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NUCLEATE-BOILING STUDIES WITH AQUEOUS ThO_2 SLURRIES

D. G. Thomas
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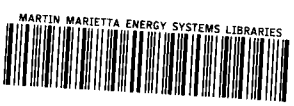

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NUCLEATE-BOILING STUDIES WITH AQUEOUS ThO_2 SLURRIES

D. G. Thomas L. D. Felten[1] R. M. Summers

SUMMARY

Nucleate-boiling heat-transfer measurements were made with aqueous thorium oxide slurries containing up to about 1000 g of Th per kg of H_2O (0.105 volume fraction of solids, 1- to 3-μ average diameter). Boiling took place from the surface of $\frac{1}{16}$- and $\frac{1}{8}$-in.-dia platinum tubes submerged in slurry. The results may be represented in terms of the equation

$$q/A = K(\Delta T)^n ,$$

where

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

K = dimensional constant,

ΔT = temperature difference between heated tube wall and bulk slurry temperature, °F.

For the slurries studied, the heat flux at a ΔT of 10°F was about 10^4 Btu/(hr)(ft^2) regardless of slurry concentration. However, the value of the exponent, n, decreased as the volume fraction of solids was increased. The value of n was 3.3 with no thorium oxide present and approached unity at a volume fraction of solids of 0.10.

The maximum heat flux attainable under nucleate-boiling conditions (often called the critical heat flux or burnout heat flux) at slurry concentrations of 200 g of Th per kg of H_2O was about the same as for water. However, at a concentration of 1000 g of Th per kg of H_2O, the burnout heat flux wos 210,000 Btu/(hr)(ft^2), compared with a value of 490,000 Btu/(hr)(ft^2) for water under corresponding conditions.

At constant heat flux, the temperature difference between the heated tube surface and the fluid saturation temperature increased 5 to 6°F per hour. This result might be explained by a "soft" film that surrounded the heated metal surface. This film was apparently less than $\frac{1}{32}$ in. thick and was never distinguishable as an adhering film after the tube was removed from the slurry system. No hard cakes were observed on the surface from which boiling took place during any of the tests.

The nucleate-boiling tests were made with aqueous thorium oxide slurries which had non-Newtonian laminar flow characteristics and which were almost Newtonian under turbulent flow conditions. No phenomena were observed which could be attributed to the effect of the solid particles on the gross physical properties of the slurry; for example, the non-Newtonian laminar flow characteristics of the slurry had no discernible effect on the nucleate-boiling heat transfer.

INTRODUCTION

Boiling at the core-blanket interface of large-scale (440 thermal Mw) two-region homogeneous reactors has been predicted (*1*) on the basis of calculated heat generation rates in the core-vessel wall. Also, it has been postulated (*2*) that boiling might be at least partially responsible for caking in high-temperature loops. Although much information has been reported in the literature on nucleate-boiling heat transfer in homogeneous liquid systems, information is meager concerning this phenomenon in systems containing appreciable quantities of suspended solids.

Objectives of the present study were to determine

1. The nucleate-boiling heat-transfer characteristics of aqueous ThO_2 suspensions. The presence of solids might be manifested in two different ways: (*a*) thorium oxide particles deposited on the tube surface could catalyze the rate of nucleation and hence increase the slurry nucleate-boiling heat-transfer coefficient,

[1] Summer employee, 1957.

or (*b*) thorium oxide particles in suspension might influence the coefficient by markedly affecting the laminar flow characteristics of the suspending medium.

2. Whether concentrated thorium oxide slurries would form a hard, tightly adhering layer on a surface on which nucleate boiling was occurring.

Nucleate-Boiling Resume for Pure Liquids

When natural convection cannot maintain a submerged heated surface below the boiling point of the saturated liquid, bubbles begin to form at nucleation centers, resulting in nucleate boiling (*3*). One of two processes may be controlling in nucleate boiling (*4*): the nucleation and growth of bubbles at the surface or the disengagement of the bubbles and their growth in the superheated liquid adjacent to the surface. Semitheoretical relations have been developed on the basis of each of these hypotheses, and some correlations of the rate of nucleate-boiling heat transfer as a function of fluid properties are given in Table 1.

In this table semitheoretical and empirical relations are considered as products of individual physical properties raised to the appropriate power; the particular value of the exponent is recorded. In some cases the variables chosen by the investigator included other variables implicitly, thus making comparison difficult. These cases are noted in. the table. Examination of the table shows that there is very poor agreement on the effect of different physical properties on the nucleate-boiling heat-transfer rate, though there is relatively good agreement that the heat flux, q/A,

Table 1. Empirical and Semitheoretical Versions of the Dependence of Nucleate-Boiling Heat Transfer upon Fluid Properties

Dependence given in terms of the exponent of the equation: Heat flux, q/A = Constant $\prod X_i^{n_i}$

Variable Property, X_i	n_i						
	a	*b*	*c*	*d*	*e*	*f*	*g*
ΔT	1	3	0.24	3.39	3.7	3.33	3
Viscosity	0.13	−4.1	−0.29	−3.45	1.85	0	0
Surface tension	−0.8	−0.5	−0.5	−1.65	−1.85	−1.67	−1
Thermal conductivity of liquid	0.87	5.1	0.79	2.97	1.83	1.67	1.0
Specific heat of liquid	0.55	−2.1	0.45	0.43	1.85	1.67	1.0
Latent heat of vaporization	−0.8	−2	−0.24	0	−2.7	−1	~(−1)
Contact angle, through liquid	−1	−1	0	0	0	0	−1
Density of liquid, ρ_L	0.4	0	0.49	3.1	1.85	2.7	2
Density of vapor, ρ_v	0	0	−0.24	0	2.7	1.67	~(−1)
$(\rho_L - \rho_v)$	2	0.5	0	0	0	0	0
$(p_v - p_\infty)$	1.4	0	0.75	0	0	0	0
Tube diameter	0	0	0	2.1	0	0	0

[a] H. K. Forster and R. Grief, *Trans. Am. Soc. Mech. Eng., Series C* 81, 43-54 (1959). [Temperature effect included in $(p_v - p_\infty)$; p_v = vapor pressure inside bubble; p_∞ = vapor pressure from flat surface.]

[b] W. M. Rohsenow, *Trans. Am. Soc. Mech. Eng.* 74, 969 (1952).

[c] H. K. Forster and N. Zuber, *J. App. Phys.* 25, 474 (1954).

[d] D. S. Cryder and E. R. Gilliland, *Ind. Eng. Chem.* 24, 1382 (1932).

[e] C. F. Bonilla and C. W. Perry, *Trans. Am. Inst. Chem. Eng.* 37, 685 (1941). (Data for atmospheric pressure only.)

[f] T. H. Insinger and H. Bliss, *Trans. Am. Inst. Chem. Eng.* 36, 491 (1941).

[g] S. Levy, *Trans. Am. Soc. Mech. Eng., Series C* 81, 37-43 (1959).

is proportional to the 3rd to 4th power of the temperature difference, with most investigators reporting values between 3.3 and 3.5. The semi-theoretical treatment of Rohsenow yields a value of 3.0.

Nucleate Boiling in the Presence of Suspended Solids

Suspended solids have been reported (*4*) as either increasing or decreasing the nucleate-boiling heat-transfer coefficient, depending on the nature of deposition of the solids: if the solids deposit on the surface as a thin film, bubble nucleation may be enhanced and the observed heat transfer rate increased; if, on the other hand, the deposit is bulky, the observed heat-transfer rate may be decreased. (These observations were based on results of tests with only small quantities of suspended solids; hence, no information is available on the effect of suspended solids at concentrations sufficiently large to affect the physical properties of the suspension.)

If the change in physical properties due to suspended solids does affect the nucleate-boiling process it would be expected to do so during one or the other of the controlling stages, that is, during the nucleation and growth of the bubbles *on* the heated surface or during their growth in the superheated liquid near the surface *after* disengagement.

Nucleation. – Nucleation of the bubbles is mainly a function of the condition of the surface and the variation of vapor pressure with temperature. If this stage is controlling, the presence of up to 0.1 volume fraction of suspended solids might be expected to exert an influence on nucleate boiling in the nucleation stage through catalytic effects. Catalytic effects previously observed have resulted in the heat flux being proportional to $(\Delta T^{7 \text{ to } 12})$ instead of $(\Delta T^{3 \text{ to } 4})$ commonly observed. The presence of up to 0.1 volume fraction of suspended solids should not have sufficient effect on the variation of vapor pressure of the suspending medium with temperature – or on other physical properties – to affect nucleate boiling at the early stages of the boiling process. Effects observed at this stage would probably be confined to an increase in the value of the exponent of the ΔT term.

Growth After Disengagement. – Growth of the bubbles after disengagement is primarily a function of the Prandtl number and latent heat of vaporization. If this stage is the controlling one, the presence of up to 0.1 volume fraction of suspended solids should have no appreciable effect on the latent heat of vaporization of the suspending medium; however, the Prandtl number could be appreciably affected on a macroscopic scale, with some uncertainty being associated with the viscosity term. This uncertainty arises because suspensions of ThO_2 can exhibit marked non-Newtonian laminar flow characteristics. Detailed discussions of this subject are available elsewhere (*5,6*), it being sufficient here to note that at low rates of shear the apparent viscosity may be quite large. [The apparent viscosity may be defined as the point condition described by $\tau/(dV/dr)$, which is the shear stress divided by the velocity gradient. This ratio is constant for laminar conditions with Newtonian materials and is not constant for non-Newtonian materials.] A specific viscosity effect that has been observed is the shifting of the maximum ΔT for saturated nucleate boiling from 58 to 220°F on changing from pure water to pure glycerin (*3*).

The effect of altered physical properties due to attractive forces between slurry particles on the growth of bubbles should occur only after the bubbles have become large compared with the slurry particles. If bubble growth at this stage is no longer controlling, then the suspended particles should have little or no effect on nucleate-boiling phenomena.

EXPERIMENTAL EQUIPMENT

The slurry nucleate-boiling tests were made in the 4 × 12 × 15 in. stainless steel tank and auxiliaries shown in Figs. 1 and 2. The boiling took place on resistance-heated platinum tubes either $\frac{1}{8}$ or $\frac{1}{16}$ in. in diameter immersed in ThO_2-H_2O slurry. A 1-gpm centrifugal pump recirculated the slurry and maintained it in suspension, and resistance heaters on the tapered bottom of the tank maintained the slurry at its boiling point. Vapor condensers were used to maintain the slurry at the desired concentration. The platinum-tube wall temperature was measured with a thermocouple inserted along the axis of the resistance-heated platinum tube. A thick glass window whose surface projected sufficiently far into the tank that the platinum tube could be moved over adjacent to

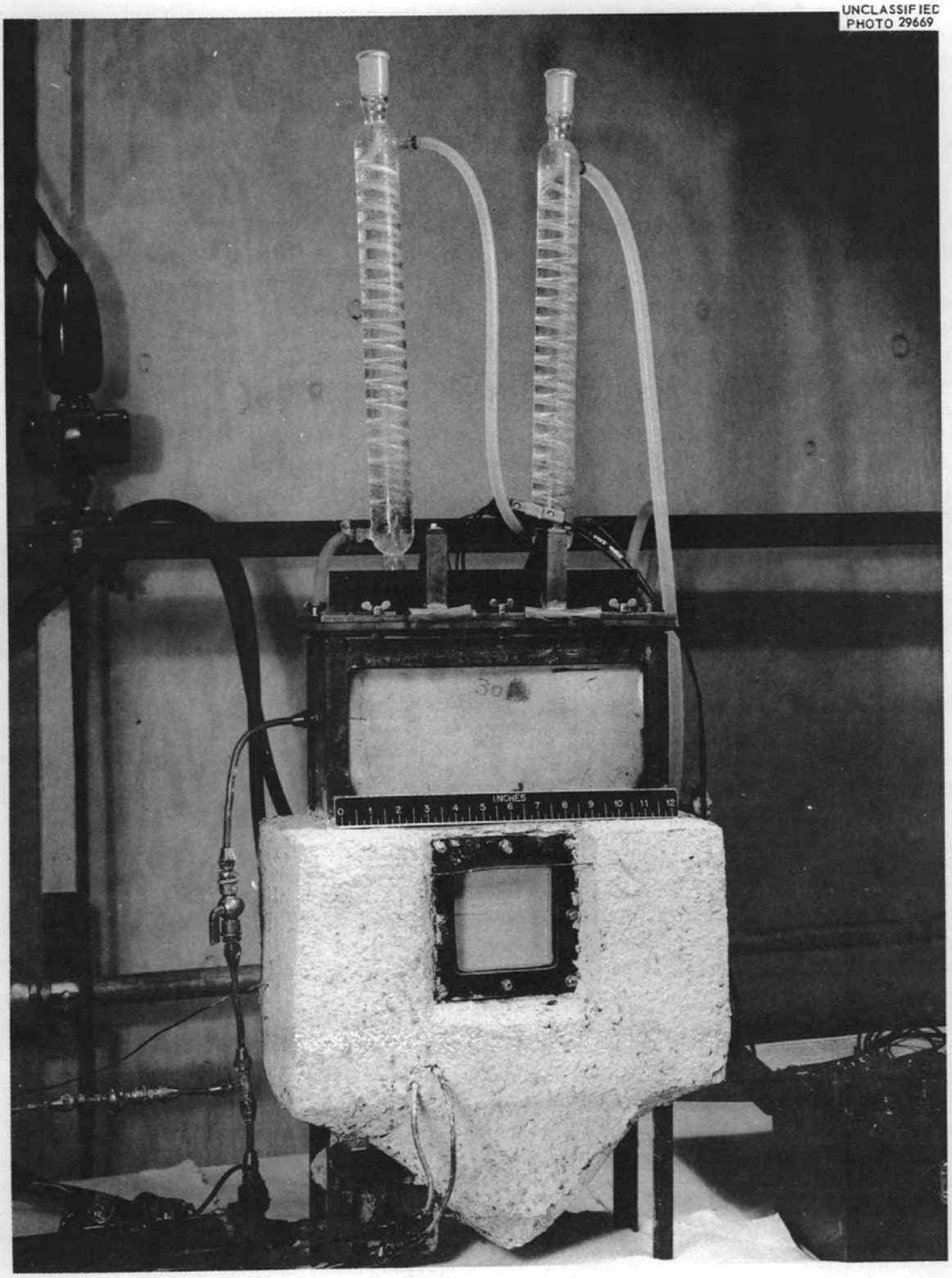

Fig. 1. Experimental Equipment for Nucleate-Boiling Experiments.

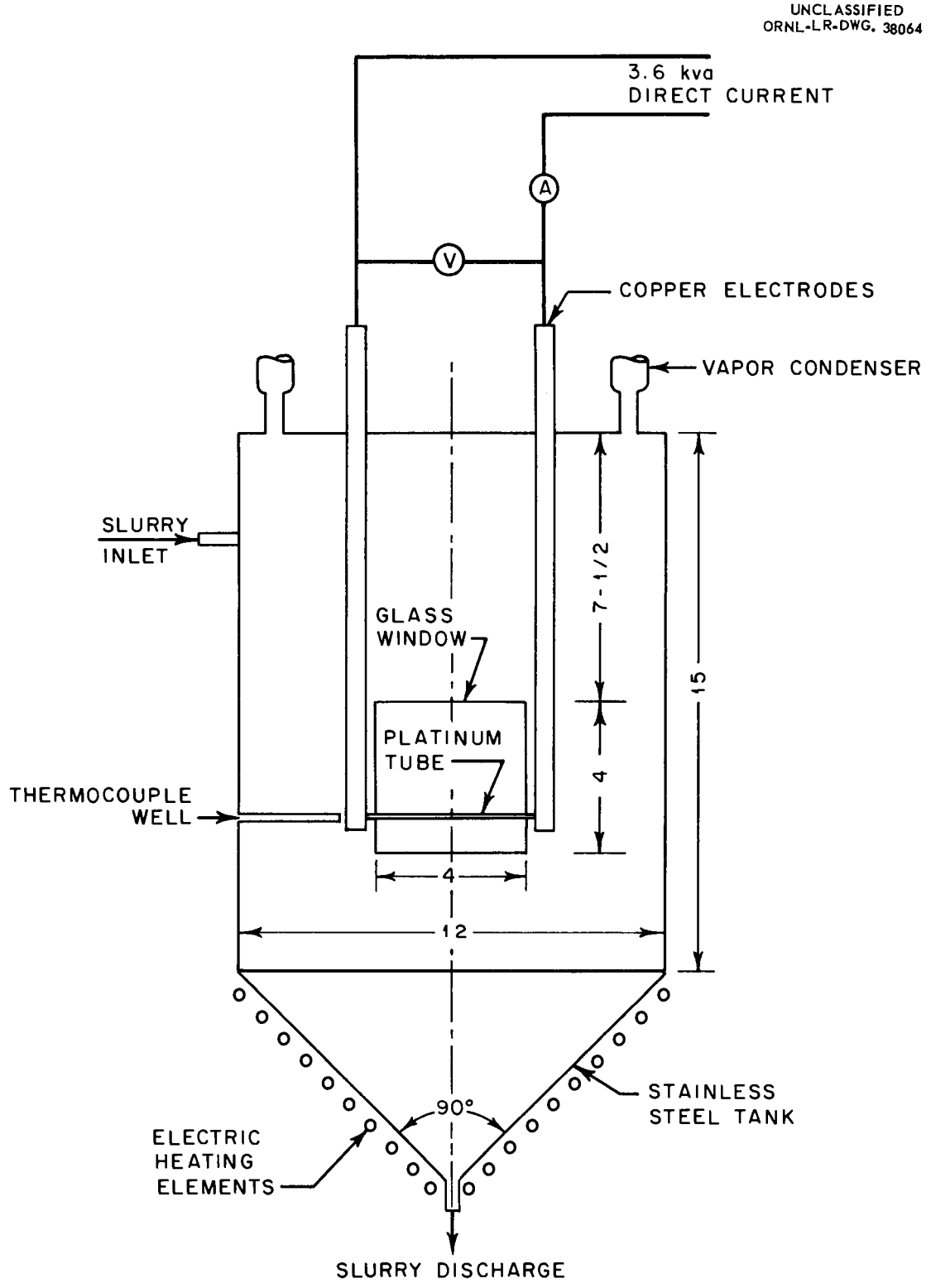

Fig. 2. Stainless Steel Slurry Reservoir Used in Nucleate-Boiling Experiments. Dimensions are in inches.

it allowed the existence of boiling to be visually verified.

Before the nucleate-boiling tests were started on the platinum tube, the slurry was thoroughly mixed by recirculating it with the 1-gpm pump and was heated to the boiling point by the heaters placed on the bottom of the reservoir. The nucleate-boiling heat flux was obtained from the voltage drop and current through the platinum tube. The temperature inside the tube was measured with a 28-gage platinum–platinum 10% rhodium thermocouple connected to a Leeds and Northrup electronic potentiometer. Correction for the temperature drop through the platinum tube was always less than 0.1°C for nucleate boiling and heat fluxes greater than 5000 Btu/(hr)(ft^2). The platinum tubes were 4 in. long and either $\frac{1}{16}$-in. OD with 0.004-in. walls or $\frac{1}{8}$-in. OD with 0.004-in. walls.

EXPERIMENTAL RESULTS

Water Calibration Tests

Initial tests were made with water to demonstrate satisfactory operation of the system and to determine the effect of the small amount of forced convection due to the 1-gpm recirculation rate on the nucleate-boiling curve (a 1-gpm flow rate corresponds to one system volume recirculated every 3 to 4 min or to a mid-plane velocity of less than 0.01 fps; this flow rate was chosen as the minimum required to maintain the ThO_2 in suspension, not particularly to study forced-convection effects). The results of the free and slightly forced convection tests with water are shown in Fig. 3.

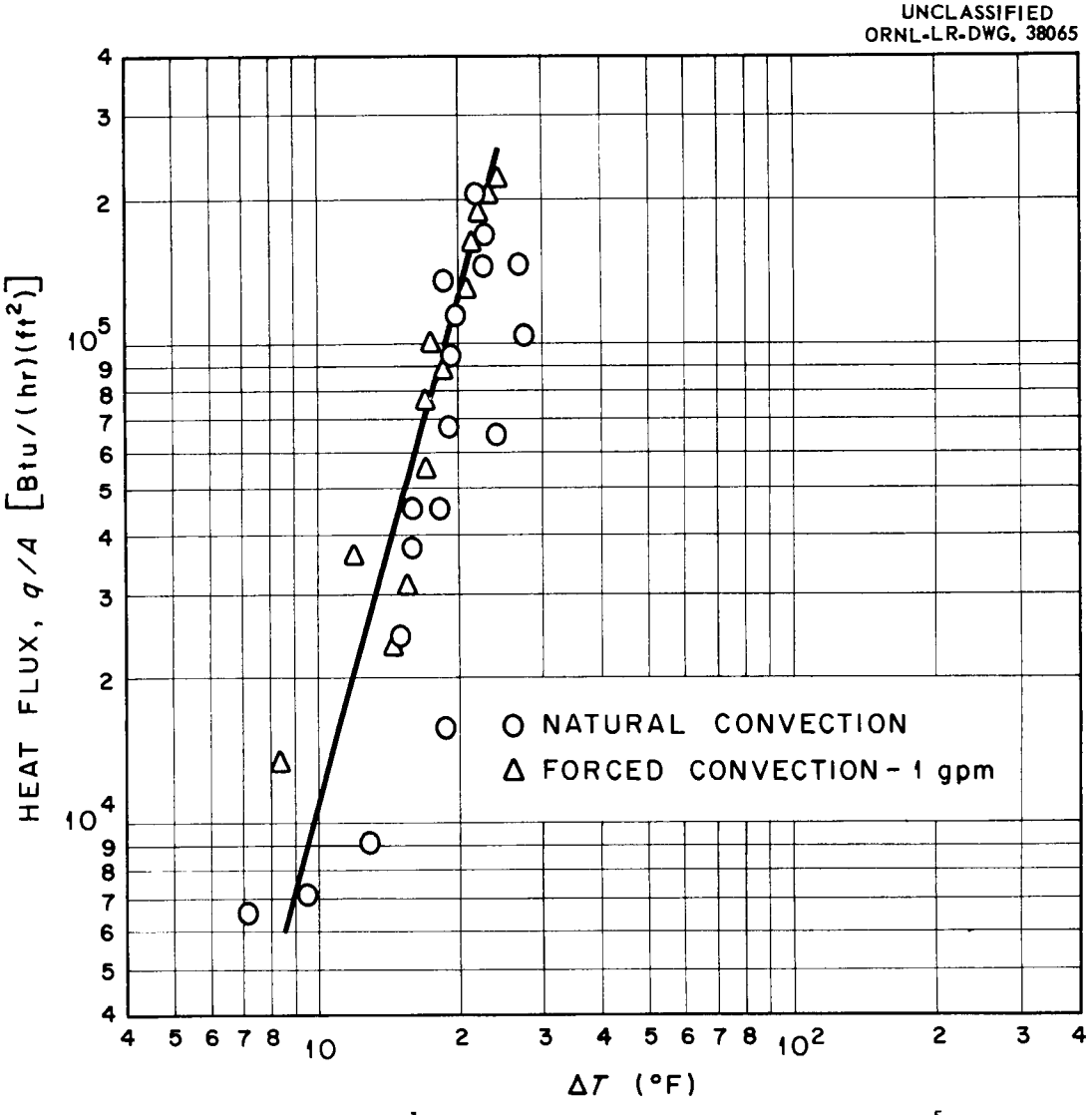

Fig. 3. Nucleate Boiling of Water on $\frac{1}{16}$-in.-dia Platinum Tube. Tube spaced at least $\frac{5}{8}$ in. from wall.

The principal effect of operation with the pump running was to reduce the scatter of the data; there was no apparent shift of the nucleate-boiling curve. The data are in very close agreement with data of previous investigations (*3,4,7*) and are consistent with the observations that forced circulation has little effect on the nucleate-boiling curve at high heat fluxes. The principal forced-circulation effects have been observed at heat fluxes less than 10^4 Btu/(hr)(ft^2) and ΔT less than 10°F. Thus the use of this low fluid circulation rate to maintain solids in suspension is believed to have little effect on the observed boiling curves of slurries.

Slurry Pool Boiling

The effect of 0 to 0.101 volume fraction of solids on pool boiling from platinum tubes is shown in Fig. 4. In order to minimize hysteresis effects,

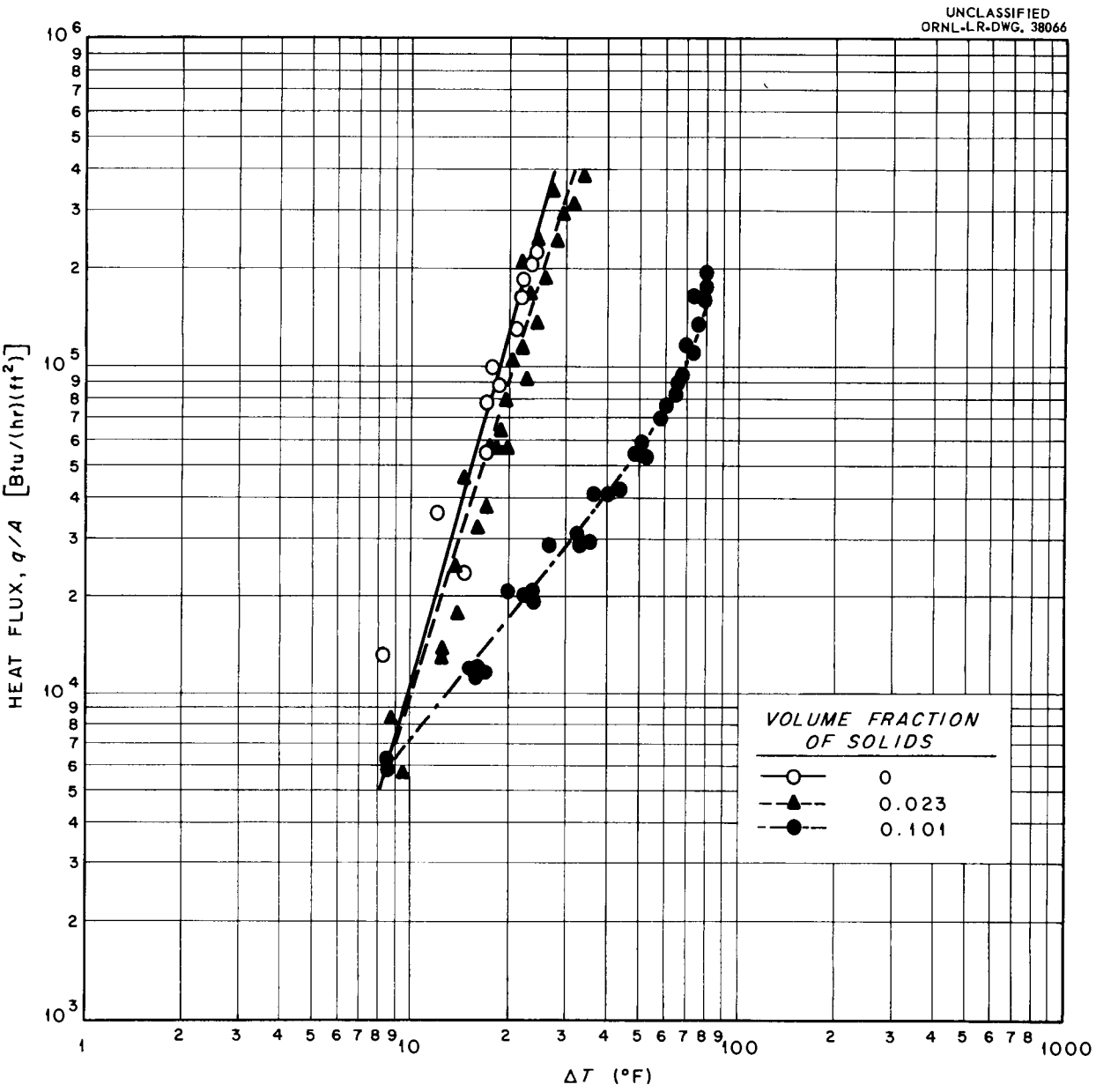

Fig. 4. Effect of ThO_2 Suspension Concentration on Nucleate Boiling from Platinum Tube. Forced convection flow rate was ~1 gpm in a tank containing ~3 gal slurry.

the tube was first heated till it was at least 30°F above saturation temperature. The tube was then cooled down and heated up for several cycles as data were taken at different heat fluxes. These heating and cooling cycles are identified on the figures shown in the appendix, Figs. 9–13, and the reproducibility of the data is seen to be quite good. However, it was observed in the course of 3 to 4 hr of alternate heating and cooling cycles that there was a pronounced increase of ΔT for any given heat flux. At no time during or at the end of these tests was a hard deposit of ThO_2 observed on the surface of the platinum tube. The increase of ΔT with time will be discussed in more detail later.

In order to verify the existence of boiling for heat fluxes greater than 15,000 Btu/(hr)(ft^2), the platinum tube was moved until it was adjacent to the glass plate. Bubbles were observed rising from the wire at all values of the heat flux. Photographs taken at heat fluxes of 13,700, 45,100, 122,200, and 250,500 Btu/(hr)(ft^2) showed no evidence of a thorium oxide sediment filling the space between the platinum tube and the glass. At the higher heat fluxes there were many vapor bubbles adjacent to the glass and portions of the tube were readily identifiable. However, in no case was a metallic surface visible; instead the tube surface appeared to be covered with a layer of wet thorium oxide. Measurements on the photograph (Fig. 5) taken at a heat flux of 250,000 Btu/(hr)(ft^2) indicate that the thickness of the film was less than $\frac{1}{32}$ in. Pool boiling data obtained with the platinum tube adjacent to the glass for volume fraction solids of 0.024, 0.062, and 0.104 are shown in Figs. 11, 12, and 13 in the

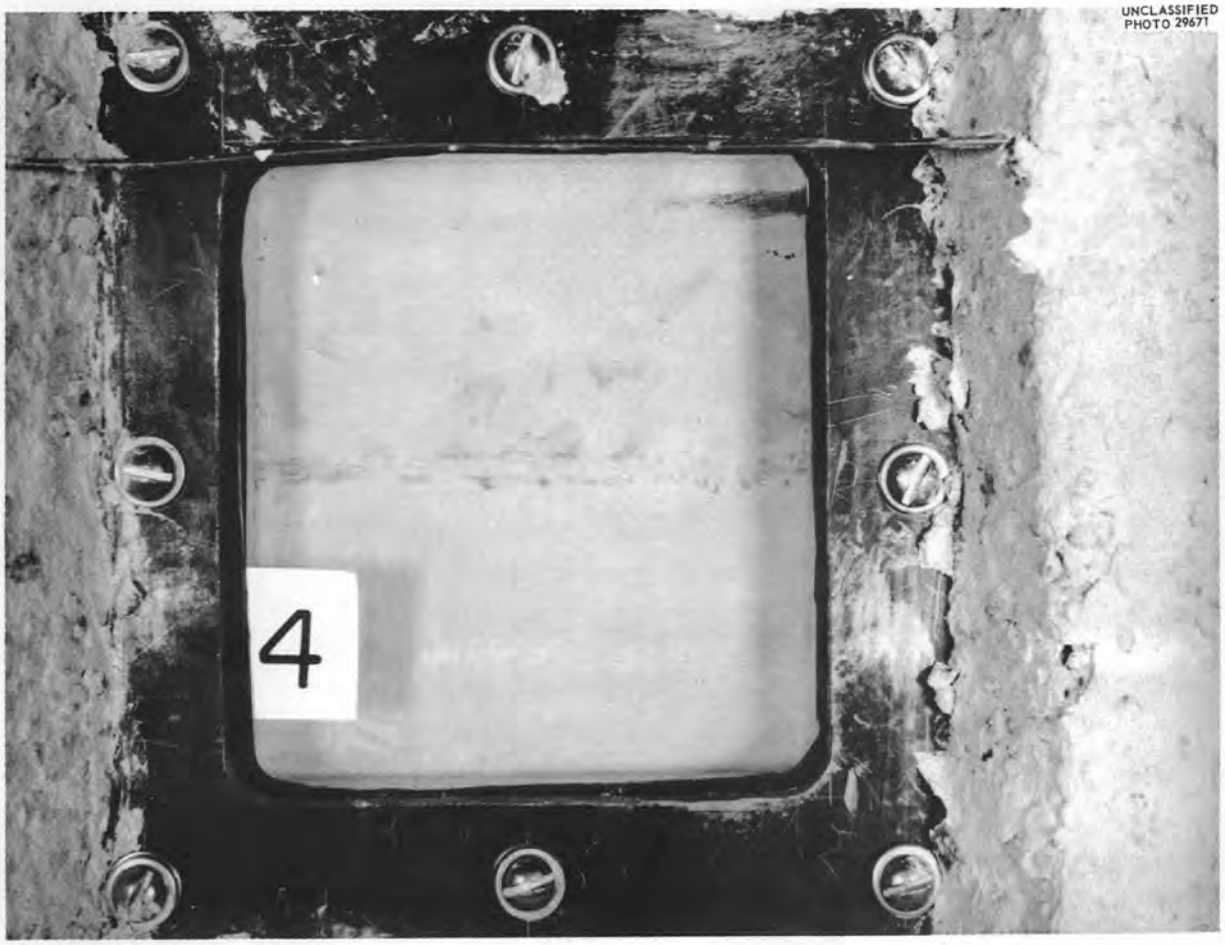

Fig. 5. Nucleate Boiling of Aqueous ThO_2 Slurry Containing 0.064 Volume Fraction of Solids at a Heat Flux of 250,000 Btu/(hr)(ft)^2.

appendix. The data are substantially the same as those taken with the tube away from a surface. The reproducibility on successive cooling and heating cycles was similar to that observed with the free tube.

Slurry physical properties were measured in conjunction with forced-convection heat transfer studies (5). Laminar flow characteristics of the slurry were arbitrarily fitted with the Bingham-plastic model, which describes the flow in terms of two parameters. One parameter, the yield stress, represents the force required to initiate flow, while the other parameter, the coefficient of rigidity, is the limiting viscosity at very high shear rates. Slurry physical properties as a function of concentration are given in Table 2. A more detailed discussion of ThO_2 slurry physical properties is available elsewhere (8).

Constant-Heat-Flux Measurements

During the course of 3 to 4 hr of alternate heating and cooling cycles it was observed that there was a pronounced increase in the ΔT required to achieve any given heat flux. In order to determine the rate of surface-temperature increase with time, three measurements were made at constant heat flux with 0.062 volume fraction solids; the tube temperature was measured as a function of time. The results are shown in Fig. 6. The data indicate that the ΔT increased about an average of 5 to 6°F per hour during heating at the three different rates of heat flux. At the end of the tests the tube was removed from the slurry, and the loosely adhering slurry film was washed off readily by a flowing stream of water.

Burnout

Burnout (4) is said to occur when the heat flux becomes so large that nucleate boiling cannot be sustained and there is a rapid transition to film boiling with a consequent 10- or 20-fold increase in ΔT. If the melting point of the tube on which the boiling is taking place is exceeded, true burnout is observed. If the tube is of a noble metal with a high melting point, then stable film boiling may be achieved instead of actual burnout.

Maximum heat fluxes that have been observed (4) with water are between 300,000 and 400,000 Btu/(hr)(ft^2), and the critical ΔT (associated with maximum heat flux under nucleate-boiling conditions) is often between 45 and 50°F. Good correlations of heat flux at burnout have been achieved with the relation (9)

$$\frac{(q/A)_{max}}{\lambda \rho_v} = 143 \left(\frac{\rho_L - \rho_v}{\rho_v} \right)^{0.6} , \qquad (1)$$

where

λ = latent heat of vaporization, Btu/lb,

ρ_L = density of liquid, lb/ft^3,

ρ_v = density of vapor, lb/ft^3,

$(q/A)_{max}$ = maximum heat flux under nucleate-boiling conditions, Btu/(hr)(ft^2).

Film boiling and burnout data observed in the present investigation with water and ThO_2 slurries are given in Table 3. The value of 490,000 Btu/(hr)(ft^2) obtained experimentally for maximum heat flux with water is in satisfactory agreement with the value of 420,000 Btu/(hr)(ft^2) obtained from Eq. (1). The maximum heat flux for burnout

Table 2. Thorium Oxide Slurry Physical Properties* at a Temperature of 95°C

Slurry Concentration		Yield Stress (lb/ft^2)	Coefficient of Rigidity, η		Prandtl Number, Using η for Viscosity
g of Th per kg of H_2O	Volume Fraction of Solids		(cp)	$\left[\frac{lb}{(ft)(sec)}\right]$	
220	0.024	0.002	0.6	0.004	2.5
710	0.074	0.066	1.7	0.011	4.7
1100	0.110	0.49	3.2	0.022	8.0

*Estimated values.

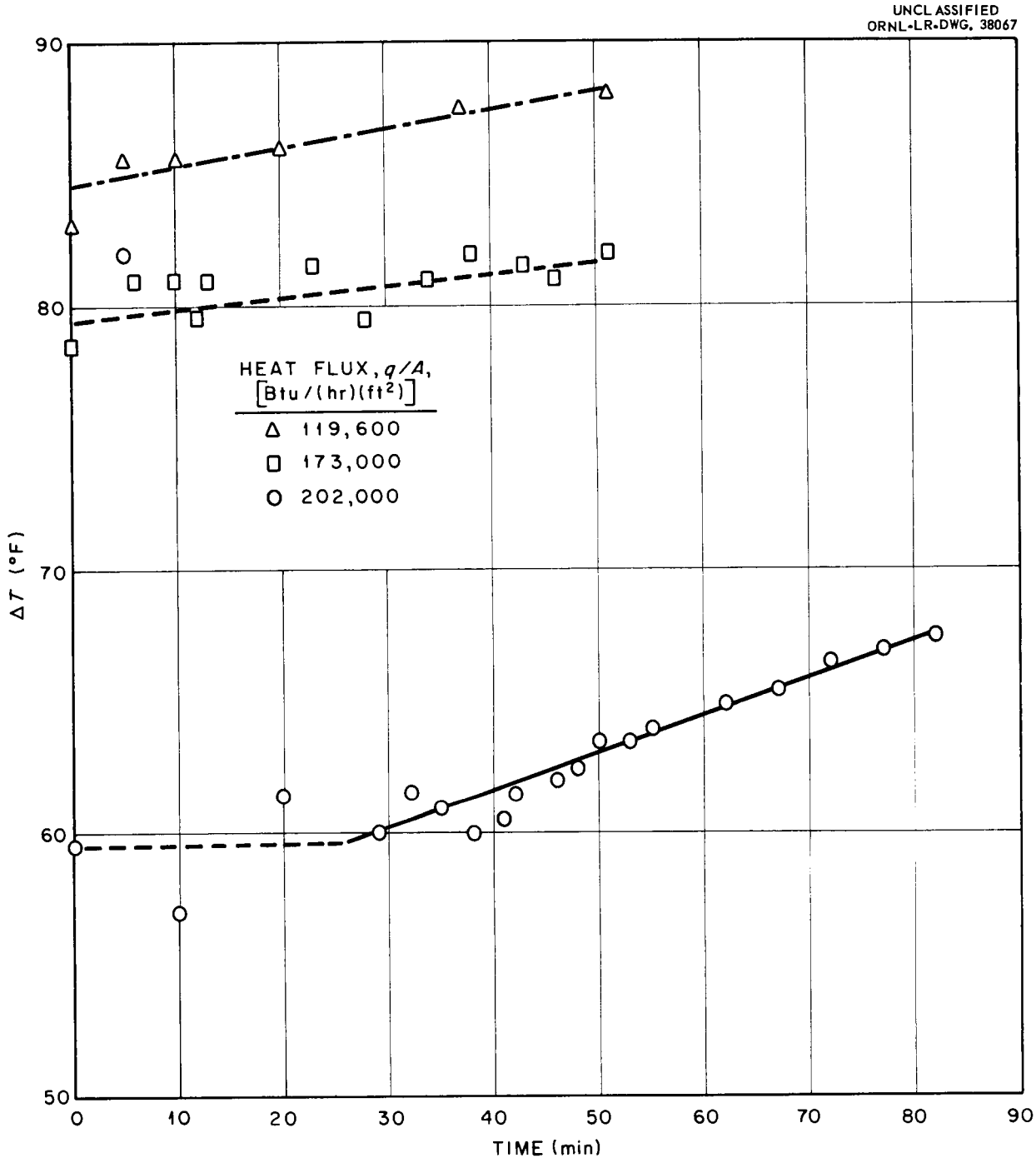

Fig. 6. Increase of ΔT as a Function of Time at Constant Heat Flux for $\frac{1}{8}$-in.-dia Platinum Tube. Tube adjacent to glass plate; 1 gpm forced convection flow.

Table 3. Burnout* Data for Pool Boiling of Water and Aqueous ThO_2 Slurries Using Platinum Tubes

Tube Diameter (in.)	Placement of Tube**	Slurry Concentration (g of Th per kg of H_2O)	Phenomena Observed	$(q/A)_{max}$ [Btu/(hr)(ft^2)]
1/16	B	0	Burnout	490,000
1/8	A	740	Film boiling	223,500
1/8	B	986	Film boiling	214,000
1/8	A	1015	Film boiling	160,000
1/16	B	1000	Burnout	240,000

*Burnout occurs when the heat flux becomes so large that nucleate boiling cannot be sustained.

**Designation A refers to placement adjacent to window; B refers to placement 5/8 in. from window.

observed with the concentrated slurries averaged 210,000 Btu/(hr)(ft^2), or about half the value observed with water. This difference in $(q/A)_{max}$ corresponds to a reduction from 10,000 to 2000 Btu/(hr)(ft^2)(°F) in the maximum heat transfer coefficient.

Although no data on burnout were obtained for more dilute slurries, some information can be obtained from the data of Fig. 8 taken with a slurry having 0.023 volume fraction of solids (about 200 g of Th per kg of H_2O). It was possible to achieve heat fluxes of at least 400,000 Btu/(hr)(ft^2) with no evidence of the peaking that would be expected to precede transition from nucleate to film boiling. However, at 0.059 volume fraction of solids (about 580 g of Th per kg of H_2O), a definite peaking (see Fig. 9) was observed at a flux of about 200,000 Btu/(hr)(ft^2). Thus, appreciable (>200 g of Th per kg of H_2O) concentrations of slurry are apparently required before maximum burnout heat fluxes are significantly reduced.

DISCUSSION OF RESULTS

Comparison of the nucleate-boiling curves of Fig. 4 shows that at a ΔT of about 10°F the heat flux was of the order of 10^4 Btu/(hr)(ft^2) regardless of the slurry concentration. Also, the slope of the curves of log q/A vs log ΔT decreased as the volume fraction of solids increased. A plot of the value of this slope vs volume fraction of solids is given in Fig. 7 for all data taken in this study. The value of the slope, n, decreased regularly with volume fraction of solids, asymptotically approaching a value of $n = 1$ at a volume fraction of solids of about 0.1. The maximum heat flux for burnout with concentrated slurries (0.1 volume fraction of solids) was consistently less than half that for pure water. In limited experiments in which the heat flux was held constant, the ΔT increased at an average rate of 5 to 6°F per hour.

Catalytic effects normally cause the exponent on the ΔT term to increase as the volume fraction solids is increased. Since the exponent was observed to decrease in the present investigation, it is believed that there is no evidence for a catalytic effect in the concentration range 0.02 to 0.1 volume fraction of solids.

Comparison of the slurry physical properties given in Table 2 with those for water under the same conditions shows that at 0.1 volume fraction solids the physical properties of the water were markedly affected by the solids. However, a corresponding change in the boiling curves (as predicted by the physical-property effects listed in Table 1) was not observed. Apparently the 1- to 3-μ slurry particles were too large to interfere with the physical-property effects controlling the nucleate-boiling phenomena in the manner predicted by previous theory and experiments.

It is believed that the lack of correlation between the observed experimental results and previous theory or experiment may be explained by the deposition of a loose, soft film of solids on the surface of the tube. Under these conditions the results in Fig. 7 indicate that the thickness

and/or concentration of the deposited material is proportional to the volume fraction of solids up to a value of about 0.08 to 0.10; Fig. 6 indicates that this thickness also increases slowly as a function of time (at least for times of the order of 1 hr) in spite of the presence of vigorous boiling in the vicinity of the surface. A deposit with a density of 4 and thickness of 0.010 in. would account for the observed effect. This is in qualitative agreement with the thickness of $\frac{1}{32}$ in. estimated from the photographs of slurry nucleate boiling.

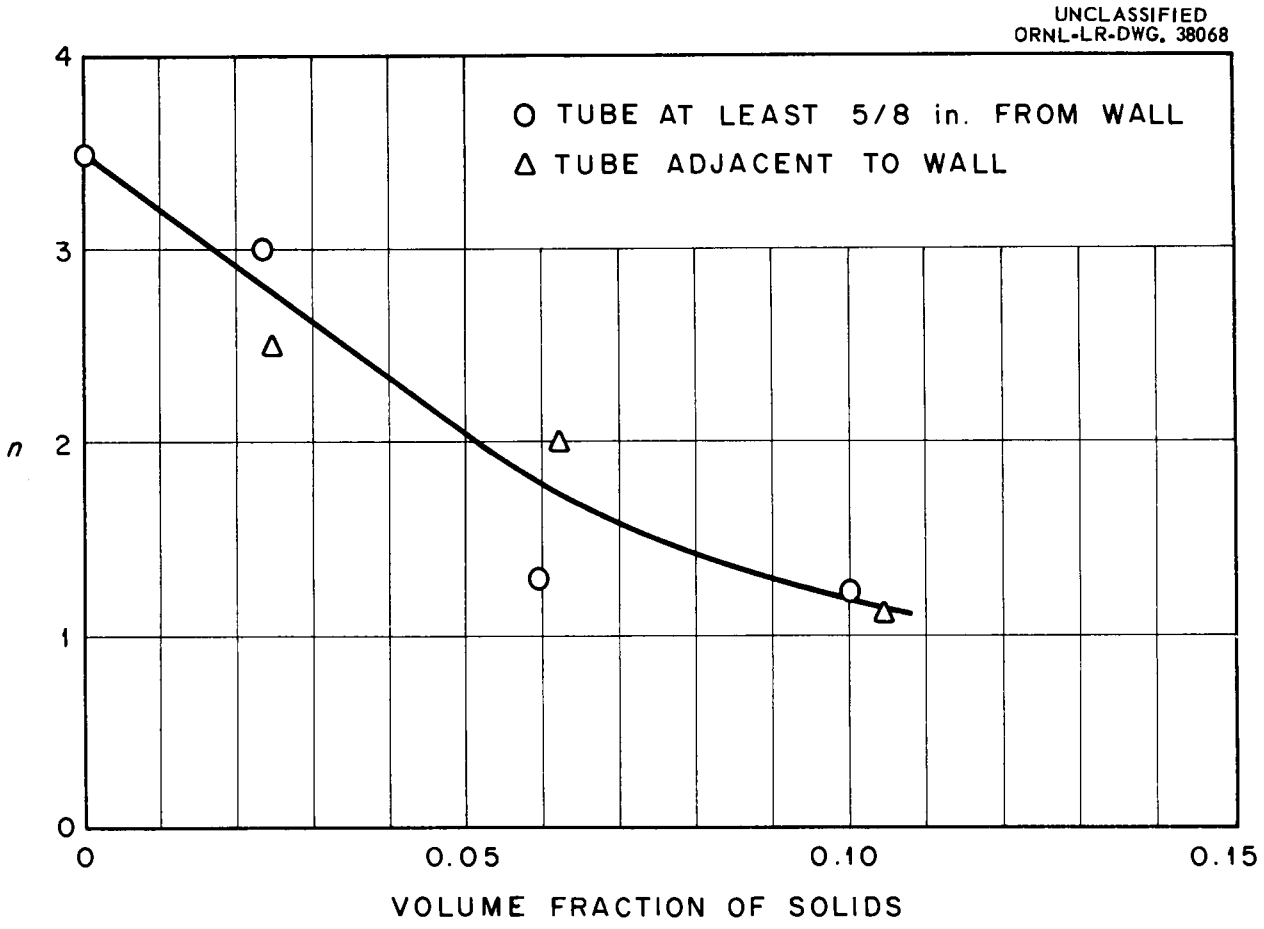

Fig. 7. Effect of Volume Fraction of Solids in ThO_2 Slurry on Exponent of Nucleate Boiling Expression, $q/A = K(\Delta T)^n$.

APPENDIX

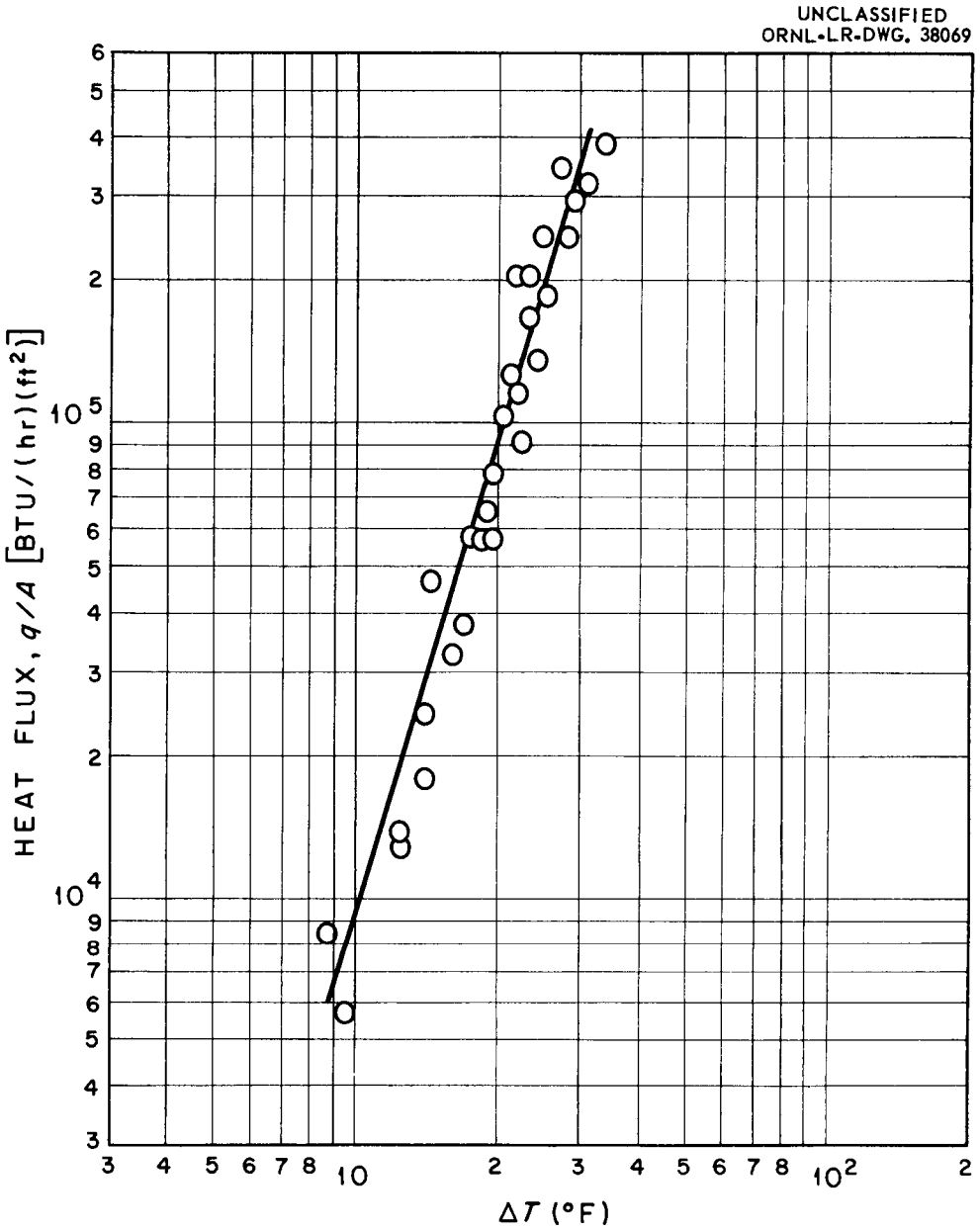

Fig. 8. Nucleate Boiling of Slurry Having 0.023 Volume Fraction of Solids (ThO_2). Used $\frac{1}{8}$-in.-dia platinum tube at least $\frac{5}{8}$ in. from nearest surface; ~1-gpm forced convection flow in tank containing ~3 gal slurry.

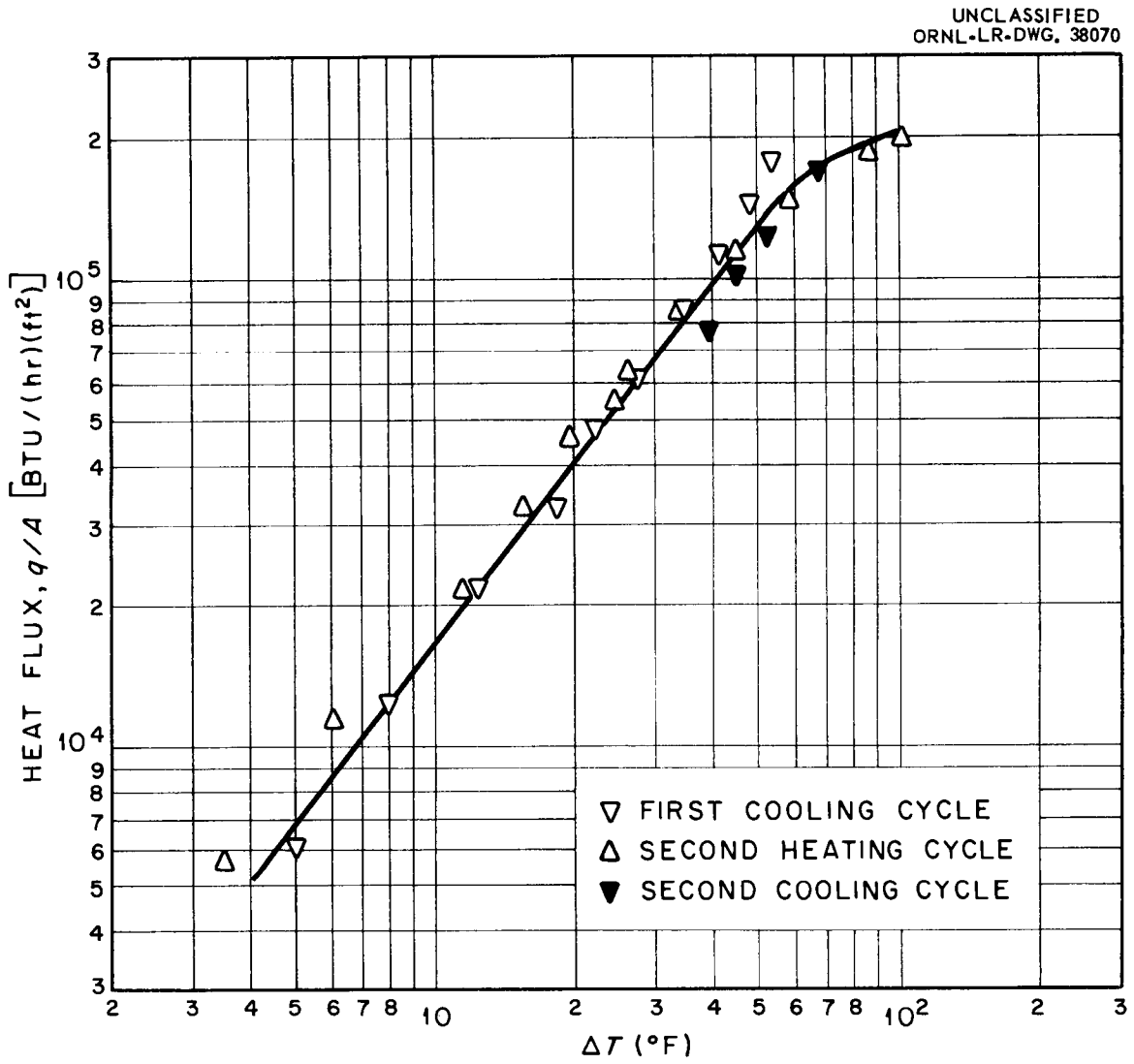

Fig. 9. Nucleate Boiling of Slurry Having 0.059 Volume Fraction of Solids (ThO_2). Used $\frac{1}{16}$-in.-dia platinum tube at least $\frac{5}{8}$ in. from nearest surface; ~1-gpm forced convection flow in tank containing ~3 gal slurry.

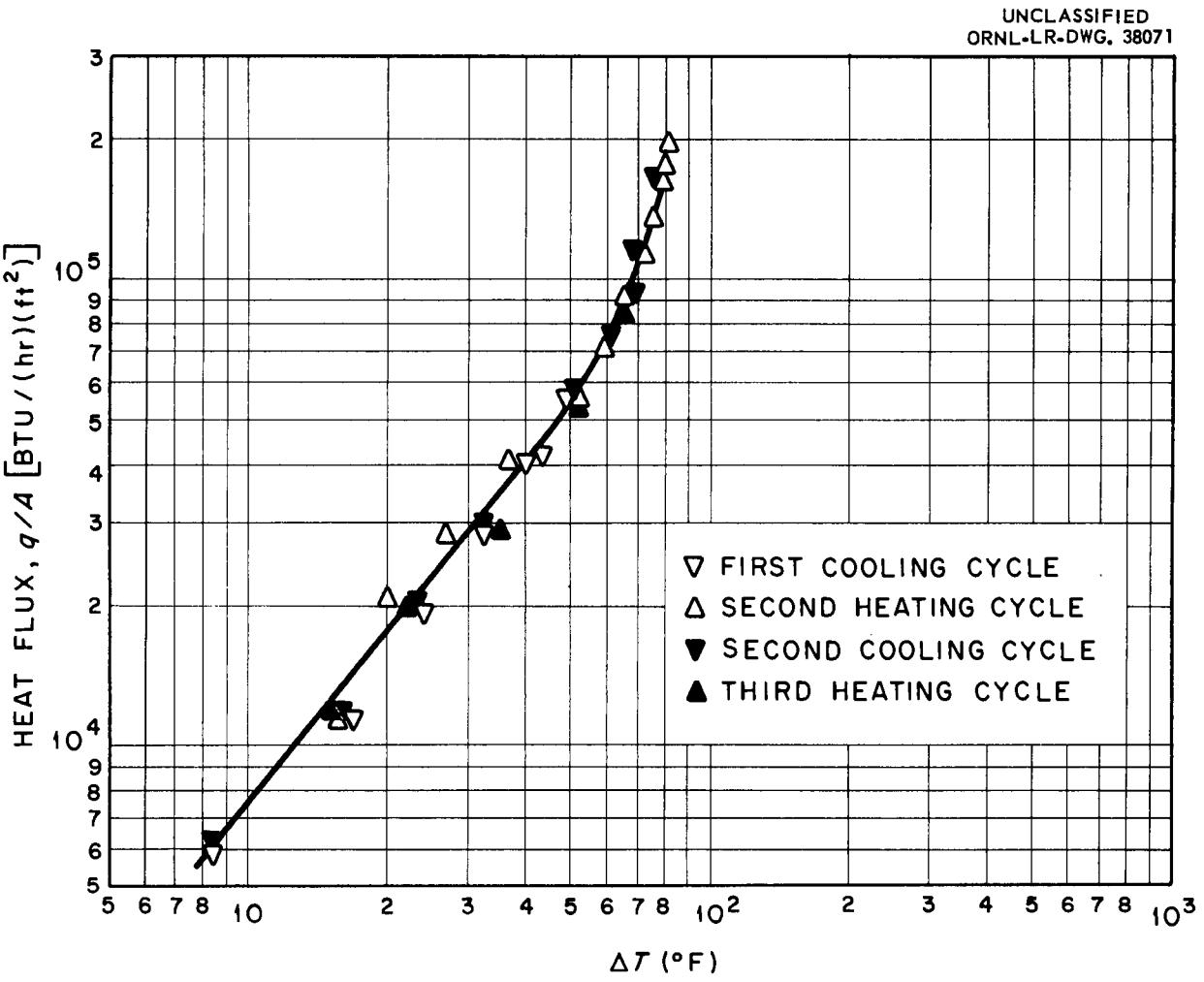

Fig. 10. Nucleate Boiling of Slurry Having 0.101 Volume Fraction of Solids (ThO_2). Used $\frac{1}{8}$-in.-dia platinum tube at least $\frac{5}{8}$ in. from nearest surface; ~1-gpm forced convection flow in tank containing ~3 gal slurry.

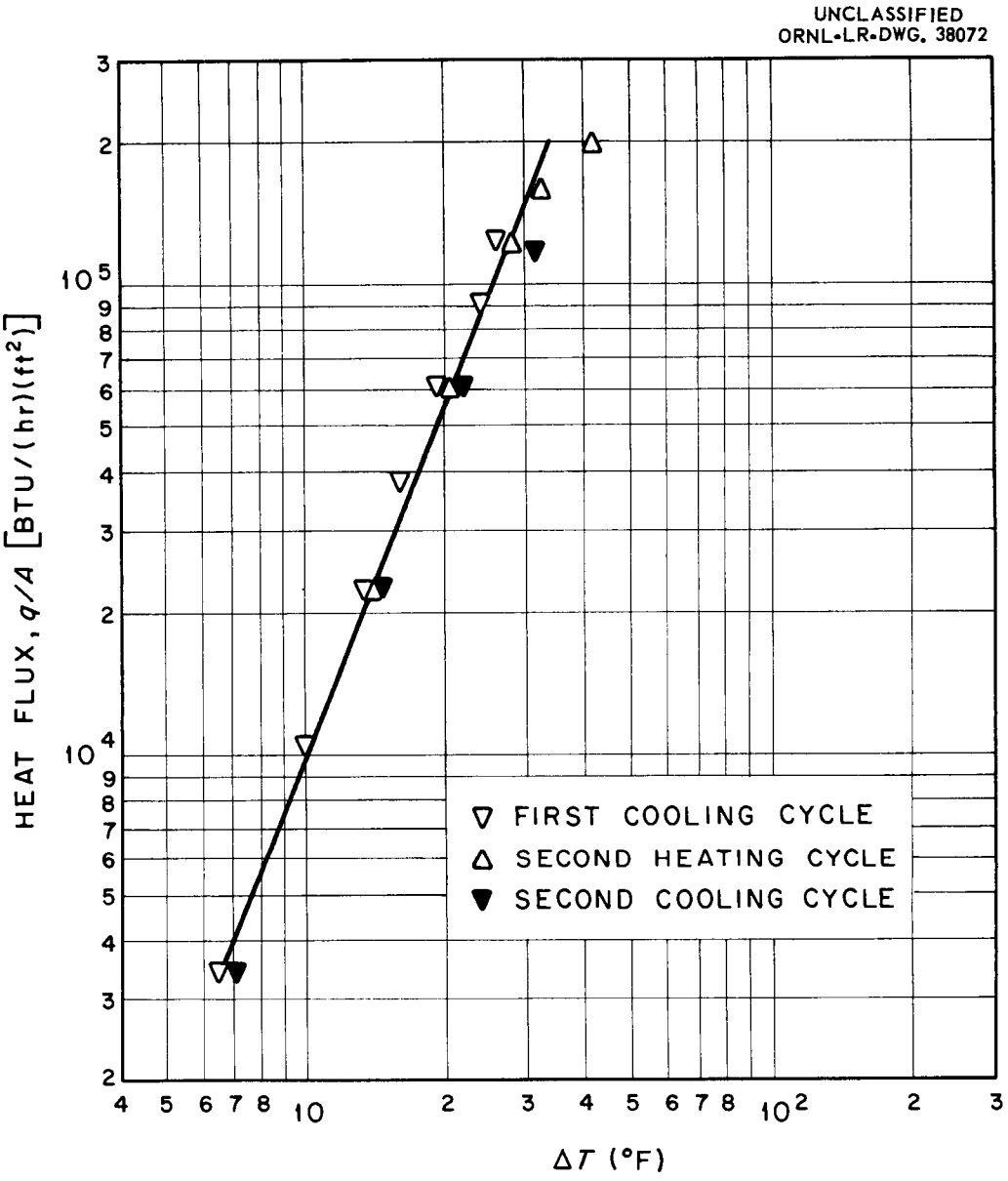

Fig. 11. Nucleate Boiling of Slurry Having 0.024 Volume Fraction of Solids (ThO_2). Used $\frac{1}{8}$-in.-dia platinum tube adjacent to glass plate; ~1-gpm forced convection flow in tank containing ~3 gal slurry.

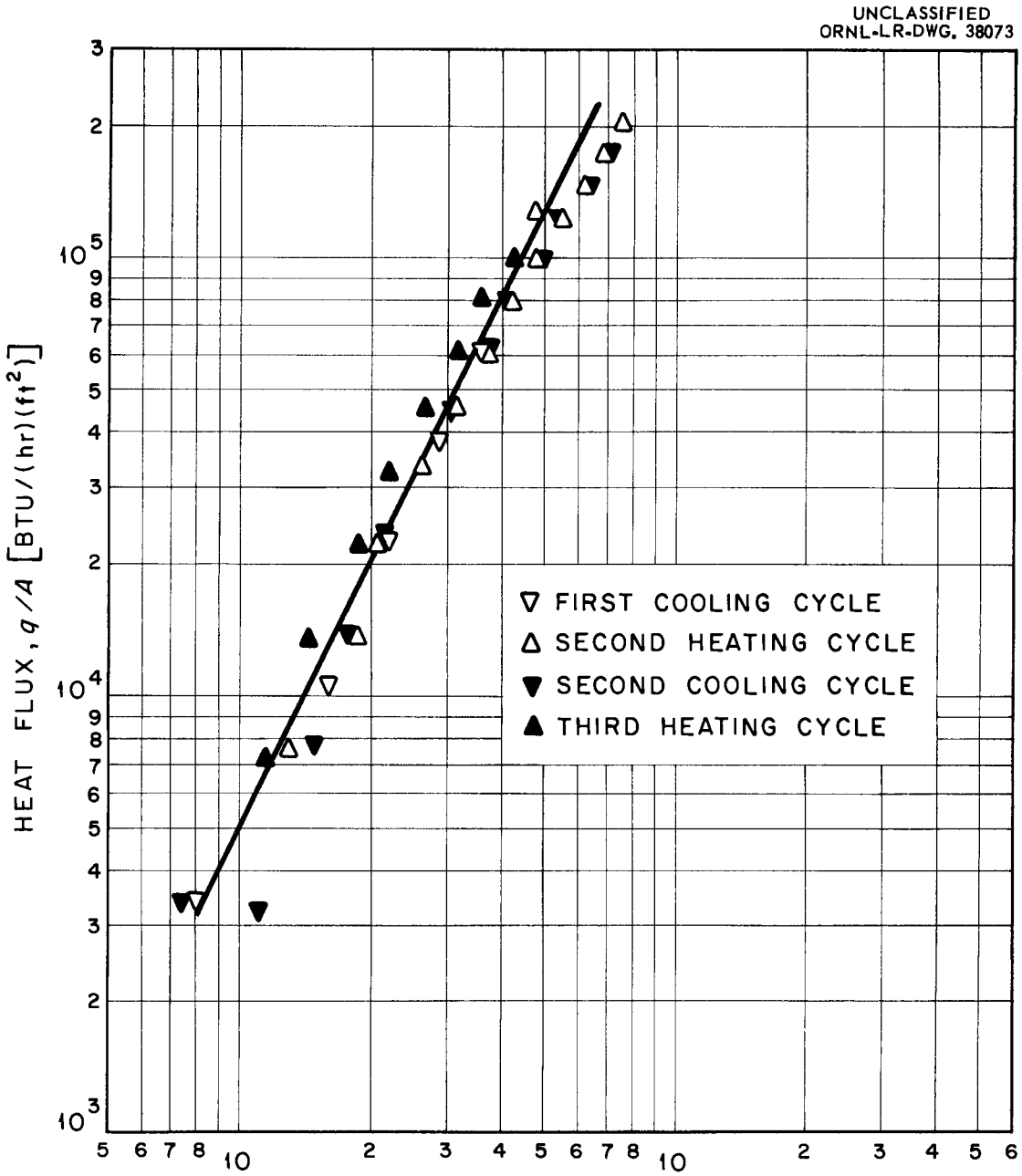

Fig. 12. Nucleate Boiling of Slurry Having 0.062 Volume Fraction of Solids (ThO_2). Used $\frac{1}{8}$-in.-dia platinum tube adjacent to glass plate; ~1-gpm forced convection flow in tank containing ~3 gal slurry.

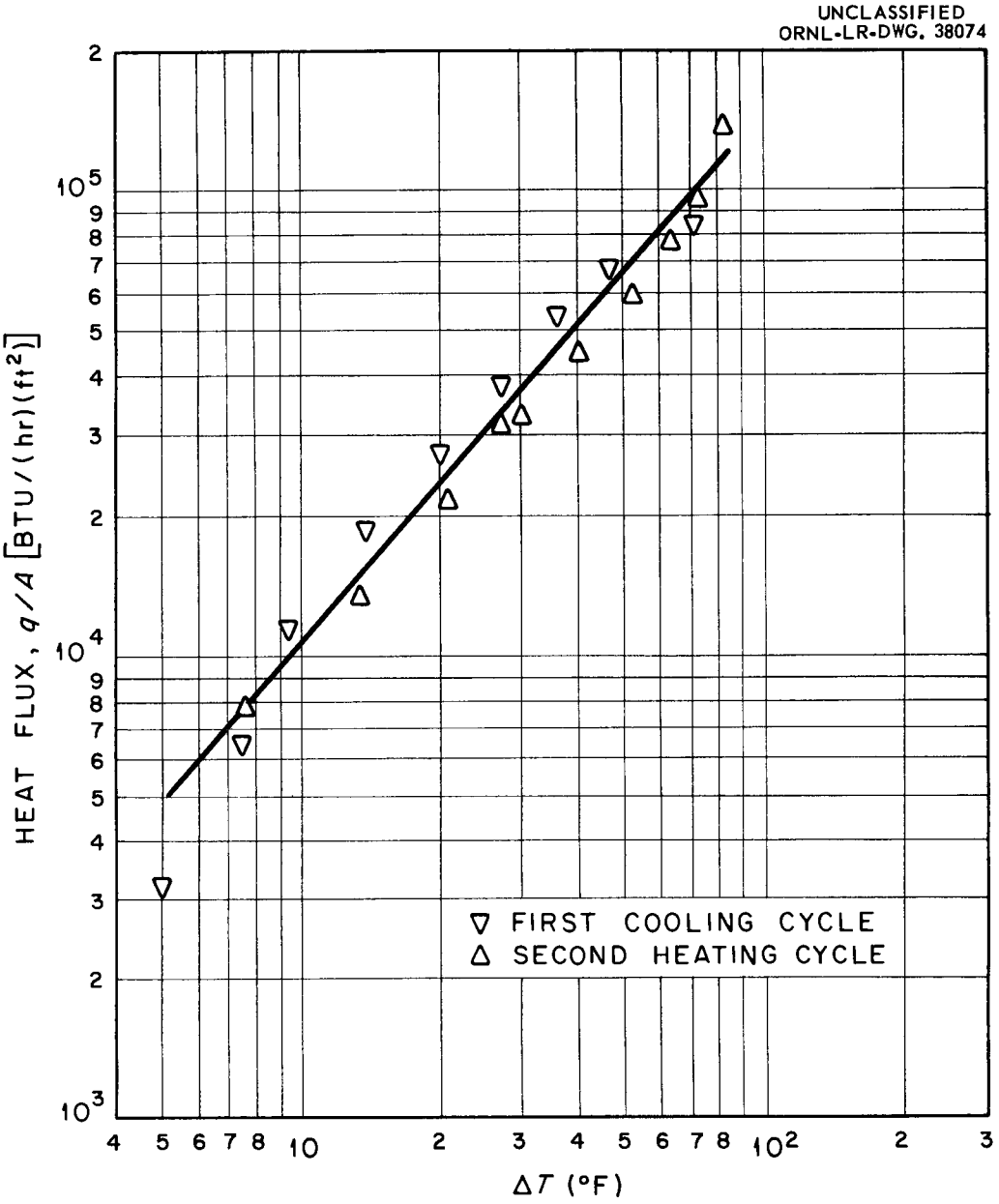

Fig. 13. Nucleate Boiling of Slurry Having 0.104 Volume Fraction of Solids (ThO_2). Used $\frac{1}{8}$-in.-dia platinum tube adjacent to glass plate; ~1-gpm forced convection flow in tank containing ~3 gal slurry.

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