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AN EXPERIMENTAL STUDY OF TRANSIENT BOILING

M. W. Rosenthal
R. L. Miller

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Reactor Experimental Engineering Division

AN EXPERIMENTAL STUDY OF TRANSIENT BOILING

by

M. W. Rosenthal and R. L. Miller

Date Issued APR 29 1957

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The transient power regulator and the associated control equipment used in this program were developed and designed by Odell Eason. The authors are indebted to P. R. Kasten, M. Tobias, and H. W. Hoffman for suggestions regarding this report.

ABSTRACT

An experimental investigation of heat transfer to subcooled water under transient conditions has been conducted. Heat was generated electrically in platinum and aluminum ribbons in such a manner as to produce exponentially increasing heat generation rates which simulated reactor excursions. Surface temperature was measured and the events were photographed with a high-speed camera.

The temperature attained by the surface before boiling commenced was determined and the time delay between passage of the boiling point and the beginning of boiling was measured. Heat flux at the beginning of film boiling was obtained. The effects of water temperature, exponential period, and gas concentration were studied. Periods ranged from 5 to 75 milliseconds. The bulk water temperature was varied from 90°F to near the boiling point; in all experiments the water was initially stagnant and at atmospheric pressure.

INTRODUCTION

If, through sudden addition of reactivity, a nuclear reactor is brought prompt-critical, the power increases rapidly and the reactor temperature quickly rises. This excursion continues until the reactor power becomes high enough to produce changes which result in a reduction in reactivity. In a reactor with water-cooled and -moderated solid fuel elements --- such as a "swimming pool" or an MTR type --- the inherent reactivity reduction which brings the system under control can result from ejection of moderator from the core following steam formation. Occurrence of this event, of course, depends on the incidence of boiling.

During a power excursion the fuel elements rise in temperature more rapidly than the coolant, and the element surface temperature exceeds the boiling point of water while the bulk liquid temperature is still below saturation. Since the surface temperature rises very rapidly, there has been speculation that the boiling point of water may be appreciably exceeded before boiling commences. If this occurs, the resulting time delay could mean the difference between safe curtailment of an excursion and a dangerous release of energy. One analysis of a particular situation(1) indicated that a delay of the order of ten milliseconds in bubble formation would result in the fuel elements exceeding the melting point. (Recently information has been released on kinetic experiments with swimming-pool type reactors designed to determine their behavior following large reactivity injections --- the Borax(2) and Spert(3) experiments. These experiments revealed that except under the most extreme conditions --- beyond what is likely to occur accidently --- steam formation in reactors of this type results in a decrease in reactivity that interrupts a surge before serious damage occurs.)

The research reported in this memorandum was undertaken with the purpose of determining experimentally whether there is actually a time delay before the beginning of boiling and to study the various phenomena associated with heat transfer to water under transient conditions. This information is needed for use in mathematical analyses of the behavior of fuel elements during reactor transients.

APPARATUS AND METHOD

The basic experimental system was a thin metal ribbon (0.1" wide, 0.001" thick, approximately 3" long) positioned vertically in a transparent tank of water with heat generated electrically in the ribbon. (See Fig. 1). Current, originating in a bank of storage batteries, passed in series through a transient power regulator and the ribbon. The regulator consisted of 100 thyratrons connected in parallel. A different bias could be put on the grid of each and the system so set that a signal of increasing voltage applied simultaneously to all tubes fired them in a sequence that approximated the desired function. A peak current of about 500 amperes (heat flux of the order of 5×10^6 Btu/hr - sq ft in the system used) could be produced, with the duration of the power surge ranging from 30 to 500 milliseconds. Any power function with current increasing monotonically could be set on the regulator. The controls for setting the individual grid biases can be seen in Fig. 2.

The voltage drop across the ribbon was obtained from fine-wire potential taps attached near the ends, and current was measured using a calibrated shunt in the current circuit. The voltage taps (0.003 in. dia) were soldered to the edge of a ribbon in such a manner that very little surface area was disturbed. Instantaneous values of millivolt signals proportional to current and voltage were recorded by a Hathaway fast-response oscillograph. A typical recorder trace is illustrated in Fig. 3. In taking data from the oscillograph record, values were read at times corresponding to the flat parts of steps to obtain the best precision.

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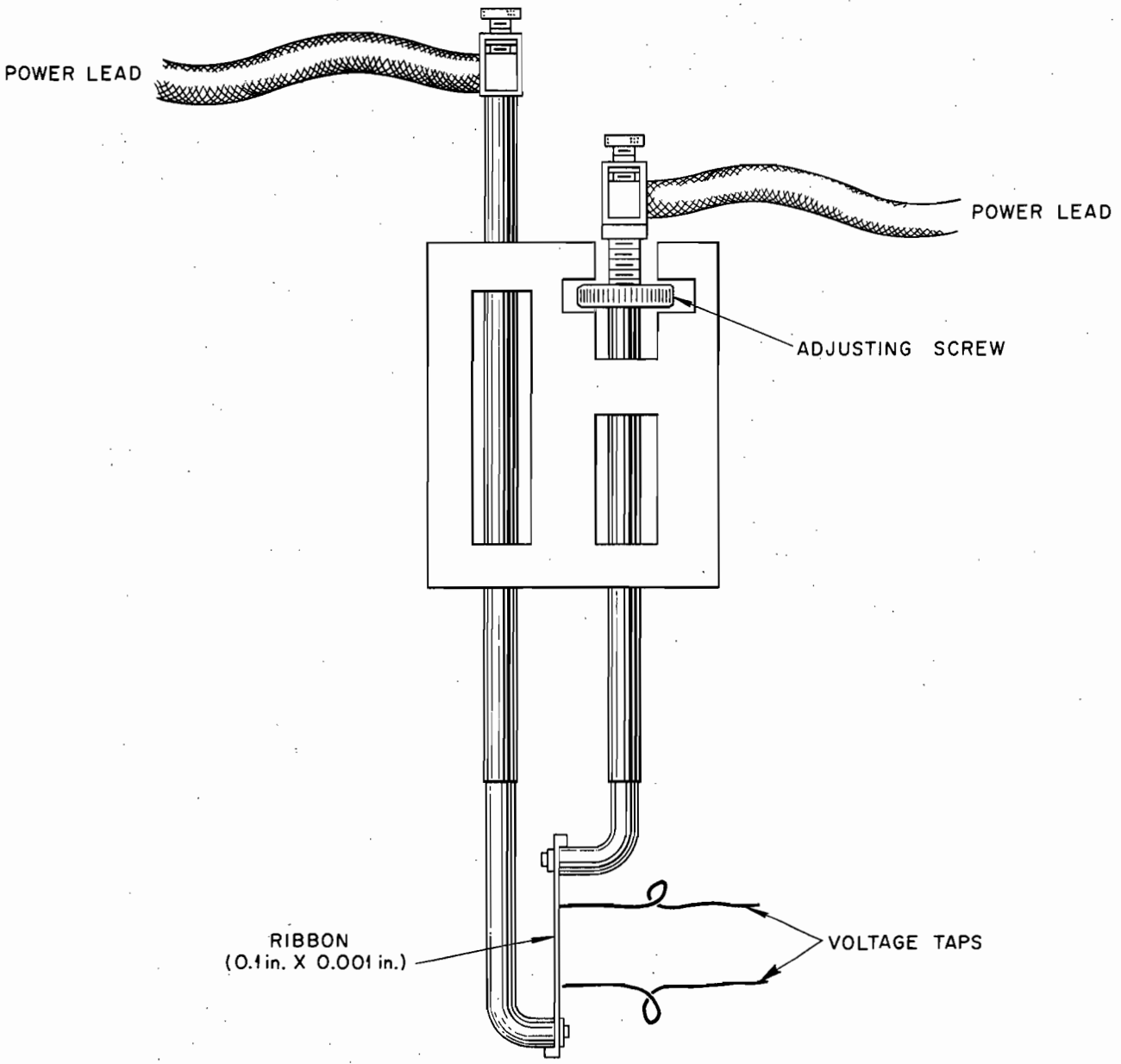

Fig. 1. Ribbon Support Assembly.

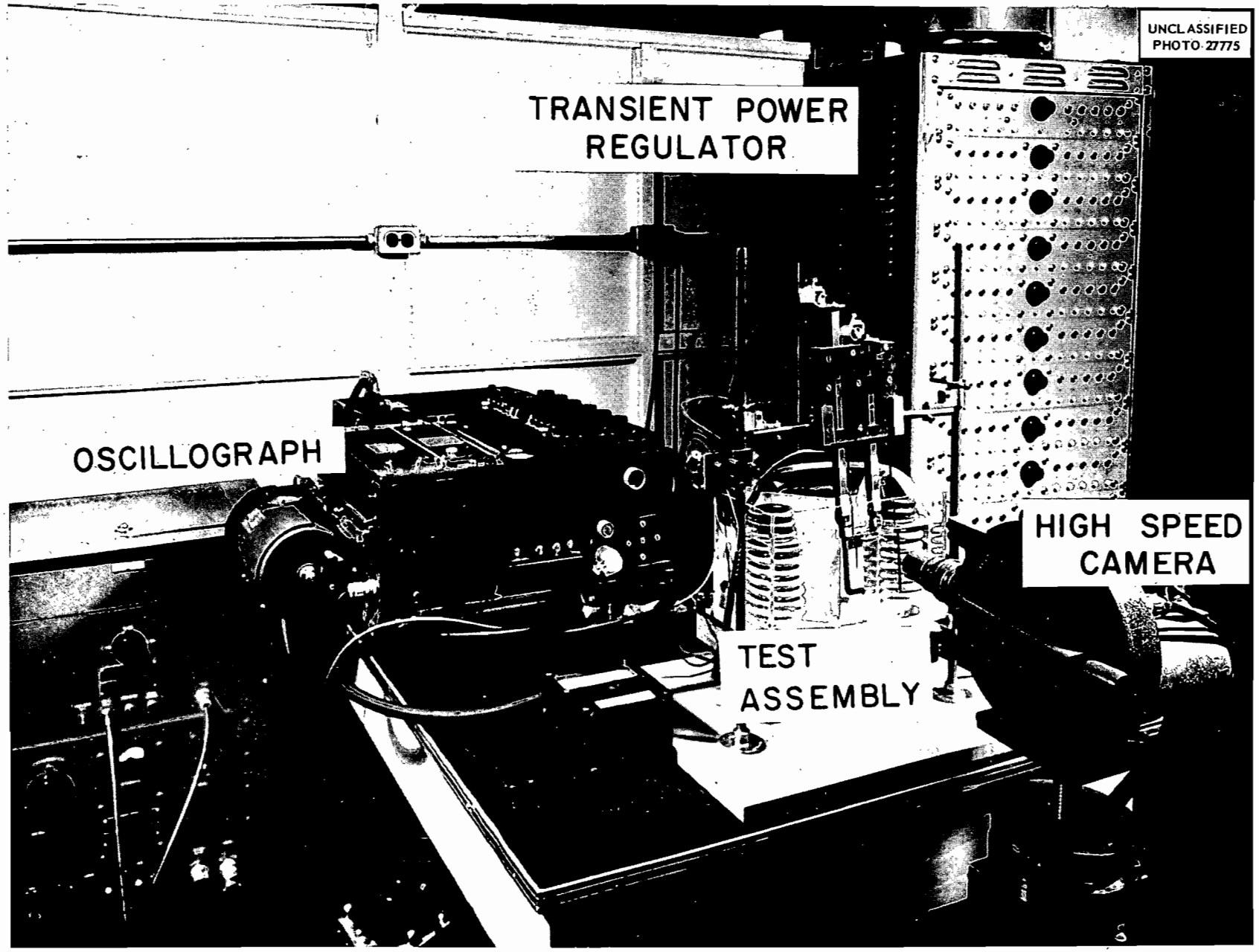

Fig. 2. Transient Boiling Apparatus.

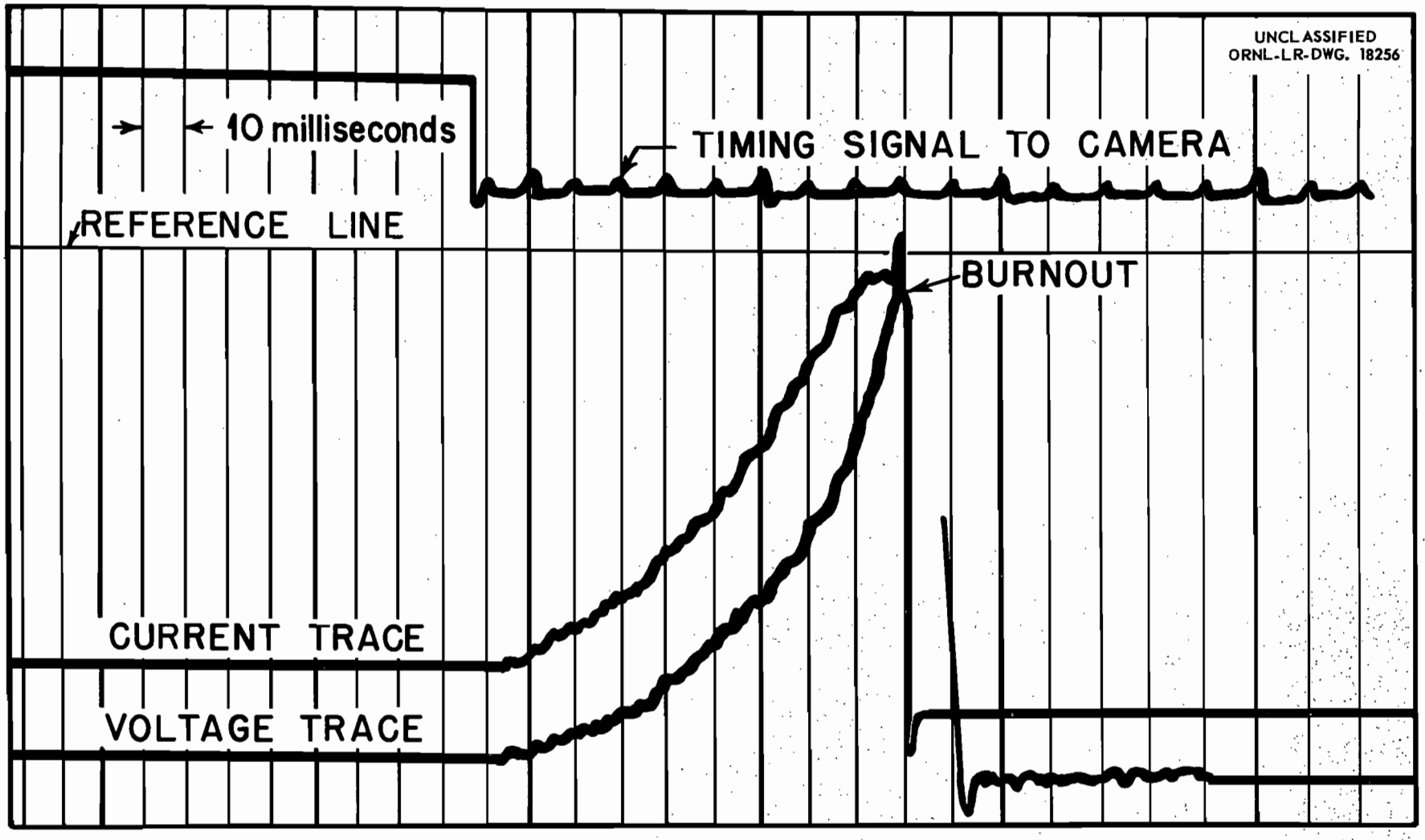

Fig. 3. Typical Hathaway Oscillograph Record.

A 16 mm FASTAX high-speed motion picture camera was used to photograph the event at a repetition rate of 6000 frames per second. The camera was pointed parallel to the ribbon surface and backlighting was employed. Closing of a single switch initiated the operation of all the equipment, with a time delay provided in which the camera could accelerate to full speed before current was passed through the ribbon. Synchronization and timing marks were applied simultaneously to the recorder trace and the 16 mm film.

From the information recorded, instantaneous values of power generation rate and ribbon resistance were obtained. Previous calibration of the ribbon as a resistance thermometer permitted determination of the ribbon temperature as a function of time (the temperature drop within the ribbon was negligible). Heat flux was calculated from the power generation rate and the known size of the ribbon. Boiling on the ribbon surface and burnout were observed by projection of the high-speed movies at normal speeds giving a time magnification factor of about 400.

RANGE OF EXPERIMENTS

In order to simulate reactor conditions, experiments were performed in which the power increased exponentially according to the equation

$$P = P_o e^{t/p} \tag{1}$$

where P is power (heat generation rate), t is time from the beginning of the excursion, and p is exponential period or e-folding time. The value of P_o, the initial power, was not of consequence in the experiments since it was kept so low that no significant change in ribbon temperature occurred during the early part of an excursion. Hence, various values of p were employed with a single value of P_o.

A range of bulk water temperatures extending from 90°F to the boiling point was studied. For most runs the oxygen concentration (taken as indicative of the total gas concentration) was held below 1.0 ppm, but a series of experiments was performed with oxygen concentration as the variable. In order to provide uniformity of surface condition, clinging air bubbles were removed by immersing all ribbons in boiling water for 1.0 minute just prior to a run, and transferring them to the test bath while still wet.

Ribbons of platinum and aluminum were employed, but difficulties in maintaining voltage-tap attachments with aluminum resulted in most of the experiments being performed with platinum. The platinum surface was specular, whereas the aluminum was "bright-finish."

In all cases the water was stagnant at the beginning of an experiment and the pressure was atmospheric.

The ranges of the variables investigated are tabulated below:

Exponential period, milliseconds	5	-	75
Initial water temperature, ^{o}F	90	-	212
Oxygen concentration of water, ppm	0.2	-	5.0
Initial water condition	Static		
Pressure	Atmospheric		
Ribbon material	Pt and Al		

RESULTS AND DISCUSSION

Using the data from the recorder traces, the temperature of the ribbon and the heat generation rate were obtained as functions of time for each experiment. Together with the visual record from the high-speed camera, these provide a physical description of the phenomena which occur at water-cooled surfaces undergoing rapid heating, as well as quantitative information on the heat transfer behavior. The results are presented and discussed in the sections which follow.

Description of Event

Fig. 4 is a typical record of the ribbon temperature as a function of time for an experiment with subcooled water. The solid curve is a smoothed representation of the data which are indicated by the plotted points. During the run shown the ribbon temperature increased initially in an exponential manner. The rapidly rising temperature passed the saturation value for water, and before boiling commenced, exceeded it by an amount termed the "temperature overshoot." Suddenly, as seen in the motion pictures, there was an almost explosive formation of bubbles, and the ribbon temperature decreased. This boiling surge expired and for a moment the surface was nearly free of bubbles. Then boiling commenced which was similar in appearance to local boiling with steady generation of heat. The rate of bubble formation grew more and more rapid until the surface became blanketed with vapor and burnout occurred. There was a violent agitation of the system at the moment of burnout. In all cases the photographic record corresponded to what can be deduced from the temperature record as having occurred at the same time.

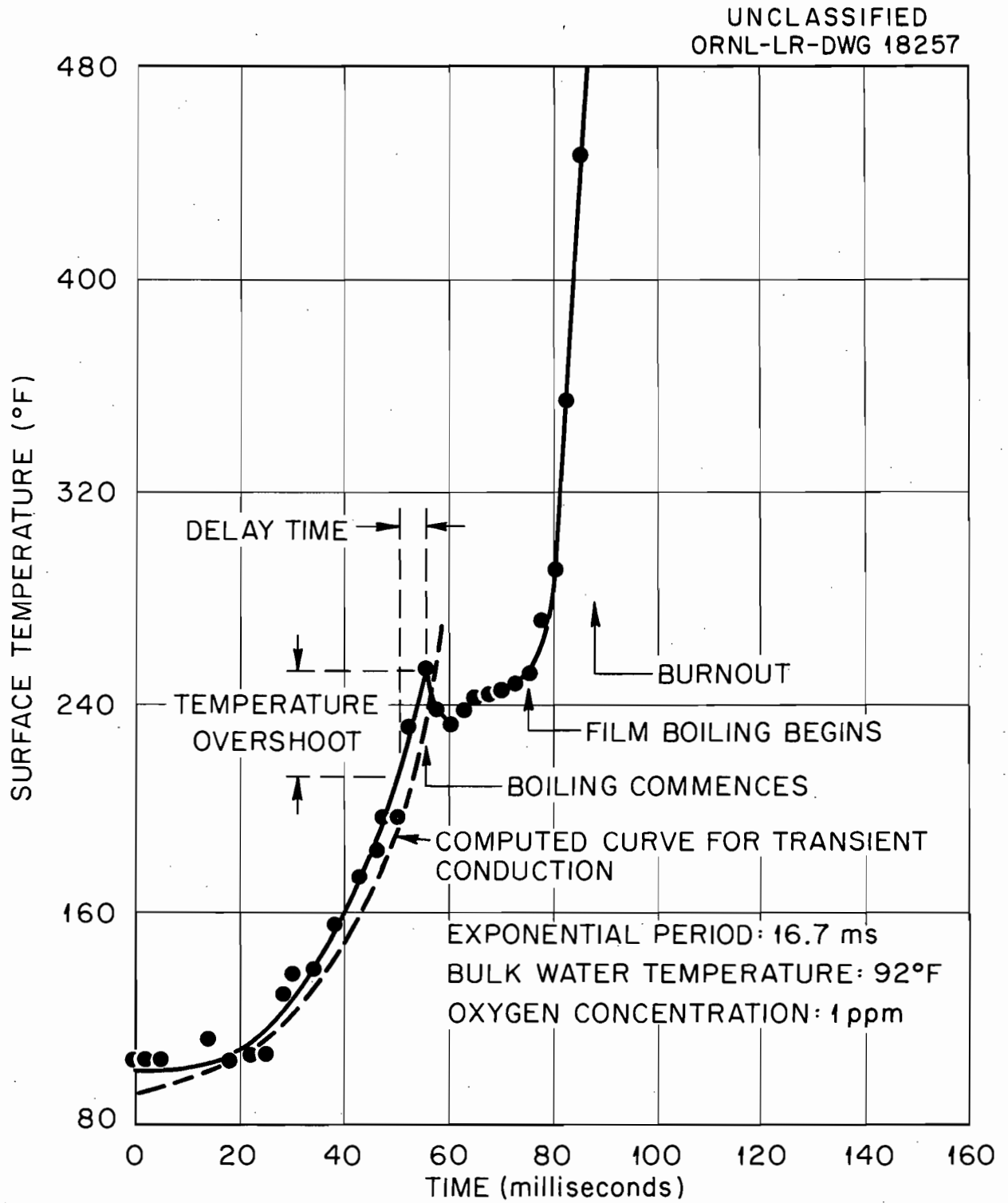

Fig. 4. Typical Temperature–Time Record for Platinum Ribbon in Sub-Cooled Water.

The period between the surface reaching the saturation temperature and the commencement of boiling is termed the "delay time."

When the bulk water temperature was high or the period was long, there was no initial surge as described above. Instead, boiling began at a few spots on the surface and then additional points of nucleation developed as the heat generation rate increased.

Power-Time Relation

Because of the thinness of the ribbon elements used in the experiments there was little thermal lag resulting from heat storage in the ribbon. For illustration, the heat release rate per unit surface area is plotted in Fig. 5 as a function of time for a typical experiment (the same run as depicted in Fig. 4). The solid line through the data points is an exponential-type curve representing the rate at which heat was generated in the ribbon. If a continuous record were taken from the recorder trace with sufficient precision, the heat generation rate would be found to actually increase in a series of small steps rather than in the smooth manner plotted.

The dashed line in Fig. 5 represents the rate of heat transfer to water, or heat flux. The heat flux was obtained by subtracting the rate of heat storage in the ribbon, $H\ dT(0,t)/dt$, from the heat generation rate. When the ribbon temperature was rising there was heat storage in the metal and the flux curve lies below the heat generation curve. However, when the ribbon temperature fell at the beginning of boiling, the stored heat was released to the water and the flux underwent the sudden increase seen at 55 msec.

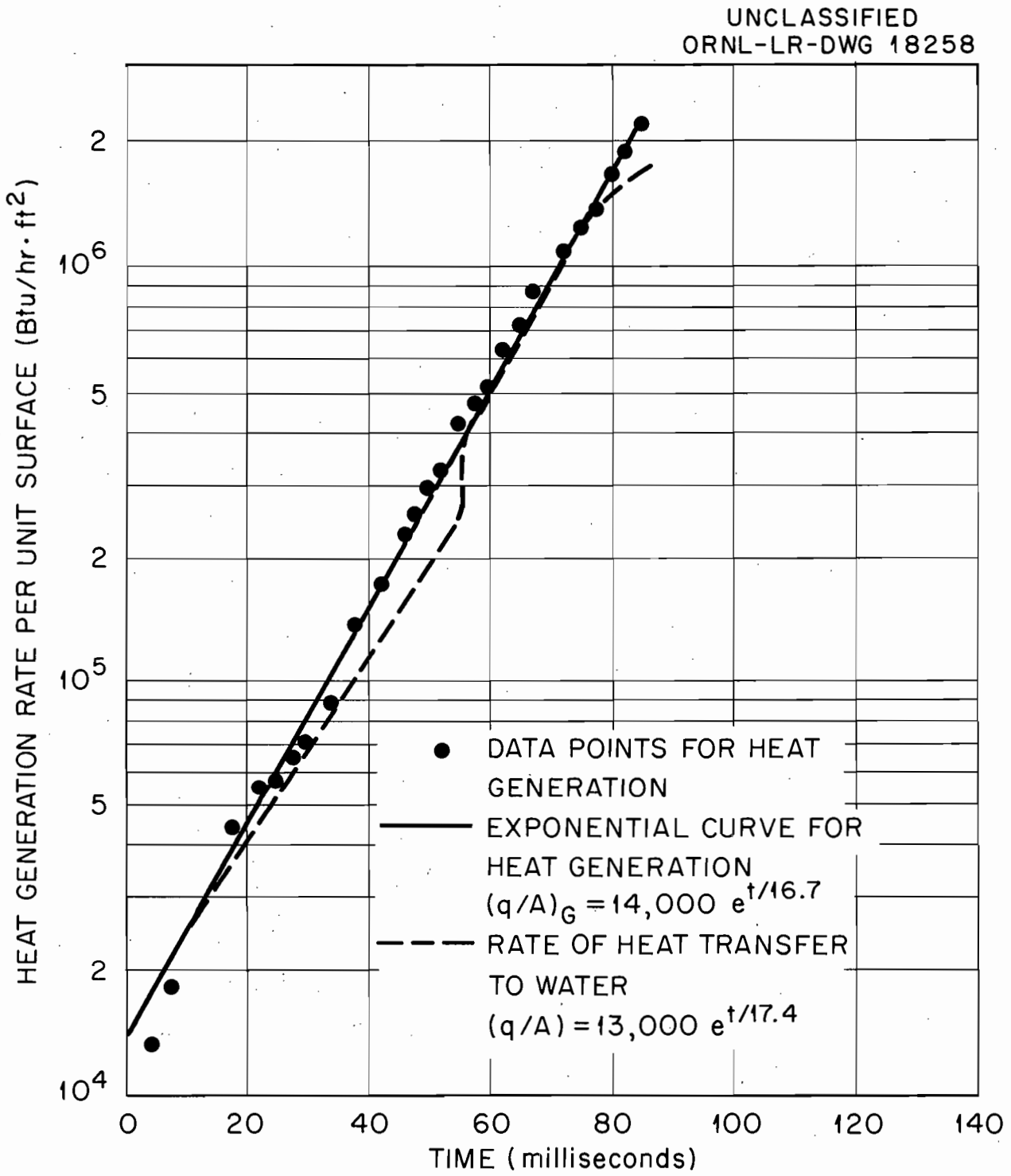

Fig. 5. Typical Power-Time Record for Exponential Heating Experiment.

For the run shown in Fig. 5 a value of 16.7 msec is obtained for the period if it is based on the solid line, whereas the period is 17.4 msec if based on the straight part of the dashed line. The small difference between these two values is typical of all runs, and for convenience the values based on heat generation rate are used to characterize the experiments.

In contrast to the experimental system, the temperatures in the interior of a fuel element during a reactor excursion do not follow exactly the exponential rise in power because of heat conduction between the fuel-bearing and non-fuel-bearing regions. The heat transfer from the element to the coolant similarly lags behind the power. The behavior of a given system depends on the specific design. Since the thermal characteristics of the experimental system and a reactor will differ, the heat transfer rate at a fuel-element surface may not correspond to that obtained for the same period in the experiments. In application of the experimental results to a reactor, therefore, the conditions should be selected which have the same heat-flux-versus-time behavior at the surface.

Analysis of Temperature - Time Behavior

Before boiling commenced, the rate at which the surface temperature rose was too rapid for natural convection to contribute appreciably to heat transfer. If the water is presumed to act with regard to heat transfer as a semi-infinite solid, the temperature rise can be computed by transient conduction theory. Assuming the ribbon to have heat capacity but no resistance to heat conduction, the following differential equation and boundary conditions describe the system for exponentially increasing power.

$$\frac{\partial T(x,t)}{\partial t} = \frac{k}{\rho c_p} \frac{\partial^2 T(x,t)}{\partial x^2} \qquad (x \geqq 0) \tag{2}$$

$$T(x,0) = 0 \tag{3}$$

$$-k \frac{\partial T(0,t)}{\partial x} = (q/A)_{G,0} \; e^{t/p} - H \frac{\partial T(0,t)}{\partial t} \tag{4}$$

$$\lim_{x \to \infty} T(x,t) = 0 \tag{5}$$

The solution of the preceding set of equations for $x = 0$ is given by equation (6).

$$T(0,t) = \frac{(q/A)_{G,0}}{\sqrt{k \rho c_p}(1 - B^2/p)} \left[\sqrt{p} \; e^{t/p} \; \mathrm{erf} \sqrt{t/p} - Be^{t/p} + Be^{t/B^2} \; \mathrm{erfc} \sqrt{t/B^2} \right] \tag{6}$$

The dashed curve of Fig. 4 was computed using equation (6) with $(q/A)_{G,0} = 14{,}000$ and $p = 16.7$. The actual temperature rise is seen to differ little from the computed curve; this similarity was true for all runs.

If the heat capacity of the filament is neglected ($B = 0$), equation (6) is simplified.

$$T(0,t) = \frac{\sqrt{p}(q/A)_{G,0}}{\sqrt{k \rho c_p}} \; e^{t/p} \; \mathrm{erf} \sqrt{t/p} \tag{7}$$

Defining ΔT as the change in temperature which accompanies a change of time Δt, the ratios of the temperatures at two times can be obtained from equation (8) (note that T is the temperature rise above the bulk liquid temperature).

$$\frac{T(0,t) + \Delta T}{T(0,t)} = \frac{e^{\Delta t/p} \operatorname{erf} \sqrt{(t + \Delta t)/p}}{\operatorname{erf} \sqrt{t/p}} \tag{8}$$

The error function changes slowly in value for arguments above 1.0. Thus, after an elapsed time equal to one period, little error is introduced by considering the ratio of error functions in equation (8) to equal unity. Equation (8) then after rearrangement yields equation (9) which gives the time required for a change in temperature, ΔT.

$$\Delta t = p \ln \frac{T(0,t) + \Delta T}{T(0,t)} \tag{9}$$

If T_s is the temperature rise of the water to saturation, the delay time, Δt_d, can be calculated from the temperature overshoot, ΔT_{os}, and the period

$$\Delta t_d = p \ln \frac{T_s + \Delta T_{os}}{T_s} \tag{10}$$

As shown by the agreement between the computed and measured temperature-time curves, the preceding treatment appears to adequately describe the behavior of the system before the beginning of boiling.

Once sufficient energy has been stored in a thin layer of water adjacent to the ribbon surface, bubbles form and boiling commences. In the initial spurt of boiling the bubbles grow to a size that is larger than in the more steady period which follows, probably because of the

greater amount of energy stored near the surface in the nonboiling phase. Penetration of the growing bubbles into colder fluid brings about their condensation, and the resulting inrush of cold water cools the surface and momentarily clears it of bubbles.

In the intermediate period the behavior is similar to that described by Gunther and Kreith[4] for steady subcooled boiling. A bubble grows rapidly to a size which reaches into the cooler water beyond the heated layer near the surface. This contact with cooler liquid causes condensation to begin and the overextended bubble collapses to a sphere of residual air. A magnified sequence of the life cycle of a single bubble during this period is shown in Fig. 6.

The frequency of bubble formation is so great relative to the rate of increase in power that there is little effect of the transient power condition during this phase. However, when the power has increased sufficiently the number of bubbles existing on the surface at one time becomes so large that the bubbles merge to form a vapor film. The ribbon temperature then rises rapidly and burnout occurs. The violent surge at the time of burnout probably results from explosive steam formation caused by the molten ribbon at the position of burnout being brought in contact with liquid water.

Effect of Period, Platinum Ribbon

In Fig. 7 the effect of exponential period on overshoot and delay time is shown for water temperatures around 90°F and dissolved oxygen concentrations of less than 1.0 ppm. Each plotted point represents the results of a single experiment. The lower curve in Fig. 7 is a mean curve through the data and the average deviation from it is 11%. The upper curve was computed in the manner discussed below.

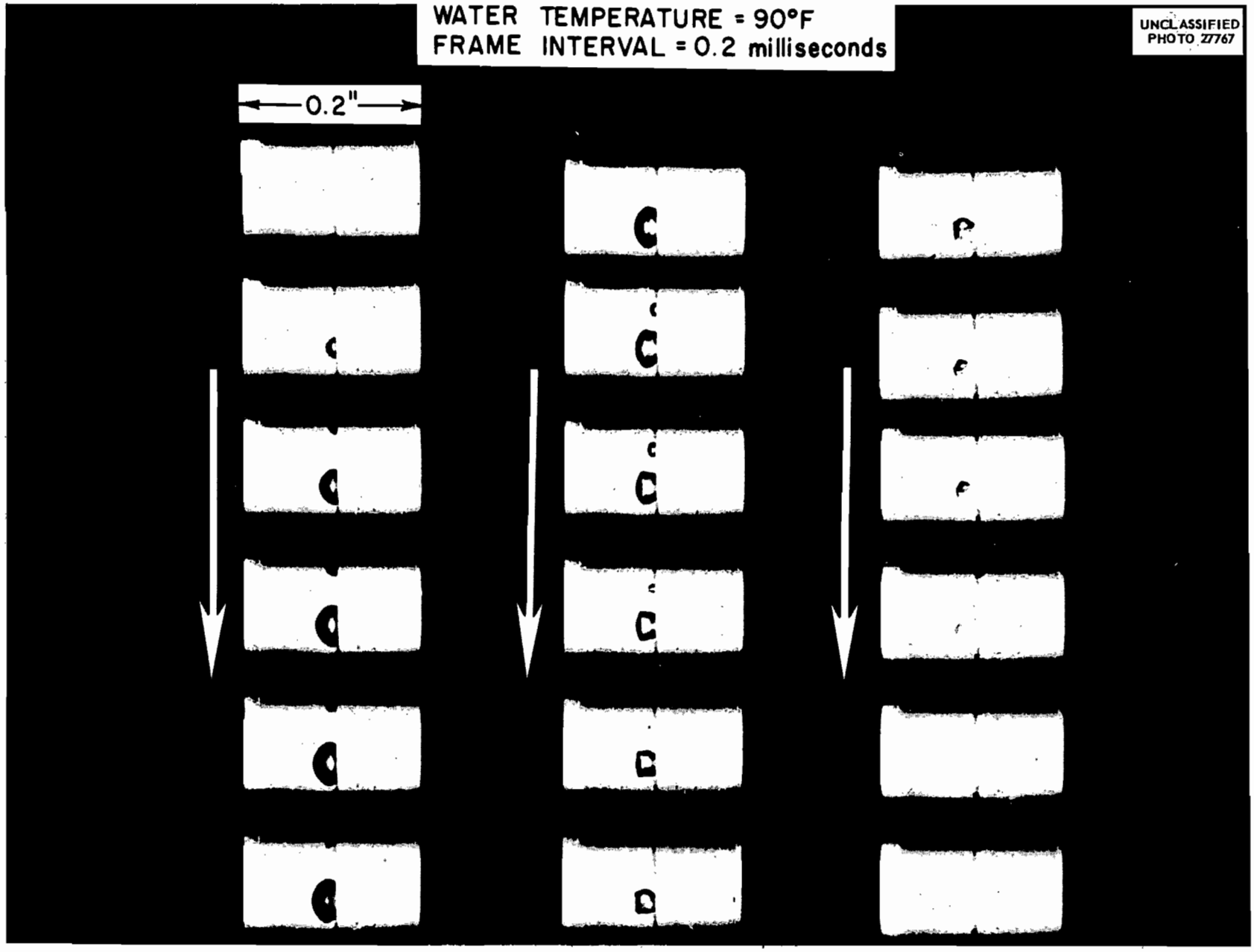

Fig. 6. Life Cycle of a Bubble.

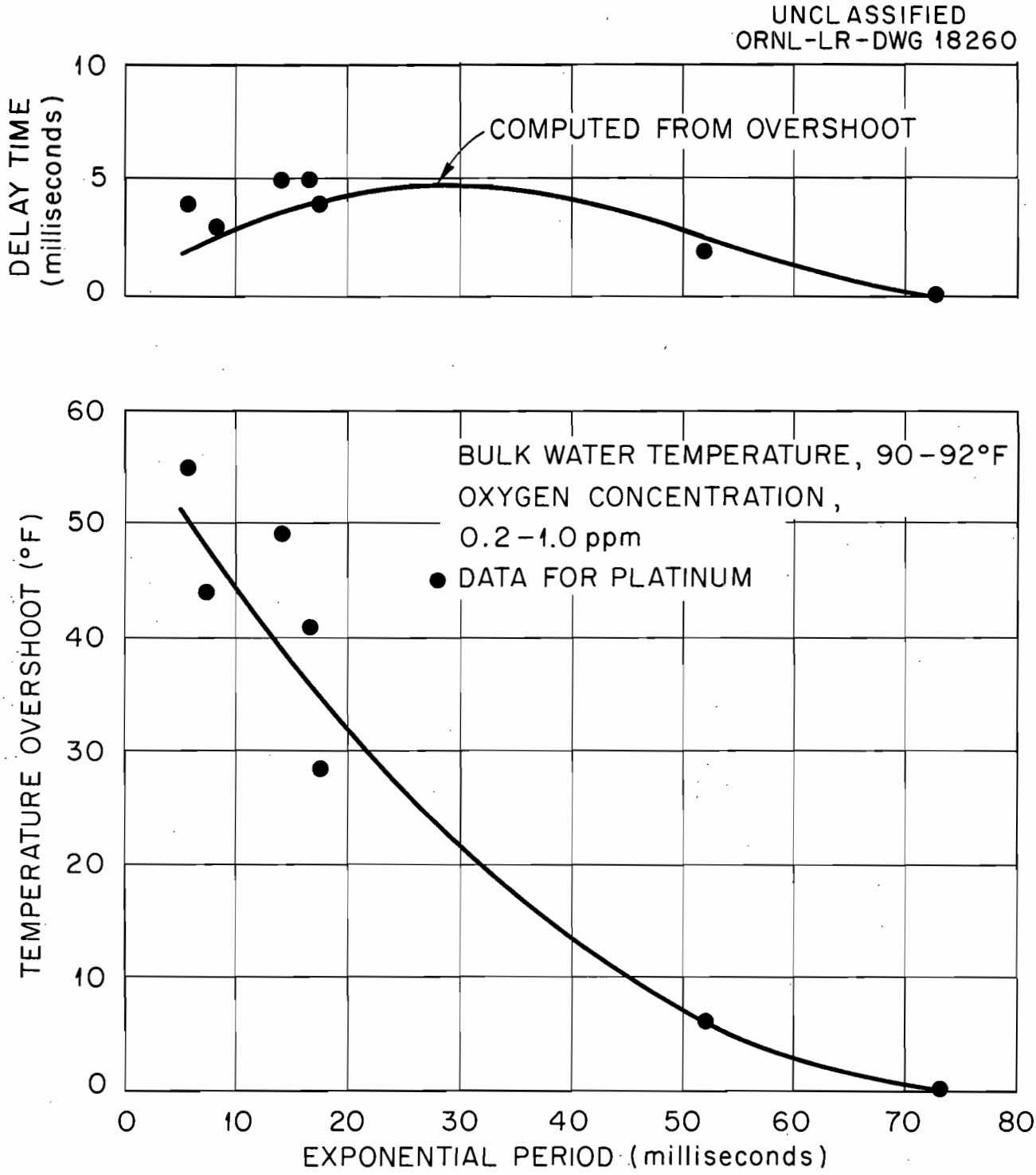

Fig. 7. Effect of Period on Delay Time and Overshoot for Platinum Ribbons.

As shown in the figure, temperature overshoot decreased with increase in exponential period and fell to near zero at periods in excess of 70 msec. At 5 msec the overshoot was about 50°F and the curve appears to be increasing sharply with decrease in period.

This behavior would be expected, since with a short period when the surface temperature has reached a given level less energy has been transferred to the water than with a longer period, and the temperature gradient in the water is more steep. In forming a bubble the temperature of the liquid region near the surface must be high enough to yield a vapor pressure that will overcome the resistance of surface tension to bubble growth. With a short period, to bring the region near the surface to the same energy content the surface temperature must be higher than it would be for a longer period. Thus temperature overshoot increases with decreasing period.

The delay-time curve plotted in the upper part of Fig. 7 was computed using equation (10) and overshoot values from the lower curve. Within the precision of the measurements (approximately 1.0 msec), delay time appears to be correctly related to overshoot by equation (10). In general, the data points which are above the calculated delay curve are those for which the overshoot values are above the mean curve. As indicated by the data and the curve, delay time goes through a maximum as a function of period, being low for short periods where the rate of temperature increase is extremely rapid, and also being low for long periods where the temperature overshoot is small.

Effect of Water Temperature, Platinum Ribbon

The effect of bulk water temperature on overshoot and delay time is revealed in Fig. 8 for platinum surfaces. With a period of about 15 msec and with low oxygen concentration, the temperature overshoot decreased with increasing water temperature, falling to zero as the boiling point was approached. The average deviation of the overshoot data from the mean curve was about 9%.

The relation between overshoot and water temperature can be explained in the same manner as the effect of period on overshoot. In comparing two runs with different bulk water temperatures, when the same surface temperature has been attained, the temperature in the colder water at any point is lower than in the hotter liquid. Thus, to raise the liquid region near the surface to a condition which will sustain bubble growth, the surface temperature must rise higher with lower bulk water temperature than with a higher water temperature.

The delay-time curve in Fig. 8 was obtained using equation (10) and values from the overshoot curve. Since the period was constant, delay time decreased as overshoot decreased.

Effect of Dissolved Gas, Platinum Ribbon

In several experiments the dissolved gas content of the water was deliberately increased by aeration and oxygen concentrations of 3 to 5 ppm resulted (at 1 atm. and 90°F, the solubility of oxygen in water is 7 ppm). Although the total concentration of dissolved air was probably over two-fold that of oxygen alone, for ease in analysis oxygen was used as an indicator of gas content.

As shown in Fig. 9, the data for these runs scattered widely whereas no appreciable randomness was found in the large number of runs in which the oxygen concentration was below 1.0 ppm. The three experiments with high gas

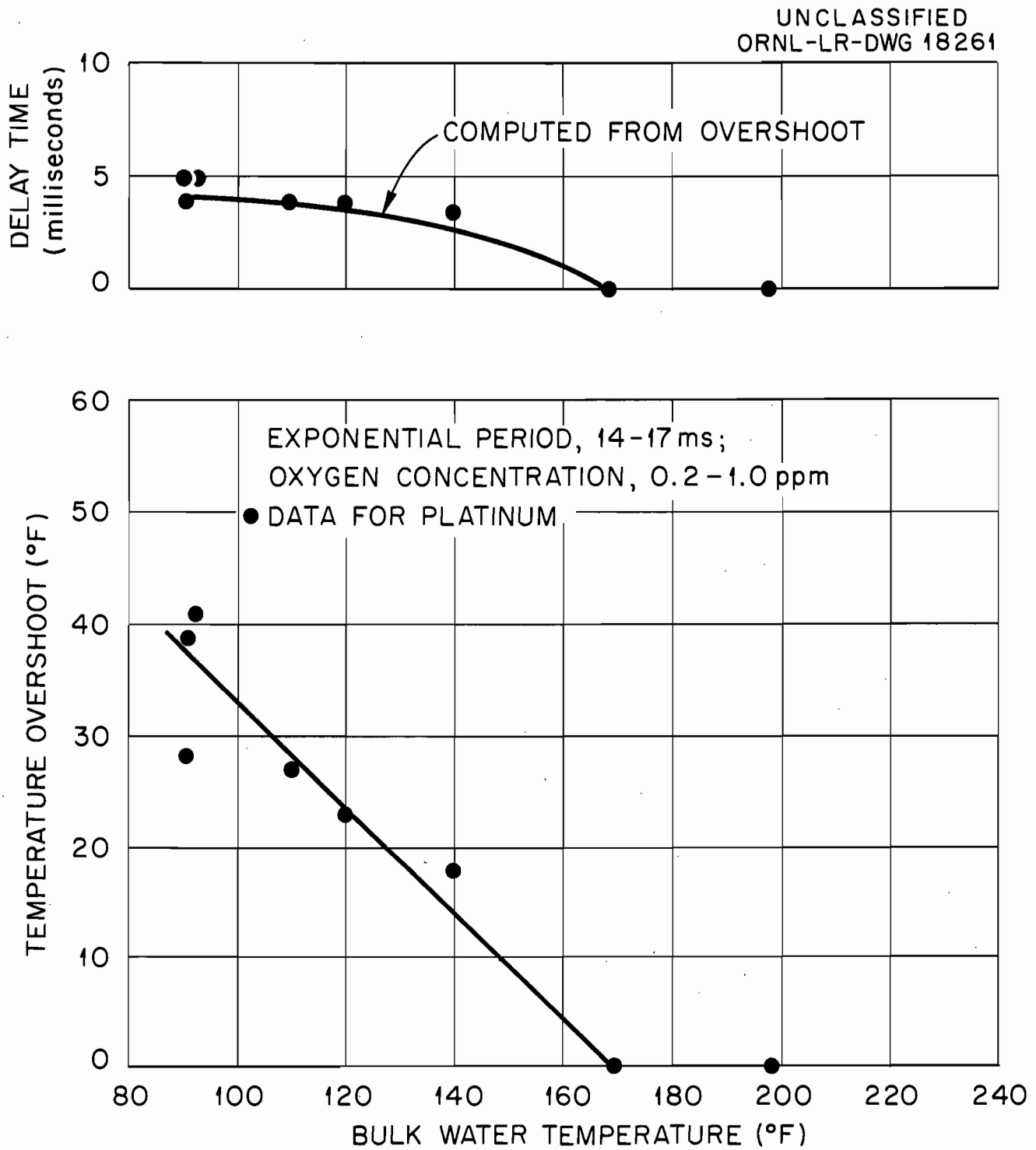

Fig. 8. Effect of Water Temperature on Delay Time and Overshoot for Platinum Ribbons.

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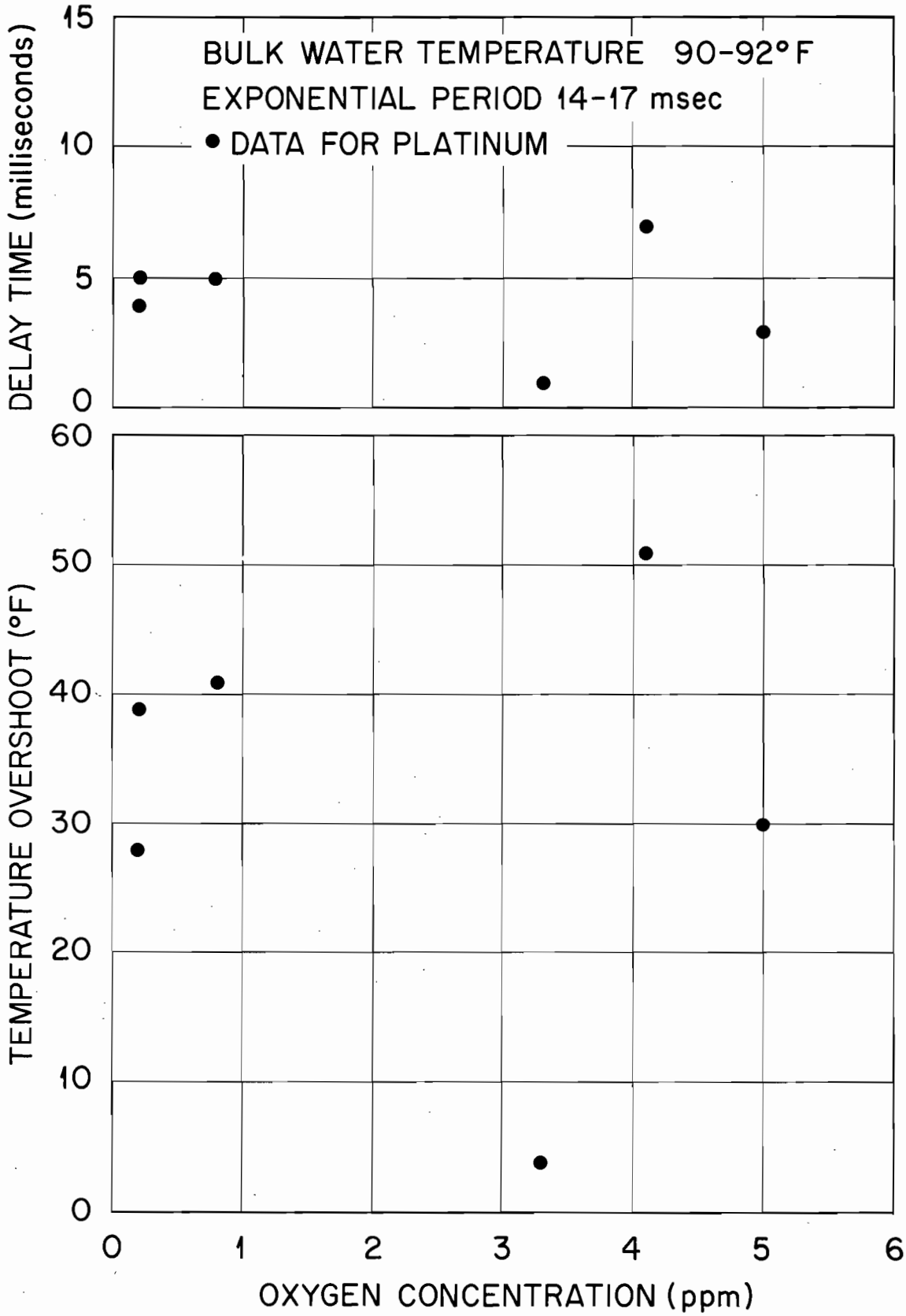

Fig. 9. Effect of Dissolved Oxygen on Delay Time and Overshoot for Platinum Ribbons.

concentration were interspersed among the ones with low concentration and performed in exactly the same manner. The precision and accuracy of the results for these runs should not differ from those of the others. Hence, the variation appears to actually be in the phenomenon and not the measurements.

Delay Time and Overshoot for Aluminum

The temperature-overshoot and delay-time values obtained using aluminum ribbon are plotted in Figs. 10 and 11. The curves for platinum from Figs. 7 and 8 are shown for comparison. As revealed in the figures, the same type of behavior was found with aluminum as with platinum, and the magnitudes of the results were the same for both materials. However, appreciably more scatter appeared in the results for aluminum.

In experiments with aluminum, difficulty was encountered in maintaining attachment of voltage taps to the ribbon, and many attempted runs were unsuccessful because of taps becoming disconnected. Nevertheless, for all of the experiments reported, microscopic examination of the ribbon after the run revealed good bonding with the wires, and no unusual behavior was detected in the recorder traces. There is no certainty, however, that the variation in the data was actually in the phenomena and not in the measurements, although it would not be surprising if the oxide layer on the surface of aluminum introduced nucleation effects not present with platinum.

No experiments using aluminum ribbon were performed with oxygen concentrations greater than 1.0 ppm.

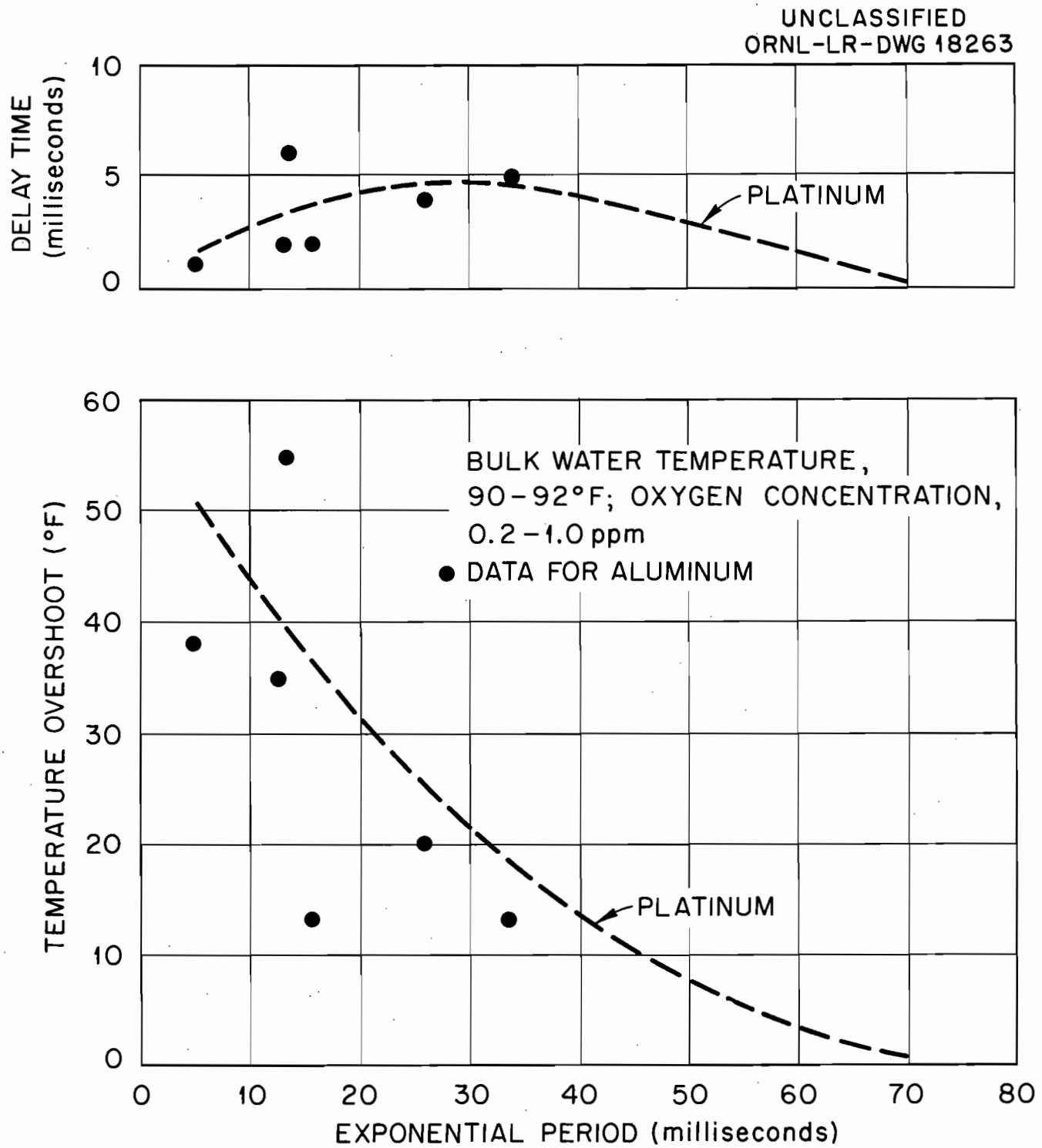

Fig. 10. Effect of Period on Delay Time and Overshoot for Aluminum Ribbons.

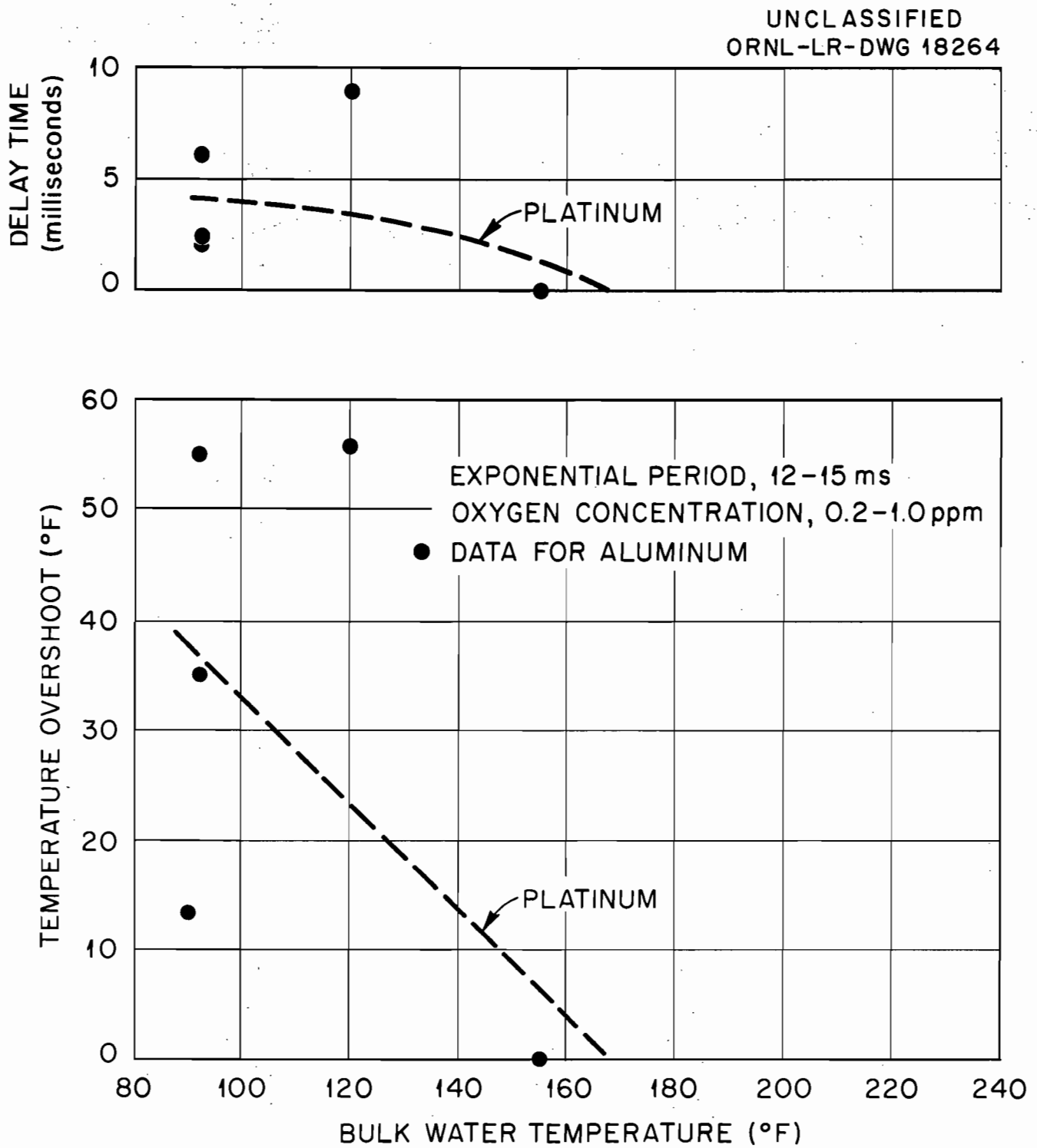

Fig. 11. Effect of Water Temperature on Delay Time and Overshoot for Aluminum Ribbons.

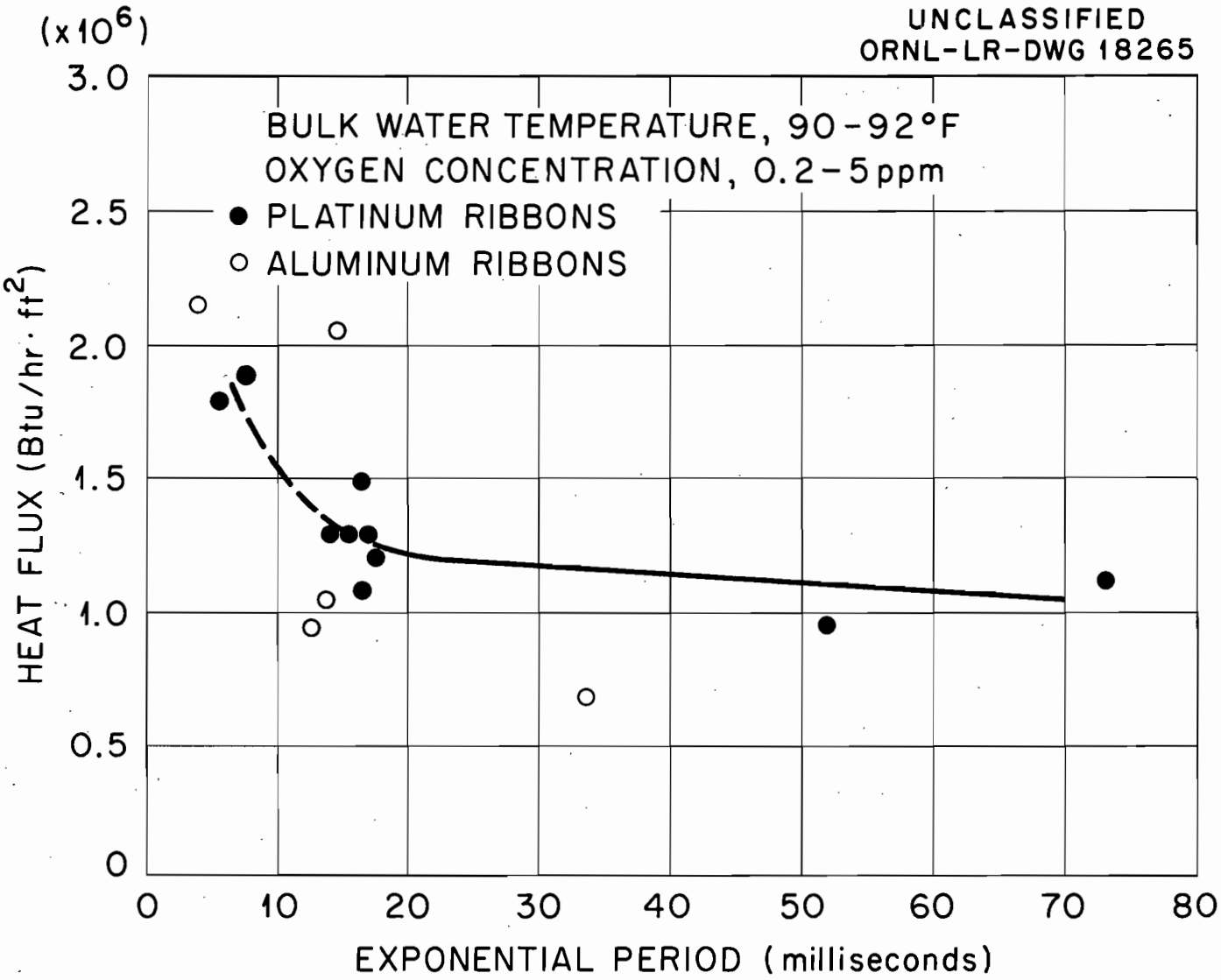

Fig. 12. Effect of Period on Heat Flux at Incidence of Film Boiling.

Incidence of Film Boiling

The heat flux at the point of incipient film boiling is plotted in Fig. 12 as a function of exponential period for bulk water temperatures of 90 - 92°F and dissolved oxygen concentrations of 0.2 - 5.0 ppm. The data are for both platinum and aluminum surfaces.

The time of the incidence of film boiling was taken as the point at which the filament temperature began an abrupt rise to burnout. The temperature rise was selected for defining this point rather than the photographic record because the moment at which formation of the vapor blanket began is difficult to identify in the films.

For periods longer than 14 msec there does not appear to be a significant change in critical flux with period. This result is in agreement with the earlier observation that in this phase of the runs there was little disturbance from the transient power increase. In effect, for the longer periods the condition of the system at any instant was not far different from what it would have been with steady boiling at the heat flux existing at that moment.

In contrast with the behavior of longer period experiments, for periods in the range of 6 msec the power rose so rapidly that the flux was relatively high when the first bubble formed, and film boiling began almost immediately after the initial boiling surge.

The critical heat flux is shown in Fig. 13 as a function of bulk water temperature for experiments in which the exponential period was essentially constant. The critical flux decreased in a linear manner as the water temperature was increased towards saturation. This behavior is of the same type encountered with steady sub-cooled boiling experiments in which burnout flux values are obtained. As an example of steady boiling

results, the critical flux curve of Gunther and Kreith[4] is shown in Fig. 13. Although their experiments were performed with horizontal stainless-steel ribbon, the two curves do not differ appreciably over much of the range. This similarity probably indicates that the high turbulence near the surface with rapid sub-cooled boiling makes the general convection pattern unimportant.

The burnout data for aluminum scatter much more than those for platinum just as do the overshoot and delay-time results.

The critical flux values for the platinum runs with high oxygen content are plotted among the other results in Figs. 12 and 13 and are not distinguishable from the other points by any greater variation from the mean curves. Hence, the effect of dissolved gas concentration on the flux at which film boiling began does not appear to have been appreciable.

Values of heat generation rate at the time of actual ribbon burnout are obtainable but have not been given because they have no significance. The burnout condition is determined by the amount the power rises during the period required to heat the metal to the melting point and thus is mainly a function of the heat capacity of the ribbon.

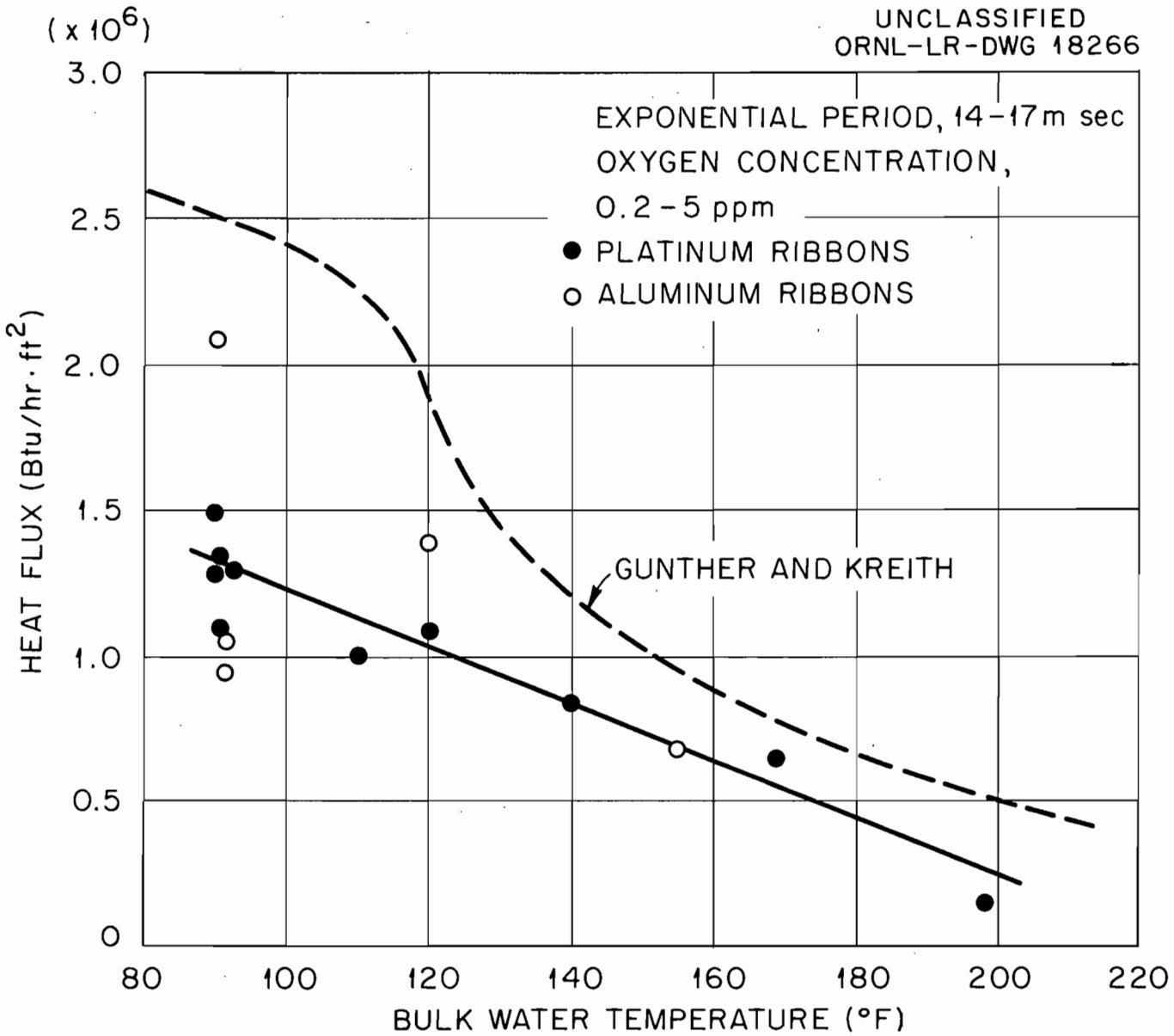

Fig. 13. Effect of Water Temperature on Heat Flux at Incidence of Film Boiling.

CONCLUSIONS

The following conclusions apply to conditions within the range of variation investigated in this program:

1. When a metal surface in contact with water which is below the boiling point is heated rapidly, there is a measurable rise in surface temperature above the boiling point before boiling commences. Associated with this "temperature overshoot" is a "delay time."

2. There is no measurable temperature overshoot or delay time when the bulk water temperature is near the boiling point.

3. During that part of an excursion preceding the beginning of boiling, the rate at which the surface temperature rises is too rapid for natural convection to contribute to heat transfer. The stagnant water acts as a semi-infinite solid with regard to heat transfer, and the temperature rise can be computed by transient conduction theory.

4. For exponential increases in the heat generation rate, the temperature overshoot and delay time increase as the bulk water temperature is decreased.

5. The temperature overshoot increases as the exponential period is decreased. Under some conditions the delay time goes through a maximum with variation in period, being small for long periods that have little temperature overshoot, and also being small for short periods where the rate of temperature rise is rapid.

6. Once quasi-steady boiling has begun during an excursion, for periods greater than 15 milliseconds with large sub-cooling, behavior of the system at any instant is not appreciably different than it would be for steady boiling. The critical heat flux (flux at the point of incipient film boiling) for these conditions is not greatly influenced by the transient state of the power.

NOTATION

B ..... $H\sqrt{k\rho c_p}$

c_p ..... Specific heat of water, Btu/lb-^{o}F

$\mathrm{erf}(y)$ ..... $\left(2/\sqrt{\pi}\right)\int_0^y e^{-u^2}\,du$

$\mathrm{erfc}(y)$..... $1.0 - \mathrm{erf}(y)$

H ..... Heat capacity of filament per unit surface area, Btu/sq ft-^{o}F

k ..... Thermal conductivity of water, Btu/hr-ft-^{o}F.

P ..... Heat generation rate in ribbon, Btu/hr

p ..... Exponential period, milliseconds

(q/A) ..... Heat flux, Btu/hr-sq ft.

$(q/A)_G$ ..... Heat generation rate per unit surface area, Btu/hr-sq ft.

$T(x,t)$ ..... Temperature increase above bulk water temperature, ^{o}F

t ..... Time, hours or milliseconds

x ..... Distance into water from surface of ribbon, feet

ρ ..... Density of water, lb/cu ft.

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