DRI #2227

REPORT

Project 308

Final Report

NASA Grant NsG-143-61

Supplement No. 1

17 May 1965

rec'd 6/1/65

SUBCOOLED BOILING IN A NEGLIGIBLE GRAVITY FIELD

UNIVERSITY OF DENVER
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Prepared for
National Aeronautics and Space Administration

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I. ABSTRACT

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Subcooled and saturated nucleate pool boiling was observed at camera framing rates from 6000 to 8000 pps in order that the dynamic forces acting on these bubbles at normal gravity could be evaluated. Water at atmospheric pressure was used at heat fluxes of 50, 000, 70, 000 and 100, 000 Btu/hr-ft^2 with subcoolings of 0, 10, 20 and 30°F for both normal and inverted heater orientations. Each bubble was analyzed frame by frame to determine, by graphical integration, its volume and center of mass position as a function of bubble lifetime. Graphical means were then used to evaluate the bubble forces associated with gravity, pressure, inertia, surface tension and viscous drag.

By analysis of the bubbles it was determined that a wide range of bubble sizes exist at a given subcooling. In order to remove the size variation difficulty, reduced parameters for volume, center of mass, and time were used. With this adjustment it was found that bubbles of a given subcooling behaved in a similar manner as to their growth and force history for both normal and inverted boiling.

The influence of gravity as a removal force was evaluated and it was found that for saturated bubbles the net removal force was very small and was due almost completely to gravity. This was not true for subcooled bubbles where the gravity force amounted to only 20 to 40 percent of the net removal force near separation. It is therefore concluded that in a negligible gravity environment subcooled, rather than saturated, boiling is the desired condition to use when nucleate boiling is being contemplated as a heat transfer mechanism.

II. INTRODUCTION

Increased interest in the space program has recently been responsible for a large amount of research effort devoted to the investigation of the influence of the gravity force on many types of processes. As a part of this effort, a contract was entered into between the University of Denver and the National Aeronautics and Space Administration entitled, "Subcooled Boiling in a Negligible Gravity Field." This process is of particular interest in the space program because nucleate pool boiling, and especially subcooled boiling, permits high heat transfer coefficients to be obtained. This is important because it tends to reduce the size of heat transfer equipment needed to handle a given heat load.

Of additional interest is the situation where liquid hydrogen, helium, or oxygen are carried as fuel components on a coasting space flight. In such a situation, zero gravity is essentially obtained and solar heat is being applied to the surface of the liquid container. The heat source may cause nucleate boiling with the problem of whether the vapor formed remains on the surface or enters the bulk liquid before condensing.

This vapor position problem is of critical importance because of the insulating properties of the vapor if it remains on the heated surface. This can cause heater burnout in a heat transfer device or excess vapor buildup in a liquid storage tank.

The purpose of this research effort was to evaluate the forces acting on a bubble formed in a nucleate boiling situation and to specifically determine the effect of gravity on the forces causing removal of a vapor bubble from a heated surface.

III. TECHNICAL PROGRAM

A. Theoretical Development

In nucleate boiling research work performed at zero gravity, whether in drop towers, aircraft trajectories, or rocket shots, it became apparent that the effect of gravity could not be effectively evaluated because there was a lack of reliable data on the nucleate boiling phenomena at normal earth gravity conditions. It was felt that, with a better understanding of the normal gravity situation, it would be possible to predict the results of a process occurring in the absence of the gravity force.

In a simple analysis of the forces acting on a bubble, the removal forces are the inertia and buoyant forces, whereas surface tension and viscous drag tend to prevent bubble removal. Further investigation of bubble mechanics indicate that there is an additional force causing removal. This force can be described as a pressure force acting against the heater surface as long as the bubble is attached to the surface.

Initial work in this field (1, 2, 3) dealt only with the buoyant force and the inertia force as removal agents. At normal gravity, the buoyant force could be a significant part of the total removal force, whereas, at zero gravity, it would be completely absent. Then, if the gravity-influenced buoyant force was the primary removal agent, the vapor bubbles would tend to remain on the heater surface. That this is not the case has been shown by the experimental work of Hedgepeth and Zara (4), Seigel and Keschock (5), and many others.

With this background, it became necessary to indicate the exact form of the force expressions associated with bubble formation, growth, and removal in nucleate boiling.

Inertia Force -- The inertia force, or dynamic force, acting on a bubble is not the inertia of the vapor mass but rather the inertia of the liquid mass placed in motion by the initial explosive expansion of a bubble from its nucleation site on the heater. In this situation, the inertia force expression is obtained from the time rate of change of the momentum of the liquid displaced by the bubble, i. e. :

$$F_d = \frac{d}{d\theta}(mv) \tag{1}$$

The above expression is simplified because the initial expansion of the bubble is not necessarily completely upward or perpendicular to the heater surface. Davidson (6) has indicated that the inertia force actually acting towards bubble removal is only 11/16 of the total. Thus, the actual inertia force is:

$$F_d = \frac{11}{16}\frac{d}{d\theta}(mv) \tag{2}$$

These expressions would be appropriate if the bubble reached maximum mass (i.e., maximum volume) after separation. However, the initial bubble expansion sets a certain volume of liquid in motion which remains in motion after the bubble begins to condense and reduce in volume. In this case, the inertia force would be better represented by two expressions as follows:

$$F_d = \frac{d}{d\theta}(mv) \quad \text{for} \quad \theta < \theta_{m_{max}} \tag{3}$$

and:

$$F_d = \frac{d}{d\theta}(m_{max}v) \quad \text{for} \quad \theta > \theta_{m_{max}} \tag{4}$$

For a liquid whose density is essentially constant, these inertia forces can be expressed as:

$$F_d = \rho\frac{d}{d\theta}(V_b\, U_b) \quad \text{for} \quad \theta < \theta_{m_{max}} \tag{5}$$

and:

$$F_d = \rho\, V_{b_{max}}\frac{d\, U_b}{d\,\theta} \quad \text{for} \quad \theta > \theta_{m_{max}} \tag{6}$$

Equations 3 and 4 will be appropriate for saturated nucleate boiling where the maximum volume may occur after separation, and also for subcooled boiling where the maximum volume occurs prior to separation.

Previous inertia force expressions have been derived from Eq. 1 when an assumption of a spherical bubble shape has been made. In this case, the velocity used is the change of radius with time. The expression is:

$$F_d = \pi \rho \left[D^3 \frac{d^2 D}{d\theta^2} + 3D^2 \left(\frac{dD}{d\theta} \right)^2 \right] \tag{7}$$

which requires some analytical expression for the diameter versus time for its solution. For an exact determination of the inertia force, the use of Eq. 7 is not justified.

Gravity Force -- Gravity acts on a bubble because of the difference in density of the vapor and the liquid which it displaces. This force will be acting whether the bubble is attached to the heater surface or is freely moving in the liquid above it. Simply stated, the gravity force is:

$$F_g = g\, V_b\, (\rho - \rho_v) \tag{8}$$

For practical purposes, the density of the vapor can be neglected with respect to the liquid density. Therefore:

$$F_g = g\, \rho\, V_b \tag{9}$$

Pressure Force -- When the bubble is attached to a solid surface, a pressure is exerted on the surface. This can be visualized by recalling that if a bubble were formed in a liquid under super-saturated conditions at zero gravity, it would expand freely in all directions and its center of mass would not change position as the bubble grew. However, if the bubble is formed in contact with a solid boundary, it is limited in the directions in which it can expand. Thus, its center of mass moves away from the initial point on the surface as the bubble grows. In other words, the bubble exerts a pressure on the solid heater surface which forces the bubble away from the surface.

The pressure inside a freely suspended bubble is essentially the same as the pressure in the liquid outside the bubble. For an attached bubble the internal pressure must be greater than the external pressure to account for the pressure exerted against the solid surface. Since this pressure is acting against the surface area in contact with the bubble, the pressure force can be represented as:

$$F_p = (P_i - P_e) \frac{\pi D_b^2}{4} \tag{10}$$

The pressure difference at the bubble base can be expressed according to Kutateladze (7) by:

$$P_i - P_e = \sigma \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \tag{11}$$

where σ is the surface tension and R_1 and R_2 are the principal radii of curvature. R_1 is the radius of curvature of the circular area of contact between the vapor and the solid. As such, the angle of contact between the bubble and the surface is important if the actual vertical pressure component is desired. Keshock and Siegel (8) obtain, then, the following expression for the pressure difference:

$$P_i - P_e = \sigma \left(\frac{\sin\phi}{R_1} + \frac{1}{R_2} \right) \tag{12}$$

which becomes, upon substitution of the bubble base diameter D_b:

$$P_i - P_e = \frac{2\sigma \sin\phi}{D_b} + \frac{\sigma}{R_2} \tag{13}$$

The pressure force then becomes:

$$F_p = \frac{\pi D_b}{4} \left(\frac{2\sigma \sin\phi}{D_b} + \frac{\sigma}{R_2} \right) \tag{14}$$

For a first approximation, the bubble base radius is much smaller than the curvature of the bubble surface near the base. For these conditions, Eq. 14 becomes:

$$F_p = \tfrac{1}{2}\pi \, D_b \, \sigma \, \sin \phi \tag{15}$$

Surface Tension Force -- The surface tension at the contact between the liquid, vapor, and surface results in a force tending to hold the vapor bubble to the surface. This force is due to the surface tension properties of the liquid and acts at the circumference of the bubble base. Since the vapor contact is at an angle to the surface, the vertical component is obtained from the sine of the contact angle. Therefore, the surface tension force is:

$$F_s = \pi \, D_b \sigma \sin \phi \tag{16}$$

Viscous Drag Force -- As the bubble moves away from the surface, it causes fluid to flow past the vapor surface. When relative motion of this type occurs, a viscous drag force is set up and, for the case of the bubble leaving a surface, this force tends to retard the removal of the bubble. If the bubble is treated as a sphere moving through a fluid, it will have a certain resistance dependent on its velocity through the fluid. Keshock and Siegel (8) have evaluated this force in terms of a drag coefficient:

$$F_v = \frac{1}{8} \rho \quad C_d \pi \, D_h^2 \, v^2 \tag{17}$$

where the drag coefficient is evaluated by Moore (9) as:

$$C_d = \frac{48}{N_{Re}} = \frac{48\mu}{D_h \rho \; v} \tag{18}$$

The viscous drag force then becomes:

$$F_v = 6 \pi \mu D_h U_b \tag{19}$$

The above expressions for the forces acting on a bubble in nucleate boiling will be used to evaluate the net force acting on the bubble. From this force balance, the effect of the gravity force as a bubble removal agent will be compared to the total removal forces giving an indication of the importance of this term under other than normal gravity conditions. This can conveniently be done in terms of a modified Froude number as outlined by Werner (1) and Warner (2), or by an actual ratio of gravity force to total removal force. The modified Froude number is the ratio of the inertia force to the gravity force, that is

$$N_{Fr'} = \frac{F_d}{F_g} \tag{20}$$

At zero-gravity, this relation becomes infinite in value. Therefore, a better relation would be:

$$\psi = \frac{1}{N_{Fr'}} = \frac{F_g}{F_d} \tag{21}$$

Because other removal forces are at work, the proper ratio for the normal heater orientation should be

$$\Gamma = \frac{F_g}{F_g + F_p + F_d} \tag{22a}$$

and for the inverted heater orientation

$$\Gamma = \frac{F_g}{F_d + F_p} \tag{22b}$$

To determine if a bubble will indeed separate, it is necessary to make a force balance on the bubble as it grows on the heater surface. The net removal force for the normal heater orientation would then be:

$$\Delta F_r = (F_g + F_p + F_d) - (F_s + F_v) \tag{23}$$

and for the inverted heater

$$\Delta F_r = (F_d + F_s) - (F_s + F_g + F_v) \tag{24}$$

The relations outlined here will be evaluated as a function of the life-time of the bubble so that a history of the bubble forces can be shown.

B. Experimental Equipment and Procedures

The first phase of this research program was devoted to the development of zero-gravity test facilities for the investigation of subcooled nucleate boiling. These facilities are described by Reihman (10, 11) and Kottenstette (12). Subsequently, it became apparent that detailed normal gravity data would be necessary for proper evaluation of the zero-gravity effect. Consequently, the test boiler apparatus was designed for use in a normal gravity situation.

The experimental program entailed the photographing of bubbles formed in saturated and subcooled water in such a manner that the growth velocity and volume could be obtained as a function of time.

Photographic Equipment -- In order that as many pictures as possible of a given bubble could be obtained, a Fairchild HS101A Motion Analysis camera was used. This camera was powered by a 60-volt 135-amp battery supply which drove a 100-foot roll of 16-mm duPont 931A reversal film at a framing rate of up to 8050 pictures per second. Data was obtained from a framing rate of 4360 to 7950 pictures per second with the majority obtained near 7000 pictures per second. A 400 cycle per second square wave timing signal was used to place timing marks on the film. With this photographic technique it was possible to obtain bubble pictures as little as 125 microseconds apart.

Initial test data was obtained by placing the camera so that it was looking vertically downward at the top of the bubbles through a lens system. A side view was obtained from a mirror mounted at a 45° angle beside the heater surface. Lighting was supplied by three flood lamps and a Sylvania "sun-gun". When it became obvious that a better side view was needed, the camera was placed so that a side view of the bubbles could be obtained. These photographs were taken against a white background lighted by a single "sun-gun". These photographs were taken at a lens setting of f/2.5 at 3.5 feet.

The 16-mm bubble photographs were then projected with a resultant magnification of 22 to 30 times as determined from the projected image of a 1/16-inch diameter thermocouple well. The bubble outlines were then traced, frame by frame, for use in obtaining the desired experimental data.

Boiler Apparatus -- The boiler apparatus consisted of a heater block contained in a boiler cell. This was used during both the vertical and horizontal photographic portions of the experimental program. The heater was a Nichrome V wire, cold rolled into a strip 0.005 inch thick, 0.080 inch wide, with an effective heating length of 0.688 inch. The surface was finished with #600 emery paper and polished with 2/0 emery polishing paper. The heater strip was mounted to the heater base by a brass tension block and sealed on its underside with high temperature epoxy resin. Power for the heater was supplied by a 6-volt automobile storage battery.

The original cylindrical boiler cell was a 3-inch inside diameter plexiglass container approximately 5 inches deep. The cell used for the majority of the experimental work was a 6-inch inside dimension cube made from 1/2-inch thick plexiglass. The details of the later cell and boiler placement are shown in Figure 1, with the overall experimental setup shown schematically in Figure 2.

Instrumentation -- The surface temperature of the heater was obtained from a Fenwal thermistor epoxied just beneath the

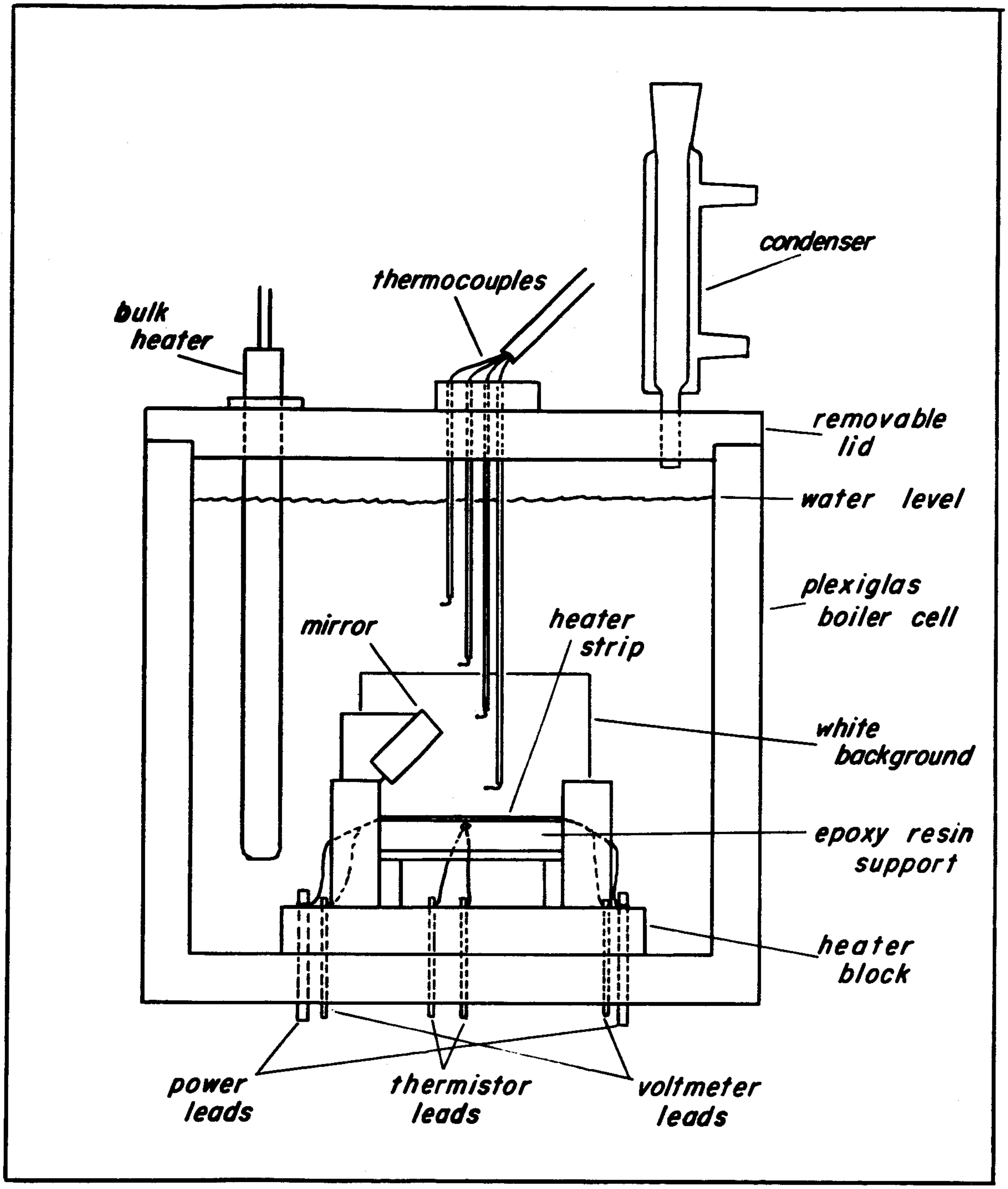

Figure 1. Schematic of the Boiler Cell.

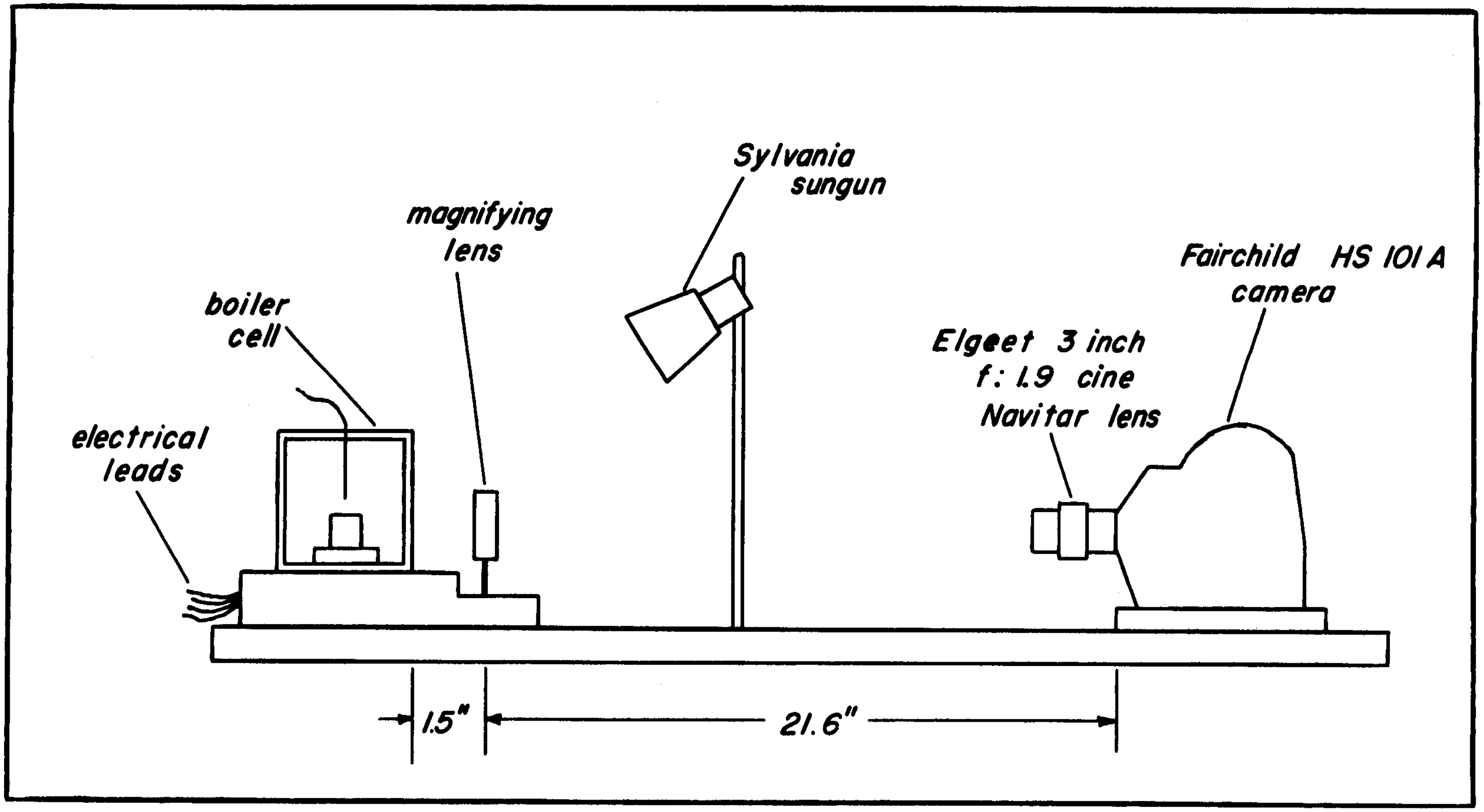

Figure 2. Arrangement of Experimental Components.

heater strip. A calibration for the extrapolation of the thermistor temperature to the actual heater surface temperature permitted an accuracy of ± 1°C for the boiling conditions used. A discussion of this extrapolation procedure is given by Werner (2). Bulk fluid temperatures were obtained from four 30-gauge iron-constantan thermocouples positioned directly above the heater strip. The thermistor current was measured with a Keithley micro-ammeter and recorded by a G. E. recording potentiometer. Thermocouple voltages were read from a Gray potentiometer-galvanometer. The heat flux was calculated from the power input to the heater. The heater current was measured across a 15-amp shunt with a G. E. DP-9 millivoltmeter, while the voltage drop across essentially only the heater strip was obtained from a Weston model 430 d. c. voltmeter.

Experimental Procedure -- Distilled water was redistilled immediately prior to a run and then boiled and degassed for an hour before carefully being transferred to the boiler cell. The water in the test cell was then brought to saturation temperature and boiled an additional 30 minutes. Prior to placing water in the cell, the heater assembly was removed from the cell, the heater strip washed with ethyl alcohol, baked at 90°C for one hour, rinsed again while hot with ethyl alcohol, then placed in the boiler cell and the appropriate electrical connections made. An experimental run was made when an appropriate power input to the heater was established and an appropriate bulk temperature obtained. The thermistor temperature and bulk temperatures were noted. The "sun-gun" light source was turned on one or two seconds prior to starting the pre-focused camera. The camera run lasted approximately one second. The "sun-gun" was then turned off, and the power to the heater turned off to allow the bulk liquid to cool so that another run could be made at a lower bulk temperature. In this way a series of four runs was made with one filling of the boiler cell. At the completion of the test series the water was discarded and the boiler dried and cleaned, and the heater assembly block was removed and prepared for the next series of runs.

Experimental Range -- To fully investigate the effect of gravity as a removal force in nucleate boiling the following experimental conditions were used. Heater position: boiling was accomplished from the top and from the bottom of a horizontal strip. Heat flux: three heat fluxes were used, corresponding to 50,000, 70,000 and 100,000 Btu/hr-ft^2. Subcooling: bulk temperatures were adjusted to provide subcoolings of approximately 0°, 10°, 20° and 30°F.

A more detailed discussion of some of the experimental equipment and procedures can be obtained from Warner (1) and Werner (2).

C. Experimental Results

The experimental data for each of the test runs to be discussed here are listed in Appendix A. The heat flux was calculated from the relation:

$$q/A = \frac{(\text{volts})\ (\text{amperes})\ (3.413\ \text{Btu/watt-hr})}{(0.000416\ \text{ft}^2)} \tag{25}$$

The actual heater surface temperature was calculated from Werner's (2) relation where:

$$T_s = \frac{T_{th} - \gamma T_b}{1 - \gamma} \tag{26}$$

where the correction factor γ was found to equal 0.175 for bulk temperatures between 150° and 210°F.

The saturation temperature was determined from the vapor pressure relations for water. At the Denver altitude where the experimental work was performed, the boiling point of water varied from 201° to 204°.

The driving force temperature, ΔT_{sat}, was determined as

$$\Delta T_{sat} = T_s - T_b \tag{27}$$

It was felt that this total temperature difference would be more realistic in the calculation of heat transfer coefficients. Although the calculation for the heat transfer coefficients was not carried out, it can easily be done by use of the tabulated data.

The calculated information obtained from these relations is tabulated in Appendix A. The E, F, and G series are for the runs for boiling from the upper surface of the heater, while the H, I, and J series are for the runs for boiling from the inverted heater.

Examination of the photographs obtained in the vertical and horizontal photographic sequences indicated that three types of bubbles were generally obtained. For convenience, these are separated as to type as follows:

Type 1 - Oscillating bubbles, which were generally small, grew and partially collapsed through a number of cycles while remaining attached to the heater surface. These bubbles would oscillate at an average frequency of from 40 to 2000 cps, with a decrease in frequency of approximately 4 times from initiation to separation, as shown in Table I. These bubbles had both an expanding and contracting mode as well as a horizontal mode of vibration. Many of these bubbles were observed to grow in a gradual manner contracting less than they had expanded with a maximum to minimum volume ratio of from 1.5 to 2.5. After a number of oscillations, these bubbles would separate from the surface and at other times completely collapse while still attached to the surface. Actual volume and center of mass data for some of these bubbles are listed in Appendix B. This bubble type was observed in all the subcooled experimental runs.

Type 2 - Continuous growth and decay bubbles do not exhibit any oscillation and do not form into continuous columns. These bubbles are more or less uniform in shape regardless of their maximum volume. Of particular interest is the evidence that the vertical view of these bubbles is exactly circular within experimental measurement whereas the side view is far from circular. Figure 3 is the side view tracing of an actual Type 2 bubble at various points in its lifetime. Type 1 and Type 2 bubbles are the only ones which were not influenced by contact with neighboring bubbles. The ratios between the number of Type 1 and Type 2 bubbles for different subcoolings are shown in Figure 4. Type 2 bubbles were observed in all the runs except the inverted, saturated boiling experiments.

Type 3 - Multiple group bubbles contained both oscillating and continuous growth bubbles but appeared to form simultaneously from a number of closely associated sites. They generally would occur after the heater surface had been devoid of bubbles for a period of time. This type of bubble would then form very rapidly and separate or soak up other nearby bubbles in a violent manner. The shape of these bubbles was highly irregular and changed very rapidly. This prevented any exact determination of the forces acting on these bubbles. Type 3 bubbles accounted for approximately 90 percent of the bubbles

TABLE I

DATA FOR TYPE 1 OSCILLATING BUBBLES

Bubble	Number of Cycles to separate	Maximum Volume $cm^3 \times 10^3$	Oscillation period, μsec	Average Frequency cps	Initial Oscillation period, μsec	Final Oscillation period, μsec	Final Period over Initial Period
E-10-03	8	2.47	2600	385	1900	5000	2.6
F-2-01	3	5.75	1430	700	1220	1680	1.4
F-3-01	5	6.58	21800	46	9600	38500	4.0
F-5-01	8	4.85	3030	320	1300	5200	4.0
F-8-01	10	8.40	1010	990	440	1540	3.5

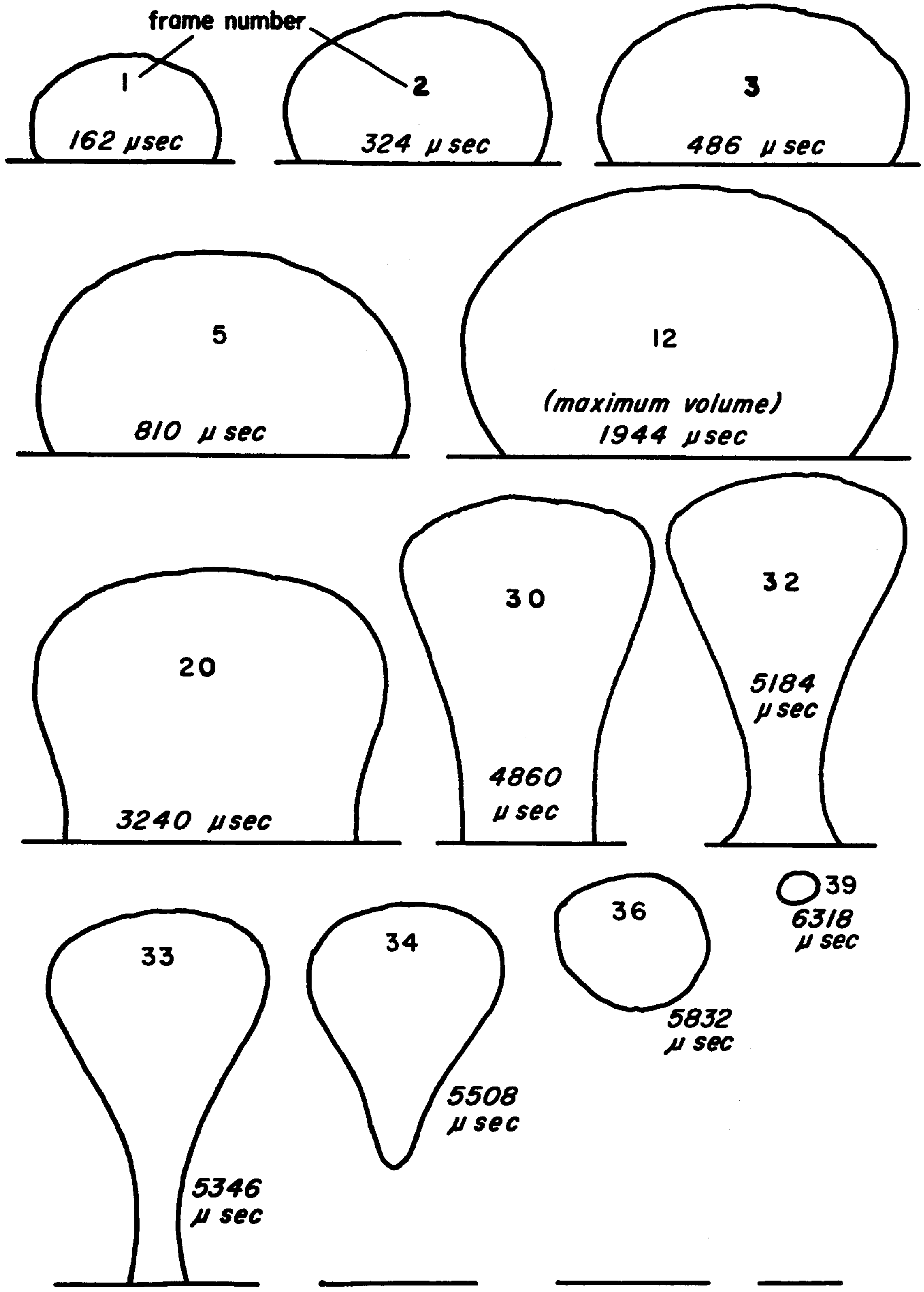

Figure 3. Sideview of Bubble E-13-3. T_{sub} = 30°F, Magnified 26X.

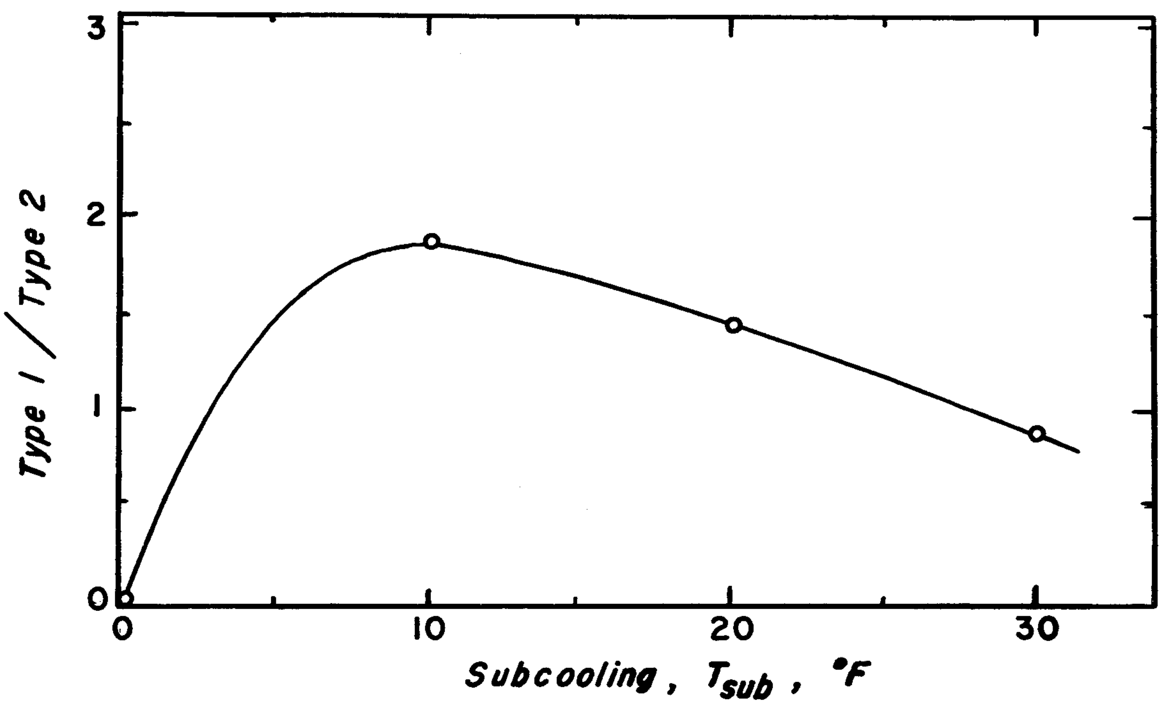

Figure 4. Ratio of Number of Bubbles of Type 1 to Type 2.

formed in nucleate boiling for both the normal and inverted heater orientations. This was the only type of bubble observed in the inverted, saturated boiling runs.

As mentioned earlier, the data from the vertical photographic sequence did not give adequate information on the side view configuration of the bubbles. This became quite obvious when a force analysis was attempted using the assumption of a spherical bubble. This analysis was accomplished by assuming the bubble to be a sphere whose diameter was obtained from the bubble dimensions as follows:

$$D_m = \frac{1}{3} (D_{h_1} + D_{h_2} + z) \tag{28}$$

With this assumption, the photographic data could be reduced such that the modified Froude number of Eq. 2 would become:

$$N_{Fr'} = \frac{1}{g}\left[\frac{3v \dot{R}_{sm}}{R_{sm}} + \dot{v}\right] \tag{29}$$

However, it was found that when the experimental data (reduced for an assumed spherical model) was applied to this relation, the results could not be reconciled with the apparent situation taking place. These calculations for the vertical series are tabulated by Warner (1).

It was at this time that it became obvious that the actual bubble volume must be used in the calculation of the forces acting on a bubble in a nucleate boiling situation. With this in mind, and with the firm experimental evidence that the bubble was circular when viewed perpendicular to the heating surface, the remaining E through J series were run where only the side view of the bubble was observed. The traced outlines of the bubbles were, therefore, segmented into circular discs whose volume was determined by:

$$\Delta V = \pi D^2 \Delta h_b \tag{30}$$

with the total volume being the sum of the volume of all the discs. It was also felt that the center of mass of the bubble was the characteristic dimension to be used in calculating the bubble velocity. The center of the mass was determined from the location of the line parallel to the heater surface which divided the bubble in half with respect to its total volume. Forty bubbles have been analyzed in this way. Figure 5 is a plot of the center-of-mass position as a

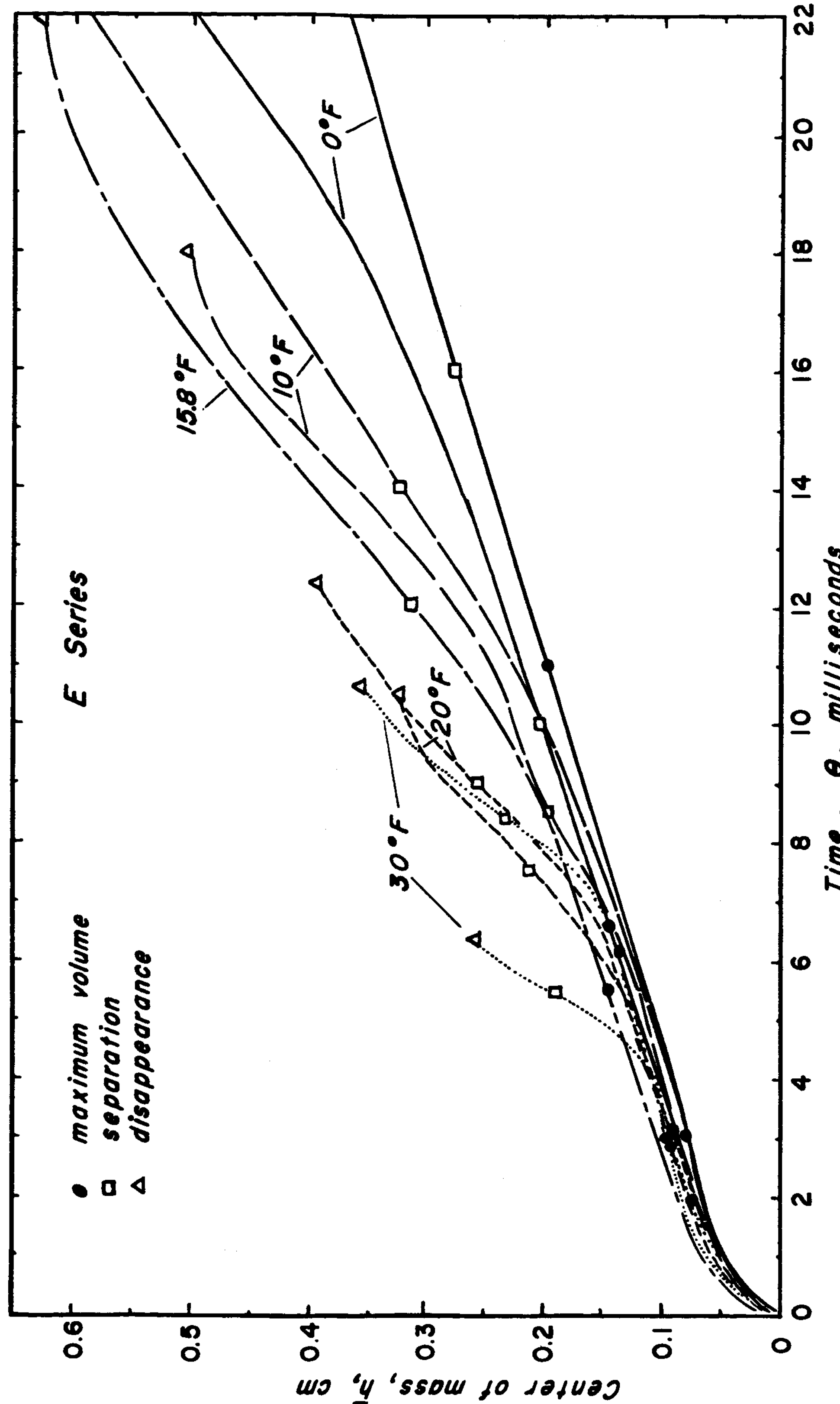

Figure 5. Center of Mass Versus Time Relations for Nine E Series Bubbles.

function of time for a range of subcoolings, while Figure 6 is a plot of the bubble volume versus bubble lifetime. Figures 5 and 6 are for the E series bubbles and are characteristic of the other bubble series.

From a large-scale plot of the center-of-mass versus time data, graphical methods were then used to determine the bubble inertia force. This required graphically obtaining the slope of the momentum curve where the momentum was obtained from:

$$\text{momentum} = V_b \, \rho \, U_b \quad \text{for } \theta < \theta_{m_{max}} \tag{31}$$

and

$$\text{momentum} = V_{b_{max}} \, \rho \, U_b \quad \text{for } \theta > \theta_{m_{max}} \tag{32}$$

The inertia force results shown in Figure 7 for some E and F series bubbles are typical of the results for the other series.

The gravity force was obtained by substitution of the bubble volume into Eq. 9 with the results being essentially a scaled-up version of the volume curve in Figure 6.

The bubble base diameter and surface to bubble contact angle for the E and F series are shown in Figures 8 and 9, respectively. The other series are similar. This data was then substituted into Eqs. 15 and 16 in order that the pressure force and surface tension force could be calculated.

The viscous drag force was calculated from Eq. 19 with the necessary data obtained from previously calculated items.

Examination of the volume data in Appendix B indicates the maximum bubble volume varies by a factor of 6 or so. To remove this size variance, the center-of-mass position is plotted versus a reduced time parameter, θ_r, where:

$$\theta_r = \frac{\theta}{\theta_{separation}} \tag{33}$$

The result of this plot for the E series is shown in Figure 10 and for the F series in Figure 11. The inverted H, I and J series have similar shaped curves except the magnitude of the center of mass

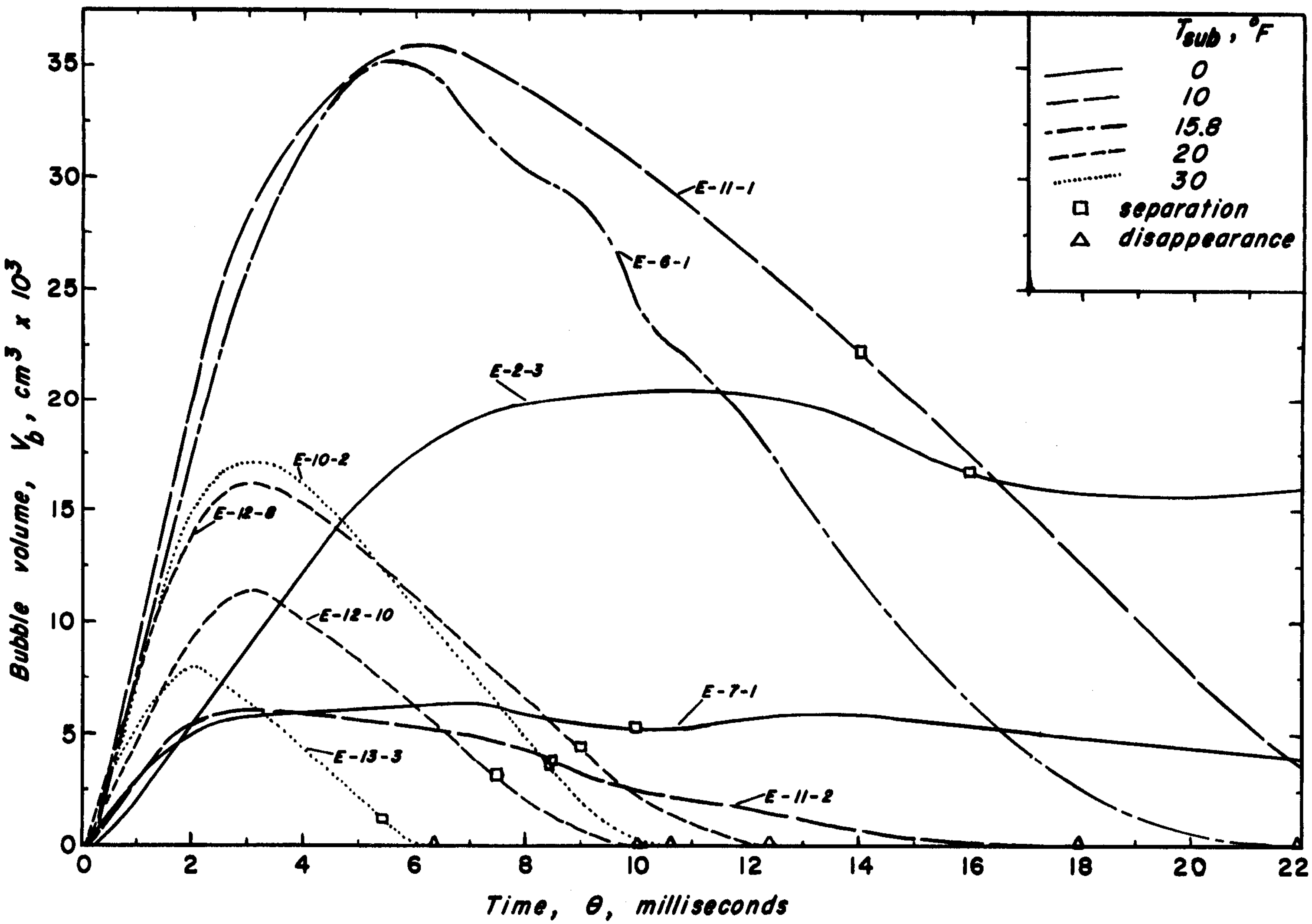

Figure 6. Bubble Volume Versus Bubble Lifetime for Nine E Series Bubbles.

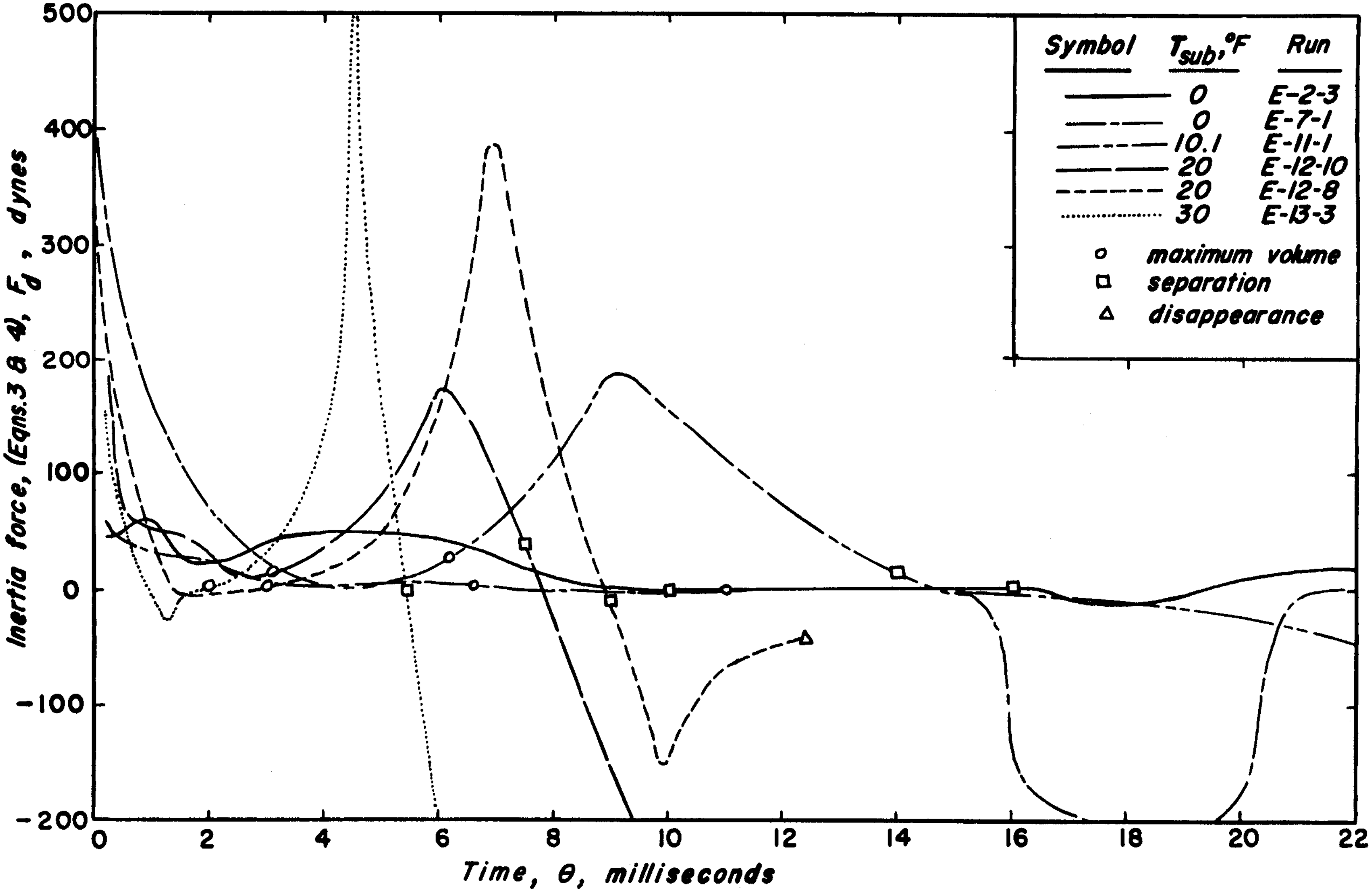

Figure 7. Comparison of the Inertia Force at Different Subcoolings.

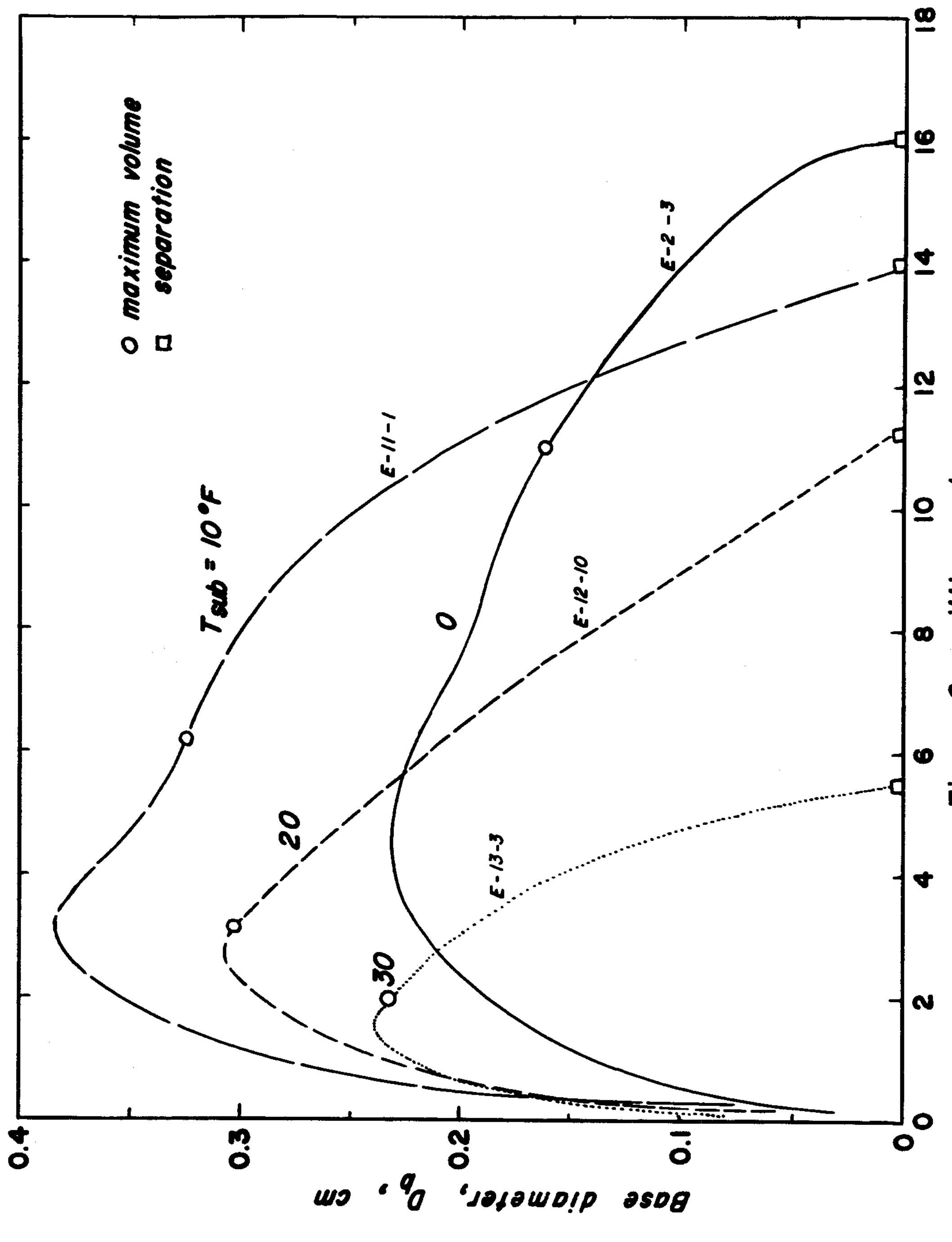

Figure 8. Bubble Base Diameter Variations.

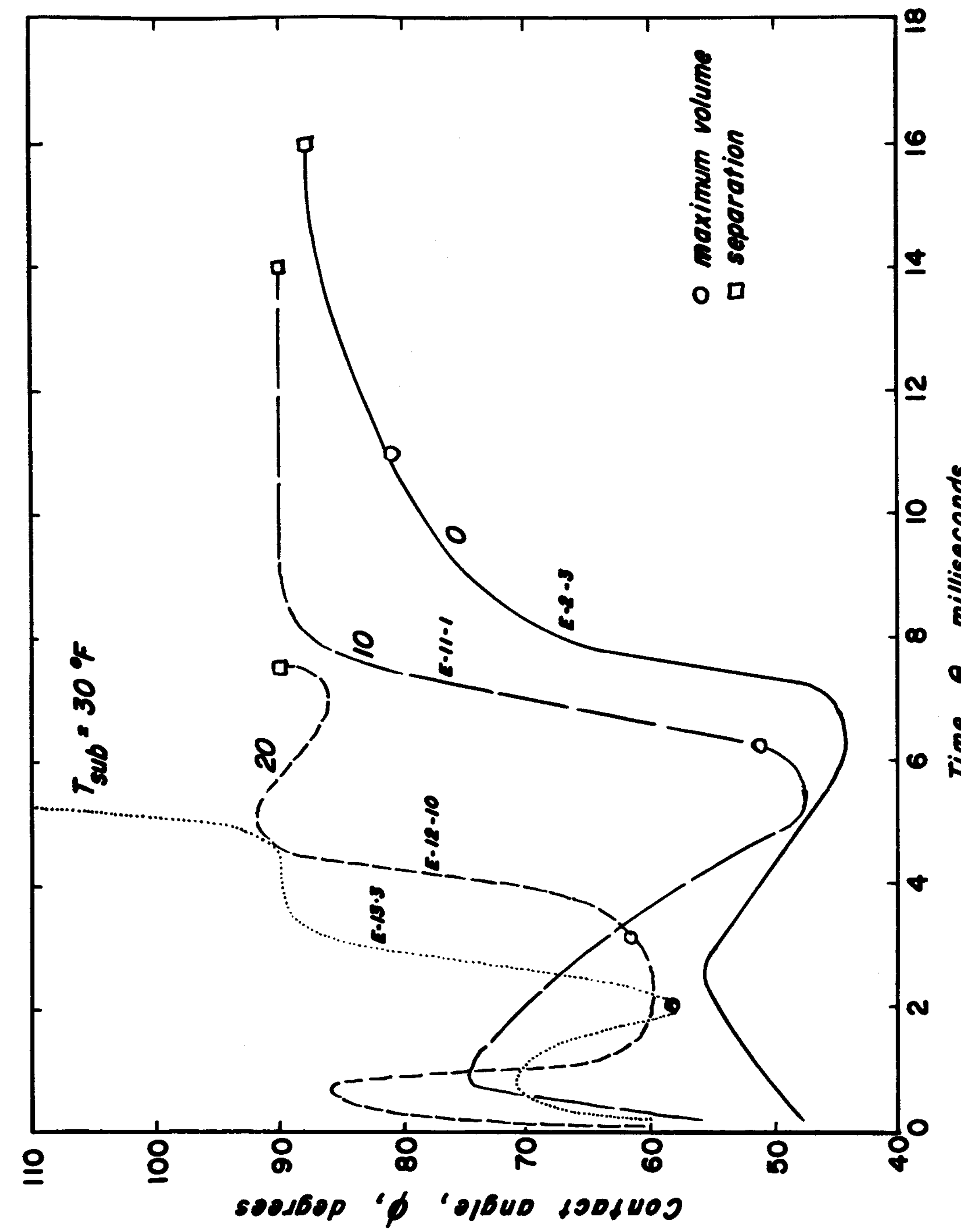

Figure 9. Contact Angle Variations at Different Subcoolings.

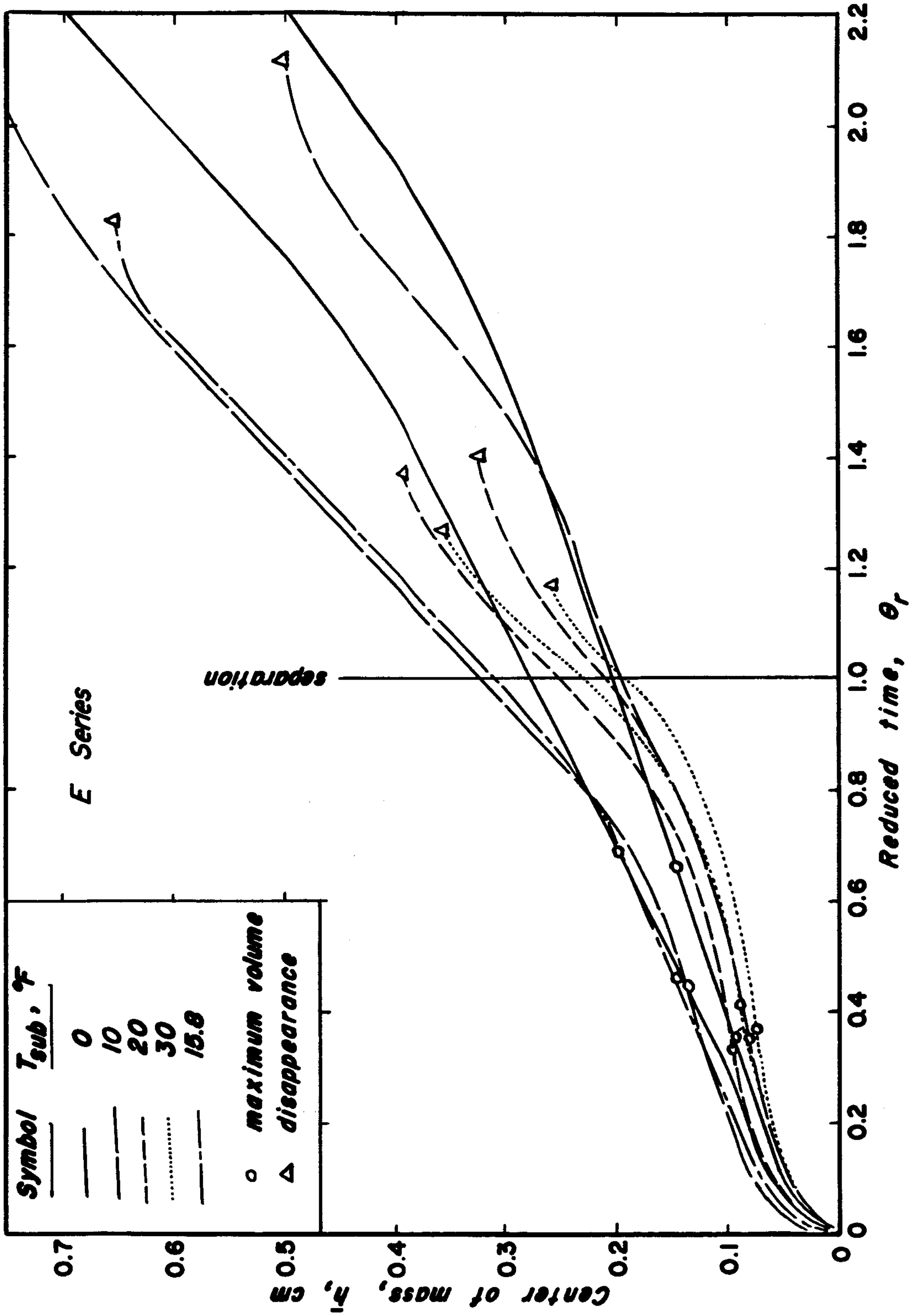

Figure 10. Center of Mass - Reduced Time Relations for Nine Bubbles at $q/A = 70,000$ Btu/hr ft^2.

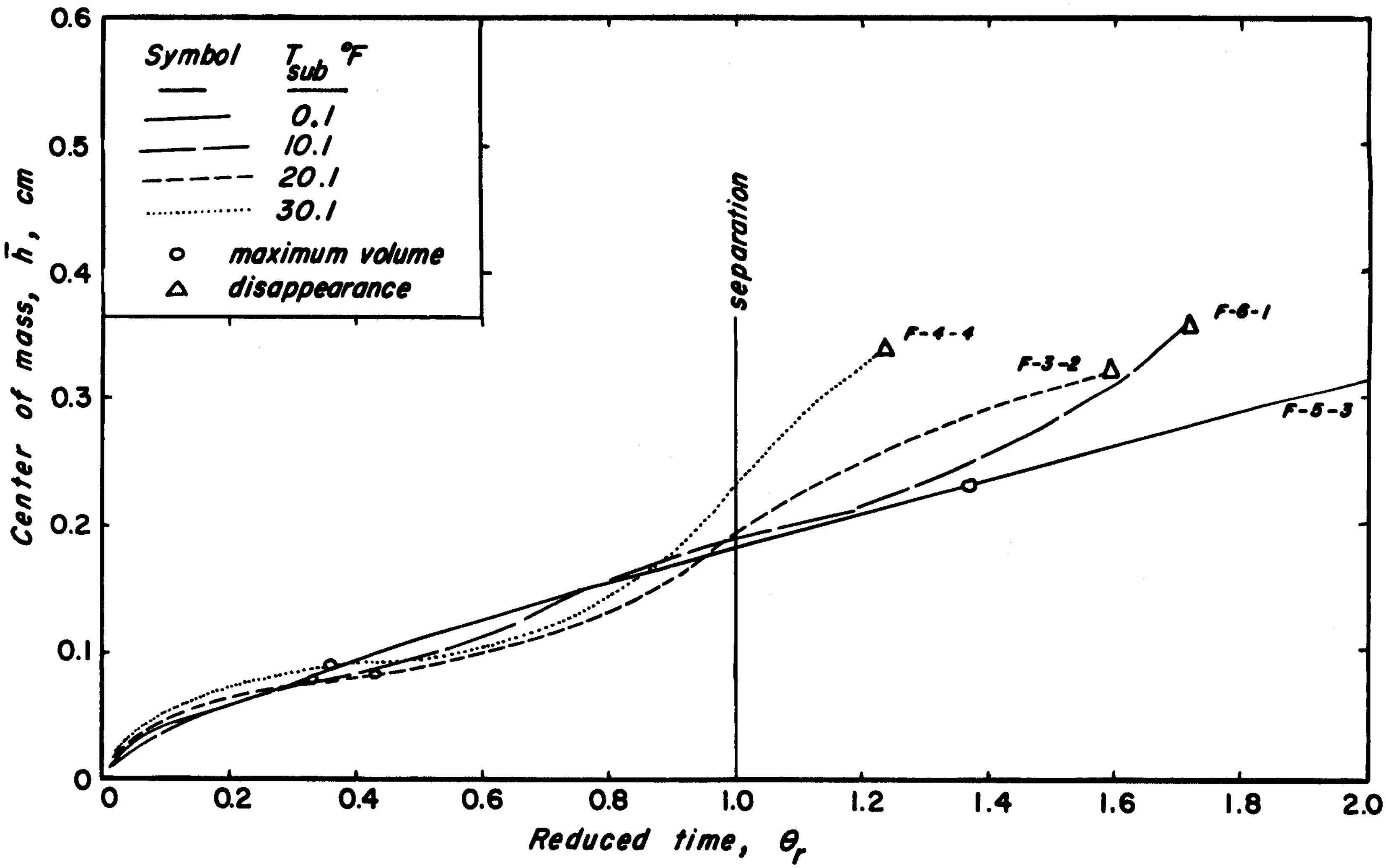

Figure 11. Center of Mass - Reduced Time Relations for Four Bubbles at q/A = 50,000 Btu/hr ft^2.

coordinate is approximately 1/3 of that for the E and F series shown in Figure 12.

Very interesting correlations between subcooling and the bubble parameters can be shown if the reduced center-of-mass is plotted versus the reduced time, and also by a plot of the reduced volume versus the reduced time. These reduced parameters are:

$$\bar{h}_r = \frac{\bar{h}}{\bar{h}_{separation}} \tag{34}$$

and

$$V_r = \frac{V_b}{V_{b_{separation}}} \tag{35}$$

The reduced center-of-mass time curves are shown in Figures 13 through 18 for all the experimental series, while the reduced volume curves are shown in Figures 19 through 24.

A feeling for the force balance around a bubble can be satisfactorily shown by a plot for each particular bubble. A typical plot is shown in Figure 25 for a saturated bubble and in Figure 26 for a subcooled bubble, while an inverted, subcooled bubble is shown in Figure 27. In Figures 25, 26 and 27 removal forces are considered to be positive while retention forces are negative.

The actual effect of the gravity force on bubble removal can be shown by a plot of the ratio of the gravity force to the total removal force versus the reduced time. This is shown in Figure 28 for the normal heater orientation and in Figure 29 for the inverted heater series. Each subcooling curve is an average of three to six bubbles from each heat flux. The magnitude of the heat flux appears to have no significant effect on the ratio of the gravity force to the total removal force.

D. Discussion of Results

Examination of the tabulated and plotted data for all the experimental series indicates that there does not exist a clear-cut differentiation between bubbles observed at different heat fluxes and subcoolings. However, certain interesting relations are obtainable from the experimental data reported here.

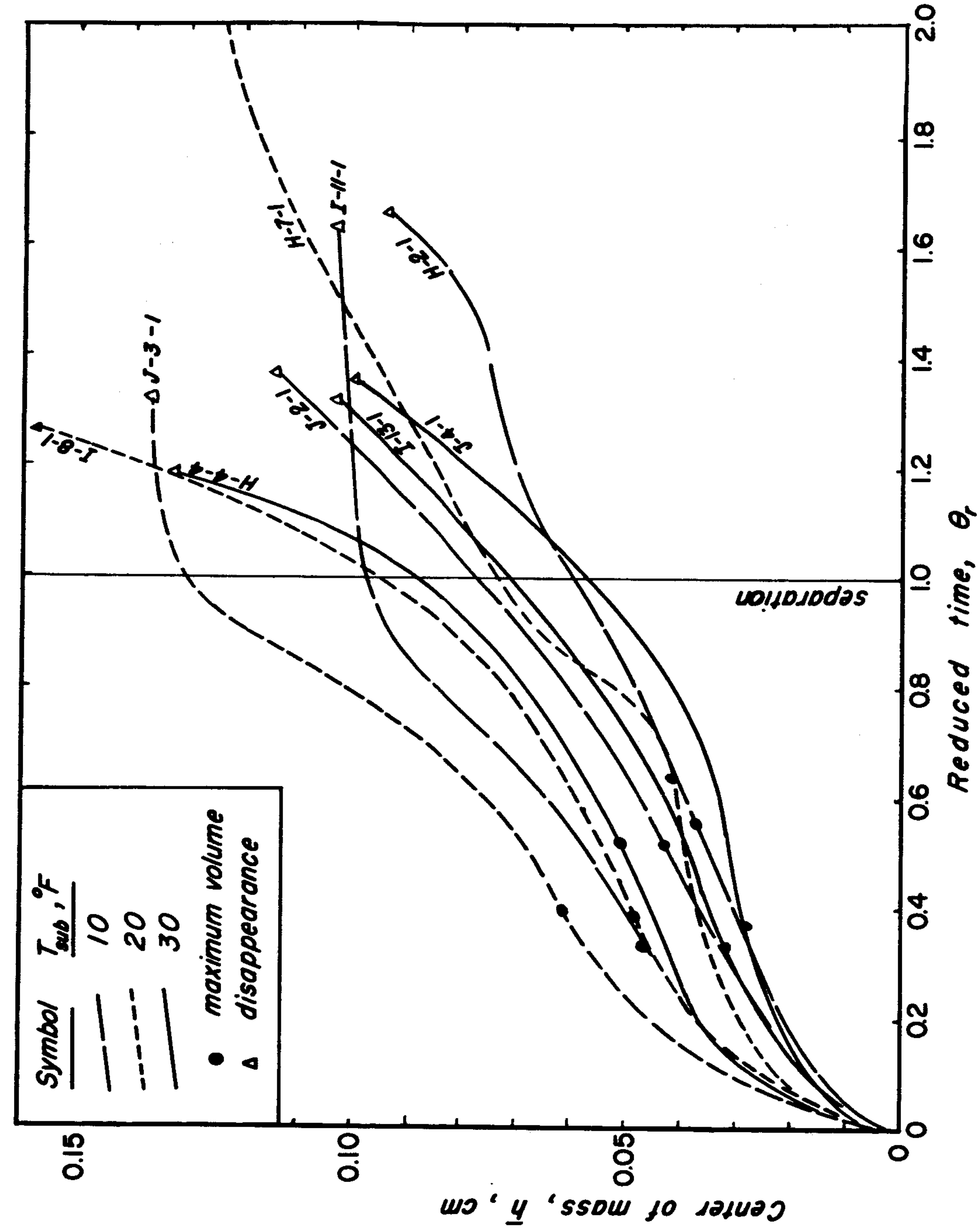

Figure 12. Center of Mass - Reduced Time Relations for Nine Inverted Bubbles.

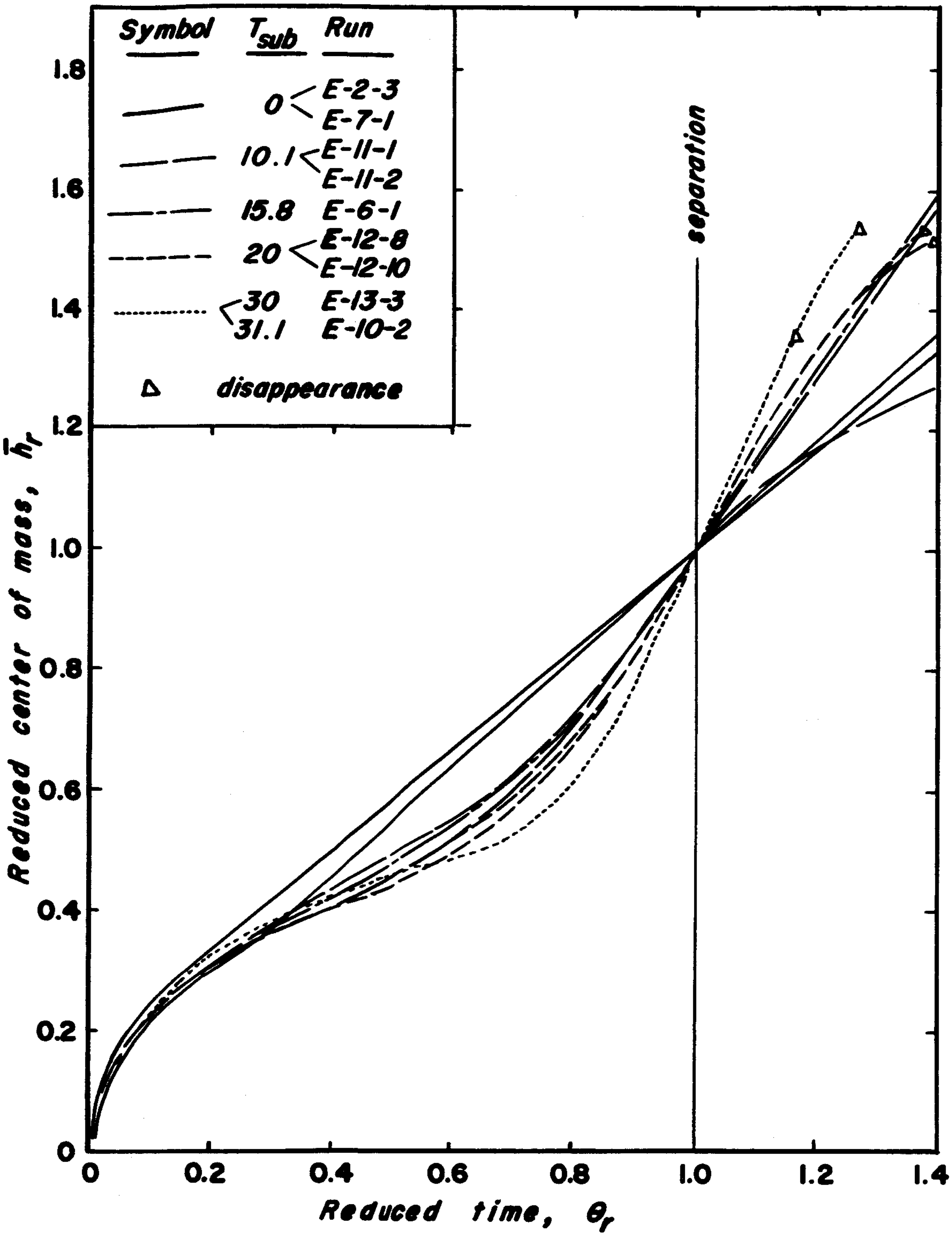

Figure 13. Reduced Position and Time Relations for Nine Bubbles at $q/A = 70,000$ Btu/hr ft^2.

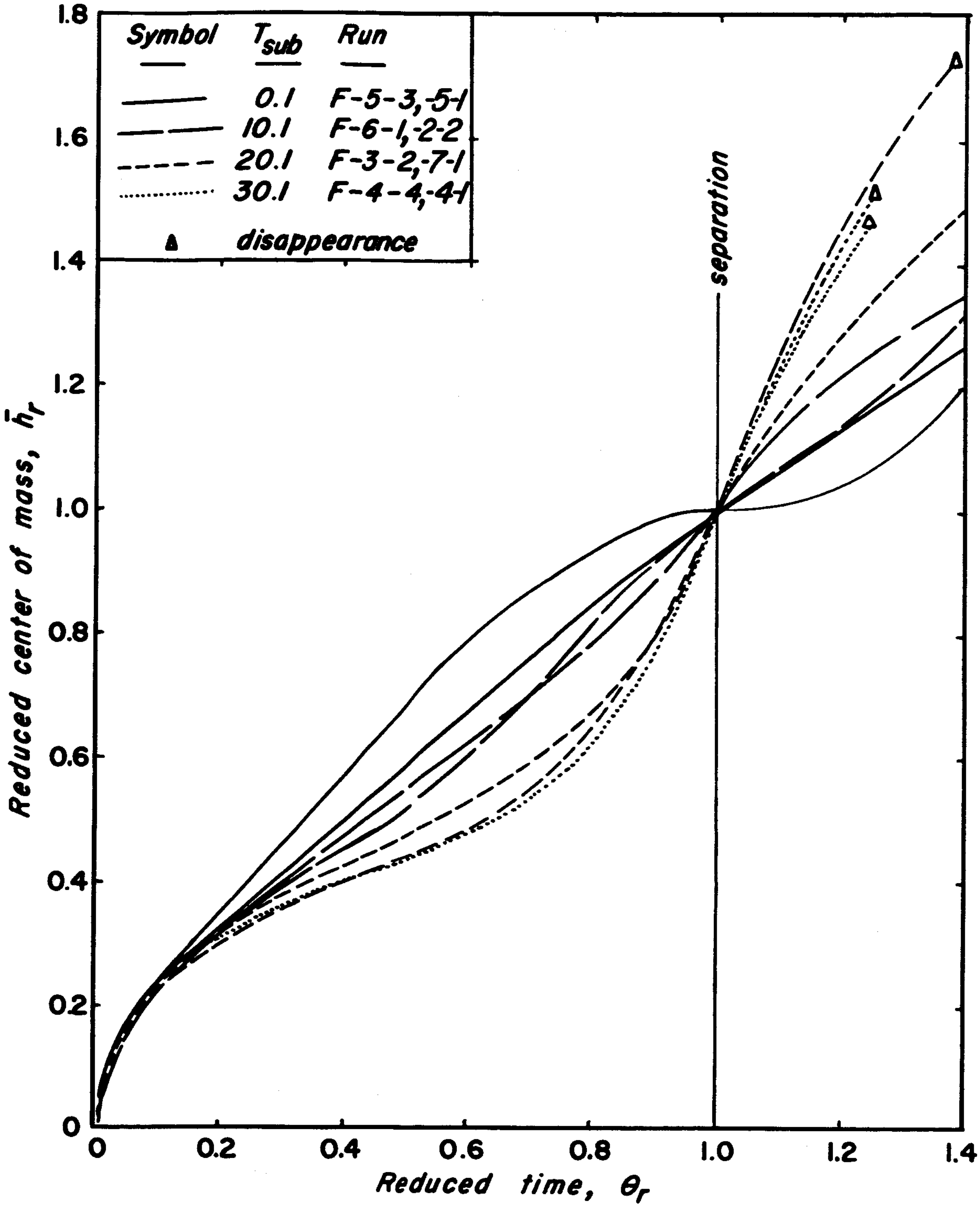

Figure 14. Reduced Position and Time Relations for Eight Bubbles at $q/A = 50,000$ Btu/hr ft^2.

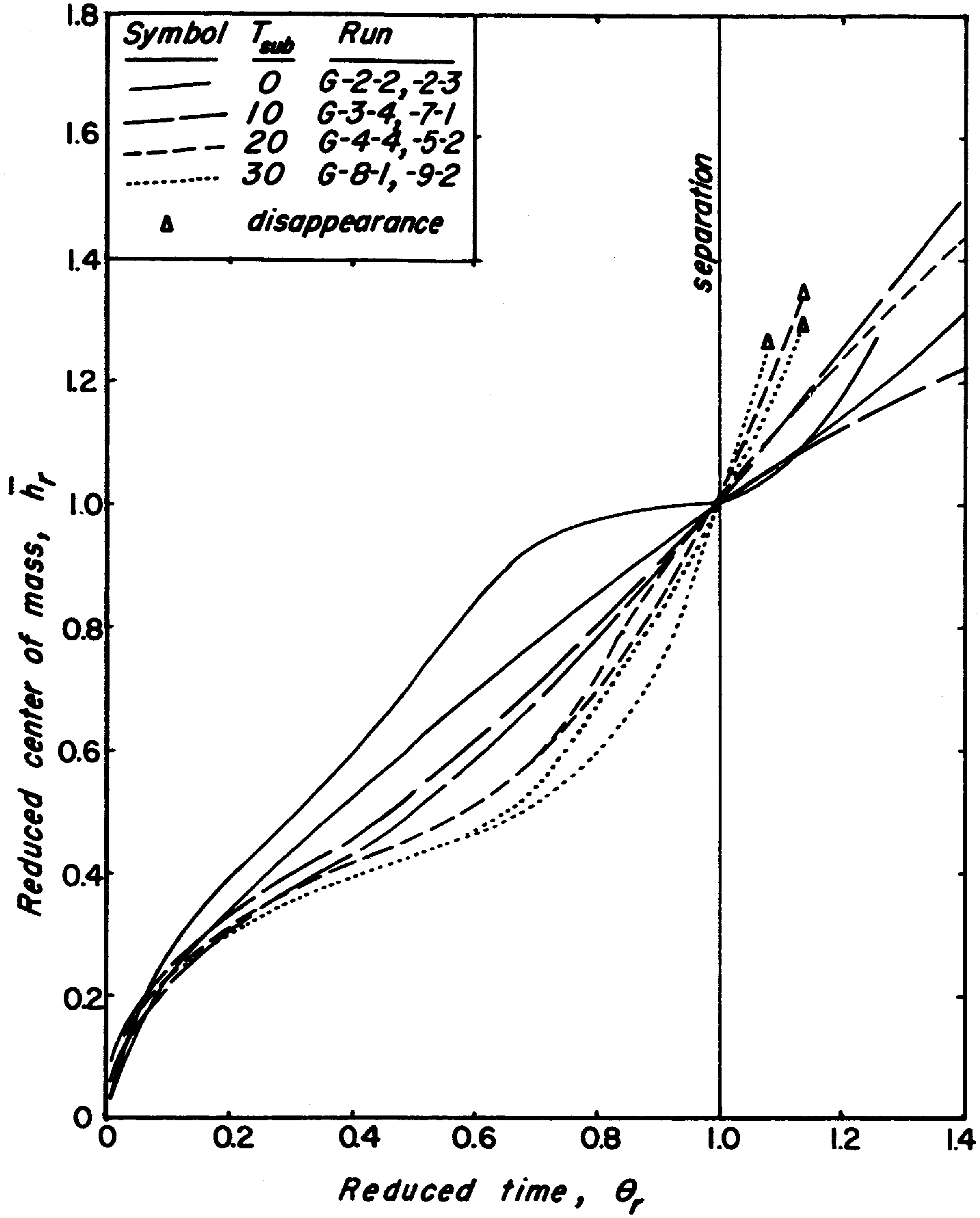

Figure 15. Reduced Position and Time Relations for Eight Bubbles at $q/A = 100,000$ Btu/hr ft^2.

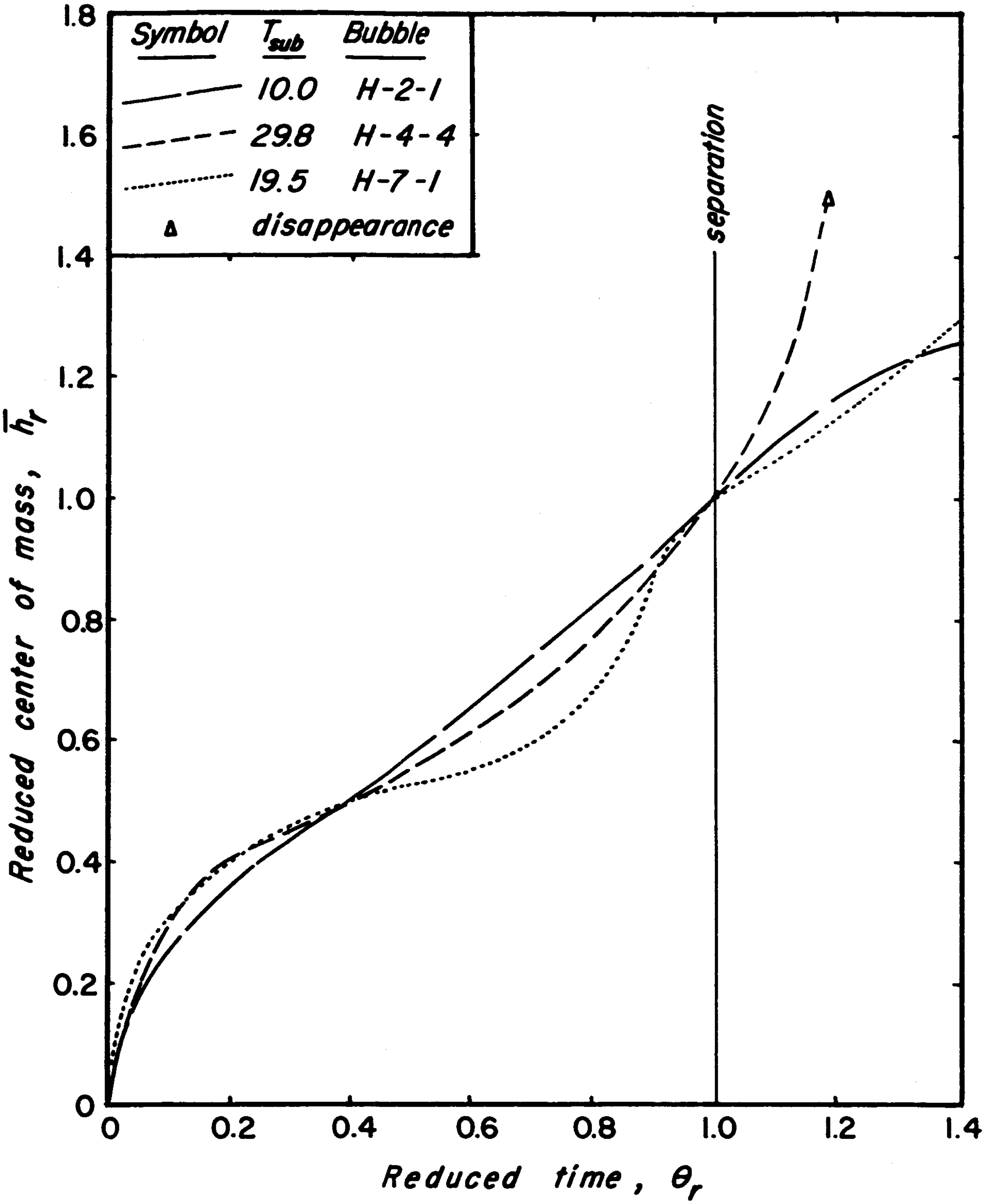

Figure 16. Reduced Time and Position Relations for Three Inverted Bubbles at q/A = 50, 000 Btu/hr ft^2.

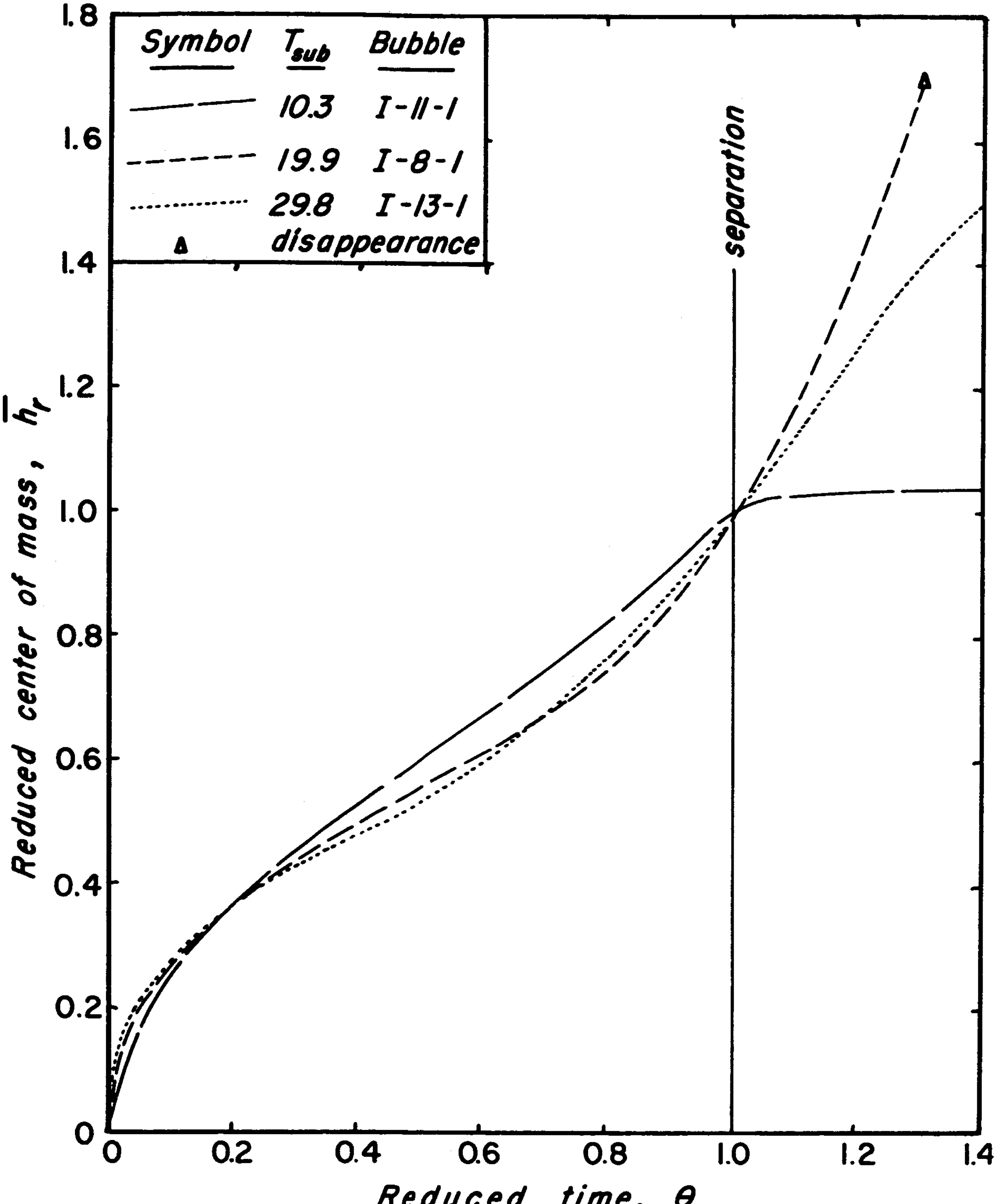

Figure 17. Reduced Time and Position Relations for Three Inverted Bubbles at q/A = 70, 000 Btu/hr ft^2.

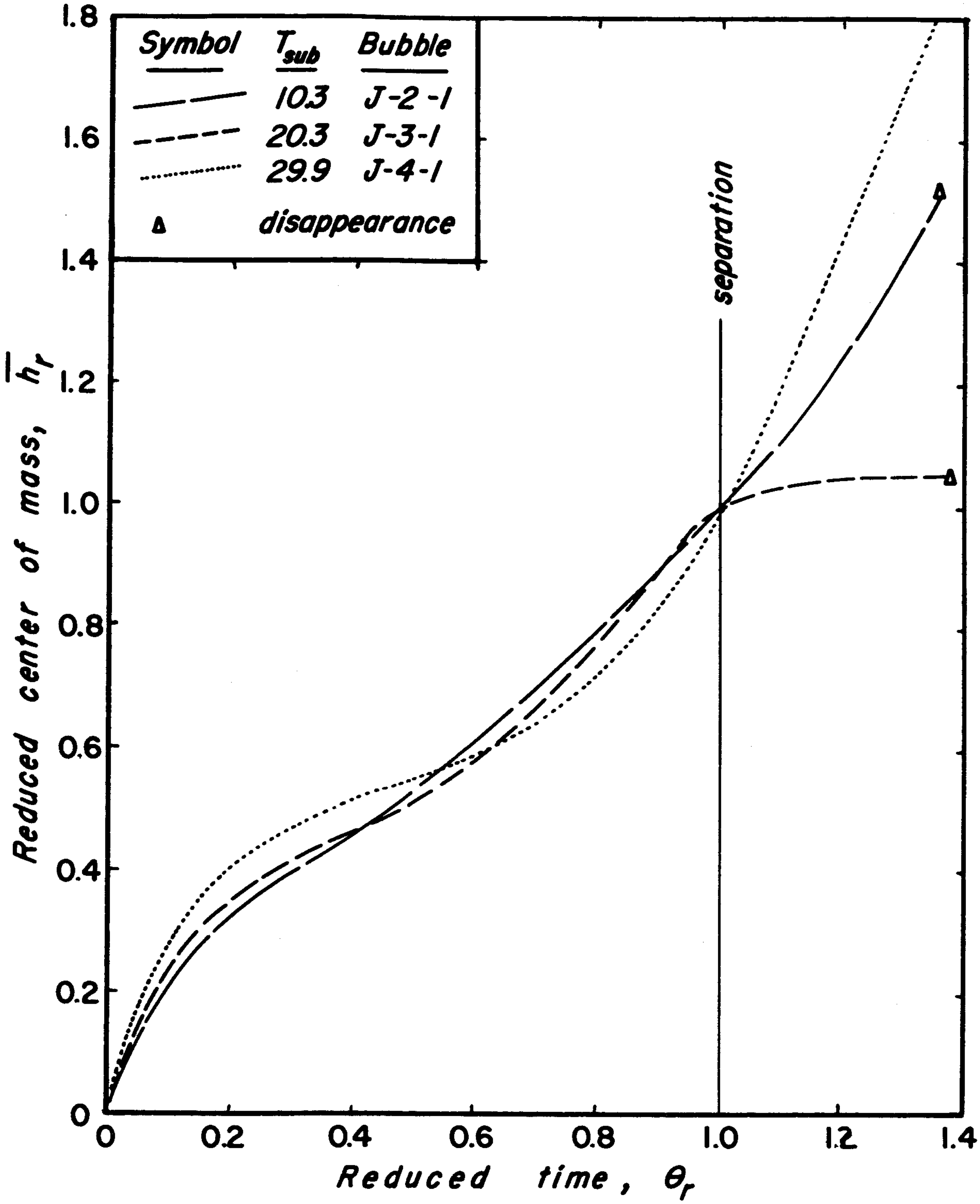

Figure 18. Reduced Time and Position Relations for Three Inverted Bubbles at q/A = 100,000 Btu/hr ft^2.

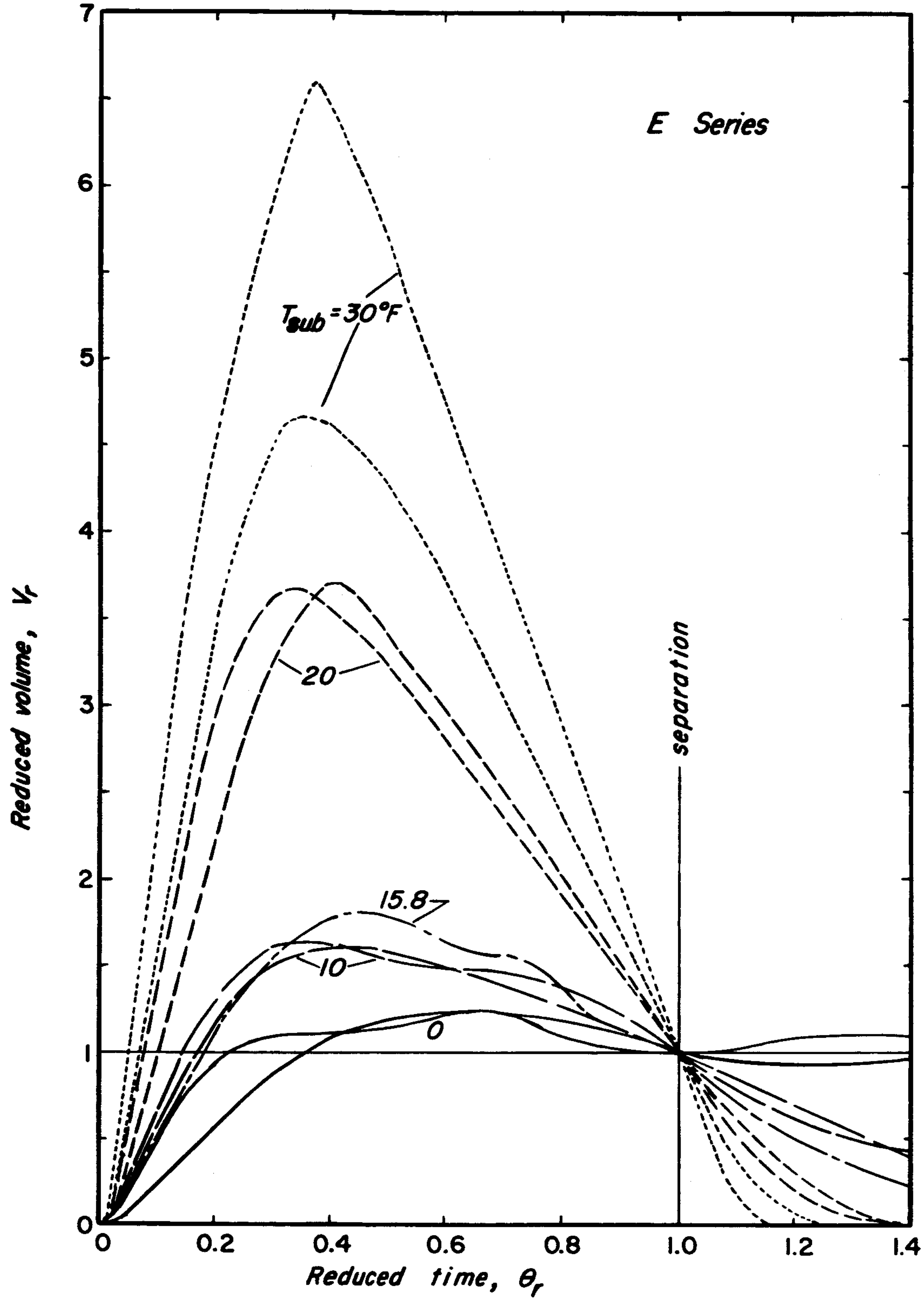

Figure 19. Reduced Volume and Time Relations for Nine E Series Bubbles at q/A = 70, 000 Btu/hr ft^2.

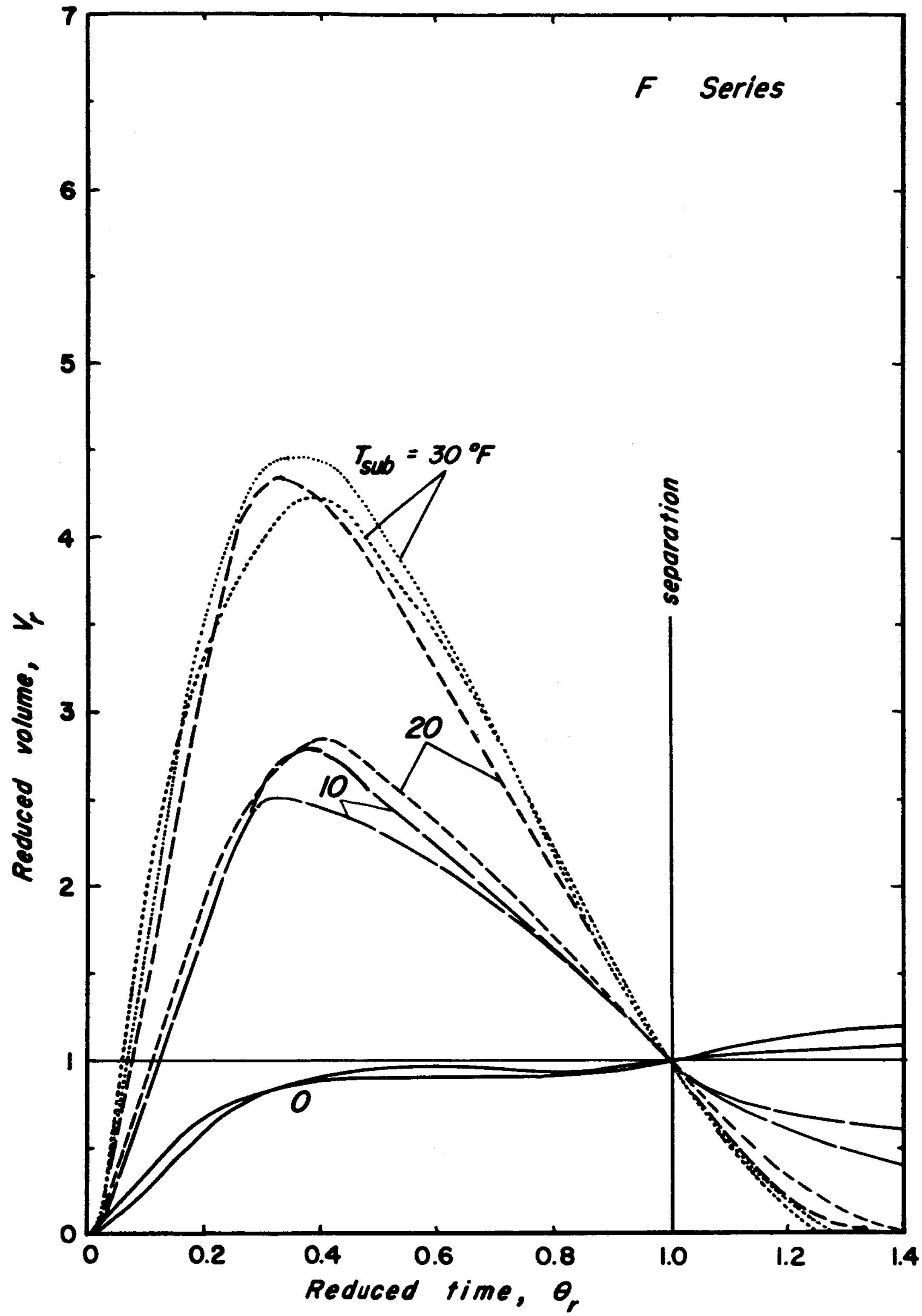

Figure 20. Reduced Volume and Time Relations for Eight F Series Bubbles at q/A = 50, 000 Btu/hr ft^2.

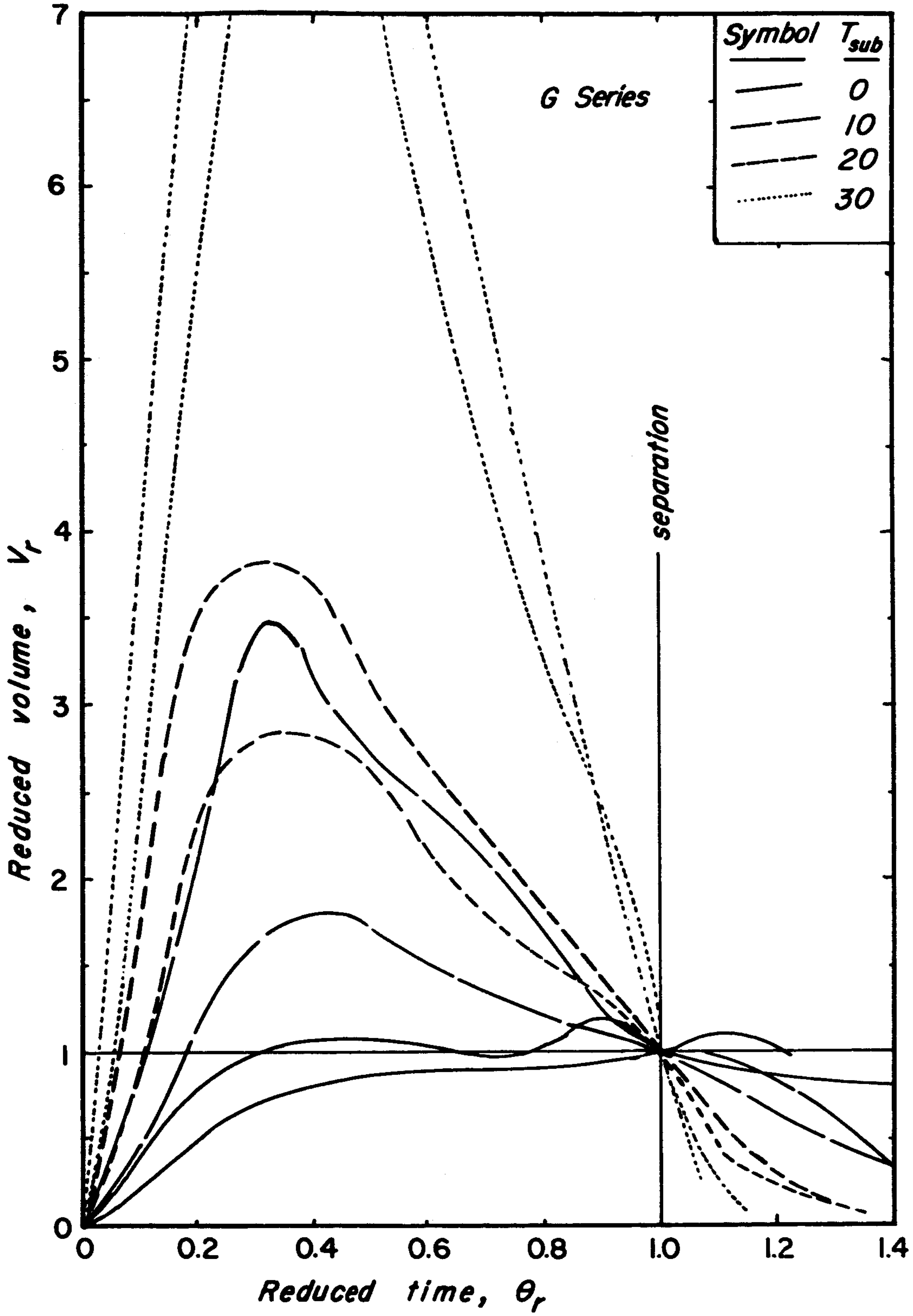

Figure 21. Reduced Volume and Time Relations for Eight G Series Bubbles. q/A = 100,000 Btu/hr ft^2.

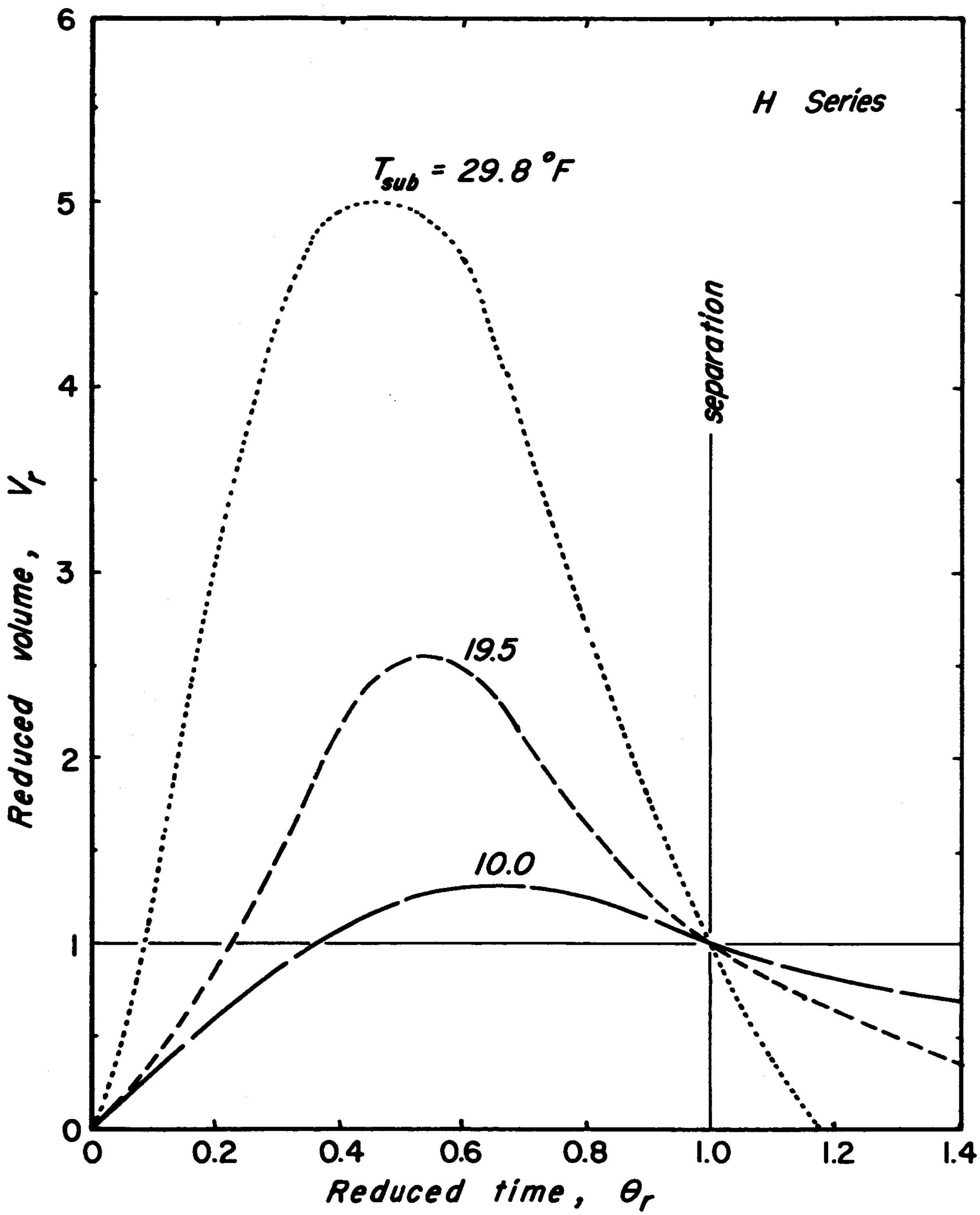

Figure 22. Reduced Volume and Time Relations for Three Inverted H Series Bubbles. $q/A = 50,000$ Btu/hr ft^2.

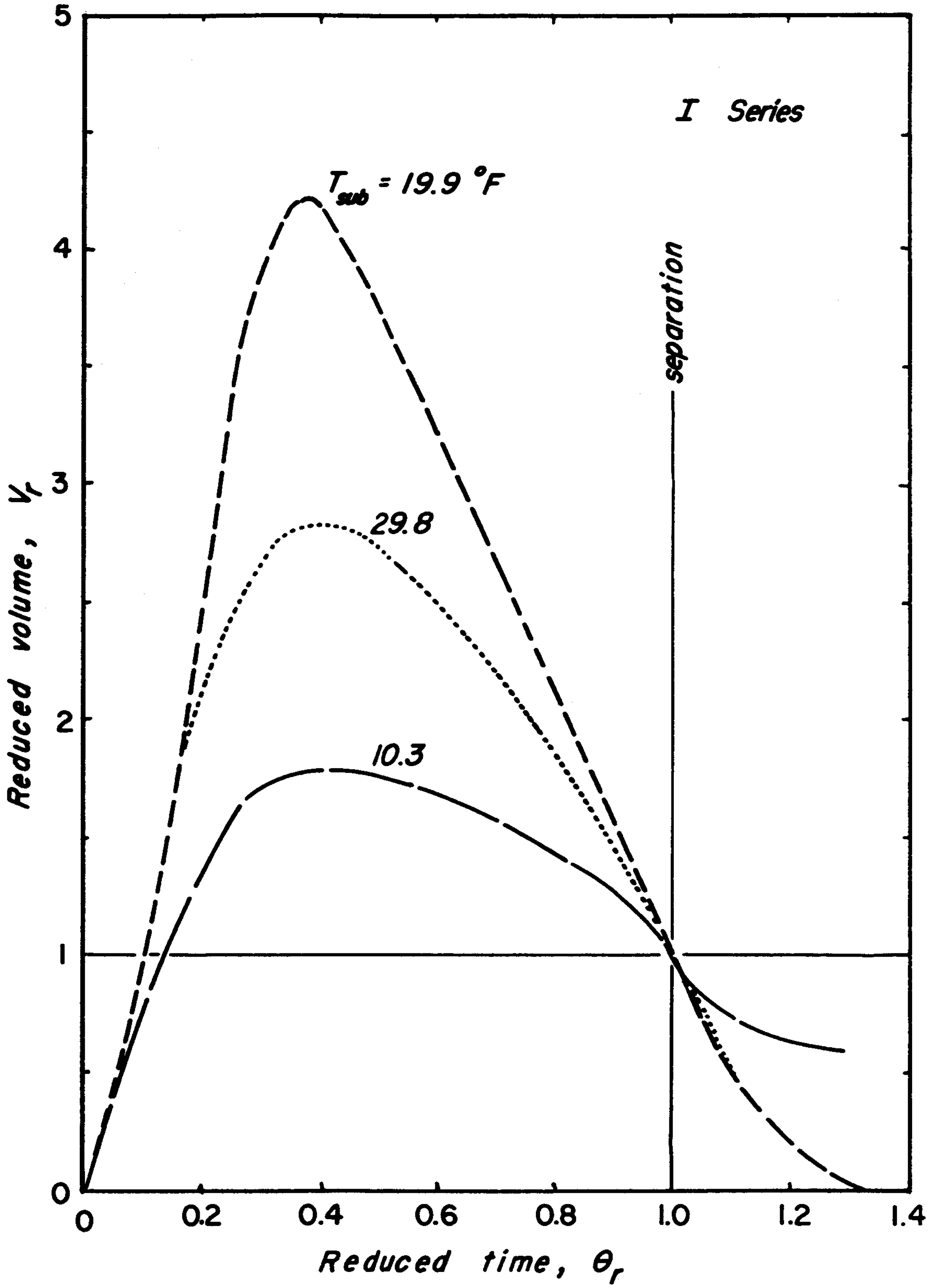

Figure 23. Reduced Volume and Time Relations for Three Inverted I Series Bubbles. q/A = 70,000 Btu/hr ft^2.

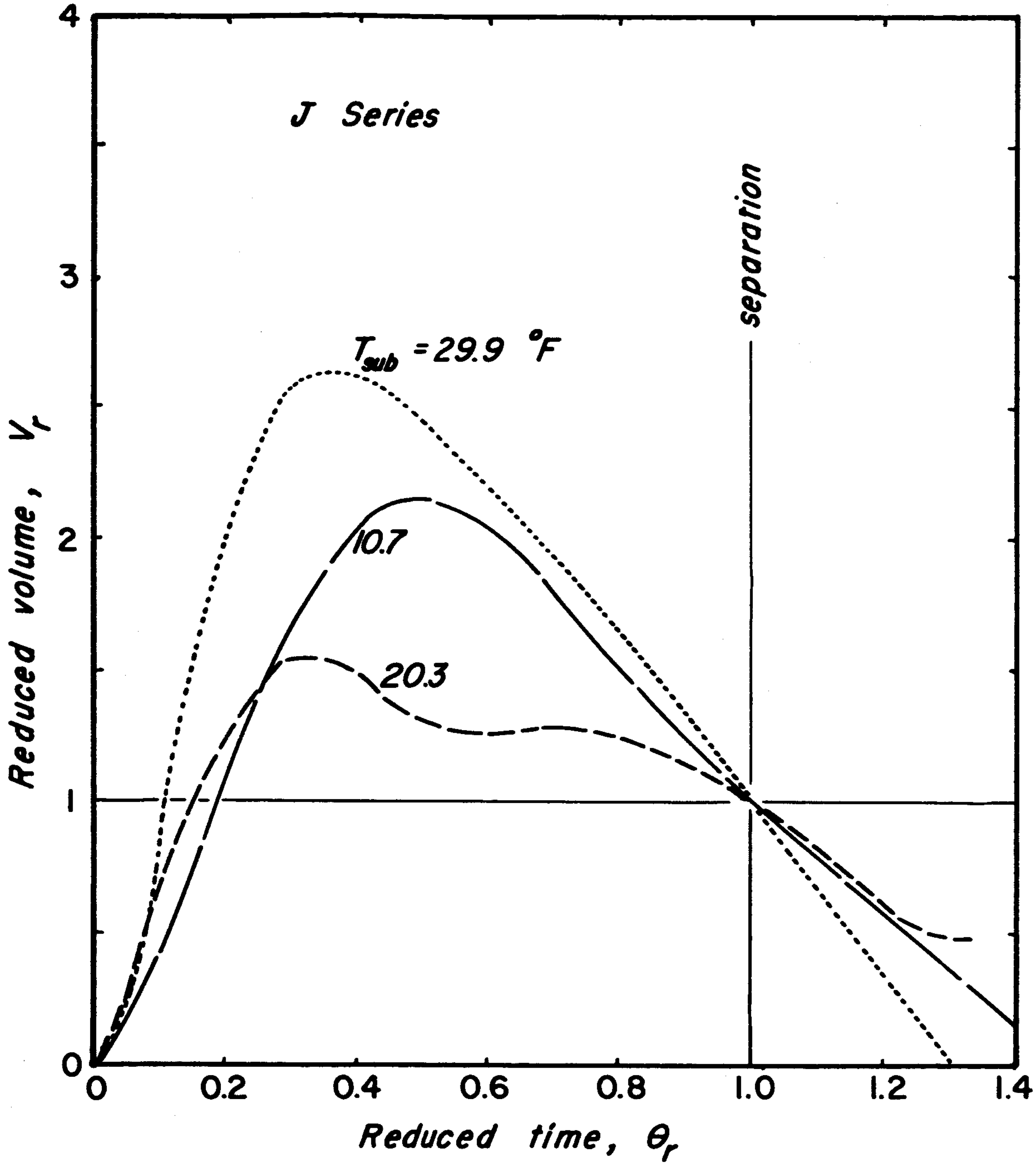

Figure 24. Reduced Volume and Time Relations for Three Inverted J Series Bubbles. q/A = 100, 000 Btu/hr ft^2.

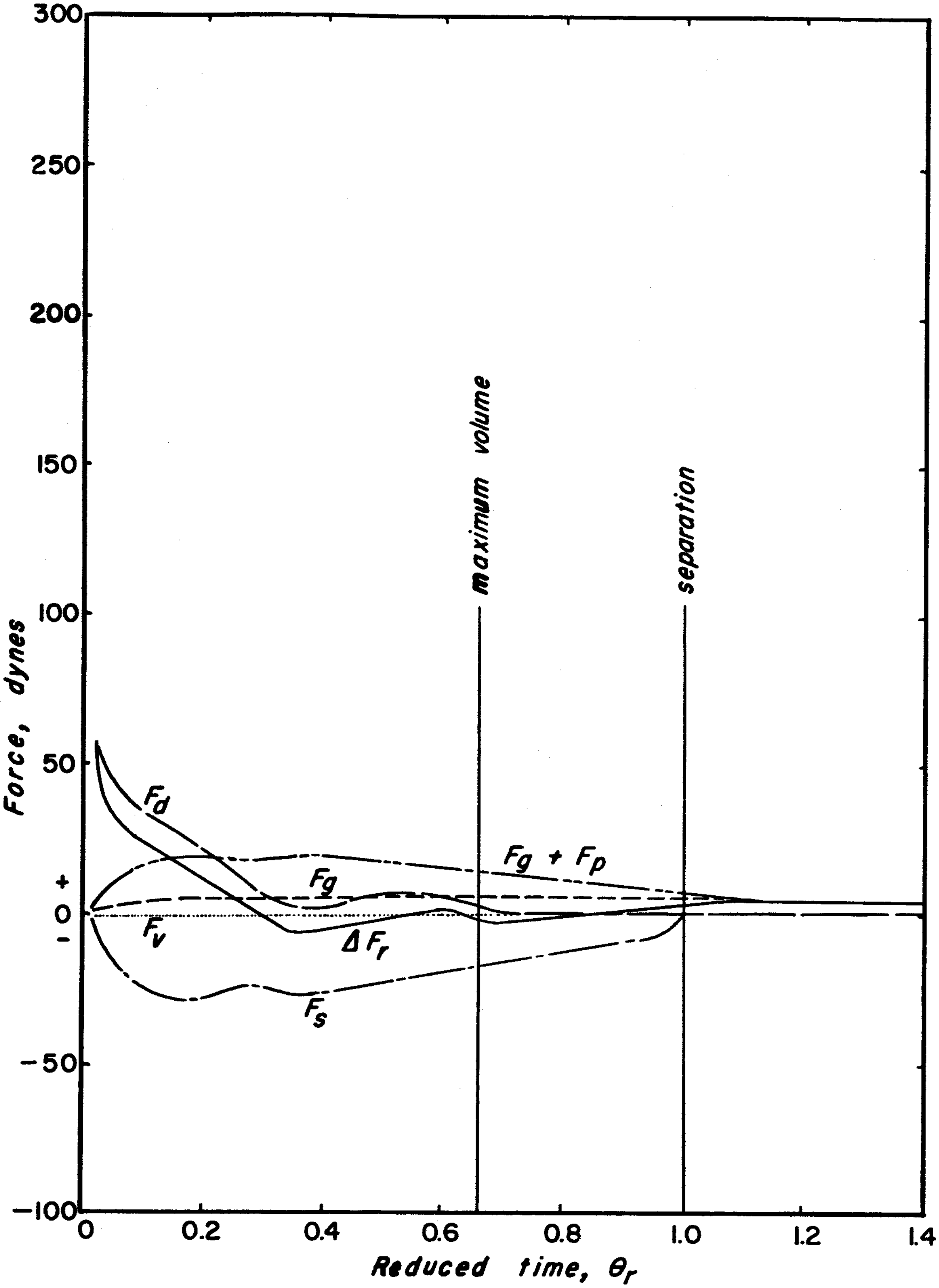

Figure 25. Force - Time Relationships for a Small, Saturated Bubble. Data for Bubble E-7-1.

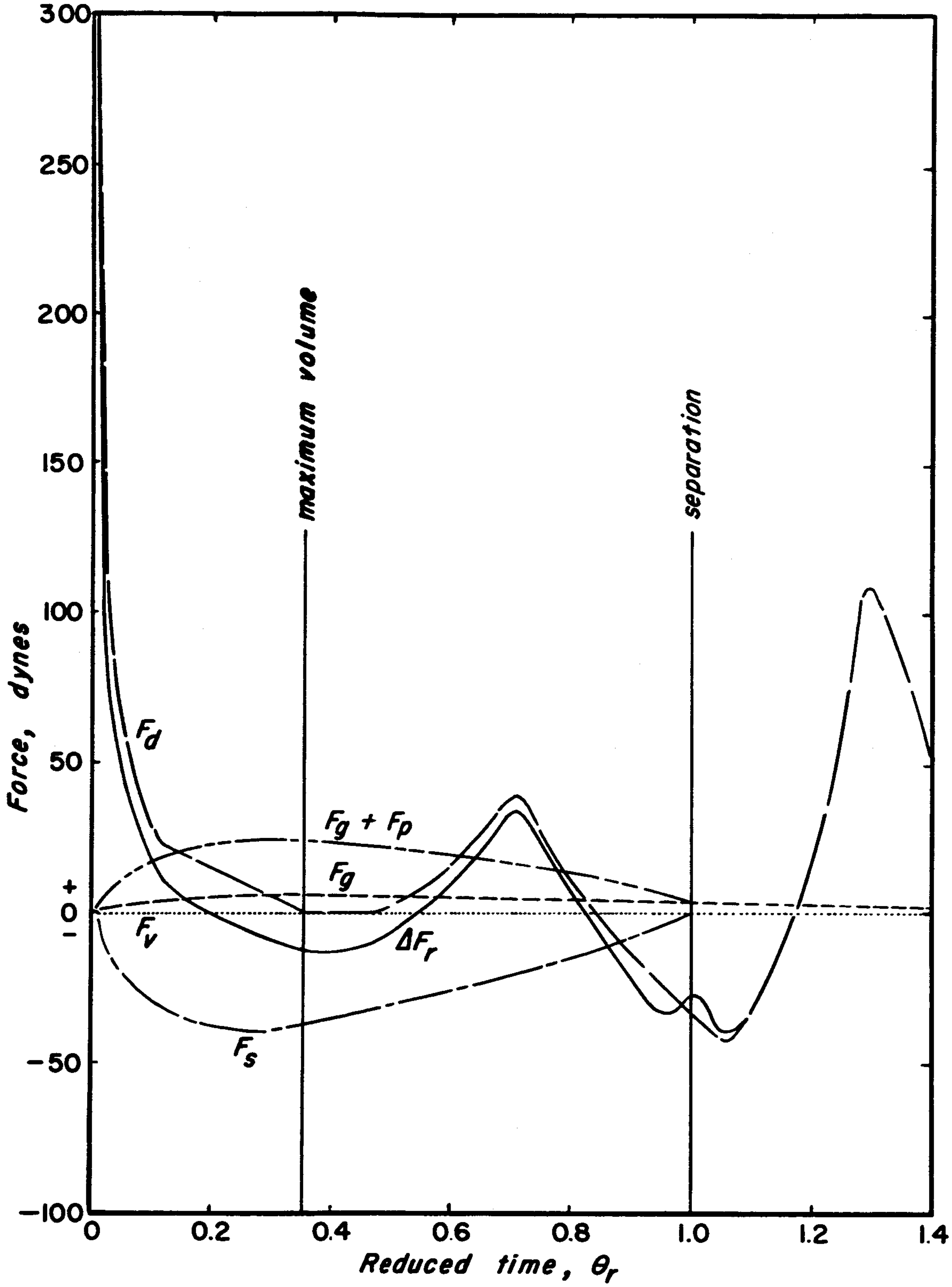

Figure 26. Force - Time Relations for a Small, Subcooled Bubble. Data for Bubble E-11-1. T_{sub} = 10.1°F. Volume Essentially the Same as Bubble E-7-1.

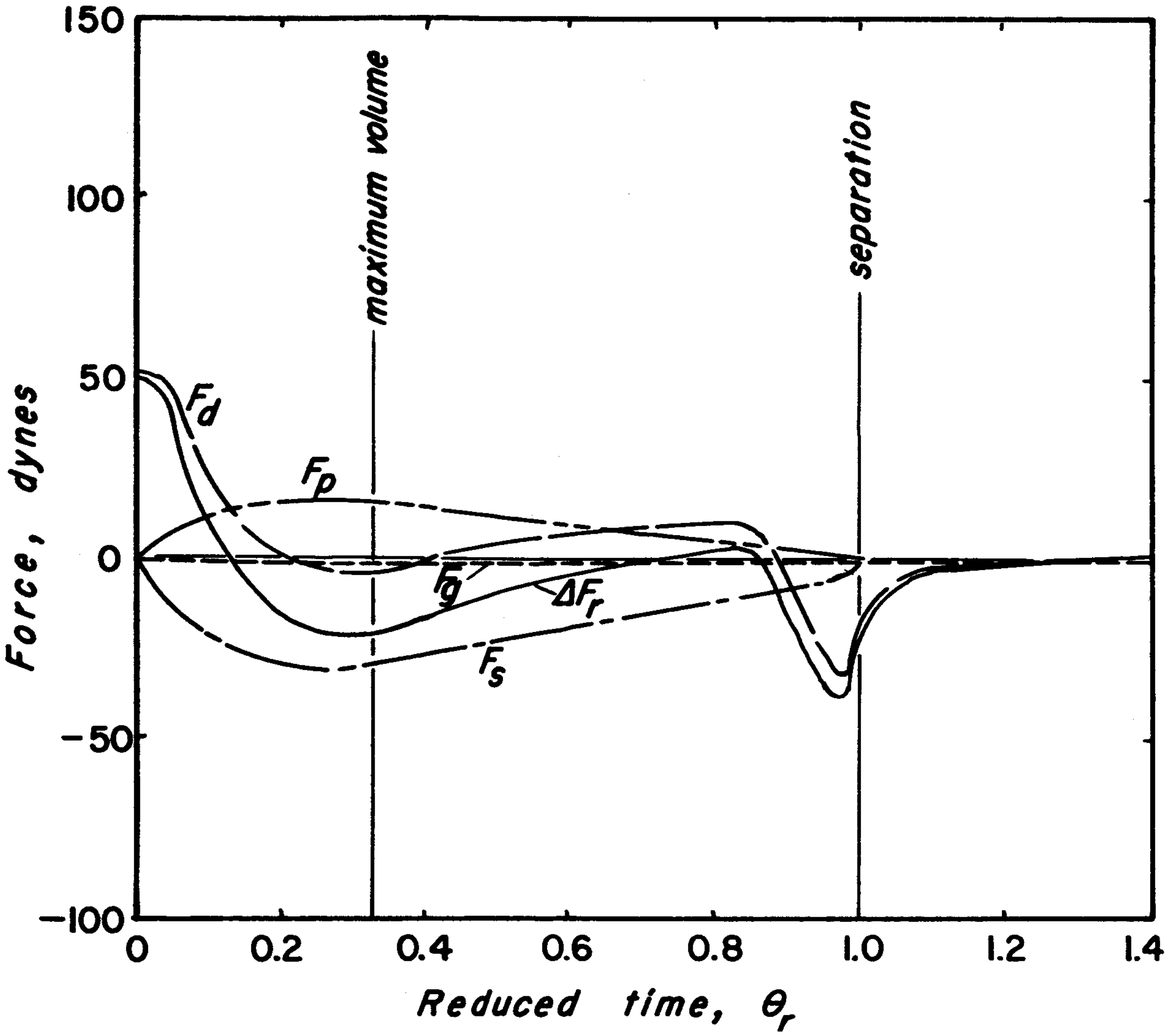

Figure 27. Force - Time Relations for a Small, Inverted, Subcooled Bubble. Data for Bubble I-11-1. T_{sub} = 10.3°F.

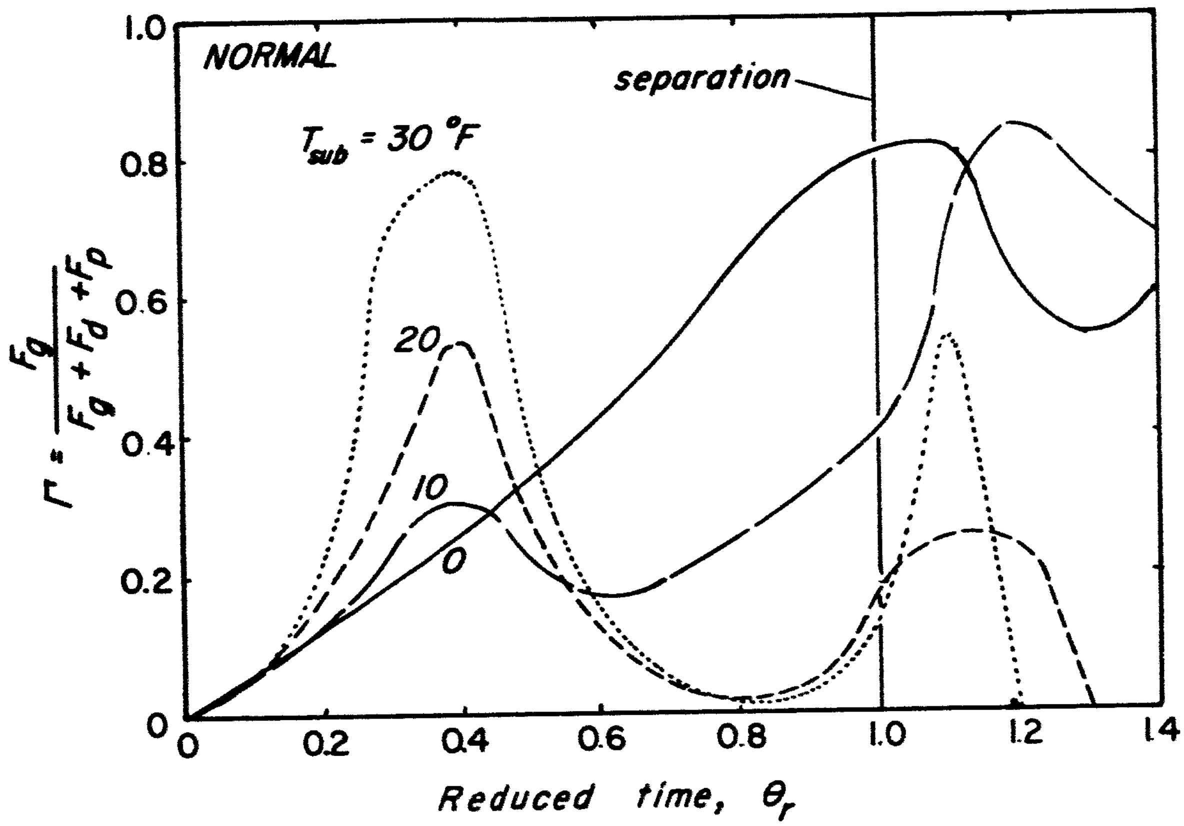

Figure 28. Subcooling Effect on the Ratio of Gravity Force to Total Removal Forces. Boiling of Water on Upper Surface of Heater. E, F, and G Series.

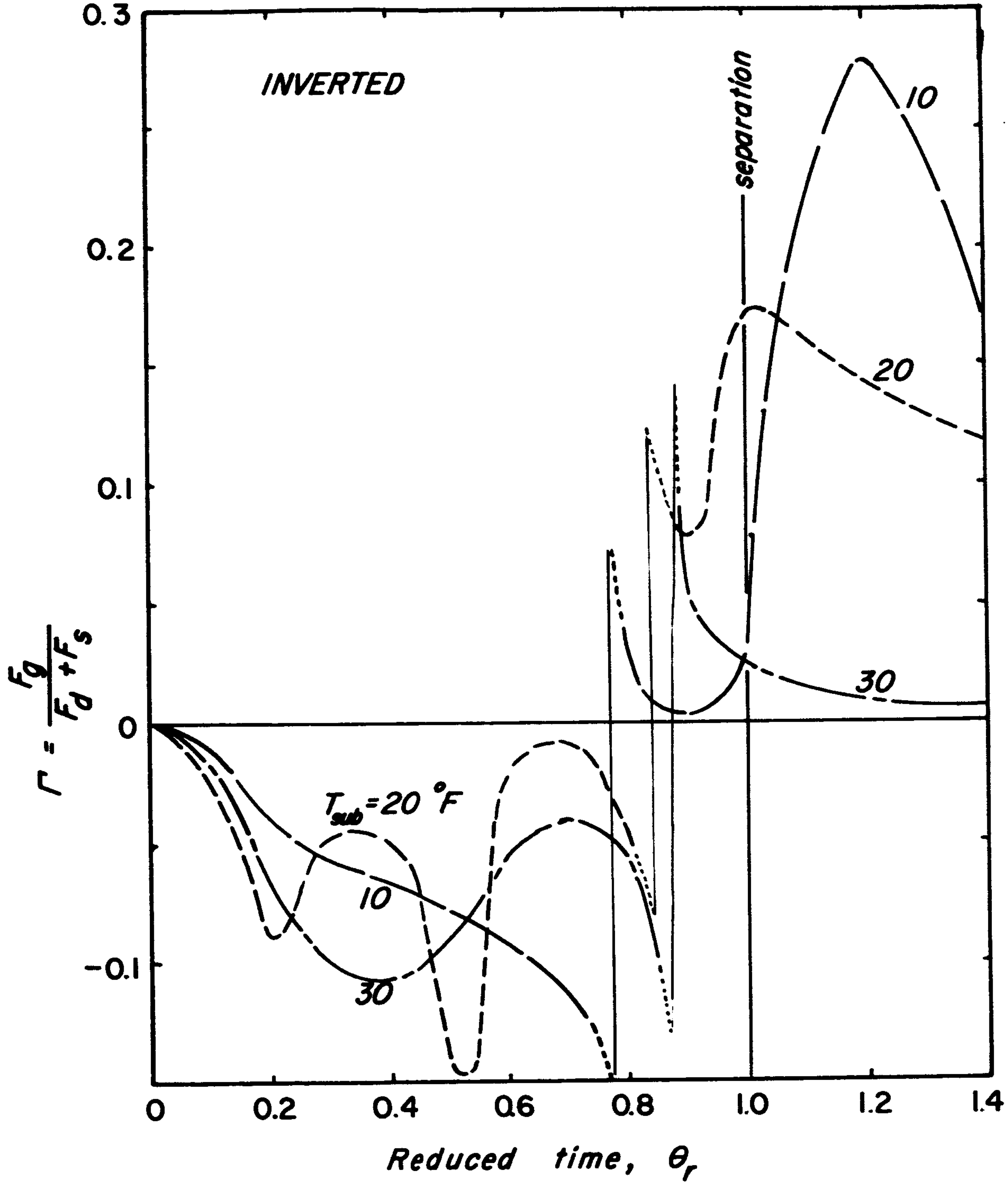

Figure 29. Average Ratio of the Gravity Force to the Total Removal Force for Boiling on an Inverted Heater. H, I, and J Series.

Figure 3 conclusively indicates that an assumption of a spherical bubble shape for boiling in water is not valid. Although Figure 3 is for a 30°F, Type 2, subcooled bubble, all the other observed Type 2 bubbles, regardless of heat flux or subcooling, have essentially the same shape at similar points in their lifetime.

The absence of oscillator bubbles at saturated boiling conditions, as shown in Figure 4 and as observed in all the saturated runs, is explained by the fact that the bubble is growing in a liquid which is at the same temperature as the vapor in the bubble. Therefore no condensation is occurring at the top of the bubble and therefore no loss in volume occurs which could show up as oscillation. At a subcooling of 30°F the number of oscillators is reduced over that at, say, 10°F subcooling because the bubbles that form have a relatively short lifetime and are therefore less likely to experience the contracting mode associated with oscillator type bubbles.

That the lifetime of continuous growth bubbles is a direct function of subcooling is shown by Figures 5 and 6. It is seen that 30°F subcooled conditions produce bubbles within lifetimes of $\frac{1}{2}$ to $\frac{1}{4}$ of those for 10°F subcooled conditions. Figure 6, as well as other data from the appendices, clearly indicates that different sizes of bubbles are produced at the same subcooling, with similar sized bubbles being produced at different subcoolings. It is this wide range of sizes that seriously complicates a detailed statement of what to expect in regards to bubble dynamics and heat transfer at a given set of boiling conditions. Investigation of the photographs of bubbles obtained in this experimental program strongly indicates that some types of statistical treatment of the data would be necessary to obtain a complete prediction of bubble behavior.

This complication is further pointed out by the nature of the inertia force-time relations shown in Figure 7. It is interesting to note that the inertia force, as calculated from Eqs. 3 and 4, has a relatively large positive peak immediately prior to separation for all subcooled bubbles. It is felt that this large positive inertia force peak causes the bubble to separate. It is noted that the saturated bubbles do not have this peak. Also, the peak becomes more pronounced with an increase in subcooling. If the inertia force had been calculated using the liquid mass equivalent to the bubble volume, it would have been found that the inertia force was quite often strongly negative prior to separation. This then caused the net removal force to be negative prior to separation. That this is not the case is indicated by the fact that the bubbles do separate.

Figures 8 and 9 show the conditions at the bubble base during the bubble lifetime. The relative magnitude of the base diameter is again a function of bubble size and not subcooling as shown in Figure 8. The variation in contact angle with bubble lifetime shown in Figure 9 is seen to be essentially uniform regardless of subcooling. The tendency is for the contact angle to approach 90° at separation. The general contact angle variation can also be seen in Figure 3.

The reduced parameters for time, center of mass, and volume are used in an effort to overcome some of the complications of different bubble sizes. Figures 10, 11 and 12 indicate the improvement obtained in the center of mass-time relations. In all of these plots, bubble size can be determined by the value of the center of mass at separation, the larger bubbles naturally have the larger center of mass values. It should be noted that the inverted series (Fig. 12) have relations similar to the normal series except that center of mass is only 1/3 of that for the normal at separation.

It is when the reduced center of mass is plotted against the reduced time that the bubble size problem is eliminated. Figures 13 through 18 conclusively show that bubbles of a given subcooling, whether it be 0 or 30°F, normal or inverted, follow the same general growth curve regardless of maximum size. A more conclusive picture of bubble growth can be shown if the bubble velocity at separation is plotted versus subcooling as in Figure 30. This indicates that the greater the subcooling the more rapid is the bubble movement away from the surface. This is true for both normal and inverted bubbles. In general no significant influence on the bubble velocity is shown by a change in heat flux.

The reduced volume-reduced time plot shown in Figures 19 through 24 also indicate the elimination of the bubble size complication. It is seen that the volume-time relationships are essentially similar for given subcoolings and appear to be independent of bubble size and heat flux. In the E series it is noted that saturated conditions produced, here at least, bubbles which reached maximum volume prior to separation. This is generally considered to be contrary to reported data. In general as the subcooling increases, the ratio of maximum volume to volume at separation also increases. This is the case for both normal and inverted bubbles.

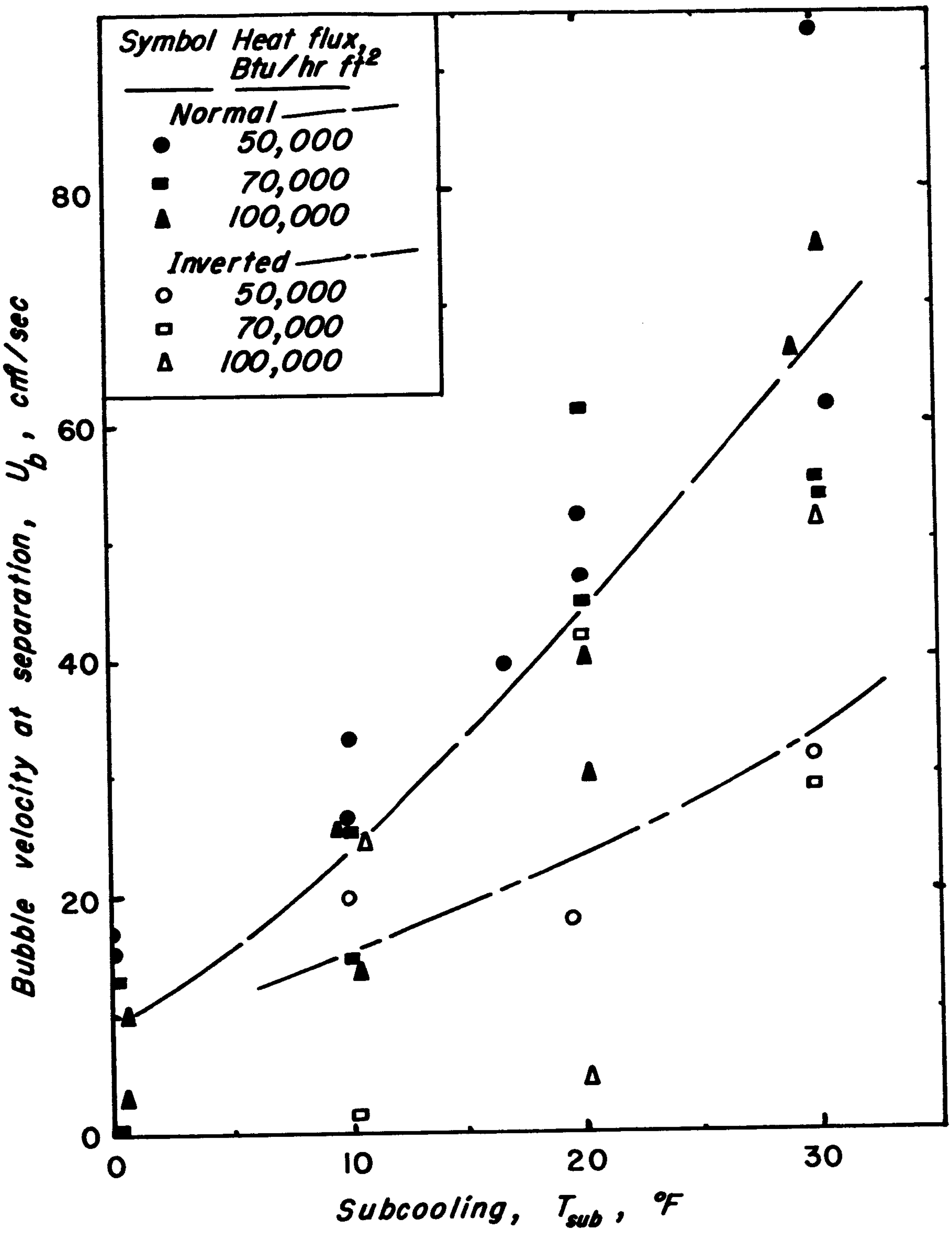

Figure 30. Bubble Velocity at Separation as a Function of Subcooling for Both Normal and Inverted Boiling of Water.

The force analysis on a particular bubble can best be shown only one bubble at a time as in Figures 25, 26 and 27. For saturated conditions, it is seen that there is only a very slight net removal force prior to separation. Since the gravity force makes up a significant portion of this removal force, it is felt that at zero-gravity conditions a saturated bubble will not separate. The general shape of the force-time curves for other saturated bubbles of the same or different size are similar in shape and vary only in magnitude. The force curve for a subcooled, normal, bubble is shown in Figure 26. A large positive peak prior to separation is evident. The magnitude of this peak increases both with bubble size and subcooling. It is felt then that since the gravity force is only a small portion of the net removal force the absence of gravity will not prevent the removal of the bubble from the surface.

The inverted bubble shown in Figure 27 has a slight positive net removal force prior to separation but is more similar to a saturated bubble than it is to a subcooled bubble. Part of the problem here is that in all the inverted runs only very small bubbles separated. This indicates that for larger bubbles the magnitude of the buoyant force rapidly becomes very large in comparison to the total removal forces. Since in inverted boiling, gravity serves to hold the bubble to the surface, no large bubbles will separate from the heater surface. This is further shown in Figure 29 where the ratio of the buoyant force to the total removal force for inverted boiling is shown. Prior to separation this term is negative and only just slightly goes positive at separation.

The relationship between the gravity force and the total removal forces is shown in Figure 28 for the normal heater orientation, where it is seen that just prior to separation the gravity force is only 20 to 40 percent of the total removal force for the subcooled bubbles whereas it approaches 80 percent for the saturated bubbles. This again indicates that the absence of the gravity force will tend to cause vapor to collect on the heating surface in saturated boiling conditions, whereas subcooled boiling will at least cause the vapor bubbles to disengage from the heater surface, although they may not move too far from the surface.

E. Bibliography

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IV. CONCLUSIONS AND RECOMMENDATIONS

Conclusions obtained from this research work are as follows:

1. Bubbles cannot be assumed to be spherical if an accurate analysis of bubble dynamics and heat transfer relations are desired.

2. Oscillating, continuous growth, and agglomerate bubbles occur in nucleate boiling, with agglomerate bubbles accounting for approximately 90% of the bubbles formed.

3. Bubble lifetime varies inversely with the magnitude of the subcooling.

4. A wide range of bubble sizes is produced at any given subcooling, indicating that a statistical treatment of bubble data may be necessary for proper predictive relations.

5. The inertia force after maximum bubble volume when calculated from the liquid mass set in motion at maximum bubble volume appears to fit the actual force-time relations better than when varying bubble volume is used.

6. Reduced parameters referred to magnitude at separation can be used to eliminate complications associated with different bubble sizes.

7. Reduced parameters indicate that bubbles of a given subcooling have the same growth characteristics regardless of size or, to a certain extent, heat flux, for both normal and inverted heater orientation.

8. A force analysis of both normal and inverted saturated bubbles in water, indicates that the gravity force is a significant removal force. Its absence may prevent saturated bubble separation. No saturated bubbles separate from an inverted heater surface at normal gravity.

9. Subcooled bubbles in water exhibit a large positive removal force prior to separation. The magnitude of this force is sufficient to cause bubble removal even in the absence of the gravity force.

10. For bubbles in water forming on a normal heater surface, the magnitude of the ratio of the buoyant force to the total removal force decreases from 80% at saturation to 15% at a subcooling of 30°F.

11. For inverted bubbles in water at normal gravity, only small bubbles separate. For larger bubbles the buoyant force exceeds the removal force, thus holding the bubble to the heater surface.

12. For zero-gravity applications it is concluded that when nucleate boiling of water is being used as a heat transfer mechanism it should be done under subcooled conditions.

Recommendations for further study in boiling heat transfer are as follows:

1. The treatment of the inertia force as done in this research program is to a certain extent unsatisfactory. Further force analysis work would be required to elucidate this matter.

2. Inspection of the photographic data indicates that another removal force should possibly be considered. This force is a shear force exerted on the bubble surface by liquid motion set up by the initial expulsion of liquid above the bubble as it explodes from its nucleation site. Further work with other fluids having varying viscosities would be helpful in answering this question.

3. The relative magnitudes of the pressure force and the surface tension force are also in question to a certain extent. Further work with fluids of varying surface tension would be needed in this area.

4. Because of the broad range of bubble sizes obtained at a given heat flux and subcooling it seems essential that many more bubbles be analyzed with an attempt at a statistical correlation to ascertain the relative influence of heat flux and subcooling on bubble behavior.

5. The research work on boiling in water, reported here, has used only a small fraction of the experimental data contained

in the some fifty photographic runs. There remains a great deal of work which needs to be done, most of which can be accomplished without further experimental data gathering. It is hoped that this work will be possible in the future.

APPENDICES

APPENDIX A

EXPERIMENTAL CONDITIONS

The data contained in this appendix are for the experimental runs for which the bubbles were observed from the side. Series E, F, and G are for boiling of water off the top of the heater. Series H, I, and J are for boiling of water off the bottom side of the heater, i.e., inverted boiling.

q/A = heat flux, Btu/hr ft^2

T_{sub} = subcooling, $T_{sat} - T_{bulk}$, °F

T_{sat} = boiling point temperature at heater surface, °F

T_s = temperature of the heater surface, °F

ΔT_{sat} = the total driving force temperature $T_s - T_{bulk}$, °F

T_{bulk} = temperature of bulk water approximately 1.0 cm vertically away from the heater surface, °F

Run Number	q/A	T_{sub}	T_{sat}	T_s	ΔT_{sat}	Date
E-1	72,200	14.2	202.9	226.0		15 May 64
2	72,000	0	203.1	231.5		19 May 64
3	70,400	0.2	202.5	231.0		22 May 64
4	70,400	10.2	202.5	229.0		"
5	68,500	0.1	203.1	225.0		26 May 64
6	68,800	15.8	203.1	228.7		"
7	70,000	0	202.7	231.0		28 May 64
8	70,000	9.9	202.7	230.0		"
9	69,000	20.1	202.7	231.0		"
10	69,000	31.1	202.7	228.0		"
11	69,700	10.1	202.0	232.3		1 Jun 64
12	69,800	20.0	202.0	232.4		"
13	69,500	30.0	202.0	230.0		"
14	70,600	10.0	202.7	228.8	36.1	3 Jun 64
15	70,700	19.9	202.7	231.3	48.5	"
16	69,400	29.7	202.7	229.6	56.6	"
F-1	48,100	1.0	203.3	226.8	24.5	23 Jun 64
2	48,000	10.0	203.3	224.4	31.1	"
3	48,200	20.1	203.3	221.7	38.5	"
4	49,600	30.0	203.3	217.4	44.1	"
5	49,000	0.1	203.1	226.2	23.2	26 Jun 64
6	49,000	10.1	203.1	225.3	32.3	"
7	49,100	20.1	203.1	220.9	37.9	"
8	49,000	30.1	203.1	218.0	45.0	"
G-1	98,300	1.0	203.0	221.6	19.6	23 Oct 64
2	101,900	0.6	203.6	226.2	23.2	7 Dec 64
3	102,900	9.6	203.6	224.2	30.2	"
4	103,300	20.6	203.6	224.1	41.1	"
5	100,800	28.9	203.6	220.9	46.2	"
6	99,700	0	202.6	229.7	27.1	8 Dec 64
7	101,900	10.3	202.6	227.9	35.6	"
8	100,100	20.3	202.6	226.0	43.7	"
9	100,100	30.3	202.6	218.2	45.9	"

Run Number	q/A	T_{sub}	T_{sat}	T_s	ΔT_{sat}	Date
H-1	49,300	0	202.6	226.8	24.2	18 Dec 64
2	49,600	10.0	202.5	230.2	37.7	"
3	49,200	20.1	202.5	228.7	46.3	"
4	49,700	29.8	202.5	215.7	43.0	"
5	48,400	0	201.9	220.1	18.2	28 Dec 64
6	47,200	11.5	201.8	223.5	33.2	"
7	47,800	19.5	201.8	228.9	46.6	"
8	48,500	29.8	201.8	218.2	46.2	"
I-1	70,100	0	202.0	218.6	16.6	29 Dec 64
2	70,500	0	202.0	218.6	16.6	"
3	70,100	11.0	202.0	220.9	29.9	"
4	70,300	20.0	202.0	222.8	40.8	"
5	70,000	30.0	202.0	212.2	40.2	"
6	69,800	0	202.4	218.5	16.1	12 Jan 65
7	68,800	10.1	202.3	224.7	32.5	"
8	69,500	19.9	202.2	230.6	48.3	"
9	70,400	29.5	202.2	239.3	56.6	"
10	70,200	0	202.7	215.7	13.0	26 Jan 65
11	69,600	10.3	202.6	221.3	29.0	"
12	70,800	20.2	202.5	230.0	47.7	"
13	70,700	29.8	202.5	215.4	42.7	"
J-1	101,500	0	202.0	216.1	14.1	29 Jan 65
2	98,800	10.7	202.0	223.8	21.8	"
3	99,600	20.3	201.9	*	*	"
4	99,700	29.9	201.9	*	*	"

*Surface temperature not available due to equipment breakdown.

APPENDIX B

EXPERIMENTAL DATA

The data listed here are that taken from the magnified films of the bubbles on a frame by frame analysis. D_h, Z, D_b, and ϕ are taken directly from the bubble outline tracings, while V and $\bar{h}$ are calculated from the bubble outlines by means of a graphical summation technique. The bubble dimensions, D_h, Z, and D_b, listed here must be reduced by the magnification factor to obtain the actual bubble dimensions. The bubble volume, V, and center of mass, $\bar{h}$, are listed as the actual values.

D_h = maximum horizontal diameter of the bubble on magnified trace, mm

Z = vertical bubble dimension as taken from magnified trace, mm

D_b = bubble base diameter of attachment to heater surface as taken from magnified trace, mm

V = actual bubble volume in cm^3 times 1000

$\bar{h}$ = position of the center of mass of the bubble above the heater surface, cm

ϕ = contact angle between bubble surface and heater surface, degrees

θ = time from initial start of bubble formation, microseconds

(Zero time is taken as the frame immediately prior to the initial appearance of the bubble, thus the bubble actually initiated at some time during the time from frame zero to frame one. For the work reported here, this time error varied from 0 to approximately 150 microseconds.)

BUBBLE E-2-3

T_{sub} = 10.1°F   q/A = 72,000 Btu/hr ft²   Magnification = 22X

D_h	Z	D_b	V	$\overline{h}$	ϕ	θ
14.6	9	11	.109	.0182	50	230
22.7	14.5	17.2	.413	.0291	47	460
31	19.2	24.2	1.08	.0395	49	690
31	22.4	26.8	1.59	.0445	51	920
42.6	25.4	33.5	2.48	.0486	54	1150
46	28.7	34.4	3.26	.0554	51	1380
50.3	30.1	38	4.29	.0609	50	1610
52	32.8	40.2	5.01	.0664	56	1840
55	35.2	39.8	5.67	.0709	53	2070
58.6	36.7	45.5	6.70	.0714	58	2300
60.6	40.8	47.8	8.01	.0759	56	2759
64.2	43	48.6	9.73	.0854	55	3217
67	44.8	50	11.2	.0895	51	3675
70	48.2	51.4	12.6	.0936	48	4133
72.2	51	50.2	14.3	.103	50	4591
75	56.2	52	16.9	.113	47	5735
76.2	59.8	43	18.8	.134	40	6875
76.6	65.8	41.6	19.8	.151	70	8015
77	69.8	41	20.2	.160	75	9151
77.5	75	37.8	20.9	.187	78	10286
73.8	80	34.4	19.7	.207	84	11419
71.6	85	29.6	20.1	.227	85	12549
70	90	24	19.5	.248	88	13679
65.8	92.5	17.6	16.7	.257	86	14804
66.2	98	6.5	17.5	.274	88	15929
65	93.2		16.9	.280		16151
64.5	85		15.9	.284		16379
65	81.2		16.2	.292		17051
65.6	73		15.9	.307		18171
65	65.5		15.4	.327		19286
69	61		15.4	.344		20401
81.4	58		16.5	.369		22621
84.5	57		17.3	.420		24831
86.2	47		17.0	.463		27031
80.8	50		15.3	.515		29221
77	53		15.1	.580		31401
73	49		13.4	.654		33571
71	42		11.3	.710		35731
74	38		9.59	.780		37881
71	36.8		9.15	.840		40021
74	36		9.23	.961		44271

BUBBLE E-7-1

$T_{sub} = 0$ q/A = 70, 000 Btu/hr ft^2 Magnification = 26X

D_h	Z	D_b	V	$\overline{h}$	ϕ	θ
17.6	13.8	10	.140	.0246	43	182
27.2	20	21	.509	.0331	51	364
37.2	22.8	33	1.075	.0415	70	546
43	27.6	35	1.703	.0438	59	728
48.2	30	38	2.39	.0516	54	910
51	33.2	40.8	2.90	.0554	58	1092
54.8	34	43.2	3.73	.0542	54	1274
56	36	44.6	3.73	.0592	60	1456
57.8	40	47.8	4.68	.0665	54	1820
59.6	41	45	4.86	.0715	53	2184
63	45	45.2	5.80	.0758	47	2548
61	47.4	42	5.72	.0819	51	2912
64	48	40	6.22	.0888	60	3276
61.3	49	39.6	5.87	.0954	81	3640
61	53.4	36.2	5.94	.110	89	4368
59.6	58	32	6.17	.120	85	5096
60.6	61.4	26	6.43	.136	87	5824
60	66	26	6.68	.145	87	6552
58.6	69	19.6	6.45	.155	84	7280
54	74	16.2	5.65	.175	89	8008
53	77	12.8	5.41	.180	88	8736
51.8	80.6	10	5.37	.197	102	9464
53.4	85.4	12	5.69	.211	136	9828
49	75.4		4.95	.208		10010
50.8	70.4		5.31	.205		10192
53.8	63		5.40	.223		10920
56.4	57.2		5.83	.2296		11830
60.6	53.4		5.97	.247		12740
63	47.4		5.55	.279		14560
62.8	50.2		5.76	.321		16380
56	53.8		4.63	.369		18200
59	46		4.39	.435		20020
58	40		3.81	.492		21840
52	40		3.75	.553		23660
48.8	45		3.54	.615		25480
54	39.2		3.62	.697		27300
54	35.2		3.05	.756		29120
50	37		2.92	.815		30940
43	41.8		2.43	.884		32760

BUBBLE E-10-2

T_{sub} = 31.1°F q/A = 69,000 Btu/hr °F Magnification = 26X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
21	15	19	.239	.0242	76	154
30.5	20	28	.624	.0323	69	308
45	26.5	42.5	1.92	.0419	75	462
54.6	33	49.8	3.52	.0515	69	616
61	35.8	53	4.23	.0561	59	770
67	38.4	59.4	6.26	.0569	57	924
70	43	60	7.73	.0654	56	1078
76.3	45	67.8	9.37	.0673	62	1232
80.5	47.6	67.5	10.75	.0735	58	1540
86.2	52.2	74	13.42	.0831	52	1848
89	53	73.3	15.34	.0835	60	2156
92.5	57.3	74.5	16.44	.0935	60	2464
94.6	57	75	17.46	.0935	60	2772
92.6	57.8	75	16.79	.0961	64	3080
91.7	56.8	72.5	15.91	.0981	55	3388
90.8	58	73	16.09	.0996	60	3850
86.5	60	64	15.29	.1096	65	4620
82.5	59.7	60.4	12.25	.124	87	5390
72	60.3	55	9.90	.125	90	6160
66	68	41.6	8.36	.147	94	6930
60	74.7	21	5.88	.1904	90	7700
52	77.2	6	4.13	.2165	92	8316
49.8	59.5		3.19	.237		8470
50.3	51.8		3.04	.245		8624
44	38		2.07	.262		8932
41.4	32		1.56	.289		9240
26	18.2		.372	.332		10010
7.8	5.4		.012	.358		19626

BUBBLE E-11-1

T_{sub} = 10.1°F   q/A = 69,700 Btu/hr ft^2 Magnification = 26X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
18.6	12.4	14	.146	.0404	55	160
38.3	22	32.5	1.064	.0500	59	320
54.5	29	51	2.829	.0573	65	480
65.5	37	62	5.18	.0592	70	640
71.4	39	69	6.95	.0596	71	800
79.5	43	77	9.06	.0642	79	960
85.5	46.1	82	10.97	.0665	77	1120
88.6	48	83	12.51	.0715	75	1280
90	49.8	80	12.76	.0746	62	1440
97	53	87	15.45	.0804	66	1600
99.8	56.5	88.3	18.88	.0896	62	1920
104	59	95.4	21.13	.0908	71	2240
107.5	64	98	25.68	.1019	69	2560
112	63	103	26.66	.1003	70	2880
113.8	64.5	97.8	27.9	.1027	62	3200
115.5	71.6	99	32.8	.120	61	4000
120	72.9	88	34.96	.126	49	4800
118	75.3	86	35.07	.130	47	5600
119.6	81	81	37.85	.1446	51	6400
116.4	82	82.2	35.16	.1465	82	7200
112.2	85.7	77	32.64	.1596	92	8000
111.9	85.5	73.3	32.58	.1704	90	8800
108	90	69.3	30.9	.188	91	9600
103.8	96	60	29.86	.2131	89	10400
101	99.3	50.5	27.79	.229	90	11200
101.5	104.8	38.5	27.6	.2496	90	12000
98.5	110	25	24.1	.279	90	12800
101	118	15.5	24.23	.307	90	13600
93.6	119	8	20.26	.324	90	13920
97	107		21.62	.325		14080
96	98		22.89	.329		14240
98.5	95		22.15	.341		14400
95	78		19.6	.364		15200
90.5	69		17.21	.393		16000
94.5	65.3		18.74	.412		16800
87	59.5		14.74	.476		17600
83.6	57		11.62	.472		18400

BUBBLE E-11-1 (Cont.)

T_{sub} = 10.1°F   q/A = 69,700 Btu/hr ft^2 Magnification = 26X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
81.7	52.7		10.63	.495		19200
66.5	43		5.53	.548		20800
44	36		2.51	.596		22400
36	46		1.31	.611		24000
43	43.5		2.35	.694		25600
22	23		.313	.728		27200
26	19		.380	.755		28800
15	10.5		.048	.771		30400
8	6.8		.0122	.782		32000

BUBBLE E-11-2

T_{sub} = 10.1°F q/A = 69,700 Btu/hr ft^2 Magnification = 26X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
16	9	12.3	.079	.0169	57	151
31	18	27	.615	.0300	63	302
36.2	21	34	.989	.0323	75	453
42.3	26.5	38.7	1.47	.0388	73	604
46	27	42.3	1.85	.0404	74	755
49	30	45	2.59	.0481	67	906
52.8	32.7	48	3.21	.0511	72	1057
56.9	35.1	50.2	3.75	.0542	68	1208
57.8	35.4	53.1	4.04	.0546	69	1359
58.9	37.5	54.6	4.14	.0646	81	1510
60.5	37	54.7	4.60	.0592	80	1661
62.9	38.2	56.6	4.95	.0611	87	1812
64	40.2	56	5.44	.0654	78	2114
63.5	43.5	55.7	6.06	.0727	88	2416
64.5	46.8	54.9	6.43	.0800	83	2718
63.3	45	52	6.12	.0796	83	3020
60	49.5	49	5.78	.0915	105	3775
58.5	54	45	5.83	.116	120	4530
56	57.8	30.8	5.40	.1185	89	5285
60	57.8	31.2	5.68	.125	94	6040
56	64	24	5.16	.145	90	6795
54	70.3	16	4.62	.167	88	7550
50.9	73	12.8	3.96	.186	108	8305
53.5	72.4	8	3.86	.189	94	8456
49	65.3		3.74	.200		8607
48.2	57.8		3.42	.204		8758
47.1	53		3.21	.211		9060
41	44.7		2.56	.226		9815
42.5	44		2.00	.222		10570
42.7	39.6		1.71	.250		11325
49.3	31		1.93	.278		12080
51.5	22.7		1.95	.313		12835
42.8	22.4		1.27	.336		13590
27.2	27.2		.462	.381		14345
15	18		.127	.421		15100
15.4	14.2		.028	.446		15855
9.8	9.6		.008	.490		16610
7	6		.0037	.489		17365
5.8	4.2		.0006	.505		18120
3.8	3					

BUBBLE E-12-10

T_{sub} = 20.0°F q/A = 69,800 Btu/hr ft^2 Magnification = 26X

D_h	Z	D_b	$\bar{h}$	V	ϕ	θ
15.5	10.8	11.7	.0194	.103	57	149
32.9	19.3	32	.0284	.692	82	298
44.3	24.6	42	.0371	1.67	78	447
50.8	28.5	50.5	.0415	2.56	86	596
55.6	31.1	55	.0453	3.18	87	745
60.3	33.5	58	.0491	4.22	79	894
63.1	34.6	58	.0526	4.76	70	1043
66	37	58	.0557	5.23	60	1192
68.3	40.8	59	.0617	6.02	63	1341
70.5	40.7	59.7	.0656	7.08	60	1490
74.4	43.6	63	.0703	8.28	59	1788
76.2	46.2	65.5	.0757	9.54	66	2086
79.5	47.2	64.2	.0787	9.90	57	2384
80	51.1	65	.0839	11.16	65	2682
81	51.5	64	.0862	11.40	57	2980
73.5	54	55.8	.0937	10.21	64	3725
66.7	55.7	52	.1080	8.50	91	4470
62.5	60.6	45.4	.1268	7.87	92	5210
57.4	64.7	35.5	.1458	6.33	87	5960
51.1	70.6	21.7	.1768	4.86	84	6705
42	75.8	10	.2075	3.26	89	7450
40.5	72.2		.2215	2.75		7599
38.9	59.3		.2285	2.45		7748
40	54.0		.2275	2.81		7897
32.2	44.0		.243	1.43		8195
26.2	27.2		.282	.612		8940
20	14.5		.306	.190		9685
9.5	9		.325	.0217		10430

BUBBLE E-12-8

T_{sub} = 20.0°F q/A = 69,800 Btu/hr ft^2 Magnification = 26X

D_h	Z	D_b	$\bar{h}$	V	ϕ	θ
27.9	18	22.5	.0292	.467	62	153
45	23.3	41.6	.0350	1.50	70	306
53.3	27.7	48.9	.0396	2.50	61	459
60	32.3	55	.0480	3.87	67	612
66.9	36.2	60.8	.0515	5.33	55	765
69	36.7	61.2	.0558	5.49	54	918
74.8	41.6	69	.0604	7.48	64	1071
77.5	44.8	69	.0700	9.53	63	1224
78.7	46	69	.0696	10.2	63	1377
82	48.5	71	.0742	10.9	60	1530
86.5	50.6	70	.0804	12.8	53	1836
91.3	52.5	74.5	.0850	14.4	54	2142
93.2	54	75.5	.0881	15.8	51	2448
92.5	56.8	74	.0927	15.8	54	2754
94	57.2	74	.0969	17.3	54	3060
88	57	65.5	.1000	15.1	56	3825
81.5	62	63	.116	14.1	86	4590
78.8	63.4	58	.125	12.1	87	5355
73.4	68.6	52.7	.145	11.0	90	6120
62.3	73	42.5	.162	9.78	91	6885
61.8	76.4	31.2	.190	7.25	98	7650
58.7	82	17	.229	5.56	91	8415
54.8	86.8	12.6	.245	5.01	96	8721
52.8	86.7	13	.245	5.12	105	8874
51.8	78.6		.257	4.40		9027
49.7	71.5		.277	4.40		9180
42	48.5		.305	2.49		9945
32	34.2		.336	1.51		10710
33	21		.355	.679		11475
15.8	12.3		.393	.081		12240

BUBBLE E-13-3

T_{sub} = 30.0°F   q/A = 69,500 Btu/hr ft^2 Magnification = 26X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
31.5	17.9	28.5	.608	.0261	62	162
44.7	25	40.2	1.73	.0396	65	324
51.3	27	47	2.36	.0408	61	486
60	30.6	56.6	3.80	.0504	71	648
62.8	34.5	57	4.37	.0511	71	810
64.9	36.9	58	5.19	.0561	70	972
67	39.5	60	6.04	.0642	68	1296
71	42.7	62.1	7.46	.0704	64	1620
73.3	46.2	59.5	8.31	.0761	56	1944
70.6	45	57.7	7.63	.0781	61	2268
67.5	46.4	55.7	7.37	.0796	68	2592
64.5	45.7	52.1	6.45	.0877	86	2916
59.5	47	48.7	5.62	.0896	87	3240
57.5	48.5	46.3	5.14	.0969	90	3564
52.7	51.6	40.9	4.73	.103	90	3888
49.5	54.5	36	4.07	.111	88	4212
47	54.5	29	3.15	.127	88	4536
42.7	59	22.2	2.51	.150	88	4860
40.5	62.5	19	1.92	.167	125	5184
37	63	10	1.47	.180	106	5346
33.2	45		1.01	.192		5508
30.1	32.3		.882	.211		5670
24.9	22.9		.424	.225		5832
21.4	18.5		.254	.241		5994
18.2	10		.099	.250		6156
6.9	4.9		.00728	.258		6318

BUBBLE F-2-2

T_{sub} = 10.0°F q/A = 48,000 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
16.6	10	13	.0733	.0154	47	129
27.2	15	22	.3021	.0261	55	258
33	18	27	.546	.0289	57	387
39	20	33	.886	.0307	52	516
43	22	35	1.11	.0329	50	645
45	26	38	1.44	.0386	48	774
49	27	40	1.82	.0418	45	903
52	28	43	2.10	.0425	52	1032
53	31	43.5	2.43	.0479	51	1290
58	35	45	3.23	.055	46	1548
61.3	37	51.7	3.87	.0561	57	1806
65	39	52	4.38	.0586	51	2064
64	43	47.7	4.78	.0679	52	2322
66	43	51	5.15	.0671	53	2580
68	47	50	5.85	.0743	50	3225
64	50	46	5.34	.0861	79	3870
61	52	40.4	4.80	.0932	82	4515
59	54	37	4.54	.103	81	5160
54.4	57	32	4.03	.112	82	5805
55	61	27.3	4.14	.126	81	6450
49.2	63	22	3.32	.137	89	7095
43	68	19	2.79	.148	89	7740
37.5	74	13.7	2.25	.158	89	8385
38	77	3.5	2.13	.174	90	8772
37	73		2.03	.180		8901
36	65		1.88	.177		9030
34	52		1.41	.189		9675
36	35		1.26	.213		10320
42	28		1.43	.214		10965
47	27.5		1.38	.219		11610
45	28.5		1.49	.225		12255
30	33		.881	.231		12900
19	37		.31	.257		13545
23	21		.28	.274		14190
25	21					14835
15	19		.099	.290		15480
16	11		.062	.281		16125
7	6		.000	.274		16770
5	4		.000	.270		17415

BUBBLE F-3-2

T_{sub} = 20.1°F q/A = 48,200 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
23.6	13.6	17	.207	.0218	45	128
35	19	28	.641	.0286	46	257
42.6	22.4	35	1.10	.0328	46	385
46	23.8	39.5	1.51	.0378	50	514
53	25.8	45	1.88	.0357	56	642
56	29	47	2.42	.0421	52	771
58	31	49.5	2.85	.0453	53	899
64	31	56	3.48	.0446	50	1028
65.6	34.8	54	4.05	.0518	49	1285
68	39.4	56.5	5.05	-.0581	47	1542
73	42.5	57.6	6.09	.0636	44	1799
73	43	57	6.51	.0678	47	2056
75	45.2	59.5	6.99	.0696	50	2313
76	49	56.6	7.61	.0771	47	2570
77.4	52	53.8	8.47	.0871	48	3212
73	55	50.6	7.88	.0914	55	3855
69.2	56.2	50	7.22	.0957	71	4497
61	58	47.8	6.62	.100	76	5140
63	61	42.6	6.10	.115	88	5782
61	63.4	35.6	5.29	.127	88	6425
56.8	68.8	24	4.62	.152	88	7067
52.6	72.8	13.4	3.36	.170	96	7710
52	75.6	6	2.98	.190	95	8095
57	67		2.86	.191		8224
48	61		2.68	.199		8352
43.6	46		1.73	.234		8995
33	34.8		.953	.251		9637
25	25.6		.463	.263		10280
22	22		.281	.278		10922
23.6	18.4		.229	.292		11565
12.6	14		.053	.305		12207
8	7.4		.0135	.320		12850
3.6	3.4		.00046	.352		13107

BUBBLE F-4-1

T_{sub} = 30.0°F   q/A = 49,600 Btu/hr ft²   Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
12.8	13	10.6	.240	.0204	49	143
25.2	24	22.2	1.63	.0339	48	286
30.2	29	28.2	2.83	.0400	65	429
33.6	34	32.6	4.23	.0468	77	572
37.6	36	35.6	5.25	.0482	65	715
40	42	36.8	7.08	.0582	64	858
42	44	37.4	8.10	.0607	58	1001
43.6	45	39.4	9.14	.0632	61	1144
46.6	49	41	11.3	.0696	58	1430
47.8	51	42	12.6	.0732	57	1716
49.4	52	42.2	13.6	.0757	58	2002
50.2	53	42.4	14.3	.0779	54	2288
50.4	56	41	15.6	.0864	53	2574
51	59	40.4	15.6	.0907	52	2860
49.4	60	38	15.8	.0946	54	3575
48.4	59	37.2	14.6	.0982	79	4290
46	60	35.6	13.4	.107	86	5005
42	61	31.6	11.4	.117	89	5720
38.2	66	26.4	9.44	.128	85	6435
34.4	72	19.2	7.24	.156	88	7150
30.6	77	11.4	4.74	.191	86	7865
29.6	83	2	3.87	.229	90	8580
29.2	35.4		3.45	.230		8723
27.6	29.6		3.04	.240		8866
26.2	20		2.56	.265		9295
21.4	10.6		.94	.314		10010
			~ 000	.348		10725

BUBBLE F-4-4

T_{sub} = 30.0°F   q/A = 49,600 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
20.2	11.6	15	.128	.0189	49	128
39.5	20	33	.851	.0303	53	256
54	27.2	48	2.09	.0378	56	384
64	30	58	3.22	.0407	54	512
71.6	32.3	64.5	4.30	.0436	56	640
78	38	68.6	6.22	.0543	50	768
79	40.6	76.2	6.73	.0543	73	896
82.2	41.8	77.8	7.27	.0553	72	1024
87.8	46	81	9.25	.0661	69	1280
94.6	48.8	83.5	11.36	.0678	57	1536
97.4	51.8	82.8	13.16	.0746	53	1792
100	51.2	86	13.89	.0753	53	2048
102	52.8	86	14.77	.0771	53	2404
103	57	84.6	16.43	.0864	53	2560
104	58.2	83.2	16.97	.0886	53	3200
100	61	78	16.58	.0964	55	3840
97.6	62.2	74	15.75	.1021	63	4480
92.6	62.8	72	14.0	.1096	86	5120
86.8	61.2	68.2	12.3	.1146	88	5760
79.6	65.8	58.4	10.47	.126	89	6400
74.6	69.6	47	8.64	.145	89	7040
69.6	73.4	35	5.20	.151	89	7680
64.2	79.4	17.6	4.95	.203	87	8320
61	83	7.2	3.78	.229	89	8832
60	80.9		3.81	.232		8960
59	69		3.73	.242		9088
53.2	39.4		2.67	.266		9600
44.6	25.4		1.20	.306		10240
24	12.8		.182	.336		10880
6	5		.004	.328		11520

BUBBLE F-5-1

T_{sub} = 0.1°F q/A = 49,000 Btu/hr ft² Magnification = 26X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
16	9	14	.088	.0138	73	170
25.6	13.8	21.8	.285	.0188	72	340
26.8	17.2	24	.429	.0262	67	510
30.8	18	26.5	.602	.0288	59	680
36	21	32.5	.901	.0312	60	850
38.8	23	30.5	1.17	.0377	55	1020
42.4	25	36	1.55	.0392	60	1190
44	26.5	39	1.74	.0408	58	1360
46.8	29.7	35	2.23	.0515	51	1530
48.4	31	34	2.40	.0523	43	1700
49.6	33	34.5	2.73	.0573	46	2040
51.2	35.5	38	3.23	.0604	51	2380
56	39	37	4.05	.0677	45	2720
52.8	42	38	4.02	.0715	47	3060
55.6	44	36	4.46	.0785	50	3400
56.4	50	32	4.99	.0938	54	4245
57.2	55	33	5.44	.103	58	5090
56	59	29	5.85	.121	59	5935
56.8	62	24	5.99	.133	59	6780
55.2	68	23	6.09	.145	61	7625
52	74	19	5.75	.159	60	8465
52	76	19.5	5.93	.163	62	9305
50.8	77	16.3	5.78	.167	62	10145
50	82	14.5	5.49	.177	62	10985
52.4	83	13	6.35	.185	71	11825
54.8	82	8	6.39	.186	73	12665
50.4	80	6	5.18	.182	78	12999
54	75		6.24	.182		13166
55.2	70		6.11	.199		13333
55.2	70		6.29	.183		13500
58.8	63		6.73	.187		14335
58.8	58		6.40	.190		15170
64.4	55		6.99	.197		16835
63.6	55		6.97	.227		18495
60	61		6.58	.244		20155
59.2	64		6.92	.288		21795

BUBBLE F-5-3

T_{sub} = 0.1°F   q/A = 49,000 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
24.8	14.6	20.5	.243	.0214	48	126
28	16.2	24	.337	.0228	53	252
36	19	31	.664	.0278	57	378
40	21.6	34	.917	.0311	55	504
41	24	36	1.09	.0343	53	630
45.6	26.2	36.5	1.48	.0386	46	756
49	26	41	1.66	.0375	52	882
48.3	27.4	39.4	1.77	.0418	44	1008
53	30	44	2.51	.0493	50	1260
55.6	33.3	45	2.72	.0500	53	1512
55.8	36.2	45.5	3.27	.0578	52	1764
57.8	39	44.5	3.52	.0611	52	2016
60	40	46.8	3.82	.0614	51	2268
60.8	40.5	47.5	4.10	.0639	55	2520
62	46	40.6	4.53	.0750	49	3150
57.6	53	37	4.33	.0918	86	3780
58	56.6	34.2	4.58	.1014	85	4410
56.6	60	33.5	4.60	.110	86	5040
55	64.2	29.6	4.58	.124	86	5670
52.6	69	27.2	4.57	.134	85	6300
52.4	71.8	23.6	4.57	.144	76	6930
52.2	78	23.6	4.80	.158	84	7560
52	82.4	20.2	4.88	.166	83	8190
51	84	14.4	4.63	.168	85	8820
52.2	86	9.6	4.81	.174	99	9450
54	83.6		5.2	.182		9576
53	81		5.14	.192		9702
54	73.2		4.85	.193		10080
58.8	68.8		5.62	.202		10710
59	63		5.52	.205		11340
60.5	60		5.74	.212		11970
66	60.5		6.36	.219		12600
69	55.4		6.23	.232		13230
63	57.5		5.13	.243		13860
63.6	54		5.45	.252		14490
63	53.5		5.11	.259		15120
59	57		4.70	.273		15750
56	59.6		4.69	.271		16380
55.4	61.4		5.00	.297		17640

BUBBLE F-6-1

T_{sub} = 10.1 °F   q/A = 49,000 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
10.2	8	6.4	.023	.0143	46	133
22	14.2	21.6	.284	.0214	44	266
35.2	17.8	30.2	.591	.0250	47	399
41.8	20.4	35	.912	.0289	55	532
46	23	39	1.24	.0321	46	665
50	26	44.2	1.75	.0371	58	798
52.8	27.4	45	1.99	.0389	48	931
57	28.8	47.4	2.43	.0414	50	1064
60	32	51	3.16	.0478	51	1330
64.6	36.2	55	4.09	.0528	52	1596
68	38.6	56.2	4.85	.0593	60	1862
70	41.6	55.8	5.62	.0664	58	2128
71.8	44	57.6	6.23	.0686	58	2394
73	46	56	6.68	.0736	47	2660
72.6	49.2	50	6.74	.0828	58	3325
68.4	51.2	49.4	6.42	.0864	62	3990
65.4	54.8	45.8	6.17	.0982	81	4655
64	58.8	44	5.90	.109	86	5320
60	62.4	38	5.45	.120	87	5985
59.8	67	31	4.91	.144	88	6650
55	69.8	27	4.24	.159	87	7315
47.4	73.8	22.2	3.72	.165	87	7980
43	80	15.8	3.05	.180	89	8645
39.6	83	6	2.47	.189	92	9044
40	72.6		2.66	.189		9177
40	69		2.52	.191		9310
39.8	65.4		2.41	.199		9443
39	59.4		2.25	.199		9709
38.6	57		2.26	.199		9975
39.4	44.4		1.94	.214		10640
47	37		1.70	.219		11305
47.2	28.8		1.53	.234		11970
42	27.8		1.24	.248		12635
27.6	36.6		.764	.268		13300
22	39		.447	.294		13965
22.8	22		.271	.311		14630
26.4	16.4		.278	.333		15295
11.4	12		.041	.360		15960
4.6	4.2		.003	.372		16625

BUBBLE F-7-1

T_{sub} = 20.1°F   q/A = 49,100 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
19	11	16	.103	.0154	55	129
33	17	28	.523	.0261	50	258
44	21	39	1.11	.0304	57	387
49	24	45	1.64	.0354	67	516
53	27	50	2.00	.0364	64	645
56	28	54	2.38	.0389	76	774
59.7	31	56	2.97	.0429	75	903
60	32	54	3.15	.0464	67	1032
63	34	60	3.61	.0461	71	1161
65	36	56	4.21	.053	60	1290
68	36	62	4.48	.0511	66	1548
69	39	57	5.09	.0604	60	1806
67.5	39	59	4.86	.0582	64	2064
63	42	53.5	4.72	.0661	70	2322
62	42	51	4.49	.069	71	2580
56	42	44	3.75	.076	82	3225
51.5	45	39	3.12	.084	90	3870
44.5	50	28.2	2.40	.105	85	4515
41	56	16	1.63	.133	89	5160
34.5	63	8.2	1.15	.156	89	5547
34	54.5		1.04	.160		5676
33	48		.955	.177		5805
24	24		.34	.216		6450
15	10		.06	.249		7095
5	3.6		.003	.277		7740

BUBBLE G-2-2

T_{sub} = 0.6°F   q/A = 101,900 Btu/hr ft^2 Magnification = 32X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
10.4	5	7	.015	.007	20	168
20	12	13	.09	.019	36	335
27.4	17	19	.21	.023	33	503
34	20	23	.37	.027	29	671
37	23	28	.57	.030	40	839
43.4	27	34	.87	.040	49	1006
50	30	40	1.35	.039	49	1174
58	31	45	1.83	.039	37	1342
57	35	44	1.94	.047	37	1510
61	37	47	2.52	.049	35	1678
65.4	40	51	2.81	.052	45	2013
69	42	53	3.44	.051	48	2348
70	46	50	3.78	.060	43	2684
75	49	51	4.87	.069	44	3019
76	51	56	5.26	.067	45	3355
78	53	59	5.75	.075	49	3690
79	56	58	5.80	.077	54	4026
79	58	56	8.14	.070	55	4361
83	61	54	7.04	.086	50	4697
83	63	52	7.03	.092	51	5032
85	67	54	7.69	.094	49	5871
83	72	49	8.10	.110	59	6710
79.6	77	46	7.75	.125	76	7549
77	80	43	8.63	.129	69	8387
74	85	39	8.60	.143	64	9226
72	90	34	8.09	.153	72	10065
70	94	34	8.83	.154	83	10904
68.6	98	33	8.96	.172	80	11742
69	100	28	8.88	.174	84	12581
71	103	24	7.34	.170	90	13420
73	104	20	9.59	.193	100	14259
75	108	13	9.50	.205	89	15097
79	109	4	10.50	.204	85	15600
77	104		10.00	.214		15768
77	97.6		8.09	.210		15936
80	88		9.04	.218		16775
80	83		8.32	.227		17614

BUBBLE G-2-2 (Cont.)

$T_{sub} = 0.6°F$ $q/A = 101,900$ Btu/hr ft^2 Magnification = 32X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
80	80		9.59	.240		18452
84	76		8.03	.248		20130
85	76		7.56	.266		21807
84	69		6.76	.292		23485
91	61		8.47	.316		25162
85	57		6.62	.355		26840
83	66		6.25	.417		28517
88.6	65		7.85	.444		30195
86	67		8.02	.485		31872
90	64		8.51	.502		33550
91	68		9.00	.599		35227
72	65		5.48	.699		41937

BUBBLE G-2-3

T_{sub} = 0.6°F q/A = 101,900 Btu/hr ft^2 Magnification = 32X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
21	10	18	.076	.013	54	164
26	14	22	.18	.019	50	330
34	20	28	.41	.026	46	490
38	23	28	.53	.031	45	655
45	26	36	.87	.033	45	820
47	29	38	1.22	.039	38	985
53	31	40	1.55	.043	42	1150
55	33	42	2.02	.042	51	1310
60	36	48	2.41	.048	56	1475
59	38	44	2.43	.054	41	1640
63	42	46	3.22	.059	47	1970
69	43	50	3.54	.057	47	2295
71	48	50	4.17	.069	48	2625
74	49	52	4.86	.069	48	2950
74	52	52	5.13	.074	37	3280
76	57	54	5.89	.083	54	4100
74	62	46	6.08	.095	64	4920
76	68	44	6.47	.103	78	5740
76	73	44	6.54	.116	83	6560
76	78	40	6.97	.129	85	7380
70	81	36	5.97	.139	83	8200
70	85	32	6.25	.156	86	9020
68	88	30	6.13	.172	83	9840
64	95	28	6.17	.172	85	10660
62	95	24	5.74	.168	81	11480
64	100	24	6.42	.183	88	12300
66	101	22	6.93	.185	84	13120
68	103	18	6.89	.191	85	13940
70	104	12	6.44	.190	86	14760
68	101	6	5.95	.189	88	15415
70	97		6.28	.186		15580
74	86		6.88	.192		16400
68	81		6.13	.204		17220
72	76		6.77	.209		18040
76	79		6.17	.220		18860
82	62		5.12	.241		19680

BUBBLE G-3-4

T_{sub} = 9.6°F　　q/A = 102,900 Btu/hr ft^2　　Magnification = 30X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
28.2	16.4	20	.280	.0173	43	163.8
41.8	21.6	35.5	.804	.0283	48	327.6
46	25.3	37	1.164	.035	48	491.4
53	30	42.8	1.835	.0413	49	655.2
59.2	33.4	47.5	2.54	.0460	46	819.0
62	35	49	2.87	.0486	48	982.8
69.6	38	53	3.818	.052	45	1146.6
70	39	55.5	4.10	.0533	49	1310
73.7	41	58.5	4.79	.0566	43	1474
77.7	45.8	60.5	5.78	.0623	49	1638
81.3	47	66	6.82	.0653	43	1966
85	51.8	69	8.18	.0720	48	2293
90	56.5	70.5	9.93	.0806	48	2621
91.5	58.8	72	10.90	.084	53	2948
94.3	60.5	74.5	12.02	.088	51	3276
96	65	70	13.05	.097	52	4095
96.5	71	66.5	14.34	.108	53	4914
92.5	75	62	13.55	.116	53	5933
88	80	54.5	12.6	.132	49	6552
84.8	82	51	11.18	.142	55	7371
83.2	85.5	43.6	10.64	.164	77	8190
78.5	91	35	9.51	.180	84	9009
76.2	94.5	29	9.01	.194	87	9828
72.1	102.5	21.3	8.66	.215	85	10647
69	105.7	7.5	7.76	.232	85	11466
70	109	3	7.86	.241	84	11630
68.8	96		7.74	.237	88	11794
67	84		7.10	.258	88	12285
65	74		6.28	.280		13104
59	66.2		4.97	.302		13923
56.8	59		4.10	.320		14742
58.5	49.5		3.32	.347		15561
57	46		2.57	.366		16380
51.4	41		2.06	.391		17199
47	36.5		1.53	.412		18018
36	31.5		.80	.430		18837
33	33		.705	.466		19656

BUBBLE G-3-4 (Cont.)

T_{sub} = 9.6°F   q/A = 192,900 Btu/hr ft²   Magnification = 30X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
36	30		.729	.504		20475
34	20		.44	.548		21294
13	14		.09	.573		22113
12.5	10		.03	.594		22932
7.8	7		.008	.597		23751
2	2		≅ gone			24079

BUBBLE G-4-4

T_{sub} = 20.6°F q/A = 103,300 Btu/hr ft^2 Magnification = 31X

D_h	Z	D_b	$\bar{h}$	V	ϕ	θ
19.5	10	15	.014	.067	33	167
37	18	32	.022	.45	29	333
47	24	40	.030	.95	35	500
55.5	31	49	.038	1.87	51	667
59	31	52	.039	2.02	54	833
64	34	57	.041	2.62	55	1000
69	38	60	.048	3.57	57	1167
70.5	39	60	.051	3.90	47	1333
73.5	41	60	.055	4.26	48	1500
77.5	46	62	.061	5.36	49	1667
79	47	63	.067	6.17	49	2000
81	49	65	.067	6.39	52	2333
82	49	69	.066	6.29	58	2667
79	52	62	.072	6.55	51	3000
78	54	60	.075	6.67	50	3333
72	55	56	.085	5.82	72	4167
66	58	48	.096	4.82	80	5000
61	61	39	.116	4.29	82	5833
56	71	28	.144	3.66	84	6667
53	80	16	.174	3.40	82	7500
45	86	9	.189	2.52	90	8167
43	68		.190	2.06		8333
31	45		.222	.85		9167
33	33		.235	.55		10000
34	23		.273	.43		10833
19	16		.273	.10		11667
9	7		.276	.011		12500

BUBBLE G-5-2

T_{sub} = 28.9°F   q/A = 100,800 Btu/hr ft^2 Magnification = 30X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
25	9.6	23.5	.142	.0133	66	165
41.6	19	38.4	.709	.0276	61	330
49.6	24	42.5	1.28	.0313	47	495
56	26.2	53	1.79	.0357	56	660
60.4	29	54	2.33	.0380	52	825
65.2	32.4	57	2.96	.0423	50	990
65	33.2	57.4	3.13	.0443	50	1155
56	36	56.4	3.41	.047	44	1320
70	37.2	58.5	3.96	.0503	42	1485
72.2	38.4	59	4.33	.053	47	1650
70	38	56.5	4.16	.0543	45	1980
62	37.5	50	3.29	.0563	60	2310
56.8	39.5	42.8	2.70	.0646	84	2640
54	41.3	41.8	2.53	.070	87	2970
49	42	35	2.05	.0753	84	3300
41	45	26	1.46	.0846	85	3630
39	46.4	18.8	1.11	.101	84	3960
32	47	7.6	.654	.110	89	4290
28	51	3.8	.497	.123	90	4455
27.8	28		.373	.135		4620
19	15		.116	.156		4950
8	6		.008	.184		5280

BUBBLE G-7-1

T_{sub} = 10.3°F   q/A = 100,100 Btu/hr ft^2 Magnification = 30X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
20	13.5	15.5	.126	.0167	53	162
27	17.5	21	.282	.0260	54	324
35.5	20	32	.567	.0273	61	486
41	24	34.5	.916	.0343	57	648
45.8	27.4	38	1.25	.0373	53	810
52	28	45.5	1.71	.0380	47	972
53.4	29.6	46.2	1.86	.0407	54	1134
57.4	32	50	2.23	.0417	57	1296
59	33.6	53	2.56	.0443	55	1458
61	35.8	53.8	2.90	.0470	56	1620
63	38.8	53.4	3.45	.0547	61	1944
63.6	40	54	3.66	.0570	57	2268
59.6	42.5	48.5	3.41	.0627	64	2592
59.6	43.3	44	3.37	.0657	57	2916
59	44.8	39.5	3.38	.0703	50	3240
53.3	48.2	32	2.71	.0837	75	4050
46.6	44.5	25.2	2.27	.102	77	4860
37	62.6	21	1.77	.119	83	5670
33	68	15	1.28	.125	88	6480
33	69	3.5	1.11	.141	82	6966
32.4	59.2		1.06	.141		7128
33.2	54		1.12	.144		7290
38	34.6		1.07	.155		8100
41.8	26		.746	.157		8910
29.3	27		.399	.171		9720
15	30		.160	.184		10530
12.8	12		.042	.200		11340
4	4		.0018	.200		12150

BUBBLE G-8-1

T_{sub} = 20.3°F q/A = 100,100 Btu/hr ft^2 Magnification = 32X

D_h	Z	D_b	$\bar{h}$	V	ϕ	θ
30	21	28	.023	.30	67	185
52	32	48	.033	1.32	55	370
70	41	66	.038	2.80	50	550
80	48	72	.046	4.36	50	735
92	49	86	.051	6.32	53	920
96	51	90	.055	7.47	67	1105
102	53	94	.058	9.07	67	1290
104	54	96	.059	9.11	54	1470
110	56	104	.064	11.50	69	1655
112	58	102	.068	12.75	57	1840
116	61	110	.073	14.95	68	2210
120	62	108	.077	15.92	61	2575
118	62	102	.080	16.28	45	2945
120	61	100	.082	16.52	38	3315
118	60	98	.084	16.15	42	3680
118	63	92	.090	16.21	49	4600
106	64	82	.093	12.83	78	5520
92	66	78	.095	11.06	80	6440
96	70	70	.120	10.92	85	7360
86	79	56	.139	8.50	86	8280
74	87	36	.163	6.33	86	9200
72	94	21	.202	5.40	86	10125
68	95	4	.216	4.15	86	10675
70	90		.225	4.15		10860
64	68		.238	3.22		11045
58	43		.272	2.73		11960
50	31		.319	1.14		12885
22	23		.348	.17		13805
8	7		.354	.008		14725

BUBBLE G-9-2

T_{sub} = 30.3°F q/A = 100,100 Btu/hr ft^2 Magnification = 30X

D_h	Z	D_b	$\bar{h}$	V	ϕ	θ
31	15	27	.019	.304	54	165
45	22	31	.027	.902	57	330
54	27	48	.034	1.53	54	490
57	28	51	.037	1.98	56	655
60	30	55	.037	2.25	63	820
63	34	63	.045	2.88	52	985
66	34	56	.046	3.16	53	1150
68	36	55	.051	3.44	52	1310
70	35	57	.050	3.80	48	1475
67	36	55	.049	3.31	45	1640
66	38	54	.051	3.40	69	1970
63	38	50	.055	3.12	65	2295
60	38	50	.065	2.90	83	2625
55	40	43	.065	2.81	81	2950
50	41	40	.071	2.29	84	3280
43	42	34	.074	1.61	88	3610
39	47	24	.097	1.18	88	4100
31	51	8	.125	.48	87	4590
28	52	2	.135	.34	87	4755
24	27		.151	.25		4920
19	17		.161	.12		5085
12	7		.177	.019		5250

BUBBLE H-2-1

T_{sub} = 10.0°F   q/A = 49,600 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	$\bar{h}$	V	ϕ	θ
16	9	14	.012	.057	60	150
22	12	20	.016	.152	65	310
25	14	23	.021	.226	59	470
30	16	28	.023	.405	62	620
31	18	30	.028	.496	66	780
33	20	30	.028	.571	65	940
34	23	31	.031	.763	68	1090
37	25	34	.033	.904	63	1250
35	28	28	.043	.938	57	1400
35	29	26	.042	.909	64	1560
33	27	25	.041	.776	86	1720
32	29	24	.046	.643	85	1870
30	30	22	.051	.659	89	2030
28	29	21	.049	.595	81	2180
25	30	18	.048	.432	87	2340
23	30	15	.054	.442	87	2500
25	31	5	.059	.422	79	2650
23	27		.058	.326		2810
23	25		.067	.295		2960
21	20		.074	.207		3120
24	19		.071	.274		3280
25	17		.073	.262		3430
22	15		.068	.185		3590
19	15		.065	.128		3740
19	12		.072	.109		3900
17	14		.072	.084		4060
13	11		.078	.038		4210
10	10		.086	.020		4370
8	8		.107	.011		4520
5	4		.114	.002		4680

BUBBLE H-4-4

T_{sub} = 29.8°F   q/A = 49,700 Btu/hr ft^2 Magnification = 29X

D_h	Z	D_b	$\bar{h}$	V	ϕ	θ
24	13	20	.014	.164	38	160
33	17	33	.023	.476	77	310
45	23	40	.030	1.007	54	470
48	25	47	.034	1.492	77	620
49	28	46	.037	1.557	64	780
51	29	47	.040	1.812	59	940
56	31	51	.040	2.126	56	1090
56	32	49	.044	2.297	59	1250
59	35	52	.048	2.985	52	1400
56	35	50	.046	2.408	54	1560
57	36	49	.049	2.570	56	1870
51	37	45	.052	2.222	63	2180
46	40	40	.058	2.008	90	2500
41	39	34	.061	1.628	87	2800
37	40	24	.066	1.295	88	3120
34	43	17	.078	1.034	86	3430
32	44	12	.083	.700	92	3590
31	42	7	.089	.597	91	3740
30	34		.103	.525		3900
25	21		.110	.293		4060
23	11		.113	.080		4210
16	9		.136	.053		4370
6	3		.132	.001		4520

BUBBLE H-7-1

T_{sub} = 19.5°F   q/A = 47,800 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	$\bar{h}$	V	ϕ	θ
24	13	20	.019	.204	42	160
31	18	27	.024	.449	62	320
32	18	29	.026	.533	68	480
37	21	33	.030	.839	55	640
38	23	32	.034	.873	44	800
41	23	36	.036	1.058	58	960
40	25	32	.035	1.164	53	1120
43	25	40	.043	1.096	57	1280
41	26	35	.036	1.373	52	1440
37	27	32	.040	1.030	58	1600
42	27	36	.041	1.312	63	1760
44	29	40	.043	1.563	64	1920
41	32	38	.046	1.662	78	2080
35	34	29	.054	1.206	89	2240
38	36	30	.061	1.239	89	2400
36	39	15	.073	.991	86	2560
39	40	6	.081	1.390	78	2720
36	36		.081	1.046		2880
35	35		.077	.974		3040
33	34		.077	.771		3200
36	34		.084	.924		3360
33	34		.080	.883		3520
32	35		.096	.862		3680
30	33		.091	.636		3840
32	32		.103	.805		4160
29	31		.103	.703		4480
29	29		.119	.680		4800
27	23		.121	.416		5120
24	18		.124	.250		5440
24	15		.134	.198		5760
17	11		.118	.065		6080
18	11		.132	.083		6400
8	5		.138	.007		6720
6	3		.175	.002		7200

BUBBLE I-8-1

T_{sub} = 19.9°F q/A = 69,500 Btu/hr ft^2 Magnification = 27X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
21	13	17	.18	.019	45	150
31	17	28	.43	.024	62	310
39	21	37	.96	.028	61	460
43	23	37	1.17	.033	50	610
46	24	40	1.49	.034	50	760
52	26	49	2.27	.038	63	920
54	27	51	2.48	.039	65	1070
53	29	45	2.50	.045	50	1220
53	32	43	2.82	.050	43	1380
54	30	48	2.65	.043	60	1530
52	31	44	2.61	.047	49	1680
51	32	38	2.36	.049	40	1840
53	31	37	2.49	.053	60	1990
51	33	37	2.40	.055	78	2140
47	32	30	1.95	.057	75	2300
47	33	27	2.22	.060	66	2450
45	33	25	1.80	.064	74	2600
42	33	21	1.65	.064	77	2750
42	34	21	1.71	.063	75	2910
40	35	19	1.15	.073	82	3060
38	35	19	1.19	.067	85	3210
37	36	16	1.22	.076	92	3370
37	38	14	1.03	.085	94	3520
36	40	13	.99	.090	108	3670
34	40	6	.87	.096	90	3830
32	33		.65	.1018		3980
29	26		.46	.1062		4130
24	20		.33	.1122		4280
23	18		.24	.1174		4440
19	14		.15	.1337		4590
17	10		.09	.1481		4740
12	10		.03	.1556		4900
11	9		.03	.1630		5050
8	5		.01	.1667		5200
4	3			.1667		5360
4	3			.1778		5510

BUBBLE I-11-1

T_{sub} = 10.3°F   q/A = 69,600 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
11	8	9	.024	.013	44	160
27	15	25	.269	.020	51	330
35	18	34	.537	.023	77	490
40	20	39	.830	.027	76	650
42	24	41	1.174	.034	80	820
45	24	44	1.246	.032	81	980
45	26	43	1.332	.035	85	1140
47	27	45	1.578	.038	81	1310
48	29	46	1.831	.039	70	1470
51	29	48	1.784	.039	75	1630
49	31	46	1.902	.046	79	1960
45	33	41	1.909	.052	80	2290
45	34	37	1.858	.055	75	2620
43	36	34	1.802	.061	80	2940
42	37	32	1.898	.061	78	3270
42	39	28	1.820	.061	68	3600
42	41	26	1.788	.067	80	3920
39	44	23	1.644	.073	79	4250
38	44	21	1.351	.084	82	4580
38	46	19	1.526	.089	85	4900
37	45	14	1.324	.089	78	5230
36	46	13	1.319	.099	82	5560
30	48	8	1.038	.105	81	5880
30	49	6	.970	.104	84	6050
28	44		.858	.097		6210
29	40		.703	.097		6540
30	36		.861	.102		6860
34	29		.950	.095		7350
35	28		.778	.096		8170
20	37		.458	.105		8990
19	29		.285	.100		9800
36	18		.602	.091		10620
18	30		.196	.104		11440
21	22		.268	.088		12260
18	20		.183	.081		13070

BUBBLE I-11-1 (Cont.)

T_{sub} = 10.3°F   q/A = 69,600 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
16	18		.090	.073		13890
8	13		.023	.068		14710
11	11		.026	.068		15530
11	10		.027	.064		16340
6	6			.050		17160
3	3			.050		17980
3	2			.046		18800

BUBBLE I-13-1

T_{sub} = 29.8°F q/A = 70,700 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
22	10	22	.114	.012	96	150
28	15	27	.296	.020	77	310
32	17	30	.444	.021	60	460
35	20	33	.632	.027	73	620
37	21	35	.766	.028	77	770
38	22	36	.867	.031	68	930
38	23	35	.793	.033	86	1080
38	23	34	.828	.032	88	1240
36	24	32	.870	.037	89	1390
34	24	31	.778	.035	88	1550
30	26	25	.682	.043	79	1850
29	28	22	.592	.047	84	2160
28	30	18	.569	.057	88	2470
25	33	9	.371	.069	86	2780
23	34	3	.355	.071	88	2940
20	26		.210	.074		3090
18	22		.183	.082		3240
17	18		.106	.085		3400
18	12		.084	.089		3710
15	12		.056	.102		4020
5	5		.002	.129		4330

BUBBLE J-2-1

T_{sub} = 10.7°F q/A = 98,800 Btu/hr ft^2 Magnification = 27X

D_h	Z	D_b	$\bar{h}$	V	ϕ	θ
11	6	10	.008	.02	72	150
22	13	19	.018	.20	59	300
27	16	20	.024	.39	48	450
31	17	28	.024	.57	64	600
34	20	32	.030	.73	72	750
37	19	35	.026	.82	64	900
39	21	35	.030	.91	64	1050
39	22	31	.035	1.09	60	1200
38	23	32	.035	1.03	65	1350
36	25	31	.043	1.22	82	1500
34	25	27	.043	.98	75	1650
34	27	23	.053	.93	84	1800
32	29	21	.056	.95	78	1950
32	29	19	.058	.81	84	2100
32	31	17	.060	.78	77	2250
29	30	13	.061	.64	83	2400
26	34	9	.070	.63	83	2550
25	34	7	.073	.52	58	2700
23	35	4	.078	.49	65	2850
23	31		.074	.45		3000
21	28		.078	.43		3150
22	21		.091	.26		3450
20	17		.096	.17		3750
14	15		.144	.08		4500
3	3		.170			5250

BUBBLE J-3-1

T_{sub} = 20.3°F   q/A = 99,600 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
21	6	21	.051	.006	110	165
38	15	35	.58	.021	68	330
46	20	44	.97	.026	65	495
53	23	50	1.56	.030	66	660
56	26	54	2.16	.034	64	830
57	28	54	2.43	.038	65	990
57	30	53	2.45	.039	54	1160
60	31	55	2.92	.044	55	1320
59	33	54	3.18	.047	60	1490
60	34	57	3.44	.048	70	1650
60	35	54	3.84	.054	67	1980
60	37	55	3.60	.058	72	2310
59	40	53	4.00	.063	75	2640
57	41	51	3.84	.061	76	2970
55	42	47	3.31	.061	63	3300
54	45	46	3.44	.065	68	3630
55	45	42	3.20	.064	60	3960
53	50	39	3.30	.080	63	4300
50	50	36	3.08	.083	62	4630
49	52	31	3.15	.081	66	4960
49	53	30	3.15	.088	76	5290
49	55	28	3.00	.102	77	5620
48	58	24	3.00	.106	83	5950
50	57	21	3.55	.108	88	6280
49	57	18	3.12	.114	90	6610
49	59	15	2.84	.124	89	6940
48	62	10	2.66	.133	85	7270
48	59	5	2.39	.130	72	7430
48	55		2.58	.134		7600
45	52		2.23	.136		7930
41	48		1.51	.121		8260
36	39		1.21	.138		9090
37	37		1.11	.134		9910
29	33		.68	.135		10740
30	37		.67	.150		11560
20	30		.24	.160		12390
20	16		.10	.173		13220
7	9					
3	2					

BUBBLE J-4-1

T_{sub} = 29.9°F q/A = 99,700 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	ϕ	θ
16	9	15	.06	.013	76	150
28	15	27	.30	.019	66	300
34	19	33	.52	.024	74	450
35	19	34	.58	.025	76	600
34	19	33	.65	.027	67	750
35	19	33	.60	.025	66	900
34	20	32	.62	.026	74	1050
33	21	29	.61	.033	80	1200
30	22	26	.51	.034	85	1350
29	23	23	.46	.037	87	1500
27	24	21	.47	.042	88	1650
25	25	19	.36	.041	90	1800
23	26	15	.34	.042	83	1950
21	28	10	.26	.055	72	2100
20	25		.20	.064		2250
18	19		.15	.066		2400
16	15		.11	.080		2550
12	10		.04	.086		2700
10	8		.02	.089		2850
5	4			.098		3000
3	3			.102		3150

BUBBLE E-10-03

$T_{sub} = 31.1°F$ $q/A = 69,000$ Btu/hr ft^2

$T_{sat} = 202.7°F$

θ μsec	V cm^3 × 10^3	$\bar{h}$ cm
167	0.02	0.013
333	0.058	0.021
500	0.068	0.021
666	0.126	0.027
832	0.116	0.027
1000	0.151	0.031
1165	0.135	0.031
1330	0.144	0.033
1665	0.114	0.032
2000	0.08	0.023
2330	0.094	0.021
2660	0.099	0.024
3000	0.117	0.028
3330	0.099	0.031
4160	0.093	0.023
4995	0.123	0.031
5830	0.104	0.026
6660	0.122	0.028
7490	0.134	0.037
8325	0.153	0.025
9102	0.164	0.035
9930	0.169	0.027
10760	0.226	0.024
11585	0.219	0.036
12410	0.128	0.027
13240	0.287	0.027
14070	0.273	0.036
14895	0.23	0.032
15720	0.218	0.023
16550	0.429	0.033
17270	0.336	0.048
18095	0.357	0.046
18920	0.21	0.021
19740	0.81	0.034
20560	0.641	0.049

BUBBLE E-10-03

$T_{sub} = 31.1°F$ $q/A = 69,000$ Btu/hr ft^2

$T_{sat} = 202.7°F$

θ μsec	V $cm^3 \times 10^3$	$\bar{h}$ cm
21385	0.526	0.053
22210	0.44	0.064
23030	0.264	0.056
23850	0.156	0.024
24675	0.918	0.033
25340	2.021	0.042
26160	2.469	0.057
26980	1.893	0.071
27795	1.847	0.089
28610	0.844	0.120
28940	0.64	0.132
29430	0.328	0.150
30250	0.132	0.176
31065	0.013	0.200
31880	0.003	0.226

BUBBLE F-2-01

T_{sub} = 10.0°F   q/A = 48,000 Btu/hr ft^2 Magnification = 30X

D_h	Z	D_b	V	$\bar{h}$	θ	φ
6	5	2	.0025	.008	170	24
9.5	8	7	.017	.012	680	28
12.5	12	9	.042	.019	1020	43
28	22	20	.35	.034	1700	38
40	30	30	1.02	.046	2540	49
46	39	67	1.71	.06	3390	30
47	41	31	2.01	.066	4210	61
47	43	27	2.11	.071	5050	57
45	48	13	1.87	.084	5900	75
41	51	21	1.66	.091	6690	75
39	54	22	1.52	.094	7530	72
38	53	23	1.28	.087	8360	72
42	44	22	1.49	.078	10035	82
47	36	27	1.5	.056	11640	39
54	39	35	2.09	.058	13300	45
58	45	35	3.16	.07	14870	47
56	52	34	3.05	.87	16520	69
49	59	31	2.75	.102	18070	84
42	65	28	2.19	.105	19710	80
44	57	28	2.15	.098	21250	80
52	47	30	2.41	.082	22890	75
53	38	37	2.13	.055	24370	44
62	40	47	3.18	.058	26000	49
66	48	47	4.2	.072	27500	54
66	53	41	4.51	.084	29110	50
61	62	41	4.84	.105	30590	76
55	72	36	4.40	.127	32200	83
44	80	31	3.58	.140	33650	78
44	74	30	3.0	.125	35250	82
56	60	27	3.14	.119	36680	82
58	53	26	2.9	.097	38280	83
55	44	33	2.67	.07	39690	48
60	37	46	2.8	.054	41270	35
65	42	46	3.86	.063	41870	46
67	44	51	3.91	.062	42660	55
70	53	47	5.14	.077	44240	52
68	59	43	5.75	.093	45600	58
65	67	41	5.7	.119	47170	81

BUBBLE F-2-01 (Cont.)

T_{sub} = 10.0°F   q/A = 48,000 Btu/hr ft^2 Magnification = 30X

D_h	Z	D_b	V	$\bar{h}$	θ	φ
59	74	36	4.81	.145	48510	82
48	86	30	3.14	.173	50080	87
44	86	26	3.15	.148	51480	85
53	78	20	3.92	.159	53040	86
58	74	15	3.76	.154	53560	88
62	72	6	3.63	.15	54180	88
61	64		3.73	.124	54340	
60	43		3.06	.127	55890	
53	48		2.87	.141	57160	
45	59		1.86	.123	58710	
47	61		2.68	.131	60060	
52	37		2.07	.154	61600	
44	39		1.34	.169	62730	
41	50		1.47	.168	64260	
45	48		1.77	.197	65570	
43	27		0.87	.228	67100	
30	37		0.59	.242	68240	
34	26		0.54	.302	69800	
19	13		0.08	.357	70970	
7.5	7		0.007	.396	72480	

BUBBLE F-3-01

T_{sub} = 20.1°F q/A = 48,200 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	θ^*	ϕ
9	8	4	0.035	0.015	0.42	45
18	11.5	14.5	0.2	0.018	2.1	51
14	18	7	0.16	0.032	4.2	45
18	11	13	0.17	0.018	6.3	33
29	17	23	0.71	0.025	8.4	43
26	24	16	0.83	0.04	10.5	39
24	30	16	0.9	0.051	12.6	51
22.5	30.5	15	0.78	0.051	14.7	61
27	23	18	0.87	0.04	16.8	56
31	20	21	0.99	0.033	18.9	33
35.5	20	29	1.3	0.031	21.0	47
39	27.5	29	2.16	0.044	23.1	41
35	32	23.5	1.8	0.054	25.2	56
31	37	20	1.74	0.067	27.3	70
27	39.5	18	1.41	0.068	29.4	71
26.5	35.5	17.5	1.18	0.06	31.5	70
30.5	27	21	1.21	0.051	33.6	90
36	23	28	1.55	0.037	35.7	36
39	25	33	1.98	0.038	37.8	62
43.5	27	36	2.5	0.04	39.9	49
41.5	31	34	2.71	0.047	42.0	56
38	36	29	2.58	0.059	44.1	65
33.5	40	23	2.13	0.076	46.2	78
32	45.5	22	2.19	0.081	48.3	80
27	45	21	1.67	0.077	50.4	87
27	36	22	1.48	0.063	52.5	80
34	28.5	22	1.46	0.055	54.6	80
39	25	30	1.91	0.04	56.7	57
43.5	25	37	2.35	0.037	58.8	53
48.5	29	40	3.37	0.045	60.9	54
49.5	30.5	41	3.87	0.048	63.0	58
47	35	37	3.98	0.058	65.1	69
41.5	40.5	32	3.57	0.051	67.2	72
38.5	45	25.5	2.99	0.088	69.3	84
35.5	51	25	2.96	0.095	71.4	88
33	57	22	2.78	0.104	73.5	86
26	54	20.5	1.94	0.098	75.6	91
30	45	20	1.84	0.093	77.7	88

BUBBLE F-3-01 (Cont.)

T_{sub} = 20.1°F   q/A = 48,2000 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	θ^*	ϕ
34	39	19	1.76	0.086	79.8	88
38.5	32.5	20.5	1.96	0.068	81.9	85
42	27.5	30	2.46	0.047	84.0	62
43	23.5	37	2.27	0.037	86.1	56
52.5	26.5	44	3.76	0.045	88.2	50
56.5	33	49	5.44	0.049	90.3	48
58	38	48	6.58	0.06	92.4	55
56	42	42	6.14	0.074	94.5	50
52.5	47	39	5.79	0.078	96.6	78
52.5	52	30	6.37	0.095	98.7	69
50	54	31	5.96	0.105	100.8	83
46	58	27.5	5.67	0.117	102.9	82
43	64	22.5	5.07	0.129	105.0	81
40	68	20	4.51	0.14	107.1	87
37	71	16	3.63	0.149	109.2	89
33	67	7	2.46	0.156	111.3	88
32	65.5	3.5	2.37	0.155	111.7	86
34	58		2.65	0.158	112.1	
33.5	43.5		2.16	0.166	113.4	
38.5	32.5		2.19	0.159	115.5	
42	30		2.04	0.167	117.6	
34	31		1.72	0.154	119.7	
27	37		1.14	0.162	121.8	
21.5	39		0.73	0.164	123.9	
29	21.5		0.84	0.163	126.0	
29	25.5		0.93	0.169	128.1	
19	27		0.44	0.165	130.2	
19	18		0.34	0.174	132.3	
20	20		0.36	0.182	134.4	
12	13		0.089	0.198	136.5	
11	11.5		0.059	0.216	138.6	
2	2			0.246	140.7	

*θ here in milliseconds.

BUBBLE F-5-01

T_{sub} = 0.1°F

T_{sat} = 203.0°F

q/A = 49,000 Btu/hr ft^2

θ μsec	V $cm^3 \times 10^3$	$\bar{h}$ cm
136.5	0.0135	0.0113
270	0.037	0.016
407	0.043	0.018
540	0.059	0.02
680	0.073	0.021
815	0.06	0.021
1085	0.074	0.025
1355	0.083	0.024
1625	0.08	0.022
1900	0.09	0.019
2170	0.13	0.021
2440	0.18	0.025
2710	0.16	0.025
3390	0.31	0.037
4065	0.28	0.038
4740	0.31	0.035
5420	0.34	0.038
6100	0.62	0.039
6775	0.70	0.042
7400	0.73	0.051
8070	0.73	0.051
8740	0.87	0.057
9415	1.04	0.061
10090	1.07	0.062
10760	1.18	0.062
12100	1.53	0.054
13550	1.78	0.055
14690	2.32	0.061
16020	2.26	0.07
17350	2.87	0.065
18640	2.53	0.074
20030	2.85	0.086
21200	2.93	0.083
22530	2.61	0.085
23850	3.77	0.10
25180	4.85	0.106

BUBBLE F-8-01

T_{sub} = 30.1°F   q/A = 49,000 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	θ	φ
7.5	7	4	0.01	0.009	360	48
10	8	5	.019	.012	1805	43
12	12	8	.045	.02	3610	50
24	19	16	.28	.03	5380	49
27	25	16	.457	.044	7170	41
22	24	11	.32	.055	8900	38
28	20	17	.407	.038	9790	35
36	27	24	.905	.043	10680	35
30	30	20	.72	.048	11505	44
28	34	18	.79	.054	12390	44
26	32	18	.63	.054	13275	60
30	28	20	.66	.044	14160	54
36	26	22	.89	.042	14960	43
40	31	26	1.29	.05	15840	25
42	35	28	1.56	.054	16720	36
35	38	22	1.22	.063	17600	48
30	40	22	.93	.062	18375	62
36	37	21	1.26	.06	19250	54
38	29	24	1.1	.053	20125	55
44	29	30	1.56	.047	21000	37
48	33	36	2.13	.05	21750	55
48	35	36	2.05	.052	22620	49
48	39	34	2.42	.062	23490	55
42	43	32	2.08	.068	24360	70
40	46	30	1.93	.071	25085	72
36	47	30	1.96	.08	25950	74
40	38	30	1.58	.06	26815	66
42	32	28	1.44	.054	27680	61
46	30	34	1.56	.044	28300	61
52	32	42	2.22	.046	29155	63
54	34	44	2.70	.051	30010	49
54	40	40	3	.062	30870	64
50	44	38	2.93	.068	31540	68
46	49	36	3.03	.079	32400	68
42	55	34	2.62	.085	33250	78
40	55	34	2.52	.082	34100	64
40	47	32	2.10	.077	34700	72
46	39	32	2.33	.072	35600	66

BUBBLE F-8-01 (Cont.)

T_{sub} = 30.1°F   q/A = 49,000 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	θ	φ
48	34	34	2.15	.056	36450	57
54	33	36	2.83	.053	37300	29
58	34	48	3.24	.051	37900	33
64	38	48	4.32	.059	38750	44
64	41	48	4.31	.06	39600	52
60	45	46	4.52	.072	40450	67
56	49	46	4.29	.077	41040	73
48	56	40	4.01	.093	41875	83
46	62	40	3.88	.097	42710	75
42	62	38	3.14	.091	43550	85
42	58	36	2.92	.089	44120	81
46	49	36	3.05	.084	44950	75
48	43	40	2.94	.074	45800	87
54	40	38	3.02	.069	46600	66
58	37	42	3.15	.056	47000	43
62	37	50	3.75	.052	47800	49
70	40	54	5.03	.058	48700	52
70	43	54	6.12	.069	49500	53
68	44	56	5.64	.071	50000	69
62	49	54	5.48	.08	50800	86
60	54	52	5.71	.09	51700	80
56	60	48	5.59	.097	52500	81
54	67	44	5.81	.105	53000	80
50	70	44	4.88	.101	53800	85
46	71	42	4.3	.107	54600	85
44	65	38	3.71	.101	55400	79
46	57	38	3.41	.094	55900	85
48	49	36	3.45	.087	56700	86
58	46	38	3.79	.089	57500	77
58	40	40	3.39	.069	58300	48
60	38	46	3.97	.061	58800	53
66	39	58	4.4	.053	59600	55
74	41	60	5.74	.056	60400	59
78	46	54	7.41	.071	61200	41
72	48	50	6.7	.074	61800	51
72	41	56	7.00	.084	62600	81
66	55	56	6.87	.094	63400	88
66	59	52	7.62	.103	64200	87

BUBBLE F-8-01 (Cont.)

T_{sub} = 30.1°F   q/A = 49,000 Btu/hr ft^2 Magnification = 28X

D_h	Z	D_b	V	$\bar{h}$	θ	φ
56	70	46	6.33	.113	65400	77
48	79	42	4.92	.121	67000	85
46	67	40	3.93	.112	68400	80
56	55	40	4.58	.103	70000	87
64	45	38	4.82	.083	71100	85
68	39	50	4.68	.058	72700	50
78	43	62	6.72	.061	73800	54
74	48	54	6.98	.075	75400	65
70	57	58	8.4	.094	76400	86
64	65	52	7.72	.113	78000	90
54	78	46	6.33	.126	79300	85
46	83	40	5.24	.129	80900	87
50	74	38	4.94	.126	81900	88
64	51	40	5.45	.096	84700	88
70	38	60	5.16	.056	87200	48
70	52	60	7.08	.08	89800	56
46	87	38	5.11	.137	95100	75
60	38	48	4.18	.059	102100	36
50	88	30	6.13	.153	110200	80
60	67	6	4.55	.155	114300	90
60	57		3.9	.124	114450	
60	59		4.04	.126	114750	
60	50		4.63	.1	114900	

BUBBLE E-4-1 i

T_{sub} = 10.2°F q/A = 70,400 Btu/hr ft^2

θ	x	$\frac{dx}{d\theta}$	y	$\frac{dy}{d\theta}$
200	.236	125	.36	210
400	.273	125	.39	210
600	.312	125	.44	210
800	.312	125	.49	210
1000	.328	125	.52	210
1200	.375	135	.60	210
1400	.396	150	.64	210
1600	.423	178	.66	210
1800	.477	206	.71	200
2000	.510	250	.73	170
2200	.591	280	.75	150
2400	.623	172	.81	120
2600	.636	115	.80	92
2800	.668	68	.85	52
3000	.668	43	.82	0
3200	.682	20	.83	
3400	.677	40	.82	
3600	.682	96	.79	
3800	.727	180	.82	
4000	.772	410	.81	

x = distance from apparent nucleation site to center of mass of bubble effected by initial fluid ejection.

y = distance from site to far side of ejected bubble.

BUBBLE E-10-1 i

$T_{sub} = 31.1°F$ $q/A = 69,000$ Btu/hr ft^2

θ	x	$\frac{dx}{d\theta}$	y	$\frac{dy}{d\theta}$
204	.245	214	.359	280
408	.267	182	.378	273
612	.319	167	.478	265
816	.348	150	.530	253
1020	.389	137	.577	244
1224	.407	126	.633	224
1428	.418	119	.666	184
1632	.459	108	.700	100
1836	.481	102	.703	28
2040	.507	98	.703	0
2244	.515	90	.703	0
2448	.526	88		

x = distance from apparent nucleation site to center of mass of bubble effected by initial fluid ejection.

y = distance from site to far side of ejected bubble.

APPENDIX C

FORCE CALCULATIONS

The items tabulated here are for the forces acting on a bubble during its lifetime.

The forces are measured in dynes, while the time, θ, is in microseconds.

The individual forces are as follows:

$$F_d = \frac{d}{d\theta}(\rho V_b U_b) \quad \text{for } \theta < \theta_{m_{max}}$$

$$= \rho V_{b_{max}} \frac{dU_b}{d\theta} \quad \text{for } \theta > \theta_{m_{max}}$$

$$F_g = g \rho V_b$$

$$F_p = 0.5 \pi D_b \sigma$$

$$F_s = \pi D_b \sigma \sin \phi$$

$$F_v = 6 \pi \mu D_h U_b$$

$$\Delta F_r = (F_d + F_g + F_p) - (F_s + F_v)$$

θ values are taken from appropriate points on the experimental data plots and are therefore different than the times in Appendix B.

BUBBLE E 2-3

$T_{sub} = 0°F$

$V_{max} = 20.4 \times 10^{-3}$ CM^3

$\theta_{max. vol.} = 11,000$ µsec

Q/A = 72,000 BTU/hr ft^2

$V_{sep} = 16.72 \times 10^{-3}$ CM^3

$\theta_{sep} = 16,000$ µsec

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	44.3	0.07	2.8	5.5	0.3	41.4
400	47.1	0.304	5.3	10.6	0.2	41.9
600	53.5	0.7	7.2	14.4	0.2	46.8
800	59.4	1.28	8.5	17	0.2	52
1000	58.5	1.92	9.7	19.5	0.2	50.4
1500	29.2	3.57	12.1	24.3	0.2	20.4
2000	21.8	5.2	13.9	27.9	0.2	12.8
2500	28.6	6.82	15.6	31.2	0.2	19.6
3000	39.8	8.44	16.3	32.5	0.2	31.8
4000	47.3	11.6	16.6	33.1	0.2	42.2
5000	50	14.7	16	32	0.2	48.5
6000	45	16.7	14.4	28.8	0.2	47.1
7000	26.5	17.9	13.3	26.6	0.3	30.8
8000	8.2	18.7	16.4	32.8	0.3	10.2
9000	3	19.0	16.5	32.9	0.3	2.3
10000	1.3	19.2	15.8	31.6	0.3	4.4
11000	0	19.2	14.7	29.4	0.3	4.2
12000	0	19.1	13.2	26.4	0.2	5.7
13000	0	18.6	11.5	23	0.2	6.9
14000	0	17.8	9.4	18.8	0.2	8.2
15000	0	17.1	6.6	13.2	0.2	10.3
16000	0	15.8	0	0	0.2	15.6
17000	-5.7	15.1			0.2	9.2
18000	-12.2	14.9			0.2	2.5
19000	0	14.7			0.2	14.5
20000	12	14.7			0.2	26.5
25000	26.5	16.1			0.4	42.2
30000	16	14.8			0.5	30.3
35000	0	11.3			0.4	10.9
40000	0	8.9			0.4	8.5
45000	0	8.9			0.4	8.5

BUBBLE E 6-1

T_{sub} = 15.8°F

V_{max} = 35.22 × 10^{-3} CM^3

$\theta_{max\ vol}$ = 5500 μsec

O/A = 68,800 BTU/hr ft^2

V_{sep} = 19.2 × 10^{-3} CM^3

θ_{sep} = 12,000 μsec

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
100	306	0.186	2.7	5.5	1.1	302.3
200	237	0.588	5.7	11.3	0.8	231.2
400	197	1.73	9	18.1	0.5	189.1
600	188	3.41	11.2	22.4	0.4	179.8
800	182	5.26	13	26.1	0.4	173.8
1000	120	7.18	15.2	30.3	0.4	111.7
1500	108	11.9	19.9	39.8	0.4	99.6
2000	125	16.5	21.7	43.4	0.3	109.5
2500	132	21.2	21.9	43.8	0.3	131
3000	123	24.6	21.3	42.7	0.4	125.8
3500	105	27.5	20.7	41.5	0.4	111.3
4000	81	30.1	20.3	40.6	0.4	90.4
4500	49.7	32.2	19.7	39.4	0.4	61.8
5000	24.3	33.2	19.1	38.2	0.4	38
5500	3.6	33.4	18.6	37.1	0.4	18.1
6000	0	33.2	17.4	34.7	0.4	15.5
7000	0	30.6	16.4	32.9	0.4	13.7
8000	58	28.7	18.8	37.7	0.4	67.4
9000	359	27.6	15.7	31.4	0.5	370.4
10000	388	22.6	12.4	24.8	0.7	397.5
11000	5	20.8	9	18.1	0.8	15.9
12000	0	18.2	0	0	0.7	17.5
13000	0	14.3			0.7	14.6
14000	0	10.4			0.6	9.8
16000	0	5.88			0.5	5.4
18000	-2	2.04			0.4	-3.6
20000	-25.4	0.33			0.1	-25.2
22000	-500.0	0			0	-500.0

BUBBLE E 7-1

$T_{sub} = 0°F$ | $Q/A = 70,000$ BTU/hr ft^2

$V_{max} = 6.56 \times 10^{-3}$ CM^3 | $V_{sep} = 5.32 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 7000$ μsec | $\theta_{sep} = 10,000$ μsec

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	58.8	0.3	2.6	5.19	0.3	56.2
400	43.1	0.8	6	11.96	0.3	37.6
600	38.2	1.4	9.1	18.3	0.3	30.1
800	35.3	2	11.3	22.5	0.3	25.8
1000	32.8	2.5	12.3	24.7	0.2	22.7
1500	26.9	3.8	13.9	27.7	0.2	16.7
2000	20.6	4.7	13.8	27.6	0.2	11.3
2500	12.7	5.3	12.1	24.2	0.2	5.7
3000	4.9	5.5	12	24.0	0.2	-1.8
3500	1.2	5.6	12.9	25.9	0.2	-6.7
4000	2.5	5.6	12.9	25.8	0.2	-5
5000	4.6	5.8	11.5	22.9	0.2	-1.2
6000	5.5	6.1	9.7	19.3	0.2	1.8
7000	0	6.2	7.9	15.8	0.2	-1.9
8000	0	5.5	6.1	12.3	0.2	-0.9
9000	0	5.1	4.4	8.8	0.2	0.5
9500	0	5.1	3.5	7.1	0.2	1.3
10000	0	5	2.9	5.9	0.2	1.8
10500	0	5			0.2	4.8
11000	0	5.1			0.2	4.9
12000	0	5.5			0.2	5.3
14000	0	5.5			0.2	5.3
16000	21.6	5.1			0.2	26.5
18000	21.6	4.6			0.2	26
20000	21.6	4.1			0.2	25.5
25000	0	3.4			0.2	3.2
30000	0	2.9			0.2	2.7
33000	0	2.3			0.2	2.1

BUBBLE E 10-2

$T_{sub} = 31.1°F$ | $Q/A = 69,000$ BTU/hr ft^2

$V_{max} = 17.08 \times 10^{-3}$ CM^3 | $V_{sep} = 3.68 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 3000\ \mu sec$ | $\theta_{sep} = 8400\ \mu sec$

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
100	0.292	0.109	4.5	9.0	0.2	278.4
200	0.264	0.328	9.2	18.5	0.2	253.8
300	0.238	0.706	11.6	23.2	0.2	213.9
400	0.214	1.47	13.5	26.9	0.2	196.9
500	0.190	2.36	14.9	29.9	0.2	176.2
750	0.134	4.61	16.8	33.6	0.1	117.7
1000	0.089	6.85	17.8	35.7	0.1	77.8
1250	0.052	9.08	19.2	38.4	0.1	37.6
1500	0.024	11.2	20.5	41.0	0.1	11.1
1750	0.002	13.0	21.6	43.2	0.1	-8.7
2000	-0.012	14.5	22.4	44.9	0.1	-20.1
2500	-0.021	16.5	23.3	46.5	0.1	-27.6
3000	-0.021	17.0	23.1	46.2	0.1	-13.2
3500	-0.021	16.7	22.5	45.0	0.1	-7.9
4000	-0.021	16.0	21.6	43.2	0.1	-5.7
5000	-0.020	13.6	21.1	42.3	0.1	-6.7
6000	0.060	10.7	20.0	40.0	0.1	58.6
7000	0.073	7.8	14.6	29.2	0.2	375.0
8000	-0.162	4.85	4.2	8.5	0.3	6.2
8400	-0.172	3.66	1.4	2.8	0.2	2.1
9000	-0.153	2.0			0.2	0
9500	-0.098	0.9			0.1	-9.0
10000	-0.045	0.33			0.1	-155
10650	-0.020	0			0	-260

BUBBLE E 11-1

$T_{sub} = 10.1°F$ $Q/A = 69,700$ BTU/hr ft^2

$V_{max} = 36.15 \times 10^{-3}$ CM^3 $V_{sep} = 22.28 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 6000\ \mu sec$ $\theta_{sep} = 14000\ \mu sec$

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	29.3	0.4	5.7	11.5	0.4	287.2
400	252	1.96	13.1	26.1	0.4	240.6
600	215	4.06	20.1	40.2	0.4	198.6
800	185	6.34	24	48	0.4	166.9
1000	154	8.51	26.8	53.8	0.4	135.2
1400	114	12.8	28.8	57.6	0.4	97.6
1800	76.5	17	30.5	61	0.4	62.6
2200	54.5	21	31.7	63.4	0.4	43.4
2600	36.5	24.2	32.4	64.7	0.4	28
3000	18.1	26.7	32.4	64.7	0.4	12.1
4000	2.5	31.4	28.8	57.5	0.4	4.8
5000	6.3	33.7	23.5	47	0.3	16.2
6000	20.2	34.5	22.9	45.8	0.3	31.5
7000	54	34	27.4	54.8	0.3	60.3
8000	110	32.6	28	56	0.3	114.3
9000	195	30.9	25.9	51.8	0.4	199.6
10000	165	29.2	22.8	45.6	0.4	171
11000	110	27.3	18.9	37.8	0.5	117.9
12000	63	25.3	13.8	27.6	0.6	73.9
13000	50	23.4	7.9	15.8	0.7	64.8
14000	12.5	21.3	0	0	0.7	33.1
16000	-1	17			0.7	15.3
18000	-7.5	12.5			0.6	4.4
20000	-22	7.2			0.5	-15.3
24000	-82	1.3			0.2	-80.9
28000	-120	0.4			0.1	-119.7
30000	-120	0.2			0.1	-119.9
32000	-320	0			0	-320

BUBBLE E 11-2

T_{sub} = 10.1°F

$V_{max} = 6.16 \times 10^{-3}$ CM^3

$\theta_{max\ vol}$ = 3000 μsec

Q/A = 69,700 BTU/hr ft^2

$V_{sep} = 3.75 \times 10^{-3}$ CM^3

θ_{sep} = 8500 μsec

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
100	300	0.001	2.7	5.25	0.56	300
200	140	0.22	5.6	11.1	0.6	140
300	98	0.54	8	16	0.5	98
400	70.6	0.87	9.9	19.8	0.5	70.6
500	54.5	1.18	11.5	22.8	0.5	54.5
750	34.3	1.99	14.1	28.2	0.4	34.3
1000	22.5	2.78	15.8	31.6	0.4	22.5
1250	19.8	3.56	16.9	33.8	0.4	19.8
1500	17.2	4.21	18.6	37.2	0.3	17.2
2000	11.2	5.14	19.8	39.6	0.3	11.2
2500	6	5.76	19.6	39.1	0.3	6
3000	0	5.83	19	38	0.2	0
3500	0	5.73	18.1	36.2	0.2	0
4000	0	5.46	16.3	32.5	0.2	0
5000	13.2	5.34	13.8	27.5	0.2	13.2
6000	41	5.28	10.8	21.6	0.3	41
7000	4.6	4.73	7.4	14.7	0.3	4.6
8000	-21	3.95	3.2	6.4	0.3	-21
8500	-30	3.54	0	0	0.3	-30
9000	-44	3.15			0.2	-44
10000	0	2.37			0.2	0
11000	113	1.73			0.2	113
12000	39	1.78			0.1	39
14000	0	0.72			0.1	0
16000	-74	0.02			0	-74
18000	-93	0			0	-93

BUBBLE E 12-8

$T_{sub} = 20.0°F$ $Q/A = 69,800$ BTU/hr ft^2

$V_{max} = 16.31 \times 10^{-3}$ CM^3 $V_{sep} = 4.43 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 3000$ μsec $\theta_{sep} = 9000$ μsec

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
150	415	0.2	6.3	12.7	1.4	407.4
200	190	0.7	9.3	18.6	1.4	180
300	148	1.4	12.4	24.9	1	135.9
400	137	2.2	14.6	29.1	0.7	124
500	121	2.9	16.1	32.2	0.6	107.2
750	77	4.9	18.6	37.2	0.5	62.8
1000	48	6.8	19.9	39.9	0.5	34.3
1250	19	8.7	20.8	41.6	0.5	6.4
1500	-10	10.5	20.9	41.9	0.3	-20.8
2000	-2.5	13.5	21.3	42.5	0.3	-10.5
2500	0.8	15.0	21.2	42.4	0.3	-5.7
3000	3.9	15.5	21	42	0.3	-1.9
3500	5.9	15.2	21	42	0.3	-0.2
4000	14.6	14.4	22	44	0.3	6.7
5000	36	12.6	21.6	43.1	0.3	26.8
6000	153	10.6	18.7	37.4	0.3	144.6
7000	415	8.4	14.5	29	0.6	408.3
8000	113	6.3	9.3	18.5	0.7	109.4
9000	-8	4.1	0	0	0.6	-4.5
10000	-163	2.4			0.4	-161
11000	-64	1.1			0.3	-63.2
12000	-45	0.3			0.2	-44.9
13000	-36	0			0	-36

BUBBLE E 12-10

T_{sub} = 20.0°F

V_{max} = 11.36×10^{-3} CM^3

$\theta_{max\ vol}$ = 3000 μsec

Q/A = 69,800 BTU/hr ft^2

V_{sep} = 4.08×10^{-3} CM^3

θ_{sep} = 7500 μsec

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
150	406	0.1	3.5	7.1	0.6	401.9
200	256	0.3	5.3	10.5	0.6	250.5
300	142	0.8	9.8	19.6	0.5	132.5
400	86.3	1.3	13.5	27	0.4	73.7
500	72.4	1.8	15.9	31.9	0.4	57.8
750	58	3	19.5	39.1	0.4	41.0
1000	52	4.3	19.7	39.4	0.3	36.3
1250	51.6	5.5	18.8	37.5	0.3	38.1
1500	48	6.7	18.8	37.5	0.3	35.7
1750	41.2	7.8	19.6	39.2	0.3	29.1
2000	32.8	8.8	19.6	39.2	0.3	21.7
2250	18.3	9.6	20	40	0.3	7.6
2500	11.2	10.2	20.2	40.3	0.3	1.0
2750	10.9	10.6	20	40	0.3	1.2
3000	13.8	10.8	19.9	39.8	0.3	4.4
3250	15.0	10.8	19.5	39	0.3	6
3500	21.1	10.4	19.4	38.7	0.3	11.9
4000	33.6	9.5	19.2	38.4	0.3	23.6
4500	53	8.7	18.9	37.8	0.3	42.5
5000	85	7.8	17.1	34.2	0.3	75.4
6000	177	5.9	11.7	23.5	0.4	170.7
7000	94	3.9	5.3	10.7	0.5	92
7500	20.2	1.9	1.4	2.9	0.4	20.2
8000	-39	0.5			0.3	-38.8
9000	-150	0.3			0.2	-149.9
9500	-200	0.1			0.2	-200
10000	-250	0			0.1	-250
10500					0	

BUBBLE E 13-3

$T_{sub} = 30.0°F$

$V_{max} = 8.18 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 2000\ \mu sec$

$Q/A = 69,500$ BTU/hr ft^2

$V_{sep} = 1.24 \times 10^{-3}$ CM^3

$\theta_{sep} = 5450\ \mu sec$

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	156	0.8	10.1	20.2	0.7	146
400	80	2	14.6	29.2	0.6	66.8
600	43.7	3.1	18.2	36.3	0.6	28.1
800	22.6	4.2	19.9	39.8	0.5	6.4
1000	-2.7	5.1	20.9	41.8	0.4	-18.9
1250	-29.2	5.9	20.3	40.7	0.3	-44
1500	-5.2	6.7	20.1	40.3	0.3	-19
1750	0	7.5	19.2	38.4	0.3	-12
2000	2	7.8	18.3	36.5	0.3	-8.7
2500	10.8	7.1	18.3	36.6	0.3	-0.70
3000	31.4	6.2	18.2	36.4	0.2	+19.2
3500	80.0	5.2	16.4	32.8	0.2	68.6
4000	123.5	4.2	14.1	28.1	0.4	113.3
4500	52.9	3.2	11.2	22.4	0.7	520.3
5000	147	2.1	7.3	14.6	0.8	141.0
5450	0	1.2	0	0	0.8	.4
5500	-49	1.1			0.8	-48.7
6000	-196	0.2			0.7	-196.5
6350	-686	0			0.2	-686

BUBBLE F 2-2

$T_{sub} = 10.0°F$ | $Q/A = 48,000$ BTU/hr ft^2

$V_{max} = 5.63 \times 10^{-3}$ CM^3 | $V_{sep} = 2.04 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 3,500$ μsec | $\theta_{sep} = 8,800$ μsec

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	37	0.21	6.3	9.92	0.22	33.37
400	32	0.6	9.27	15.2	0.2	26.47
600	31	1.03	10.31	16.3	0.2	25.84
800	30	1.47	12.79	19.6	0.19	24.47
1000	28.8	1.9	13.9	21	0.19	23.41
1500	25.4	2.97	15.85	23.95	0.18	20.09
2000	21.3	4.02	16.78	25.7	0.19	16.2
2500	14.5	4.81	16.87	26.5	0.19	9.5
3000	7.8	5.25	16.50	26.7	0.19	2.7
3500	0.4	5.33	15.76	27.3	0.2	-6
4000	0	5.05	14.73	28.9	0.18	-9.3
5000	1.3	4.38	12.61	24.9	0.17	-6.8
6000	6.2	3.74	10.38	20.5	0.17	-0.4
7000	13.9	3.10	7.97	15.9	0.17	8.9
8000	30	2.46	5.1	10.2	0.18	27.2
8800	25.5	1.93	0	0	0.2	27.2
9400	0	1.53			0.18	1.3
10000	-53	1.30			0.14	-51.8
12000	0	1.21			0.09	1.1
14000	0	0.25				0.2
16000	-100	0.06				-100
17500	-100	0				-100

BUBBLE F 3-2

$T_{sub} = 20.1°F$

$Q/A = 48,200$ BTU/hr ft^2

$V_{max} = 8.19 \times 10^{-3}$ CM^3

$V_{sep} = 2.9 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 3500\ \mu sec$

$\theta_{sep} = 8200\ \mu sec$

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	69.4	0.39	5.4	10.8	0.5	63.9
400	62.3	1.06	8.4	16.9	0.3	54.6
600	54.6	1.705	10.9	21.8	0.3	45.1
800	48.9	2.37	12.3	24.6	0.3	38.7
1000	44.9	3.07	13.2	26.4	0.3	34.5
1500	35.3	4.83	13.4	26.8	0.3	26.4
2000	4.7	6.26	13.7	27.5	0.3	-3.1
2500	-9.2	7.16	13.9	27.9	0.3	-16.3
3000	-19.4	7.76	13.2	26.5	0.2	-25.1
3500	-12	7.78	13.2	26.5	0.2	-17.7
4000	11	7.36	13.8	27.7	0.2	-6.6
5000	39.5	6.41	15.4	30.8	0.2	30.3
6000	104	5.46	13.2	26.4	0.3	96
7000	104	4.42	8.7	17.4	0.4	99.3
8000	4	2.92	2.5	5.1	0.6	3.7
8200	-20	2.70	0	0	0.5	-17.8
9000	-91.9	1.67			0.4	-90.6
10000	-4.44	0.59			0.1	-43.9
11000	-9.2	0.24			0.1	-9.7
12000	-2	0.85			0.1	-2
13000		0.02			0.1	

BUBBLE F 4-1

T_{sub} = 30.0°F

V_{max} = 15.85 × 10^{-3} CM^3

$\theta_{max\ vol}$ = 3200 μsec

Q/A = 49,600 BTU/hr ft^2

V_{sep} = 3.76 × 10^{-3} CM^3

θ_{sep} = 8600 μsec

θ	Fd	Fg	Fp	Fs	Fv	ΔFr
100	725	0.1	2.6	3.9	0.4	724
200	457	0.8	5.7	8.5	0.3	453
400	195	2.6	9.2	15.6	0.3	191
600	105	4.4	10.8	20.6	0.3	99.3
800	52	6.2	11.9	21.6	0.2	48.3
1000	16	7.9	12.6	22.2	0.2	14.1
1500	-21.4	11.2	13.6	23.1	0.2	-19.9
2000	-21.4	13.2	14	22.9	0.2	-17.3
2500	-21.4	14.6	13.8	22.1	0.2	-15.3
3200	-21.4	15.4	13	20.6	0.1	-13.7
4000	14.5	14.7	12.4	23.2	0.1	-10.7
5000	49	13	11.7	23.2	0.1	50.4
6000	261	10.4	9.9	19.8	0.1	261
7000	270	7.6	7	14	0.2	271
8000	152	5	3	6	0.3	154
8600	8	3.7	0	0	0.4	11.3
9000	0	2.9			0.4	2.5
10000	0	0.9			0.3	0.6
10700	0	0			0	0

BUBBLE F 4-4

$T_{sub} = 30.0°F$

$V_{max} = 16.85 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 3000\ \mu sec$

$Q/A = 49,600$ BTU/hr ft^2

$V_{sep} = 3.78 \times 10^{-3}$ CM^3

$\theta_{sep} = 8900\ \mu sec$

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	286	0.67	8.5	17.1	0.9	277
400	152	2.24	14.2	28.4	0.6	139
600	112	3.76	18	36	0.6	98
800	89	5.3	21.2	42.5	0.5	72
1000	73	6.9	23.6	47.2	0.4	56
1500	18	10.7	23.2	46.5	0.4	5
2000	17	13.7	22.8	45.6	0.3	7.1
2500	-26.5	15.4	22.7	45.4	0.3	-34.1
3000	-25	16.1	22	44	0.2	-31
3500	-22	16.1	21.5	43.1	0.2	-27.7
4000	-21	15.5	21.3	42.7	0.2	-27.2
5000	33	13.6	23.8	47.5	0.2	22.7
6000	170	11	21.4	42.9	0.3	159.2
7000	252	8.2	16.6	33.2	0.5	243.1
8000	240	5.5	9.5	19.0	0.6	253.4
8900	100	3.7	0	0	0.7	103
9000	0	3.4			0.7	2.7
10000	-336	1.6			0.5	-335
11000	-400	0.33			0.5	-400

BUBBLE F 5-1

$T_{sub} = 0.1°F$

$Q/A = 49,000$ BTU/hr ft^2

$V_{max} = 6.9 \times 10^{-3}$ CM^3

$V_{sep} = 6.32 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 22,000$ μsec

$\theta_{sep} = 13,000$ μsec

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	24.6	0.112	5	10	0.19	19.5
400	24.3	0.287	6.7	13.4	0.18	17.7
600	24	0.52	7.9	15.8	0.18	16.4
800	23.4	0.813	9.1	18.1	0.17	15
1000	22.8	1.11	10	20	0.17	13.7
1500	20.9	1.84	10.1	20.2	0.17	12.4
2000	18.8	2.57	9.7	19.4	0.16	11.5
3000	14.8	3.94	9.5	19	0.17	9
4000	10.8	4.57	9.7	19.3	0.18	5.6
5000	7	5.07	9.2	18.4	0.18	2.7
6000	4.74	5.48	8.6	17.1	0.18	1.5
7000	0	5.73	7.8	15.1	0.16	-2.2
8000	-32.7	5.71	7.0	14	0.14	-34.1
9000	-4.3	5.6	6.2	12.4	0.11	-5
10000	0	5.46	5.4	10.7	0.09	+0.1
11000	-5.7	5.48	4.4	8.7	0.08	-4.6
12000	-36.2	5.67	3.4	6.7	0.04	-33.8
13000	0	5.96	0	0	0	6
14000	11	6.22			0.01	17.2
16000	28	6.43			0.09	34.3
18000	15.8	6.48			0.16	22.1
20000	2.7	6.50			0.22	9.0
22000	0	6.51			0.21	6.3

BUBBLE F 5-3

$T_{sub} = 0.1°F$ | $Q/A = 49,000$ BTU/hr ft^2

$V_{max} = 6.19 \times 10^{-3}$ CM^3 | $V_{sep} = 5.08 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 13,000$ μsec | $\theta_{sep} = 9,500$ μsec

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	59.6	0.302	6.2	12.5	0.2	43.4
400	28.6	0.66	8.4	16.8	0.2	20.7
600	26.3	1.02	9.5	19	0.2	17.6
800	25.7	1.37	10.1	20.3	0.2	16.7
1000	25	1.73	10.6	21.3	0.2	15.8
1500	22.9	2.66	11.4	22.8	0.2	14
2000	18.4	3.41	11.9	23.8	0.2	9.7
2500	10.4	3.84	12	24.1	0.2	1.9
3000	5.7	4.08	12.3	24.6	0.2	-2.7
3500	2.9	4.2	12.5	25	0.2	-5.6
4000	1.6	4.26	11.6	23.2	0.2	-5.9
5000	0.4	4.31	10.6	21.1	0.2	-6
6000	0	4.32	9.3	18.6	0.2	-5.2
7000	-2.2	4.32	8.3	16.5	0.2	-6.3
8000	-7.4	4.45	7.1	14.3	0.2	-10.4
9000	-4.2	4.65	4.2	8.5	0.1	-3.9
9500	-0.2	4.79	0	0	0.1	4.59
10000	3.8	4.93			0.2	8.6
11000	13.2	5.23			0.2	18.2
12000	15.2	5.5			0.2	20.5
13000	0	5.84			0.2	5.84
14000	0	5.39			0.2	5.39
15000	0	4.66			0.2	4.66
16000	0	4.49			0.2	4.49
17000	0	4.6			0.2	4.60

BUBBLE F 6-1

T_{sub} = 10.1°F

$V_{max} = 6.75 \times 10^{-3}$ CM^3

$\theta_{max\ vol}$ = 3000 μsec

Q/A = 49,000 BTU/hr ft^2

$V_{sep} = 2.70 \times 10^{-3}$ CM^3

θ_{sep} = 9500 μsec

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	63.7	0.1	3.81	7.63	0.1	59.9
400	61.6	0.6	7	14	0.2	55
600	58.9	1.1	8.8	17.6	0.2	51
800	55.6	1.7	10.1	20.3	0.3	46.7
1000	51.4	2.2	11.5	23.1	0.3	41.7
1500	39	3.6	14	28	0.3	28.3
2000	26	5	16.1	32.2	0.3	15.1
2500	0.9	6.1	15.6	31.2	0.2	-8.8
3000	-23	6.4	14.8	29.7	0.2	-31.7
3500	-22.5	6.3	14.4	28.8	0.2	-30.8
4000	8.3	6.1	14	28	0.2	0.2
4500	34.5	5.9	14.7	29.4	0.2	25.5
5000	49.3	5.7	14.8	29.7	0.2	39.9
6000	17	5.1	12.5	25	0.3	9.3
7000	-5	4.3	9.4	18.9	0.3	-10.5
8000	-36.7	3.5	7.3	14.6	0.2	40.8
9000	-13.9	2.6	3.5	7	0.2	-14.9
9500	-6.2	2.3	0	0	0.2	-5.1
10000	1.5	2			0.1	0.5
11000	17.3	1.7			0.1	17.1
12000	44.1	1.4			0.2	43.9
13000	65.1	0.9			0.2	64.9
14000	11.2	0.4			0.2	11.0
15000	9	0.1			0.1	8.9
16000		0			0.1	

BUBBLE F 7-1

$T_{sub} = 20.1\,°F$ | $Q/A = 49,100$ BTU/hr ft^2

$V_{max} = 4.9 \times 10^{-3}$ CM^3 | $V_{sep} = 1.13 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 1800\ \mu sec$ | $\theta_{sep} = 5600\ \mu sec$

θ	F_d	F_g	F_p	F_s	F_v	ΔF_r
200	131	0.36	7.9	12.6	0.38	126.3
400	58.8	1.03	12.6	22	0.39	50
600	28.4	1.71	15.6	28.8	0.34	16.6
800	13	2.38	17.6	33.5	0.29	-0.8
1000	13	3.04	19	35.9	0.25	-1.2
1400	13	4.23	20.5	36.5	0.21	1
1800	5.4	4.65	20	35.7	0.22	-5.8
2400	0	4.40	16.9	31.2	0.20	-10.1
3000	0	3.84	15.6	30.1	0.19	-10.9
3500	21.5	3.31	13.7	27	0.19	11.3
4000	91.2	2.78	11.6	23.1	0.23	82.3
4500	157.4	2.24	9.5	18.9	0.34	149.9
5000	200	1.71	7	13.8	0.51	194.4
5600	6	1.07	0	0	0.48	6.6
6000	0	0.68			0.42	0.3
6500	0	0.3			0.34	0
7000	-90	0.08			0.23	-90
7500	-300	0.01			0.08	-300
7800	-500	0			0	-500

BUBBLE G 2-2

T_{sub} = 0.6°F

$V_{max} = 9.78 \times 10^{-3}$ CM^3

$\theta_{max\ vol}$ = 15600 μsec

Q/A = 101,900 BTU/hr ft^2

$V_{sep} = 9.78 \times 10^{-3}$ CM^3

θ_{sep} = 15600 μsec

θ	F_d	F_g	F_p	F_s	ΔF_r
200	21.6	0.029	1.41	2.9	20.14
400	21.2	0.127	3.96	3.7	21.59
600	20.8	0.304	5.65	5.65	21.10
800	21.2	0.568	7.74	8.00	21.51
1000	20.6	0.872	9.90	10.8	20.57
1500	20.6	1.77	12.7	15.3	19.77
2000	20.0	2.68	14.3	18.4	18.58
3000	18.2	4.32	16.5	23.3	15.72
4000	16.0	5.78	16.8	25.8	12.78
5000	9.6	6.76	15.8	25.6	6.56
6000	-1.2	7.35	14.6	25.0	-4.25
7000	-4.2	7.65	13.5	24.0	-7.05
8000	-5.0	7.84	12.2	22.5	-7.46
9000	-2.4	7.84	11.3	21.4	-4.66
10000	0.5	7.94	10.4	20.1	-1.26
11000	1.6	8.04	9.6	18.8	.44
12000	2.4	8.13	8.7	17.3	1.93
13000	2.4	8.42	7.5	15.0	3.32
14000	3.0	8.82	5.85	11.7	5.97
15000	2.4	9.12	3.77	7.5	7.79
15600	0.5	9.20	0.94	1.9	8.74
16000	-1.6	9.12			7.52
17000	-5.4	8.72			3.32
18000	-1.6	8.43			6.83
19000	8.0	8.13			16.13
20000	13.2	7.94			21.14
25000	40.0	7.15			47.15
30000		7.05			
35000		8.60			
40000		6.52			

BUBBLE G 2-3

$T_{sub} = 0.6°F$

$V_{max} = 6.90 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 14,000$ μsec

Q/A = 101,900 BTU/hr ft^2

$V_{sep} = 6.13 \times 10^{-3}$ CM^3

$\theta_{sep} = 15,500$ μsec

θ	F_d	F_g	F_p	F_s	ΔF_r
200	25	0.113	4.70	-5.12	24.7
400	24	0.264	7.23	-8.50	23.0
600	28	0.472	8.73	-10.76	26.4
800	34	0.754	9.95	-12.74	32.0
1000	27	1.103	10.80	-14.45	24.5
1500	16	2.24	12.58	-17.94	12.9
2000	12	3.06	13.62	-20.07	8.6
3000	11	4.47	15.02	-23.35	7.1
4000	11	5.43	15.49	-25.69	6.2
5000	10	5.85	14.84	-27.12	3.6
6000	9	6.11	13.71	-26.82	2.0
7000	7	6.30	12.21	-24.25	1.2
8000	3	6.20	10.70	-21.41	-1.5
9000	-23	5.94	9.67	-19.34	-26.7
10000	-29	5.83	8.83	-17.65	-32.0
11000	-26	5.66	7.98	-15.96	-28.3
12000	-14	5.86	7.32	-14.65	-15.5
13000	-2	6.47	6.57	-13.15	-2.1
14000	3	6.51	5.16	-10.33	4.3
15000	5	6.04	3.00	-6.01	8.0
15500	8	5.78	1.60	-3.19	12.2
16000	87	6.03			93
17000	27	6.36			33.4
18000	6	6.30			12.3
19000	-30	5.69			-24.3

BUBBLE G 3-4

$T_{sub} = 9.6°F$

$Q/A = 102,900$ BTU/hr ft^2

$V_{max} = 14.05 \times 10^{-3}$ CM^3

$V_{sep} = 6.18 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 5,000\ \mu sec$

$\theta_{sep} = 13,000\ \mu sec$

θ	F_d	F_g	F_p	F_s	ΔF_r
200	72.0	0.26	7.66	10.4	69.6
400	58.6	0.79	11.2	15.5	55.1
600	53.4	1.40	11.8	17.1	49.5
800	50.0	2.10	14.1	20.8	45.4
1000	50.0	2.86	15.8	22.8	45.9
1500	47.0	4.79	18.5	27.0	43.3
2000	41.3	6.70	20.8	30.9	37.9
3000	28.7	10.5	22.7	34.8	27.1
4000	11.4	12.8	23.3	36.2	11.3
5000	-2.0	13.3	22.7	35.8	-1.8
6000	8.1	12.5	21.1	33.7	8.0
7000	33.6	11.4	18.8	31.5	32.3
8000	-11.6	10.2	16.3	31.9	-17.0
9000	-24.8	9.1	11.8	23.4	-27.3
10000	0	8.4	10.5	20.9	-2.0
11600	0	7.3	3.55	7.06	3.8
13000	-32.0	5.8			
15000	-26.4	3.6			
17000	-16.7	1.8			
19000	-7.3	0.8			
21000	-5.6	0.3			
24000	-4.4	0			

BUBBLE G 4-4

$T_{sub} = 20.6°F$ | $Q/A = 103,000$ BTU/hr ft^2

$V_{max} = 6.53. \times 10^{-3}$ CM^3 | $V_{sep} = 2.28 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 3000\ \mu sec$ | $\theta_{sep} = 8250\ \mu sec$

θ	F_d	F_g	F_p	F_s	ΔF_r
200	130	0.19	6.02	6.20	130
400	90	0.63	10.67	13.43	87.9
600	64	1.19	13.97	19.42	59.7
800	38	1.85	15.91	23.26	32.5
1000	19	2.57	17.08	26.16	12.5
1500	13	4.47	19.60	31.32	5.8
2000	3.5	5.74	20.86	33.75	-3.7
3000	-9	6.20	20.57	34.11	116.3
4000	-8	5.87	17.56	32.56	-17.1
5000	32	4.56	15.52	30.49	21.6
6000	8.5	3.87	11.35	22.54	1.2
7000	-9	3.36	7.08	14.10	-12.7
8000	-34	2.47	3.40	6.78	-34.9
8250	-46	2.17			-43.8
8500	-46	1.84			-43.2
9000	-34	1.15			-32.9
10000	-8	0.51			-7.5
11000	-6	0.36			-5.6
12000	-7.5	0.05			-7.4

BUBBLE G 5-2

T_{sub} = 28.9°F

V_{max} = 4.12×10^{-3} CM^3

$\theta_{max\ vol}$ = 2,000 μsec

Q/A = 100,800 BTU/hr ft^2

V_{sep} = $.47 \times 10^{-3}$ CM^3

θ_{sep} = 4,500 μsec

θ	F_d	F_g	F_p	F_s	ΔF_r
200	94	.24	9.1	16.5	86.8
400	52	.865	14.64	25.1	42.4
600	25	1.51	17.0	27.8	15.7
800	10	2.14	18.5	29.2	1.4
1000	2.5	2.74	19.1	28.8	-4.5
1500	-7	3.92	19.6	28.7	-12.2
2000	-9.2	3.93	18.6	28.9	-15.6
2500	-2.5	2.95	16.5	31.1	-14.1
3000	13	2.14	13.64	27.2	1.5
3500	9	1.57	9.7	19.3	1.0
4000	-6	.99	5.24	10.45	-10.3
4500	-3.8	.45	.6	1.2	-3.9
5000	100	.107			100

BUBBLE G 7-1

$T_{sub} = 10.3°F$ | $Q/A = 100,100$ BTU/hr ft^2

$V_{max} = 3.52 \times 10^{-3}$ CM^3 | $V_{sep} = 1.08 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 2,000\ \mu sec$ | $\theta_{sep} = 7,000\ \mu sec$

θ	F_d	F_g	F_p	F_s	ΔF_r
200	27.8	.167	5.75	9.05	24.8
400	23.1	.402	9.1	14.4	18.2
600	23.0	.735	11.5	18.3	16.9
800	21.8	1.07	13.0	20.9	15.0
1000	19.8	1.49	14.4	23.3	12.4
1500	15.1	2.52	16.8	27.5	6.9
2000	9.2	3.33	16.3	27.2	1.9
3000	4.7	3.04	13.1	23.0	-2.2
4000	2.7	2.59	10.3	19.5	-3.9
5000	-1.7	2.08	7.95	15.7	-7.4
6000	-8.8	1.47	5.95	11.8	-13.2
7000	-15.4	1.02	2.88	5.7	-17.2
8000	-8.4	1.02			-7.4
9000	-2	.67			-1.3
10000	-2.8	.28			-2.5
11000	-3.7	.08			-3.6
12000	-2	.01			-2.0

BUBBLE G 8-1

$T_{sub} = 20.3°F$ $Q/Q = 100,100$ BTU/hr ft^2

$V_{max} = 16.3 \times 10^{-3}$ CM^3 $V_{sep} = 4.2 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 3,000$ μsec $\theta_{sep} = 10,700$ μsec

θ	F_d	F_g	F_p	F_s	ΔF_r
200	138	.38	9.81	17.0	131.2
400	160	1.50	15.7	25.7	151.5
600	280	3.04	20.6	31.6	272.0
800	138	4.85	23.5	38.6	127.8
1000	82	6.56	26.5	36.9	78.2
1500	31	10.45	30.4	55.1	16.8
2000	11	13.40	33.4	60.0	-2.2
3000	-94	15.49	31.4	43.6	-9.1
4000	-31	15.11	29.4	38.4	-24.9
5000	-13	13.30	27.5	49.6	-21.8
6000	103	11.31	24.5	48.4	90.4
7000	47	9.78	21.6	43.0	35.4
8000	6	8.55	18.6	37.2	-4.1
9000	2	6.94	12.8	25.5	-3.8
10000	-6	5.23	6.87	13.7	-7.6
10700	-64	3.99	1.96	3.9	-62.0
11000	-60	3.52			-56.5
12000	-52	2.09			-49.9
13000	-44	1.05			-43.0
14000	-32	.29			-31.7

BUBBLE G 9-2

$T_{sub} = 30.3°F$

$V_{max} = 3.54 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 1500$ μsec

$Q/A = 100,100$ BTU/hr ft^2

$V_{sep} = .39 \times 10^{-3}$ CM^3

$\theta_{sep} = 4800$ μsec

θ	F_d	F_g	F_p	F_s	ΔF_r
200	54	.54	8.31	13.44	49.4
400	30	1.16	13.05	20.23	24
600	0	1.76	16.22	27.51	-9.5
800	-5	2.33	18.40	31.20	-15.5
1000	-8.5	2.77	19.38	32.14	-18.5
1500	-11	3.38	18.20	24.01	-13.4
2000	-11	3.22	17.41	31.02	-21.4
3000	-3	2.33	14.84	29.52	-17.4
4000	18	1.26	8.60	17.20	10.7
4800	-80	.37			-80
5000	-80	.19			-80

BUBBLE H 2-1

$T_{sub} = 10°F$ $Q/A = 50,000$ BTU/hr ft^2

$V_{max} = .925 \times 10^{-3}$ CM^3 $V_{sep} = .360 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 1500\ \mu sec$ $\theta_{sep} = 2700\ \mu sec$

θ	F_d	F_g	F_p	F_s	ΔF_r
200	112	.085	5.46	9.55	107.8
400	94	.196	7.47	13.3	88.0
600	92	.333	9.0	16.2	84.5
800	90	.490	9.96	18.0	81.5
1000	90	.647	11.11	20.1	80.3
1500	12	.872	9.19	17.3	3.0
2000	-73	.648	7.85	15.7	-81.5
2500	-70	.412	5.17	10.3	-75.5
2700	-71	.343			-71.3
3000	-80	.274			-80.3
3500	-47	.176			-47.2
4000	-4	.078			-4.1
4500	-1	.010			-1.0

BUBBLE H 4-4

$T_{sub} = 29.8°F$ | $Q/A = 50,000$ BTU/hr ft^2
$V_{max} = 2.44 \times 10^{-3}$ CM^3 | $V_{sep} = .49 \times 10^{-3}$ CM^3
$\theta_{max\ vol} = 2000$ μsec | $\theta_{sep} = 3800$ μsec

θ	F_d	F_g	F_p	F_s	ΔF_r
200	119.2	.25	8.9	12.4	115.4
400	1.9	.67	12.7	19.9	-6.0
600	-1.5	1.1	15.0	24.6	-12.2
800	-2.7	1.52	16.4	27.5	-15.3
1000	-3.7	1.87	17.1	28.8	-17.3
1500	-1.2	2.31	17.1	28.8	-15.2
2000	5.4	2.33	15.8	27.5	-8.6
2500	1.9	1.96	13.7	27.2	-13.6
3000	-9.8	1.31	9.9	19.8	-21.0
3500	-21	.77	5.15	10.3	-26.8
3800	-34.5	.47	2.0	4.0	-37.0
4000	-26.3	.28			-26.6
4500	-6.3	.01			-6.3

BUBBLE H 7-1

T_{sub} = 19.5°F

V_{max} = 1.44×10^{-3} CM^3

$\theta_{max\ vol}$ = 1800 μsec

Q/A = 47,800 BTU/hr ft^2

V_{sep} = 1.11×10^{-3} CM^3

θ_{sep} = 2800 μsec

θ	F_d	F_g	F_p	F_s	ΔF_r
100	29	.14	5.65	8.26	26.3
200	25.5	.25	7.35	11.26	21.3
300	23	.36	8.57	13.51	17.7
400	19	.46	9.42	15.24	12.7
600	14	.67	10.74	17.81	6.2
800	9	.85	11.59	19.21	0.5
1000	5	1.02	12.25	20.06	-3.8
1200	-35	1.16	12.62	20.68	-44.3
1400	-10	1.26	12.91	19.51	-17.9
1600	15	1.33	13.00	21.29	5.4
1800	61	1.36	12.72	21.56	50.7
2000	48	1.35	12.06	22.53	36.2
2500	10	1.19	8.01	16.01	0.8
2800	-34	1.05			-35
3000	-15	.96			-16
4000	9	.76			-8.2
5000	-7	.47			-7.5
6000	-2.5	.06			-2.6
7000		.01			

BUBBLE I 8-1

$T_{sub} = 19.9°F$

$Q/A = 69,500$ BTU/hr ft^2

$V_{max} = 2.70 \times 10^{-3}$ CM^3

$V_{sep} = .65 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 1500\ \mu sec$

$\theta_{sep} = 3900\ \mu sec$

θ	F_d	F_g	F_p	F_s	ΔF_r
200	48	.27	7.8	11.4	44.1
400	38	.67	11.7	17.9	31.1
600	32	1.12	14.6	23.3	22.2
800	26	1.62	16.1	26.0	14.5
1000	21	2.14	17.1	28.1	7.9
1500	-7	2.57	16.4	27.5	-20.7
2000	-18	2.28	13.6	23.6	-30.3
3000	-2	1.43	7.4	14.6	-10.6
3900	-1	.62			-1.6
4000	-1	.53			-1.5
5000	-19	.02			-19

BUBBLE I 11-1

$T_{sub} = 10.3°F$

$V_{max} = 1.88 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 2000$ μsec

Q/A = 69,600 BTU/hr ft^2

$V_{sep} = .86 \times 10^{-3}$ CM^3

$\theta_{sep} = 7000$ μsec

θ	F_d	F_g	F_p	F_s	ΔF_r
200	50	.076	5.7	8.8	46.8
400	40	.435	10.3	17.5	32.4
600	22.5	.776	12.8	23.1	11.4
800	15	1.03	13.8	25.6	2.2
1000	2	1.23	14.6	27.8	-12.4
1500	-2	1.61	15.7	30.6	-18.5
2000	-3	1.78	15.1	29.5	-19.2
3000	2.5	1.77	11.5	22.5	-10.3
4000	5.5	1.66	8.6	16.9	-4.5
5000	10	1.43	5.9	11.7	2.8
6000	-35	1.05	1.9	3.8	-38.0
6100	-13	1.02	1.3	2.7	-15.4
7000	-1	.81			-1.8
8000	-1	.63			-1.6
9000		.50			
10000		.40			

BUBBLE I 13-1

$T_{sub} = 29.8°F$

$Q/A = 70,700$ BTU/hr ft^2

$V_{max} = .81 \times 10^{-3}$ CM^3

$V_{sep} = .29 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 1000$

$\theta_{sep} = 3000$

θ	F_d	F_g	F_p	F_s	ΔF_r
200	23	.15	8.4	15.9	15.3
400	10.8	.39	10.3	19.9	0.8
600	-1.3	.58	11.6	22.6	-12.9
800	-1.9	.71	12.5	24.5	-14.8
1000	-1.2	.77	12.6	24.8	-14.2
1500	.4	.76	11.0	21.8	-11.2
2000	.4	.64	8.7	17.3	-8.8
3000	-6.8	.28			-7.1
4000	-6.8	.03			-6.8

BUBBLE J 2-1

T_{sub} = 10.7°F

$V_{max} = 1.05 \times 10^{-3}$ CM^3

$\theta_{max\ vol}$ = 1500 μsec

Q/A = 98,800 BTU/hr ft^2

$V_{sep} = .47 \times 10^{-3}$ CM^3

θ_{sep} = 3000 μsec

θ	F_d	F_g	F_p	F_s	ΔF_r
200	30	.09	4.3	6.7	27.5
400	16	.30	7.7	12.9	10.5
600	13	.53	10.1	17.8	4.8
800	12	.72	11.7	20.4	2.6
1000	11	.87	12.5	23.4	-0.8
1500	3	.99	10.3	20.1	-7.8
2000	-7	.86	7.5	14.7	-15.1
2500	-12.5	.61	4.1	8.1	-17.1
2900	-9.5	.46	1.6	3.1	-11.5
3000	-9.5	.45			-10.0
4000	-2	.09			-2.1

BUBBLE J 3-1

T_{sub} = 20.3°F

V_{max} = 3.67 × 10^{-3} CM^3

$\theta_{max\ vol}$ = 3000 μsec

Q/A = 99,600 BTU/hr ft^2

V_{sep} = 2.10 × 10^{-3} CM^3

θ_{sep} = 7500 μsec

θ	F_d	F_g	F_p	F_s	ΔFr
200	64	.095	8.8	14.8	57.9
400	60	.71	13.6	23.4	49.5
600	50	1.28	16.5	28.7	36.5
800	30	1.76	18.5	32.7	14.0
1000	20	2.19	18.9	31.7	5.0
1500	2	2.99	19.3	34.9	-16.6
2000	-21	3.47	19.1	34.9	-40.3
3000	-7	3.49	17.5	32.7	-25.7
4000	16	3.09	14.6	27.6	-0.1
5000	21	2.95	11.3	21.7	7.6
6000	4	3.01	8.2	15.4	-6.2
7000	-5	2.71	4.9	9.7	-12.5
7500	-25	2.38	1.0	1.8	-28.2
8000	-9	2.00			-11.0
9000	-5	1.33			-6.3
10000		1.05			

BUBBLE J 4-1

$T_{sub} = 29.9°F$

$V_{max} = .63 \times 10^{-3}$ CM^3

$\theta_{max\ vol} = 800$ μsec

Q/A = 99, 700 BTU/hr ft^2

$V_{sep} = .24 \times 10^{-3}$ CM^3

$\theta_{sep} = 2175$ μsec

θ	F_d	F_g	F_p	F_s	ΔF_r
200	22	.12	6.9	12.8	16.0
400	7.3	.42	11.2	21.0	-2.9
600	-4	.57	12.1	22.9	-15.4
800	-8.6	.60	12.0	22.9	-20.1
1000	-2.6	.58	11.4	22.0	-13.8
1500	5.8	.46	8.4	16.8	-3.1
2000	-4.6	.30	4.5	8.9	-9.3
2175	-25	.23			-25.2
2500	-9	.11			-9.1
3000					

APPENDIX D

NONMENCLATURE

C_d	drag coefficient (Eq. 18)
D	diameter of spherical bubble, cm
D_b	bubble base diameter, cm
D_h	bubble dimension parallel to heater, cm
D_{h_1}	horizontal plan view bubble diameter, cm
D_{h_2}	vertical plan view bubble diameter, cm
D_m	mean bubble diameter (Eq. 28), cm
F_d	inertia force, dynes
FgF_g	gravity force, dynes
F_p	pressure force, dynes
F_s	surface tension force, dynes
F_v	viscous drag force, dynes
ΔF_r	net removal force, dynes
g	acceleration of gravity, cm/sec^2
h	local heat transfer coefficient, Btu/hr-°F-ft^2
$\bar{h}$	distance of bubble center of mass above heater surface, cm
$\bar{h}_r$	reduced center of mass
$\bar{h}_{sep}$	center of mass at bubble separation, cm
Δh_b	thickness of disc used to calculate bubble volume, cm
m	mass, gm
N_{Fr}	modified Froude number
N_{Re}	Reynolds number
P_e	pressure outside bubble, $dynes/cm^2$
P_i	pressure inside bubble, $dynes/cm^2$
q/A	heat flux, Btu/hr-ft^2
R_1	radius of bubble curvature at base, cm

R_2	radius of curvature of bubble surface, cm
R_{sm}	maximum radius of spherical bubble, cm
$\dot{R}_{sm}$	velocity of center of spherical bubble, cm/sec
T_b	bulk liquid temperature, °F
T_s	heater strip surface temperature, °F
T_{sat}	saturation temperature, °F
T_{sub}	liquid subcooling, °F
T_{th}	thermistor temperature, °F
U_b	center of mass velocity, cm/sec
v	velocity, cm/sec
$\dot{v}$	acceleration, cm/sec^2
V_b	bubble volume, cm^3
$V_{b_{sep}}$	bubble volume at separation, cm^3
V_r	reduced volume
ΔV	volume of circular disc, cm^3
Z	distance from bubble top to bubble bottom, cm
γ	surface temperature correction factor
Γ	gravitation factor (Eq. 22)
μ	liquid viscosity, gm/cm-sec
ϕ	contact angle between bubble and surface, °
ψ	reciprocal of modified Froude number
ρ	liquid density, gm/cm^3
ρ_v	vapor density, gm/cm^3
σ	surface tension, dyne/cm
θ	time, sec
θ_r	reduced time
θ_{sep}	time from bubble inception to bubble separation, sec