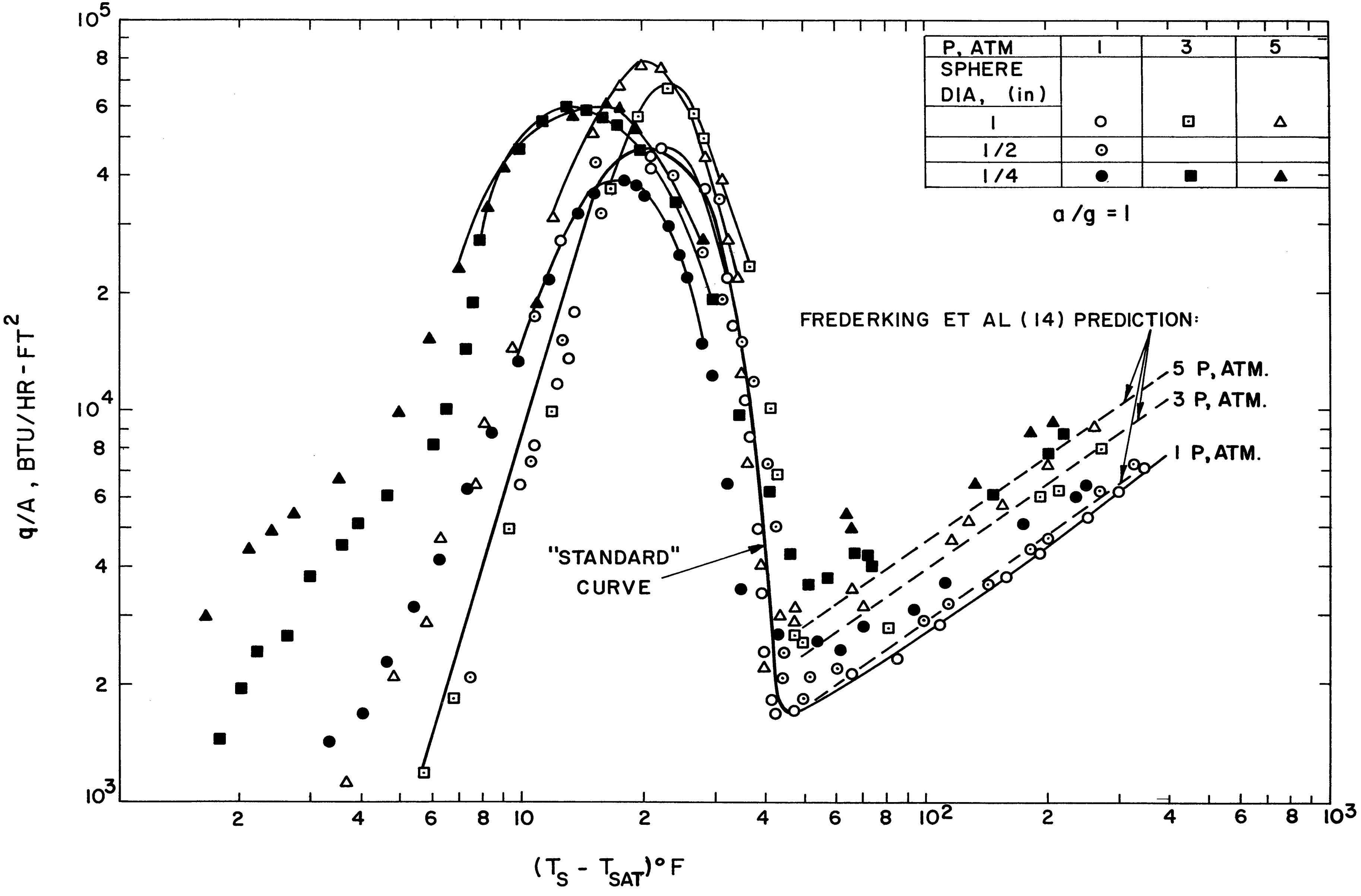


Figure 6. Boiling of Liquid Nitrogen under Standard Gravity for Several Different Diameter Spheres at Various Pressures.

In the film boiling region, the following observations may be made:

(1) at a given temperature difference, the heat flux increases with increasing pressure for a constant sphere diameter;

(2) at a given temperature difference, the heat flux increases slightly with decreasing sphere diameter for a constant pressure.

Shown for reference purposes is a "standard" curve which was obtained from many tests with the one inch sphere at $a/g = 1$ and one atmosphere pressure. Frederking et al.(14) have analyzed film boiling about a sphere and used the data from which the standard curve was drawn along with other data to determine the coefficient in the relationship:

$$\frac{\bar{h}D_o}{k_{vf}} = 0.14 \left[\frac{D_o^3 \rho_{vf}(\rho_\ell - \rho_{vf}) g}{\mu^2_{vf}} \left(\frac{c_p\mu}{k}\right)_{vf} \left(\frac{h_{fg}}{c_p\Delta t} + 0.5\right)\left(\frac{a}{g}\right)\right]^{1/3} \qquad (2)$$

This relationship is shown in Figure 6 for values of pressure of 1, 3 and 5 atmospheres. As can be seen, the agreement at the higher pressures is excellent for the one inch sphere data, but the correlation does not indicate the effect of a change in the sphere diameter.

In the transition and nucleate boiling region, the scatter of data points is more pronounced than in the film boiling region (see, e.g., Reference 1). However, there is a clear indication of an increase in heat flux with increasing pressure in both the nucleate boiling and peak heat flux region. With nucleate boiling the influence of pressure is greater for the smaller size sphere.

The value of Δt corresponding to the maximum heat flux decreases slightly with decreasing sphere size, but the value of the maximum heat flux does not appear to be dependent upon the sizes covered. Previous studies(1) reported that the best comparison of the maximum heat flux with experimental data occurred with the correlations of Noyes(15) and Zuber (discussion in Reference 16), given as:

Noyes:(15)

$$(q/A)_{max} = 0.144\, h_{fg}\, \rho_v^{1/2} \left[\frac{(\rho_\ell - \rho_v)^2}{\rho_\ell}\, g\, g_o\, \sigma\right]^{1/4} P_r^{-0.245} \left(\frac{a}{g}\right)^{1/4} \tag{3}$$

Zuber:(16)

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

where

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

(b) <u>The Effect of Gravity on Boiling</u>

A representative sampling of data over a wide range of values of a/g are presented in Figure 7. Most of the data apply to the one-inch sphere, although a few data points obtained with the one-half-inch sphere are also included to show that comparable results occur at one atmosphere pressure.

The data shown were obtained using a stationary test package for $a/g = 1$, a counterweighted test package for fractional gravity,

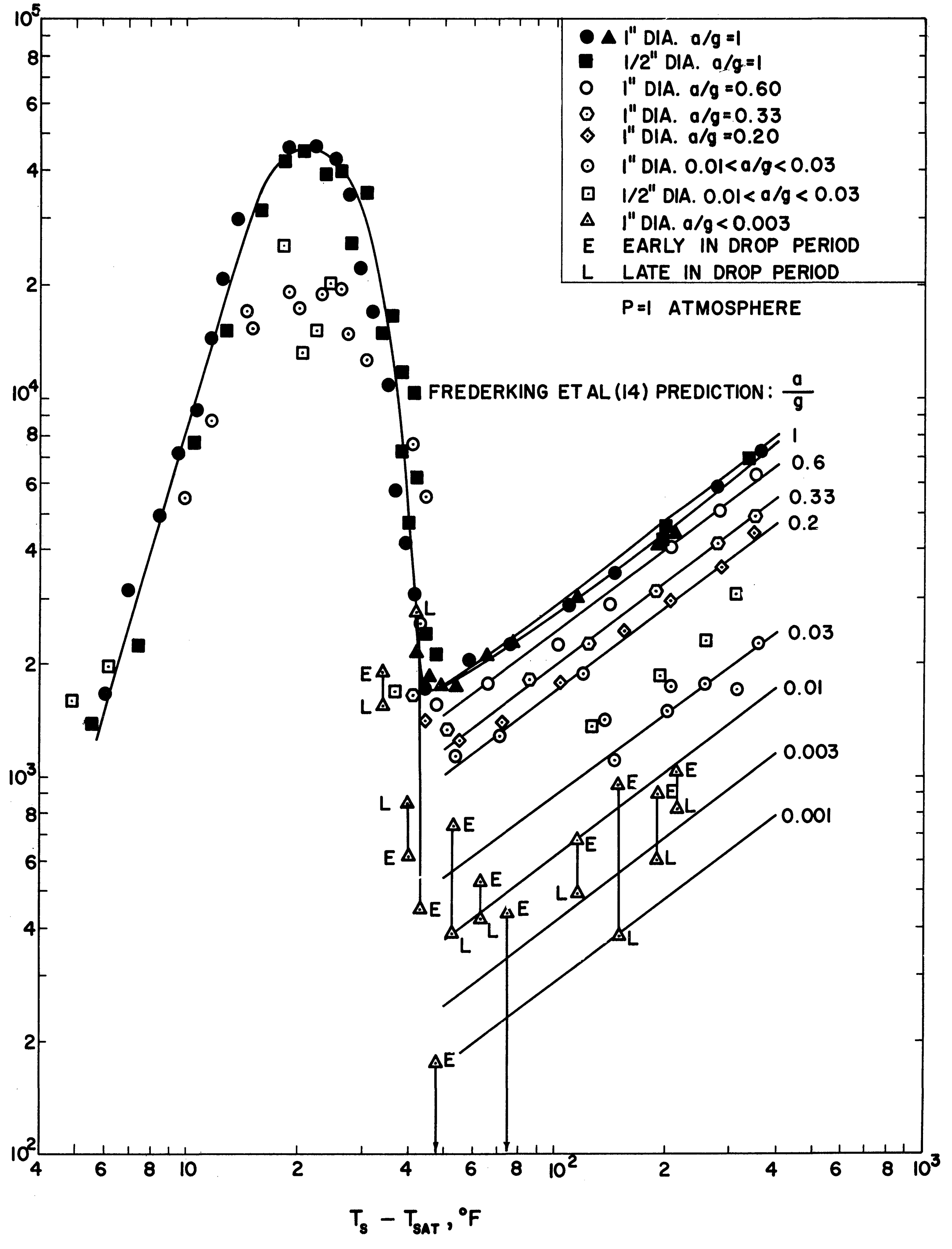


Figure 7. Boiling of Liquid Nitrogen at One Atmosphere Pressure with Standard and Fractional Gravity.

a single vessel free-fall package for near zero-gravity, and the double vessel free-fall package described earlier also for near zero-gravity. A variation in the effective value of a/g of about three orders of magnitude was thus obtained. The results obtained at very low values of a/g with film boiling are shown to vary over a significant range. Examination of the data in this region showed a transient change in the slope of the time-temperature curve after release which sometimes persisted for as long as 0.7 seconds. This is considered as the time required for the vapor film to reach a stable configuration after the abrupt change in gravity at release. A second, more gradual change was observed to continue until the system impacted on the buffer. This was identified as the result of the slow growth of the vapor film about the test object in the absence of a gravity field to remove the film by free convective processes. The heat transfer process then approaches pure conduction, with steadily decreasing heat flux as the vapor film thickness increases. If the zero-gravity environment could be maintained indefinitely, as in a satellite, and no other mechanism for vapor removal is provided the heat flux might be expected to continue to decrease as long as the test configuration could be maintained.

Also plotted in Figure 7 is the correlation(14) given in Equation (2) showing the heat flux variation with changing gravity for film boiling. A one-third power dependency of the heat flux on gravity is predicted, and the experimental data is seen to substantiate this behavior. The discrepancies from the correlation are significant only in the region of very low values of a/g , where the experimental values of a/g are not well identified.

(c) The Effect of Gravity and Pressure on Maximum Heat Flux

The correlation of Noyes(16) Equation (3), for the maximum heat flux is plotted in Figure 8 for values of a/g from 0.01 to 1.0 and a range of pressures from one to five atmospheres. Also shown is the range of maximum heat flux predicted by Zuber(17) Equation (4), for a/g = 1 only. Data points for all three sphere sizes investigated for selected pressures and values of a/g are presented. In general, the one-fourth power dependence of the peak heat flux on a/g is borne out, although there are some anomalous points. A pressure dependence is evident and in reasonable agreement with the prediction of Noyes(16) and there does not seem to be any apparent size effect. Data at the peak heat flux at the lower values of a/g is difficult to obtain, and no attempt was made at this time to cover the range of variables comprehensively.

(d) The Effect of Gravity and Pressure on Minimum Heat Flux

Based on the analysis of Zuber,(17) Berenson(16) had determined the following relation for the minimum heat flux with film boiling.

$$(q/A)_{min} = 0.09\, h_{fg}\, \rho_{vf} \left[\frac{g\, g_o\, \sigma\, (\rho_\ell - \rho_v)}{(\rho_\ell + \rho_v)^2}\right]^{1/4} \left(\frac{a}{g}\right)^{1/4} \qquad (5)$$

Again a one-fourth power dependence on a/g is indicated, but no size effect is predicted. A comparison of the predicted values at one atmosphere for the one-inch sphere is presented in Table I. These data are

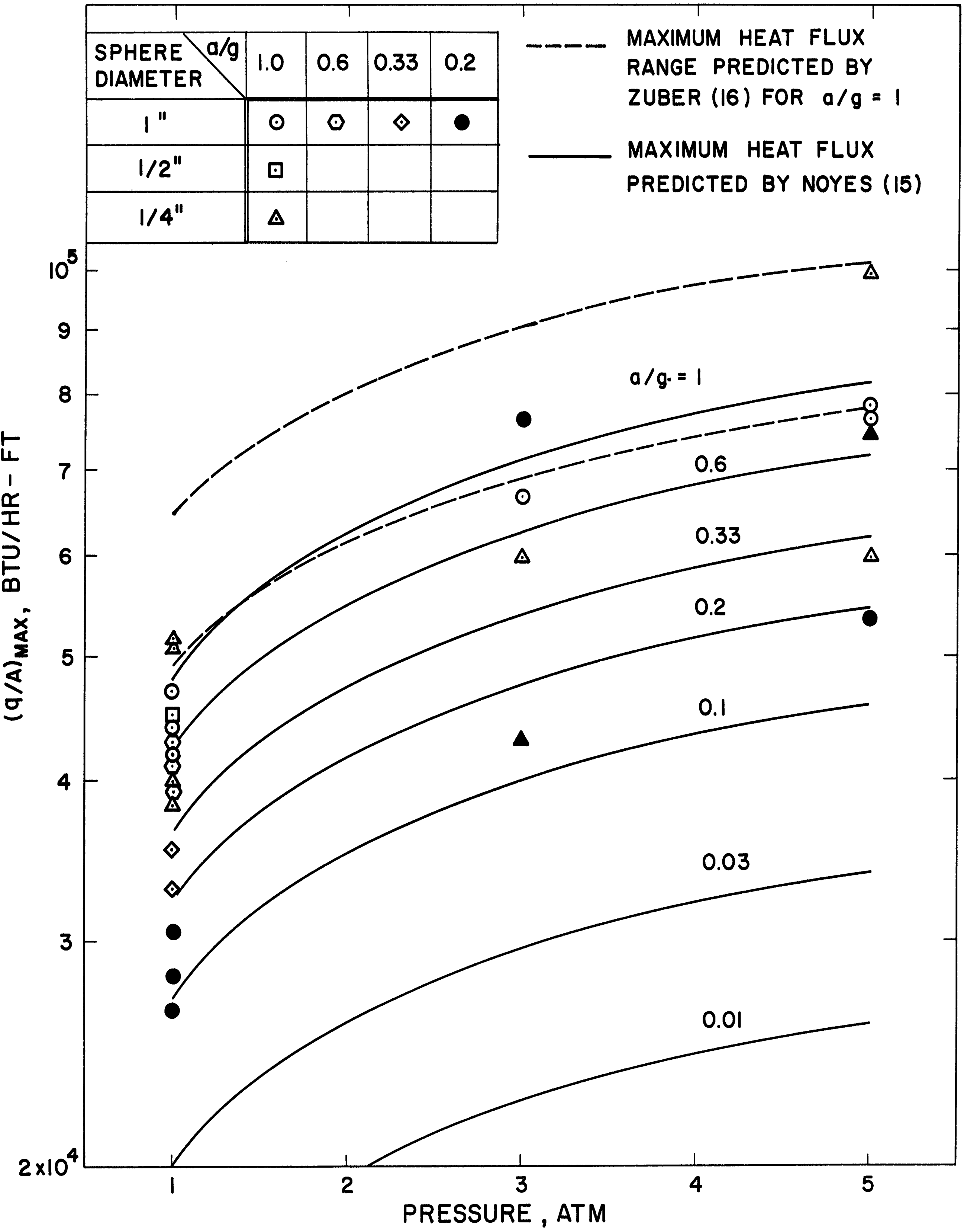


Figure 8. Comparison of Experimental Values of $(q/A)_{max}$ with Those Predicted by Noyes(15) and Zuber.(16)

TABLE I

COMPARISON OF EXPERIMENTAL AND PREDICTED VALUES
OF $(q/A)_{min}$, EQUATION (5) FOR ONE INCH
SPHERE WITH ATMOSPHERIC PRESSURE

a/g	$(q/A)_{min}$ - predicted	$(q/A)_{min}$ - experimental
1.0	2100	1700-2100
.6	1850	1550
.33	1590	1300-1400
.2	1400	1300
.03	875	870-1100
.01	666	
.003	491	180-530
.001	374	

also given in Figure 9 with stable film boiling data. The agreement is generally good, supporting the one-fourth power dependence. An increase of the minimum heat flux with increasing pressure is also indicated by Equation (5) and may be observed experimentally in Figure 6. An examination of the data in Figure 6 for the one-quarter inch sphere at one atmosphere and standard gravity reveals a substantial increase in the value of the minimum heat flux above that predicted, as well as above that observed for the one inch sphere.

(e) Correlation of Film Boiling Data

The correlation of Frederking et al.(14) was presented as Equation (2) and is predicated on the existence of a turbulent, free

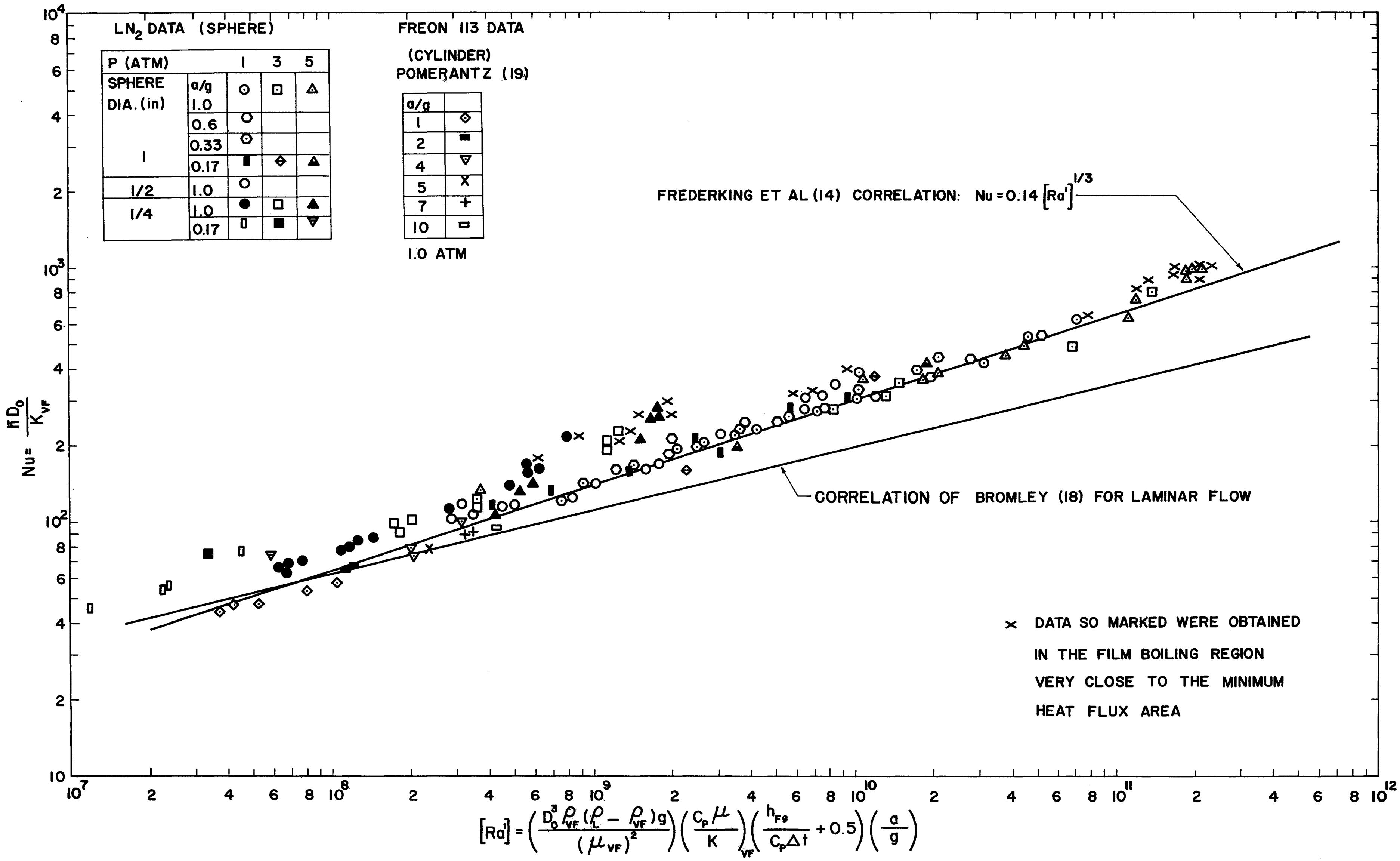


Figure 9. Comparison of Fractional Gravity Film Boiling Data for Liquid Nitrogen and Freon 113 with Correlations by Frederking et al.(14) and Bromley.(18)

convection process. No size effect is predicted. Bromley(18) worked with a horizontal tube at standard gravity and developed the following correlation for laminar conditions:

$$\frac{\bar{h}D_o}{k_f} = 0.62 \left[\frac{D_o^3 \rho_{vf}(\rho_\ell - \rho_{vf})g}{\mu_{vf}^2} \left(\frac{C_p\mu}{k}\right)_{vf} \left(\frac{h_{fg}}{C_p\Delta t} + 0.4\right)\left(\frac{a}{g}\right)\right]^{1/4} \qquad (6)$$

Pomerantz(19) also used a horizontal tube, but at values of a/g from one to ten, and added an additional dimensionless parameter to Bromley's correlation to obtain

$$\frac{\bar{h}D_o}{k_f} = 0.62 \left[\frac{D_o \rho_{vf}(\rho_\ell - \rho_{vf})g}{\mu_{vf}^2} \left(\frac{C_p\mu}{k}\right)_{vf} \left(\frac{h_{fg}}{C_p\Delta t} + 0.4\right)\left(\frac{a}{g}\right)\right]^{1/4} \left(\frac{D_o}{\lambda_c}\right)^{0.172} \qquad (7)$$

which indicates a -0.078 power dependence on diameter, rather than the -0.250 power dependence predicted by Bromley. Pomerantz also found a 0.336 power dependence of heat flux on gravity, which is in essential agreement with the correlation of Frederking et al.(14)

The correlations of Bromley(18) and Frederking et al.(14) are shown in Figure 9 in dimensionless form. The data of Pomerantz are included. Data points are given for one-quarter, one-half, and one-inch spheres at pressures from one to five atmospheres and values of a/g from 0.17 to 1.0. The one-inch data, regardless of pressure or a/g, agree well with the correlation of Frederking et al.(14) A coefficient of 0.15 for the one-half inch sphere data and 0.17 for the one-quarter inch sphere data would result in a closer comparison with the correlation. Perhaps what is indicated here is the necessity for including an additional weak size dependency term similar to the (D/λ_c) term suggested by Pomerantz in Equation (7).

A pronounced departure of the sphere data from the correlation at the higher values of Ra' for each size is felt to be an indication that a state of incipient transition boiling has been reached. At this point the heat flux does not decrease with decreasing Δt in the fashion it had been at higher temperatures, but neither does it start to increase as is characteristic of the transition region. This phenomenon seems to be most pronounced with the one-quarter inch sphere, and may indicate the onset of localized film instability which is not propagated as it would be in the transition region.

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, $0.001 < a/g \leq 1$, and to be a weak function of the sphere diameter. The correlation of Frederking et al.(14) was found to predict the experimental results well for the one inch diameter sphere, and the one-half and one-quarter inch diameter spheres if the empirical coefficients of 0.15 and 0.17, respectively, are used instead of 0.14.
2. In the nucleate boiling region, the heat flux increases with increasing pressure at a given temperature difference, but does not show any sphere size dependence.

3. The maximum and minimum heat flux values appear to exhibit a dependence on gravity as $(a/g)^{1/4}$.

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