THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Chemical and Metallurgical Engineering
Department of Mechanical Engineering

Third Quarterly Progress Report

INVESTIGATION OF LIQUID METAL BOILING HEAT TRANSFER

Richard E. Balzhiser
Project Director

Robert E. Barry
Herman Merte, Jr.
Bruce F. Caswell
Andrew Padilla, Jr.
Lowell R. Smith

ORA Project 05750

under contract with:

FLIGHT ACCESSORIES LABORATORY
AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO
CONTRACT NO. AF 33(657)-11548

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

February 1964

"To expedite dissemination of information, this report is being forwarded for your information prior to review and approval by the ASD project officer and is, therefore, subject to change. Any comments which you may have should be forwarded to ASD (Mr. Charles L. Delaney), Wright-Patterson AFB, Ohio, within 15 days of receipt to insure correction of errors before final approval is given."

FOREWORD

This report summarizes progress during the period November 15, 1963 to February 15, 1964 on Contract AF 33(657)-11548. This contract provides for continuation of the experimental programs initiated under the original contract between the University of Michigan and ASD. The investigation is being conducted in the Liquid Metals Laboratory of the Department of Chemical and Metallurgical Engineering. Professor Richard E. Balzhiser is serving as Project Director at the University of Michigan. Messrs. Barry, Caswell, Padilla and Smith, all graduate students in chemical engineering are responsible for specific portions of the program.

Progress on the agravic studies with boiling mercury will be summarized in these reports. This work is being conducted by Professor Herman Merte, Jr. and Mr. Samuel Walker in the Mechanical Engineering Department.

Mr. Charles L. Delaney is project engineer for ASD.

ABSTRACT

Burnout data has been obtained for water and sodium in the same equipment used previously for potassium studies. These data confirm Addom's water data and Noyes' sodium data remarkably well. Further studies with sodium will be attempted after which rubidium will be charged to the system and similar studies undertaken. Recent film boiling data obtained by condensing sodium on the bottom side of a horizontal disk on top of which potassium is boiled have yielded inconclusive results. Stable film boiling was observed to have occurred with the pressure in the potassium chamber less than 1 inch of mercury. Upon increasing the power to the sodium instabilities were observed which caused the system to oscillate as if in the transition regime. Agravic studies with mercury at accelerations up to 20 gees were delayed by an equipment failure. Operation is expected to resume within several weeks.

The forced circulation apparatus was used early in this last quarter to obtain additional two phase pressure drop data after which it was shut down and the test section removed for repair. A brittle failure had occurred in the Haynes-25 bellows which had permitted sodium to enter the potassium system. Repairs are almost complete and the loop is expected to be operative by mid-March. An analysis of the two phase pressure drop data has revealed departures from the Martinelli-Nelson or Lockhart type of correlation. Similar deviations have been observed with other data for metallic fluids. A friction factor correlation is proposed which correlates data for metallic systems.

TABLE OF CONTENTS

POOL BOILING STUDIES

Bruce F. Caswell

1. Studies with Water.

The burnout heat flux for water was measured at pressures from 15 to 135 psia. Boiling occurred on the surface of 3/8" OD by 1 1/4" long bayonet tube, the same system used by Colver in his potassium burnout studies (5). The data is presented in Table I and compared in Figure 1 with the correlations of Rohsenow-Griffith (18) and Zuber-Tribus (21) and with the data of other investigators (1, 11). The data from this work follows the relation:

$$(q/A)_c = 1.70 \times 10^5 \ p^{0.25}$$

where $(q/A)_c$ is in Btu/(hr)(sq ft) and p is in psia. This pressure dependence is less than that predicted by Zuber and Tribus but greater than that found by Rohsenow and Griffith. Colver's results with potassium (5) obtained on the same equipment varied with pressure to the power 0.167. The results are in good agreement with the flat plate data of Kazakova (11) and with Addom's data (1). Data at pressures below atmospheric were not obtained because of difficulty in condensing the vapor at the lower temperatures.

2. Studies with Sodium.

Two burnout points for sodium were obtained in the initial series of runs. These data are tabulated in Table II and are plotted in Figure 2. Good agreement with the data of Noyes (13) was found. These two points fall exactly on the curve which Noyes drew through his data and thus tend to confirm the pressure dependence his earlier studies suggested. The Zuber-Tribus correlation predicts a much lower magnitude for the burnout flux than was found here but it does predict the correct pressure dependence:

$$(q/A)_c \sim (p)^{0.50}$$

Colver (5) also found that the Zuber-Tribus relation predicted a lower burnout flux for potassium but he did not obtain agreement on the pressure dependence as was found here.

The burnout points were obtained by maintaining a constant heat flux while slowly decreasing the pressure until burnout occurred. In run A-2 the temperature of the heating surface was fluctuating 200°F just before burnout occurred. A sudden temperature excursion during which the surface temperature exceeded its normal peak fluctuating temperature by several hundred degrees was used as an indication of burnout. The power was immediately shut off and a second point obtained the following day at higher pressures. No apparent damage had been done to the boiling tube in the first burnout excursion.

In run A-3 a hole was formed in the boiling tube during rapid temperature fluctuations and the run was stopped without being certain that burnout had occurred. The fluctuations were slightly less in magnitude and were accompanied by a gradually rising surface temperature. In these respects this burnout was unlike those observed in earlier runs. The absence of a sudden large temperature excursion produces some doubt as to whether the actual burnout point had been reached. In this respect one might consider the point at 3 psia to represent a minimum for the burnout point.

Similar behavior was encountered in run A-1 when a gradual temperature excursion occurred which required about a minute to cause the surface temperature to rise close to its melting point. This could be due to a gradual lowering of the sodium level below the tube. Holdup in the condenser may increase at higher pressures resulting in a drop in the liquid level. The pressure level and flux at which it occurred were about the same as run A-3. It resembled run A-3 in every respect except that it was made by increasing the heat flux at constant pressure.

Nucleate boiling data were obtained for sodium at 3-4 psia. Unusually high surface temperatures were observed and it is planned to obtain additional data on subsequent tubes. The boiling tube design leads to uncertainty in ΔT calculations for nucleate boiling. The tubes were designed for burnout studies and uncertainty in effective tube wall conductivity and thermocouple location causes some uncertainty in wall temperature calculations.

TABLE I
Burnout Data for Water

Pressure PSIA	$(q/A)_c \; \frac{\text{Btu}}{(\text{hr})(\text{sq ft})}$
15	490,000
15	425,000
15	485,000
35	740,000
80	705,000
118	765,000
118	800,000
135	845,000

TABLE II
Burnout Data for Sodium

Run	Pressure PSIA	$T_{\text{saturated}}$	$(q/A)_c \; \frac{\text{Btu}}{(\text{hr})(\text{sq ft})}$
A-2	0.65	1150°F	5.30×10^5
A-3	2.0	1300°F	8.45×10^5

FILM BOILING

Andrew Padilla, Jr.

During the last quarter, operation has been directed at increasing the pressure range of data. However, the occurence of instabilities in the boiling system has necessitated determining the nature and cause of these instabilities. Analytical studies have also have also been carried out to determine the significance of edge effects. These studies will serve as a basis for interpreting the experimental results and to indicate the optimum operating conditions.

Experimental Results

Instabilities in the boiling process were first encountered during the film boiling of potassium under reduced pressure. With the potassium at approximately 1000°F and boiling plate temperatures of about 1500°F, an increase in the power to the heater for the sodium boiler resulted in oscillations of the boiling plate from 1500°F to 1000°F. The drift to the lower temperature level was accompanied by the disappearance of the sound of boiling normally attributable to sodium and the sudden rise to the high level occurred after a large knock. The cycle repeated itself about every 30 seconds.

An attempt was made to show that the instability was due to excessive superheating of the sodium. The potassium was pressurized to prevent boiling and the sodium was heated to 1400°F. However, stable boiling of sodium was observed. Within the last month, instabilities have again occurred during the film boiling of potassium under reduced pressure but these same instabilities persisted after the potassium had been pressurized into the natural convection regime.

In no case where the potassium is in nucleate boiling has there been a case of instability. During nucleate boiling of potassium, two distinct sounds can be heard indicating that both systems are boiling without excessive superheat. Boiling instability has occurred only when the potassium was in natural convection or film boiling.

The most plausible cause of the instability is a too-rapid heating of the sodium aggravated by removal of the boiling plate as an effective heat sink. If the power to the sodium is increased the sodium temperature rises until the increased power input can be dissipated. During the film boiling of potassium this energy cannot be dissipated by condensation on the boiling plate and heat losses without a substantial rise in sodium temperature (and also pressure). Evidently the nucleation process is suppressed and superheating of the liquid sodium must result. During this superheating of sodium, it will later be shown that calculation predicts the boiling plate can no longer support the boiling of potassium and the potassium reverts to the natural convection regime. Eventually the sodium gives up its superheat with a vapor burst causing the potassium to repidly traverse the boiling curve from natural convection to film boiling. The cycle repeats itself until the power to the sodium can be dissipated without superheating.

Instability can be avoided by very slowly and carefully increasing the power to the sodium. When instabilities have been encountered, the power to the sodium has been cut back sharply and then increased very slowly. Eventually, the power level exceeded that at which the instability originally occurred.

The data which has been obtained this last quarter are for the same conditions as those last Fall. These runs were made as a check on the previous ones and to generate information to be used with the analytical studies to be described presently.

Analytical Studies

In order to interpret and evaluate the results which have been obtained thus far, the heat flow through the boiling plate has been analyzed by finite-difference techniques and solved on the IBM-7090 computer.

Figure 3 shows a cross section of the boiling plate. During operation, sodium condenses on the bottom surface of the boiling plate and potassium boils on the top surface. Edge effects consist of axial conduction up the walls of the boiling tube and radiation from the boiling tube to the stainless-steel radiation shield assembly. Thermocouples are presently located on the outside of the shield assembly and on the tube wall approximately 1/4-inch above the boiling plate.

Due to symmetry, the two-dimensional grid network approximates only half of the boiling plate. The boiling tube wall was taken as 0.050 inch to enable the use of a square mesh, thereby greatly simplifying the computation. The analysis assumes constant boiling and condensing coefficients. Radiation losses were calculated on the basis of two long, gray, coaxial cylinders. The temperature of the boiling tube below the boiling plate was assumed to be equal to that of the sodium.

Some of the results of the calculations are shown in Figures 4 and 5. Figure 4 simulates nucleate boiling of potassium under reduced pressure. Three fluxes are given as a function of distance from the center of the boiling plate: the condensing flux, the measured flux, and the boiling flux.

The condensing flux is based on the assumed condensing coefficient and saturation temperature of the sodium and the calculated temperatures at the bottom surface of the boiling plate. Similarly, the boiling flux is computed using the assumed boiling coefficient and potassium temperature and the calculated temperature profile along the upper surface of the boiling plate. The measured flux is based on the known thermal conductivity and thickness of the plate and the temperatures of the top and bottom surfaces of the boiling plate. It is the flux which one would calculate if thermocouples were located exactly at the top and bottom surfaces of the boiling plate. This is slightly larger than would be measured in the boiling plate because the thermocouples are located approximately 25 mils from the surfaces. Also indicated in Figure 4 is the measured flux for a very low condensing coefficient.

These curves show that in nucleate boiling one would expect to measure fluxes very close to those for no edge effects. It also shows that nucleate boiling of potassium cannot be obtained when the condensing coefficient for the sodium is very low.

Figure 5 considers the film boiling of potassium under reduced pressure. In this case, significant edge effects are present which would result in measured fluxes approximately twice those of the ideal conditions. Fortunately, the measured fluxes vary only slightly over a large part of the boiling plate which includes the section in which the thermocouples are located.

From these calculations, several observations can be made: (1) No significant edge effects should be measured in nucleate boiling; (2) The fluxes measured in film boiling are expected to be about twice those if edge effects were not present; (3) The potassium boiling data generated thus far have been obtained under good sodium condensing rates; (4) One possible explanation for the instabilities encountered is that superheating of sodium causes the condensing coefficient to become negligible. The boiling plate can no longer support appreciable fluxes and the potassium reverts to the natural convection regime. When the sodium finally gives up its superheat, the condensing coefficient attains its normal value and causes rapid traversal of the boiling curve from natural convection to film boiling.

FORCED CIRCULATION STUDIES

R. E. Barry

The objective of this program is to compare the two-phase heat transfer characteristics of liquid metals in swirl and straight-tube flow. The studies are to be carried out in the forced circulation loop constructed under Contract AF 33(616)-8277. In this loop, potassium is preheated to a desired quality be means of external resistance heaters and then passed through a test section consisting of a length of ½-inch tube. Sodium vapor condensing on the outside of this tube supplies a flux of 1-million Btu/(hr)(sq ft). A condenser, a cooler and pump complete the circuit.

A number of problems developed during the initial operation of the loop (2) and as a result several modifications are being made in the design.

1. Excessive heat losses: These losses were of such a magnitude in the condenser and subcooler that they prevented operation of the loop at temperatures higher than 1450°F. The condenser and subcooler heat transfer area has been cut in half and more insulation is to be added to all loop components.
2. Burnout of heaters: The resistance heaters on the preheater and sodium boiler are being charged to make use of 13 ga. Kanthal wire rather than the 18 ga. wire used previously. In addition, special care is being taken by the manufacturer to insure a homogeneous refractory imbedment of the wires. Heater element temperature will be observed. As a backup, four heating elements utilizing ¼-in Kanthal rod are on order. Our previous plans to use Nichrome wire were changed when the specified operating temperature of the wire was dropped from 2000°F to 1832°F.

3. Boiling instabilities: While not a serious problem in the preheaters, boiling instability of large magnitude was noted in the sodium boiler. A series of cones (with the open end down) will be installed in both the boiler and preheater. They are intended to serve as vapor traps so that nucleation of vapor in the boiler will not require excessive superheat. In addition, nucleation sites will be provided in the boiler by welding a length of $\frac{1}{4}$-inch tube at two locations on the boiler. These tubes will be open to the boiler fluid and will be heated to temperatures of 200-300°F above the saturation temperature.
4. Failure of the test section: The brittle failure of the Haynes-25 bellows led to our use of an Inconel bellows. This will reduce the operating temperature of the loop to 1600°F but should afford more reliability. The test section is also being modified so that a more accurate determination of the fluid enthalpy entering the heat transfer section will be possible. This is done by measurement of the temperature distribution in a cylinder surrounding the length of tube where development of the velocity profile is occurring.

Twenty-five gallons of high purity potassium was purchased and charged into the cleaned supply tank.

Personnel of MSA Research Corporation will begin reinstallation of the loop components on February 24. Insulation and rewiring will begin on February 29. Hot-trapping of the potassium, preliminary operation of the sodium boiler, and runs to determine the heat balance of the loop will begin March 12.

TWO-PHASE FLOW STUDIES

Lowell R. Smith

I. Two-Phase Pressure Drop Correlation for Potassium

The two-phase pressure drop data for potassium were previously presented as plots of pressure drop against quality, with total mass flow rate taken as a parameter. It was also found that the average pressure level in the test section influenced the observed pressure drops.

With respect to potassium data, the following are believed to be the primary influencing variables:

Total mass velocity	G lbm/hr/ft^2
Mixture quality	x (mass fraction vapor)
Pipe inside diameter	D ft
Vapor density	ρ_g lbm/ft^3

The dependent variable is the two-phase pressure gradient, $(\Delta P/\Delta L)$, psi/ft. The effect of system pressure is accounted for by the vapor density, since this quantity is most heavily influenced by pressure. Over the range of temperatures encountered, the liquid density and viscosity of both phases did not vary widely. A simple dimensional analysis produced a two-phase friction factor as a function of quality.

$$f = \phi(x) \tag{1}$$

where

$$f = \frac{\rho_g D \left(\frac{\Delta P}{\Delta L}\right) g_c}{G^2}$$

Figure 6 presents a plot of f as a function of quality, developed from all the two-phase potassium pressure drop data (226 points). The data had formerly been separated into two groups: those occurring under nearly isothermal conditions, and those occurring under non-isothermal conditions.

A t-test of the isothermal and non-isothermal lines, of the type given in Figure 6, indicated that no significant difference exists between the isothermal and non-isothermal points. Hence, the correlation in Figure 6 is presented for all the data. The pressure drop represented by the data in Figure 6 are almost entirely frictional in nature--i.e., for nearly all the points, the kinetic energy contribution to the pressure drop was negligible compared with the friction loss. The least squares line through the data in Figure 6 is given by

$$\ln f = -4.2839 + 1.5395 \ln x \tag{3}$$

In terms of the linear correlation coefficient (20), this is a highly significant correlation.

The friction factor defined by Equation (2) may be normalized by dividing by a single-phase friction factor. The f values were all normalized against f_g, which is the Moody friction factor for all-vapor flow at total flow rate and at the same average temperature. A plot of normalized friction factor is given as a function of quality in Figure 7. It appears that f/f_g approaches unity as flows become all-vapor ($x=1$), an interesting and significant result.

In Figure 8, the correlation line for potassium is compared with values predicted by the correlations of Lockhart and Martinelli (12) and Bertuzzi, Tek, and Poettmann (4). Both these correlations were developed from air-liquid data. The predicted frictional pressure drops are appreciably high. Also in Figure 8, the potassium correlation is compared with data taken from several sources in the literature 6, 8, 9, 10, 15, 16. The steam-water data (8, 15) and the air-water data (6, 9, 19) fall significantly higher than the potassium data of this study.

A very interesting result given in Figure 8 is that the mercury-nitrogen data of Koestel(10) compare favorably with the potassium data. That metallic systems behave differently is suggested, although the differentiating parameters are not clear.

The potassium results are presented on a Martinelli type of plot in Figure 9. Most of the data fall between the turbulent-turbulent and viscous-viscous correlation lines of Lockhart and Martinelli(12). The Martinelli comparisons in Figure 8 were made using the turbulent-turbulent line, since all potassium Reynolds numbers (liquid and vapor) were well into the turbulent range. Figure 9 also shows the air-water data of Richardson (17), which were also of the turbulent-turbulent flow type.

It appears that the two-phase friction factor defined by Equation (2) is a good correlating parameter for a single fluid system. An attempt is being made to determine what additional parameter distinguishes the potassium data from those of other fluid systems.

II. Metallic Void Fraction Correlation

A study of recently reported void fraction data for potassium-mercury amalgams and also pure mercury (19) indicated that the potassium data from this study might yield a correlation of the Lockhart-Martinelli type (12). In this type of correlation, the void fraction is plotted as a function of the variable X which is given by

$$X = (\Delta P_L/\Delta P_g)^{0.5} \qquad (4)$$

where

ΔP_L = pressure drop that would occur if the liquid were passed through the tube at its own flow rate

ΔP_g = pressure drop that would occur if the vapor were passed through the tube at its own flow rate.

For flows in which the vapor and liquid each exhibit Reynolds numbers in the turbulent range, X may be approximated as

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_g}\right)^{0.1} \qquad (5)$$

where

X_{tt} = X for turbulent-turbulent flow type

x = quality

ρ_g = vapor density

ρ_l = liquid density

μ_g = vapor viscosity

μ_l = liquid viscosity

The void fraction data for this study, together with Allison's data (19) and Noyes' four points for sodium (14) are plotted as liquid fraction versus X_{tt} in Figure 10. The least squares line through the data is indicated. Although the data show a large amount of scatter about the line, a statistical test of the correlation (20) showed that the linear fit on log-log paper is highly significant.

The metallic void fraction correlation is compared with other data and correlations in Figure 11. The Lockhart-Martinelli correlation (based primarily on air-liquid data) predicts significantly higher void fraction values. The air-water data of Richardson (17) and Hewitt, et al. (7) fall near the Lockhart-Martinelli curve. Baroczy's so-called general correlation (3), which is based entirely on the data of Hewitt (7) and Koestel (10), predicts void fraction values very much higher. Koestel's data for the mercury-nitrogen system are also indicated in Figure 11.

It is evident that the void fraction results for the single-component metallic systems are significantly lower than those from the other studies mentioned. It is interesting that Koestel's pressure drop data compare favorably with the results of this study, but that his void fractions are much higher. It is thought that wettability may be of influence in void fraction phenomena, since Koestel's mercury-nitrogen data were obtained from a glass test section.

The comparisons offered in Figure 11 lead to the conclusion that velocity slip ratios for single-component metallic systems are higher than for such systems as air-water. This conclusion may be reached from examination of the following equation for slip ratio.

$$S = \frac{V_g}{V_l} = \left(\frac{x}{1-x}\right)\left(\frac{1-\alpha}{\alpha}\right)\left(\frac{\rho_l}{\rho_g}\right) \qquad (6)$$

where

= void fraction

V_g and V_l are vapor and liquid average velocities

All other variables are as previously defined. For conditions where the factor

$$\left(\frac{x}{1-x}\right)\left(\frac{\rho_l}{\rho_g}\right)$$

may be constant between two flowing two-phase systems, the system with inherently lower void fractions will display higher slip ratios.

LIQUID METAL BOILING IN AGRAVIC FIELDS

Herman Merte

The test vessel has been assembled and installed in the centrifuge with all instrumentation leads connected and tested. It had been anticipated that some data would be available at this time, but additional unforeseen difficulties arose, most of which have been corrected.

Pressure testing of the assembled vessel revealed leaks in the main stainless steel O-ring and the packing gland fittings. The pressure switch was found to be leaking due to a defective internal seal and had to be replaced. A number of defective thermocouple connections were found and corrected.

Upon testing the cooling system a restriction was found within the condenser coil. It was possible to obtain only 0.99 gpm of water through the $\frac{1}{4}$-inch OD by .180-inch ID tubing with full line pressure of 54 psig, rather than the anticipated maximum flow rate of 1.7 gpm. This is believed due to a deformation of the tubing where it was welded in place through the upper chamber walls. It is not felt that this restriction in itself will cause difficulty since the flow velocity within the tube is approximately 12 ft/sec, for 1 gpm, giving an estimated heat transfer coefficient on the water side of 4,000 Btu/(hr)(sq ft)(°F). This, along with the increased acceleration due to swirl within the tubes, is expected to prevent film boiling of the water.

Further detailed pressure testing of the cooling coil revealed a minute leak between the water side and the inner boiling space, again most likely at the welded junction. Correction of this "pinhole" leak would require a major dissassembly and refabrication of the upper part of the inner vessel, with an attendant time delay. Rather than resort to this, it is felt that operation could continue satisfactorily without leaking water into the mercury space if testing is performed at pressures greater than the water line pressure. Accordingly, instead of making the initial tests near atmospheric pressure as was originally planned, tests will begin at 60 psia of mercury pressure. Should results at higher pressures indicate the desirability of also conducting tests at the lower pressures, fabrication of a new upper chamber could be accomplished while testing is underway, and installed with a minimum of delay.

A mercury vapor analyzer has been obtained and will continuously monitor the testing area.

The test vessel is now being insulated externally, and testing should commence within several days.

LITERATURE CITED

1. Addoms, J. N. Sc.D. Thesis in Chemical Engineering, Massachusetts Institute of Technology. 1948.

2. Balzhiser, R. E. et al. "Investigation of Liquid Metal Boiling Heat Transfer." RTD-TDR-63-4130. (Nov. 1963) Contract AF33(616)-8277.

3. Baroczy, C. J. "Correlation of Liquid Fraction in Two-Phase Flow with Application to Liquid Metals." NAA-SR-8171. Atomics International, Div. of North American Aviation, Inc., Canoga Park, California. April 15, 1963.

4. Bertuzzi, A. F., Tek, M. R., and Poettmann, F. H. "Simultaneous Flow of Liquid and Gas Through Horizontal Pipe." Journal of Petroleum Technology. Vol. 8, January 17, 1956.

5. Colver, C. P. "A Study of Saturated Pool Boiling Potassium up to Burnout Heat Fluxes." Ph.D. Thesis in Chemical Engineering, The University of Michigan, September,1963.

6. Govier, G. W. and Omer, M. M. "The Horizontal Pipeline Flow of Air-Water Mixtures." Canadian Journal of Chemical Engineering. Vol. 40, 1962, p. 93.

7. Hewitt, G. F. et al. "Holdup and Pressure Drop Measurements in the Two-Phase Annular Flow of Air-Water Mixtures." British Chemical Engineering. Vol. 8, May 1963, p. 311.

8. Isbin, H. S. et al. "Void Fractions in Two-Phase Steam-Water Flow." AIChE Journal. Vol. 3, March 1957, p. 136.

9. Johnson, H. A. and Abou-Sabe, A. H. "Heat Transfer and Pressure Drop for Turbulent Flow of Air-Water Mixtures in A Horizontal Pipe." ASME Transactions. Vol. 74, 1952, p. 977.

10. Koestel, A. Thompson-Ramo-Wooldridge, Inc., Cleveland, Ohio, in private communication furnished tabulated data which had been previously published in TRW Report ER-4104, June 1960.

11. Kazakova, E. A. "The Influence of Pressure on the First Crisis in Boiling Water from a Flat Surface." G.E.I., Moscow, 1953.

12. Lockhart, R. W. and Martinelli, R. C. "Proposed Correlation of Data for Isothermal Two-Phase, Two-Component Flow in Pipes." Chemical Engineering Progress. Vol. 45, 1949, p. 39.

13. Noyes, R. C. "Boiling Studies for Sodium Reactor Safety, Part I." NAA-Sr-7909. Atomics International, Div. of North American Aviation, Inc., Canoga Park, California. August 30, 1963.

14. Noyes, R. C. "Summary of Recent Results of Sodium Boiling Studies." Presented at Third Annual High-Temperature Liquid Metal Heat Transfer Conference, Oak Ridge National Laboratory, September 4-6, 1963.

15. Pike, R. W. and Ward, H. C. "Adiabiatic, Evaporating, Two-Phase Flow of Steam and Water in Horizontal Pipe." AIChE Preprint, 1963.

16. Reid, R. C. et al. "Two-Phase Pressure Drops in Large-Diameter Pipes." AIChE Journal. Vol. 3, September 1957, p. 321.

17. Richardson, B. L. "Some Problems in Horizontal Two-Phase, Two-Component Flow." ANL-5949. December, 1958.

18. Rohsenow, W. M. and Griffith, P. "Correlation of Maximum Heat Flux Data for Boiling of Saturated Liquids." Chap. 9 of Heat, Mass and Momentum Transfer. W. M. Rohsenow and H. Y. Choi. Prentice-Hall, New York, 1961. (Also NP-5738.)

19. Tang, Y. S., Smith, C. R. and Ross, P. T. "Potassium-Mercury Amalgam Boiling Heat Transfer, Two-Phase Flow, and Properties Investigation." Allison Division, General Motors Corp., Indianapolis, Indiana, Engineering Department Report No. 3549. September 16, 1963.

20. Volk, William. Applied Statistics for Engineers. New York, McGraw-Hill. Chapter 8. 1958.

21. Zuber, N. and Tribus, M. "Further Remarks on the Stability of Boiling Heat Transfer." AECU-3631. January, 1958.

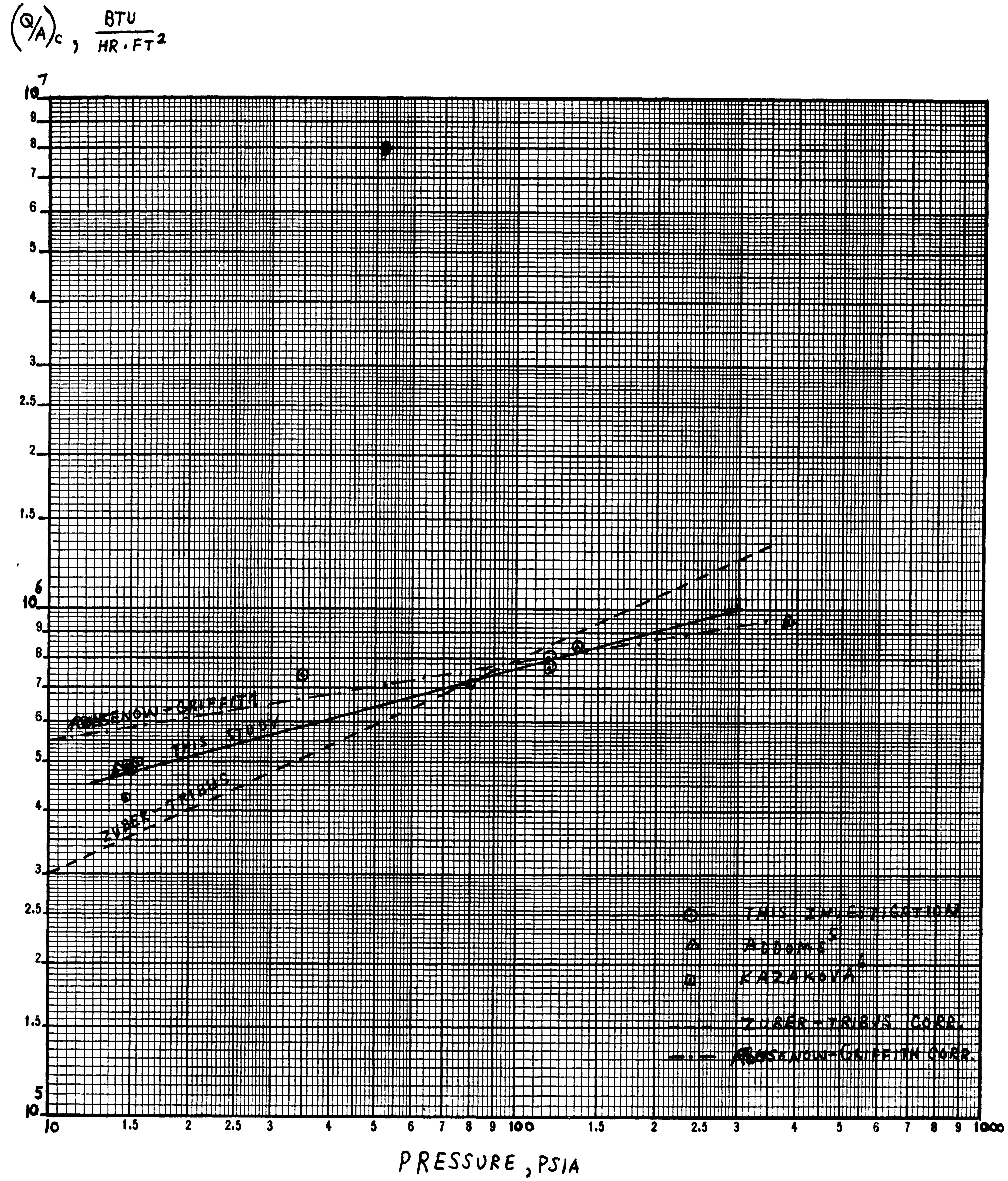
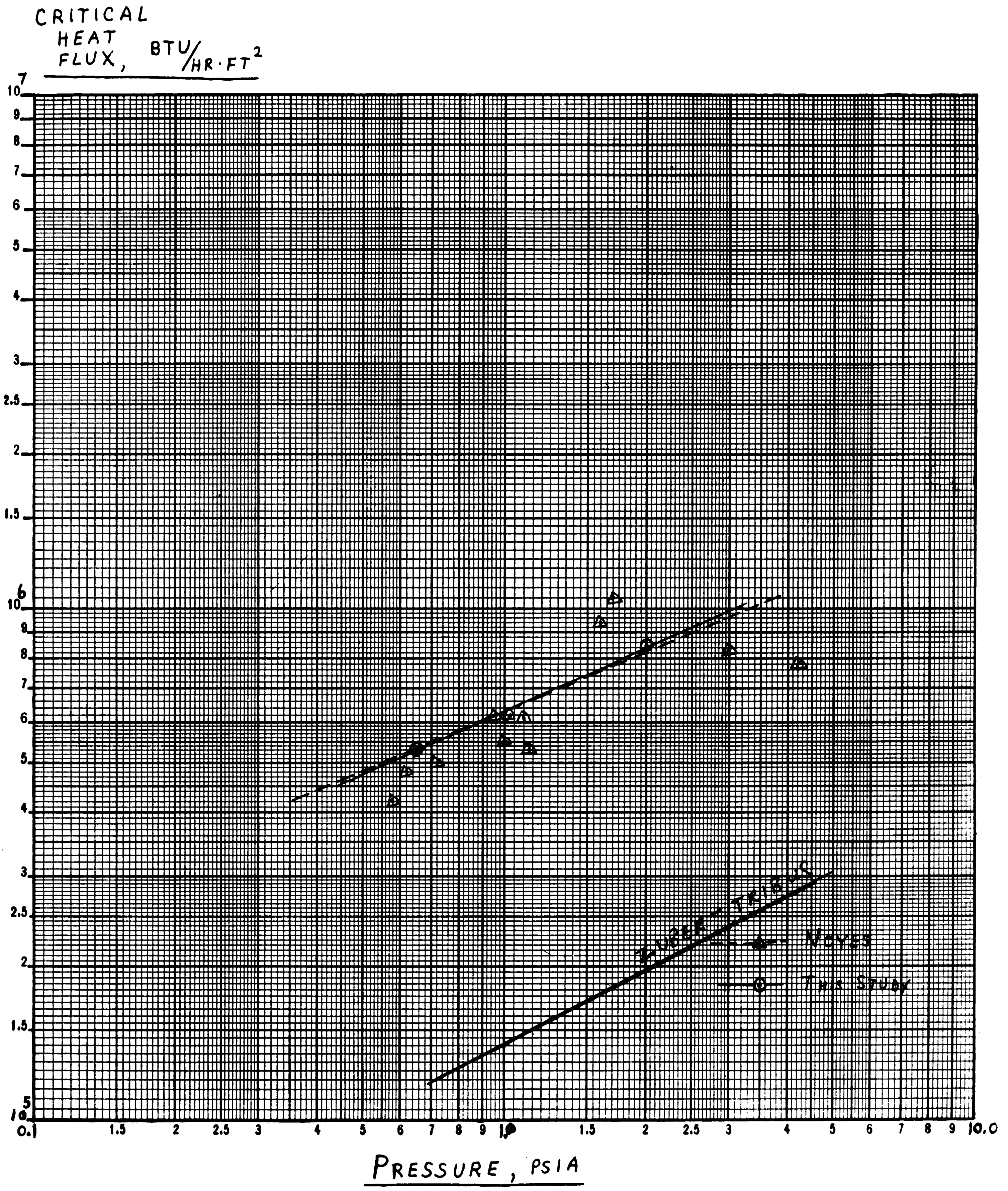


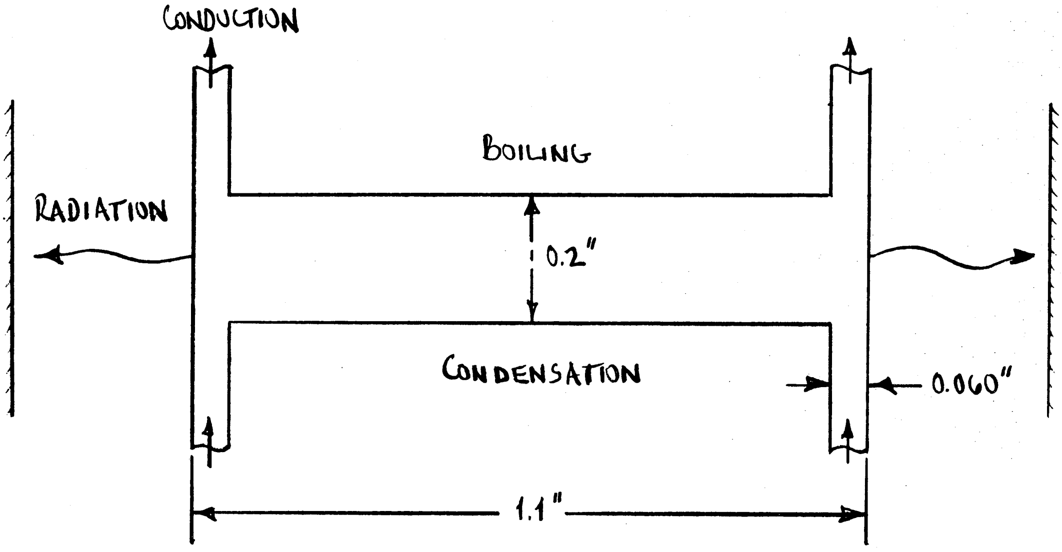
Figure 1. Burnout Data for Water



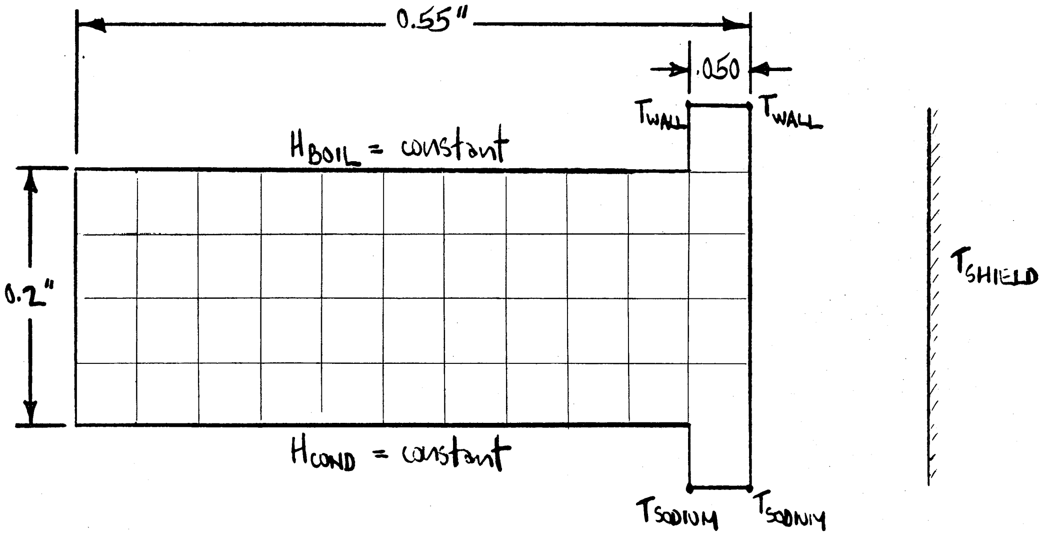
CRITICAL HEAT FLUX FOR POOL BOILING OF SODIUM.

FIGURE 2

FIGURE 3. MODEL FOR ANALYTICAL STUDY OF BOILING PLATE FLUXES



ACTUAL BOILING PLATE



MODEL FOR ANALYTICAL STUDY

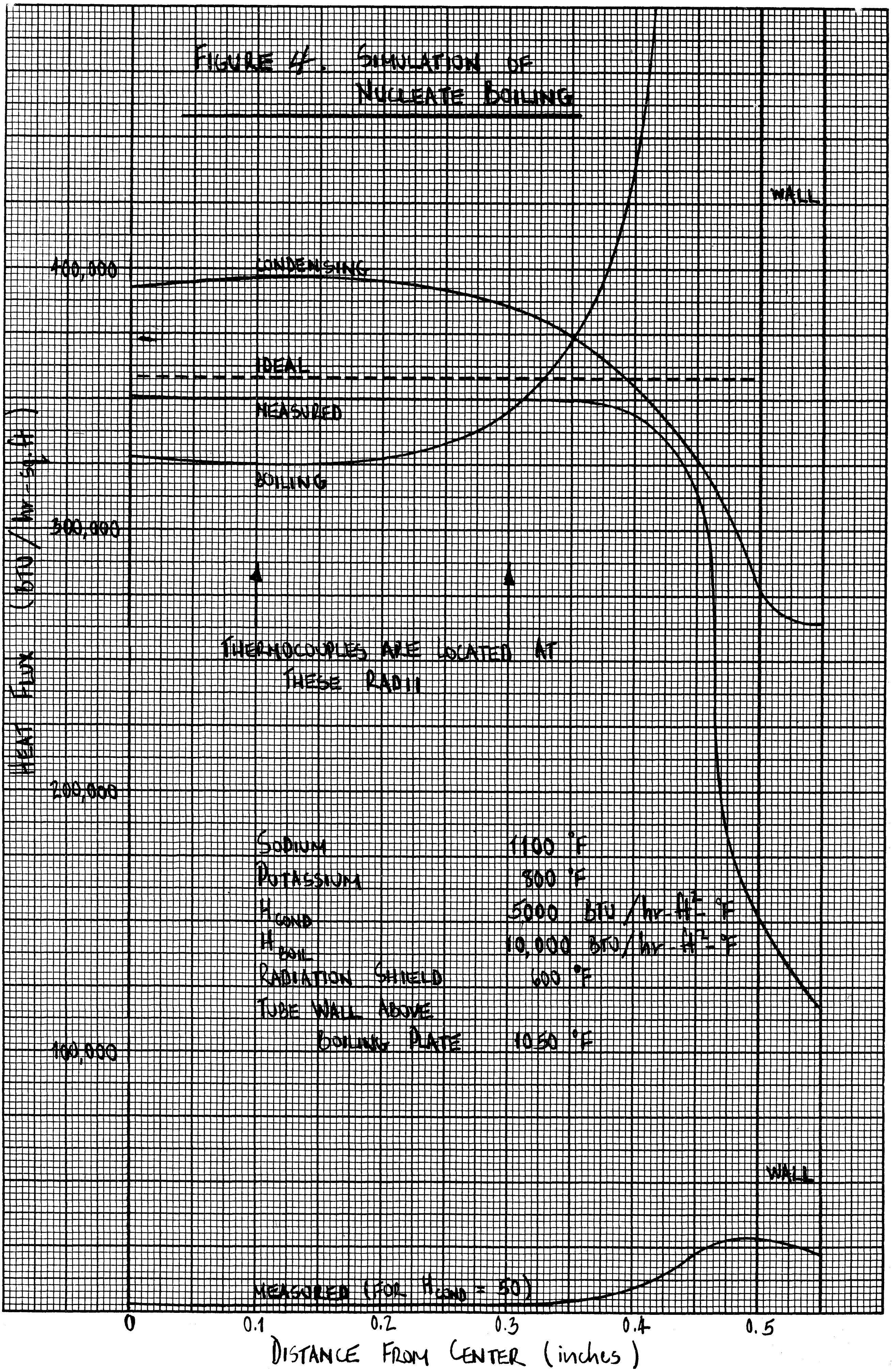


FIGURE 4. SIMULATION OF NUCLEATE BOILING

THERMOCOUPLES ARE LOCATED AT THESE RADII

SODIUM	1100 °F
POTASSIUM	800 °F
H_{COND}	5000 BTU / hr-ft^2-°F
H_{BOIL}	10,000 BTU / hr-ft^2-°F
RADIATION SHIELD	600 °F
TUBE WALL ABOVE BOILING PLATE	1050 °F

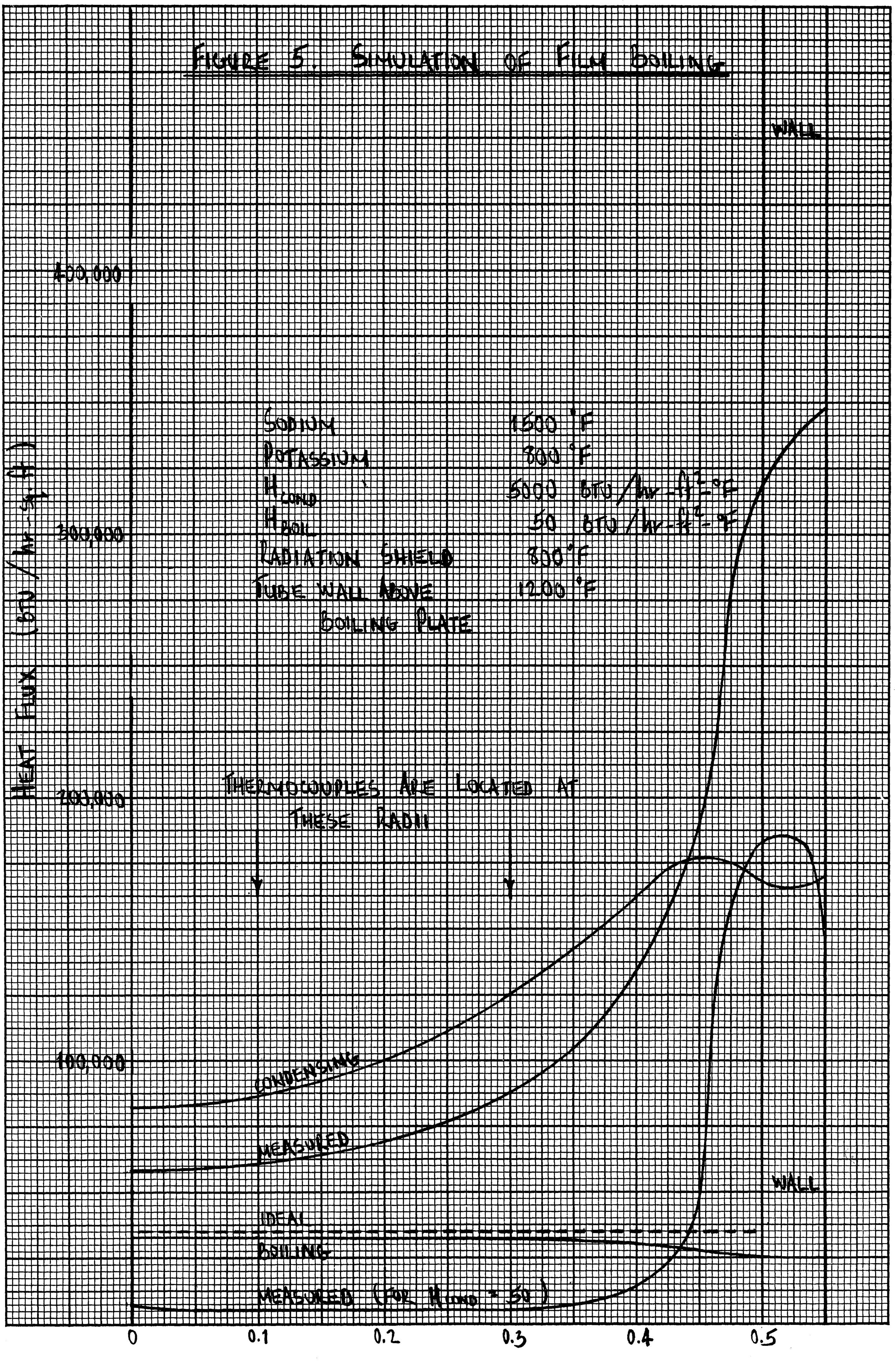
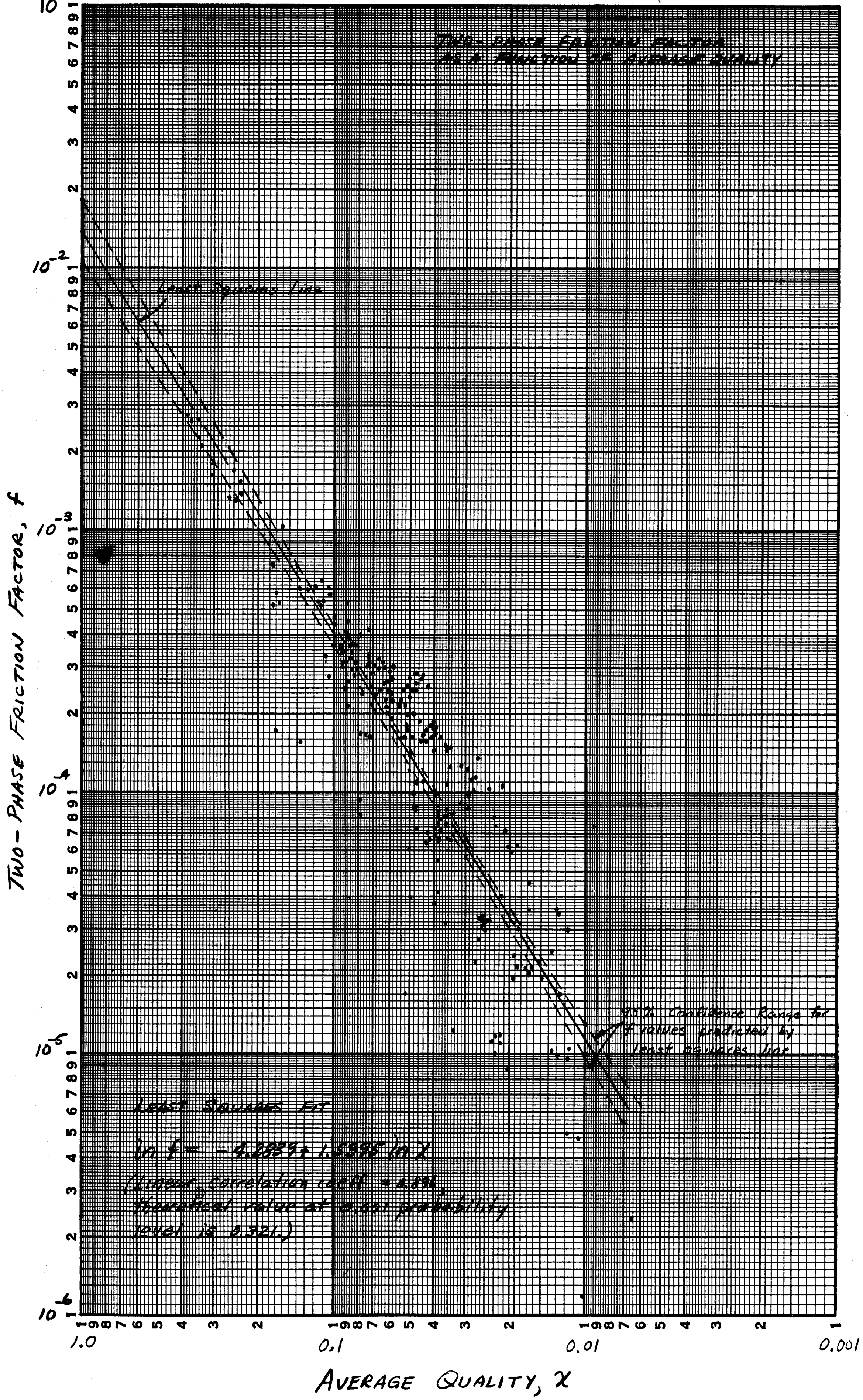
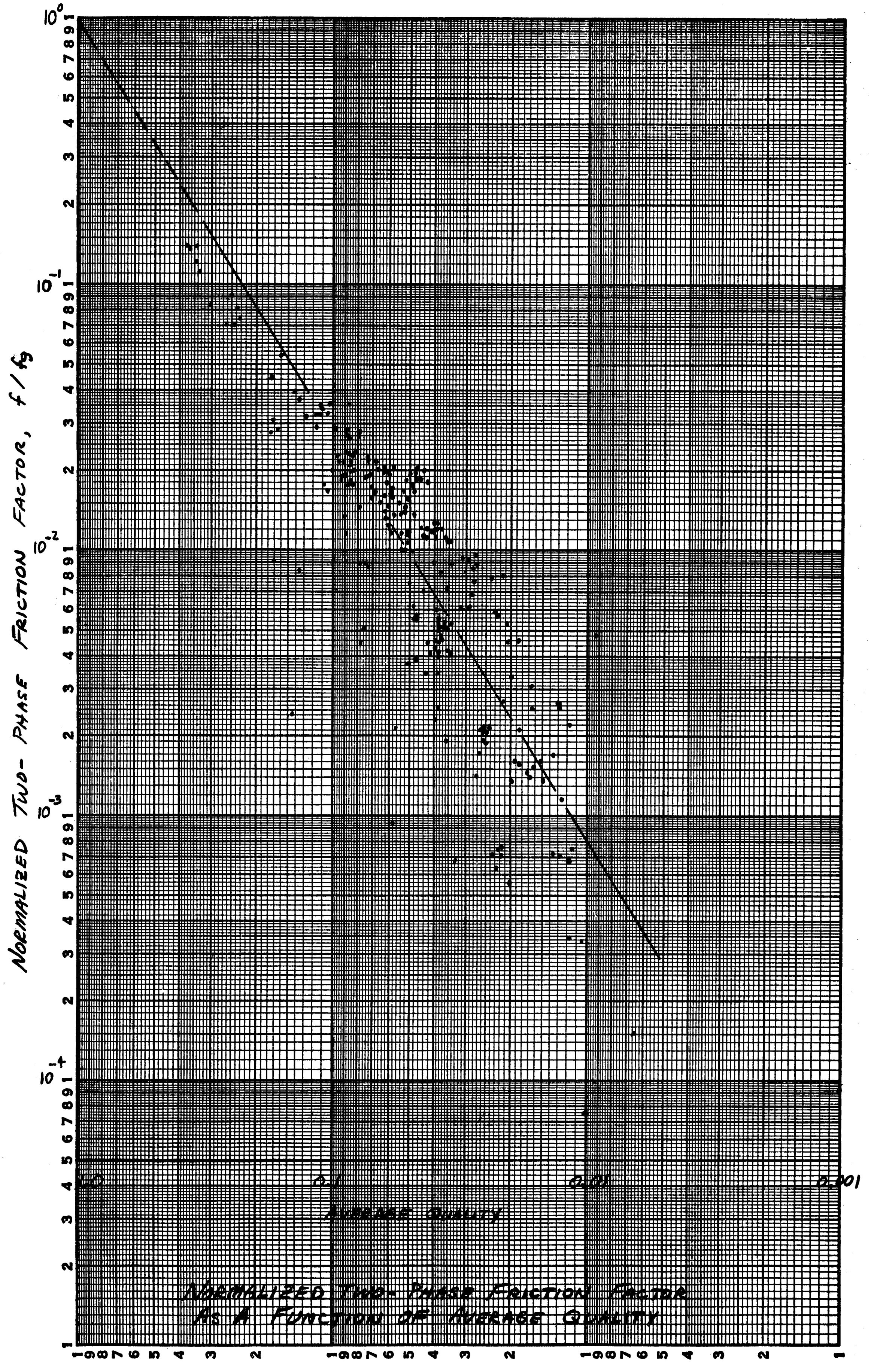


FIGURE 5. SIMULATION OF FILM BOILING

FIGURE 6

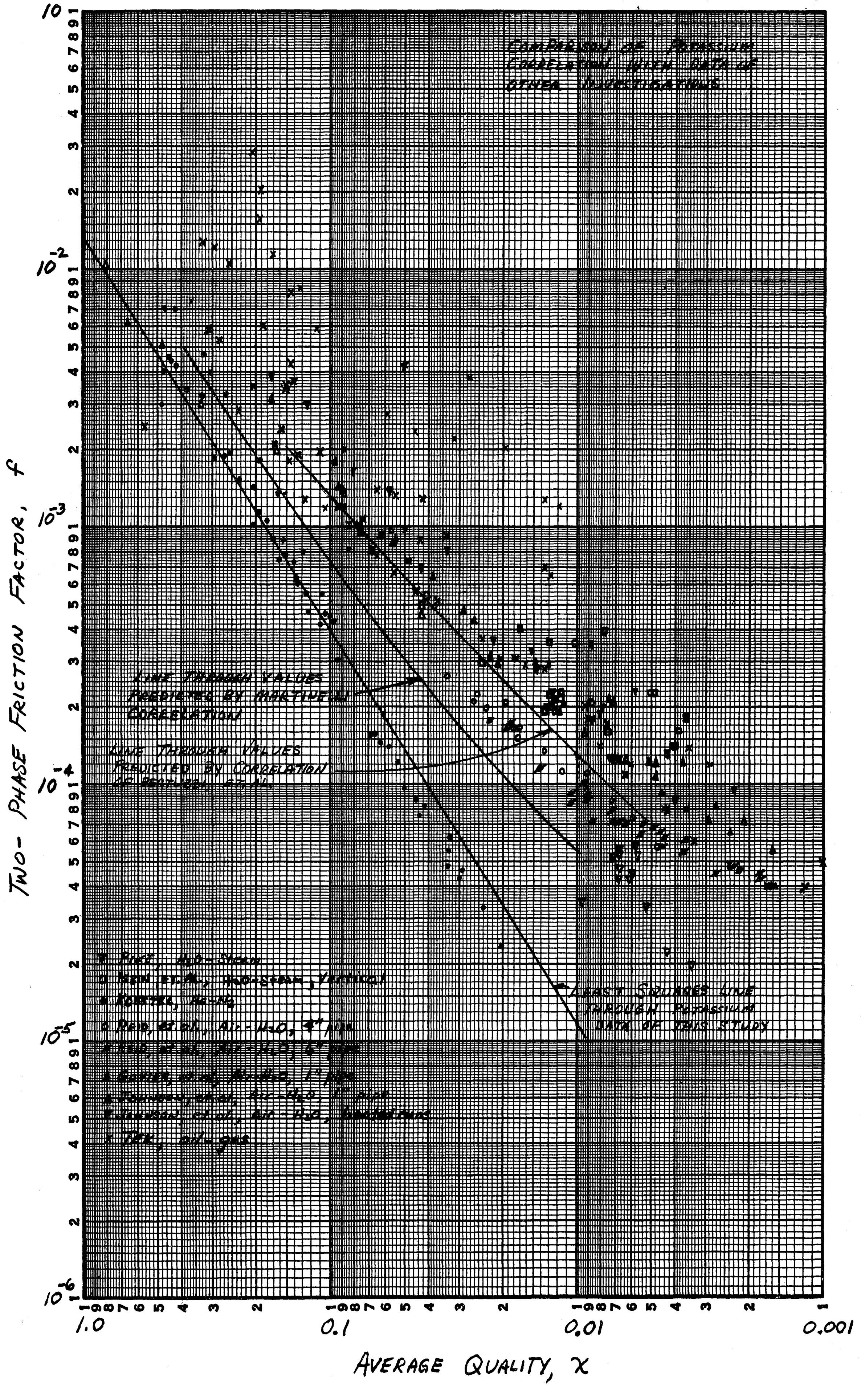

TWO-PHASE FRICTION FACTOR
AS A FUNCTION OF AVERAGE QUALITY
Least Squares line
95% Confidence Range for
f values predicted by
least squares line
LEAST SQUARES FIT
ln f = -4.2829 + 1.5595 ln X
(linear correlation coeff = 0.896,
theoretical value at 0.001 probability
level is 0.321.)
TWO-PHASE FRICTION FACTOR, f
AVERAGE QUALITY, X
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
1.0
0.1
0.01
0.001



NORMALIZED TWO-PHASE FRICTION FACTOR
AS A FUNCTION OF AVERAGE QUALITY

FIGURE 7

FIGURE 8


COMPARISON OF POTASSIUM
CORRELATION WITH DATA OF
OTHER INVESTIGATIONS
LINE THROUGH VALUES
PREDICTED BY MARTINELLI
CORRELATION
LINE THROUGH VALUES
PREDICTED BY CORRELATION
OF BERTUZZI, ET. AL.
LEAST SQUARES LINE
THROUGH POTASSIUM
DATA OF THIS STUDY
▼ PIKE, H2O-STEAM
○ ISBIN ET. AL., H2O-STEAM, VERTICAL
■ KOESTEL, HG-N2
○ REID, ET AL, AIR-H2O, 4" PIPE
● REID, ET AL, AIR-H2O, 6" PIPE
▲ BAKER, ET AL, AIR-H2O, 1" PIPE
▲ JOHNSON, ET AL, AIR-H2O, 1" PIPE
▼ JENKINS, ET AL, AIR-H2O, RECTANGULAR
X TEK, OIL-GAS
TWO- PHASE FRICTION FACTOR, f
AVERAGE QUALITY, x
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
1.0
0.1
0.01
0.001

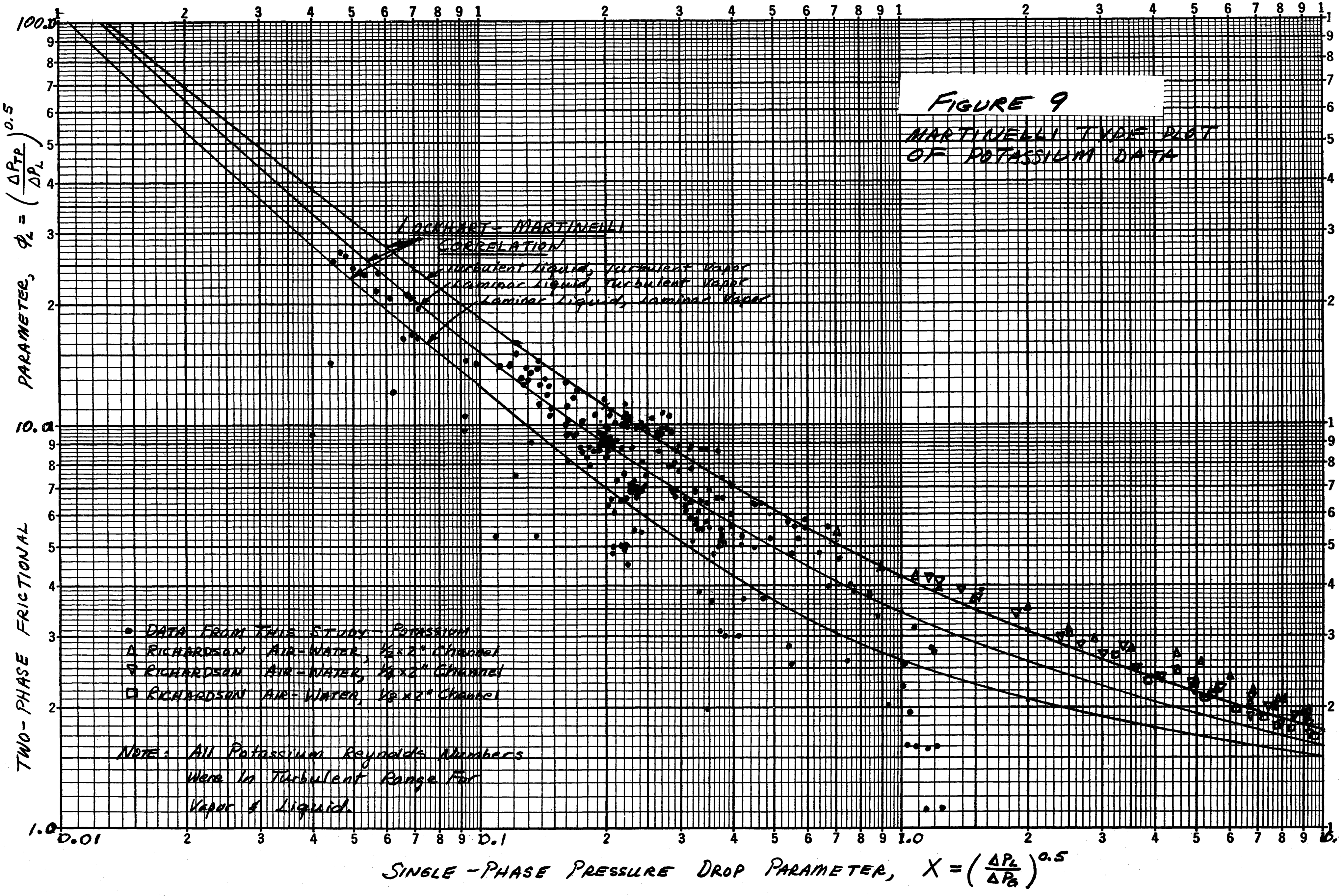


FIGURE 9

MARTINELLI TYPE PLOT OF POTASSIUM DATA

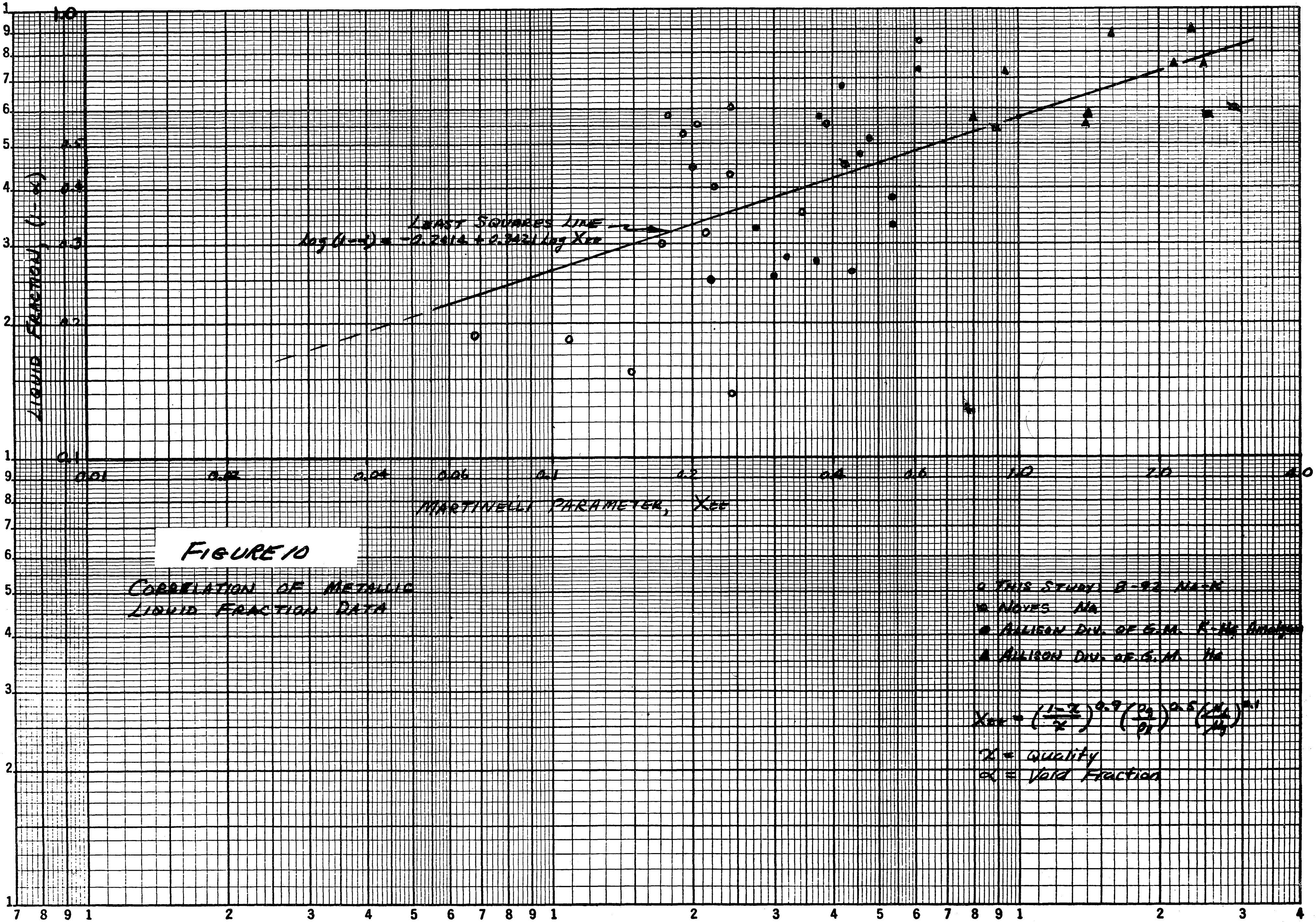


FIGURE 10

CORRELATION OF METALLIC LIQUID FRACTION DATA

METALLIC FIT: $\log(1-\alpha) = -0.2414 + 0.3421 \log X_{tt}$

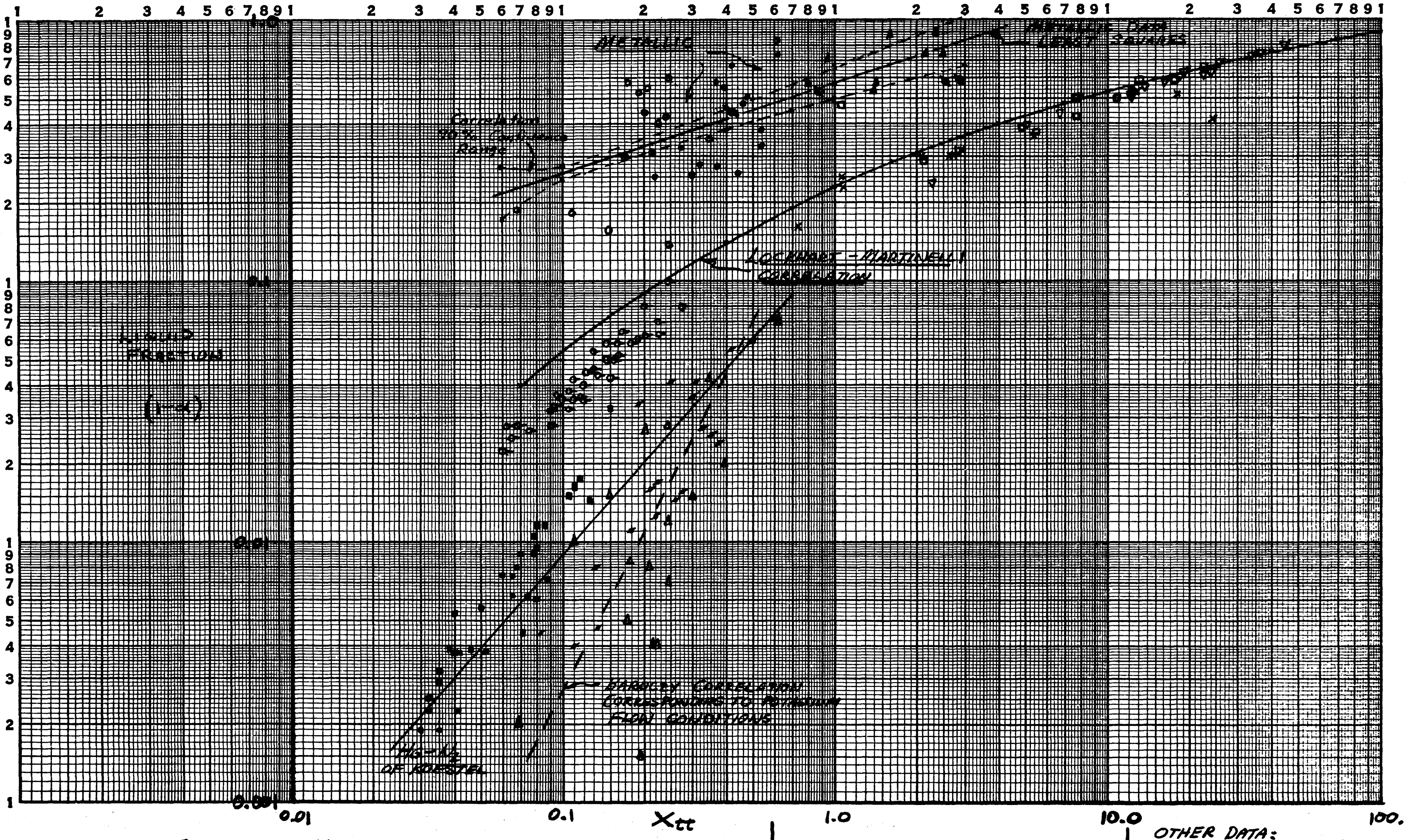


FIGURE 11

VOID FRACTION RESULTS

α = Void Fraction

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1}$$

METALLIC CORRELATION DATA:

- ○ SMITH 8-92 Na-K
- ⊗ NOYES Na
- ● ALLISON K-Hg Amalgam
- ▲ ALLISON Hg

OTHER DATA:

- ○ HEWITT ET. AL. AIR-H2O
- ● ■ KOESTEL & KIRALY Hg-N2
- x RICHARDSON Air-H2O ½x2" Sect.
- ▽ RICHARDSON Air-H2O ¼x2" Sect.
- □ RICHARDSON Air-H2O ⅛x2" Sect
- △ Values predicted by Baroczy for Smith Flow conditions