J. BRENT TURNER
Atlantic Richfield Company,
Richardson, Texas

C. PHILLIP COLVER
Director and Associate Professor,
School of Chemical Engineering and
Materials Science,
University of Oklahoma,
Norman, Okla.

Heat Transfer to Pool-Boiling Mercury From Horizontal Cylindrical Heaters at Heat Fluxes up to Burnout

Reproducible and consistent data were obtained for heat transfer to pool-boiling mercury from horizontal, 304 stainless steel, cylindrical heaters at heat fluxes up to 1,100,000 Btu/hr· ft². One actual burnout determination was made during the course of the study. In other runs, a heat-flux level was reached where the slope of the boiling curve decreased significantly so that subsequent increases in heat flux were accompanied by large increases in ΔT. This heat-flux level was termed the "departure heat flux." Observed maximum departure heat fluxes ranged from 400,000 Btu/hr·ft² for a 2-in. pool depth above the heater to 950,000 Btu/hr·ft² for an 8.5-in. depth. The burnout correlations of Noyes [17, 22][1] and Addoms [1] satisfactorily predicted the maximum departure heat fluxes for each pool depth studied.

Introduction

Most previous pure mercury-boiling studies have encountered problems of wettability between the liquid and the heat-transfer surface with the resultant lack of consistent behavior, particularly in the nucleate boiling regime. Consequently, in an attempt to obtain better wetting characteristics investigators have either altered the heat-transfer surface or introduced additives to the mercury test liquid. For example, Bonilla, et al. [5] found that parallel scratches spaced about two bubble diameters apart on the boiling surface increased the heat-transfer coefficient considerably for boiling mercury. Others [4, 8, 14, 18, 19] on adding trace amounts of magnesium and titanium hydride have enhanced mercury wettability. In one case [4] prolonged aging of the boiling surface also appeared to enhance surface wetting.

In such cases where wetting was obtained for pure pool-boiling mercury [4, 23], data have been reported up to maximum heat-flux levels of about 125,000 Btu/hr·ft². Even where additives have been used, reported heat-flux levels for pool boiling have not exceeded 200,000 Btu/hr·ft². In a thermal-syphon mercury-boiling loop, Romie, et al. [25] operated an electrically heated, copper-plated tube with heat fluxes reported up to 600,000 Btu/hr·ft² with no apparent indication of reaching burnout. However, their calculated heat flux was an upper limit since significant electrical power was dissipated in liquid mercury flowing through the test section. It should be further noted that the test section was located about 4 ft below the condenser in one leg of the U-loop.

In the present work it was desired to study the effects of pressure, liquid depth, and different heaters on the pool-boiling characteristics of mercury. It was further hoped to achieve a wetted surface condition without resorting to additives. Where conditions premitted, it was hoped to extend the experimental boiling curves to heat fluxes up to and including burnout.

Apparatus

The experimental apparatus, shown schematically in Fig. 1, was comprised of the insulated boiling vessel, bayonet test heater, condenser, knockout drum, charge vessel, manifold system, power supply, and instrumentation. All vessels containing mercury were fully contained in a vented enclosure. Since the entire experimental apparatus has been completely described elsewhere [26], only the most important components will be detailed here.

Boiling Vessel and Associated Components. The boiling vessel was fabricated from an 8-in. length of 316 stainless steel seamless pipe (5.76-in. ID by 6.625-in. OD) and two 6-in. schedule 80S stainless welding caps. Fig. 2 gives details and dimensions of the vessel. Note that thermowells in the boiling vessel were staggered from side to side so temperature measurements could be made at 1-in. depth intervals in the boiling liquid. Chromel-alumel thermocouples (28 gauge) were used for all thermowell temperature measurements. Holes for the three auxiliary heaters

[1] Numbers in brackets designate References at end of paper.

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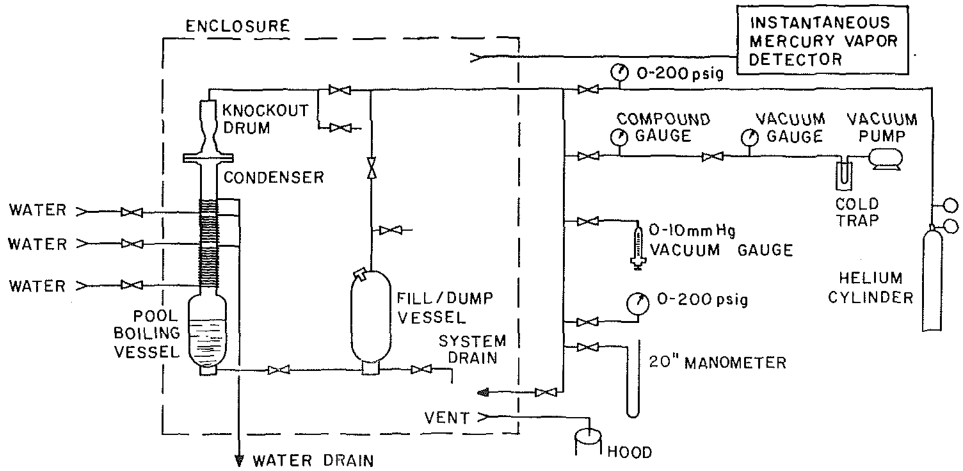

Fig. 1 Schematic diagram of experimental apparatus

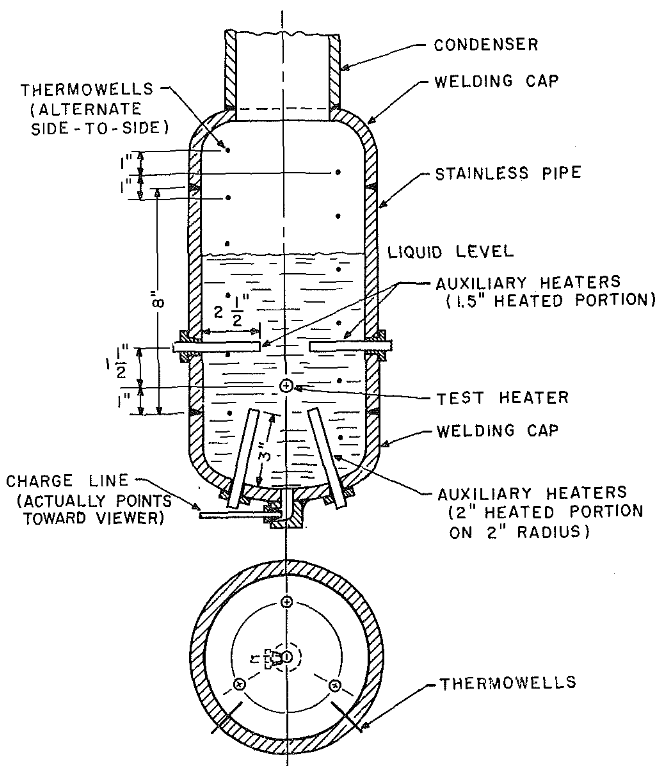

Fig. 2 Boiling vessel

entering through the bottom welding cap were drilled on a 2-in. radius and spaced at 120-deg intervals. The other two auxiliary heaters entered the vessel on opposite sides, 5 in. from the bottom of the vessel. Auxiliary heating required to maintain the pool at saturation temperature was supplied by 5 Watlow firerods with a combined capacity of 1800 watts.

The condenser was constructed from a 30-in. length of 316SS seamless pipe (3.35-in. ID by 4.0-in. OD), with five thermowells spaced at 5-in. intervals along its length. An iron pipe was split in half longitudinally, tinned inside with soft solder, clamped around the stainless condenser pipe and spot-welded to hold securely. This was done to lessen chances of damaging the stainless steel by thermal stresses and to give a surface to which cooling coils were more easily soldered. Three sets of cooling coils (with 5, 10, and 15 turns respectively) were soldered to the condenser.

One end of the condenser was then welded to the boiling vessel and the other end to a 3.5-in. schedule 40S flange. An O-ring groove was machined in the flange to accommodate a Viton rubber O-ring which could withstand temperatures up to 600 deg F. This flange served as the connection between the condenser and the knockout drum, which consisted of an 8-in. length of 316 SS pipe (4-in. ID by 4.5-in. OD) containing stainless steel gauze. The gauze was to facilitate condensation of any vapor that migrated past the condenser.

A charge vessel was formed from a 12-in. length of 6-in. stainless pipe with welding caps making up the ends. A THY-442 Hoke bellows valve was installed in the fill line between the charge vessel and the boiling vessel. The Hoke bellows valve, with a maximum operating pressure of 600 psia at a temperature of 1200 deg F, had a 316 stainless body and a 347 stainless bellows seal welded to the body, permitting all wetted parts of the valve to be metal. A flexible shaft leading to the bellows valve with a rotating seal through the enclosure wall allowed remote operation of the valve when the enclosure door was in place.

The system was equipped to obtain data over the pressure range from about 1 mm mercury to 200 psig. This required the use of vacuum pumps for subatmospheric pressures and a helium cylinder to provide inert cover gas pressures above atmospheric. The vacuum pumps and helium cylinder were connected to the system through the manifold arrangement shown in Fig. 1. Proper use of the valves allowed the system, or any part thereof, to be adjusted to the desired pressure level. For pressure runs (above the capability of the mercury manometer) a calibrated 10-in-dia 0–200 psig Marsh gauge was used. A mercury manometer was used for subatmospheric runs from 1 in. mercury to atmospheric pressure. For 0–10 torr pressures, a Gilmont cartesian-diver vacuum gauge was used.

Test Heater. The bayonet heater has shown itself to be quite versatile and capable of producing the high flux levels required in liquid metal boiling studies [7, 22]. However, thermocouple placement in such heaters has presented considerable difficulty. In both the studies of Noyes [22] and Colver and Balzhiser [7], thermowells or sheathed thermocouples were brazed into longitudinal grooves cut in the external surface of the heater. In both instances, extensive erosion and/or melting of the brazing material occurred during operation (especially during burnout determinations). Noyes suggested that in his work, "premature burnout may have been in some way caused by the thermocouple grooves and/or the associated brazing alloy." In at least one case, a heater used by Colver failed by splitting lengthwise along a thermocouple groove. Colver also encountered some difficulty in accurately extrapolating measured temperatures to the heater surface. Since the thermal conductivity of the braze material

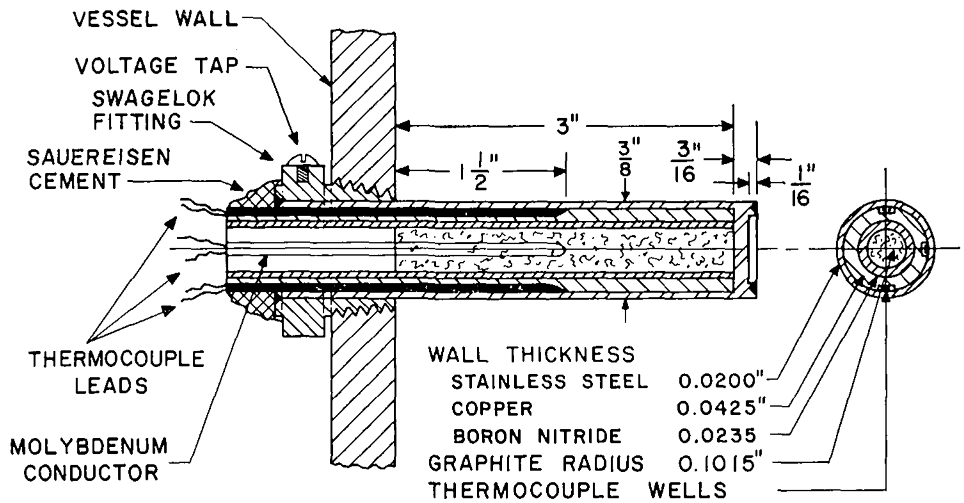

Fig. 3 Cross section of test heater

surrounding the heater thermocouples was not precisely known, certain approximations were necessary.

Though the present design is similar in many aspects, the thermocouple installation represents considerable improvement from the brazing method used by Noyes and Colver. The composite heater consisted of a 304 stainless sheath, a grooved cylinder of tinned copper for thermocouple placement, a machined boron nitride tube, and a graphite-rod heating element. A detailed view of the assembled test section is shown in Fig. 3. The use of a Swagelok male connector (No. 600-1-8-316) allowed easy interchange of heaters.

The outside surface of the copper tube was tinned with solder and all excess solder was wiped away leaving a smooth shiny surface. The thermocouple grooves (0.050 in. wide by 0.025 in. deep) were then milled longitudinally in the copper surface at 90-deg intervals. The grooves extended to the midpoint of the heater, except for two heaters which were equipped with one or two grooves extending to the midpoint as before, but the other two extended to within $^1/_4$ in. of each end. The placement of thermocouples near the ends of the heater allowed a determination of any longitudinal temperature variations. Insulated 30 gauge chromel-alumel thermocouple wire was used for internal heater temperature measurements. After assembly of each heater, with thermocouples in place, Sauereisen cement was used to cover the exposed copper and to affix the thermocouple leads in place, avoiding undue flexing or breakage.

Heater Surface Treatment. The surfaces of test heaters used in the preliminary water work were finished in a lathe with 400C grit silicon carbide paper. Test heater 1 (used in the first mercury runs) was further smoothed with 600 grit paper. A final finish was obtained by hand rubbing the surface with crocus cloth. Previous studies [2, 14] have shown that mercury does not readily wet stainless steel; consequently this surface was silvered by the technique described by Watt, et al. [27]. Test heater 2 was electroplated with silver, since it was felt a wetting condition could possibly be achieved by plating with a material which was completely wetted by mercury.

Power Supply and Instrumentation. A 20-kva Udylite rectifier supplied d-c power to the test heater. A stepless variable transformer controlled the output from 0–1000 amp at 0–20 v with no more than 5 percent ripple. A 50-mv, 800-amp shunt was used along with a calibrated Simpson multirange d-c millivoltmeter to measure heater amperage. Test heater voltages were measured with a calibrated Simpson multirange d-c voltmeter and a Sanborn recorder. Though the recorder readings did not yield the accuracy afforded by the meter, the continuous voltage trace along with simultaneous thermocouple traces gave an easily discernible record of each power increase and resultant temperature increase.

To protect against failure of test heaters, a controlling pyrometer and control module by Assembly Products automatically cut off the rectifier when temperatures in the heater exceeded a set-point value. Two 11-position Leeds and Northrup thermocouple switches were used to obtain selective readings from the various thermocouples. For added convenience a 3-way, double-pole switch was employed so that signals from each thermocouple switch could be relayed to a Hewlett-Packard digital voltmeter without changing leads. For monitoring pool and vapor temperatures, a Leeds and Northrup Speedomax W 12-point recorder was connected to the top 4 thermocouples in the pool and 8 others located in the vapor space above the boiling pool. The three test heater thermocouples were connected, respectively, to the controlling pyrometer setup, a fast-response oscillographic recorder, and a standard strip-chart recorder. The fast-response, variable-range oscillographic recorder gave this equipment excellent capability for recording rapid temperature fluctuations.

Experimental

Preliminary Preparation. All instrumentation was checked for operability and calibrated where possible before incorporating it into the experimental system. Each component of the apparatus making contact with the test liquid or vapor was thoroughly cleaned with dichloroethylene prior to installation, to remove any oil or grease films present. After installation, the entire system was vacuum-checked for leaks. In addition, the system was pressured to 200 psig and found to hold nicely at this level.

To refine the operating procedure and acquaint the operator with the system, 16 experimental runs were made with de-ionized distilled water. Though no subatmospheric runs were made with water, nucleate boiling runs were made at pressures up to 200 psig and heat fluxes up to 790,000 Btu/hr·ft^2. The test water was dumped from the system and replaced with fresh water 5 times during the 16 runs, so that dissolved impurities would be flushed from the system.

To prepare the system for charging mercury, the water was dumped from the system and the test vessel heated to about 500 deg F while the vacuum pumps continued evacuating the system. Condensed moisture collected and froze in the liquid nitrogen cold trap and had to be removed twice when the trap became clogged with ice. After a few hours, no further collection

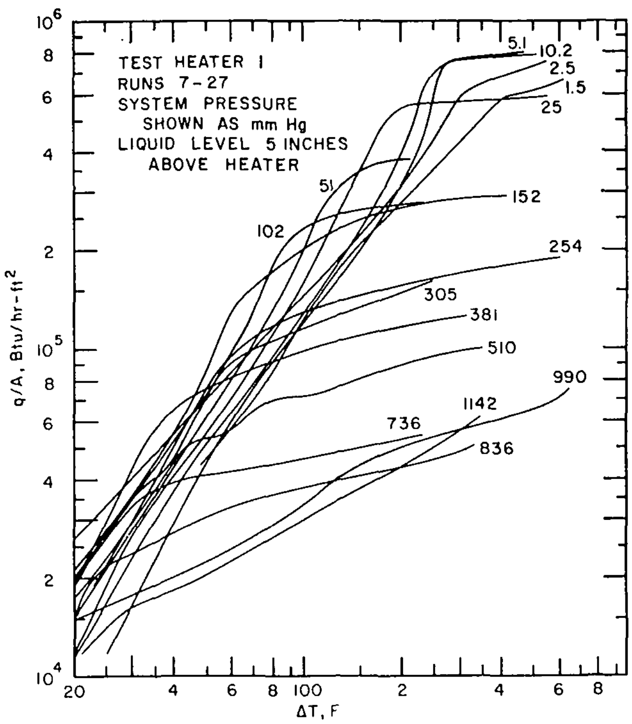

Fig. 4 Mercury results for a 5-in. liquid depth above test heater 1

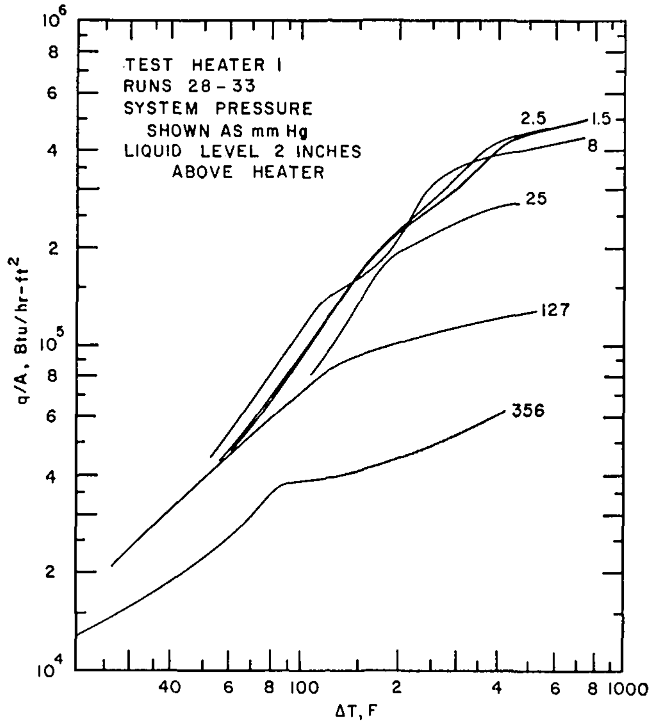

Fig. 5 Mercury results for a 2-in. liquid depth above test heater 1

of water occurred and the system was allowed to cool after being filled with helium to maintain a slight positive pressure.

Each time the system had been filled with water, a 1-gal quantity was sufficient to give a 10-in. liquid level in the boiling vessel. Since the test heater location was at the 3.5-in. level and the upper auxiliary heaters at the 5-in. level, 100 lb of mercury (0.887 gal) was charged to the system through the charge vessel, giving a maximum liquid level of 8.5 in. After filling, the charged vessel was evacuated and repressurized with helium.

Mercury was transferred to the boiling vessel by evacuating it and opening the transfer valve. Reverse transfer from the boiling vessel to the charge vessel was likewise accomplished by evacuating the charge vessel and opening the transfer valve. This procedure was required only when it was desired to change heaters or change the liquid level. The mercury remained in the boiling vessel between runs except when one of the above changes was made.

Experimental Procedure. To begin a run, the auxiliary heaters were turned on and set at about 670 w total input to the pool. At this setting, the heat-flux level in each heater was 19,000 Btu/hr·ft². As the pool temperature approached saturation, power to the auxiliary heaters was decreased to a heat flux slightly above 10,000 Btu/hr·ft².

During heat-up, system pressure was always initially set above the operating pressure to allow the pool temperature to exceed the desired saturation value. The pressure was then dropped to the desired level with the resulting boil-off assuring saturated conditions. At this point, the liquid level was determined by taking thermocouple readings along the entire depth of the boiling vessel and condenser.

Once all preliminary thermocouple readings were made, the system pressure was again checked (and adjusted if needed, as it was after each power increase) before turning on the rectifier. Power to the test heater was increased incrementally with the following information being recorded: test heater voltage, amperage, heater thermocouple readings, and liquid thermocouple readings. At low heat fluxes, very short times were required for the system to reach steady state after a power increase; at high levels, longer times were required as shown by the continuous heater thermocouple traces. In each case, sufficient time for steady state was allowed before taking the above readings. At intermediate heat fluxes, the pool temperature was again recorded along its entire depth.

Initially, small induced voltages were observed in the heater thermocouple signals. These induced voltages were observed and measured by the method described by Davenport, et al. [9] and later used by Mednick and Colver [21]. With the fast-response oscillographic recorder monitoring thermocouple output, the rectifier was quickly turned off and on. Induced voltage could then be read directly as the amplitude difference between the "off" and "on" thermocouple output. After a few runs, no induced voltage was observed. This was taken to mean that the free end of the heater achieved good electrical contact with the mercury pool so that the pool carried a major portion of the current. Comparing the overall voltage drop and heater voltages observed in both the water and mercury studies, it was concluded that negligible power dissipation occurred in the mercury pool.

To obtain maximum information from each run, and to detect any aging of the surface during high heat-flux operation, the power level was adjusted stepwise upward until it was felt that burnout was imminent or until the temperature exceeded the pyrometer set-point, which automatically turned off the rectifier. The power was then adjusted stepwise downward with pertinent information being recorded at each setting. In case of pyrometer cut-off, the rectifier powerstat was turned down slightly and the rectifier reactivated to accomplish the downward cycle.

With the peculiar behavior observed for boiling mercury, a clearly defined burnout point was only observed once; however, a change in nucleate boiling behavior was easily detectable in the test heater thermocouple traces. Though only constant-pressure boiling curve determinations were made for mercury, the "decreasing pressure" method of burnout determination used by Noyes [22] and Colver and Balzhiser [7] was employed successfully to obtain 5 burnout values for water at various pressures. In addition, 15 burnout determinations were made for water at 6 different pressures using the increasing heat-flux approach.

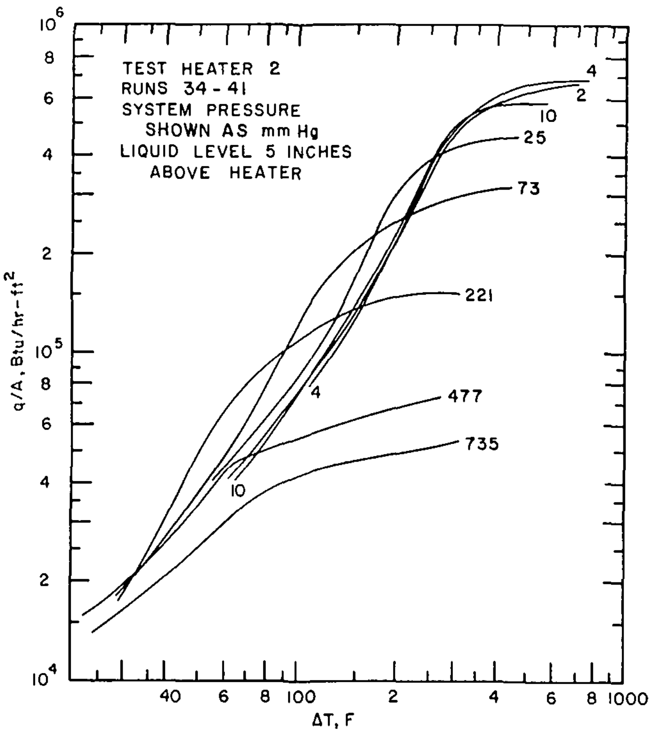

Fig. 6 Mercury results for a 5-in. liquid depth above test heater 2

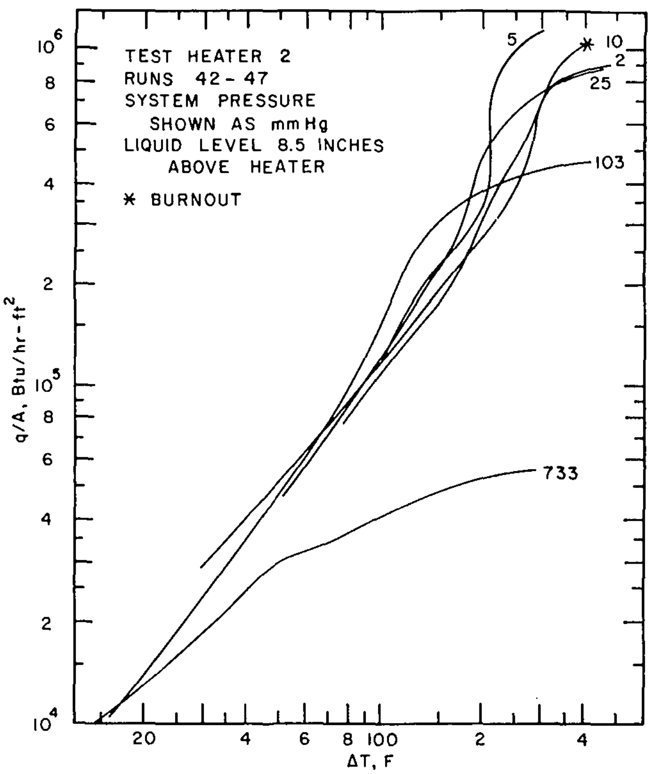

Fig. 7 Mercury results for an 8.5-in. liquid depth above test heater 2

Results and Discussion

Water Experiments. A preliminary study using water was performed to improve and finalize the test heater design, and for the purpose of comparing results from the present apparatus to published data. Although not shown, the nucleate boiling water results compare favorably with other investigations using tube heaters [18] and horizontal plate heaters [3, 12].

In each nucleate boiling run, the heat flux was increased incrementally until a large instantaneous temperature rise in the test heater indicated burnout. In addition to these burnout determinations, five burnout determinations were obtained at a constant heat flux by gradually decreasing the system pressure until burnout ensued. For these determinations, the pyrometer turned off the rectifier at the onset of burnout. Good agreement was achieved for burnout values obtained by either method. Water burnout data ranged from about 200,000 Btu/hr·ft² at atmospheric pressure to 790,000 Btu/hr·ft² at 200 psig.

Boiling Mercury Experiments. Two test heaters were used in carrying out the boiling mercury investigation. Test heater 1 was used for 33 runs at system pressures ranging from 1 mm to 1143 mm mercury (45 in. mercury). Fourteen additional runs were made with test heater 2 over a comparable pressure range. Plots and tables of the data from all individual runs are included in the thesis [26]. Heat fluxes extended to 1,100,000 Btu/hr·ft² when operating with the greatest liquid pool depth (8.5 in. above the heater) at a system pressure of 5 mm mercury.

Runs 1 through 6 exhibited considerable hysteresis and lacked the consistency observed in subsequent nucleate boiling runs. Specific behavior encountered in these runs will be discussed later, as undoubtedly, the surface of test heater 1 was not yet fully conditioned to boiling mercury. The present discussion will then be restricted to runs which gave representative data for a conditioned surface. Boiling curves for runs 7 through 27, made with test heater 1, are shown in Fig. 4. These runs were made with an 8.5-in. liquid depth in the boiling vessel, but since the test heater was located 3.5 in. from the bottom of the pool, this corresponded to a 5-in. liquid level above the heater. Runs 28 through 33 were made with the liquid level 2 in. above the heater. Boiling curves for these runs are shown in Fig. 5. Fig. 6 shows the results of runs 34 through 41 made with a 5-in. liquid level above test heater 2. Runs 42 through 47, shown in Fig. 7, were made with an 8.5-in. liquid level above the heater. Individual curves in each figure are presented to best reflect the average trend of the data in each run, and in most cases the boiling curves were from data obtained both on the upward and downward cycles of the boiling curve. Note that each set of runs in Figs. 4–7 forms a homologous group of curves. Moreover, it is readily seen in the figures that in each run, a heat-flux level was reached where the slope of the boiling curve decreased markedly. This point of transition or departure, herein termed "departure heat flux," is of particular interest and will be discussed in a later section.

Reproducibility of Mercury Data. Considering the scatter often observed in liquid metal boiling studies, it was felt that exceptional reproducibility was attained in this study. Composite plots of the data shown in Figs. 4–7 give an initial indication of the consistency and, therefore, reproducibility of the data. For additional comparison, runs 10, 17, and 38 are shown in Fig. 8. Recall that runs 10 and 17 were made with test heater 1 and run 38 with test heater 2. Fig. 8 shows that exceptional reproducibility was obtained for test heater 1. Note that, while observed ΔT's in runs 10 and 17 are very close, the surface has aged slightly during the interim 4-week period to give a higher departure heat flux in run 17. Considering the slight difference in surface treatment between test heaters 1 and 2, run 38 shows very good agreement with the runs 10 and 17 made with test heater 1. It can also be seen in Fig. 8 that very close agreement was shown for the increasing and decreasing heat-flux cycles.

Effects of Surface Aging. It appeared that the heater surface of test heater 1 became conditioned to boiling mercury after run 6. However, in run 4 the ΔT increased to about 400 deg F and suddenly dropped to less than 70 deg F at a constant heat flux as shown in Fig. 9. This marked decrease in ΔT was a definite sign that nucleation had begun. The same behavior was observed

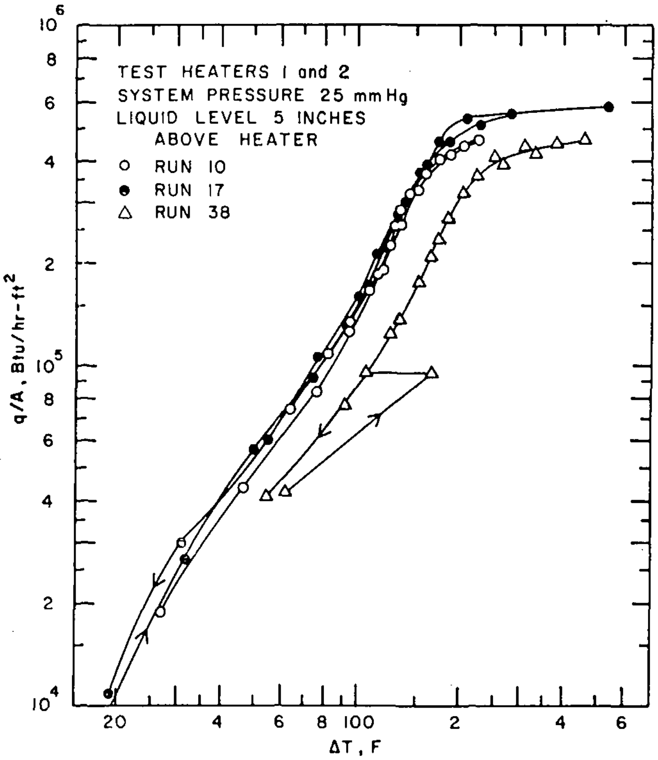

Fig. 8 Reproducibility of mercury results

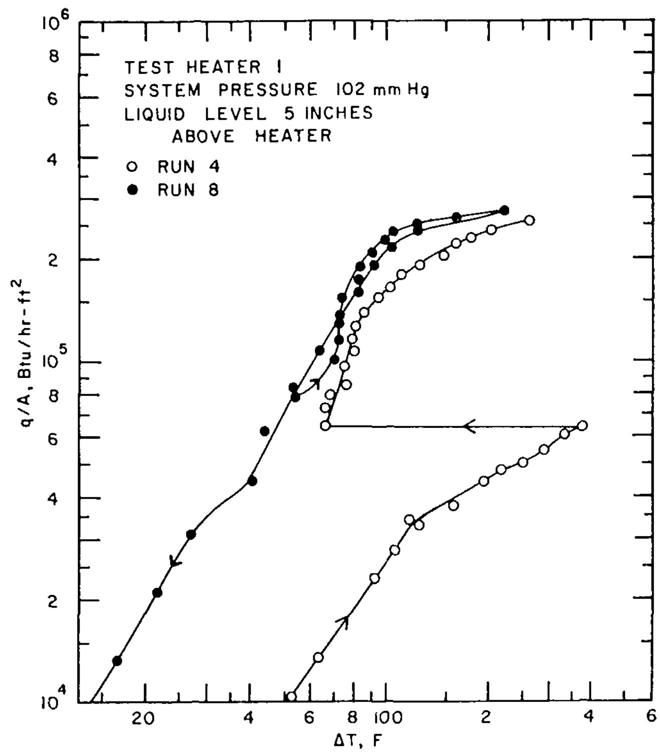

Fig. 9 Effects of aging on test heater 1

during run 5, but this drastic temperature drop was not observed in subsequent runs with test heater 1. In fact, succeeding runs exhibited much lower ΔT's for the lower (and what appeared to be totally convective) portion of the boiling curve. Run 8, also shown in Fig. 9, was made at the same pressure and pool depth as run 4. These runs agreed closely above 60,000 Btu/hr·ft², but the effects of hysteresis (apparently as the result of surface aging) gave widely varying ΔT's at lower heat fluxes. Note also that the departure heat flux (point of slope decrease) is more abrupt in run 8 than in run 4.

In later runs with test heater 1, it appeared that the surface had aged sufficiently so that the transition from apparent convective heat transfer to nucleate boiling occurred more easily. This was felt to be an indication that stable nucleation sites had been established. During run 25, the heat flux was by chance set at a heat flux (212,000 Btu/hr·ft²) where periodic changes from convection to nucleate boiling and back could be observed in the heater temperature trace. This behavior is illustrated in Fig. 10 where the surface temperature gradually rose 50 to 60 deg F, indicating destabilization of nucleation, then it would suddenly fall to its original level and repeat the cycle.

When test heater 1 was removed from the system, the surface had a frosty gray appearance, which upon immersion part way into a beaker of clean mercury showed complete nonwettability. However, a portion of the Swagelok fitting which had been in contact with boiling mercury was still wetted by mercury as the entire test heater surface had been previous to installation.

The silver-plated test heater 2 also exhibited aging, but in a different manner than test heater 1. During run 34, which was the initial run using test heater 2, the system was allowed to run for an extended period at a heat flux of about 55,000 Btu/hr·ft². After a period of time, heater temperatures rose about 200 deg F

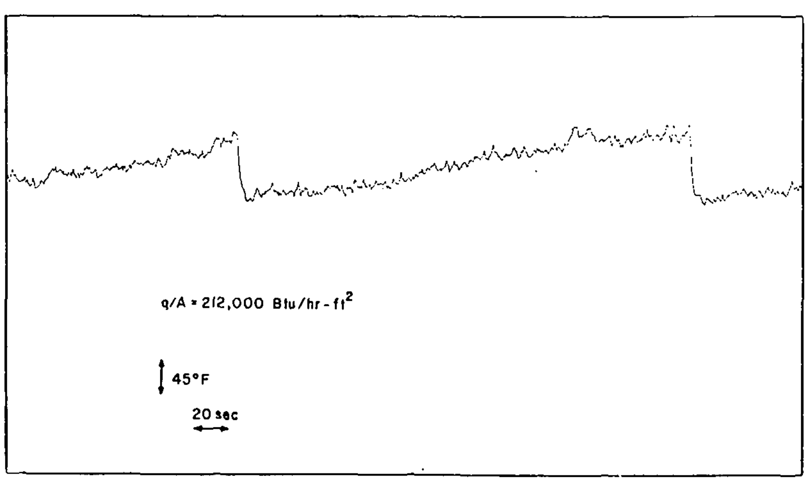

Fig. 10 Test heater temperature trace during run 25

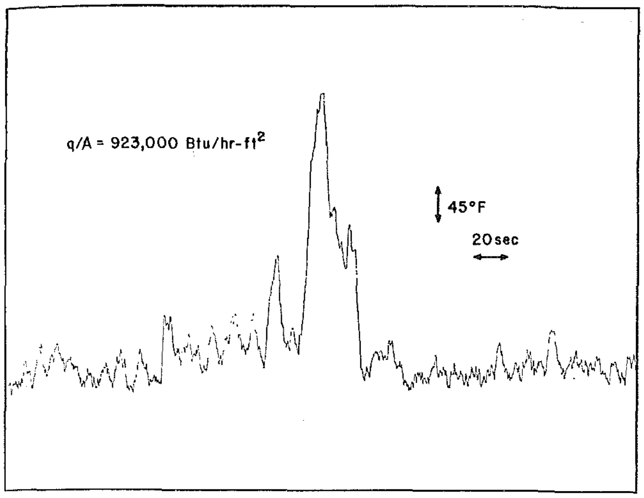

Fig. 11 Typical test heater temperature excursions above the departure heat flux

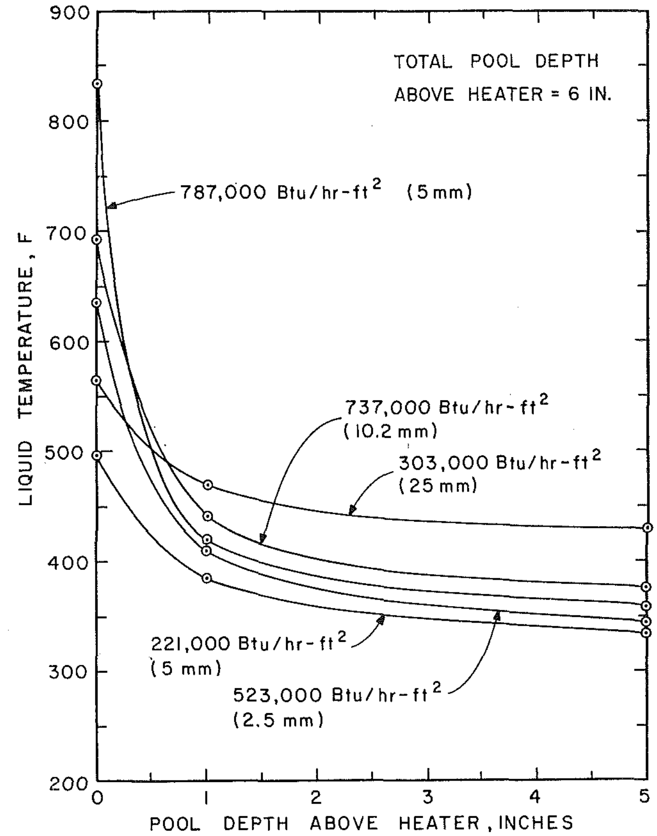

Fig. 12 Pool temperature gradients

while operating at this heat flux, indicating that perhaps the silver plating had dissolved away from the surface.

Test heater 2 never gave as smooth a change from convective to nucleate boiling as had test heater 1. Most of the boiling curves obtained with test heater 2 exhibited a discontinuity at intermediate heat-flux levels. Moreover, the apparent absence of active nucleation sites resulted in high ΔT's, but upon reaching an adequate heat-flux level, sufficient superheat was achieved at the heater surface to activate sites and provide the sudden establishment of nucleate boiling. This caused the ΔT to immediately drop to a substantially lower value. When the heat flux was increased, the temperature rose rapidly and then fell to a stable level indicating that the surface was supporting nucleation. Frequently surface temperatures rose about 200 deg F above the level corresponding to stable nucleate boiling. However, when the heat flux was further increased, more-stable boiling was achieved. This behavior was very similar to that observed by Colver and Balzhiser [7] for boiling potassium.

Other Effects. Although noise from the vacuum pumps and the cooling fan on the rectifier made it difficult to characterize low-level noises, a distinguishable rumbling sound emanated from the enclosure once nucleate boiling was established. This sound was accompanied by discernible vibration of the outer enclosure. As the heat flux was further increased, the vibration became more pronounced.

Internal heater temperature fluctuations were quite significant at all heat-flux levels. Figs. 10 and 11 show typical internal heater temperature fluctuations observed at relatively low and high heat fluxes. As noted in Fig. 11, when the departure heat flux was surpassed much larger fluctuations occurred, and were occasionaly accompanied by large temperature excursions (oftentimes >200 deg F).

The existence of pool temperature gradients have been reported in previous liquid metal studies by Colver and Balzhiser [7] and Madsen and Bonilla [20]. Similarly, it was found that such gradients existed in this study. Using readings obtained from the thermocouple positioned 1 in. above the test heater, the thermocouple in the liquid nearest the free surface, and a heater surface thermocouple, Fig. 12 was prepared. Pool thermocouples other than that 1 in. above the heater indicated that sufficient mixing was present so that most of the pool was at a fairly uniform temperature for system pressures near atmospheric and was only 10 to 20 deg F hotter than the free-surface temperature for low system pressures.

Comparison of Data With Previous Mercury Studies. Maximum heat fluxes in previous studies have been less than 150,000 Btu/hr·ft² for pure pool-boiling mercury and only 200,000 Btu/hr·ft² for pool-boiling mercury with additives. This compares to heat fluxes achieved in this study in excess of 1,000,000 Btu/hr·ft².

The nucleate boiling data of Bonilla, et al. [4], Korneev [16], Lyon, et al. [18, 19], and Farmer [23], compare favorably with the present results, particularly with respect to the slope of the boiling curve. In fact, Korneev [16] observed a departure heat flux for data at 1 atm pressure. It would also appear that the data of Bonilla, et al. [4] exhibited a departure heat flux but they did not join the two portions of their boiling curves for system pressures of 130 and 287 mm mercury.

Comparison of Data to Correlations. The prediction of Eckert [10], as modified by Hyman, et al. [15], for free-convection heat transfer from horizontal pipes to liquid metals, satisfactorily predicted the slope of experimental data in the convective region; however, predicted ΔT's were about an order of magnitude higher than the present data after the test heater surface had fully aged. The convective portion of boiling curves obtained in runs 4 and 5, in which test heater 1 was not fully aged, more nearly agreed with predicted ΔT's.

Predicted nucleate boiling curves using the correlation of Forster and Zuber [11] agreed reasonably well with the data in slope and range of ΔT's; but the correlation gives a larger shift in ΔT with pressure than the actual data.

Departure Heat Flux. As previously noted, the heat flux at which the slope of the boiling curve decreased markedly was designated the "departure heat flux," $(q/A)_D$. After reaching this heat flux, further small increases in heat flux caused large increases in ΔT. Further, temperature fluctuations in the region above the departure heat flux were much more pronounced as previously discussed and shown in Fig. 11.

Fig. 13 shows that plotting the departure heat flux versus system pressure gives an envelope for each liquid level studied, with the highest heat fluxes being achieved at low system pressures and high liquid levels. Notice, however, that the envelope

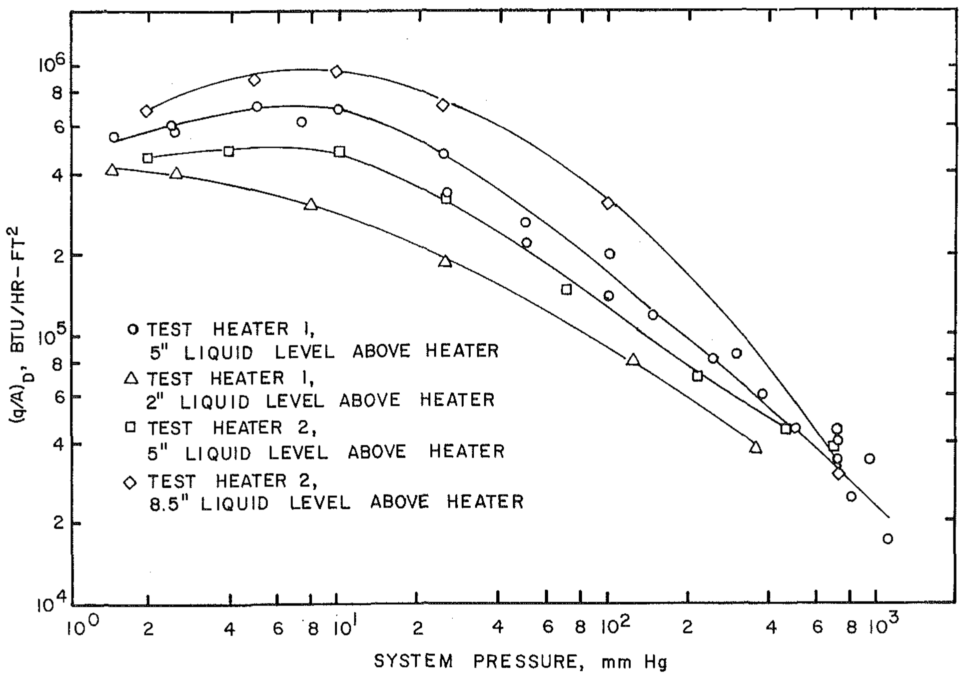

Fig. 13 Dependence of departure heat flux on system pressure and pool depth

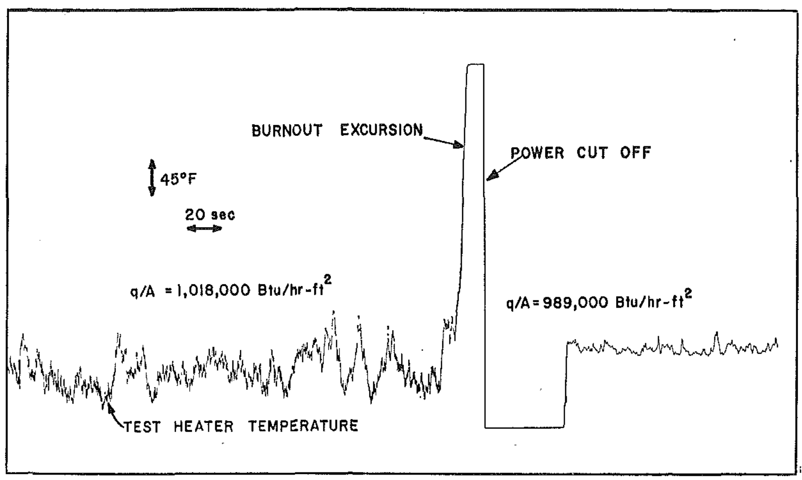

Fig. 14 Test heater temperature trace in run 45 during burnout determination

for a 5-in. level with test heater 2 lies slightly below the envelope for the corresponding level with test heater 1. Observed ΔT's at the same pressure, liquid level, and heat-flux level were generally higher for test heater 2 than for test heater 1, and it is felt that this perhaps resulted from test heater 2 not being fully conditioned or aged in the interval between its installation and the time the runs were carried out.

It can be seen in Fig. 13 that each envelope exhibits a maximum in the low pressure range. These maxima vary from slightly over 400,000 Btu/hr·ft^2 for a 2-in. liquid level above the heater to almost 1,000,000 Btu/hr·ft^2 for an 8.5-in. level. Run 46 extended to a heat flux of 1,100,000 Btu/hr·ft^2 although the departure heat flux was reached at about 900,000 Btu/hr·ft^2.

Burnout. The boiling behavior observed for the system operating near the heat-flux levels and system pressures corresponding to the maxima of the departure heat-flux envelopes more closely resembled expected behavior for a system near the burnout heat flux. During run 45, a very large temperature excursion was observed (the recorder stylus went off-scale after a 400 deg F rise) which might be justifiably called a burnout. This temperature excursion, shown in Fig. 14, occurred at a heat flux of 1,018,000 Btu/hr·ft^2. The observation of this burnout and indications in other low-pressure runs that burnout was imminent seemed to indicate that at low pressure, the system was demonstrating behavior normally expected for a wetting liquid. For this reason, the observed departure heat fluxes were plotted versus total pressure, i.e., system pressure plus static head above the heater. Fig. 15 shows that plotting the departure heat flux in this manner effectively separates the maxima exhibited for each liquid level and shows a consistent variation of the maxima with total pressure. Burnout correlations of Addoms [1] and Noyes [17, 22] are included in Fig. 15. Notice that these correlations very nearly predict the observed variation of the maximum departure heat flux. Other correlations by Rohsenow and Griffith [24], Zuber and Tribus [28], and Caswell and Balzhiser [6] fall below those shown in Fig. 15. Physical properties for saturated conditions at the heater were used in evaluating the correlations. The favorable comparison of the maximum de-

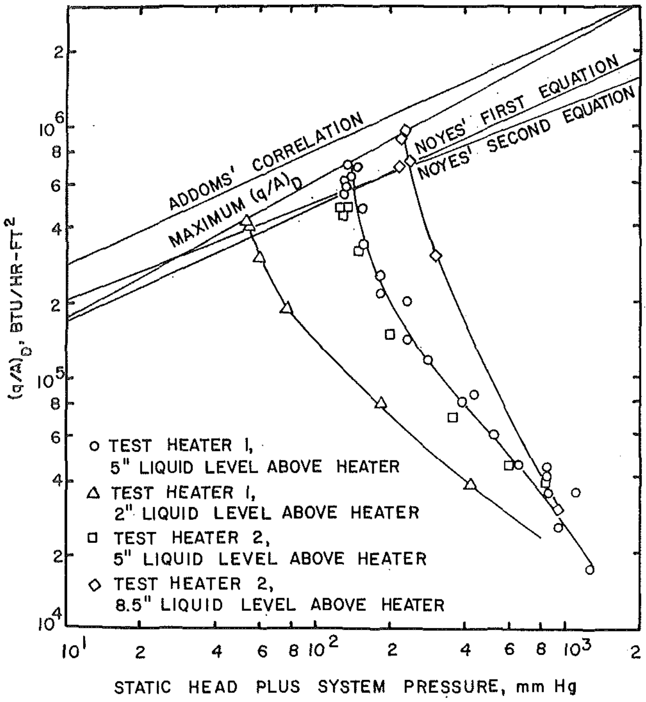

Fig. 15 Comparison of departure heat flux with correlations of Addoms [1] and Noyes [17, 22]

parture heat flux with burnout correlations further suggests that at low pressure the system exhibited boiling behavior quite similar to that expected for most wetting liquids.

Pressure Effect on the Departure Heat Flux. It has previously been noted that increasing the pool depth shifts the nucleate boiling curve to lower ΔT's. Fig. 13 displays the fact that increased departure heat fluxes were obtained with higher liquid levels. Each of these results would be expected as manifestations of pressure effects on boiling. However, one would not normally expect the departure heat flux to increase with decreasing system pressure as observed. To explain this, it was desired to find some property or feature of boiling mercury which varied with system pressure in a manner that would allow such behavior.

While endeavoring to understand why the departure heat flux increased with decreasing system pressure, many explanations were considered and discarded. It was finally concluded that the lack of pool temperature gradients except near the heater may perhaps most satisfactorily point to the reason for increased departure heat fluxes with decreases in system pressure. For low system pressures, a very steep temperature gradient (corresponding to the static pressure gradient) must exist in the pool for equilibrium saturated conditions to be present at all levels of the pool. However, it was shown in Fig. 12 that mixing in the pool resulted in fairly uniform pool temperatures (except near the heater) corresponding closely to saturated conditions for the system pressure. Consequently this had a net effect of producing inherent subcooling in the pool which increased with increasing pool depth and decreasing system pressure. The resultant effect is clearly illustrated in Fig. 16 which is a plot of departure heat flux versus inherent liquid subcooling. The ultimate consequence, of course, would be an increased departure heat flux with decreasing pressure as observed. By direct comparison, it is well known that subcooling enhances heat transfer during nucleate boiling and increases the burnout heat flux, and that this enhancement is greater at lower pressures [13, 29]. Similar enchancement should be observed for any high density boiling liquid.

Possible Boiling Mechanism Above the Departure Heat Flux. To better understand the departure heat flux, and to formulate some idea of the type of boiling occurring above this level, the data were carefully scrutinized and the literature was carefully surveyed. Previous mercury investigators [4, 16, 18, 19] have observed instances where the slope of the boiling curve was

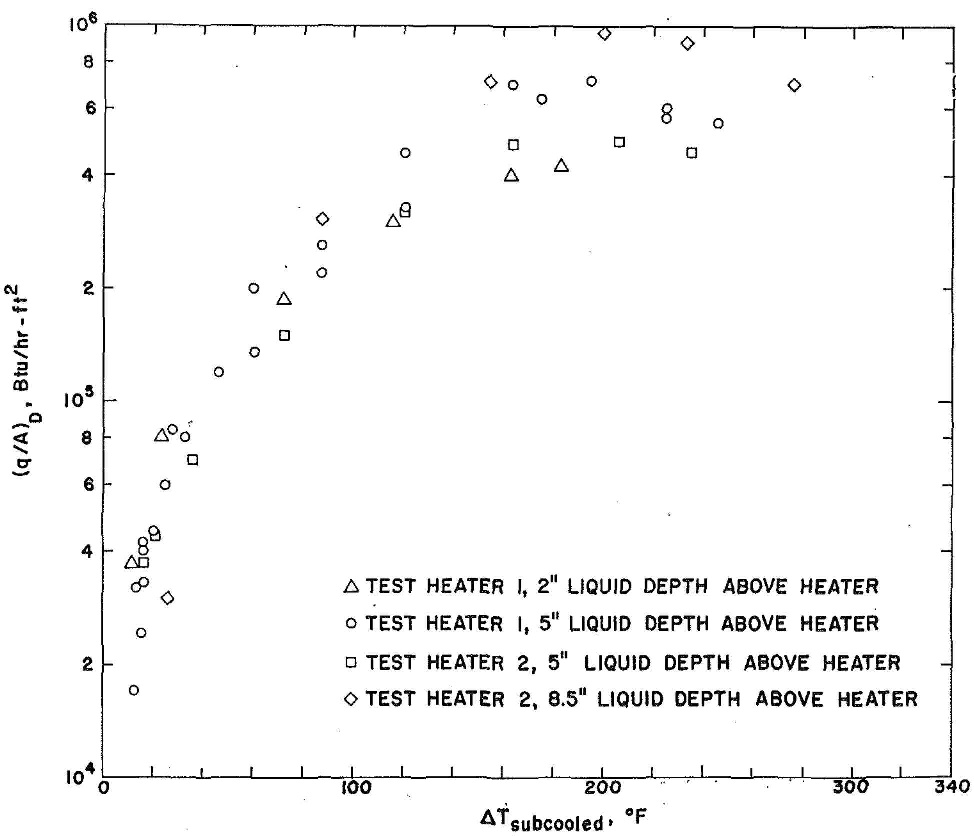

Fig. 16 Dependence of departure heat flux on inherent liquid subcooling near the test heater.

very small, and they attributed this to film boiling due to nonwetting of the surface. Observations made in this study indicated that the small slope may have indeed been a manifestation of nonwetting, but it is doubtful that fully developed film boiling was present. It is felt that the observed phenomenon can best be compared to the second transition region hypothesized by Gaertner [12] for nucleate boiling water. The second transition is the point where a change in slope for the water boiling curve was observed at a high heat-flux level. Gaertner observed that the transition occurred when vapor mushroom stems became unstable and collapsed. Considering this and the large temperature fluctuations observed above the departure heat flux as shown in Fig. 11, it is suggested that this region is likewise characterized by formation and collapse of vapor patches on the surface. This explanation for the small slope of the boiling curve is quite plausible since additional heat would generate more vapor patches which in turn would decrease the heat-transfer coefficient. This analysis is further substantiated by the observed occurrence of large temperature excursions above the departure heat flux.

Conclusions

1 Reproducible, consistent results were obtained for pool-boiling mercury even though the test heater surface was apparently unwetted.

2 Heat fluxes for boiling mercury extended to levels never before achieved on wetted or nonwetted surfaces. Heat fluxes up to 1,100,000 Btu/hr$\cdot$ft^2 were obtained at ΔT's less than 400 deg F.

3 At a particular nucleate boiling heat-flux level, the slope of the boiling curve decreased significantly so that subsequent increases in heat flux were accompanied by large increases in ΔT. The heat flux at which this pronounced decrease in slope occurred was termed the "departure heat flux."

4 Departure heat fluxes plotted versus system pressure for different pool depths above the heater formed envelopes, which exhibited maxima at a system pressure less than 25 mm mercury. Maximum observed departure heat fluxes ranged from 400,000 Btu/hr$\cdot$ft^2 for a 2-in. liquid level above the heater to 950,000 Btu/hr$\cdot$ft^2 for an 8.5-in. level above the heater.

5 The maximum departure heat fluxes showed good agreement with burnout correlations of Addoms [1] and Noyes [17, 22] when plotted as a function of total pressure at the heater.

6 Heater temperature fluctuations observed were very similar to those observed for other boiling liquid metals.

7 Nearly uniform temperatures existed in the boiling pool except near the test heater where high superheats were present.

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