FINAL
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BUBBLE GROWTH PARAMETERS IN SATURATED
AND SUBCOOLED NUCLEATE BOILING

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This final report consists of two parts. Part A, "Bubble Growth Parameters in saturated and Subcooled Nucleate Boiling", was prepared by Thomas R. Rehm, former Project Supervisor. Part B. "Bubble Growth Study in Nucleate Boiling", was prepared by C. W. Chiang, current Project Supervisor.

The study of Part A is based on the analysis of sample bubbles generated in the conventional type of boiling equipment with three different liquids, namely, water, and water solutions of 'sucrose' and 'propanol'.

The study of Part B is based on the analysis of a single bubble individually generated by the use of a laser beam on a tiny thermocouple or a thin flat plate submerged in water. The report concerning this phase of the study has been submitted to the American Institute of Chemical Engineers in the form of a paper for possible presentation at the Bubble and Drop Phenomena Technical Session to be held at Salt Lake City in May, 1967.

Part A

BUBBLE GROWTH PARAMETERS IN SATURATED AND SUBCOOLED NUCLEATE BOILING

I. INTRODUCTION

This report concerns the discussion of the work carried out under Part A of NASA Research Grant No. NGR 06-004-035. The objective of this portion of the research was to extend work done under a previous contract, dealing with the nucleate boiling of water, to fluids which have viscosity and surface tension levels significantly different than water. These fluids were a sucrose-water solution containing approximately 60 weight per cent sucrose, and a normal propanol-water solution containing essentially one per cent weight n-propanol. Throughout the remainder of the report these solutions will be referred to as 'sucrose' and propanol', respectively, with water meaning pure distilled water. These solutions were selected because they exhibited only one change in property at a time. That is, sucrose had a viscosity many times that of water but essentially similar values for its surface tension and density, whereas propanol had a surface tension only one-third that of water while maintaining the same viscosity and density. The analysis of bubble histories for these two solutions when compared to bubble histories for water leads to an evaluation of the effect of surface tension and viscosity on bubble behavior.

It must be mentioned at this time that the bubbles investigated here were obtained by boiling on a heating surface which had a large number of randomly distributed nucleation sites. As a result the conclusions made in this report may differ sharply with data obtained from artificial, single site boiling experiments.

II TECHNICAL DISCUSSION

Prior work in boiling has been concerned with the mechanisms of bubble formation, growth, and separation in both saturated and subcooled conditions. Much of this work has been of a theoretical nature such as that of Zuber (1) and others (2, 3) and has assumed that the bubble shape is spherical. Previous work by Rehm (4) and others (5, 6) has conclusively shown that this is not the case for pure water. A question was raised, though, concerning the behavior and shape of bubbles formed in liquids having physical properties different than water.

An examination of the forces considered to be acting on bubbles will help in indicating the relative importance of the magnitude of the physical properties of the liquids used in boiling research. The most obvious force acting on a bubble is that due to buoyancy. This force is calculated from

$$F_b = \frac{g}{g_c}(\rho_\ell - \rho_v)\ V_b - V_c \tag{1}$$

Where V_b is the total bubble volume and V_c is the volume of the bubble contained in the cylindrical section located above the region of contact between the bubble and the heating surface. Thus the effective portion of the bubble acted upon by gravity causing removal from an upward facing surface may be very small.

The use of this partial volume is based on the conclusion reached by Johnson, et al, (5) that the micro-layer of liquid initially found between the vapor bubble and the surface evaporates very rapidly leaving a dry area underneath the bubble. As such, when the area of attachment approaches the projected area of the maximum horizontal bubble diameter the magnitude of the buoyant force is quite small. For this situation the magnitude of the liquid density, ρ_ℓ , plays only a minor part in the determination of the overall force balance.

In the inertia force term, that is,

$$F_d = \frac{d}{d\theta}\left(\frac{\alpha}{g_c} \rho_\ell V_b U\right) \tag{2}$$

where U is the bubble center-of-mass velocity, and α is a shape factor varying from 0.5 to 1.0, the liquid density is the only physical property directly involved. Since the density was essentially the same for the bubbles formed in water, sucrose, or propanol, no variation due to density alone should be detectable. However, the magnitude of the bubble volume and bubble velocity is influenced significantly by the viscosity and surface tension of the liquid, and as a consequence the inertia force is affected.

Two force terms which are strongly influenced by the magnitude of the surface tension are the pressure force and surface tension force. The pressure force is

$$F_P = \frac{\pi}{2} \frac{D_b^2}{R_t} \sigma_{sat} \tag{3}$$

where D_b is the bubble attachment diameter, R_t is the radius of a sphere tangent to the top of the bubble and σ_{sat} is the value of the vapor-liquid surface tension at the boiling temperature of the liquid. The surface tension force is

$$F_s = D_b \pi \sigma_{sat} \sin \phi \tag{4}$$

where ϕ is the angle between the horizontal heating surface and the tangent to the bubble surface at the base. At first glance it appears that both of these forces are directly proportional to the surface tension, however, the base diameter itself is dependent on the surface tension so that both these forces are complex functions of the magnitude of the surface tension.

The viscosity of the liquid becomes important in the viscous force expressed by

$$F_v = \frac{6}{g_c} \pi \beta \mu D_h U \tag{5}$$

where β is a factor relating the portion of the bubble affected by the relative motion between the vapor bubble and the surrounding liquid, and μ is the viscosity of the liquid at the bulk liquid temperature. In previous work with water the viscosity has been so low that in comparison with the other force terms the viscous force is negligible. In addition the magnitude of the relative velocity to be used is in doubt because of the as yet not well understood behavior of the fluid immediately adjacent to a forming and growing bubble.

A frame by frame analysis of bubble behavior in sucrose and propanol solution when compared to a similar analysis of water bubbles should clarify to a certain extent the influences of surface tension and viscosity on the above mentioned forces.

III EXPERIMENTAL

The boiling experiments carried out using sucrose and propanol solutions were performed in the same apparatus and on the same heating surface used in the previously reported water experiments (4). Briefly, the heating surface was a nichrome strip 0.005 inches thick, 0.080 inches wide, and 0.688 inches long, finished with #600 emery paper and then polished using 2/0 emery polishing paper. The strip was imbedded in epoxy so that only the upper surface was in contact with the liquids. Heater power was from a 6v dc automobile battery adjusted to give a nominal heat flux of 50,000 or 100,000 Btu/hr-ft^2.

The prepared sucrose or propanol solution was put into the boiler apparatus and brought to saturation conditions by means of heat added from a bulk heater. These saturation conditions were maintained for some thirty minutes. The saturated boiling condition on the strip heater was then photographed using a Fairchild HS101 camera operating at a maximum framing rate of 8000 frames/second. The bulk liquid was then allowed to cool to temperatures 10, 20, or 30 F^{o} below the saturation temperature and photographs taken at each subcooling.

Bubbles were then selected from each of the 100 foot strips of movie film obtained for each condition of subcooling, liquid, and heat flux. The bubble outline was then traced from a projection arrangement giving an enlargement of some 50X. The time dimension was obtained from 400 cps timing marks on the film strip. The dimensions of the bubble were then obtained from the tracing. Appropriate bubble parameters were then punched on to cards for data input to a Burroughs B5500 digital computer where a series of programs provided numerical output for center-of-mass, volume, velocity, acceleration, reduced-time, -volume, and -height, as well as the four forces and their sum for buoyancy, surface tension, pressure, and inertia.

The sucrose solution was prepared by mixing together weighed amounts of doubly distilled water and food grade sugar. Its actual composition was determined by obtaining its refractive index and then its weight per cent from data tabulated in the literature (7). During the experimental boiling runs a 10 cc sample of sucrose solution was taken immediately after each photographic run so that actual solution conditions would be known. The viscosity was obtained by cross-plotting the data from tables in Perry (8) as a function of the weight per cent composition.

The propanol solution was made by placing a known weight of double-distilled, degassed water into the boiling apparatus, sealing the apparatus except for a condensor outlet, and then adding sufficient reagent grade normal propanol to make a 1.0 weight per cent mixture of n-propanol in water. The mixture was then brought to a boil and by the boiling action became thoroughly mixed. The condensor arrangement essentially prevented loss of the more volatile propanol during the experimental boiling procedure.

The experimental conditions during the sucrose and propanol runs are shown in Table I in terms of the range of liquid properties as compared to the water runs reported previously.

TABLE I

Range of Experimental Conditions

Liquid	Heat flux, Btu/hr-ft^2	Subcooling F^o	Viscosity cp	Surface tension* ergs/cm^2	Number of bubbles analyzed
Sucrose	50,000	1.5	3.7	64.2	2
		11.7	4.3	"	2
		21.4	4.8	"	2
		31.4	5.7	"	1
	100,000	1.1	4.4	64.2	1
		11.6	5.0	"	5
		20.9	5.7	"	3
		31.1	6.6	"	3
Propanol	50,000	0	0.31	19.3	3
		10.3	0.33	"	2
		18.0	0.35	19.3	2
	65,000	28.0	0.37	"	3
	100,000	0	0.31	19.5	2
		10.0	0.32	"	3
		20.0	0.35	"	3
		30.0	0.38	"	3
Water	50,000	0.1	0.30	59.8	2
		10.1	0.32	"	2
		20.1	0.34	"	2
		30.0	0.36	"	2
	100,000	0.6	0.30	59.8	2
		10.0	0.32	"	2
		20.4	0.34	"	2
		29.6	0.36	"	2

* At boiling point of liquid

IV RESULTS

The bubble size data obtained from the enlarged tracings were used to obtain volumes by the method of summation of circular discs. Thus the volume of each bubble was obtained at each frame time. In the same process the bubble center-of-mass position was also obtained. A plot of this raw data for volume or height versus time from bubble formation resulted in some scatter about a reasonably smooth curve. Therefore a least squares fit to the volume versus time and height versus time data was made using a sixth order fit. These expressions were then used to obtain the bubble velocity and acceleration, as well as the time rate of change of bubble volume. This calculated data was then used to give the individual forces at each frame time for all the sucrose and propanol bubbles listed in Table I. The digital print out of all these results is in the possession of the author from whom selected data may be obtained by request (9).

The results of the calculations indicated a wide range of maximum bubble volume, bubble height, and length of time from bubble formation to separation from the surface. As such, a comparison of bubble behavior made on actual size, height, and time tended to be inconclusive. This difficulty is partially handled by using the separation conditions as a basis and then making the conditions at all other points a ratio of the separation values. Thus for bubble time the reduced variable becomes

$$\theta_r = \frac{\theta}{\theta_{\text{separation}}} \tag{6}$$

for reduced volume

$$V_r = \frac{V}{V_{\text{separation}}} \tag{7}$$

and for reduced height

$$h_r = \frac{h}{h_{\text{separation}}} \tag{8}$$

An indication of the scatter obtained from the experimental data is shown in Fig. 1 in which the length of time of bubble attachment is plotted versus liquid subcooling.

The trend of the reduced volume and reduced height as a function of reduced time is shown in Figs. 2 and 3. The bubbles used in these figures were selected because all three had almost the same value for their maximum volumes. Similar relations are obtained for bubbles of other volumes indicating that the reduced parameter approach is a valid method of overcoming the scatter in the values of actual volume, height, and lifetime.

The cumulative affects of liquid properties on the forces is shown by a force summation versus time as presented in Fig. 4 for the same three similar maximum volume bubbles as used previously. Again these are typical results which hold in general for bubbles having non-similar volumes.

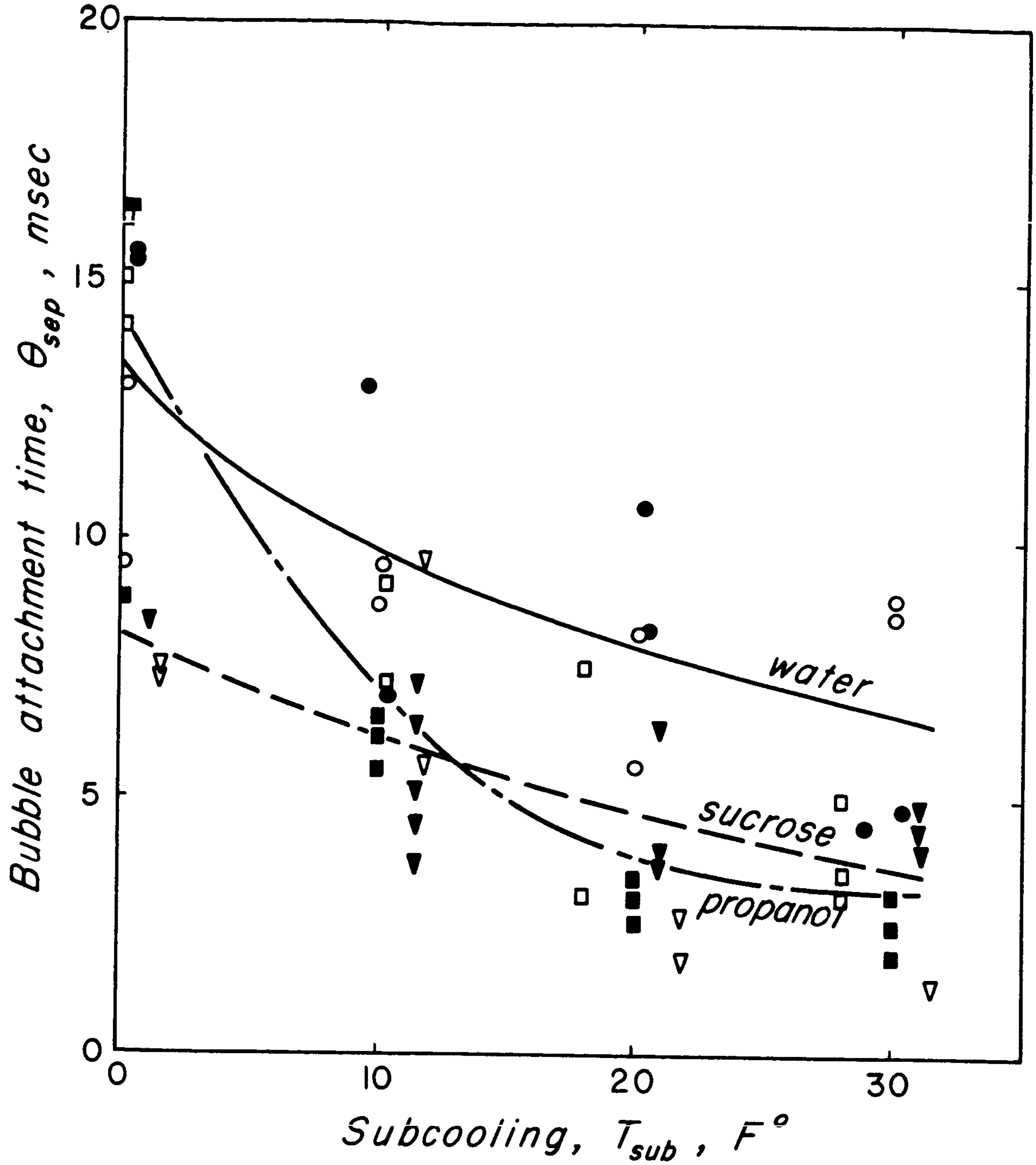

Figure 1. Comparison of bubble lifetimes for water, o, sucrose, ▽, and propanol, □, for heat fluxes of 50,000 (open), and 100,000 (solid) Btu/hr-ft^2.

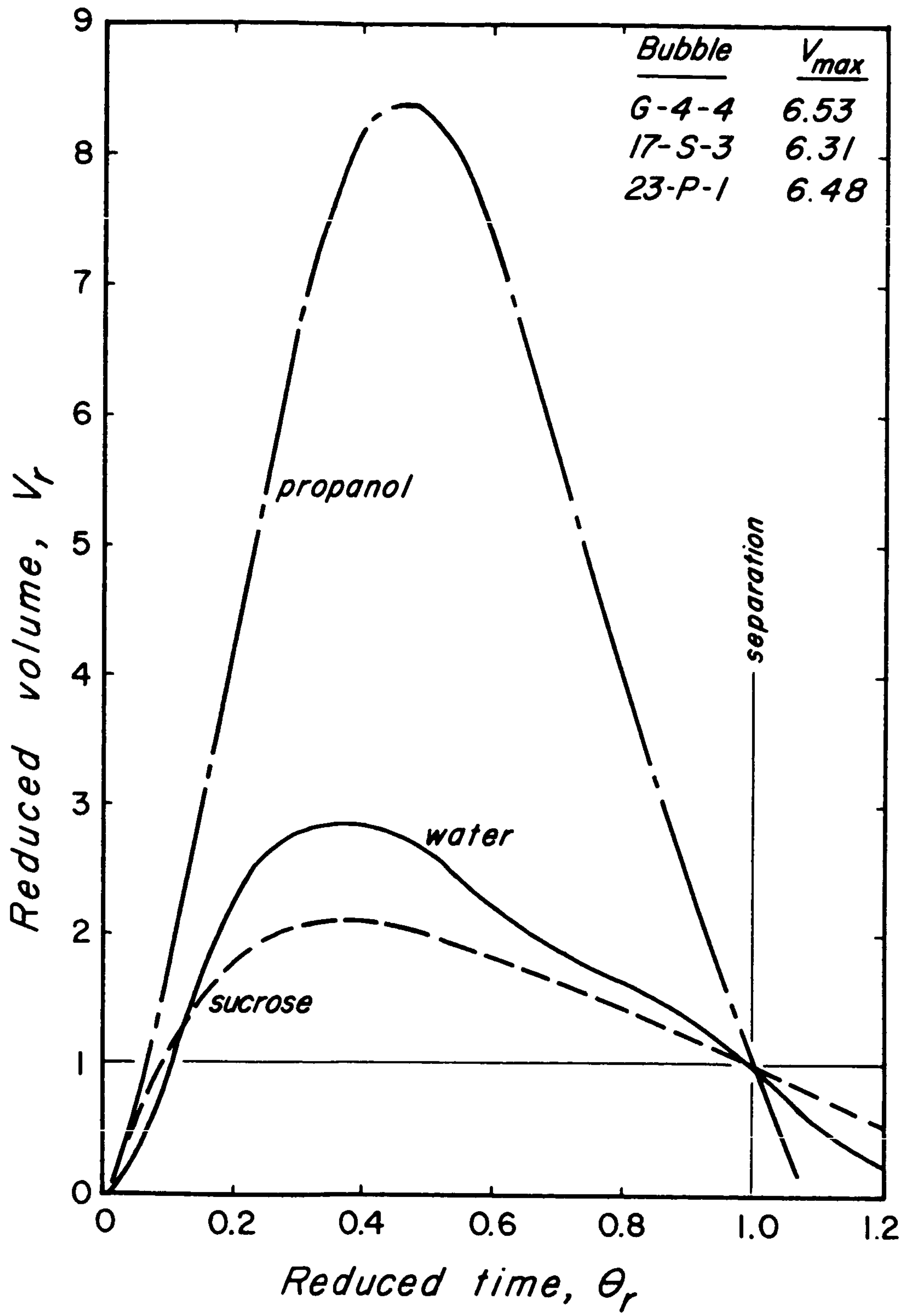

Figure 2. Comparison between reduced volume and time for bubbles having similar maximum volumes at T_{sub} = 20 F° and q/A = 100,000 Btu/hr-ft^2.

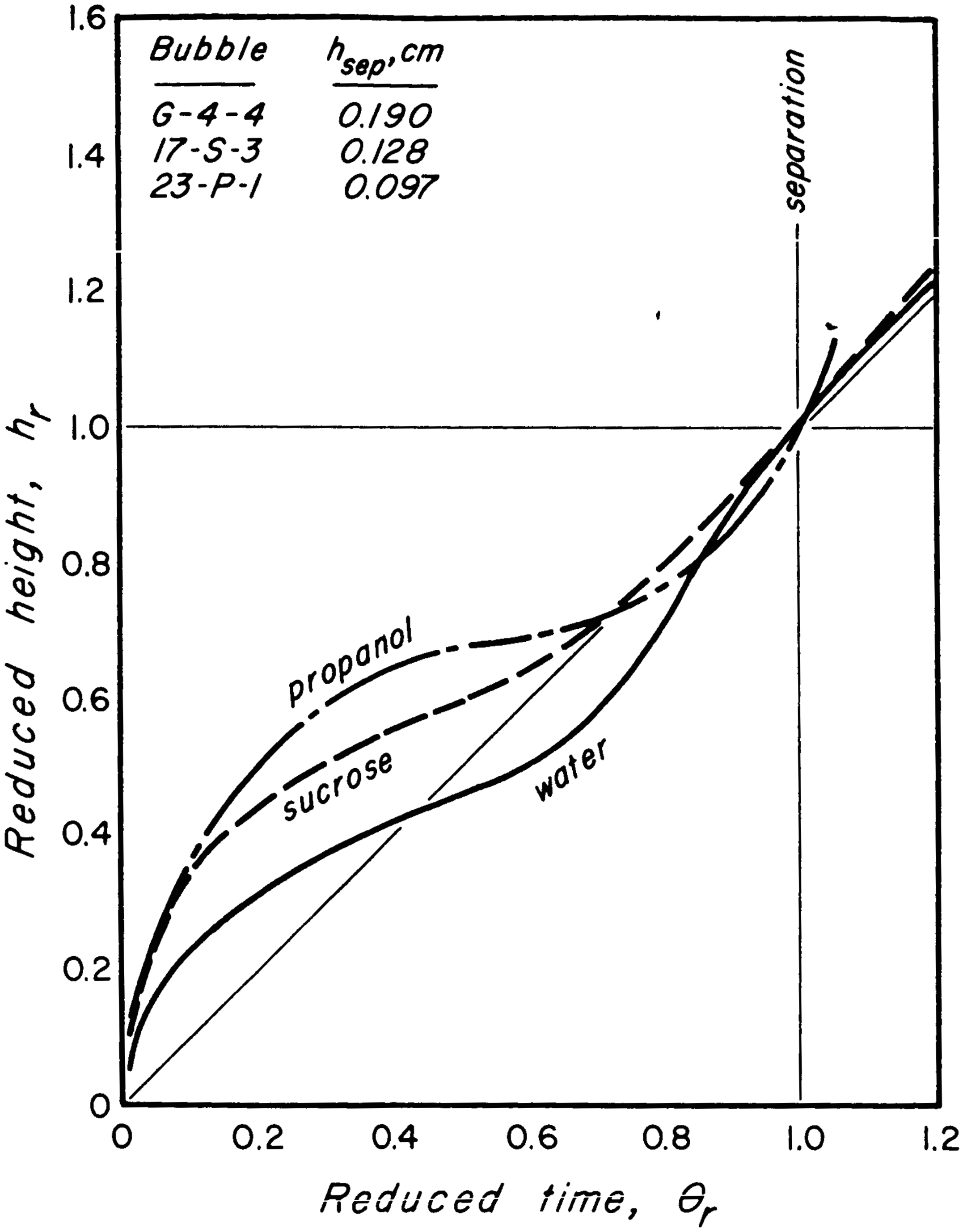

Figure 3. Comparison between reduced height and time for bubbles having similar maximum volumes at T_{sub} = 20 F° and q/A = 100,000 Btu/hr-ft^2.

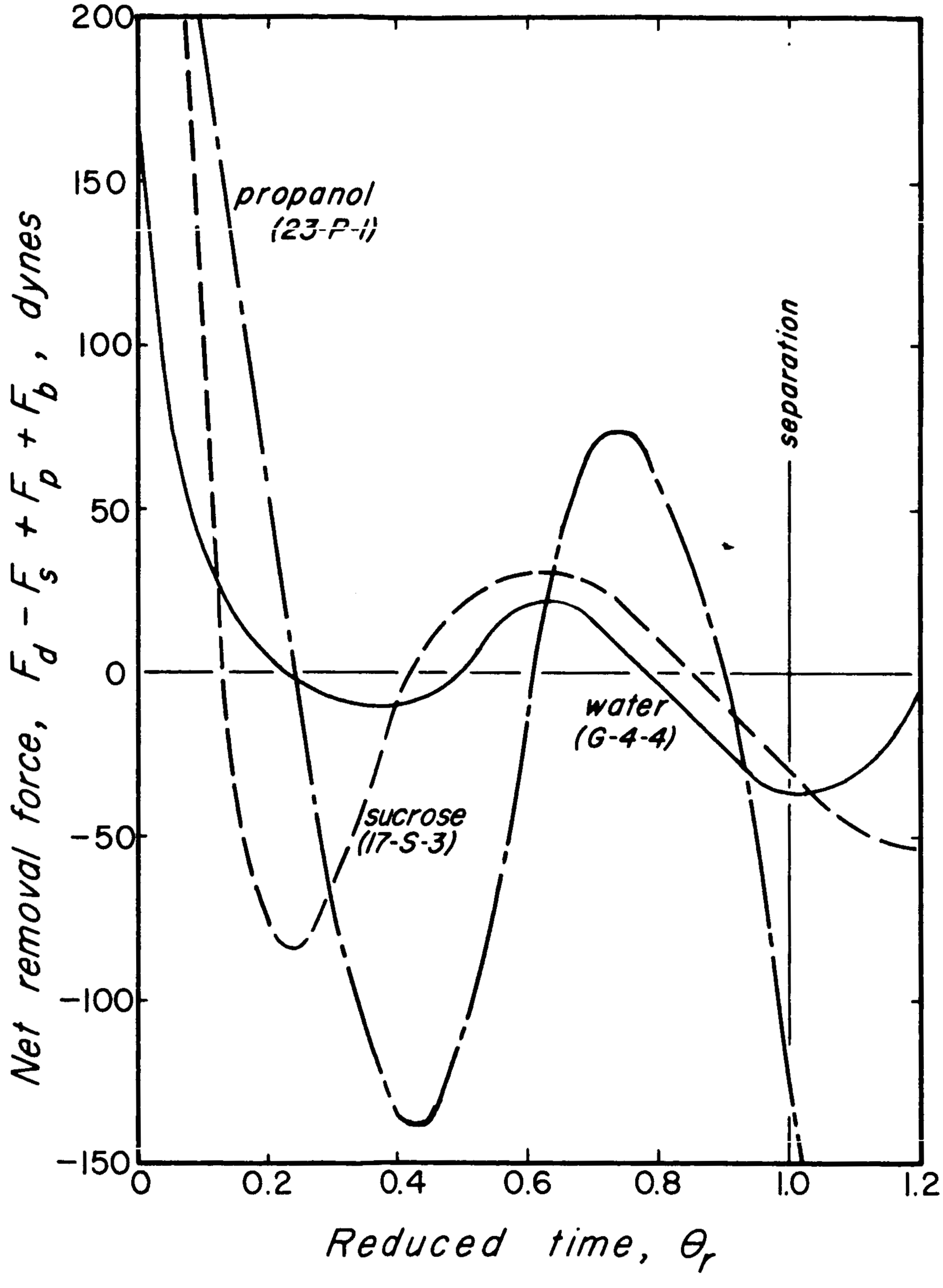

Figure 4. Comparison between summation of forces for bubbles having similar maximum volumes at T_{sub} = 20 F° and q/A = 100,000 Btu/hr-ft^2.

A typical force versus reduced time plot for a sucrose bubble is shown in Fig. 5, where the relative magnitudes of the various forces can be seen. Again this is typical of the force-time plots for other bubbles.

If all the bubbles for a particular liquid regardless of the subcooling or heat flux are averaged together the results shown in Table II are obtained.

Again because of the wide range of bubbles observed the results shown here are only selections to represent trends. A detailed analysis of each bubble in comparison with others is needed to obtain a more quantitative measure of the influence of liquid properties on bubble behavior. Such an analysis is beyond the scope of the current research project. Future plans, however, are aimed at obtaining these quantitative correlations.

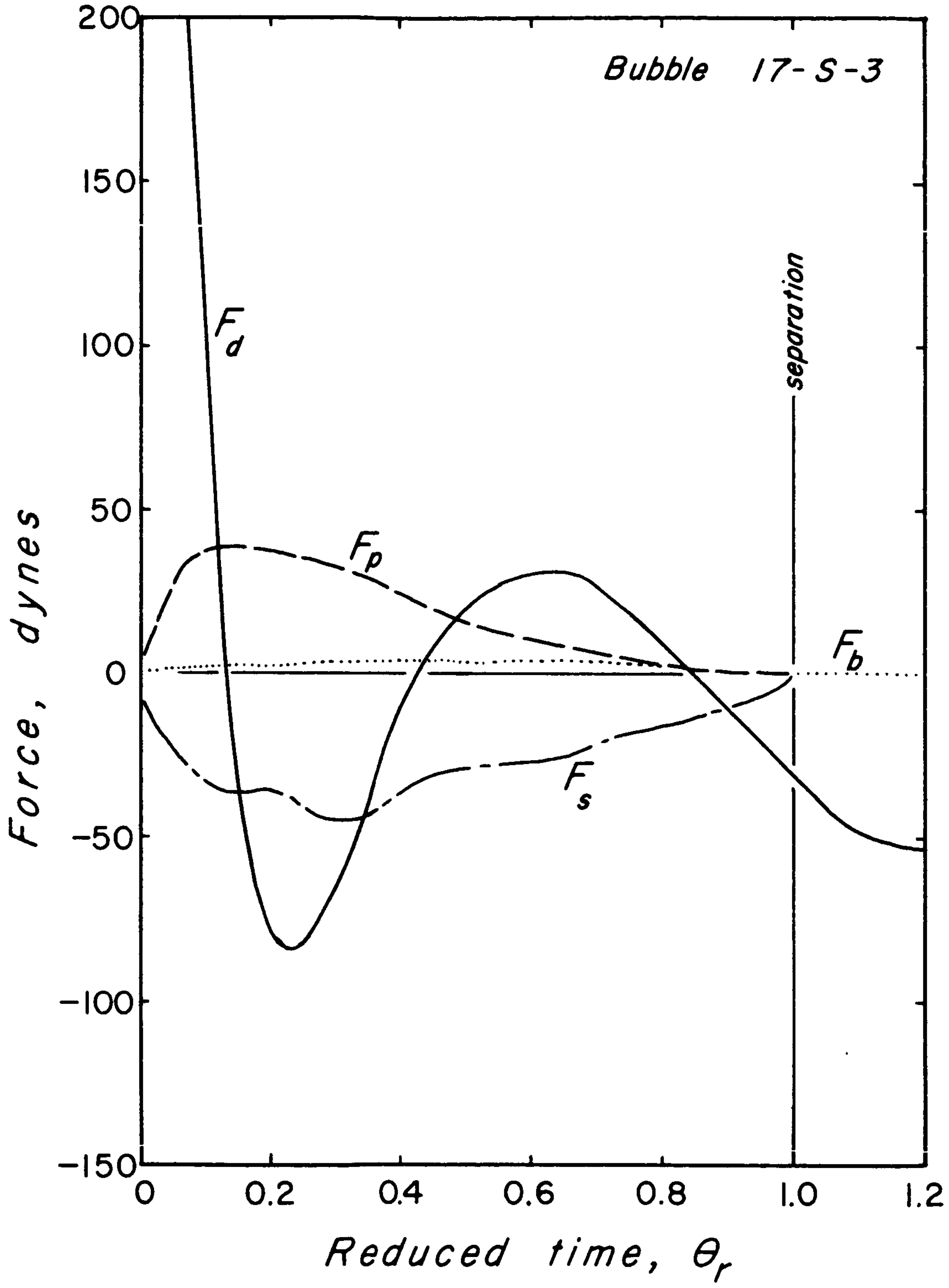

Figure 5. Force - time plot for a typical sucrose bubble.

TABLE II

Average Bubble Parameters

Parameter	Water	Liquid Sucrose	Propanol
θ_s, msec	9.5	5.2	6.9
h_s, cm x 10^2	18.9	11.4	15.2
V_s, cm^3 x 10^3	3.64	2.94	8.27
V_m, cm^3 x 10^3	8.52	5.20	13.62
μ, cp	0.34	5.1	0.34
σ, $ergs/cm^2$	66	66	20

V DISCUSSION

The wide range in bubble parameters observed at a given set of experimental conditions makes any quantitative correlation for the affects of surface tension and viscosity on bubble behavior essentially impossible until more bubbles are analyzed by the frame-by-frame procedure used here. As a result the following discussion will be of a qualitative nature.

Examination of the bubble attachment time for various subcoolings, as shown in Fig. 1, indicates conclusively that shorter attachment times are obtained for the larger subcoolings. For water and propanol this is associated with a significant decrease in bubble size. However, sucrose bubbles have essentially the same maximum volume regardless of subcooling. Thus the shorter bubble attachment time for sucrose bubbles at the larger subcoolings is apparently due solely to the viscous properties of the liquid. This is partially explained from the observation that the volume of the sucrose bubbles is only 50 to 60 per cent that of the smaller water bubbles. The additional force needed to push the more viscous sucrose away from the growing bubble accounts for this, leaving less of the gross amount of energy available to the bubble expansion and growth process.

The sharp decrease in attachment time with subcooling for the propanol bubbles is explained by the ease with which bubbles can form in a low surface tension liquid. At saturated conditions propanol bubbles are on the average 1.7 times the volume of water bubbles, indicating that more of the gross bubble energy is available for expansion against the reduced surface resistance. That is, if surface tension is considered, as it should be, as the measure of the amount of work needed to create a given amount of new surface area, i.e. having units of ergs/cm^2, then it is obvious that the surface area for low surface tension situations should be greater than for high surface tension situations. Comparison between the properties of water and propanol solutions bears this out, with a three-fold decrease in surface tension giving a 1.7 increase in volume (this is approximately $\sqrt{3}$ which brings in the relation between spherical surface area and volume).

For the subcooled cases the bubble expands with such ease that it easily penetrates through the superheated liquid layer adjacent to the heating surface. In so doing the upper portion of the bubble is exposed to subcooled liquid and heat transfer and condensation occur causing a reduction in bubble volume. Naturally as the subcooling increases this process is more pronounced so that very small bubbles are observed more often than in water or sucrose at similar subcoolings.

It is well to recall at this time that the results reported here are for bubbles of Type 1. Bubbles forming on a boiling surface can be of four types (10), namely Type 1 in which bubbles nucleate, grow, and separate in undisturbed liquid, Type II where the bubbles come from a single site at a regular, fixed rate, Type III in which the bubbles nucleate and grow but remain attached to the surface for long periods of time, and Type IV bubbles which coalesce and form large complex bubbles and are essentially impossible to analyze. The ratio of Type I bubbles observed to the total number of bubbles produced is perhaps only one per hundred for the boiling conditions encountered in this research. No Type II bubbles were observed in viewing perhaps some 25,000 bubble incidents.

The behavior shown in Fig. 2 in which the reduced volume for the propanol bubbles is approximately three times that for water can also be explained by the ease with which bubbles can grow and penetrate the superheat layer in low surface tension liquids. The sucrose bubble is lower than the bubble formed in water because of the retarding affect the more viscous liquid has on bubble motion. As such the sucrose bubble volume at separation is essentially only one half that of the maximum volume for these conditions. Similar positions for the V_r vs θ_r curves are obtained for bubbles which have the same volume at separation.

The reduced height as a function of reduced time shown in Fig. 3 is for the same bubbles as used in Fig. 2 in which the three bubbles had similar maximum volumes. Here it can be seen that the propanol bubble is in a much higher position than the sucrose or water bubbles during the first half or so of its lifetime.

This again substantiates the easy growth explanation in low surface tension liquids. The curves shown in Fig. 3 are typical of all the bubbles analyzed, a difference being noted only for different subcoolings.

The comparison between the algebraic sum of the removal and retentive forces for the previously mentioned bubbles is shown in Fig. 4. The variation in observed bubble parameters makes it relatively difficult, if not impossible, to draw any valid conclusions, since the net force plot for other bubbles may be widely different than as shown here. What can be said, however, is that the four forces associated with buoyancy, inertia, pressure, and surface tension are insufficient to account for bubble behavior. Note that for all three of these bubbles the calculated net removal force is negative at the time separation occurs, when physically it should be at least zero if not indeed positive. Two explanations are possible, the viscous force in some way plays an important role in the force balance (it has not been included in Fig. 4 because of lack of experimental data needed to calculate it) or that in the inertia force the shape factor, α , is much less than unity. Additional experimental work will be required to elucidate this force balance anomaly.

The relative magnitudes of the various forces associated with buoyancy, inertia, pressure, and surface tension are shown in Fig. 5. It can be seen that the buoyancy force is entirely insignificant throughout the bubble lifetime as postulated in section II of this report. The wavey nature of the surface tension force is a result of variations in the base diameter and contact angle and has been observed for most bubbles in water and propanol as well. The error in the magnitudes of these forces is reasonably large particularly for the inertia force, however, the general trend of the force plots for all the bubbles analyzed is as shown for the sucrose bubble presented here.

The influence of the heat flux at the heater strip surface has little significance on bubble behavior. Small bubbles and large bubbles are obtained at both heat fluxes in all the fluids investigated. The only noticable affect of heat flux was that in sucrose no bubbles could be obtained at a heat flux of 50,000 Btu/hr-ft^2 and a subcooling of 30 F$^{\circ}$. However, an increase in heat flux to 65,000 Btu/hr-ft^2 did produce boiling which was similar to that obtained under other experimental conditions.

Although the above discussion has been qualitative in nature it has brought out the influence of viscosity and particularly surface tension on the behavior of bubbles produced in saturated and subcooled nucleate boiling.

VI CONCLUSIONS

The specific conclusions enumerated here have been obtained from the analysis of numerous plots of bubble data obtained in water, sucrose and propanol. Many of these conclusions are presented without explanation of their cause.

1. Sucrose bubble lifetime is only 40 to 50 per cent that of water for all subcoolings.
2. Propanol and water bubbles have similar lifetimes at saturated conditions, however, at 10 F^o subcoolings the propanol lifetime has decreased by 30 per cent, and at 20 and 30 F^o it has decreased by 50 per cent over that for water.
3. For propanol an increase in heat flux from 50,000 to 100,000 Btu/hr-ft^2 reduces average bubble lifetime by only 10 to 15 per cent at all subcoolings, while for water and sucrose the reverse seems to be the trend.
4. For subcooled bubbles propanol gives bubbles with a volume from 2.3 to 6.0 times that for water bubbles at the same bubble time, while sucrose gives bubbles only two-thirds the size of water bubbles.
5. Maximum volume is reached at essentially the same time for subcooled bubbles of similar size in water, sucrose, and propanol, however, a decrease in time to reach maximum volume by a factor of 4.3 is associated with

a decrease in maximum volume by a factor of approximately six.

6. On the average sucrose and water bubbles have the same volume at separation.
7. At saturation propanol bubbles have separation volumes some two times greater than water bubbles.
8. Water and sucrose bubble maximum volumes and separation volumes are essentially unaffected by subcooling.
9. The reduced volume for subcooled sucrose bubbles is some 50 per cent less than that for water during mid-lifetime.
10. The reduced volume for subcooled propanol bubbles is some 1.8 times greater than for water during the middle of the bubble lifetime.
11. A fifteen-fold increase in liquid viscosity decreases maximum bubble volume an average of only 40 per cent.
12. A 3.3-fold decrease in surface tension increases bubble maximum volume an average of 60 per cent.
13. No significant effect of the magnitude of the heat flux appears evident as to the bubble size, attachment time, or force analysis for bubbles of water, sucrose and propanol.

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Part B

BUBBLE GROWTH STUDY IN NUCLEATE BOILING

LIST OF FIGURES

INTRODUCTION

Most experimental investigations [1,2,3,4] in nucleate boiling are based on the study of high speed photographs of many bubbles generated in a pool of saturated or subcooled liquids. Usually one particular bubble out of hundreds is chosen to be analyzed, the growth rate during and after the initial growth shape may be correlated with some important parameters, such as surface tension, viscosity, inertia, the surface condition of the heating surface, etc. Heat transfer may also be evaluated under various conditions.

Most analytical results [5,6,7,8] are considering the bubble to be perfectly spherical, then the Rayleigh or extended Rayleigh equation is to be solved to give the dynamics of the bubble growth in terms of various parameters such as surface tnesion, viscosity, and inertia, etc. Heat balance equations may also be written for the bubble to evaluate the rate of heat transfer.

Ultimately the analytical and experimental results are to be correlated such that the basic important parameters can be tied into the boiling heat transfer and the bubble growth dynamics into deduced usable forms for practical applications.

The assumption of the sphericity of the generated bubbles in conventional boiling, namely, the bubbles generated from the heated flat surface, is not at all very good, especially during the initial growth phase of the bubble, this is due to the characteristics of the heating surface. Furthermore, the single bubble chosen to be analyzed as in the experimental results does not represent a single bubble in an undisturbed large medium of the liquid. The hydrodynamics of one bubble is certainly influenced by the presence of many other bubbles generated before it as in the case of the conventional boiling.

APPROACH OF THIS STUDY

It is the intention of this study to generate a single spherical bubble by the use of a laser beam in an undisturbed liquid medium where the hydrodynamic influence of other bubbles is absent. Experimental observations of the bubble growth, particularly the initial growth phase, may be obtained by different subcooled conditions, energy inputs and eventually various liquids, through high speed photography of single bubble growth. If the sphericity of the growing bubble is good, the observed experimental growth rate may be compared to the analytical results which are based on the analysis of a spherical single bubble with no consideration of hydrodynamic influence of other bubbles.

In order to maintain a spherical geometry, a spherical thermocouple of approximately .012" diameter was formed by welding two .003" iron-constantan wires together. The thermocouple leads were connected to the oscilloscope such that the milivoltage output versus time can be traced after the laser beam hit the junction, thus the temperature history of the thermocouple is recorded. The motive of this instrumentation is to provide a means of measuring the heating surface temperature in addition to the spherical geometry. The rate of heat transfer to the bubble, hopefully, may be evaluated quantitatively. A second thermocouple was installed about .025" distance apart from the first one which was hit by the laser beam, (the thermocouple leads are also connected to the oscilloscope) this provides a means of measuring the temperature in the neighborhood of the interface between the vapor and the liquid. Hopefully, the thermal boundary layer thickness around the interface may be evaluated.

A single bubble was initiated on a thin flat metal plate which was a central part of the bottom plate of the liquid container by the use of a laser beam hitting the thin plate from underneath. A thermocouple was installed about a distance of .030" above the thin plate in the hope of measuring the temperature of the vapor in the bubble and also the temperature in the neighborhood of the interface of the vapor and the liquid.

Although some quantitative measurements have been made, these only represent a rather qualitative picture of all experiments and serve as more or less a prelude of future research. The emphasis right now is to see the feasibility of the initiation technique of a single bubble, preferably spherical, by the use of a laser beam. Ultimately in the future, quantitative analysis are to be considered for many different conditions.

INSTRUMENTATION AND EQUIPMENT

A boiler chamber consisting of a one-half-inch thick aluminum bottom plate containing a heating element and six-inch square glass sides was constructed for purposes of this study. A raised center section provides for the installation of special thermocouple fixtures. A laser microposition was designed and fabricated to be attached to the underside of the chamber to permit accurately positioning the laser with respect to the thermocouples. The set-up is shown in Figure 1.

The laser is a Hughes model 200 ruby with an output energy of about one joule at a wavelength of 6943 angstroms. The output energy can be varied by varying the firing voltage. At 1350 volts the output is maximum at about one joule. The threshold voltage, where the laser just operates, is at about 900 volts at room temperature. The output varies from zero to one joule as the excitation voltage is changed from 900 to 1350 volts. The laser output is quite sensitive to ambient temperature, and slight variations in output from shot to shot are not uncommon. It appears that it would be advantageous to provide temperature control and power monitoring

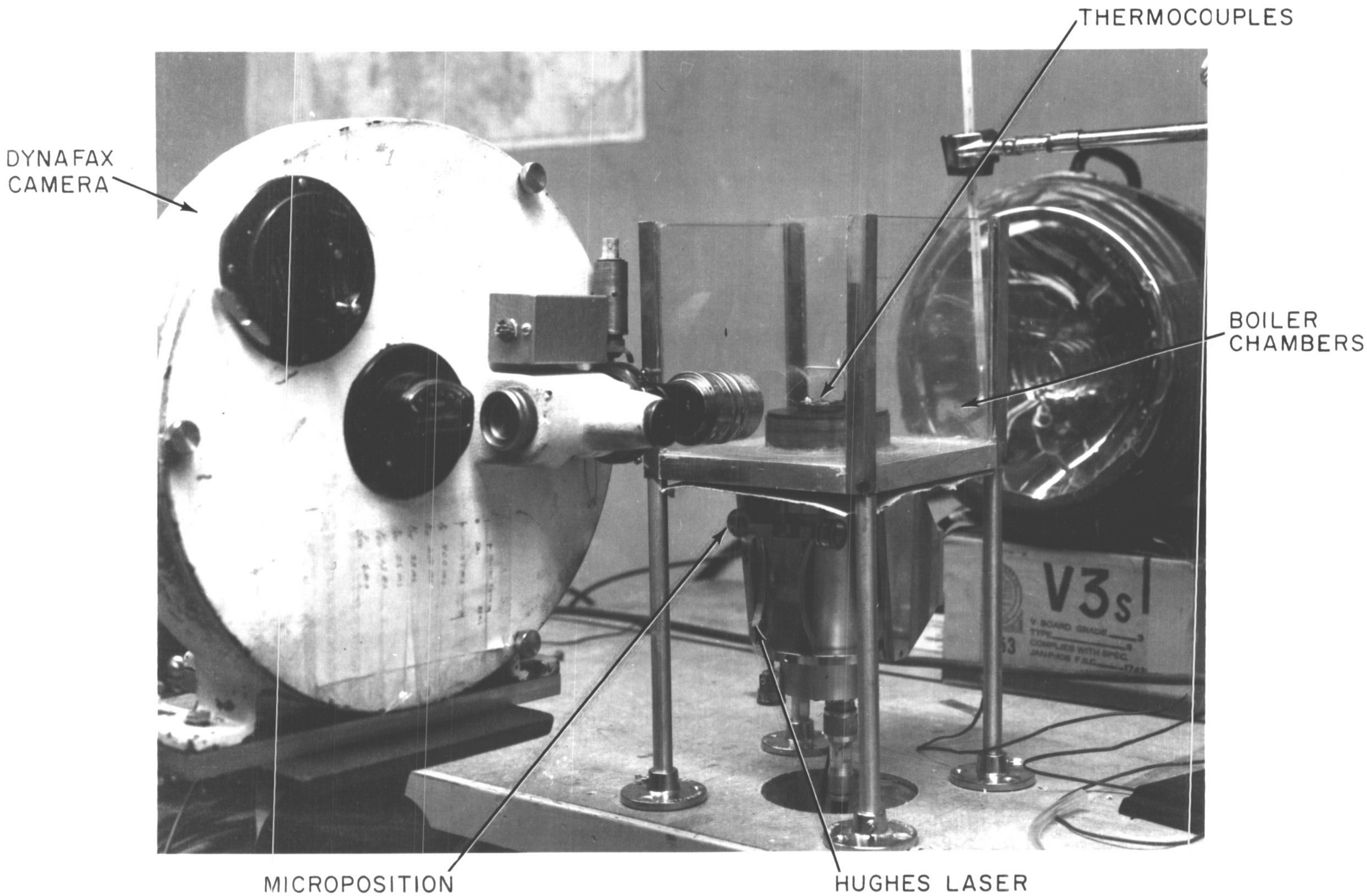


Figure 1. Equipment Set-up

facilities for future work.

The thermocouple output voltage was amplified by a set of six Kintel D. C. amplifiers and recorded photographically with a Tektronix type 547 oscilloscope equipped with a polaroid oscilloscope camera. The input to the oscilloscope was filtered with a single stage R-C filter to eliminate frequencies higher than about 5000 cycles. The oscilloscope was triggered at the same time the laser was fired by means of a trigger pulse derived from the laser control system. The oscilloscope and amplifiers are shown in Figure 2.

A Beckman & Whitley Dynafax camera was used to photograph the bubble growth. The camera was operated at 25,000 frames per second with an exposure time of 1.25 microseconds per frame. Illumination was provided by means of a xenon flash tube mounted in a parabolic reflector. The flash tube was placed behind the chamber to back light the bubble. A shadowgraph is then obtained with sharp edges which can be accurately measured to determine growth rate. The camera-chamber setup is also shown in Figure 1. A view of the entire control system is shown in Figure 3.

Test photos indicated that the flash lamp exposes 5 frames prior to initiation of the laser. The laser beam is then on for about 20 frames when operated at peak power. Most of the energy is delivered within the first 8 or 10 frames. Thus it may be assumed that the oscilloscope trace starts between the fifth and sixth frame of the dynafax record. Test shots made to determine laser operating time were on Eastman #2475 film. Test runs were made on Tri-X film, which is insensitive to the laser light.

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental Conditions

A number of experimental runs were made under various conditions to determine the feasibility of using the laser system described previously for initiating

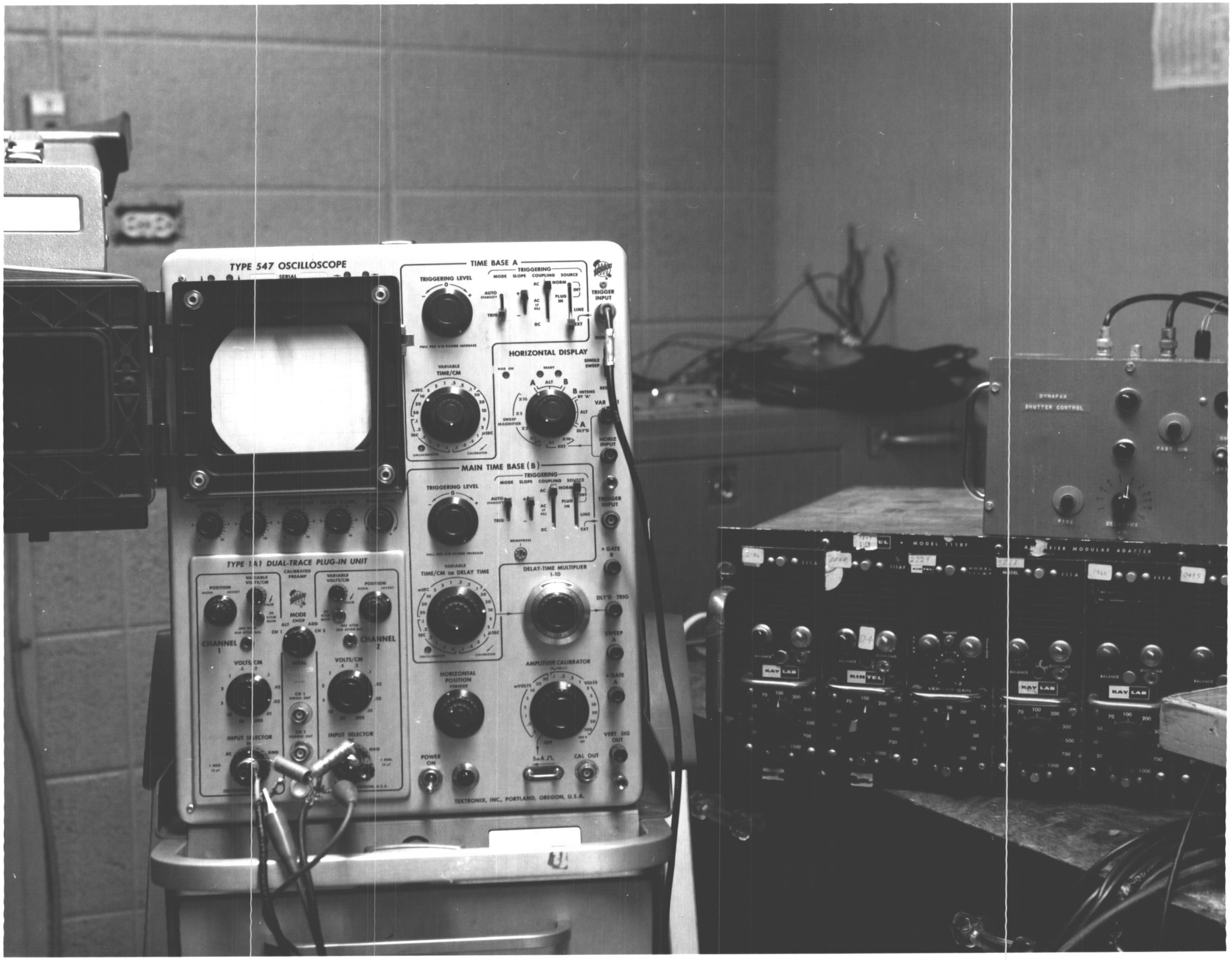


Figure 2. Oscilloscopes and Amplifiers

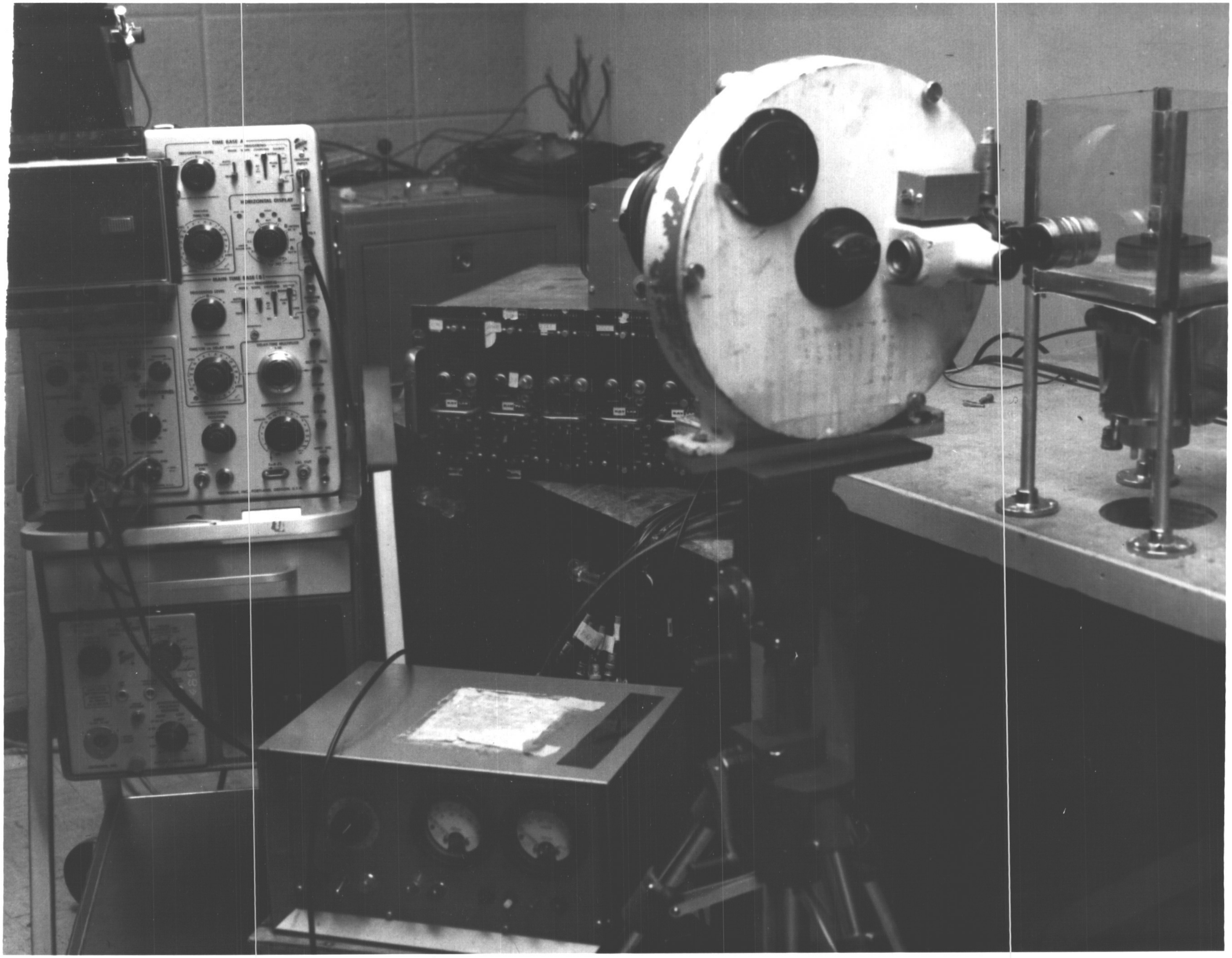


Figure 3. The Entire Control System

a single bubble. The experiments were performed under conditions as stated in the approach of the study all in subcooled water. Various conditions for a number of experimental runs are listed in Table I.

TABLE I. Conditions for Experimental Runs

Run No.	7	8	9	10	11	2A	3A	4A	5A	1B	1B
Laser Voltage	1200	1200	1200	1200	1200	1050	1100	1150	1200	1350	1200
Water Temperature	94	90	85	80	70	94	94	94	94	94	94
T. C., ^{o}F	565	225	225	225	T.C. Broken						

Typical bubble growth pictures of the first 12 frames are shown in Figure 4 through 6. The 12 frames represent the initial growth phase in a time period of 480 microseconds duration.

Figure 4 shows that a single bubble grew around a thermocouple junction after hit by the laser beam. The temperature of the water bath was kept at 94^{o}C and the laser voltage was 1150. The picture represents the experimental run 4A. The sequence of the bubble growth clearly shows that the bubble is quite spherical in shape except for the first two frames where one side of the bubble is somewhat out of shape. The bubble keeps growing at a rather slow pace after the 12th frame. After the 22nd frame the bubble begins to be oblong in shape and stays at about the same size after the 34th frame.

Corresponding to the conditions set forth for Figure 4, or the experimental run 4A. Figure 7 shows the poloroid picture of the temperature trace of the thermocouple hit by the laser beam and the temperature trace of the second thermocouple about .025-inch distance apart from the first one. The peak temperature of the first thermocouple is about 565^{o}F with 5 mv.

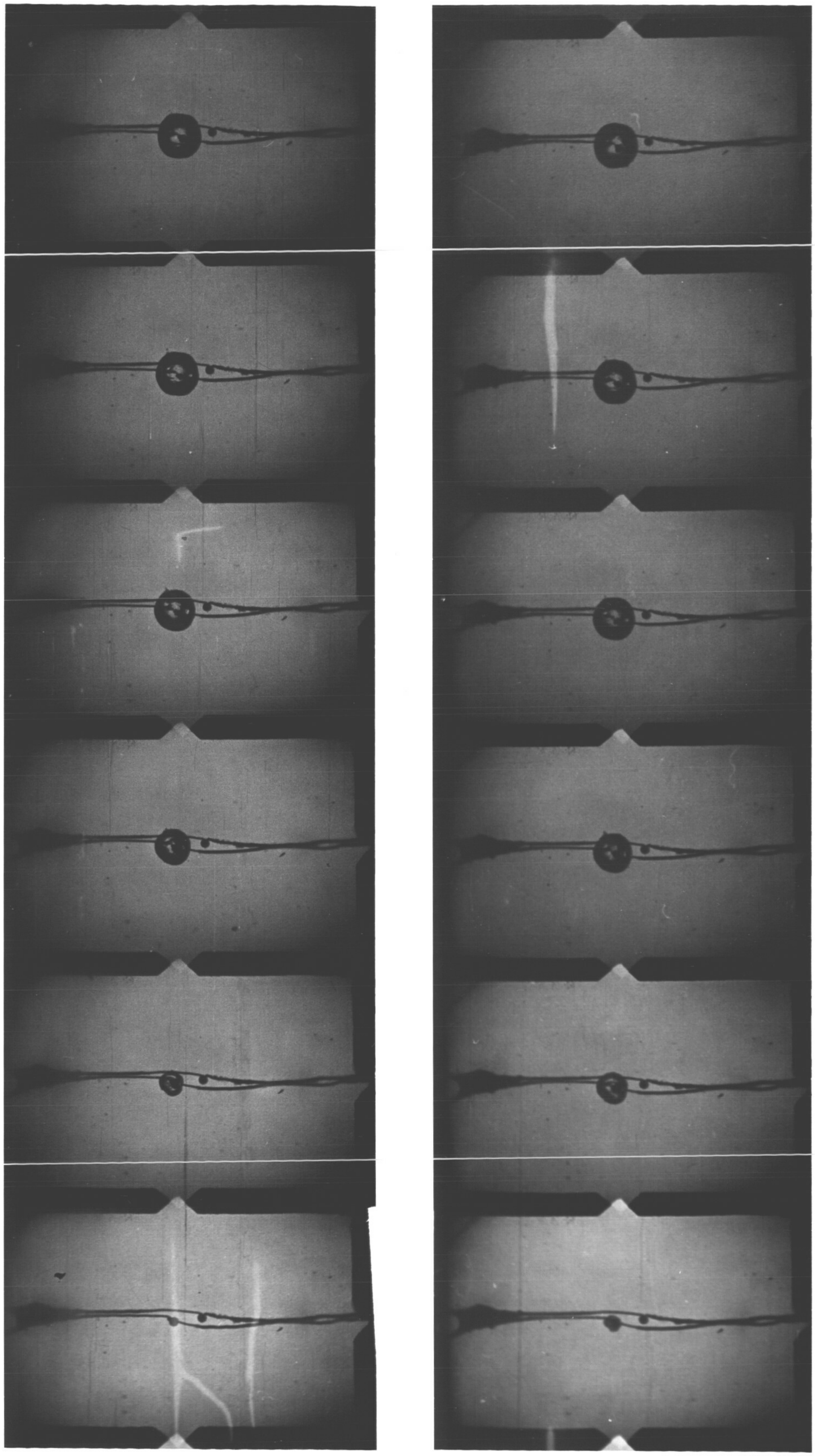


Figure 4. A Single Bubble Around a Thermocouple Junction in Water at 94° C.

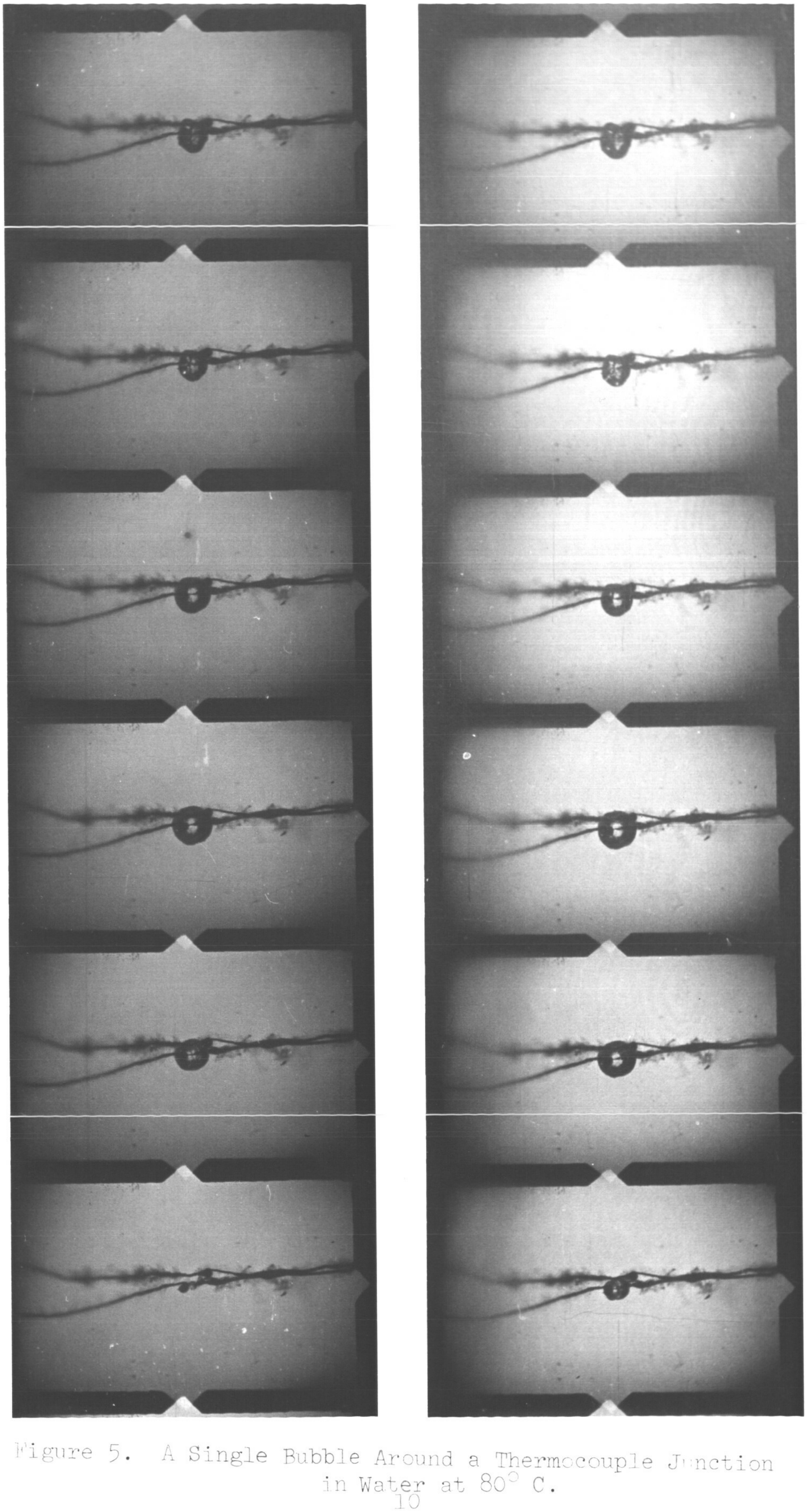


Figure 5. A Single Bubble Around a Thermocouple Junction in Water at 80° C.

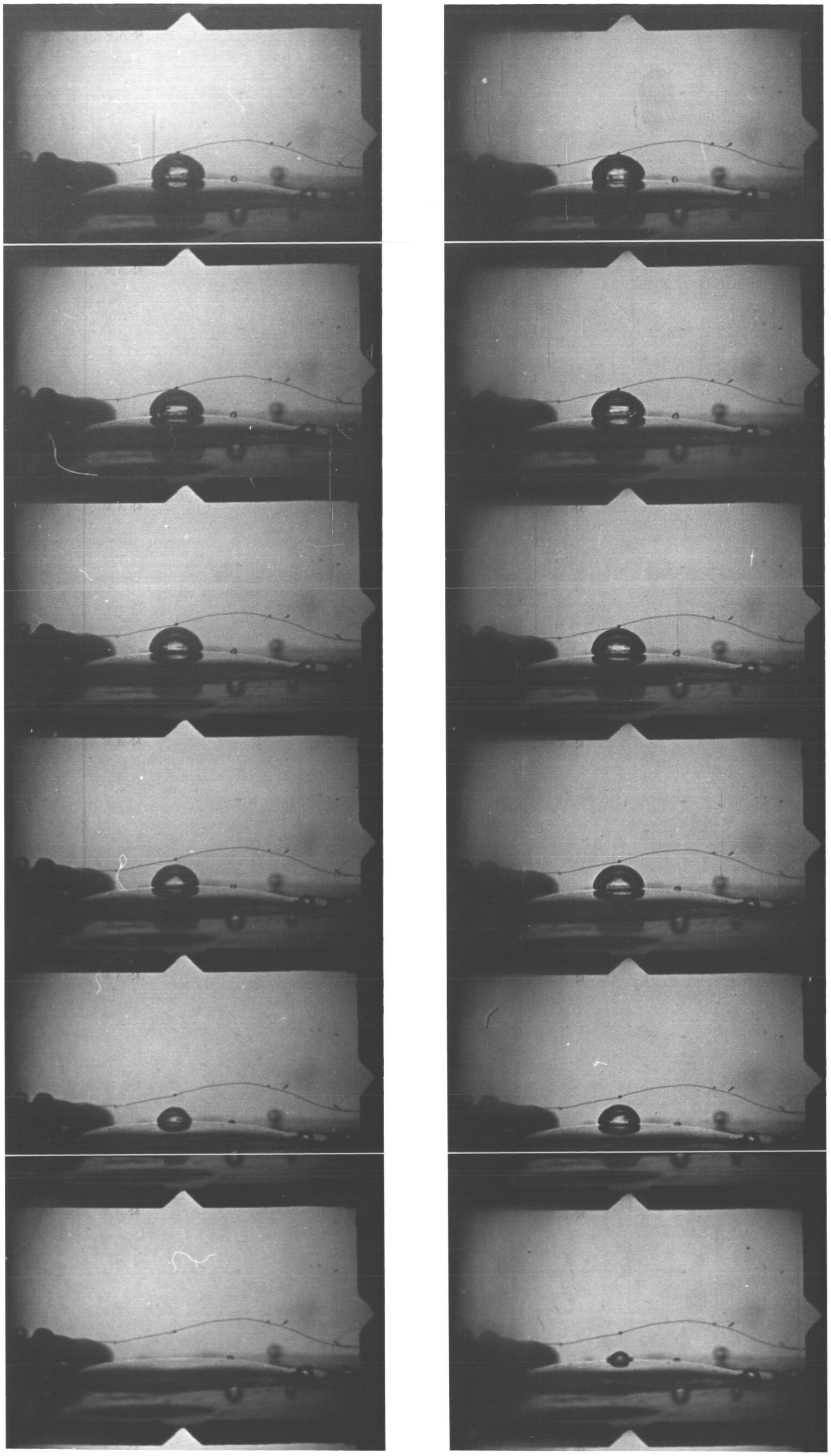


Figure 6. A Single Bubble on a Thin Flat Plate in Water at 94° F.

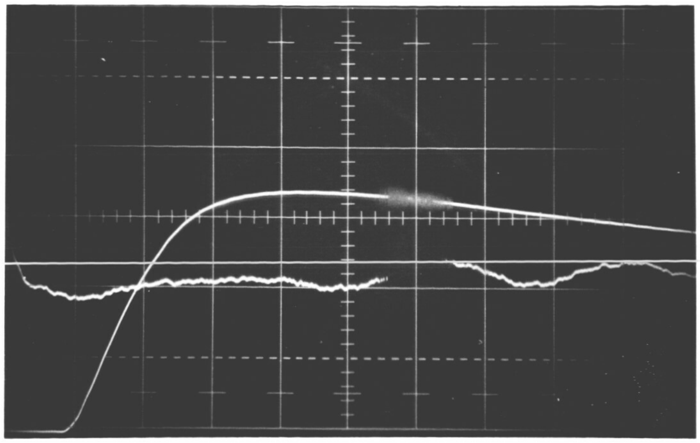


Figure 7. Thermocouple Temperature Trace Corresponding to Figure 4.

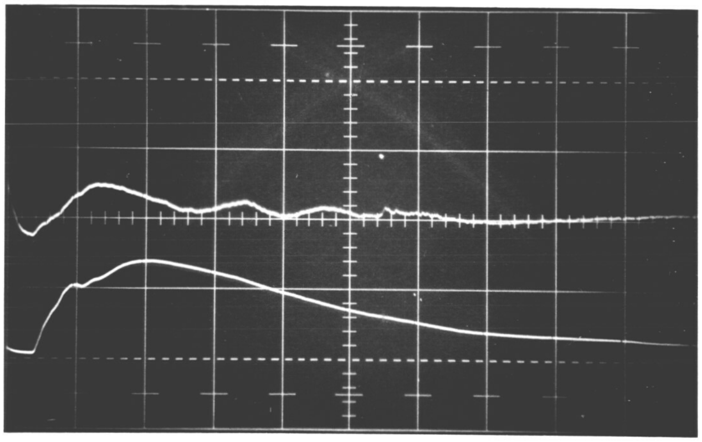


Figure 8. Thermocouple Temperature Trace Corresponding to Figure 5.

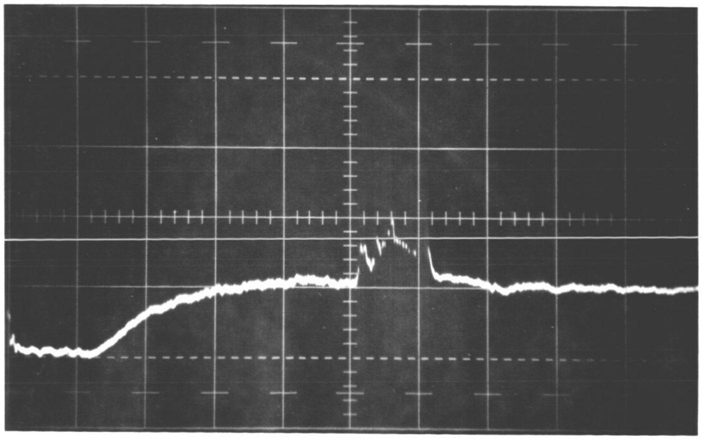


Figure 9. Thermocouple Temperature Trace Corresponding to Figure 6.

per cm. scale. This should represent the surface temperature of the thermocouple. The temperature rise from the water temperature to about 80 percent of the peak value takes about one millisecond, the time scale for the abscissa being .5 milliseconds per cm. This may be considered as the time delay due to conduction through the junction. For a very crude calculation the time lap seems to be in the right order. After the peak value the temperature does not seem to drop rapidly. This may show that the vapor in the bubble is a poor thermal conductor. In the future, the heat transfer problem of the vapor may be analyzed to correlate with the experimental measured temperature history.

Figure 5 shows the initial growth sequence of a single bubble around a thermocouple junction after being hit by the laser beam under the conditions of experimental run 10. The temperature of the water was kept at 80°C, and the laser voltage was maintained at 1200 volts. The bubble grows at a rather fast pace during the first few frames, but it begins to shrink after the 4th frame and becomes ablong in shape after about the 10th frame. After about the 16th frame the bubble begins to be unstable. This shows that the higher degree of subcooling tends to collapse the bubble as it should, although the state of the collapsing the bubble was not obtained due to the high speed chosen. The temperature trace of the second thermocouple does not shows any changes, this is due to the distance between the two thermocouples is larger than .025-inch so that the bubble did not reach the second thermocouple.

Corresponding to the conditions set forth for Figure 5, the temperature trace of the first thermocouple junction was obtained as shown in the polaroid picture of Figure 8. The trend of the temperature rise of the first thermocouple is about similar to that for Figure 7. The peak temperature is about 225°F with 5 mv. per cm. scale. (The time scale is 1 millisecond per cm for the abscissa.) The temperature trace for the second thermocouple shows a rise of peak value in the order of about .4 millivolts, which corresponds to a temperature rise of about 15°F with a scale of .5 mv. per cm. Up to this moment, not enough data are taken to give any quantitative analysis of the thermal boundary layer thickness around the interface between the vapor and the liquid. In the future, hopefully, this information may be obtained experimentally. According to the literature, this boundary layer thickness is of the order of .006 inches.

Figure 6 shows that a single bubble was initiated on a flat thin metal plate corresponding to the conditions of experimental run 1B in a water pool of 94°C, the laser voltage was 1350 volt. The non-sphericity of the bubble during its initial growth period is not as bad, although from about the 10th frame there exists contact angle between the bubble and the metal surface, thus the bubble deviates from the spherical shape. As the bubble grows larger, up to about the 18th frame, the bubble tends to be crown shaped rather than the spherical. The top part of the bubble still maintains a good spherical shape. The bubble shape seems to be similar to those bubbles produced by the conventional boiling process.

Figure 9 shows a polariod picture of the temperature obtained from the chromel-constantan thermocouple junction of about .004 inches in diameter with .001-inch diameter lead wires, placed about .030 inches above the plate. The peak temperature shows about a 19°F temperature rise with a scale of 0.2 mv. per cm. and a time scale of 1 millisecond in abscissa. The temperature seems to stay at a constant level, presumably the vapor temperature.

BUBBLE GROWTH RATE

The radius of the bubble was measured through an enlarger on a frame by frame basis. These are plotted in Figures 10 through 14.

Figure 10 represents the initial growth of the bubble around a thermocouple junction for experimental runs 2A, 3A, 4A and 5A. The initial growth rate of the bubble is faster for a higher laser voltage or laser energy, the results give a consistent trend.

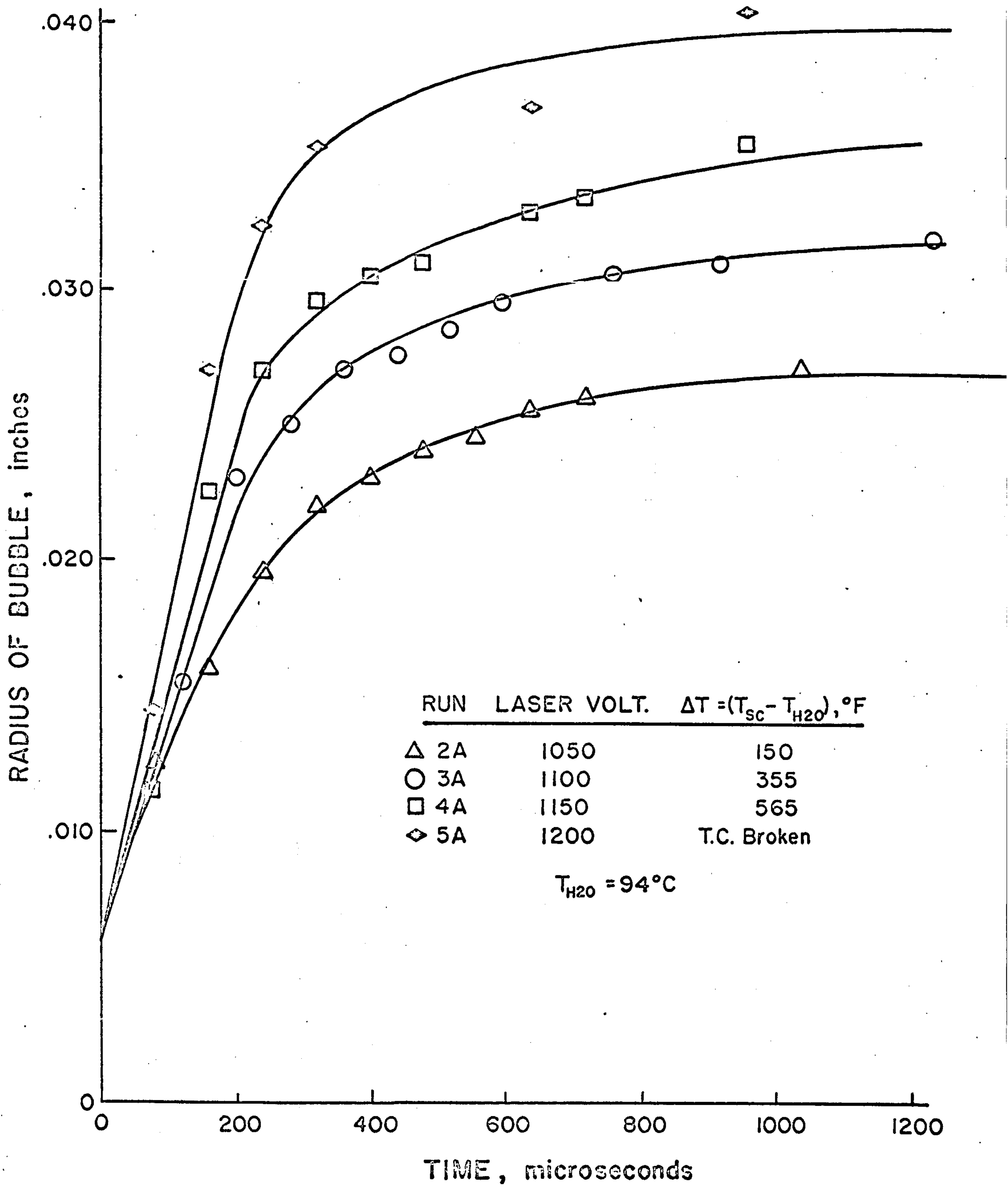
Figure 11 shows the initial growth of the bubble from a flat plate for experimental runs 1B and 3B at two different energy inputs. It is also consistent to see that the bubble grows faster in the initial phase for a higher energy input.

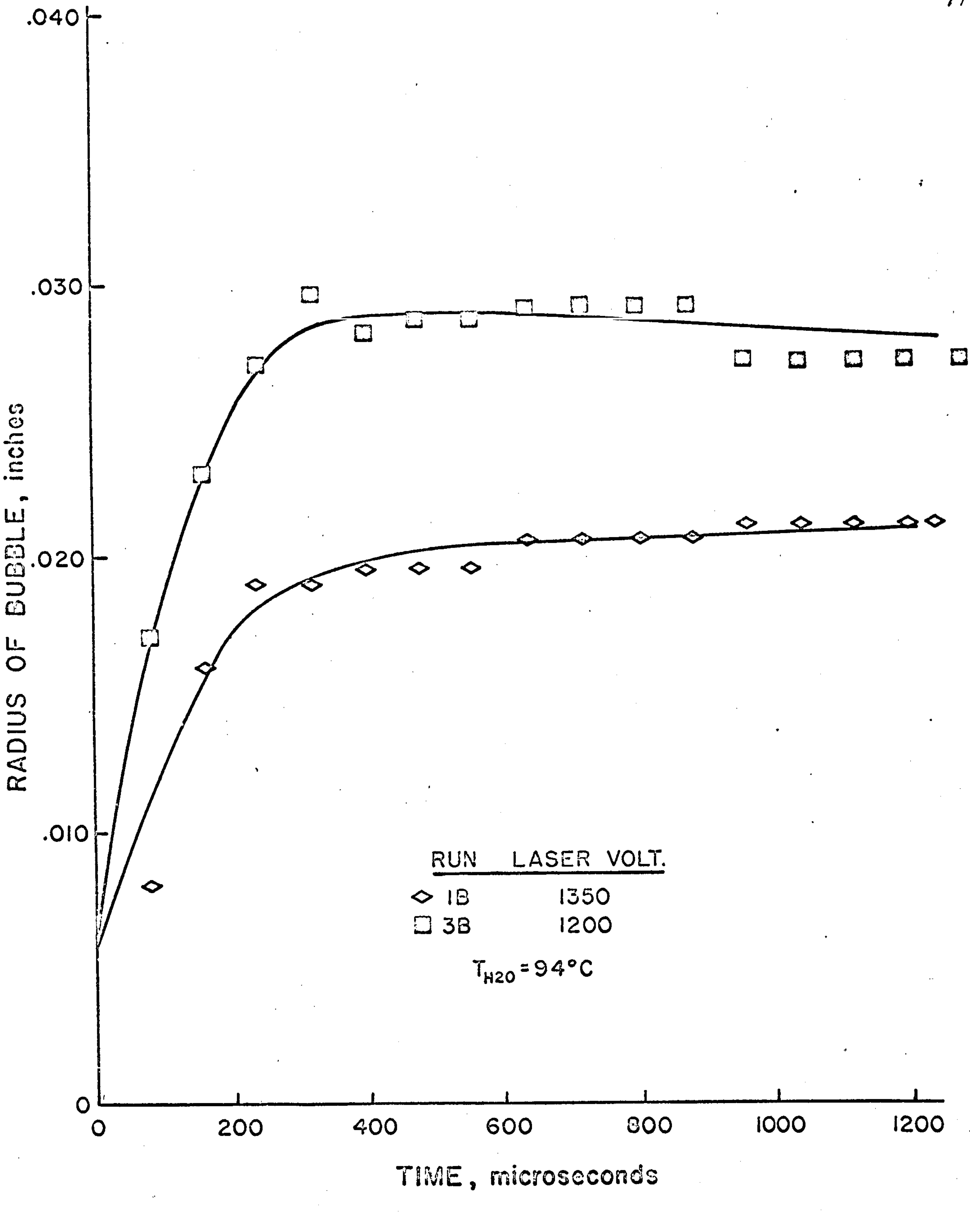
Figure 12 shows that initial growth within the first 320 microseconds of the experimental runs 2A, 3A, 4A, 5A, 1B and 3B plotted against the square root of time. It is interesting to see that most of the results follow a straight line relation as predicted in the literature.

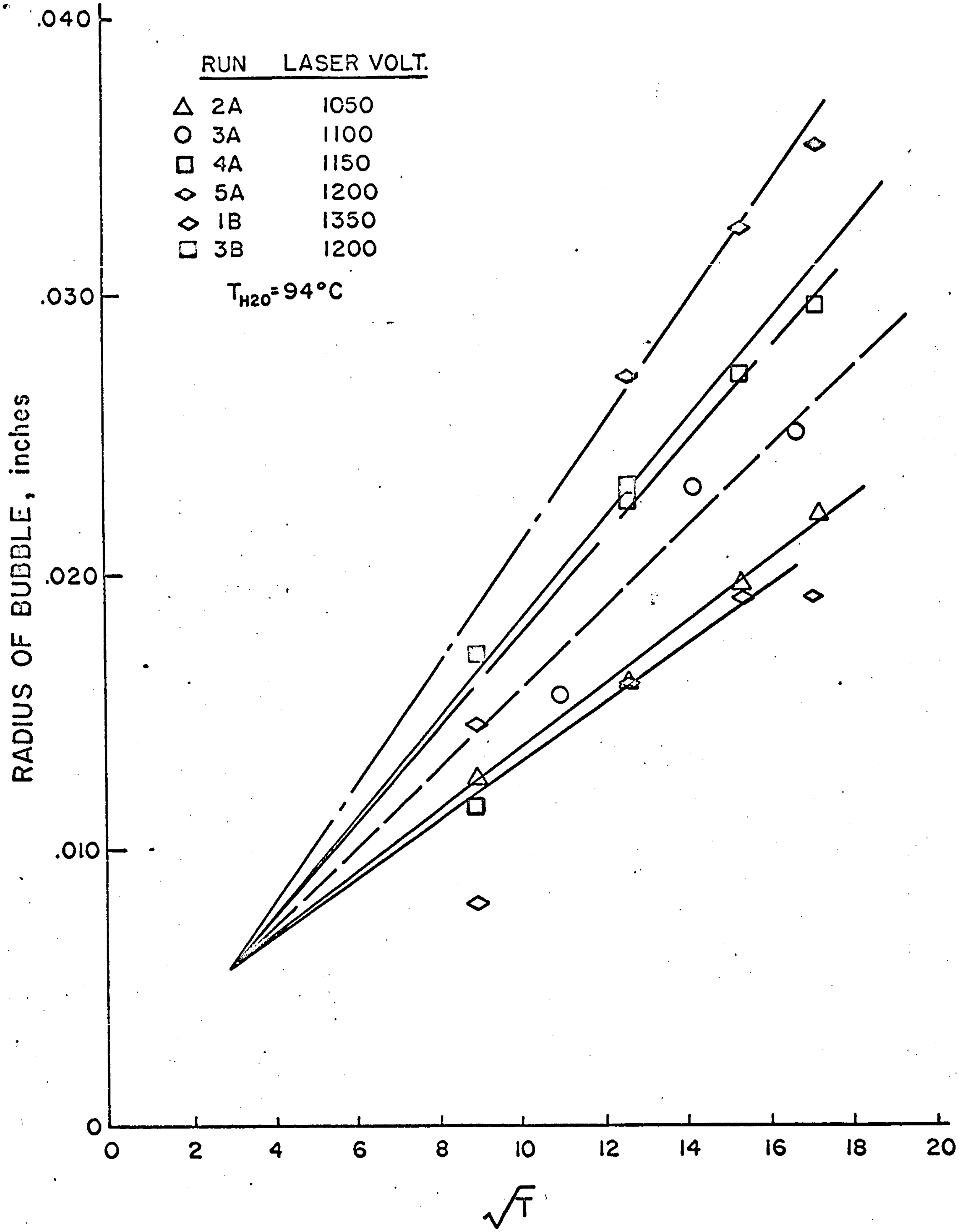
Figure 13 represents the initial growth of a single bubble around a thermocouple junction for the experimental runs 7, 8, 9, 10 and 11 at various subcooled temperatures. After about 200 microseconds it is obvious that the bubble grows less for a higher subcooled temperature or lower water temperature.

Figure 14 shows that the initial growth rate plotted against the square root of time also follows a linear relation fairly well.

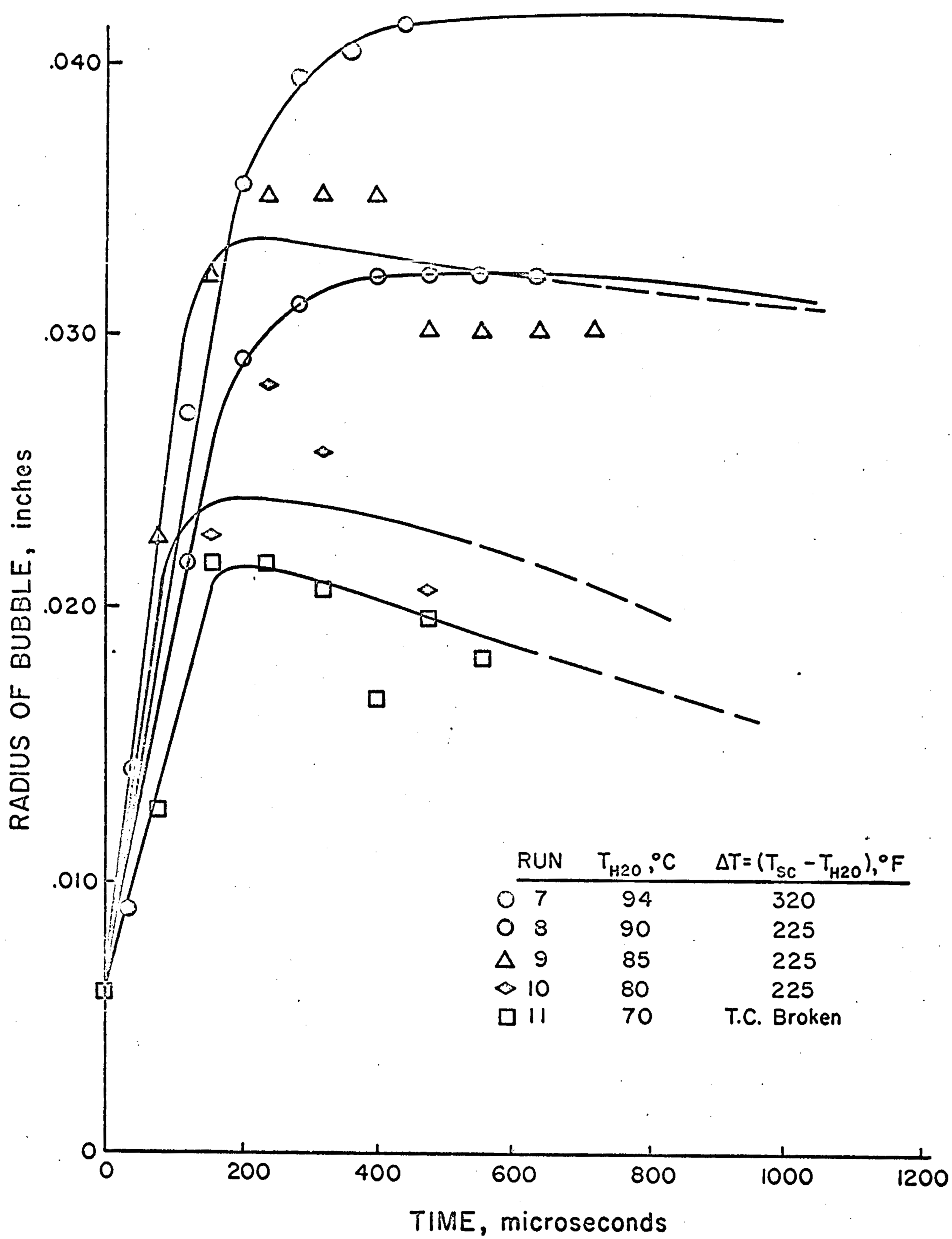
In general, the experimental results are quite consistent in trends. They do give reasonable qualitative results as well as partial quantitative


.040
.030
.020
.010
0
RADIUS OF BUBBLE, inches
0
200
400
600
800
1000
1200
TIME, microseconds
RUN LASER VOLT. ΔT =(T_SC - T_H2O), °F
2A 1050 150
3A 1100 355
4A 1150 565
5A 1200 T.C. Broken
T_H2O = 94°C

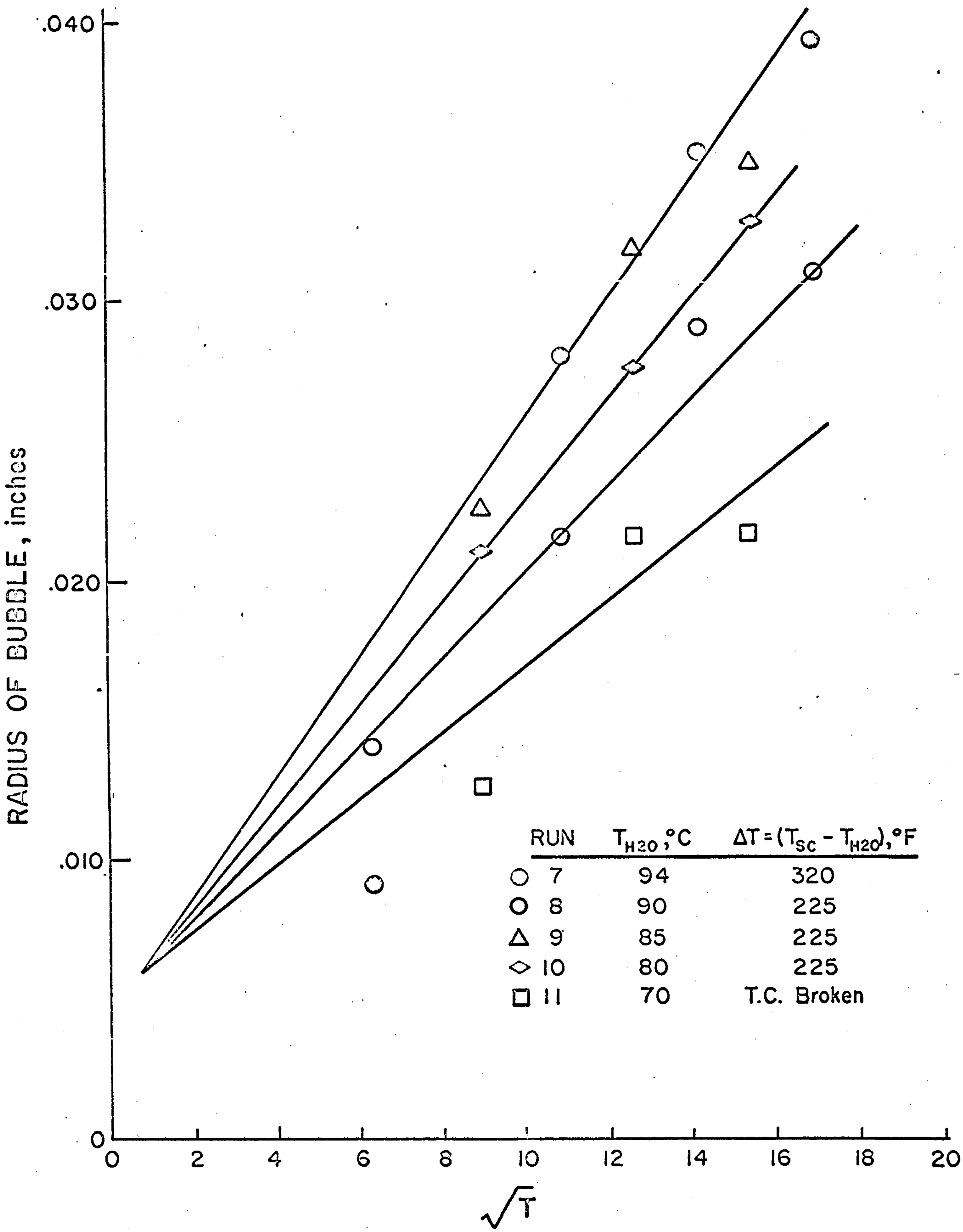

.040
.030
.020
.010
0
RADIUS OF BUBBLE, inches
0
200
400
600
800
1000
1200
TIME, microseconds
RUN LASER VOLT.
1B 1350
3B 1200
T_{H2O} = 94°C


RUN LASER VOLT.
2A 1050
3A 1100
4A 1150
5A 1200
1B 1350
3B 1200
T_{H20}= 94°C
RADIUS OF BUBBLE, inches
.040
.030
.020
.010
0
0 2 4 6 8 10 12 14 16 18 20
$\sqrt{T}$

13



RADIUS OF BUBBLE, inches
TIME, microseconds
0
.010
.020
.030
.040
0
200
400
600
800
1000
1200
RUN
T_{H2O}, °C
$\Delta T = (T_{SC} - T_{H2O})$, °F
7 94 320
8 90 225
9 85 225
10 80 225
11 70 T.C. Broken


RADIUS OF BUBBLE, inches
.040
.030
.020
.010
0
0
2
4
6
8
10
12
14
16
18
20
$\sqrt{T}$
RUN | T_{H20}, °C | $\Delta T = (T_{SC} - T_{H20})$, °F
7 | 94 | 320
8 | 90 | 225
9 | 85 | 225
10 | 80 | 225
11 | 70 | T.C. Broken

results. As more sophisticated instrumentation is developed in the future, a much more quantitative analysis will give better answers to the basic problem of bubble dynamics and boiling heat transfer.

CONCLUSIONS

In conclusion, the initiation of a single bubble by the use of a laser beam is feasible. The spericity of a single bubble is reasonably good. The growth rate during the initial stage of the bubble growth in the order of 300 microseconds seems to follow a linear relation with the square root of time as predicted in the literature, although at this stage of the study the instrumentation may not be sophisticated to give a precise quantitative result.

FUTURE STUDY

In the future, the techniques of temperature measurements are to be improved, more experiments are to be conducted to obtain good reproducible runs under various conditions, particularly various liquids of different viscosity and surface tension are to be considered such that the effect of the surface tension and viscosity may be singled out. In the mean time the analytical solution of bubble dynamics and heat transfer, including viscosity, may be obtained. The correlation between experimental runs and analytical solutions are to be considered.

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