FORCED-CONVECTION CONDENSATION INSIDE TUBES

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Report No. DSR 72591-74

American Society of Heating, Refrigeration
and Air Conditioning Engineers
Contract No. ASHRAE RP63

Engineering Projects Laboratory
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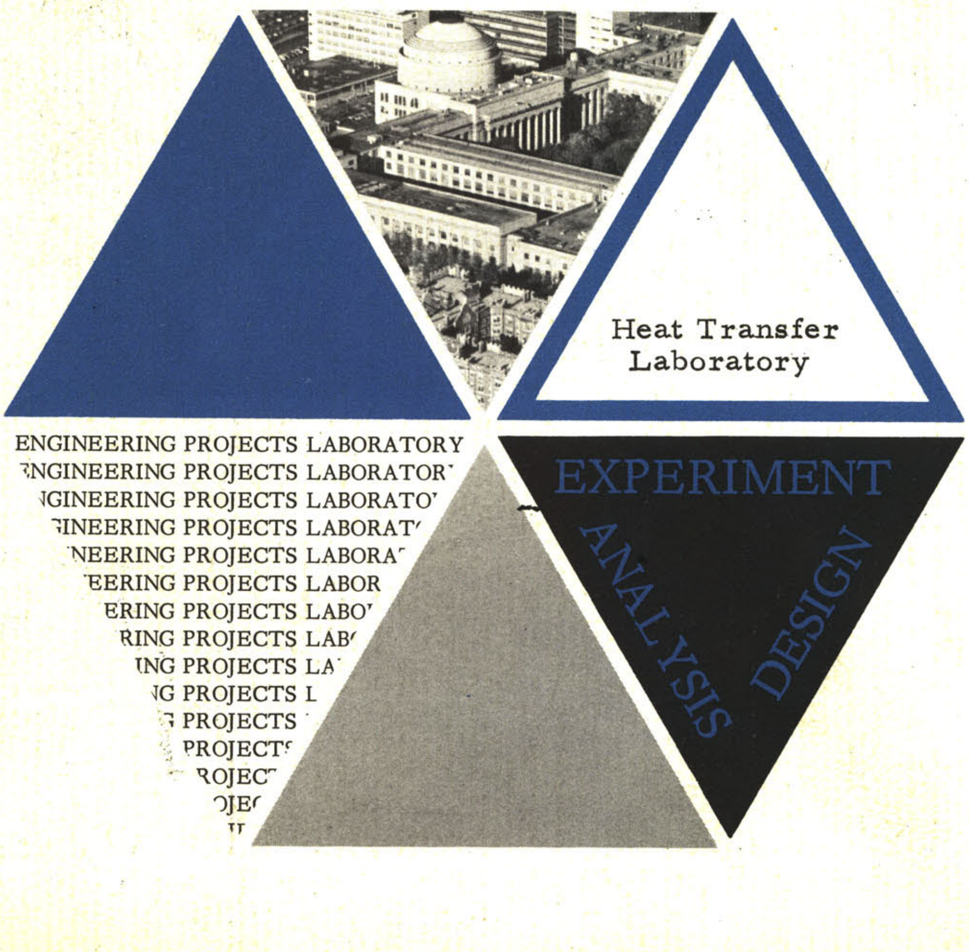
July 1, 1971



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Technical Committee 1.3

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ABSTRACT

High vapor velocity condensation inside a tube was studied analytically. The von Karman universal velocity distribution was applied to the condensate flow, pressure drops were calculated using the Lockhart-Martinelli method, and heat transfer coefficients were calculated from the momentum and heat transfer analogy. Subsequently, the analysis was reduced to an accurate, but simplified form, to facilitate calculations.

Experimental data for refrigerants R-12 and R-22 condensing in a 0.315 in. I. D. tube were obtained for mass fluxes from 1.2×10^5 to 11.3×10^5 lbm/hr-ft^2, qualities from 0.02 to 0.96, and saturation temperatures from 75 to 140°F. On the basis of the data and analysis, a simplified non-dimensional presentation of the results evolved. The agreement between the majority of the data and the analysis was within ± 15 percent.

Acknowledgement

The authors are grateful to ASHRAE Technical Committee TC 1.3 for support of this work.

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Nomenclature

A	cross sectional area ft^2
a	axial acceleration due to external force ft/hr^2
B	buoyancy modulus
c	specific heat $BTU/lbm\text{-}^oF$
D	tube inside diameter ft
E	ratio of eddy conductivity to eddy viscosity
F_0	defined in Eq. (16) $lbf/ft^2\text{-}ft$
F_2	defined in Eq. (28a,b,c)
Fr	Froude number
G	mass velocity $lbm/ft^2\text{-}hr$
g_0	constant: 4.17×10^8 $lbm\text{-}ft/lbf\text{-}hr^2$
h_z	local heat transfer coefficient $BTU/hr\text{-}ft^2\text{-}^oF$
h_{avg}	average heat transfer coefficient $BTU/hr\text{-}ft^2\text{-}^oF$
h_{fg}	latent heat of vaporization BTU/lbm
K	thermal conductivity $BTU/ft\text{-}hr\text{-}^oF$
L	total length of condensation ft
M	defined in Eq. (25)
Nu	Nusselt number
dP/dz	pressure gradient $lbf/ft^2\text{-}ft$
Pr	Prandtl number
q/A	heat flux $BTU/hr\text{-}ft^2$
Re	Reynolds number
S	perimeter ft
T	temperature ^oF

ΔT	difference between vapor and wall temperatures °F
U	mean velocity ft/hr
u_τ	friction velocity as defined in Eq. (21) ft/hr
v_z	local axial velocity ft/hr
W	mass flow rate lbm/hr
x	quality
χ_{tt}	Lockhart-Martinelli parameter defined in Eq. (6)
y	radial distance from the wall ft
z	axial distance from condenser inlet ft
α	void fraction
β	ratio of interface velocity to average liquid velocity
δ	thickness of the condensate film ft
ε_h	eddy conductivity
ε_m	eddy viscosity
μ	absolute viscosity lbm/ft-hr
ν	kinematic viscosity ft^2/hr
ρ	density lbm/ft^3
τ	shear stress lbf/ft^2

SUBSCRIPTS

e	exit
f	friction
g	gravity
ℓ	liquid
v	vapor
z	local value
0	wall

INTRODUCTION

When saturated vapor flows in a tube that is cooled by an exterior fluid, some of the vapor condenses on the tube wall and forms a liquid film. Condensation inside tubes occurs in many applications, particularly in refrigeration condensers. The main resistance to heat transfer for refrigerants and other low-conductivity fluids is the resistance to conduction through the condensate film.

The analysis of Nusselt [1] outlined the basic approach to this problem. At low flow rates and velocities, a laminar condensate film forms on the tube wall; and for a horizontal tube, the liquid accumulates at the bottom. Experimental data for this situation are in good agreement with the results [2], [3], and [4]. A turbulent condensate film evolves at higher flow rates. This problem has been studied by several investigators (for instance: Akers [5], Chen [6], Soliman [7], and Patel [8], and the resulting correlations have usually relied on empirical methods. Carpenter and Colburn [9] derived a semi-empirical equation of limited application. Rohsenow et al. [10] obtained the heat transfer coefficient for a liquid film on a vertical flat plate by using the momentum and heat transfer analogy. Later papers [11], [12], and [13] employed the same approach. More recent developments by Bae et al. [14] and Kosky and Staub [15] employed variations of the Lockhart-Martinelli pressure drop model.

In ideal annular flow, the condensate forms a film of uniform thickness on the tube wall and the vapor flows in the interior core. In practice, this pattern may be modified by waves, entrainment, and stratification. However, these effects are hard to predict or analyze, and annular flow is usually assumed to exist in the parametric range of interest. Since the vapor core is very turbulent, radial temperature gradients are neglected. In addition, the temperatures in the vapor core and at the liquid-vapor interface are assumed to be equal to the saturation temperature. Axial heat conduction and subcooling of the liquid film are also neglected.

In the present paper, the momentum and heat transfer analogy is applied to the annular model using the von Karman universal velocity distribution to describe the liquid film. This seems to be the most accurate method for describing the condensate flow and heat transfer. An order of magnitude analysis and non-dimensionalization of this theory result in a simple formulation for the local heat transfer coefficient. The analysis is compared to experimental data and the results are used to obtain a general design equation for forced-convection condensation.

EXPERIMENT

General Description of Test Facility

The basic apparatus is shown schematically in Fig. 1. It consisted of a closed-loop refrigerant flow circuit driven by a mechanical-sealed rotor pump. An electrically heated boiler generated vapor which passed through a flow meter and into the test section. An aftercondenser downstream from the test section condensed any remaining vapor and ensured liquid refrigerant at the pump inlet. The pump was connected to a by-pass loop, and a valve in the by-pass loop was used to regulate the flow rate and pressure in the test section. The return line from the boiler incorporated a filtering-drying element and a commercial sight glass and moisture indicator. Front and rear views of the experimental apparatus are shown in Fig. 2.

The test section was a tube-in-tube heat exchanger: the refrigerant flowed through the inner tube and the water flowed countercurrently in the annulus or jacket. The inner tube was a commercial 3/8 in. O. D. (0.315 in. I. D.), continuous copper tube 16 1/2 ft. long and extended 2 ft upstream from the test section.

Seven brass rings, each incorporating a pressure tap, were soldered to the inner tube at 29 in intervals. These split the annulus lengthwise into six sections. Heat transfer and pressure drop measurements were made in each of these sections. Adjoining sections of the water jacket were connected in series by flexible hoses to ensure mixing. Two differential thermocouples were located at the inlet and outlet of each water jacket for measuring the temperature rise of the water through each section. In addition, two differential thermocouples were located at the first water inlet and the last water outlet in order to check the overall water temperature rise against the sum of the six individual water temperature rises. At the mid-point of each section two thermocouples were installed: one on the outside wall of the condenser tube and one at the centerline of the tube. The wall temperature thermocouples were soldered flush to the outer surface of the copper tube; and as such, did not project into the boundary layer of the coolant. To install the centerline thermocouples, holes were bored into the copper tube and open-ended stainless steel tubes, 0.035 in. O.D., were soldered in the holes. The tip of the stainless steel tube was 1/64 in. short of the copper tube centerline. The thermocouples were then inserted so that the thermocouple beads would be at the centerline of the copper tube, subsequently the thermocouples were glued in place with epoxy. All the thermocouples were made of 0.005 in. O.D. nylon-sheathed copper and constantan wire.

Downward-sloping copper tubes connected the pressure taps to a U-tube mercury manometer through a manifold which enabled the measurement of the refrigerant pressure drop through each section. A Bourdon pressure gage, located upstream of the test section, was used to measure the inlet saturation pressure.

Calibrated flowmeters were used to measure the flowrate of the water through the annulus and aftercondenser. Thermocouples were also installed to measure the temperature of the water at the aftercondenser inlet and outlet, and of the refrigerant at the inlet of the test section and the outlet of the aftercondenser.

All the loop was insulated with fiberglass. The heat loss from the test section to the atmosphere was not measurable within the accuracy of the potentiometer.

Test Procedure

It was desirable to eliminate all possible contaminants before charging the refrigeration loop. The loop was evacuated to 30 in. Hg and filled with dry nitrogen repeatedly to eliminate moisture. Then the system was evacuated and filled with the refrigerant vapor until a pressure of 70 psig. was reached. The refrigerant was then allowed to escape through bleed valves at the aftercondenser, boiler return line, and manometer until the pressure fell to 5 psig. This was repeated twice in order to dilute any traces of non-condensibles in the system. The system was then charged with liquid refrigerant until the sight glass in the boiler showed that the heating elements were covered.

To obtain the desired conditions in the runs, several parameters could be controlled. The temperature of the water entering the annulus and the aftercondenser was controlled by mixing hot and cold feeds. The water temperature, the water flow rates, the by-pass valve setting, and boiler heat input determined the refrigerant temperature, pressure, and flow rate. Data were taken one hour after the system had reached steady state.

Data Reduction

An overall heat balance was performed for each run by comparing the heat gained by the water with the heat lost by the refrigerant in the test section and the aftercondenser. For all runs, the error was less than 7 percent. The heat flux from the refrigerant was obtained by multiplying the water flow rate by the water temperature rise and specific heat. Using the thermal conductivity of the inner tube, dimensions of the inner tube, and heat flux, the temperature drops across the tube wall were calculated. From this information the inside wall temperatures were determined. The refrigerant qualities at the midpoints of the six sections were determined from a heat balance using the thermodynamic properties of the refrigerant, refrigerant flow rate, and heat gain of the water. The condensation heat transfer coefficient was obtained by dividing the average heat flux for a section by the difference between the vapor temperature and inside wall temperature. The pressure gradient was calculated by dividing the pressure drop across one section by the length of that section.

ANALYSIS

The pressure gradient for two-phase flow in a pipe may be expressed as the sum of three components:

$$(\frac{dP}{dz}) = (\frac{dP}{dz})_f + (\frac{dP}{dz})_g + (\frac{dP}{dz})_m \qquad (1)$$

due respectively to friction, external body forces, and momentum change. The components of the total pressure gradient are related to wall shear stress, external acceleration and velocity gradients as follows[14]:

$$(\frac{dP}{dz})_f = -\tau_0 \frac{S}{A} \qquad (2)$$

$$(\frac{dP}{dz})_g = \frac{a}{g_0} [\alpha\rho_v + (1 - \alpha)\, \rho_\ell] \qquad (3)$$

$$(\frac{dP}{dz})_m = - \frac{1}{g_0 A} \frac{d}{dz} [U_v W_v - U_\ell W_\ell] \qquad (4)$$

Assuming that condensation does not affect the frictional pressure drop, the isothermal correlations are applied directly as was done by Martinelli and Nelson[18] for boiling and by Bae[14] for condensation. Following the method used by Lockhart and Martinelli[19], the frictional pressure gradient for two-phase flow is related to the pressure gradient for vapor only by:

$$\left(\frac{dP}{dz}\right)_f = \phi_v^2 \left(\frac{dP}{dz}\right)_v \tag{5}$$

where:

$$\chi_{tt} = \frac{\left(\frac{dP}{dz}\right)_\ell}{\left(\frac{dP}{dz}\right)_v} = \left(\frac{\mu_\ell}{\mu_v}\right)^{0.1} \left(\frac{1 - x}{x}\right)^{0.9} \left(\frac{\rho_v}{\rho_\ell}\right)^{0.5} \tag{6}$$

and:

$$\left(\frac{dP}{dz}\right)_v = - \frac{4}{D} \left(\frac{0.045}{Re_v^{0.2}}\right) \frac{G^2 x^2}{2g_0} = - 0.09 \frac{\mu_v^{0.2} G^{1.8} x^{1.8}}{g_0 \, \rho_v \, D^{1.2}} \tag{7}$$

The data of ref. [19] were given in an approximate curve by Soliman et al.[7] as follows:

$$\phi_v = 1 + 2.85 \, \chi_{tt}^{0.523} \tag{8}$$

combining Equations (5), (6), (7) and (8):

$$\left(\frac{dP}{dz}\right)_f \frac{g_0 D}{\frac{G_v^2}{\rho_v}} = - 0.09 \left(\frac{\mu_v}{G_v D}\right)^{0.2} \left[1 + 2.85 \left[\left(\frac{\mu_\ell}{\mu_v}\right)^{0.1} \left(\frac{1 - x}{x}\right)^{0.9} \left(\frac{\rho_v}{\rho_\ell}\right)^{0.5}\right]^{0.523}\right]^2 \tag{9}$$

The gravity component is re-written as follows:

$$\left(\frac{dP}{dz}\right)_g \frac{g_0 D}{\frac{G^2}{\rho_v}} = \frac{1}{Fr^2} \left[\frac{\rho_\ell}{\rho_v} - B\alpha\right] \tag{10}$$

where:

$$Fr^2 = \frac{(\frac{G}{\rho_v})^2}{aD} \tag{11}$$

is the Froude member based on the total flow and:

$$B = \frac{\rho_\ell - \rho_v}{\rho_v} \tag{12}$$

is the buoyancy modulus. The local void fraction is calculated using Zivi's equation[20]:

$$\alpha = \frac{1}{1 + (\frac{1 - x}{x})(\frac{\rho_v}{\rho_\ell})^{\frac{2}{3}}} \tag{13}$$

Combining Eq. (13) with Eq. (4) and performing the indicated operations yields:

$$(\frac{dP}{dz})_m \frac{g_0 D}{\frac{G^2}{\rho_v}} = - D(\frac{dx}{dz}) \, [2x + (1 - 2x) \, (\frac{\rho_v}{\rho_\ell})^{\frac{1}{3}} + (1 - 2x) \, (\frac{\rho_v}{\rho_\ell})^{\frac{2}{3}} - 2(1 - x) \, (\frac{\rho_v}{\rho_\ell})] \tag{14}$$

For most of the tube length the liquid film is thin. At 20% vapor quality the film thickness is less than 10% of the tube radius.

Therefore a flat plate approximation is used for the liquid film.

The momentum equation for an element of the liquid layer yields:

$$\tau_0 = F_0 \delta + \tau_v \tag{15}$$

where F_0 includes pressure, momentum and gravity forces acting on the film.

$$F_0 = -\left(\frac{dP}{dz}\right) + \frac{a}{g_0}\rho_\ell - \frac{G^2}{g_0 \rho_v}\frac{dx}{dz}\left[\frac{1}{1-\alpha}\left(\frac{\rho_v}{\rho_\ell}\right)^{\frac{1}{3}} - \left(\frac{(1-x)(2-\beta)}{(1-\alpha)^2}\right)\left(\frac{\rho_v}{\rho_\ell}\right)\right] \tag{16}$$

β is the ratio of the vapor-liquid interphace velocity to the average velocity in the liquid film. This was obtained from the universal velocity profile and is a function of δ^+ as shown in Fig. 3. A more detailed description of the F_0 and β terms can be found in Bae[12].

Assuming that the von Karman momentum-heat transfer analogy is applicable to the liquid layer, the shear stress and heat flux are written as:

$$\tau = \frac{\rho_\ell}{g_0}(\nu_\ell + \varepsilon_m)\frac{dV_z}{dy} \tag{17}$$

$$\frac{q}{A} = \rho_\ell c_\ell (\alpha_\ell + \varepsilon_h)\frac{dT}{dy} \tag{18}$$

E is the ratio of eddy conductivity ε_h to eddy viscosity ε_m. Some investigators[10] have[11] obtained good results with E = 1.0. Others have indicated that the ratio ranges from 1.0 to 1.7. Rearranging Eq. (17) and solving for ε_m, one obtains:

$$\varepsilon_m = [\frac{\tau g_0}{\rho_\ell} \frac{1}{u_\tau^2} (\frac{1}{\frac{dv_z^+}{dy^+}}) - 1] \nu_\ell \tag{19}$$

Where:

$$v_z^+ = \frac{v_z}{u_\tau} \tag{20}$$

$$u_\tau = \sqrt{\frac{g_0 \tau_0}{\rho_\ell}} \tag{21}$$

$$y^+ = \frac{y\, u_\tau}{\nu_\ell} \tag{22}$$

The von Karman universal velocity distribution for the liquid layer is:

$$0 < y^+ < 5 \qquad v_z^+ = y^+ \tag{23a}$$

$$5 < y^+ < 30 \qquad v_z^+ = -\,3.05 + 5 \ln y^+ \tag{23b}$$

$$30 < y^+ \qquad v_z^+ = 5.5 + 2.5 \ln y^+ \tag{23c}$$

Using Eqs. (19) and (23a, b, c), we obtain three expressions for ε_m:

For the laminar zone $\varepsilon_m/\nu_\ell << 1$ and $\tau/\tau_0 = 1$; hence,

$$0 < y^+ < 5 \qquad \underline{\varepsilon_m = 0} \tag{24a}$$

For the buffer zone, the eddy viscosity is of the same order of magnitude as the kinematic viscosity and $\tau/\tau_0 \cong 1$; hence,

$$5 < y^+ < 30 \qquad \underline{\varepsilon_m = (\nu_\ell)\left(\frac{y^+}{5} - 1\right)} \tag{24b}$$

Assuming a linear shear stress variation in the turbulent zone with $\underline{\tau = F_0(\delta - y) + \tau_v}$ and $\underline{\varepsilon_m/\nu_\ell >> 1}$, then: $\varepsilon_m \cong \left[\frac{\tau g_0}{\rho_\ell}\frac{1}{u_\tau^2}\left(\frac{1}{\frac{dv_z^+}{dy^+}}\right)\right]\nu_\ell$

$$30 < y^+ \qquad \underline{\varepsilon_m = \frac{\nu_\ell}{2.5}\left[y^+ - \frac{\textcircled{M}}{\delta^+}(y^+)^2\right]} \tag{24c}$$

where:

$$\textcircled{M} = \frac{\textcircled{F}_0\delta^+\nu_\ell}{\tau_0\, u_\tau} = 1 - \frac{\tau_v}{\tau_0} \tag{25}$$

Since $(q/A) \cong (q/A)_0$, Eq. (18) may be integrated to yield:

$$\underline{\frac{1}{h_z} = \frac{T_\delta - T_0}{\left(\frac{q}{A}\right)} = \int_0^{\delta^+} \frac{\nu_\ell}{\rho_\ell c_\ell(\alpha_\ell + E\varepsilon_m)u_\tau}\, dy^+} \tag{26}$$

Substituting Eq. (24) into Eq. (26) and completing the integration:

$$Nu_z = \frac{h_z D}{k_\ell} = \frac{\rho_\ell c_\ell D\, u_\tau}{k_\ell F_2} \tag{27}$$

where F_2 is

$$0 < \delta^+ < 5 \quad F_2 = \delta^+ Pr \tag{28a}$$

$$5 < \delta^+ < 30 \quad F_2 = 5Pr + \frac{5}{E}\ln\left(1 + EPr\left(\frac{\delta^+}{5} - 1\right)\right) \tag{28b}$$

$$30 < \delta^+ < \infty \quad F_2 = 5Pr + \frac{5}{E}\ln(1 + 5EPr) \tag{28c}$$

$$+ \frac{2.5}{E\sqrt{1 + \frac{10M}{E\delta^+ Pr}}} \ln\left[\frac{2M-1+\sqrt{1 + \frac{10M}{E\delta^+ Pr}}}{2M-1-\sqrt{1 + \frac{10M}{E\delta^+ Pr}}} \cdot \frac{\frac{60M}{\delta^+} - 1 - \sqrt{1 + \frac{10M}{E\delta^+ Pr}}}{\frac{60M}{\delta^+} - 1 + \sqrt{1 + \frac{10M}{E\delta^+ Pr}}}\right]$$

The equations for F_2 in the first two zones are fairly simple. However the third term in Eq. (28c) involves a laborious calculation.

This term can be simplified, since $\delta^{+} > 30$, $Pr_{\ell} > 3$ for refrigerants R-12 and R-22, and $0 \leq M \leq 1$. Therefore:

$$1 + \frac{10M}{EPr\ \delta^{+}} < 1 + \frac{(10)\ (1)}{(3)\ (30)} = 1.11$$

Hence using a truncated binominal expansion as an approximation of this factor would introduce an error of less than 0.05%, therefore:

$$\sqrt{\frac{10M}{EPr\ \delta^{+}} + 1} \cong 1 + \frac{5M}{EPr\ \delta^{+}}$$

And the third term of Eq. (28c) becomes:

$$\frac{2.5}{1 + \frac{5M}{EPr\ \delta^{+}}} \ln \left[\frac{2M + \frac{5M}{EPr\ \delta^{+}}}{2M - 2 - \frac{5M}{EPr\ \delta^{+}}} \cdot \frac{\frac{60M}{\delta^{+}} - 2 - \frac{5M}{EPr\ \delta^{+}}}{\frac{60M}{^{+}} + \frac{5M}{EPr\ \delta^{+}}} \right]$$

Which may be simplified and expressed as

$$\frac{2.5}{1 + \frac{5M}{EPr\ \delta^{+}}} \left[\ln \left[\frac{\delta^{+}\ EPr + 2.5}{30\ EPr + 2.5}\right] + \ln \left[\frac{\frac{M}{\delta^{+}} (30 - \frac{2.5}{EPr}) - 1}{\frac{M}{\delta^{+}} (\delta^{+} - \frac{2.5}{EPr}) - 1} \right] \right]$$

But since,

$$1 < 1 + \frac{5M}{EPr\ \delta^{+}} < 1 + \frac{(5)(1)}{(1)(3)(30)} = 1.0556$$

this factor may also be approximated as

$$1 + \frac{5M}{EPr\ \delta^+} \cong 1$$

which introduces an error of less than 6 percent in the third term of Eq. (28c) and a much smaller error in F_2.

Also, $\delta^+ EPr \geq 30\ EPr \geq 30(1)(30) = 90$

Hence 2.5 is neglected in comparison to $EPr\delta^+$ and 30 EPr. Since 2.5 is added to both the numerator and the denominator, the effect of dropping it disappears for all practical purposes.

With these simplifications the third term becomes:

$$2.5\ \ln\left[\frac{\delta^+}{30}\right] + 2.5\ \ln\left[\frac{\frac{M}{\delta^+}\left(30 - \frac{2.5}{EPr}\right) - 1}{\frac{M}{\delta^+}\left(\delta^+ - \frac{2.5}{EPr}\right) - 1}\right]$$

and Eq. (29c) can be re-written as:

$$\delta^+ > 30$$

$$F_2 = 5Pr + \frac{5}{E}\ln(1 + 5EPr) + 2.5\ \ln\left(\frac{\delta^+}{30}\right) + 2.5\ \ln\left[\frac{\frac{M}{\delta^+}\left(30 - \frac{2.5}{EPr}\right) - 1}{\frac{M}{\delta^+}\left(\delta^+ - \frac{2.5}{EPr}\right) - 1}\right]$$

term 1 term 2 term 3 term 4 (29)

The fourth term of this expression represents the correction due to the fact that $\tau_0 \neq \tau_v$. This term is negligible when the quality gradient $(\frac{dx}{dz})$ is not large. The calculation of the heat transfer coefficient is greatly simplified when this term is negligible, since the calculation of M depends on dx/dz which requires a laborious iteration. The effect of M should be included if, in Eq. (29):

$$\text{term } 4 \geq 0.05 \ (\text{term } 1 + \text{term } 2 + \text{term } 3)$$

or:

$$2.5 \ln\left[\frac{\frac{M}{\delta^+}\left(30 - \frac{2.5}{EPr}\right) - 1}{\frac{M}{\delta^+}\left(\delta^+ - \frac{2.5}{EPr}\right) - 1}\right] \geq 0.25 \left[Pr + \frac{1}{E}\ln(1 + 5EPr) + \frac{1}{2}\ln\left(\frac{\delta^+}{30}\right)\right]$$

Solving this inequality for M, one obtains:

$M \geq M_{crit} =$

$$\frac{(1 + 5EPr)^{\frac{0.1}{E}} \left(\frac{e^{0.1Pr}}{30^{0.05}}\right) (\delta^+)^{1.05} - \delta^+}{(1 + 5EPr)^{\frac{0.1}{E}} \frac{e^{0.1Pr}}{30^{0.05}} (\delta^+)^{1.05} - \frac{2.5}{EPr} (1 + 5EPr)^{\frac{0.1}{E}} \frac{e^{0.1Pr}}{30^{0.05}} (\delta^+)^{0.05} \left(30 - \frac{2.5}{EPr}\right)} \qquad (30)$$

Equation (30) gives the value of M for which an error of 5 percent results if term 4 of Eq. (29) is dropped. Since the Prandtl number is fixed for a given fluid and temperature, the value of δ^+ determines M_{crit}. To determine whether the fourth term of Eq. (29) may be neglected, one should calculate a test value of M from Eq. (25) with $\delta^+ > 30$ and compare this value to M_{crit} as determined from Eq. (30) or Fig. 4. Fig. 4 is a plot of M_{crit} versus δ^+ for several Prandtl numbers, with E taken as unity. When the fourth term may be neglected, Eq. (29c) reduces to the following:

$$\delta^+ > 30$$

$$F_2 = 5Pr + \frac{5}{E}\ln(1 + 5EPr) + 2.5\ln\left(\frac{\delta^+}{30}\right) \tag{31}$$

which is similar to the one presented by Kosky and Staub[15]. Otherwise, it is best to use Eq. (29) in its entirety.

From the definition of δ^+ and Re_ℓ:

$$\delta^+ = \frac{\delta\, u_\tau}{\nu} \tag{32}$$

$$Re_\ell = \frac{G(1 - x)\, D}{\mu_\ell} \tag{33}$$

Using continuity of mass the liquid Reynolds number may be written as:

$$Re_\ell = \frac{4}{\mu_\ell}\int_0^\delta \rho_\ell v_z\, dy = 4\int_0^{\delta^+} v_z^+\, dy^+ \tag{34}$$

Substituting Eq. (23) for v_z^+ into Eq. (34) yields:

$$\delta^+ < 5 \qquad Re_\ell = 2(\delta^+)^2 \tag{35a}$$

$$5 < \delta^+ < 30 \qquad Re_\ell = 50 - 32.2\delta^+ + 20\delta^+ \ln \delta^+ \tag{35b}$$

$$\delta^+ > 30 \qquad Re_\ell = -256 + 12\delta^+ + 10\delta^+ \ln \delta^+ \tag{35c}$$

Equations (35) may be approximated with an error of less than 4 percent by straight line segments on a log-log graph. Using these piecewise linear curve fits one can obtain δ^+ as an explicit function of Re_ℓ:

$$Re_\ell < 50 \;, \delta^+ = 0.7071\; Re_\ell^{0.5} \tag{36a}$$

$$50 < Re_\ell < 1125, \delta^+ = 0.4818\; Re_\ell^{0.585} \tag{36b}$$

$$Re_\ell > 1125, \delta^+ = 0.095\; Re_\ell^{0.812} \tag{36c}$$

Equation (36) may be substituted in Eq. (31) to yield F_2 as a function of two accessible parameters, Re_ℓ and Pr_ℓ:

$$Re_\ell < 50 \qquad F_2 = 0.707 Pr_\ell Re_\ell^{0.5} \tag{37a}$$

$$50 < Re_\ell < 1125 \qquad F_2 = 5Pr_\ell + 5\ln[1 + Pr_\ell(0.09636 Re_\ell^{0.585} - 1)] \tag{37b}$$

$$Re_\ell > 1125 \qquad F_2 = 5Pr_\ell + 5\ln(1 + 5Pr_\ell) + 2.5\ln(0.00313 Re_\ell^{0.812}) \tag{37c}$$

Equations (37a, b, c) are also presented graphically in Fig. 5 for ease of calculation.

Substituting Eqs. (2), (9), and (21) into Eq. (27) and solving for h_z:

$$h_z = \frac{1}{F_2}\,\rho_\ell c_\ell u_\tau = \frac{1}{F_2}\,\rho_\ell c_\ell [\frac{g_0}{\rho_\ell}\,\frac{D}{4}\,\frac{.090}{g_0}\,\frac{\mu_v^{0.2} G^{1.8} x^{1.8}}{\rho_v D^{1.2}}$$

$$[1 + 2.85\,[(\frac{\mu_v}{\mu_\ell})^{0.1}\,(\frac{1-x}{x})^{0.9}\,(\frac{\rho_v}{\rho_\ell})^{0.5}]^2]^{\frac{1}{2}} \tag{38}$$

or simplifying:

$$h_z = \frac{1}{F_2}\,0.15\,\sqrt{\frac{\rho_\ell}{v}}\,c_\ell \mu_v^{0.1}\,\frac{G^{0.9}}{D^{0.1}}\,x^{0.9}[1 + 2.85[\frac{\mu_\ell}{\mu_v})^{0.1}\,(\frac{1-x}{x})^{0.9}\,(\frac{\rho_v}{\rho_\ell})^{0.5}]^{0.523}] \tag{39}$$

Equation (39) may be rearranged in a more compact form by algebraic manipulations and the definition of χ_{tt}, Eq. (6), to yield:

$$\frac{Nu}{[\chi_{tt}^{-1} + 2.85\,\chi_{tt}^{-0.476}]} = \frac{0.15}{F_2}\,Pr_\ell Re_\ell^{0.9} \tag{40}$$

or equivalently:

$$\frac{NuF_2}{Pr_\ell Re_\ell^{0.9}} = F(\chi_{tt}) \tag{41}$$

→ where $$\Big[\,F(\chi_{tt}) \equiv 0.15\,[\chi_{tt}^{-1} + 2.85\,\chi_{tt}^{-0.476}]\,\Big] \tag{42}$$

Equation (40) is a good working equation since the right side is a function only of Re_ℓ and Pr_ℓ (assuming the fourth term of Eq. (29) may be neglected as previously explained). The value of Eq. (41) is in correlating condensation data for different fluids or conditions. In this case the heat transfer parameter $(NuF_2/Pr_\ell Re_\ell^{0.9})$ may be plotted as a function of only one variable: χ_{tt}.

The average overall heat transfer coefficient may be calculated for the case of a constant temperature difference $(T_{vapor} - T_{wall})$. If the temperature difference is not constant along the condenser length, as is usually the case, then an average heat transfer coefficient is of little use in determining the overall heat transfer or condenser length since:

$$q/A)_{avg} = (h\ \Delta T)_{avg} \neq h_{avg}\ \Delta T_{avg}$$

Consider the heat transfer through the liquid layer:

$$dq = -\ Wh_{fg}\ dx = h_z\ \Delta T\ \pi D\ dz \tag{43}$$

Rearranging and integrating for constant ΔT yields:

$$\int_{x_e}^{1} \frac{dx}{h_z} = \frac{\Delta T\ \pi D L_e}{Wh_{fg}} \tag{44}$$

Where x_e and L_e are the exit quality and length. By definition:

$$h_{avg} = \frac{1}{L_e} \int_0^{L_e} h_z \, dz$$

and $$q = h_{avg} \, \Delta T \, \pi D L_e = W h_{fg} (1 - x_e) \tag{45}$$

Combining Eqs. (36) and (37):

$$\frac{1}{h_{avg}} = \frac{1}{(1 - x_e)} \int_{x_e}^{1} \frac{dx}{h_z} \tag{46}$$

Calculation Procedure for Analytical Results

Analytical heat transfer and pressure drop results were calculated and compared with the experimental results with the same refrigerant mass flux, saturation temperature, temperature difference, and tube diameter. The calculations were accomplished in the following manner:

1. Using the computer, the refrigerant properties were evaluated at the average vapor temperature from a piecewise linear curve fit of tabulated property values [16,17].

2. The quality was divided into 5 per cent increments starting at 1.00 and decreasing to 0.05. The heat transfer coefficient and pressure drop were calculated at each increment.

3. X_{tt} and Re_{ℓ} were calculated from eqs. (6) and (33). F_2 was evaluated using eq. (37) or Fig. 5. (The inherent assumption in eq. (37) that $M = 0$ will be checked later in step 11.)

4. The Nusselt number (Nu) and heat transfer coefficient (h_z) were calculated from eq. (41).

5. The friction pressure gradient was determined from eq. (9).

6. Since the condenser tube was horizontal, the gravity pressure gradient was not calculated. For inclined tubes, the gravity pressure gradient may be determined from eqs. (10) and (13).

7. The quality gradient $(\frac{dx}{dz})$ was calculated from eq. (43): $\frac{dx}{dz} = - \frac{h_z \, \Delta T \, \pi D}{W \, h_{fg}}$, using the values of h_z from step 4.

8. The momentum pressure gradient was evaluated using eq. (14).

9. The total pressure gradient was determined from eq. (1).

10. δ^+ was calculated from eq. (36).

11. For $\delta^+ > 30$, τ_o and u_τ were determined from eqs. (2) and (21). In addition F_o was calculated from eq. (16) with β obtained from Fig. 3. M was then calculated using eq. (25).

12. M as calculated in step 10 was compared to M_{crit} as obtained from eq. (30) or Fig. 4. If $M > M_{crit}$ then F_2 was recalculated using eq. (29) and (36) instead of eq. (37). The heat transfer coefficient was recalculated using the new value of F_2 in eq. (41).

13. The increment of tube length (Δz) required for a 5 per cent quality change was determined from eq. (43):

$$\Delta z = \frac{W\ h_{fg} (0.05)}{h_z\ \Delta T\ \pi D} .$$

As discussed in the following chapter, the iterative steps 10 through 13 are not required if the quality gradient is small. In particular, these steps were not needed for analytical calculations based on the experimental data. This means that only steps 1 through 4 are needed to calculate the heat transfer coefficient for low to moderate condensation rates.

RESULTS

Sixteen experimental runs were made with refrigerant R-12 and eleven runs were made with refrigerant R-22 for saturation temperatures between 77 to 137°F and mass fluxes between 1.19×10^5 lbm/hr ft^2 and 1.13×10^6 lbm/hr ft^2. The absolute value of the maximum heat balance error for all runs was 7 percent. The data are presented in Appendix 1. Figures 9 through 23 show the experimental and analytical heat transfer coefficients while Figures 24 through 35 show the pressure gradient data. Some experimental pressure gradient data (runs 3, 4, 6, and 19) were omitted, because the sum of the individually measured pressure drops differed appreciably (>15 percent) from the total pressure drop. Refrigerant R-12 was used for runs 1 through 16, and refrigerant R-22 was used for runs 17 through 27. Analytical values of the local heat transfer coefficients and pressure gradients were obtained using the procedure outline in the proceeding section. One version of a computer program used for these calculations is presented in Appendix 2.

It is important to know how often term 4 of Eq. (29) which includes the effect of M was used. The ability to neglect this term with minimal inaccuracy greatly simplifies the calculations. The effect of M was important only 8 of the 27 runs, and then only for qualities less than 0.10 where the annular model is not applicable anyway. Previous data obtained by Bae [12] for a 1/2 in. I. D. tube were also checked: the term involving M was even less important for Bae's data. Hence, one can neglect term 4 of Eq. (29) for conditions similar to the experimental runs of Bae and the present authors. For higher condensation rates (higher heat fluxes and quality gradients) this term becomes important and has the ultimate effect of lowering heat transfer coefficient. In these cases, Eq. (29) should be used in its entirety.

In the derivation of the heat transfer coefficient, no restrictions were placed on the position of the condenser tube. Although in the present work data were determined from measurements with a horizontal tube, this analysis has an applicability to inclined tubes. The value of E (ratio of eddy conductivity to eddy viscosity) was taken to be 1.0 for the curves of Figures 9 through 23. Calculations with E values of 1.1 and 1.4 were also compared to experimental data, but no definite trends were observed.

Since the analysis was developed for annular flow, departures from this flow regime are presently examined. When the mass flux of the refrigerant vapor exceeded 500,000 lbm/hr ft^2 there was appreciable entrainment of liquid in the first portion of the condenser tube. Physically this occurred because the vapor had a sufficiently high velocity to pick liquid up off the wall and transport it as droplets in the vapor core. At these high mass fluxes, the thickness of the liquid layer decreased due to entrainment, and consequently, the heat transfer coefficient increased. Since the present analysis assumes that annular film condensation exists and that all of the liquid is on the tube wall, the analytical predictions were below the experimental data in this misty flow regime. This effect is shown by Figures 15, 16, 17, 22 and 23. Entrainment usually occurs only in the inlet region of the condenser tube, because the vapor velocity progressively decreases as additional condensation occurs. The existence of entrainment was also substantiated by plotting the experimental runs on a Baker flow regime map [21] as shown in Figure 6, and also by high speed photographs through the glass sight tube.

With the exception of high qualities and mass fluxes, the liquid annulus was usually thicker at the bottom of the tube than at the top. However, the analytical predictions compared well with the experimental data, because a compensating effect existed between the increased heat transfer in the upper portion and decreased heat transfer in the lower portion. At qualities of less than 0.10, the flow was observed to be in the slug flow regime. Experimental data obtained at low qualities (runs 1, 6, 8, 10, and 24 on Figures 9, 11, 12, 13, and 22) show good agreement with the analytical predictions in the neighborhood of 0.10 quality. At qualities appreciably below 0.10, a linear extrapolation between the present heat transfer equation (Eqs. 39, 40, or 41) at $x = 0.10$ and a single phase heat transfer equation gives a good estimate of the heat transfer coefficient.

On the basis of Eq. (41), all of the experimental data for refrigerants R-12 and R-22 were reduced using the non-dimensional parameters $\mathrm{Nu}\ F_2/\mathrm{Pr}_\ell \mathrm{Re}_\ell^{0.9}$ and $F(\chi_{tt}) \equiv 0.15\ [\chi_{tt}^{-1} + 2.85\ \chi_{tt}^{-0.476}]$. These data (approximately 160 data points) are presented in Fig. 7 along with the predicted values from the annular flow model (the straight line). Previous data from Bae [12] for R-22 are shown on a similar plot in Fig. 8. As observed from Figures 7 and 8, these non-dimensional parameters correlate a wide range of data very well. The experimental data and analysis are in excellent agreement for $F(\chi_{tt}) < 2$ (or $\chi_{tt} < 0.155$). For $F(\chi_{tt}) > 2$ the data are somewhat higher than the analysis predicts. Consequently, these data are represented better by the dotted line of Fig. 7, which may be expressed as:

$$\frac{\mathrm{Nu}\ F_2}{\mathrm{Pr}_\ell \mathrm{Re}_\ell} = [F(\chi_{tt})]^{1.15} \tag{47}$$

One of the reasons for the higher value of $\frac{Nu\ F_2}{Pr_\ell Re_\ell^{0.9}}$ when $\chi_{tt} > 2$ is the entrainment effect previously discussed. Even for $F(\chi_{tt}) > 2$ the non-dimensional parameters correlate the data well. This indicates that the two curves drawn through the data points of Fig. 7 should be a good design criterion for a wide range of conditions and flow regimes.

CONCLUSIONS

1. For the practical range of refrigerant condenser operating conditions the simplified analysis developed here is applicable.

2. Recommended design equations for the local heat transfer coefficient in refrigerant condensers are as follows:

$$0.1 < F(\chi_{tt}) < 1 \qquad \frac{\mathrm{Nu}\, F_2}{\mathrm{Pr}_\ell \mathrm{Re}_\ell} = F(\chi_{tt}), \qquad \pm\ 15\%$$

$$1 < F(\chi_{tt}) < 15 \qquad \frac{\mathrm{Nu}\, F_2}{\mathrm{Pr}_\ell \mathrm{Re}_\ell} = [F(\chi_{tt})]^{1.15}, \ \pm\ 15\%$$

where F_2, χ_{tt} and $F(\chi_{tt})$ are given by Eqs. (37), (6) and (42).

3. Pressure drop may be calculated by Eq. (1) with Eqs. (9), (10) and (14).

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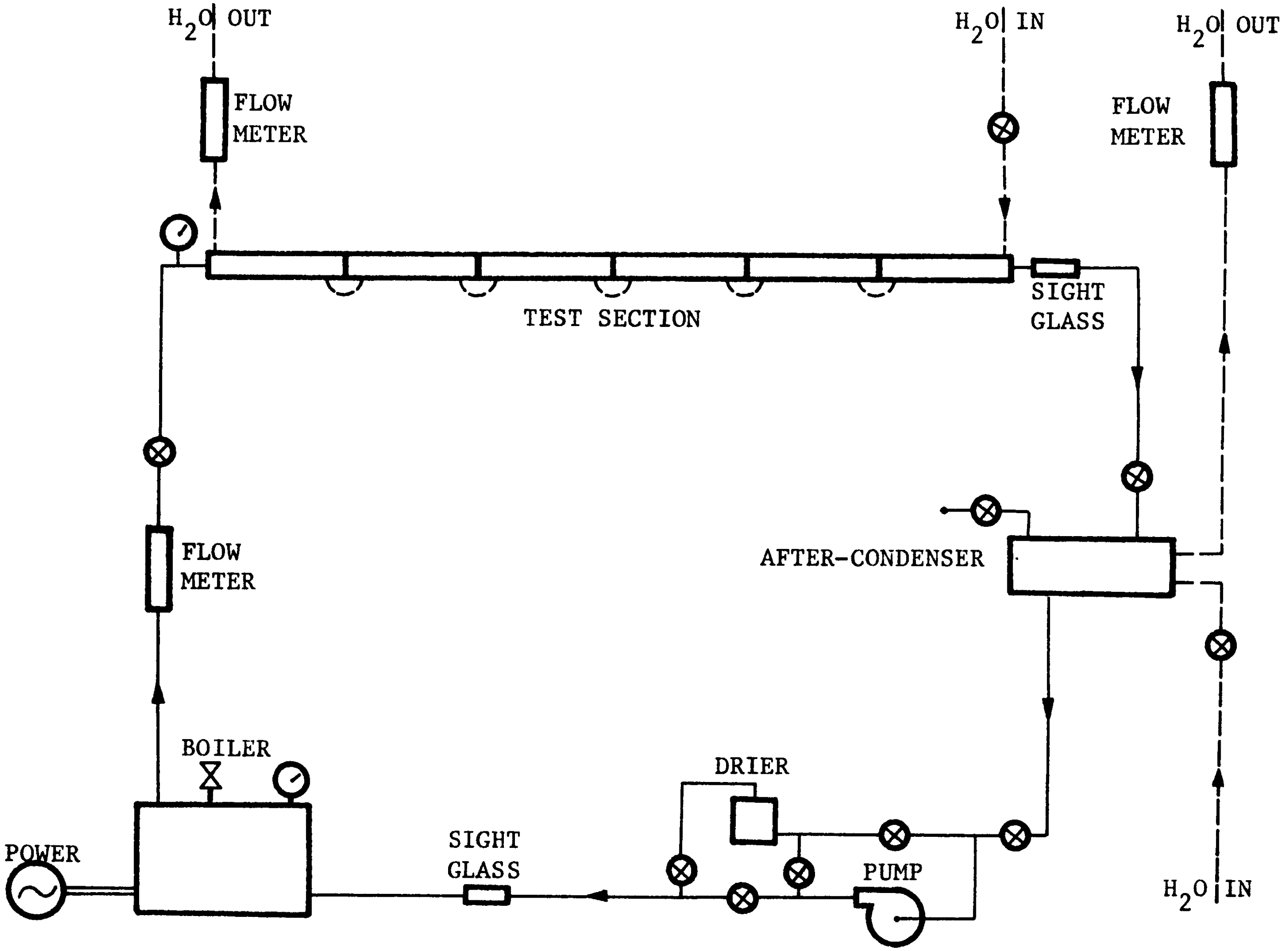
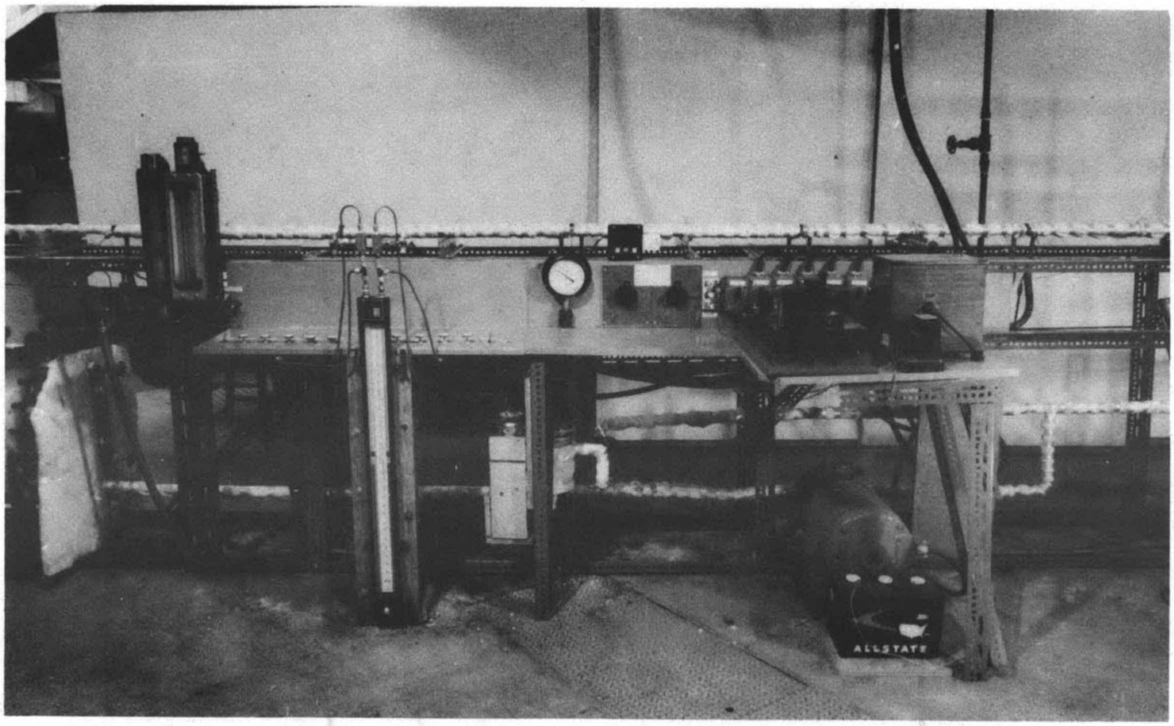
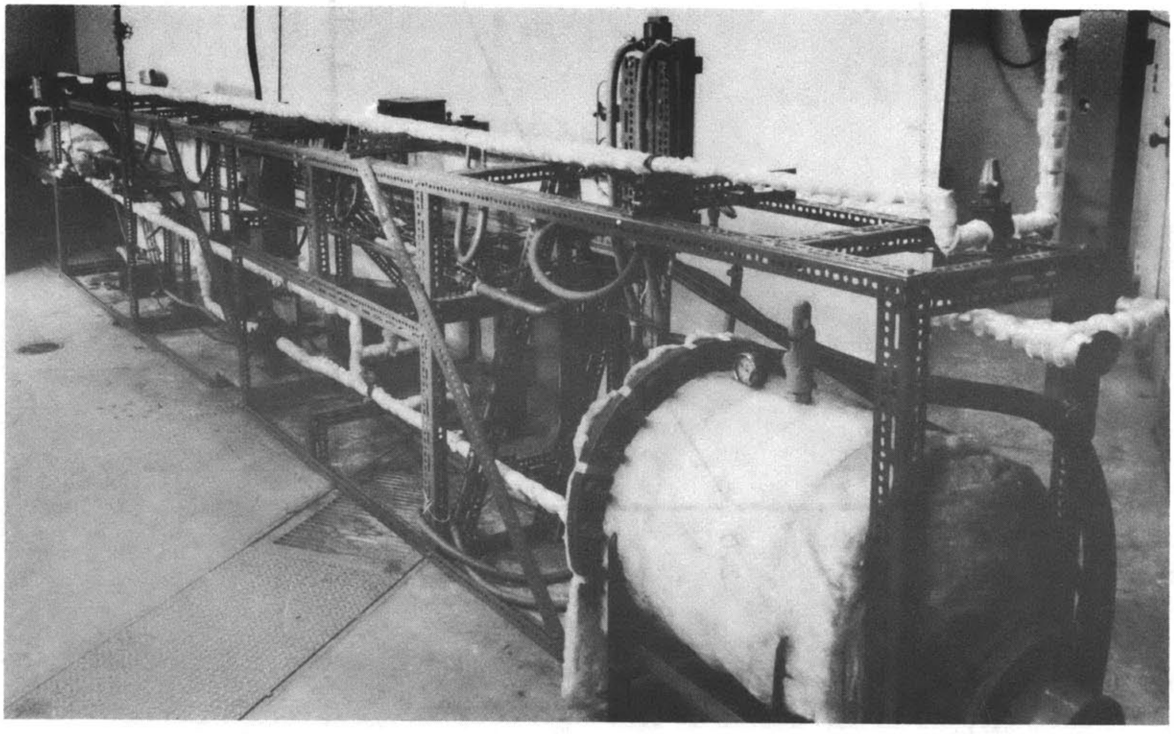


FIGURE 1 SCHEMATIC DIAGRAM OF APPARTUS



FRONT VIEW



REAR VIEW

FIGURE 2 EXPERIMENTAL APPARATUS

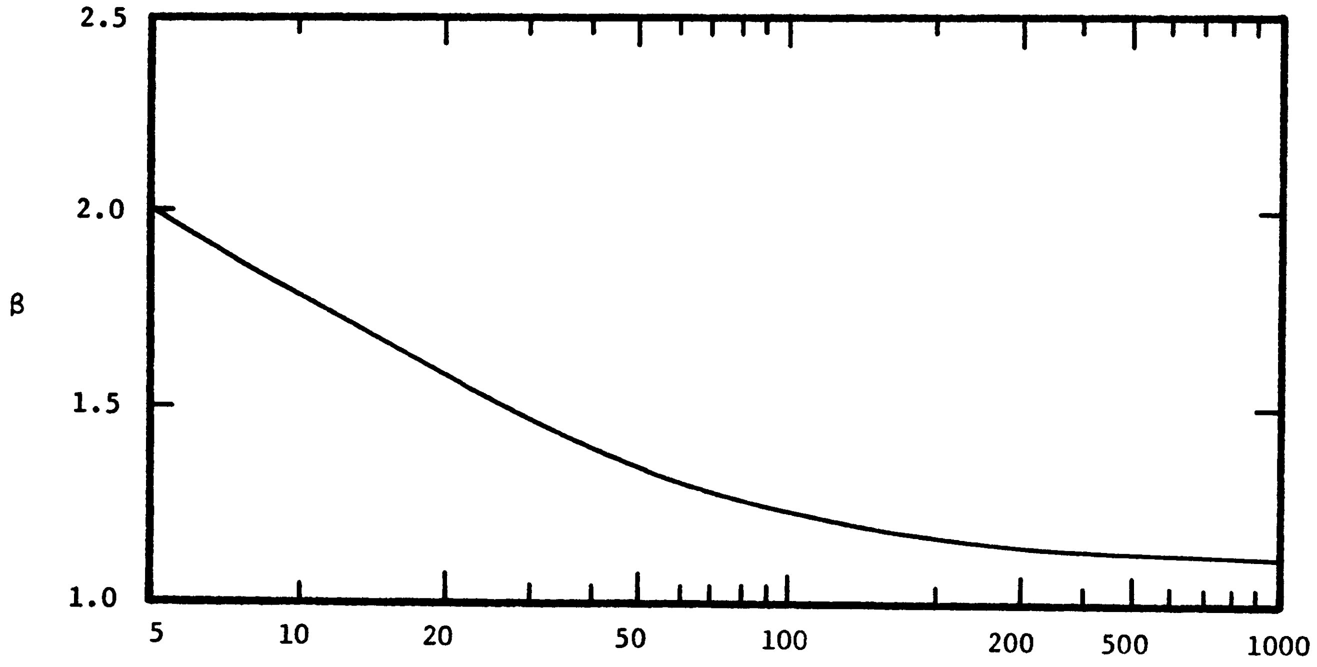


FIGURE 3 GRAPH OF β VERSUS δ^+

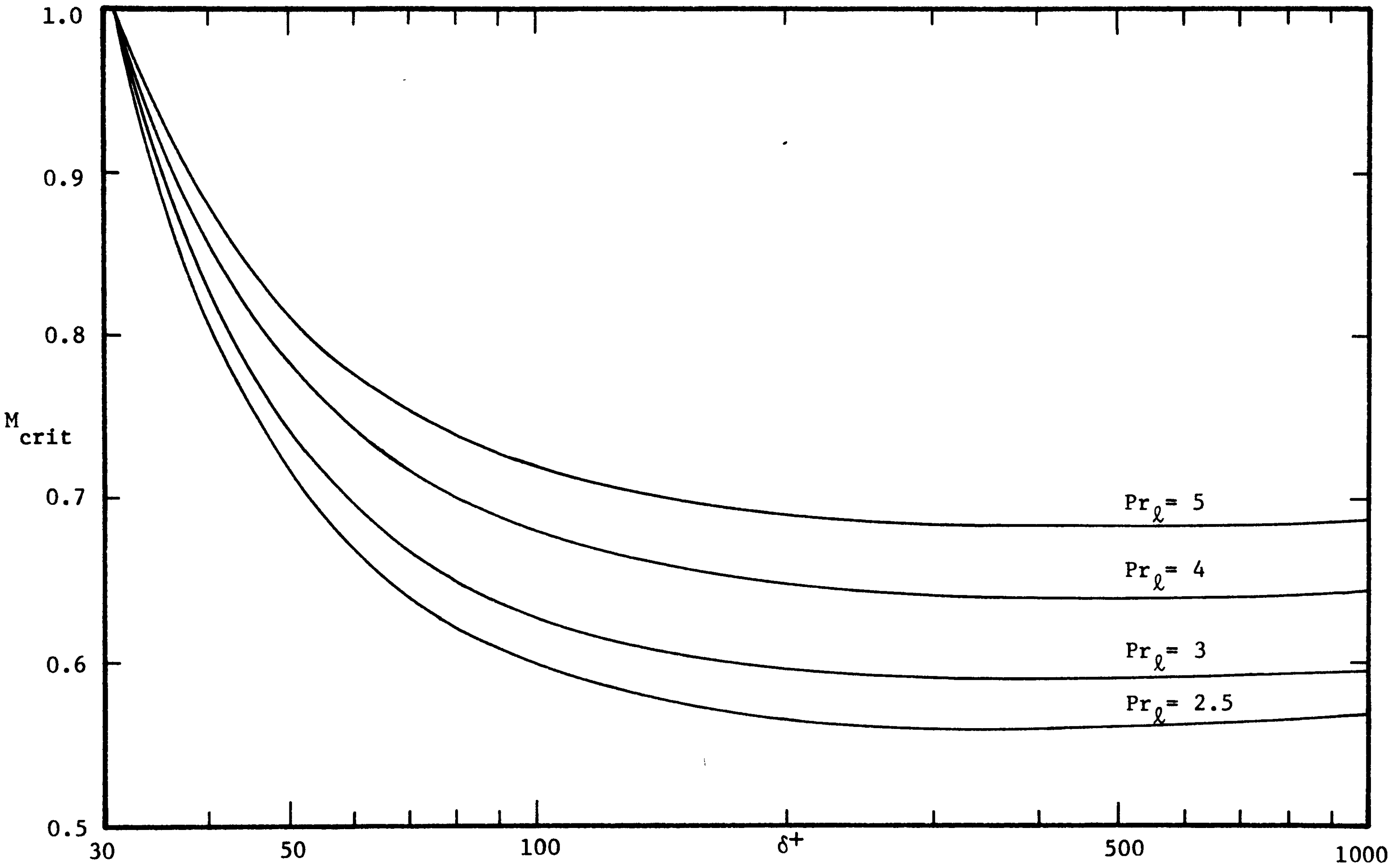


FIGURE 4 M_{crit} VERSUS δ^+ AT CONSTANT PRANDTL NUMBER

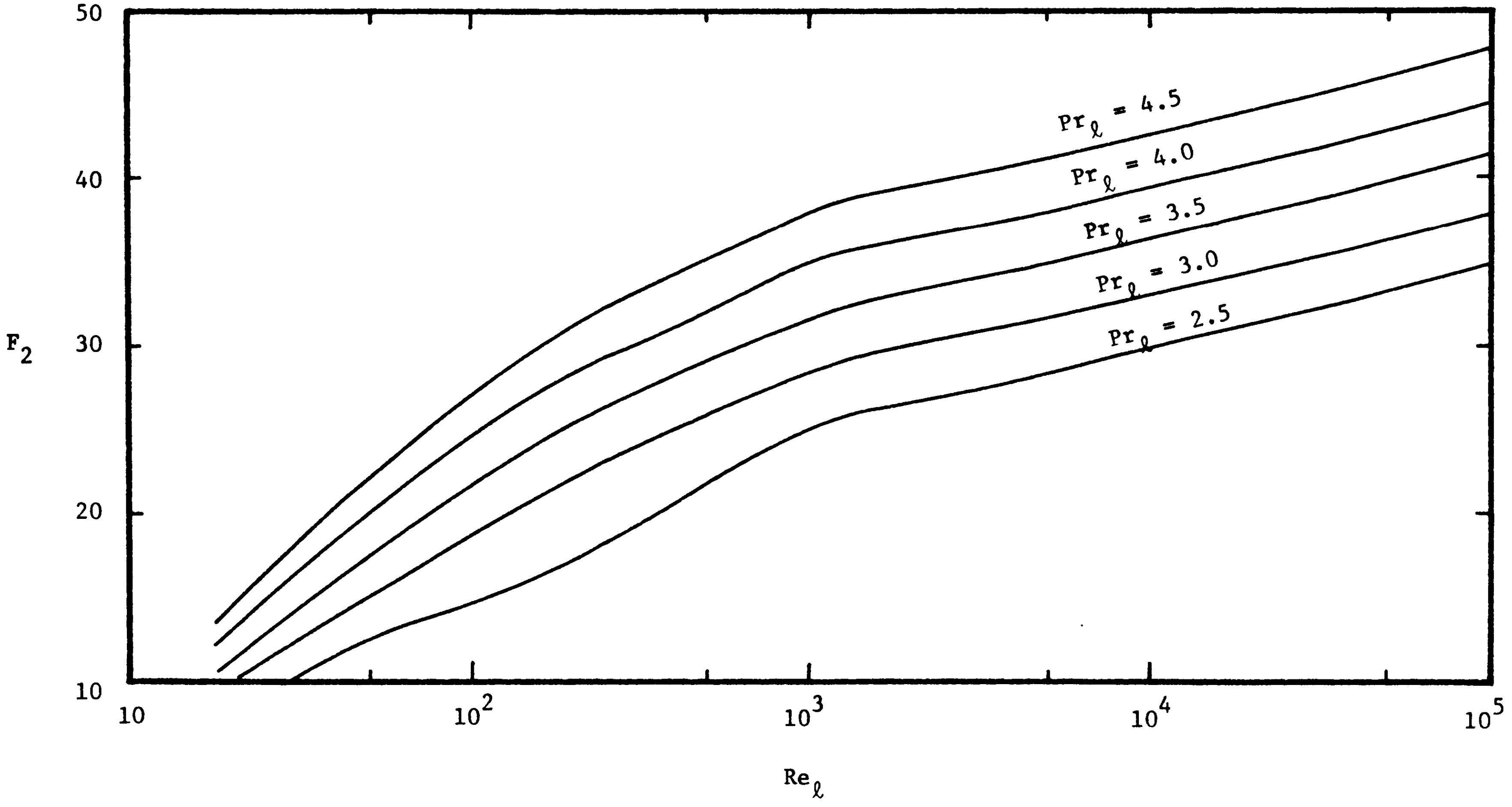


FIGURE 5 GRAPH OF F_2 VERSUS Re_ℓ AT CONSTANT Pr_ℓ

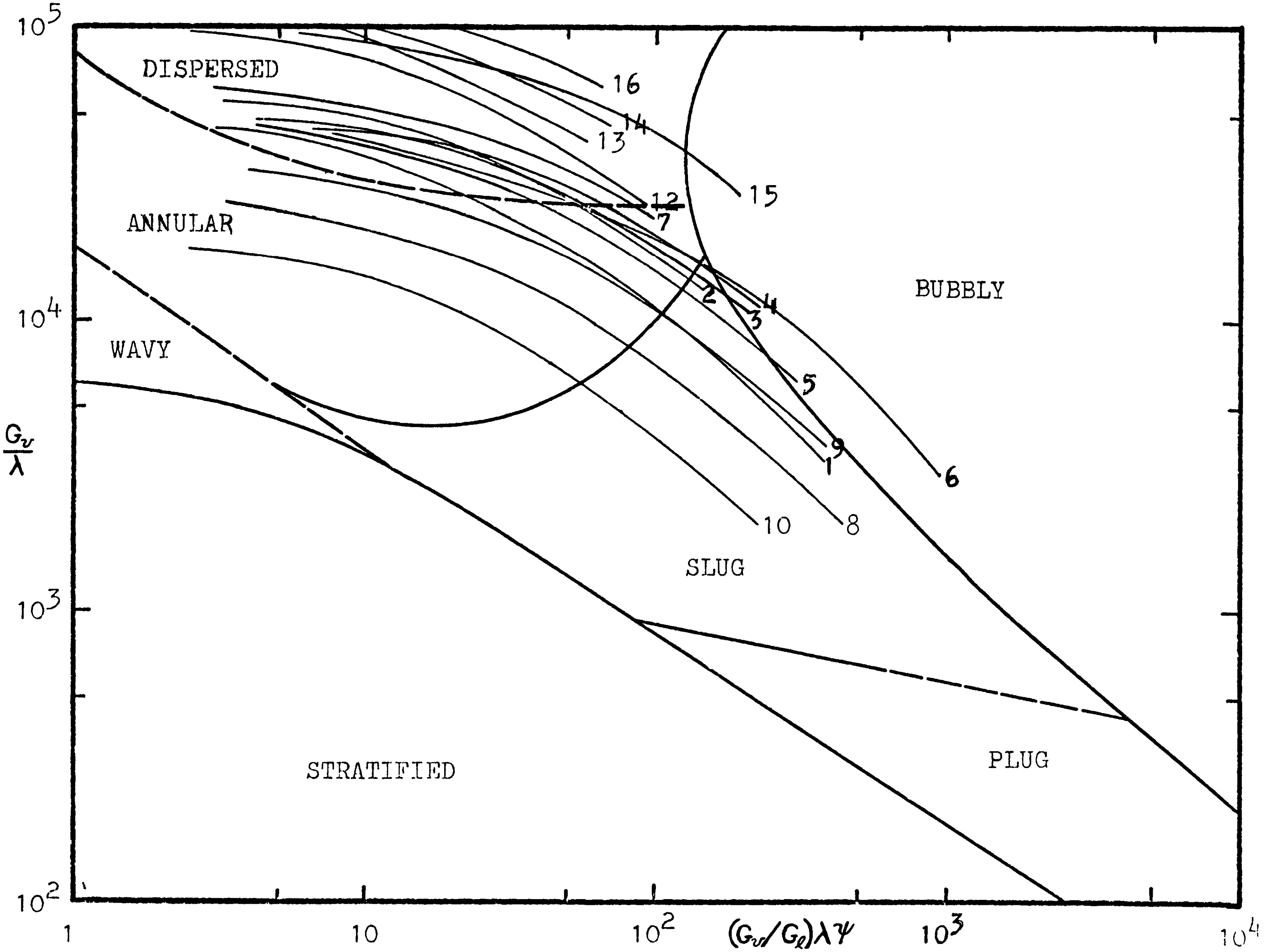


FIGURE 6 BAKER FLOW REGIME MAP OF R-12 RUNS

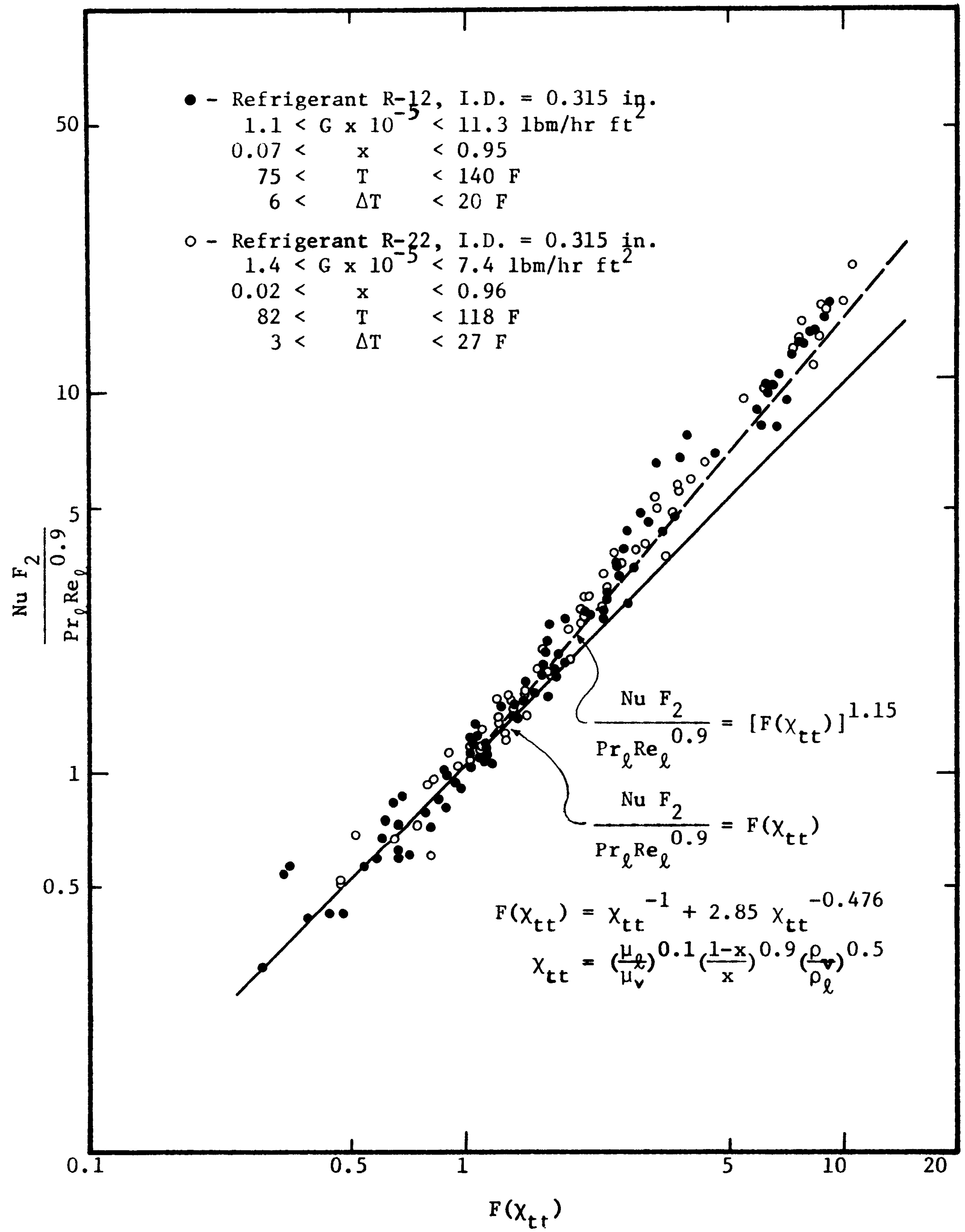


FIGURE 7 COMPARISON OF ANALYSIS AND PRESENT CONDENSATION DATA

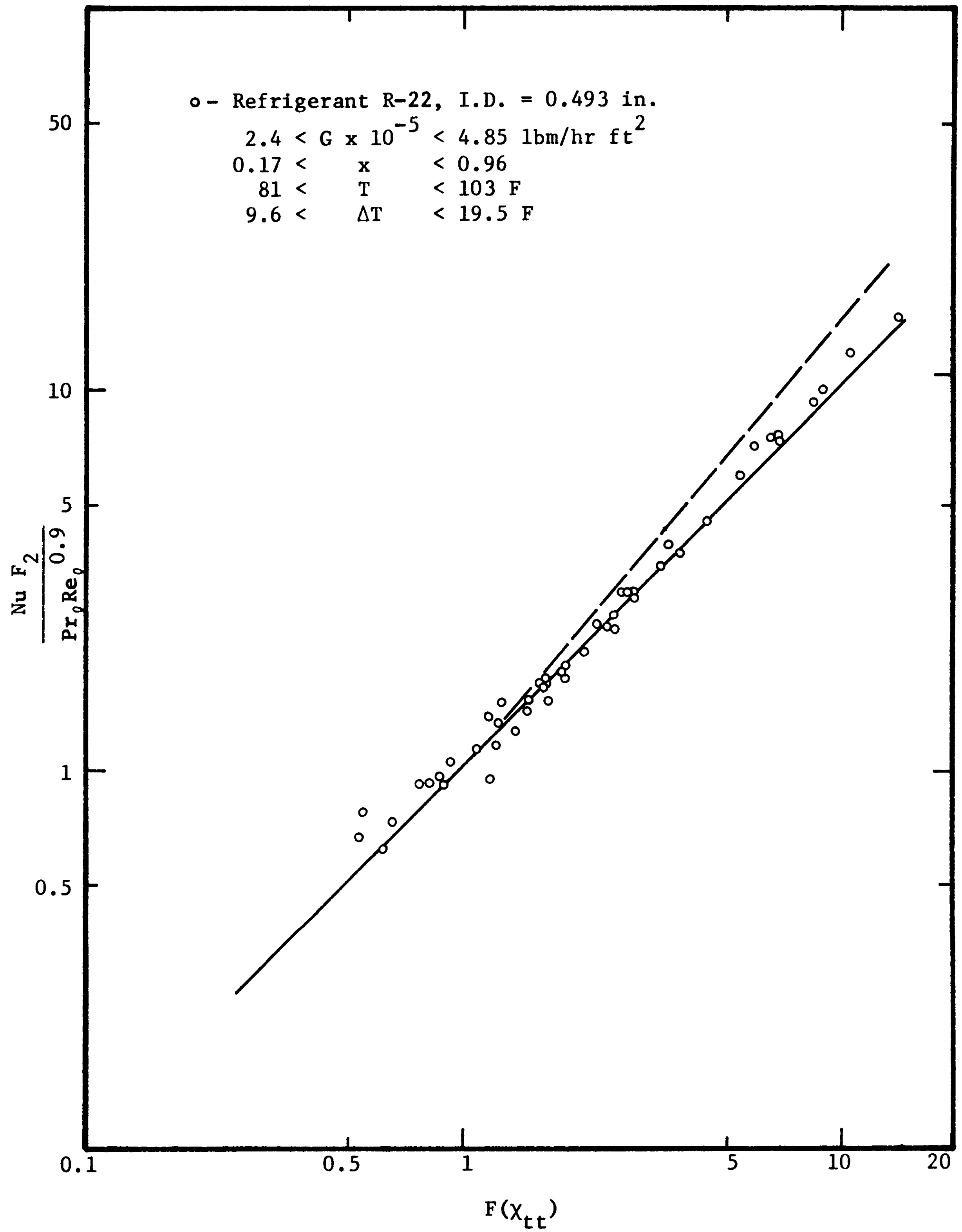


FIGURE 8 COMPARISON OF ANALYSIS AND BAE'S CONDENSATION DATA

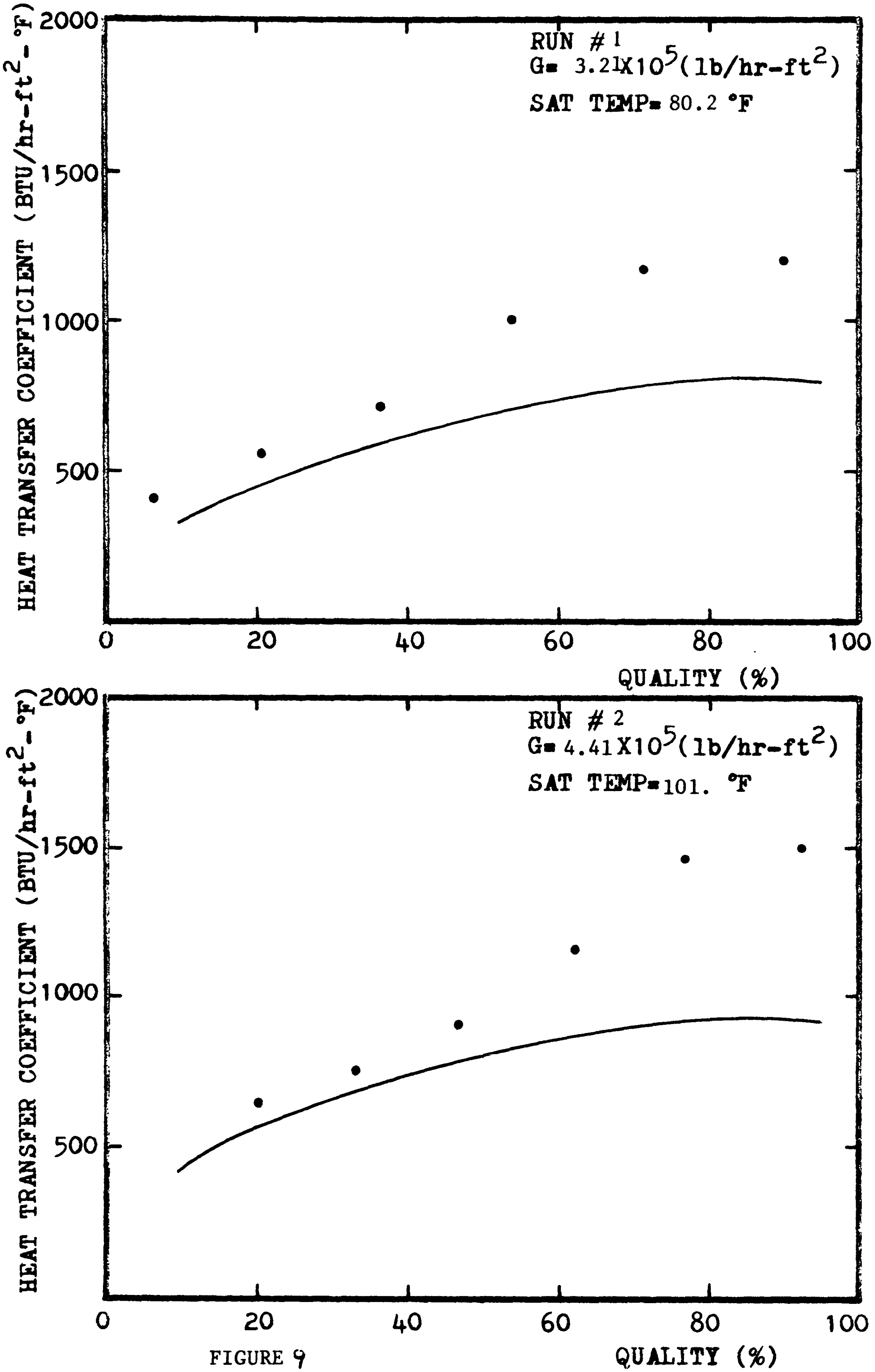

RUN # 1
G= 3.21X10^5(lb/hr-ft^2)
SAT TEMP= 80.2 °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2- °F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)
RUN # 2
G= 4.41X10^5(lb/hr-ft^2)
SAT TEMP=101. °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2- °F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)

FIGURE 9

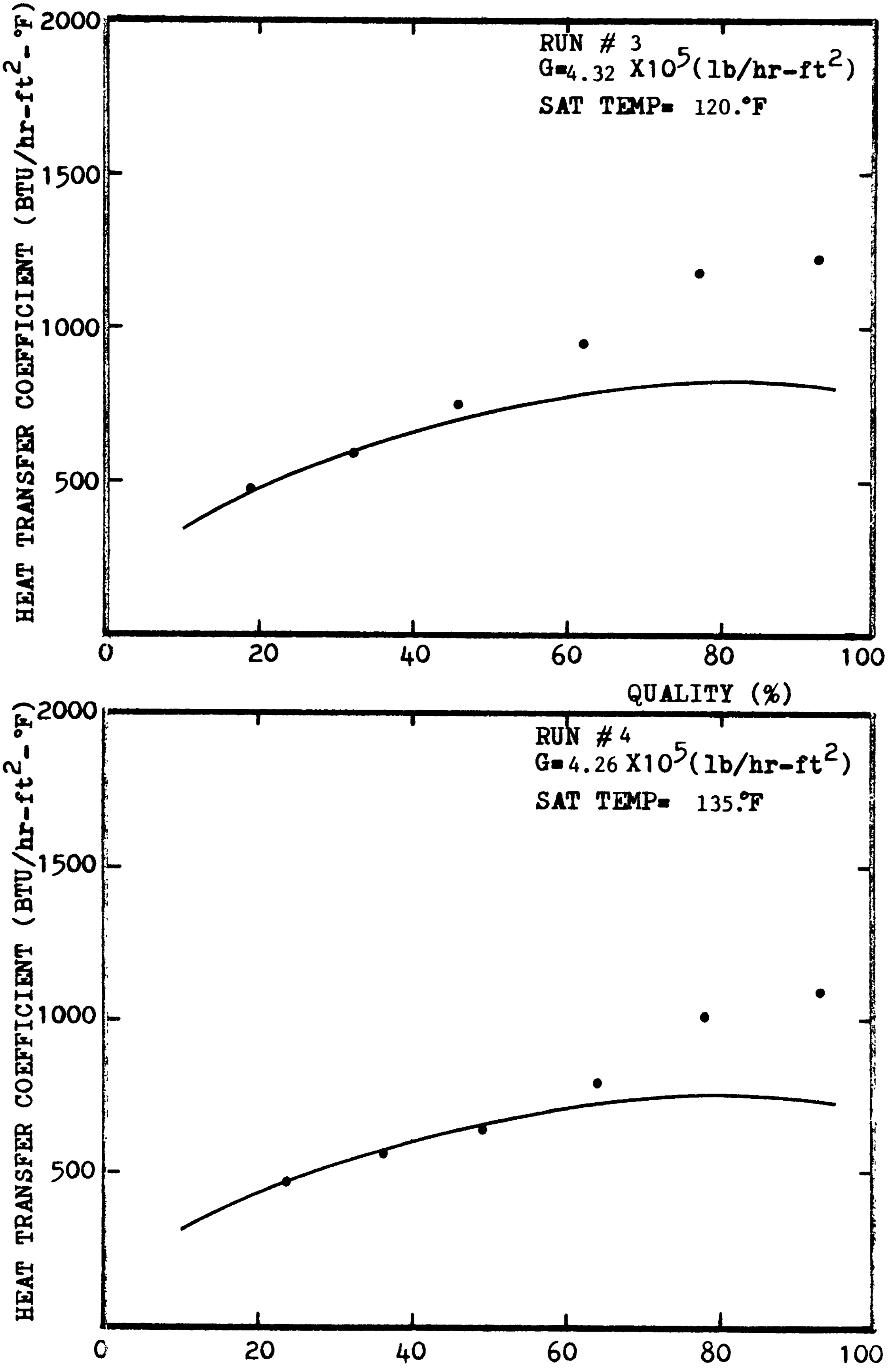

RUN # 3
G=4.32 X10^5(lb/hr-ft^2)
SAT TEMP= 120.°F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)
RUN # 4
G=4.26 X10^5(lb/hr-ft^2)
SAT TEMP= 135.°F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)

FIGURE 10

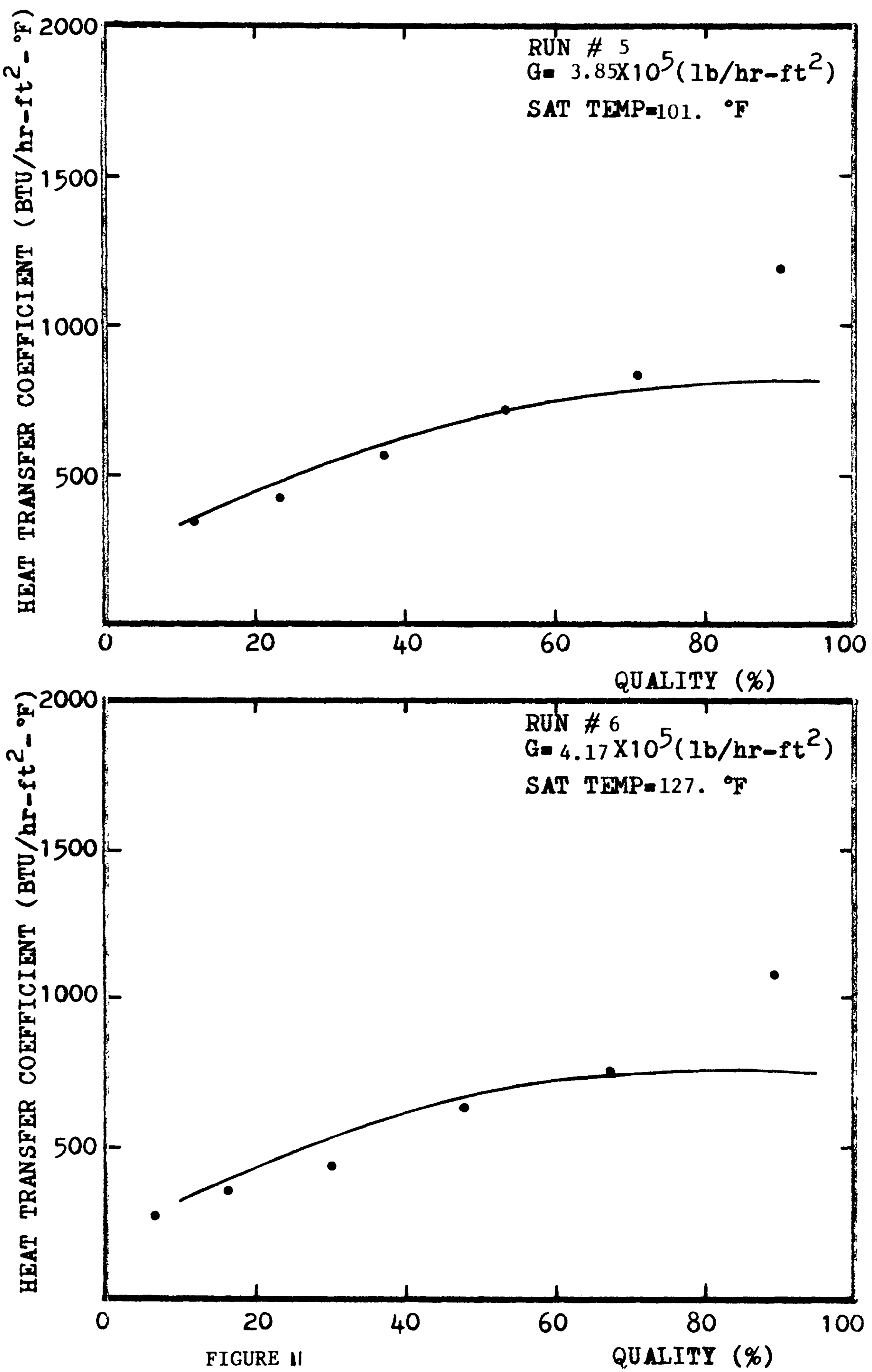

HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
RUN # 5
G= 3.85X10^5(lb/hr-ft^2)
SAT TEMP=101. °F
0
20
40
60
80
100
QUALITY (%)
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
RUN # 6
G= 4.17X10^5(lb/hr-ft^2)
SAT TEMP=127. °F
0
20
40
60
80
100
QUALITY (%)

FIGURE 11

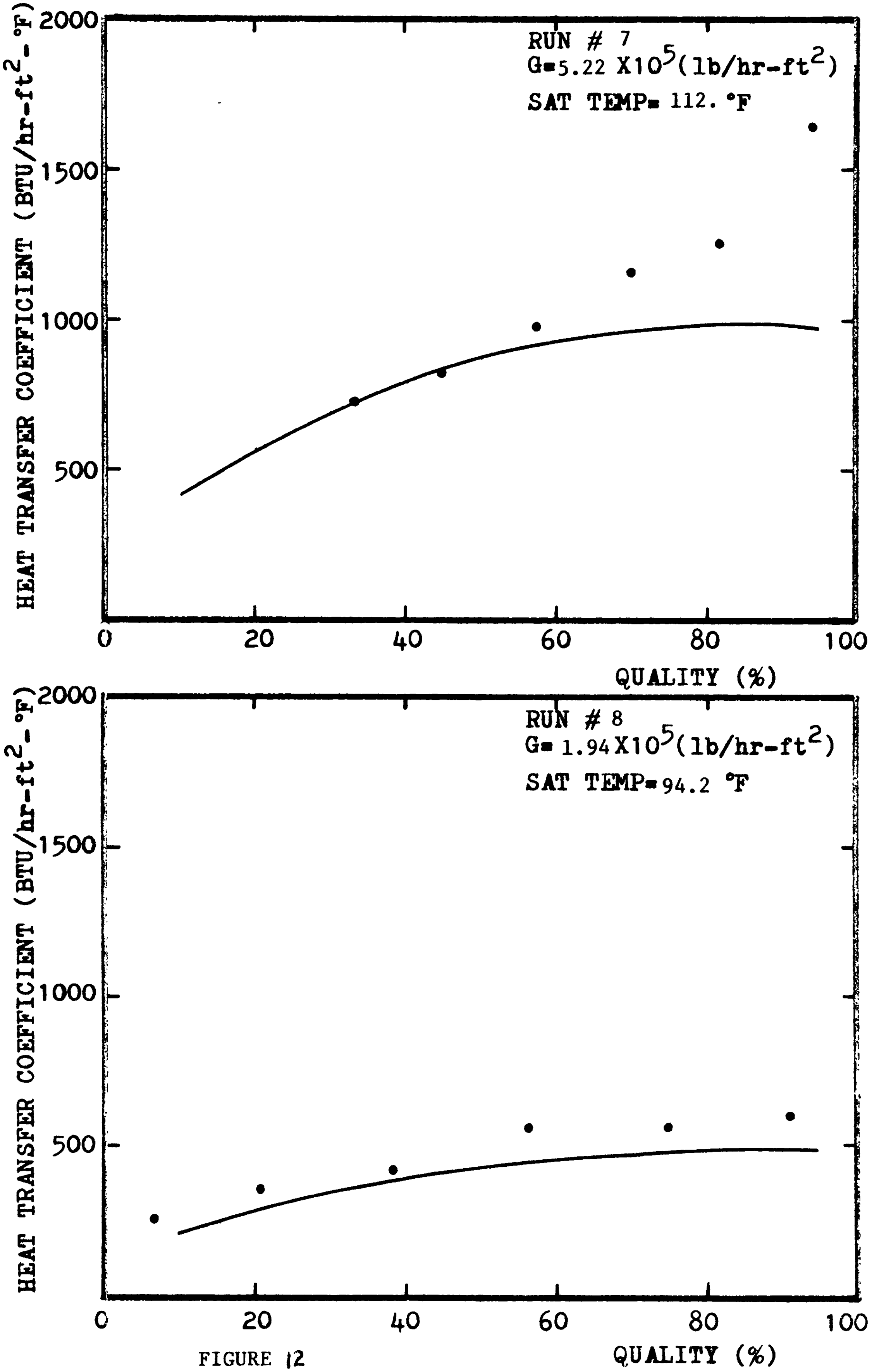

RUN # 7
G=5.22 X10^5(lb/hr-ft^2)
SAT TEMP= 112. °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)
RUN # 8
G= 1.94X10^5(lb/hr-ft^2)
SAT TEMP=94.2 °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)

FIGURE 12

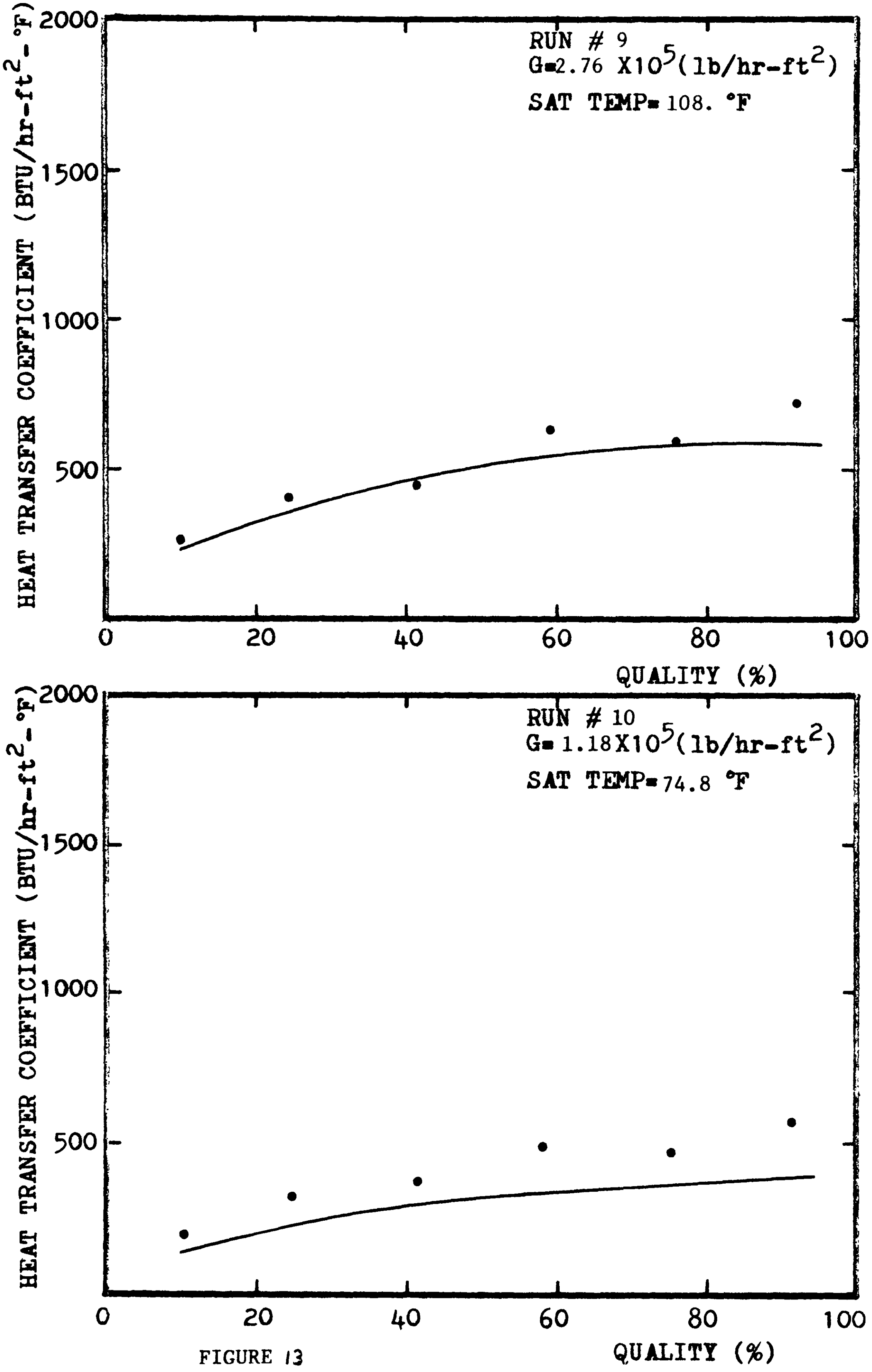
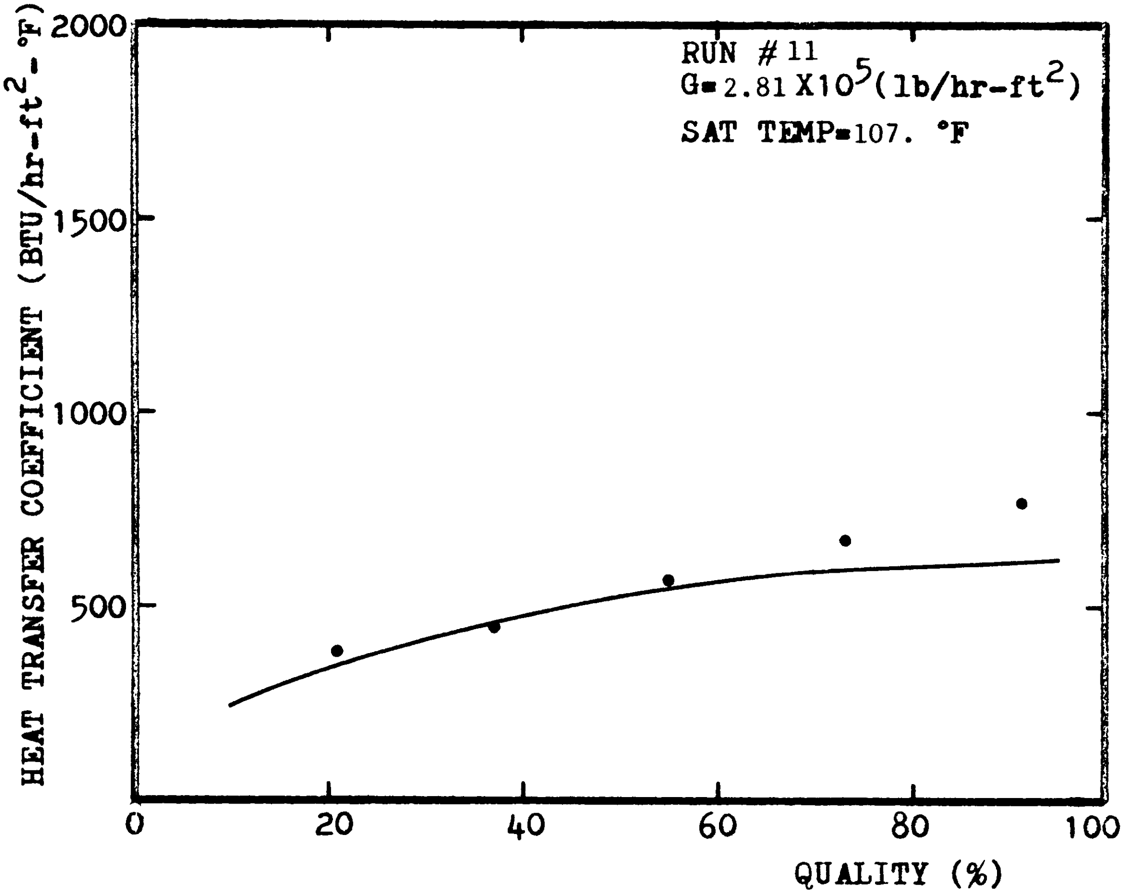

HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)
RUN # 9
G=2.76 X10^5(lb/hr-ft^2)
SAT TEMP= 108. °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)
RUN # 10
G= 1.18X10^5(lb/hr-ft^2)
SAT TEMP=74.8 °F

FIGURE 13


RUN # 11
G= 2.81 X10^5 (lb/hr-ft^2)
SAT TEMP= 107. °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2- °F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)

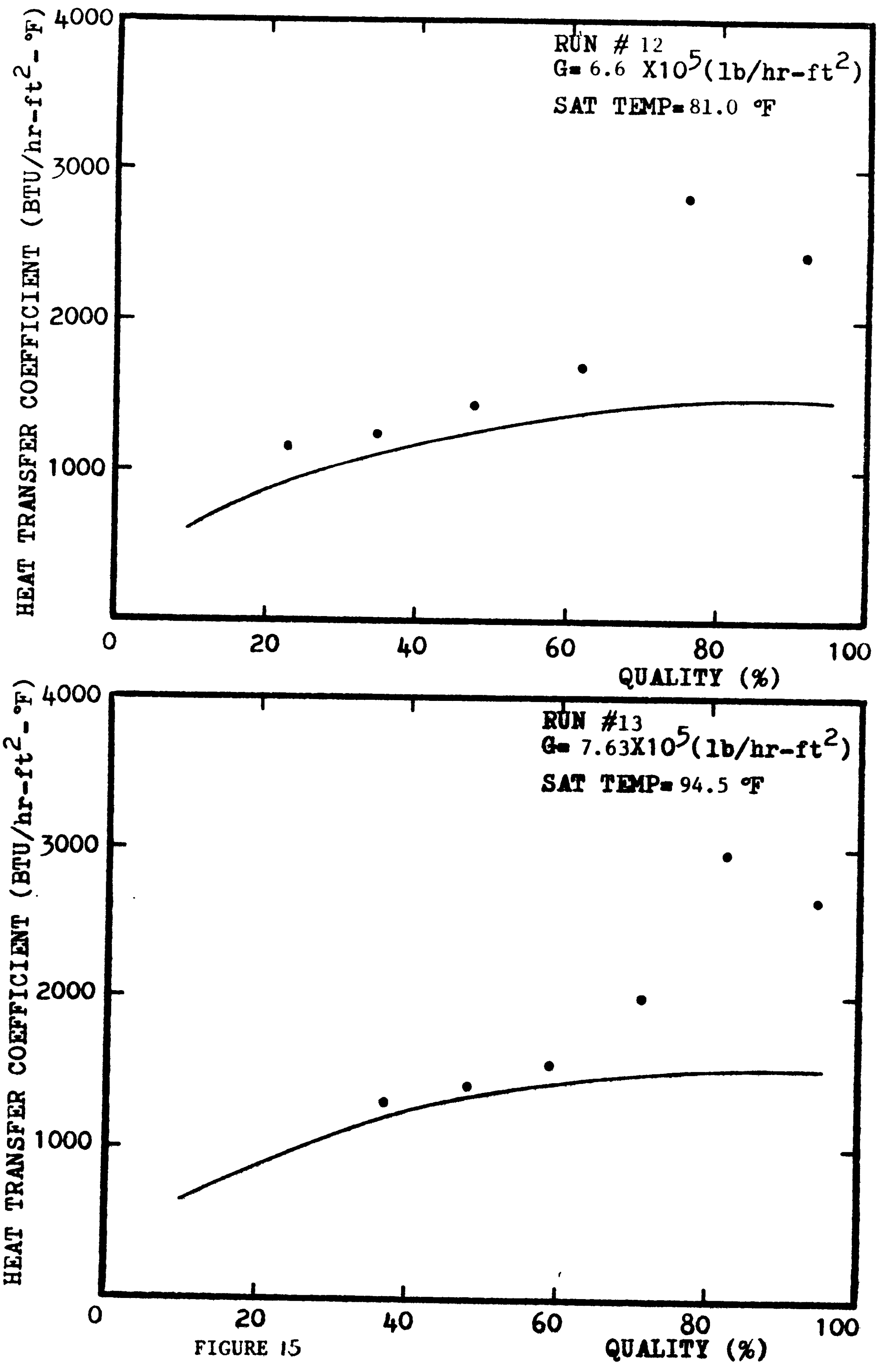

HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
4000
3000
2000
1000
0
20
40
60
80
100
QUALITY (%)
RUN # 12
G= 6.6 X10^5(lb/hr-ft^2)
SAT TEMP= 81.0 °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
4000
3000
2000
1000
0
20
40
60
80
100
QUALITY (%)
RUN #13
G= 7.63X10^5(lb/hr-ft^2)
SAT TEMP= 94.5 °F

FIGURE 15

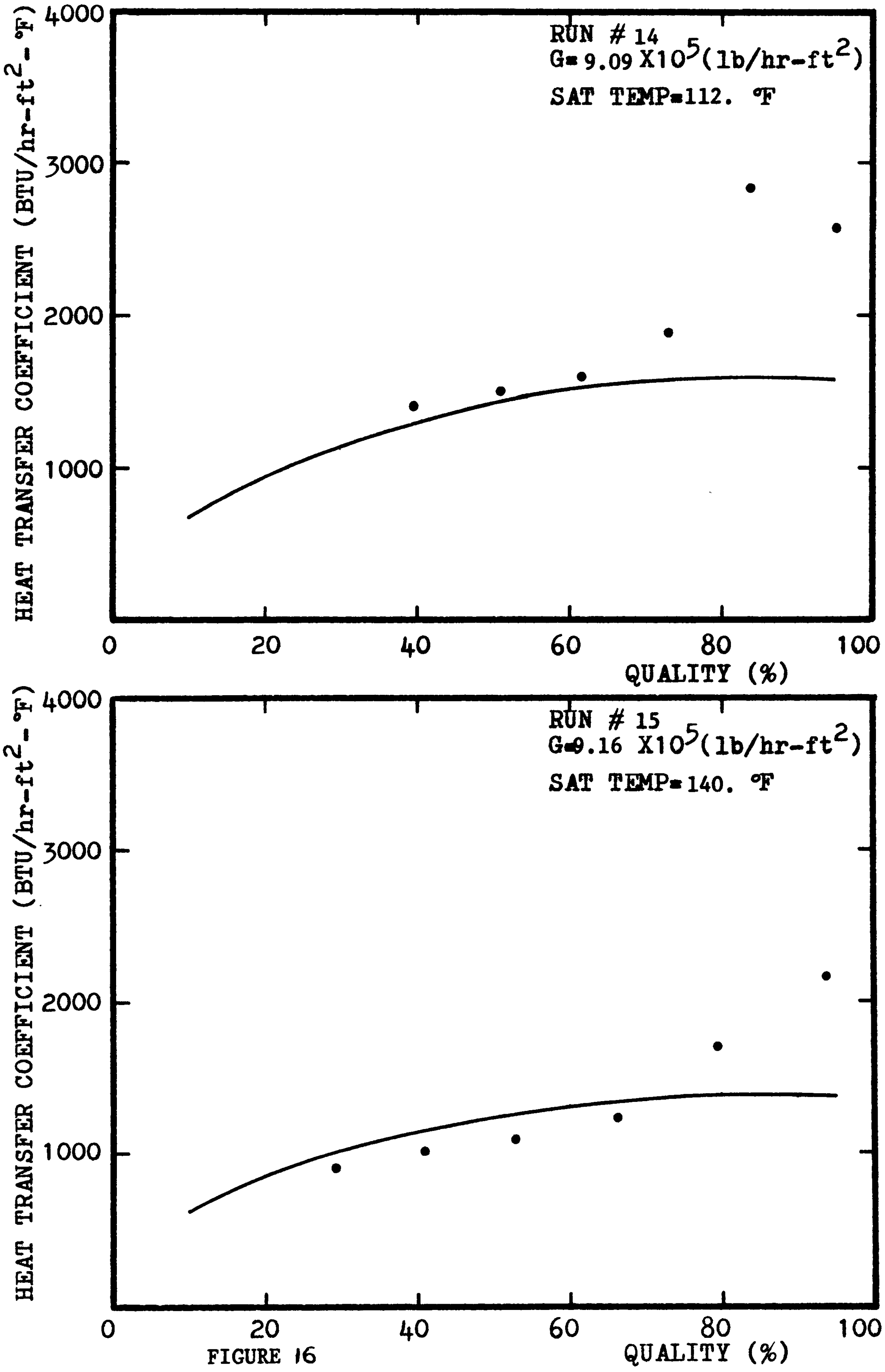
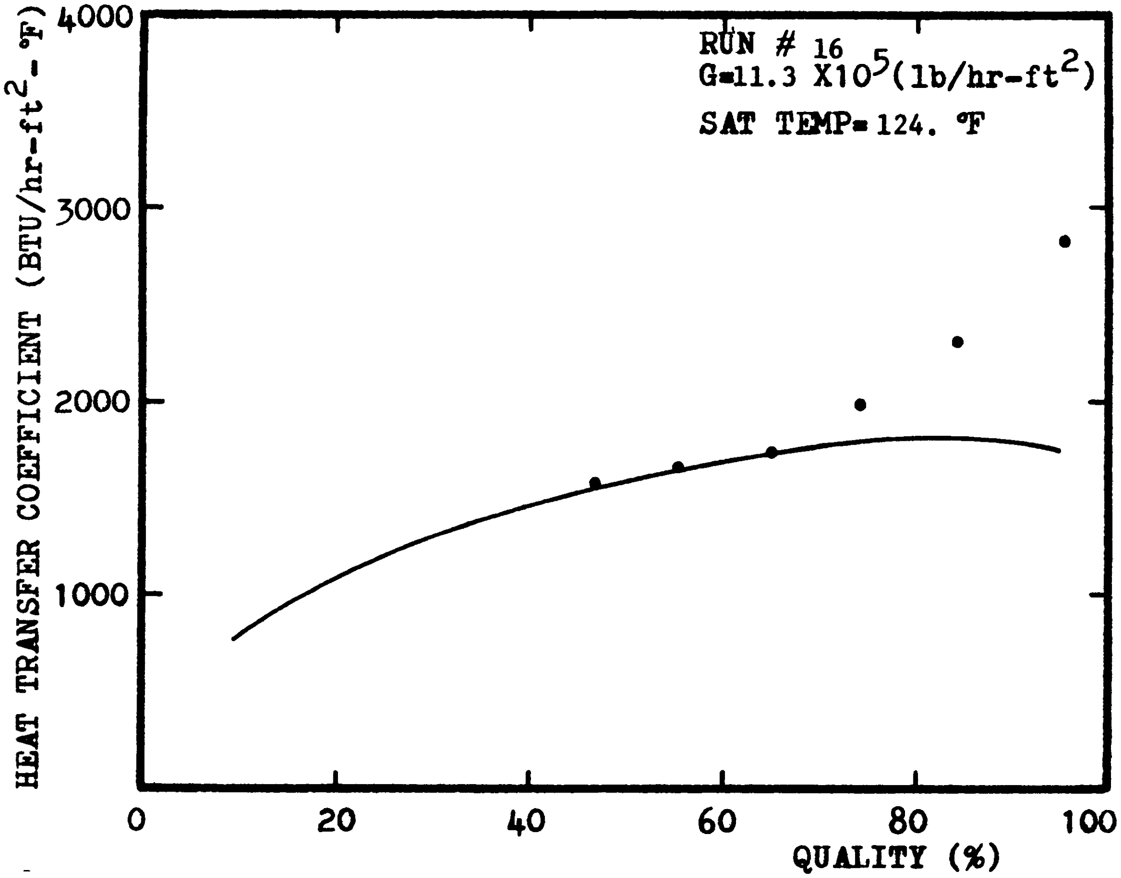

RUN # 14
G= 9.09 X10^5 (lb/hr-ft^2)
SAT TEMP=112. °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2- °F)
4000
3000
2000
1000
0
20
40
60
80
100
QUALITY (%)
RUN # 15
G=9.16 X10^5 (lb/hr-ft^2)
SAT TEMP=140. °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2- °F)
4000
3000
2000
1000
0
20
40
60
80
100
QUALITY (%)

FIGURE 16


RUN # 16
G=11.3 X10^5(lb/hr-ft^2)
SAT TEMP= 124. °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
4000
3000
2000
1000
0
20
40
60
80
100
QUALITY (%)

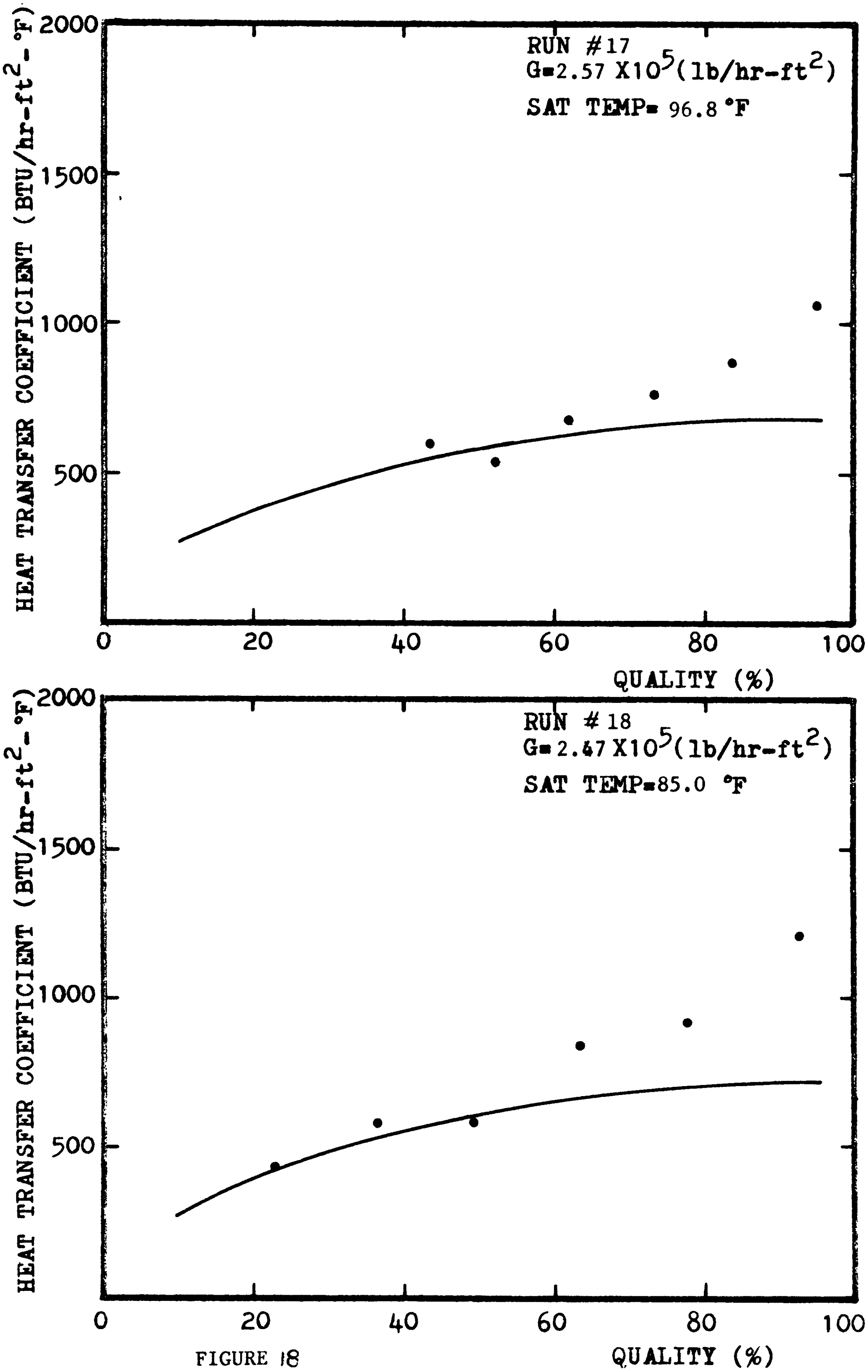

HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)
RUN #17
G=2.57 X10^5(lb/hr-ft^2)
SAT TEMP= 96.8 °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)
RUN # 18
G= 2.47 X10^5(lb/hr-ft^2)
SAT TEMP=85.0 °F

FIGURE 18

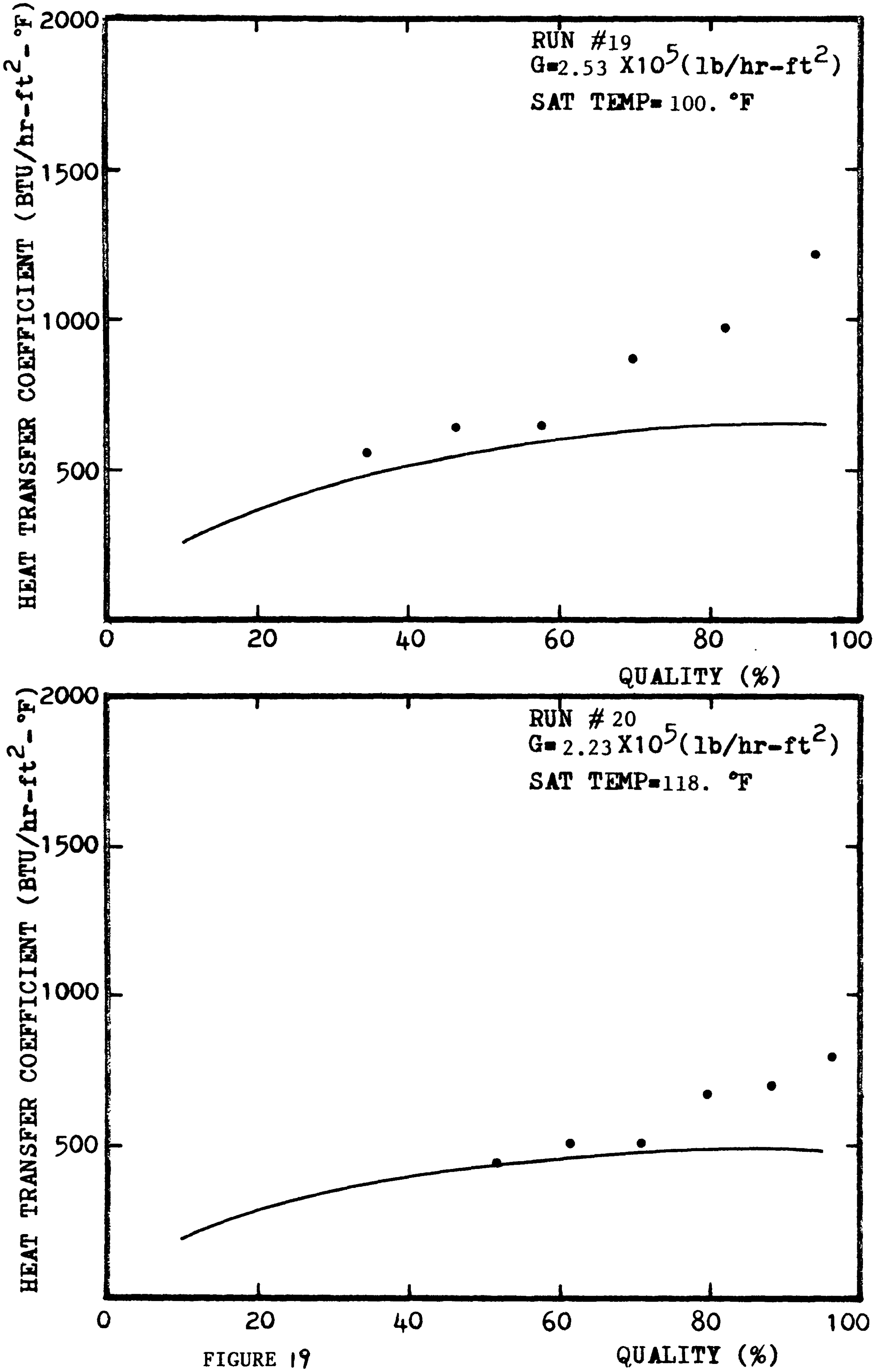

HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
RUN #19
G=2.53 X10^5(lb/hr-ft^2)
SAT TEMP=100. °F
0
20
40
60
80
100
QUALITY (%)
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
RUN # 20
G= 2.23 X10^5(lb/hr-ft^2)
SAT TEMP=118. °F
0
20
40
60
80
100
QUALITY (%)

FIGURE 19

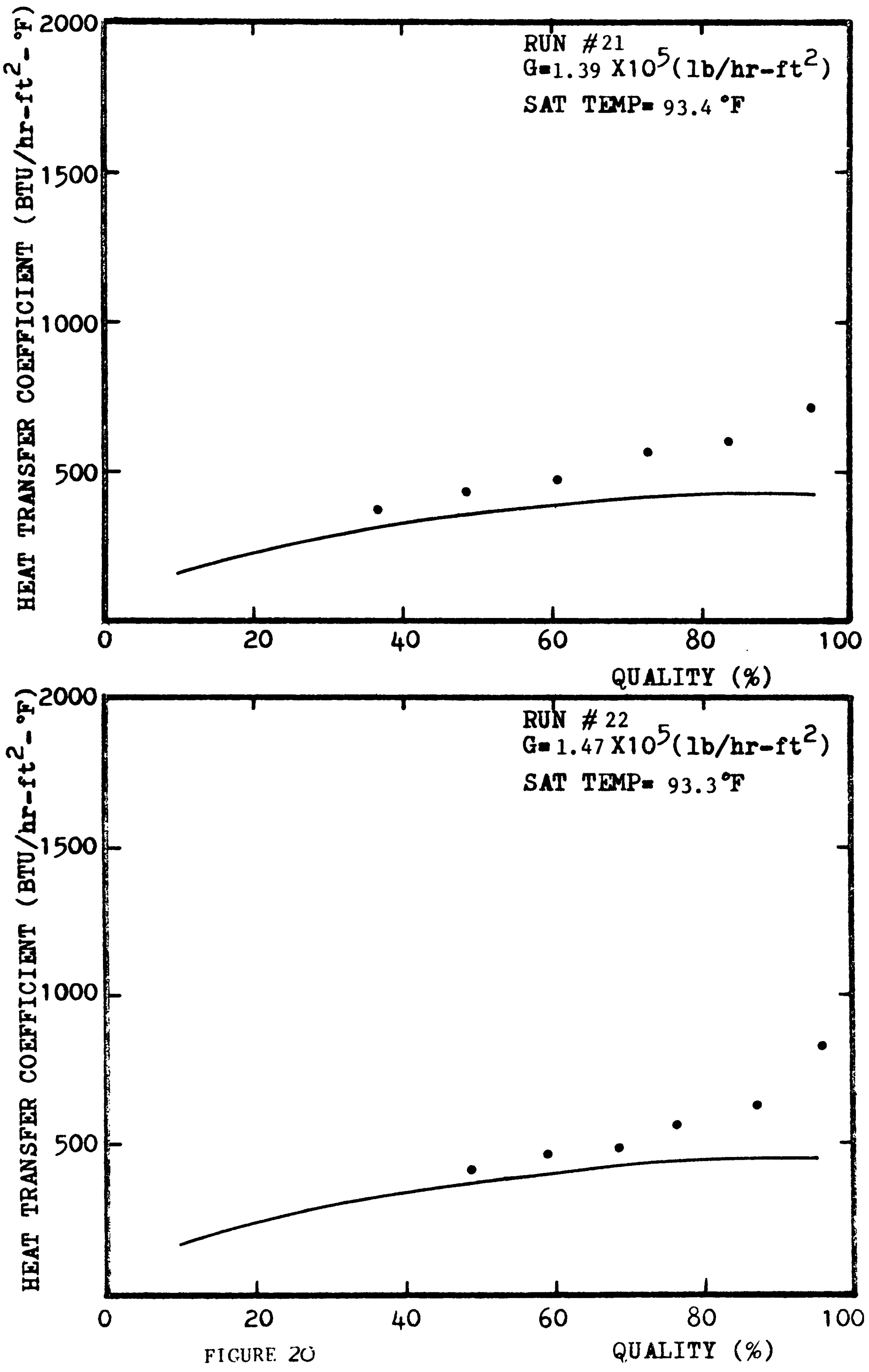
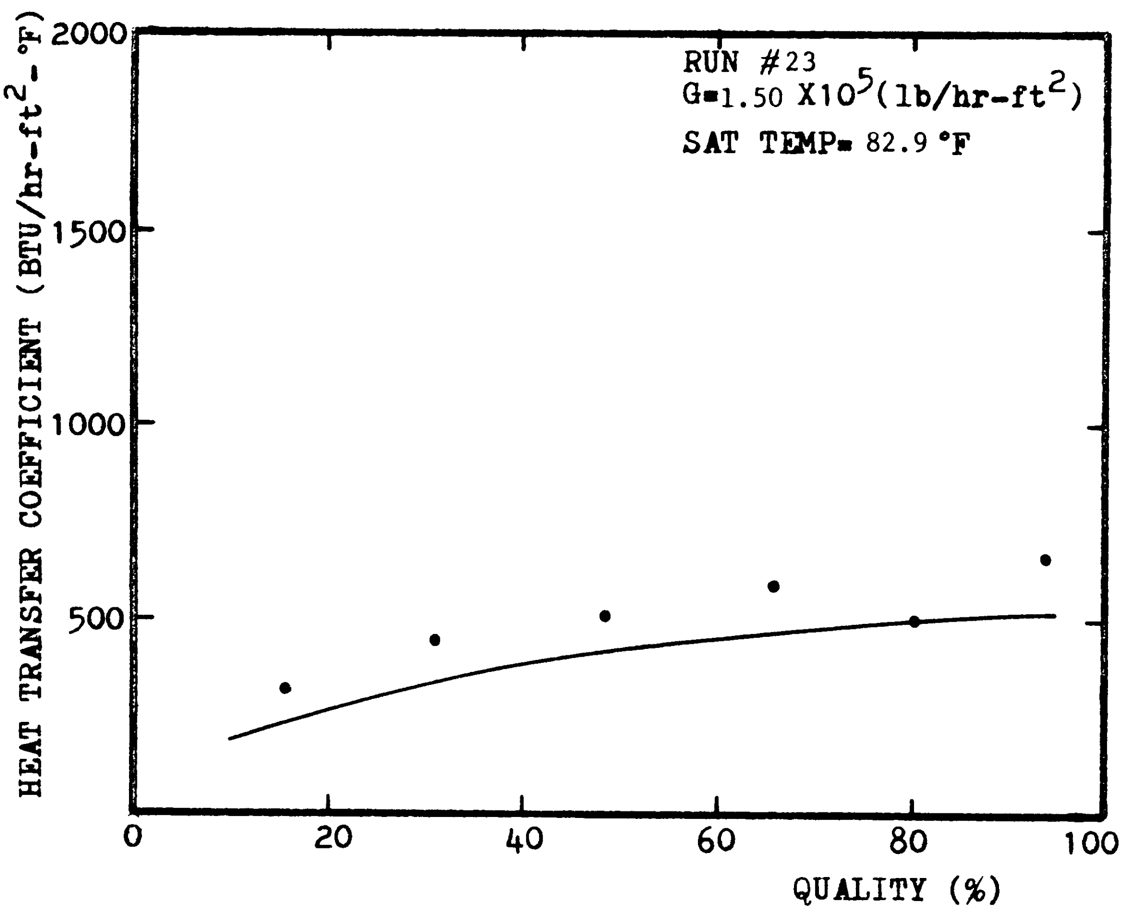

RUN #21
G=1.39 X10^5(lb/hr-ft^2)
SAT TEMP= 93.4 °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)
RUN #22
G=1.47 X10^5(lb/hr-ft^2)
SAT TEMP= 93.3°F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)

FIGURE 20


RUN #23
G=1.50 X10^5(lb/hr-ft^2)
SAT TEMP= 82.9 °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
2000
1500
1000
500
0
20
40
60
80
100
QUALITY (%)

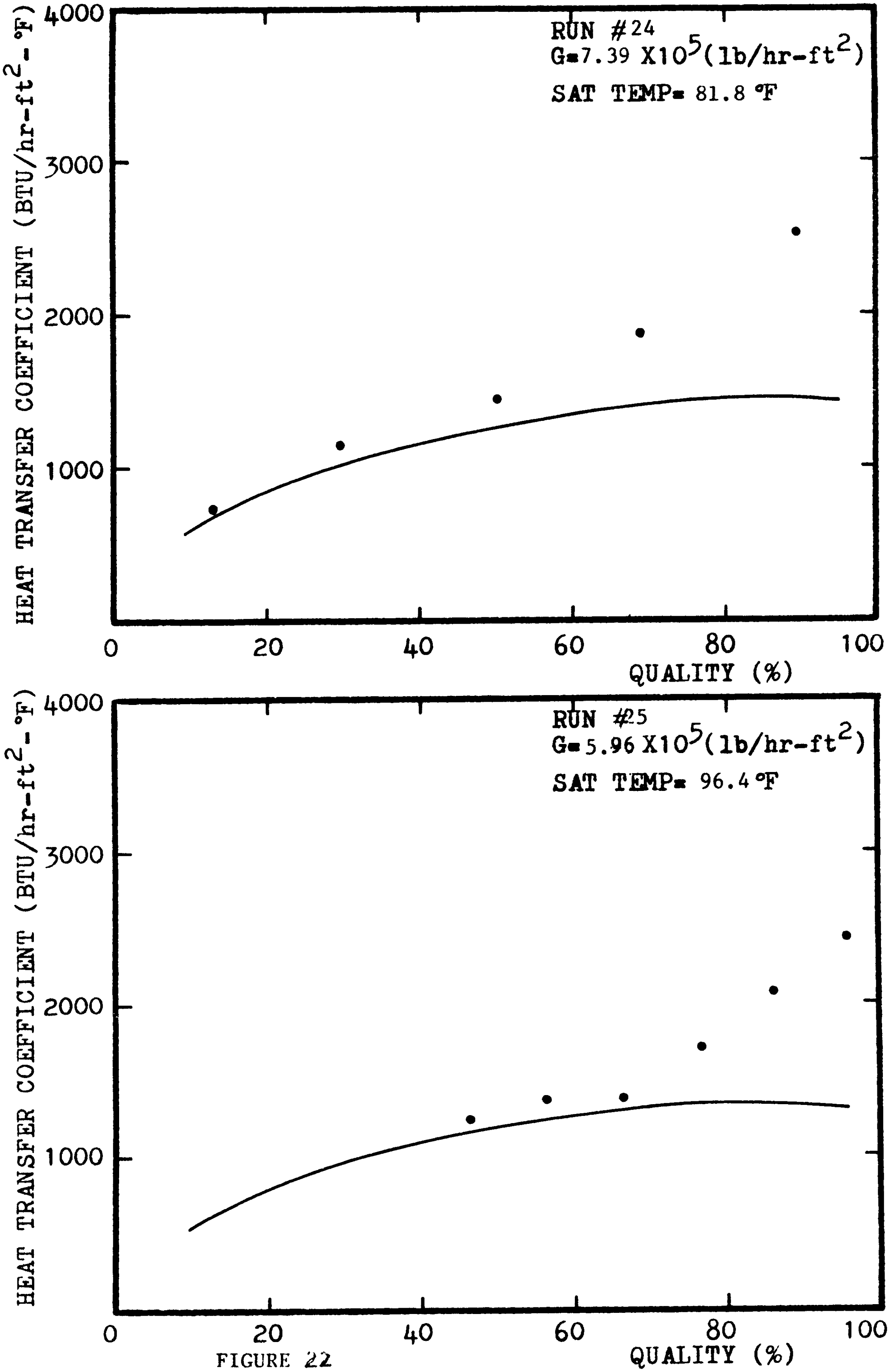

RUN #24
G=7.39 X10^5(lb/hr-ft^2)
SAT TEMP= 81.8 °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
4000
3000
2000
1000
0
20
40
60
80
100
QUALITY (%)
RUN #25
G=5.96 X10^5(lb/hr-ft^2)
SAT TEMP= 96.4 °F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
4000
3000
2000
1000
0
20
40
60
80
100
QUALITY (%)

FIGURE 22

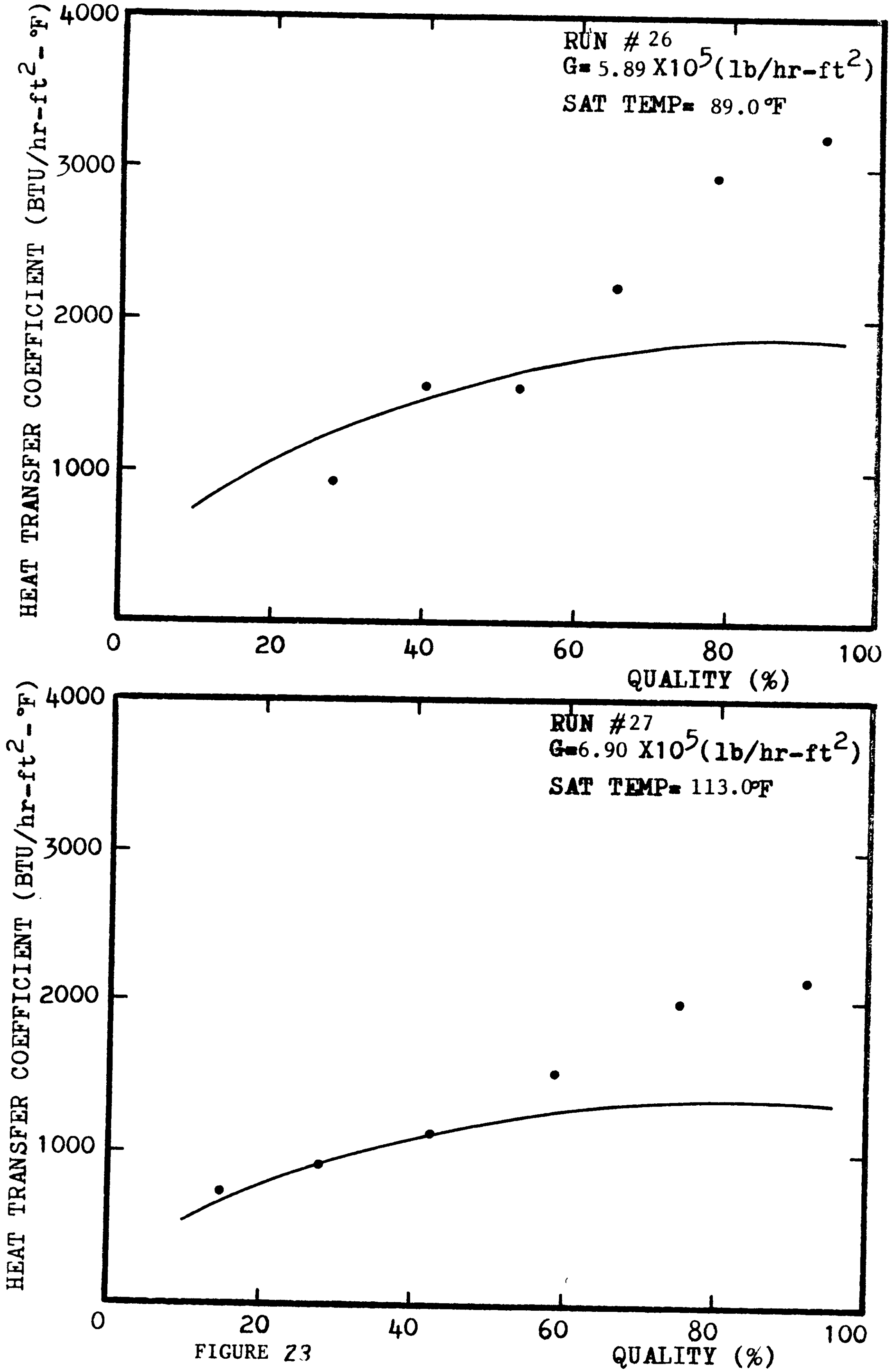

HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
4000
3000
2000
1000
0
20
40
60
80
100
QUALITY (%)
RUN # 26
G= 5.89 X10^5(lb/hr-ft^2)
SAT TEMP= 89.0°F
HEAT TRANSFER COEFFICIENT (BTU/hr-ft^2-°F)
4000
3000
2000
1000
0
20
40
60
80
100
QUALITY (%)
RUN #27
G=6.90 X10^5(lb/hr-ft^2)
SAT TEMP= 113.0°F

FIGURE 23

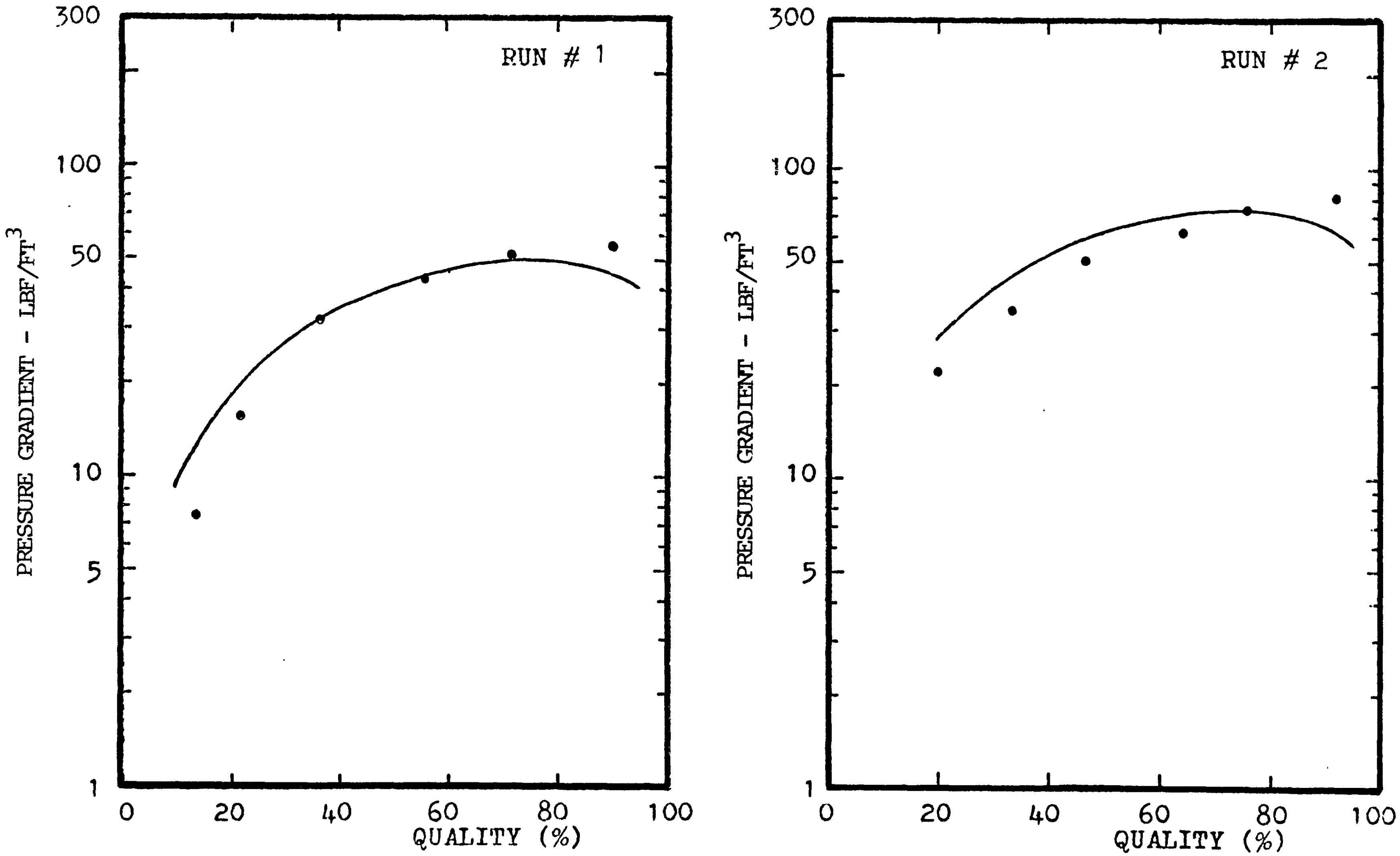

RUN # 1
PRESSURE GRADIENT - LBF/FT^3
300
100
50
10
5
1
0
20
40
60
80
100
QUALITY (%)
RUN # 2
PRESSURE GRADIENT - LBF/FT^3
300
100
50
10
5
1
0
20
40
60
80
100
QUALITY (%)

FIGURE 24

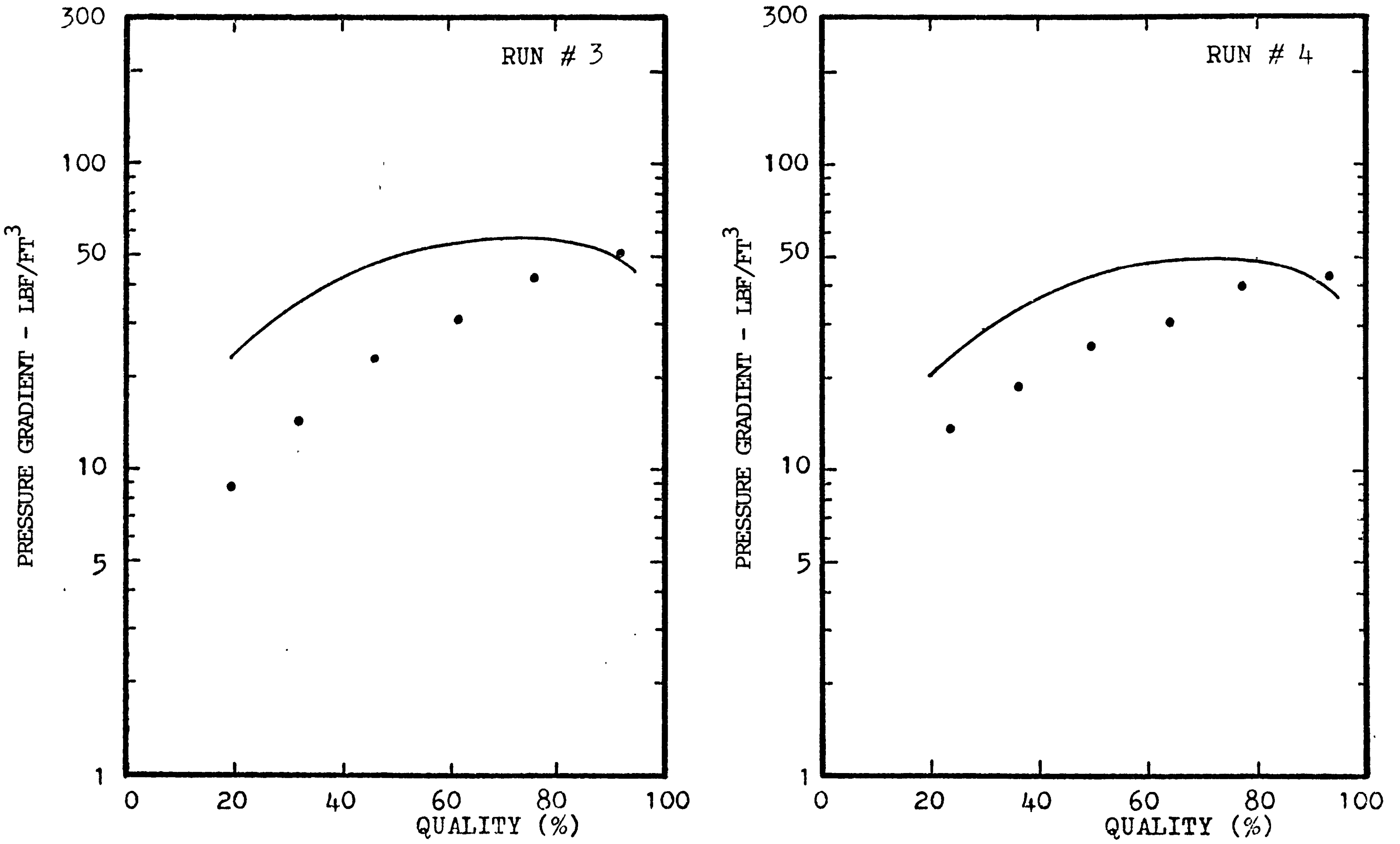

RUN # 3
RUN # 4
PRESSURE GRADIENT - LBF/FT^3
300
100
50
10
5
1
0
20
40
60
80
100
QUALITY (%)

FIGURE 25

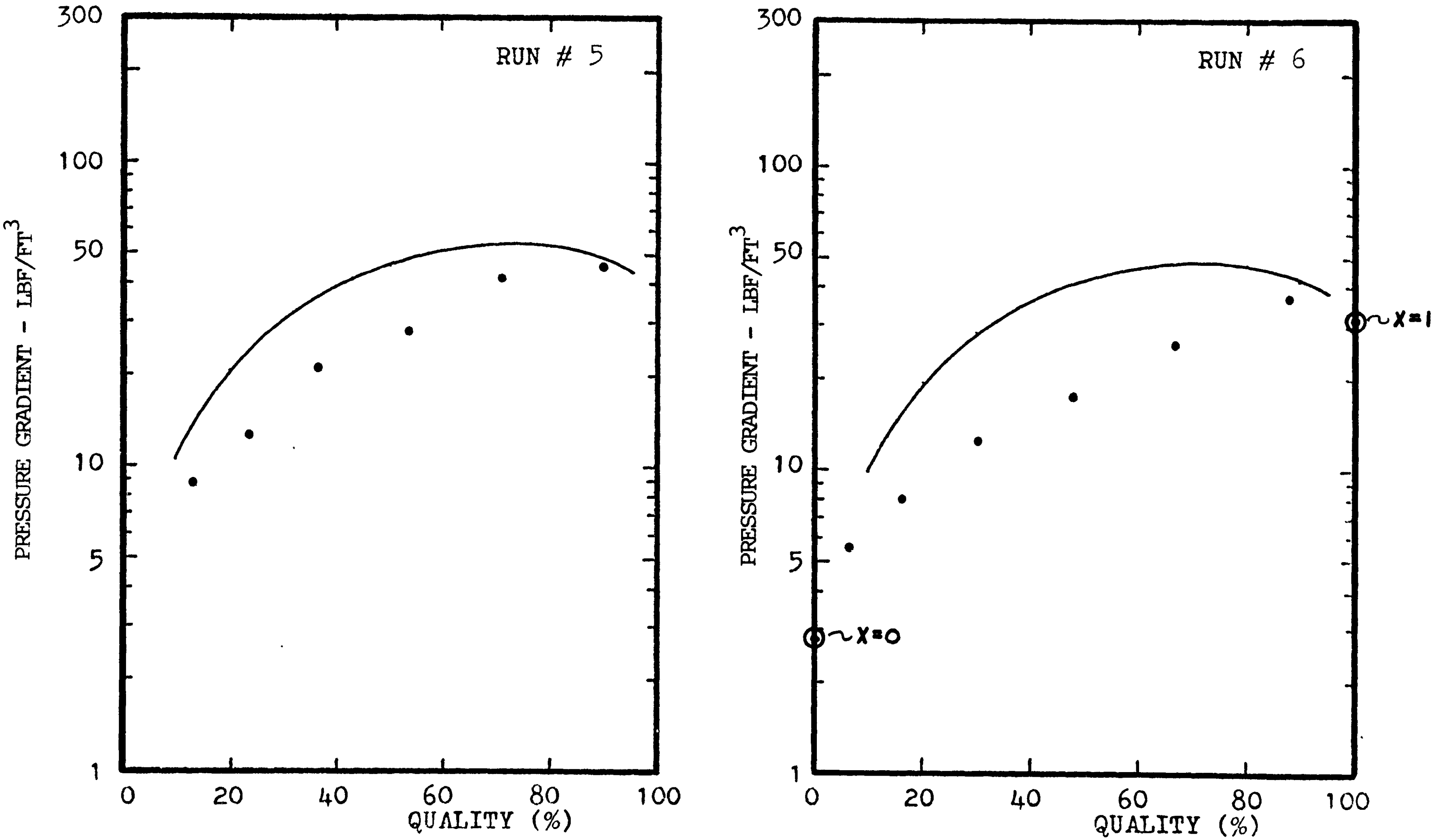

RUN # 5
RUN # 6
PRESSURE GRADIENT - LBF/FT^3
300
100
50
10
5
1
0
20
40
60
80
100
QUALITY (%)
~X=0
~X=1

FIGURE 26

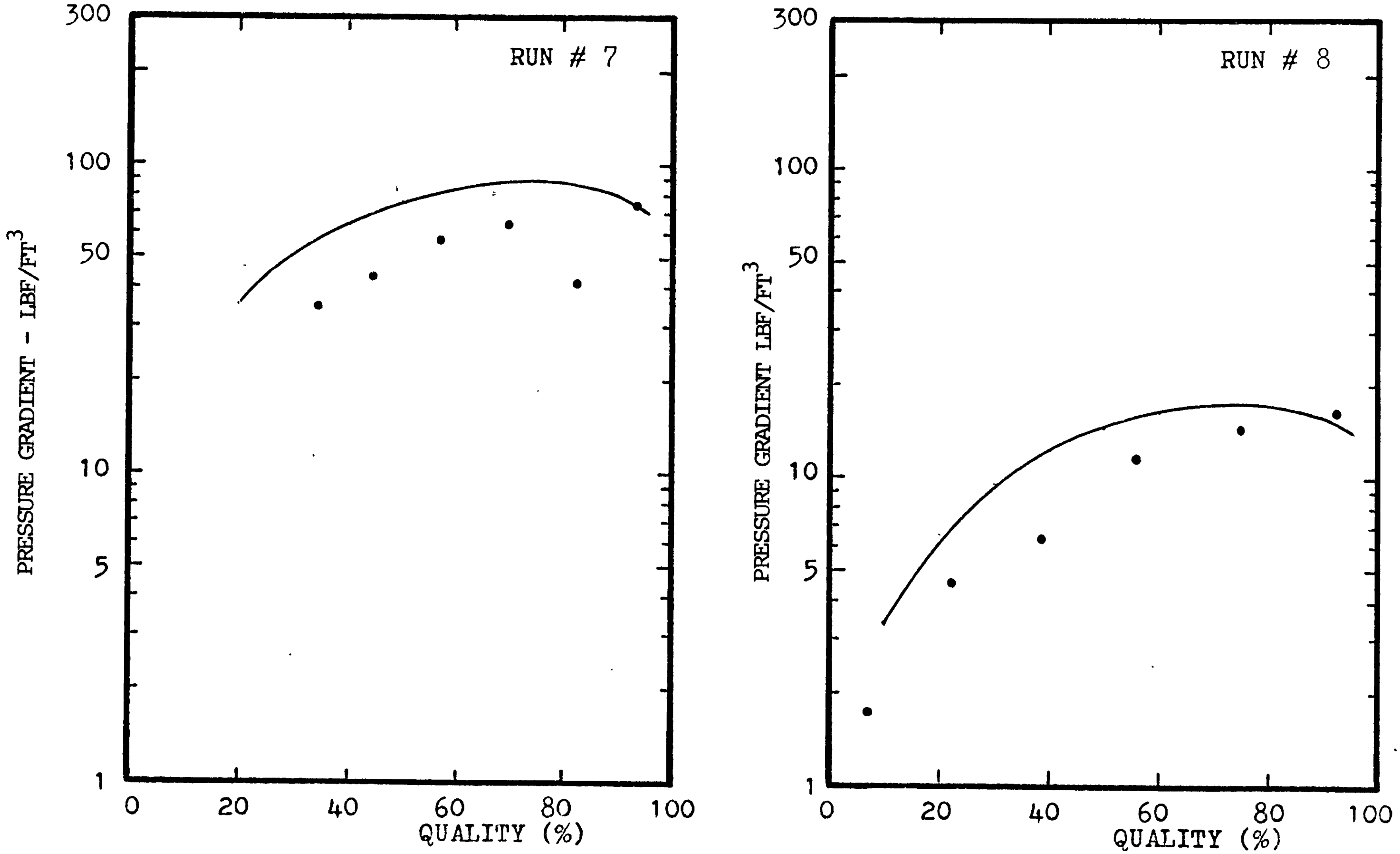

RUN # 7
300
100
50
10
5
1
PRESSURE GRADIENT - LBF/FT^3
0
20
40
60
80
100
QUALITY (%)
RUN # 8
300
100
50
10
5
1
PRESSURE GRADIENT LBF/FT^3
0
20
40
60
80
100
QUALITY (%)

FIGURE 27

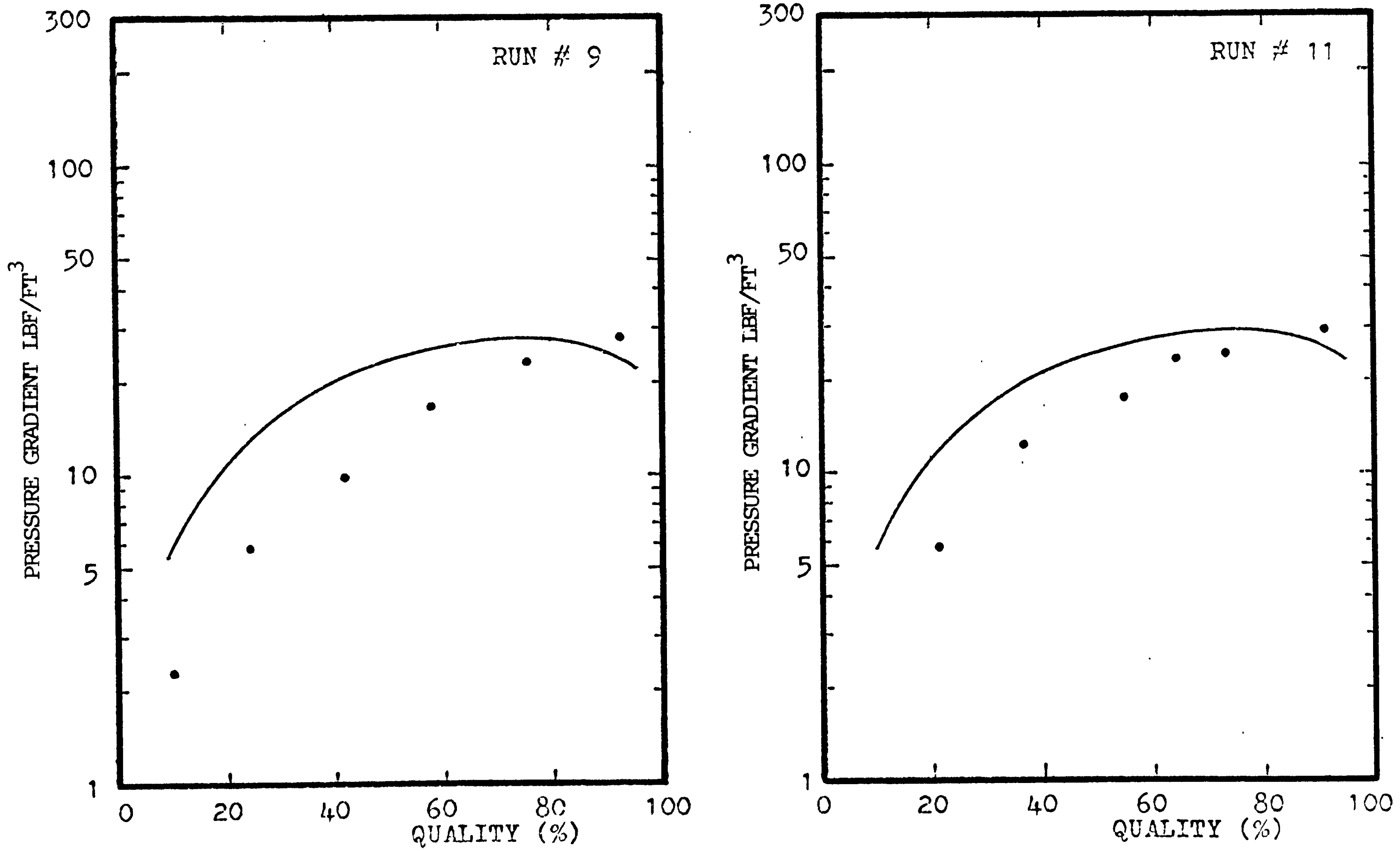

RUN # 9
RUN ≠ 11
PRESSURE GRADIENT LBF/FT^3
300
100
50
10
5
1
0
20
40
60
80
100
QUALITY (%)

FIGURE 28

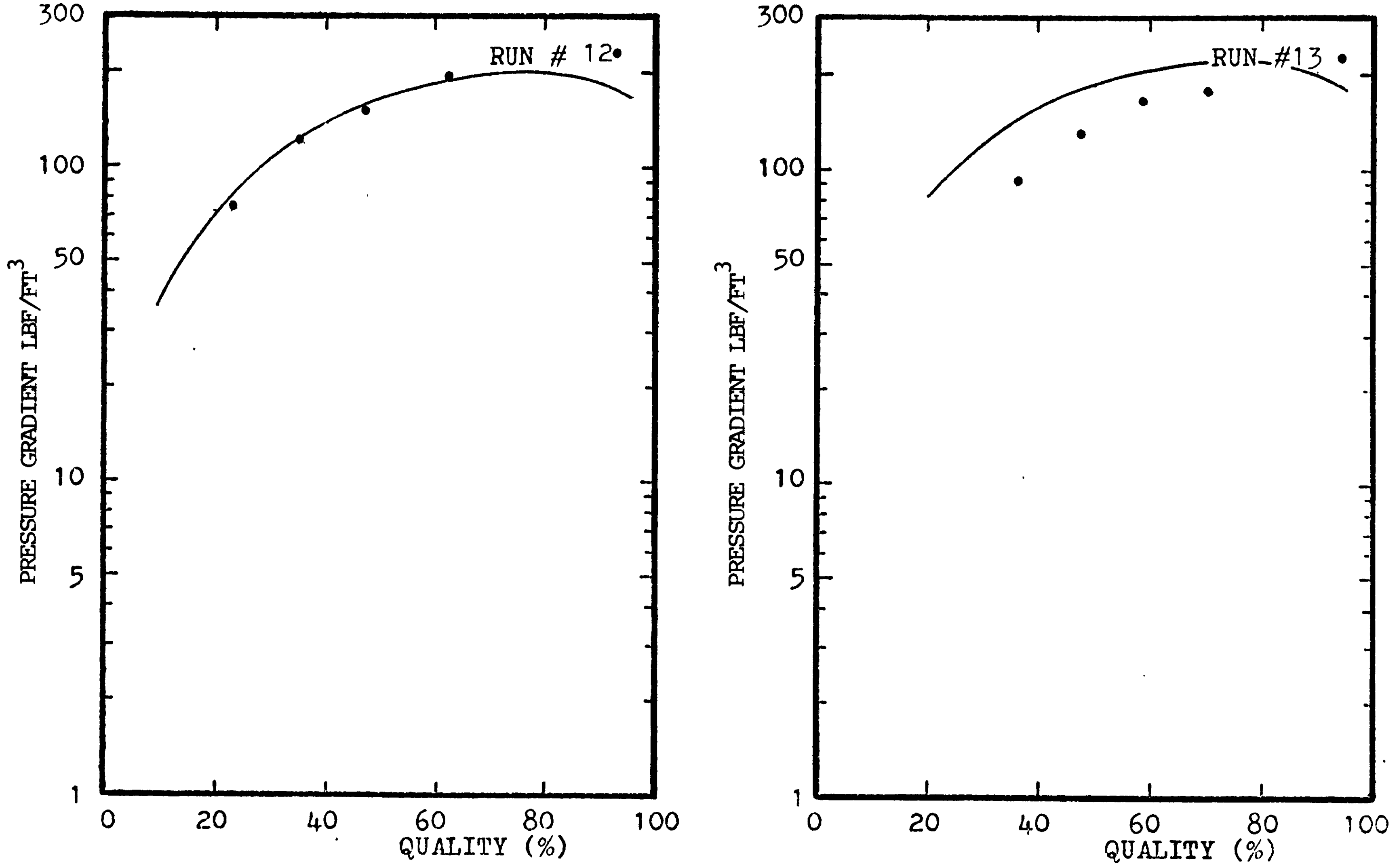

300
100
50
10
5
1
PRESSURE GRADIENT LBF/FT^3
0
20
40
60
80
100
QUALITY (%)
RUN # 12
300
100
50
10
5
1
PRESSURE GRADIENT LBF/FT^3
0
20
40
60
80
100
QUALITY (%)
RUN #13

FIGURE 27

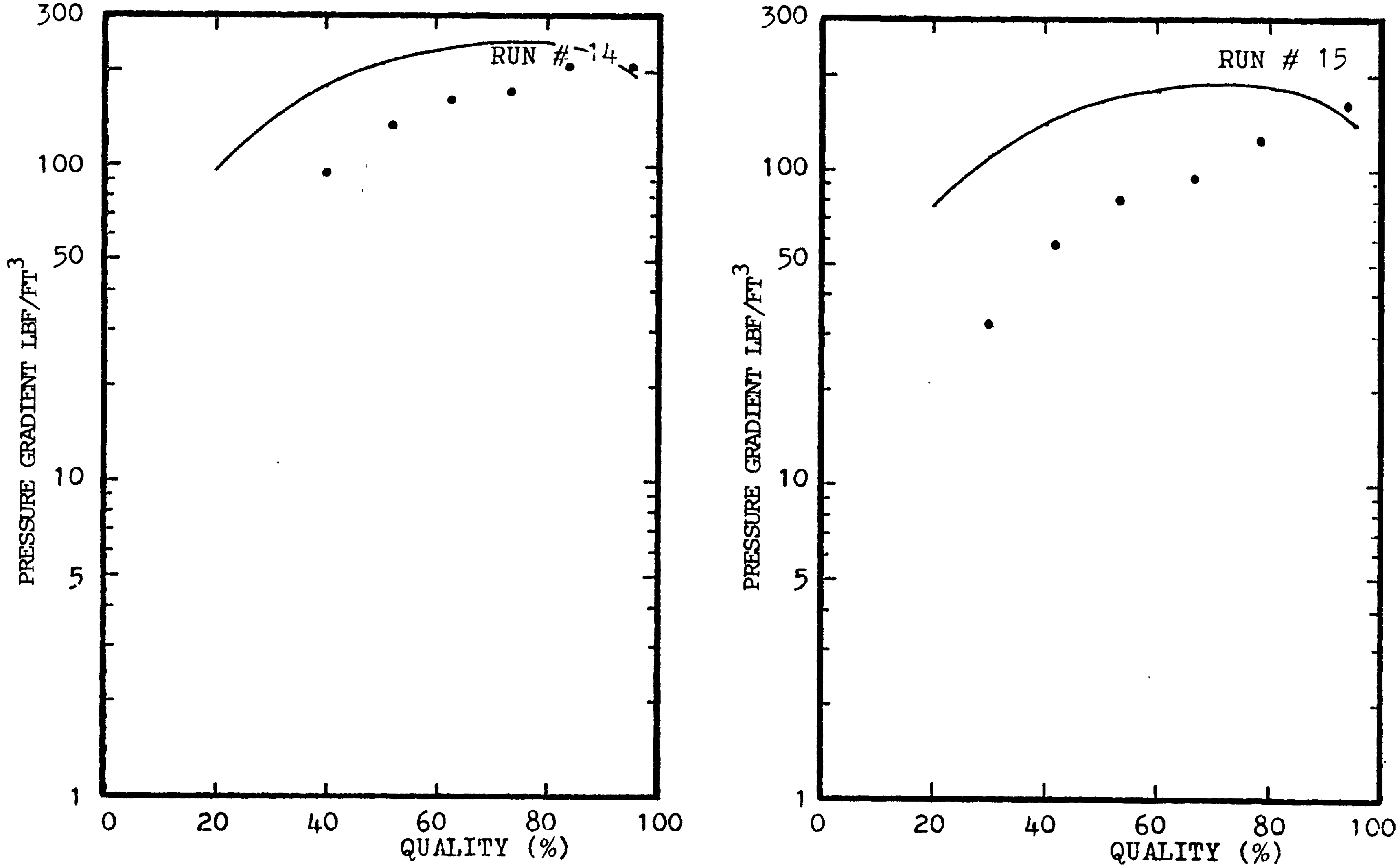

RUN # 14
300
100
50
10
5
1
PRESSURE GRADIENT LBF/FT^3
0
20
40
60
80
100
QUALITY (%)
RUN # 15
300
100
50
10
5
1
PRESSURE GRADIENT LBF/FT^3
0
20
40
60
80
100
QUALITY (%)

FIGURE 30

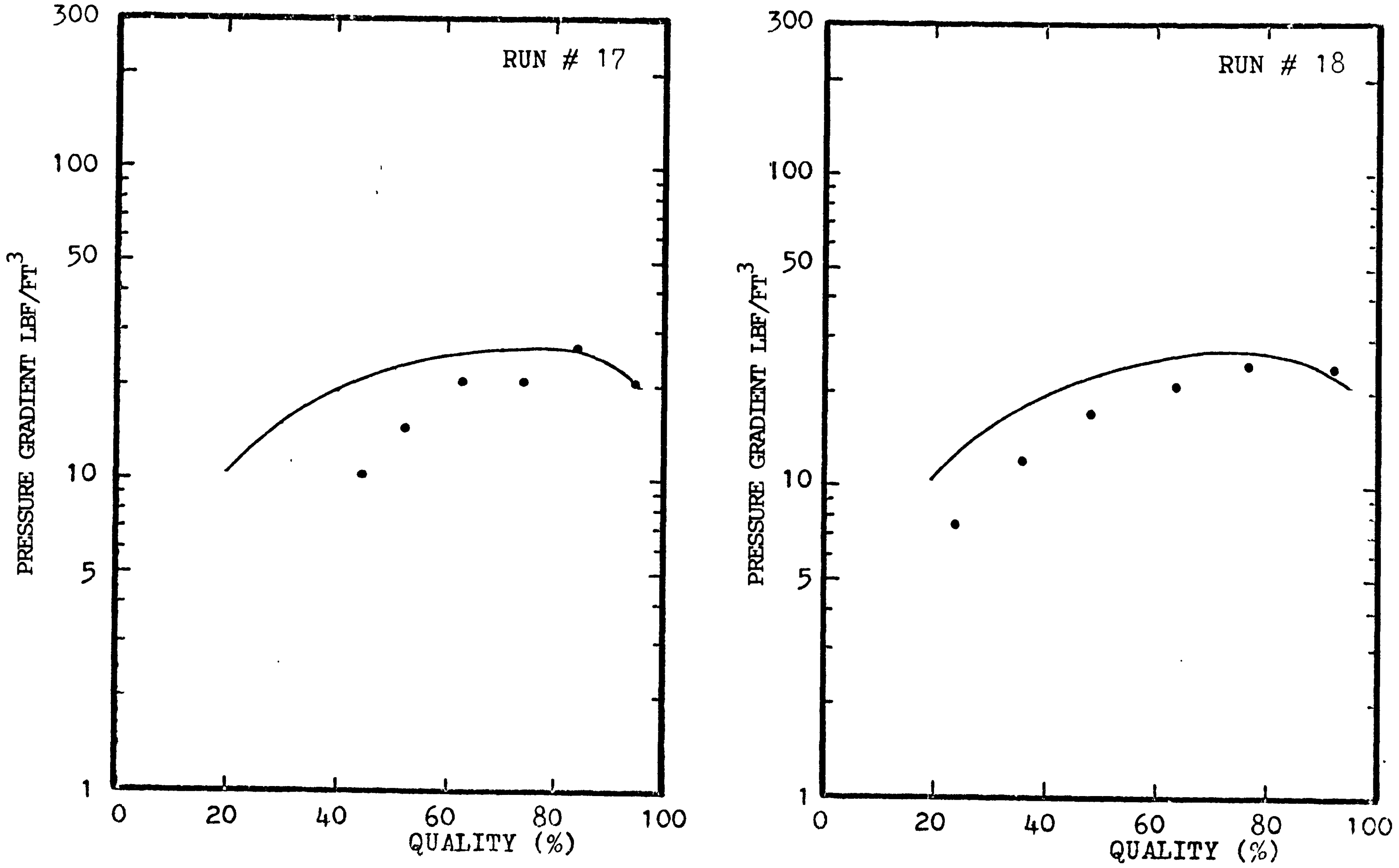

300
100
50
10
5
1
RUN # 17
PRESSURE GRADIENT LBF/FT^3
0
20
40
60
80
100
QUALITY (%)
300
100
50
10
5
1
RUN # 18
PRESSURE GRADIENT LBF/FT^3
0
20
40
60
80
100
QUALITY (%)

FIGURE 31

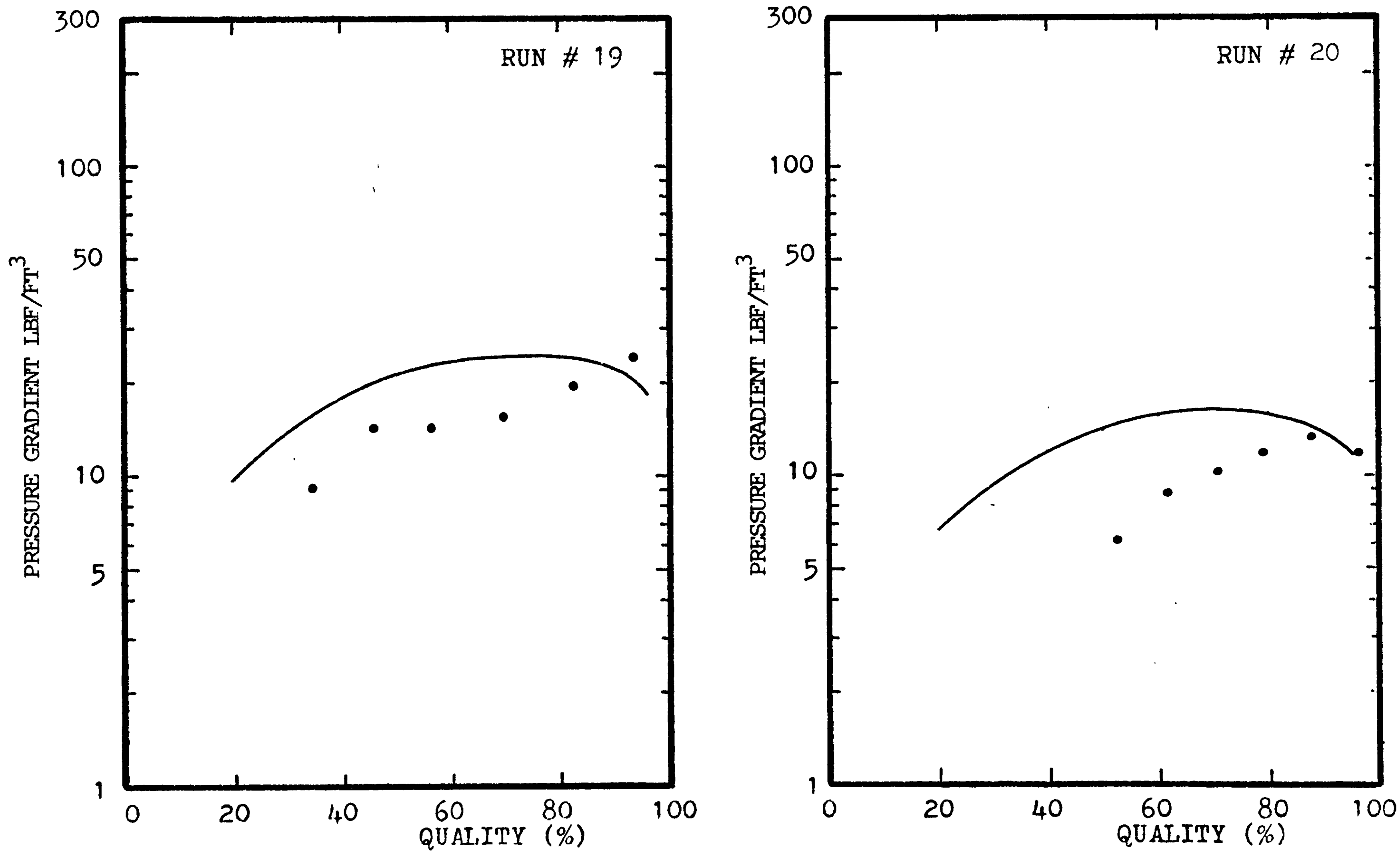

300
100
50
10
5
1
PRESSURE GRADIENT LBF/FT^3
RUN # 19
0
20
40
60
80
100
QUALITY (%)
300
100
50
10
5
1
PRESSURE GRADIENT LBF/FT^3
RUN # 20
0
20
40
60
80
100
QUALITY (%)

FIGURE 32

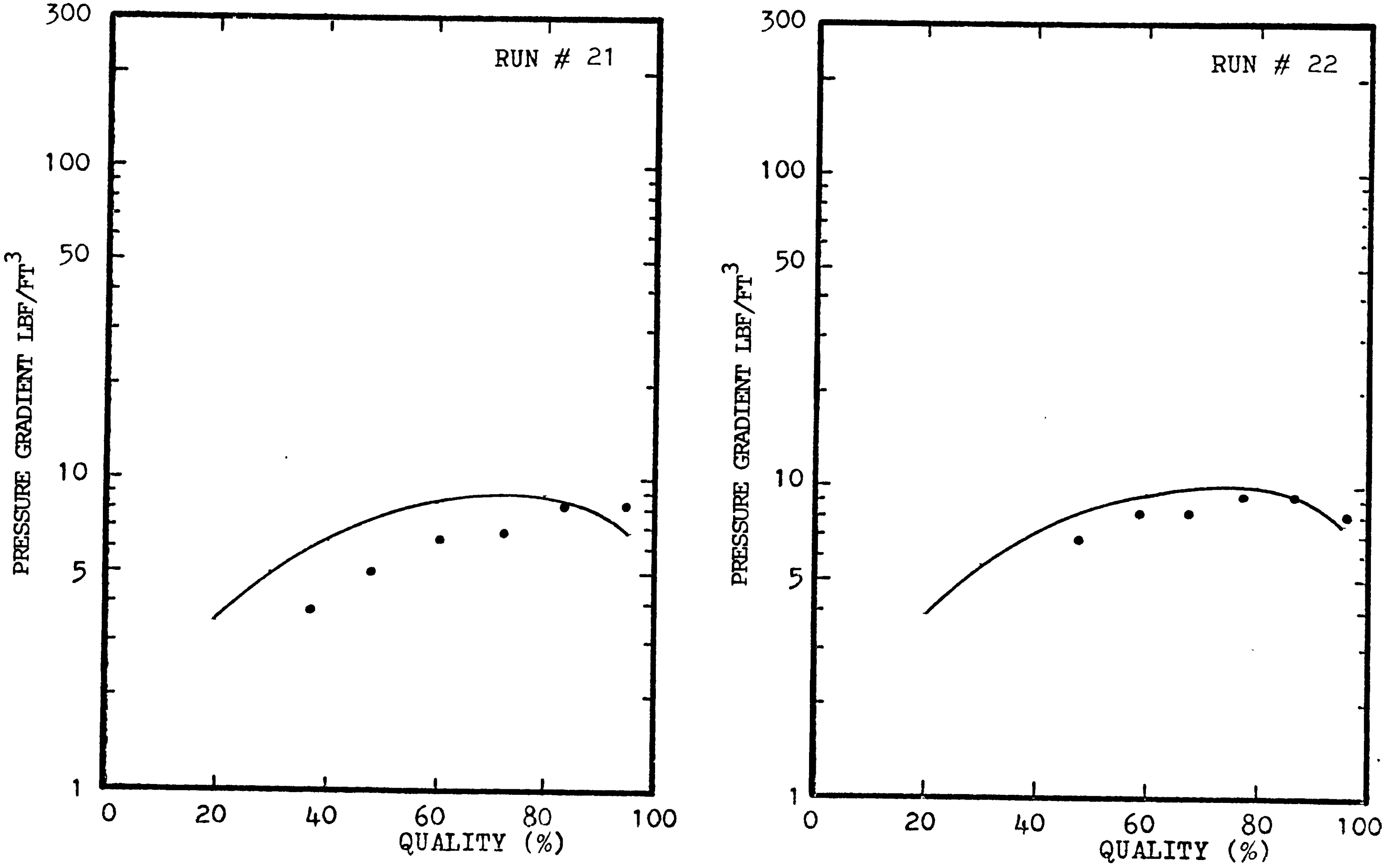
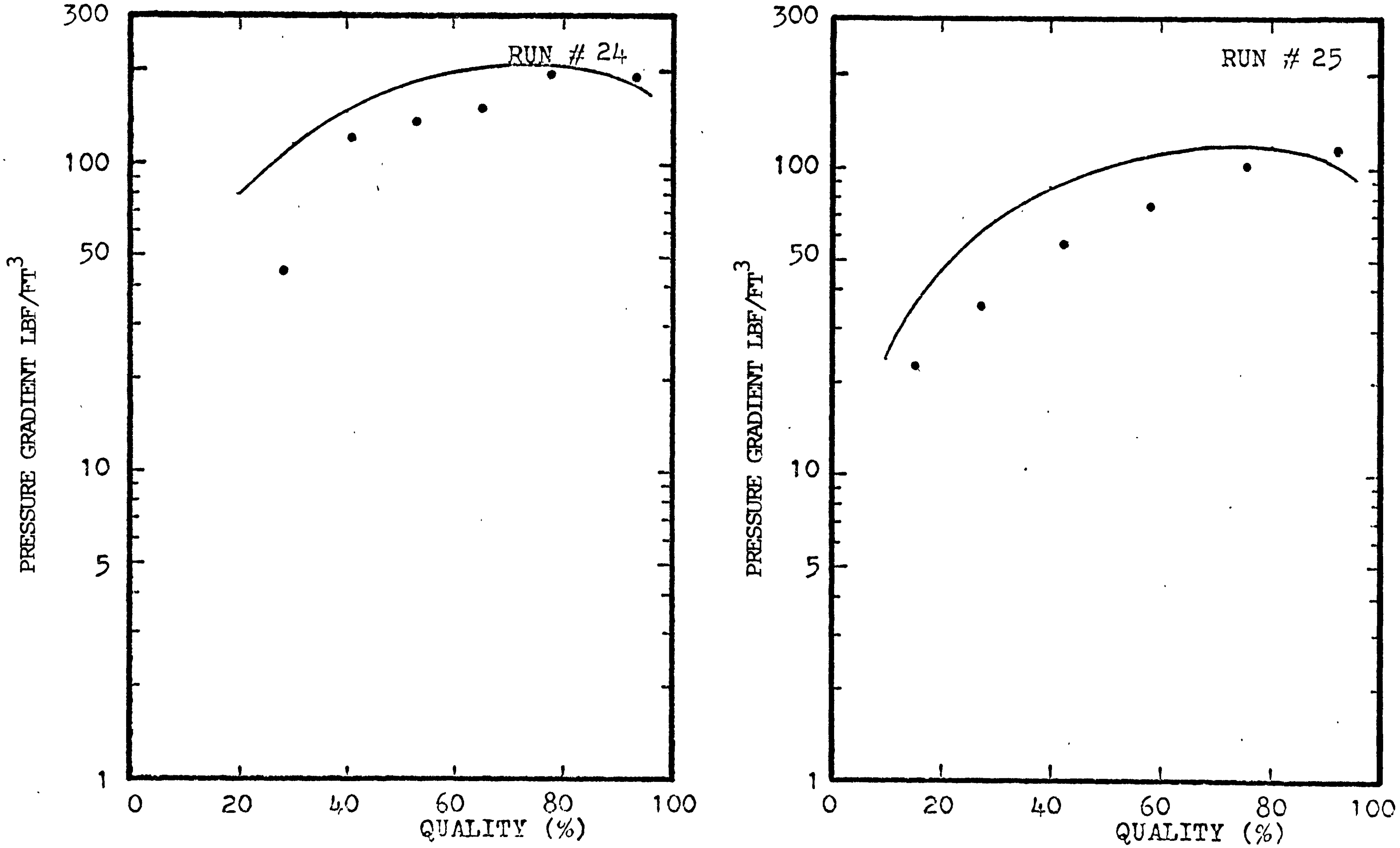

RUN # 21
RUN # 22
PRESSURE GRADIENT LBF/FT^3
QUALITY (%)
300
100
50
10
5
1
0
20
40
60
80
100

FIGURE 33



300
100
50
10
5
1
PRESSURE GRADIENT LBF/FT^3
RUN # 24
0
20
40
60
80
100
QUALITY (%)
300
100
50
10
5
1
PRESSURE GRADIENT LBF/FT^3
RUN # 25
0
20
40
60
80
100
QUALITY (%)

FIGURE 34

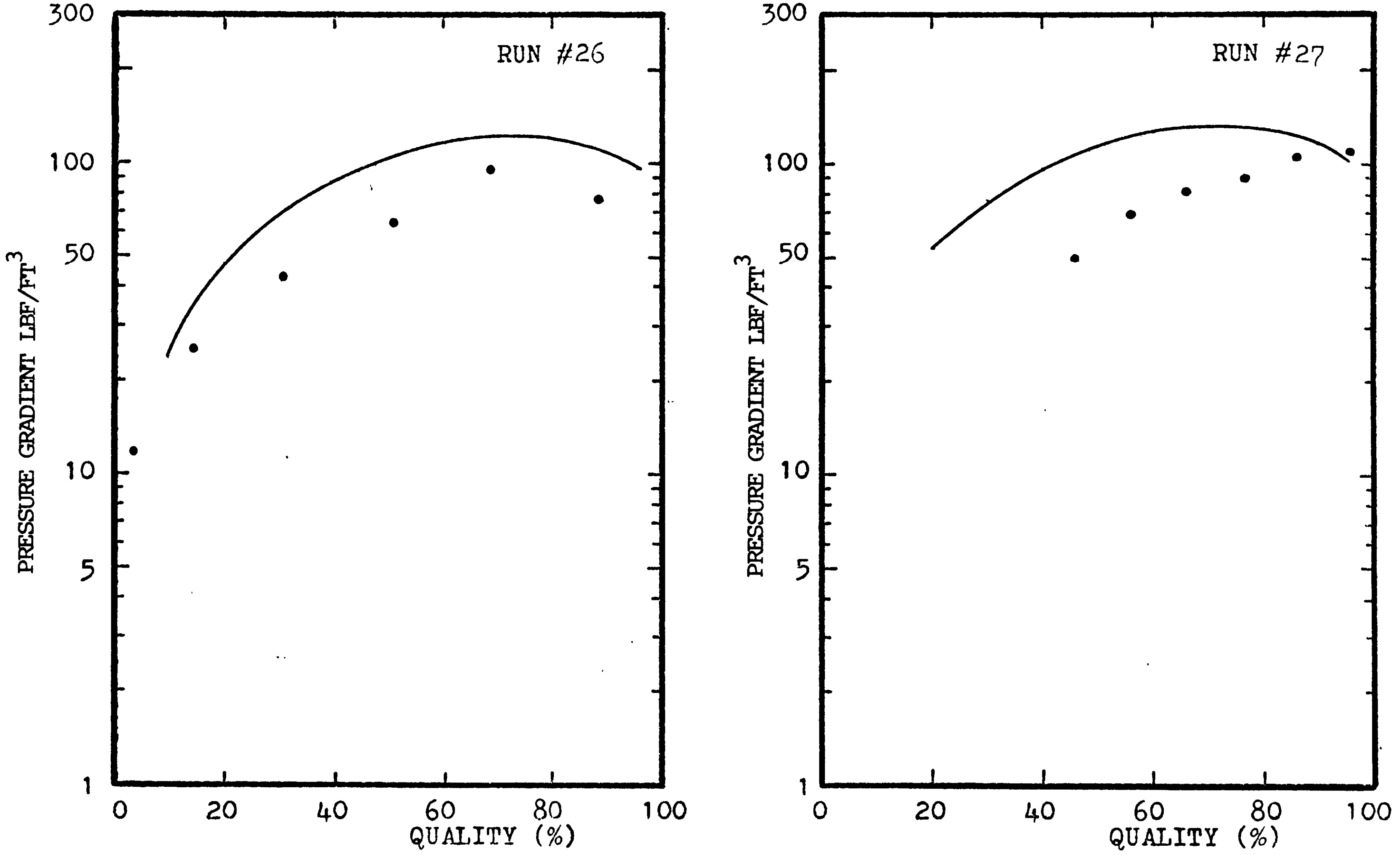

RUN #26
RUN #27
PRESSURE GRADIENT LBF/FT^3
PRESSURE GRADIENT LBF/FT^3
300
100
50
10
5
1
300
100
50
10
5
1
0
20
40
60
80
100
QUALITY (%)
0
20
40
60
80
100
QUALITY (%)

FIGURE 35

APPENDIX 1

TABLES OF DATA

```
RUN NO. 1                        REFRIGERANT 12

FREON MASS FLUX    3.2063487E 05   WTR TEMP IN     37.50     FREON TEMP IN    80.17

WTR FLOW RATE      621.65          MEAN HT COEF    842.4     HEAT BAL ERROR   0.052

                   VAPOR TEMP    OUT WALL T    DEL WTR T     P GRAD
                      (F)           (F)           (F)       (LBF/FT3)

                     79.820        71.170        3.300        55.403
                     80.040        72.430        2.790        52.487
                     78.260        68.320        3.130        43.740
                     79.050        67.140        2.710        32.076
                     77.180        62.460        2.620        15.746
                     75.400        57.460        2.370         7.581

                   IN WALL T     DEL WALL T    HEAT FLUX       H T COEF
                     (F)            (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                     71.277         8.542       10319.3        1208.0
                     72.520         7.519        8724.5        1160.3
                     68.421         9.838        9787.7         994.8
                     67.228        11.821        8474.3         716.8
                     62.545        14.634        8192.9         559.8
                     57.537        17.862        7411.1         414.8

                     QUALITY        XTT          F(XTT)   NU*F2/PR*(RE**.9)

                      0.900      3.187E-02     6.911E 00     1.082E 01
                      0.716      1.009E-01     2.758E 00     4.306E 00
                      0.542      1.963E-01     1.691E 00     2.470E 00
                      0.364      3.802E-01     1.071E 00     1.348E 00
                      0.210      7.435E-01     6.939E-01     8.782E-01
                      0.068      2.341E 00     3.492E-01     5.665E-01
```

```
RUN NO. 2                        REFRIGERANT 12

FREON MASS FLUX   4.4146437E 05   WTR TEMP IN     69.74      FREON TEMP IN   101.00

WTR FLOW RATE     966.32          MEAN HT COEF  1067.6      HEAT BAL ERROR   0.007

                 VAPOR TEMP    OUT WALL T     DEL WTR T      P GRAD
                    (F)           (F)            (F)       (LBF/FT3)

                   98.740        91.390         2.230        79.315
                   98.830        91.910         2.040        73.483
                   97.430        88.390         2.110        62.110
                   98.170        87.350         2.000        50.446
                   96.920        84.390         1.910        34.700
                   95.960        82.520         1.790        21.870

                 IN WALL T     DEL WALL T    HEAT FLUX       H T COEF
                   (F)            (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                   91.502         7.237       10839.7        1497.8
                   92.013         6.816        9916.1        1454.6
                   88.496         8.933       10256.4        1148.1
                   87.451        10.718        9721.7         906.9
                   84.486        12.433        9284.2         746.7
                   82.610        13.349        8700.9         651.7

                   QUALITY         XTT          F(XTT)  NU*F2/PR*(RE**.9)

                    0.922     2.909E-02     7.458E 00     1.247E 01
                    0.768     9.205E-02     2.959E 00     4.822E 00
                    0.622     1.711E-01     1.867E 00     2.522E 00
                    0.472     2.976E-01     1.264E 00     1.502E 00
                    0.336     4.929E-01     9.029E-01     1.019E 00
                    0.207     8.872E-01     6.216E-01     7.661E-01
```

```
RUN NO. 3                            REFRIGERANT 12

FREON MASS FLUX   4.3239100E 05    WTR TEMP IN     86.57     FREON TEMP IN   120.00

WTR FLOW RATE     827.98           MEAN HT COEF    857.2     HEAT BAL ERROR   0.045


                    VAPOR TEMP   OUT WALL T    DEL WTR T     P GRAD
                       (F)          (F)           (F)      (LBF/FT3)

                     117.250      109.040        2.360      50.738
                     117.580      109.460        2.250      42.281
                     116.480      106.090        2.330      30.909
                     117.670      104.960        2.260      22.744
                     116.570      101.740        2.080      14.580
                     115.500       99.040        1.910       8.747

                    IN WALL T    DEL WALL T   HEAT FLUX       H T COEF
                      (F)          (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                     109.142        8.107       9829.2      1212.3
                     109.557        8.022       9371.1      1168.1
                     106.191       10.288       9704.3       943.1
                     105.058       12.611       9412.7       746.3
                     101.830       14.739       8663.0       587.7
                      99.122       16.377       7955.0       485.7

                      QUALITY         XTT        F(XTT)  NU*F2/PR*(RE**.9)

                       0.925    3.237E-02    6.821E 00    1.039E 01
                       0.770    1.049E-01    2.679E 00    3.906E 00
                       0.620    1.988E-01    1.676E 00    2.065E 00
                       0.463    3.561E-01    1.120E 00    1.219E 00
                       0.322    6.038E-01    7.919E-01    7.892E-01
                       0.193    1.106E 00    5.429E-01    5.635E-01
```

```
RUN NO. 4                         REFRIGERANT 12

FREON MASS FLUX   4.2630031E 05   WTR TEMP IN   108.78      FREON TEMP IN   135.88

WTR FLOW RATE     923.24          MEAN HT COEF   768.0      HEAT BAL ERROR  -0.000

                 VAPOR TEMP    OUT WALL T    DEL WTR T     P GRAD
                    (F)           (F)           (F)       (LBF/FT3)

                  133.130       125.170        1.860       42.573
                  133.670       125.210        1.840       38.782
                  133.000       122.500        1.790       29.743
                  134.080       121.540        1.720       24.785
                  133.170       119.540        1.660       18.370
                  132.670       117.830        1.530       13.413

                 IN WALL T     DEL WALL T   HEAT FLUX       H T COEF
                    (F)           (F)     (BTU/HR-FT2)  (BTU/HR-FT2-F)

                  125.260         7.869       8638.1       1097.6
                  125.299         8.370       8545.2       1020.8
                  122.586        10.413       8313.0        798.3
                  121.623        12.456       7987.9        641.2
                  119.620        13.549       7709.3        568.9
                  117.904        14.765       7105.5        481.2

                   QUALITY        XTT          F(XTT)  NU*F2/PR*(RE**.9)

                    0.930     3.401E-02     6.546E 00     9.957E 00
                    0.781     1.113E-01     2.561E 00     3.554E 00
                    0.638     2.092E-01     1.617E 00     1.819E 00
                    0.495     3.575E-01     1.116E 00     1.101E 00
                    0.363     5.780E-01     8.143E-01     8.043E-01
                    0.239     9.885E-01     5.815E-01     5.848E-01
```

```
RUN NO. 5                      REFRIGERANT 12

FREON MASS FLUX   3.8527143E 05   WTR TEMP IN     67.59     FREON TEMP IN   101.65

WTR FLOW RATE    1047.96          MEAN HT COEF   681.9      HEAT BAL ERROR  -0.035

                 VAPOR TEMP    OUT WALL T     DEL WTR T      P GRAD
                    (F)           (F)            (F)       (LBF/FT3)

                  100.570        90.520         2.230        46.655
                  101.390        88.570         2.000        41.990
                  100.570        86.520         1.910        27.993
                   99.570        83.590         1.710        20.995
                   98.130        79.860         1.500        12.830
                   95.650        76.960         1.250         8.747

                 IN WALL T     DEL WALL T    HEAT FLUX        H T COEF
                    (F)           (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                   90.642         9.927       11755.4        1184.1
                   88.679        12.710       10543.0         829.4
                   86.624        13.945       10068.6         722.0
                   83.683        15.886        9014.2         567.4
                   79.942        18.187        7907.2         434.7
                   77.028        18.621        6589.4         353.8

                   QUALITY         XTT          F(XTT)  NU*F2/PR*(RE**.9)

                    0.901     3.761E-02     6.025E 00     8.972E 00
                    0.708     1.240E-01     2.363E 00     2.534E 00
                    0.534     2.425E-01     1.457E 00     1.487E 00
                    0.374     4.321E-01     9.843E-01     9.117E-01
                    0.236     7.767E-01     6.752E-01     5.904E-01
                    0.123     1.550E 00     4.436E-01     4.285E-01
```

```
RUN NO. 6                          REFRIGERANT 12

FREON MASS FLUX   4.1723918E 05    WTR TEMP IN     90.65     FREON TEMP IN   127.92

WTR FLOW RATE    1097.07           MEAN HT COEF    599.0     HEAT BAL ERROR  -0.039

                VAPOR TEMP   OUT WALL T    DEL WTR T     P GRAD
                   (F)          (F)           (F)       (LBF/FT3)

                 125.500      113.210        2.391       36.450
                 126.870      111.380        2.122       25.952
                 125.920      108.220        2.035       17.495
                 126.000      104.910        1.730       12.538
                 123.000      100.960        1.465        8.164
                 118.220       97.870        1.048        5.540

                IN WALL T    DEL WALL T   HEAT FLUX       H T COEF
                   (F)          (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                 113.347       12.152      13194.8       1085.7
                 111.502       15.367      11710.3        761.9
                 108.337       17.583      11230.2        638.6
                 105.009       20.990       9547.0        454.8
                 101.044       21.955       8084.6        368.2
                  97.930       20.289       5783.4        285.0

                  QUALITY        XTT          F(XTT)  NU*F2/PR*(RE**.9)

                   0.890     5.006E-02    4.773E 00    6.948E 00
                   0.674     1.735E-01    1.847E 00    1.942E 00
                   0.481     3.559E-01    1.120E 00    1.098E 00
                   0.303     7.035E-01    7.185E-01    6.099E-01
                   0.165     1.398E 00    4.717E-01    4.248E-01
                   0.069     3.240E 00    2.905E-01    3.012E-01
```

```
RUN NO. 7                        REFRIGERANT 12

FREON MASS FLUX   5.2174331E 05  WTR TEMP IN    78.61     FREON TEMP IN   112.17

WTR FLOW RATE     716.50         MEAN HT COEF  1088.5     HEAT BAL ERROR   0.027


                 VAPOR TEMP   OUT WALL T    DEL WTR T     P GRAD
                    (F)          (F)           (F)      (LBF/FT3)

                  112.000      106.130        2.601       73.191
                  112.170      104.780        2.539       40.823
                  111.430      103.260        2.583       63.568
                  111.170      100.780        2.728       56.570
                  109.750       98.130        2.614       43.156
                  108.570       96.000        2.513       34.408

                 IN WALL T    DEL WALL T   HEAT FLUX       H T COEF
                    (F)          (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                  106.227        5.772       9374.5       1624.0
                  104.875        7.294       9151.0       1254.4
                  103.357        8.072       9309.6       1153.1
                  100.882       10.287       9832.2        955.7
                   98.228       11.521       9421.3        817.6
                   96.094       12.475       9057.3        726.0

                   QUALITY        XTT         F(XTT)  NU*F2/PR*(RE**.9)

                    0.938     2.543E-02    8.350E 00    1.417E 01
                    0.817     7.732E-02    3.385E 00    4.364E 00
                    0.698     1.390E-01    2.172E 00    2.629E 00
                    0.574     2.256E-01    1.533E 00    1.629E 00
                    0.453     3.453E-01    1.143E 00    1.129E 00
                    0.337     5.295E-01    8.618E-01    8.534E-01
```

```
RUN NO. 8                                    REFRIGERANT 12

FREON MASS FLUX    1.9431068E 05   WTR TEMP IN     66.41      FREON TEMP IN    94.17

WTR FLOW RATE      625.82          MEAN HT COEF    461.6      HEAT BAL ERROR   0.011

               VAPOR TEMP    OUT WALL T     DEL WTR T       P GRAD
                  (F)           (F)            (F)        (LBF/FT3)

                93.700        85.260         1.590         16.329
                93.650        84.260         1.650         14.580
                92.910        82.910         1.780         11.663
                93.170        80.700         1.700          6.415
                92.300        78.000         1.630          4.665
                91.000        75.700         1.270          1.749

               IN WALL T     DEL WALL T    HEAT FLUX        H T COEF
                 (F)            (F)       (BTU/HR-FT2)  (BTU/HR-FT2-F)

                85.312         8.387        5005.3           596.7
                84.314         9.335        5194.2           556.3
                82.968         9.941        5603.4           563.6
                80.755        12.414        5351.6           431.0
                78.053        14.246        5131.2           360.1
                75.741        15.258        3997.9           262.0

                QUALITY         XTT          F(XTT)   NU*F2/PR*(RE**.9)

                 0.917      2.984E-02     7.300E 00     9.391E 00
                 0.748      9.782E-02     2.826E 00     3.441E 00
                 0.571      2.004E-01     1.667E 00     2.228E 00
                 0.389      3.901E-01     1.053E 00     1.264E 00
                 0.218      8.119E-01     6.567E-01     8.595E-01
                 0.073      2.505E 00     3.359E-01     5.419E-01
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RUN NO. 9                          REFRIGERANT 12

FREON MASS FLUX   2.7648256E 05    WTR TEMP IN     75.35     FREON TEMP IN   108.91

WTR FLOW RATE     706.71           MEAN HT COEF   503.0      HEAT BAL ERROR  -0.037


                      VAPOR TEMP   OUT WALL T    DEL WTR T     P GRAD
                         (F)          (F)           (F)       (LBF/FT3)

                       108.830       99.000        1.830       27.993
                       108.650       97.350        1.860       23.327
                       107.710       96.040        2.050       16.912
                       107.880       92.170        2.000        9.914
                       106.740       88.650        2.080        5.831
                       104.780       85.740        1.440        2.332

                      IN WALL T    DEL WALL T    HEAT FLUX       H T COEF
                         (F)          (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                        99.067        9.762       6505.5         666.3
                        97.418       11.231       6612.1         588.7
                        96.115       11.594       7287.6         628.5
                        92.244       15.635       7109.8         454.7
                        88.727       18.012       7394.2         410.4
                        85.793       18.986       5119.0         269.6

                        QUALITY       XTT         F(XTT)   NU*F2/PR*(RE**.9)

                         0.920    3.196E-02    6.893E 00    7.967E 00
                         0.760    1.023E-01    2.731E 00    2.791E 00
                         0.593    2.048E-01    1.641E 00    1.909E 00
                         0.418    3.886E-01    1.056E 00    1.020E 00
                         0.245    7.857E-01    6.703E-01    7.406E-01
                         0.102    1.998E 00    3.825E-01    4.205E-01
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RUN NO. 10                          REFRIGERANT 12

FREON MASS FLUX   1.1875593E 05     WTR TEMP IN     48.96      FREON TEMP IN     74.86

WTR FLOW RATE     412.63            MEAN HT COEF   418.9       HEAT BAL ERROR   -0.001

                      VAPOR TEMP    OUT WALL T     DEL WTR T      P GRAD
                         (F)           (F)            (F)       (LBF/FT3)

                        72.770        66.640         1.720         0.000
                        72.410        66.140         1.460         0.000
                        71.740        65.130         1.590         0.000
                        72.000        63.680         1.540         0.000
                        71.700        61.740         1.640         0.000
                        70.500        58.500         1.220         0.000

                      IN WALL T     DEL WALL T    HEAT FLUX       H T COEF
                         (F)           (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                        66.677         6.092        3570.1         585.9
                        66.171         6.238        3030.4         485.7
                        65.164         6.575        3300.2         501.8
                        63.713         8.286        3196.4         385.7
                        61.775         9.924        3404.0         342.9
                        58.526        11.973        2532.2         211.4

                        QUALITY        XTT          F(XTT)   NU*F2/PR*(RE**.9)

                         0.911      2.654E-02     8.055E 00     1.330E 01
                         0.743      8.270E-02     3.213E 00     4.540E 00
                         0.583      1.579E-01     1.978E 00     3.126E 00
                         0.417      2.897E-01     1.288E 00     1.812E 00
                         0.250      5.744E-01     8.176E-01     1.303E 00
                         0.103      1.472E 00     4.574E-01     6.922E-01
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RUN NO. 11                              REFRIGERANT 12

FREON MASS FLUX    2.8129662E 05        WTR TEMP IN      75.52       FREON TEMP IN    107.42

WTR FLOW RATE      696.57               MEAN HT COEF     475.3       HEAT BAL ERROR    0.003

                  VAPOR TEMP     OUT WALL T     DEL WTR T       P GRAD
                     (F)            (F)            (F)        (LBF/FT3)

                   107.380        97.430          2.160         29.160
                   107.210        95.960          2.140         24.494
                   107.120        95.000          0.000         23.327
                   106.830        93.050          2.220         17.495
                   106.000        89.960          2.060         12.247
                   105.000        87.960          1.910          5.831

                  IN WALL T      DEL WALL T     HEAT FLUX        H T COEF
                    (F)            (F)        (BTU/HR-FT2)  (BTU/HR-FT2-F)

                    97.508         9.871         7568.4          766.7
                    96.038        11.171         7498.3          671.1
                    95.000        12.119            0.0            0.0
                    93.131        13.698         7778.7          567.8
                    90.035        15.964         7218.0          452.1
                    88.029        16.970         6692.4          394.3

                   QUALITY          XTT           F(XTT)  NU*F2/PR*(RE**.9)

                    0.909      3.600E-02      6.246E 00      8.111E 00
                    0.730      1.173E-01      2.463E 00      2.835E 00
                    0.640      1.706E-01      1.870E 00      0.000E 00
                    0.548      2.404E-01      1.466E 00      1.556E 00
                    0.372      4.556E-01      9.506E-01      9.396E-01
                    0.210      9.282E-01      6.045E-01      6.759E-01
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RUN NO. 12                         REFRIGERANT 12

FREON MASS FLUX   6.6783725E 05   WTR TEMP IN    36.96     FREON TEMP IN    81.00

WTR FLOW RATE    1172.11          MEAN HT COEF  1804.1     HEAT BAL ERROR   0.025

                VAPOR TEMP    OUT WALL T     DEL WTR T      P GRAD
                   (F)           (F)           (F)        (LBF/FT3)

                  80.520        72.860         3.080       228.031
                  78.570        72.820         2.650       222.199
                  76.870        67.090         2.780       191.872
                  75.480        65.130         2.510       150.174
                  73.350        61.870         2.410       120.139
                  71.260        59.590         2.320        73.774

                IN WALL T     DEL WALL T    HEAT FLUX        H T COEF
                   (F)           (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                  73.049         7.470       18159.6         2430.7
                  72.982         5.587       15624.4         2796.4
                  67.260         9.609       16390.8         1705.7
                  65.284        10.195       14798.9         1451.4
                  62.018        11.331       14209.3         1253.9
                  59.732        11.527       13678.7         1186.6

                 QUALITY          XTT          F(XTT)  NU*F2/PR*(RE**.9)

                   0.916     2.712E-02     7.910E 00     1.356E 01
                   0.763     8.001E-02     3.297E 00     6.519E 00
                   0.619     1.455E-01     2.100E 00     2.667E 00
                   0.480     2.392E-01     1.471E 00     1.745E 00
                   0.353     3.743E-01     1.083E 00     1.256E 00
                   0.234     6.186E-01     7.797E-01     1.031E 00
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RUN NO. 13                          REFRIGERANT 12

FREON MASS FLUX   7.6344000E 05   WTR TEMP IN     47.41     FREON TEMP IN    94.48

WTR FLOW RATE     890.98          MEAN HT COEF  1989.7      HEAT BAL ERROR   0.039


                  VAPOR TEMP   OUT WALL T    DEL WTR T     P GRAD
                     (F)          (F)          (F)       (LBF/FT3)

                   91.700       85.780        3.410       226.864
                   90.220       85.430        3.080       213.742
                   87.960       80.610        3.250       174.376
                   87.700       78.870        3.020       161.254
                   85.700       75.570        3.160       128.887
                   83.860       73.350        3.040        89.521

                  IN WALL T    DEL WALL T   HEAT FLUX       H T COEF
                    (F)           (F)     (BTU/HR-FT2)  (BTU/HR-FT2-F)

                   85.939        5.760      15283.2         2652.9
                   85.573        4.646      13804.1         2971.0
                   80.761        7.198      14566.1         2023.5
                   79.011        8.688      13535.2         1557.7
                   75.717        9.982      14162.7         1418.7
                   73.491       10.368      13624.9         1314.1

                   QUALITY        XTT         F(XTT)  NU*F2/PR*(RE**.9)

                    0.939     2.175E-02     9.537E 00    1.724E 01
                    0.820     6.481E-02     3.886E 00    7.733E 00
                    0.706     1.130E-01     2.533E 00    3.490E 00
                    0.590     1.789E-01     1.808E 00    2.028E 00
                    0.481     2.616E-01     1.382E 00    1.514E 00
                    0.372     3.848E-01     1.063E 00    1.196E 00
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RUN NO. 14                          REFRIGERANT 12

FREON MASS FLUX   9.0910312E 05     WTR TEMP IN     72.05      FREON TEMP IN    112.48

WTR FLOW RATE     996.25            MEAN HT COEF  1969.4       HEAT BAL ERROR    0.046

                  VAPOR TEMP    OUT WALL T     DEL WTR T      P GRAD
                     (F)           (F)           (F)        (LBF/FT3)

                   109.710       103.390         3.160       203.536
                   108.830       103.610         2.870       212.867
                   106.870        98.570         3.070       172.044
                   106.830        97.390         2.970       166.503
                   105.170        94.570         3.140       134.719
                   103.430        92.040         3.150        96.227

                  IN WALL T     DEL WALL T    HEAT FLUX        H T COEF
                     (F)           (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                   103.555         6.154       15835.9        2572.8
                   103.759         5.070       14382.6        2836.7
                    98.730         8.139       15384.9        1890.1
                    97.545         9.284       14883.8        1603.0
                    94.733        10.436       15735.7        1507.8
                    92.204        11.225       15785.8        1406.2

                    QUALITY         XTT          F(XTT)   NU*F2/PR*(RE**.9)

                     0.944     2.258E-02     9.237E 00     1.539E 01
                     0.834     6.765E-02     3.757E 00     6.716E 00
                     0.728     1.171E-01     2.466E 00     2.952E 00
                     0.616     1.854E-01     1.762E 00     1.872E 00
                     0.508     2.714E-01     1.347E 00     1.429E 00
                     0.398     3.985E-01     1.038E 00     1.125E 00
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RUN NO. 15                         REFRIGERANT 12

FREON MASS FLUX   9.1649862E 05   WTR TEMP IN    108.96     FREON TEMP IN    140.38

WTR FLOW RATE    1810.95          MEAN HT COEF  1369.0     HEAT BAL ERROR   -0.028

                         VAPOR TEMP     OUT WALL T     DEL WTR T       P GRAD
                            (F)            (F)            (F)        (LBF/FT3)

                          138.250        129.960         1.950       160.380
                          138.040        128.000         1.860       123.055
                          136.710        123.580         1.790        92.728
                          137.500        123.380         1.700        80.190
                          136.250        121.420         1.650        56.861
                          135.080        119.460         1.550        31.784

                         IN WALL T      DEL WALL T     HEAT FLUX        H T COEF
                           (F)            (F)        (BTU/HR-FT2)  (BTU/HR-FT2-F)

                          130.145          8.104        17763.5         2191.6
                          128.176          9.863        16943.7         1717.8
                          123.749         12.960        16306.0         1258.1
                          123.541         13.958        15486.2         1109.4
                          121.576         14.673        15030.7         1024.3
                          119.607         15.472        14119.7          912.5

                           QUALITY         XTT          F(XTT)   NU*F2/PR*(RE**.9)

                            0.931      3.464E-02     6.448E 00     1.055E 01
                            0.790      1.090E-01     2.603E 00     3.241E 00
                            0.659      1.973E-01     1.685E 00     1.575E 00
                            0.528      3.242E-01     1.193E 00     1.054E 00
                            0.409      4.954E-01     8.999E-01     8.052E-01
                            0.297      7.690E-01     6.794E-01     6.190E-01
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RUN NO. 16                       REFRIGERANT 12

FREON MASS FLUX   1.1296822E 06  WTR TEMP IN    95.91     FREON TEMP IN   124.62

WTR FLOW RATE    1843.07         MEAN HT COEF  2011.8     HEAT BAL ERROR  -0.059

                 VAPOR TEMP    OUT WALL T    DEL WTR T     P GRAD
                    (F)           (F)           (F)       (LBF/FT3)

                  122.670       116.130        1.926      274.687
                  121.710       114.290        1.804      233.280
                  120.080       111.710        1.757      193.622
                  118.910       109.710        1.687       96.227
                  117.500       108.170        1.639      157.463
                  115.880       106.430        1.583      122.472

                 IN WALL T     DEL WALL T   HEAT FLUX       H T COEF
                    (F)           (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                  116.316         6.353      17856.1        2810.2
                  114.464         7.245      16725.0        2308.2
                  111.879         8.200      16289.3        1986.4
                  109.872         9.037      15640.3        1730.6
                  108.328         9.171      15195.3        1656.7
                  106.582         9.297      14676.1        1578.5

                   QUALITY        XTT          F(XTT)  NU*F2/PR*(RE**.9)

                    0.947     2.420E-02    8.710E 00    1.433E 01
                    0.840     7.199E-02    3.579E 00    4.665E 00
                    0.741     1.230E-01    2.377E 00    2.670E 00
                    0.646     1.834E-01    1.775E 00    1.783E 00
                    0.555     2.556E-01    1.405E 00    1.407E 00
                    0.468     3.449E-01    1.144E 00    1.155E 00
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RUN NO. 17                        REFRIGERANT 22

FREON MASS FLUX    2.5736990F 05   WTR TEMP IN     80.35      FREON TEMP IN    96.88

WTR FLOW RATE     1250.82          MEAN HT COEF    754.0      HEAT BAL ERROR  -0.065


                    VAPOR TEMP    OUT WALL T    DEL WTR T     P GRAD
                       (F)           (F)           (F)       (LBF/FT3)

                     95.480        89.780         0.950        20.411
                     95.960        89.610         0.870        26.243
                     95.430        88.170         0.870        20.411
                     96.120        87.740         0.910        20.411
                     95.300        86.700         0.740        14.580
                     93.910        85.700         0.780        10.205

                    IN WALL T     DEL WALL T   HEAT FLUX       H T COEF
                      (F)            (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                     89.842         5.637        5977.3        1060.2
                     89.667         6.292        5473.9         869.8
                     88.227         7.202        5473.9         759.9
                     87.799         8.320        5725.6         688.1
                     86.748         8.551        4656.0         544.4
                     85.751         8.158        4907.7         601.5

                     QUALITY        XTT          F(XTT)   NU*F2/PR*(RE**.9)

                      0.943     2.373E-02     8.855E 00     1.414E 01
                      0.832     7.080E-02     3.626E 00     4.678E 00
                      0.728     1.232E-01     2.375E 00     2.715E 00
                      0.618     1.942E-01     1.704E 00     1.852E 00
                      0.520     2.771E-01     1.328E 00     1.206E 00
                      0.432     3.774E-01     1.077E 00     1.154E 00
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RUN NO. 18                         REFRIGERANT 22

FREON MASS FLUX   2.4756590E 05    WTR TEMP IN     60.77     FREON TEMP IN    85.09

WTR FLOW RATE    1089.37           MEAN HT COEF    764.8     HEAT BAL ERROR   0.025

               VAPOR TEMP   OUT WALL T    DEL WTR T     P GRAD
                  (F)          (F)           (F)       (LBF/FT3)

                 83.270       76.610        1.460       24.202
                 84.090       76.130        1.320       24.202
                 83.230       73.740        1.450       20.995
                 84.170       72.960        1.180       17.204
                 82.910       70.960        1.280       12.247
                 84.130       69.350        1.180        7.581

               IN WALL T    DEL WALL T    HEAT FLUX       H T COEF
                  (F)          (F)       (BTU/HR-FT2)  (BTU/HR-FT2-F)

                 76.693        6.576       8000.5        1216.5
                 76.205        7.884       7233.3         917.4
                 73.822        9.407       7945.7         844.6
                 73.027       11.142       6466.2         580.3
                 71.033       11.876       7014.1         590.5
                 69.417       14.712       6466.2         439.5

                QUALITY        XTT          F(XTT)   NU*F2/PR*(RE**.9)

                  0.924     2.844E-02     7.601E 00     1.291E 01
                  0.777     8.870E-02     3.045E 00     3.944E 00
                  0.632     1.660E-01     1.907E 00     2.385E 00
                  0.492     2.810E-01     1.315E 00     1.249E 00
                  0.365     4.432E-01     9.680E-01     1.053E 00
                  0.232     7.994E-01     6.631E-01     6.684E-01
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RUN NO. 19                          REFRIGERANT 22

FRECN MASS FLUX    2.5346834E 05    WTR TEMP IN      78.43      FREON TEMP IN   100.04

WTR FLOW RATE      879.57           MEAN HT COEF    820.4       HEAT BAL ERROR   0.045


                VAPOR TEMP    OUT WALL T     DEL WTR T      P GRAD
                   (F)           (F)            (F)        (LBF/FT3)

                  98.700        93.430         1.430        24.202
                  99.260        93.220         1.310        19.828
                  98.590        91.220         1.440        15.746
                  99.300        90.430         1.300        14.580
                  98.260        88.740         1.390        14.580
                  97.780        87.090         1.350         9.331

                IN WALL T     DEL WALL T    HEAT FLUX       H T COEF
                  (F)            (F)       (BTU/HR-FT2)  (BTU/HR-FT2-F)

                  93.495         5.204        6326.9        1215.7
                  93.280         5.979        5796.0         969.2
                  91.286         7.303        6371.2         872.3
                  90.489         8.810        5751.8         652.8
                  88.804         9.455        6150.0         650.3
                  87.152        10.627        5973.0         562.0

                 QUALITY         XTT          F(XTT)   NU*F2/PR*(RE**.9)

                   0.937     2.672E-02     8.009E 00     1.520E 01
                   0.817     7.995E-02     3.299E 00     4.922E 00
                   0.697     1.440E-01     2.116E 00     2.901E 00
                   0.576     2.329E-01     1.499E 00     1.635E 00
                   0.461     3.508E-01     1.131E 00     1.328E 00
                   0.343     5.454E-01     8.454E-01     9.702E-01
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RUN NO. 20                         REFRIGERANT 22

FREON MASS FLUX   2.2254859E 05    WTR TEMP IN     98.35     FREON TEMP IN   118.26

WTR FLOW RATE     558.51           MEAN HT COEF   614.3      HEAT BAL ERROR  -0.056

                 VAPOR TEMP    OUT WALL T     DEL WTR T      P GRAD
                    (F)           (F)            (F)        (LBF/FT3)

                  116.610       112.500         1.170        11.955
                  117.210       112.350         1.220        13.121
                  116.830       111.580         1.260        11.955
                  117.420       110.260         1.300        10.205
                  116.740       108.830         1.440         8.747
                  116.260       107.540         1.430         6.123

                 IN WALL T     DEL WALL T    HEAT FLUX        H T COEF
                    (F)           (F)       (BTU/HR-FT2)  (BTU/HR-FT2-F)

                  112.534         4.075        3287.0         806.4
                  112.385         4.824        3427.5         710.4
                  111.616         5.213        3539.9         679.0
                  110.298         7.121        3652.2         512.8
                  108.872         7.867        4045.6         514.1
                  107.581         8.678        4017.5         462.9

                   QUALITY          XTT          F(XTT)  NU*F2/PR*(RE**.9)

                    0.960     2.003E-02     1.023E 01     1.718E 01
                    0.879     6.027E-02     4.116E 00     5.862E 00
                    0.794     1.058E-01     2.662E 00     3.588E 00
                    0.706     1.629E-01     1.934E 00     2.004E 00
                    0.614     2.351E-01     1.489E 00     1.593E 00
                    0.518     3.341E-01     1.169E 00     1.186E 00
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RUN NO. 21                           REFRIGERANT 22

FREON MASS FLUX   1.3886631F 05   WTR TEMP IN     75.17      FREON TEMP IN    93.43

WTR FLOW RATE     589.97          MEAN HT COEF    533.6      HEAT BAL ERROR  -0.064

                VAPOR TEMP    OUT WALL T     DEL WTR T      P GRAD
                   (F)           (F)            (F)       (LBF/FT3)

                  93.260        88.900         1.050         8.164
                  93.700        88.740         1.000         8.164
                  93.220        87.300         1.130         6.706
                  93.570        86.430         1.150         6.415
                  92.700        84.960         1.150         4.957
                  92.390        83.680         1.130         3.790

                IN WALL T     DEL WALL T    HEAT FLUX       H T COEF
                  (F)            (F)       (BTU/HR-FT2)  (BTU/HR-FT2-F)

                  88.932         4.327        3116.0         720.0
                  88.770         4.929        2967.6         602.0
                  87.334         5.885        3353.4         569.8
                  86.465         7.104        3412.8         480.3
                  84.995         7.704        3412.8         442.9
                  83.714         8.675        3353.4         386.5

                 QUALITY          XTT           F(XTT)  NU*F2/PR*(RE**.9)

                   0.944     2.275E-02     9.179E 00     1.637E 01
                   0.836     6.779E-02     3.751E 00     5.527E 00
                   0.725     1.225E-01     2.384E 00     3.382E 00
                   0.605     2.008E-01     1.664E 00     2.101E 00
                   0.486     3.076E-01     1.236E 00     1.552E 00
                   0.367     4.759E-01     9.238E-01     1.136E 00
```

```
RUN NO. 22                    REFRIGERANT 22

FREON MASS FLUX   1.4703040E 05   WTR TEMP IN    74.46     FREON TEMP IN    93.22

WTR FLOW RATE     485.72          MEAN HT COEF   568.2     HEAT BAL ERROR  -0.070

              VAPOR TEMP    OUT WALL T     DEL WTR T      P GRAD
                 (F)           (F)           (F)        (LBF/FT3)

               92.260        88.900         1.130         8.164
               92.570        88.610         1.020         9.331
               92.260        87.390         1.120         9.331
               92.700        86.780         1.180         8.164
               92.090        85.700         1.220         8.164
               91.870        84.570         1.260         6.706

              IN WALL T     DEL WALL T    HEAT FLUX        H T COEF
                (F)            (F)       (BTU/HR-FT2)  (BTU/HR-FT2-F)

               88.928         3.331        2760.9         828.7
               88.635         3.934        2492.1         633.4
               87.418         4.841        2736.4         565.2
               86.810         5.889        2883.0         489.4
               85.731         6.358        2980.8         468.7
               84.602         7.267        3078.5         423.5

               QUALITY         XTT          F(XTT)   NU*F2/PR*(RE**.9)

                0.954      1.878E-02     1.081E 01     2.108E 01
                0.866      5.420E-02     4.479E 00     6.562E 00
                0.780      9.337E-02     2.927E 00     3.845E 00
                0.685      1.451E-01     2.105E 00     2.470E 00
                0.589      2.107E-01     1.609E 00     1.887E 00
                0.488      3.029E-01     1.249E 00     1.418E 00
```

```
RUN NO. 23                        REFRIGERANT 22

FREON MASS FLUX   1.5033075E 05   WTR TEMP IN     49.68      FREON TEMP IN    82.87

WTR FLOW RATE     544.99          MEAN HT COEF    507.8      HEAT BAL ERROR  -0.028

                    VAPOR TEMP   OUT WALL T    DEL WTR T     P GRAD
                       (F)          (F)           (F)       (LBF/FT3)

                     78.870       72.000        1.640        0.000
                     79.550       71.830        1.410        0.000
                     78.830       69.520        2.000        0.000
                     79.410       68.410        2.040        0.000
                     78.130       65.610        2.050        0.000
                     76.170       61.830        1.720        0.000

                    IN WALL T    DEL WALL T   HEAT FLUX       H T COEF
                       (F)          (F)     (BTU/HR-FT2)  (BTU/HR-FT2-F)

                     72.046        6.823       4495.9        658.9
                     71.870        7.679       3865.4        503.3
                     69.577        9.252       5482.8        592.5
                     68.468       10.941       5592.5        511.1
                     65.668       12.461       5619.9        450.9
                     61.879       14.290       4715.2        329.9

                     QUALITY        XTT          F(XTT)  NU*F2/PR*(RE**.9)

                      0.932     2.444E-02     8.637E 00     1.158E 01
                      0.801     7.460E-02     3.481E 00     3.599E 00
                      0.656     1.450E-01     2.105E 00     2.678E 00
                      0.482     2.782E-01     1.324E 00     1.639E 00
                      0.311     5.275E-01     8.639E-01     1.136E 00
                      0.157     1.146E 00     5.314E-01     7.004E-01
```

```
RUN NO. 24                          REFRIGERANT 22

FREON MASS FLUX   7.3864387E 05    WTR TEMP IN     36.57     FREON TEMP IN    81.83

WTR FLOW RATE    1508.44           MEAN HT COEF  2062.5     HEAT BAL ERROR   0.028

                    VAPOR TEMP   OUT WALL T    DEL WTR T     P GRAD
                       (F)          (F)           (F)      (LBF/FT3)

                     79.050       71.220        3.190      183.707
                     79.050       72.050        2.620      189.540
                     77.460       67.410        2.850      148.716
                     77.820       65.430        2.500      134.135
                     76.090       62.410        2.770      119.555
                     74.640       55.320        2.360       43.740

                    IN WALL T    DEL WALL T   HEAT FLUX       H T COEF
                       (F)          (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                     71.472        7.577      24205.1        3194.2
                     72.257        6.792      19880.0        2926.6
                     67.635        9.824      21625.2        2201.1
                     65.627       12.192      18969.5        1555.8
                     62.628       13.461      21018.2        1561.4
                     55.506       19.133      17907.2         935.9

                     QUALITY        XTT         F(XTT)  NU*F2/PR*(RE**.9)

                      0.925     2.714E-02    7.904E 00    1.362E 01
                      0.785     8.119E-02    3.259E 00    5.154E 00
                      0.656     1.434E-01    2.123E 00    2.605E 00
                      0.527     2.334E-01    1.496E 00    1.408E 00
                      0.405     3.575E-01    1.117E 00    1.162E 00
                      0.287     5.652E-01    8.262E-01    5.975E-01
```

```
RUN NO. 25                              REFRIGERANT 22

FREON MASS FLUX    5.9624675E 05    WTR TEMP IN     53.05     FREON TEMP IN     96.42

WTR FLOW RATE     1491.60           MEAN HT COEF  1422.4      HEAT BAL ERROR    0.029


                  VAPOR TEMP    OUT WALL T     DEL WTR T      P GRAD
                     (F)           (F)            (F)       (LBF/FT3)

                    93.910        84.090         2.770      110.807
                    94.480        84.570         2.590       99.143
                    93.170        79.640         2.720       72.900
                    94.170        77.820         2.460       55.403
                    92.480        73.700         2.320       34.991
                    91.000        70.550         2.050       21.870

                  IN WALL T     DEL WALL T    HEAT FLUX        H T COEF
                     (F)           (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                    84.306         9.603       20783.6       2164.1
                    84.772         9.707       19433.0       2001.8
                    79.852        13.317       20408.5       1532.4
                    78.012        16.157       18457.6       1142.3
                    73.881        18.598       17407.2        935.9
                    70.710        20.289       15381.4        758.0

                   QUALITY          XTT          F(XTT)   NU*F2/PR*(RE**.9)

                     0.915     3.444E-02     6.479E 00     1.021E 01
                     0.748     1.110E-01     2.568E 00     3.764E 00
                     0.586     2.143E-01     1.589E 00     1.889E 00
                     0.423     3.902E-01     1.053F 00     1.064E 00
                     0.280     6.808E-01     7.336E-01     7.217E-01
                     0.151     1.361E 00     4.791E-01     5.074E-01
```

```
RUN NO. 26                              REFRIGERANT 22

FREON MASS FLUX   5.8922237E 05   WTR TEMP IN    36.33     FREON TEMP IN    89.04

WTR FLOW RATE    1569.60          MEAN HT COEF  1384.4     HEAT BAL ERROR   0.063

                  VAPOR TEMP   OUT WALL T    DEL WTR T     P GRAD
                     (F)          (F)           (F)       (LBF/FT3)

                    85.780       74.730        3.430        77.274
                    86.700       74.550        2.830        94.770
                    85.000       68.320        3.050        64.152
                    86.520       65.870        3.030        42.281
                    84.090       59.860        2.330        24.785
                    81.520       54.140        1.770        11.663

                  IN WALL T    DEL WALL T   HEAT FLUX       H T COEF
                    (F)          (F)       (BTU/HR-FT2)  (BTU/HR-FT2-F)

                    75.012       10.767      27081.5        2515.0
                    74.782       11.917      22344.2        1874.9
                    68.570       16.429      24081.2        1465.7
                    66.119       20.400      23923.3        1172.6
                    60.051       24.038      18396.4         765.2
                    54.285       27.234      13975.0         513.1

                    QUALITY        XTT          F(XTT)   NU*F2/PR*(RE**.9)

                     0.892     4.135E-02     5.574E 00     9.624E 00
                     0.689     1.360E-01     2.206E 00     2.951E 00
                     0.504     2.709E-01     1.349E 00     1.551E 00
                     0.304     5.851E-01     8.080E-01     9.344E-01
                     0.140     1.388E 00     4.737E-01     5.087E-01
                     0.020     8.808E 00     1.687E-01     3.045E-01
```

```
RUN NO. 27                         REFRIGERANT 22

FREON MASS FLUX   6.8991512E 05   WTR TEMP IN     82.91     FREON TEMP IN   113.04

WTR FLOW RATE    1153.34          MEAN HT COEF  1726.8      HEAT BAL ERROR   0.031

                     VAPOR TEMP   OUT WALL T    DEL WTR T     P GRAD
                        (F)          (F)           (F)       (LBF/FT3)

                      111.460      106.170        2.180      108.475
                      111.680      105.790        2.080      102.643
                      110.740      103.040        2.260       86.896
                      111.230      101.910        2.220       79.315
                      109.830      100.000        2.350       67.651
                      109.120       98.220        2.360       48.988

                     IN WALL T    DEL WALL T   HEAT FLUX       H T COEF
                       (F)           (F)      (BTU/HR-FT2)  (BTU/HR-FT2-F)

                      106.301        5.158      12647.5       2451.9
                      105.915        5.764      12067.3       2093.4
                      103.176        7.563      13111.6       1733.5
                      102.044        9.185      12879.6       1402.1
                      100.142        9.687      13633.8       1407.2
                       98.362       10.757      13691.8       1272.7

                       QUALITY        XTT         F(XTT)  NU*F2/PR*(RE**.9)

                        0.952     2.324E-02     9.014E 00    1.692E 01
                        0.857     6.850E-02     3.721E 00    5.742E 00
                        0.762     1.197E-01     2.426E 00    3.081E 00
                        0.662     1.871E-01     1.750E 00    1.851E 00
                        0.564     2.691E-01     1.355E 00    1.494E 00
                        0.462     3.868E-01     1.059E 00    1.129E 00
```

APPENDIX 2

LIST OF RELEVANT VARIABLES FOR THEORETICAL PROGRAM

TSAT	refrigerant temperature entering test section
DET	difference between vapor temperature and inside wall temperature
G	refrigerant flow rate
E	ratio of eddy conductivity to eddy viscosity
GR	gravitational constant
A	axial acceleration due to external forces
DDXDZ	D(dx/dz)
UL,UV	liquid and vapor viscosities
KL	liquid thermal conductivity
CL	liquid specific heat
ROL,ROV	liquid and vapor densities
RU	ratio of liquid to vapor viscosities
RRO	ratio of vapor to liquid densities
PR	Prandtl number
XL	1 minus quality
X	quality
DPF	frictional pressure gradient
V	void fraction
DPG	gravitational pressure gradient
RE	Reynolds number
DPM	momentum pressure gradient
DPT	total pressure gradient
DP	delta plus
TAO	wall shear stress

BT	β
FO	F_0
M	M
MUSED	indicator showing if M term was used in the calculation of F_2
F2	F_2
K	indicator showing number of iterations to obtain correct D(dx/dz)
YDIS	right term of Eq. (31)
HZ	local heat transfer coefficient
L	total length of condensation
DDD	new value of D(dz/dz) for iteration
HM	mean heat transfer coefficient

```
PAGE    1    TRAVISS

// JOB T  1130 1131                    1131 1131      TRAVISS

LOG DRIVE   CART SPEC   CART AVAIL  PHY DRIVE
  0000         1130        1130        0001
  0001         1131        1131        0000

V2 M09   ACTUAL  8K  CONFIG  8K

// FOR
*IOCS (CARD,1403 PRINTER)
* LIST SOURCE PROGRAM
      REAL L,M,KL
      DIMENSION SH(19)
      DATA D/.0265/
      READ (2,10) N
10    FORMAT (I6)
      DO 21 II=1,N
      READ (2,11) TSAT,DET,G,E
11    FORMAT (4F8.0)
      GR=4.17E8
C     GRAVITY FORCE
      A=0.0
C     QUALITY GRADIENT
      DDXDZ=-.001
C     PHYSICAL PROPERTIES
      UL=0.673-(0.00135*TSAT)
      UV=0.028+((0.5*TSAT)/10000.)
      KL=0.0699-((0.235*TSAT)/1000.)
      ROL=86.056-(.149*TSAT)
      IF(TSAT-100) 5,5,6
5     ROV=(.05*TSAT)-1.1115
      HFG=98.363-(0.255*TSAT)
      CL=.255+.6*TSAT/1000.
      GO TO 7
6     ROV=.0665*TSAT-2.6593
```

```
      HFG=101.6-(0.288*TSAT)
      CL=.24+.75*TSAT/1000.
7     RU=UL/UV
      RRO=ROV/ROL
      PR=UL*CL/KL
      WRITE(5,12) TSAT,G,D,DET,E
12    FORMAT(1H1,5X'FREON 22 AT ',F5.1,5X'G= ',F9.1,5X'D= ',
     1F6.4,5X,'DET='F4.1,5X,'E=',F4.1/)
      WRITE(5,13) UV,UL
13    FORMAT(5X'VAPOR VISCOSITY',F8.4,5X'LIQUID VISCOSITY',F7.3/)
      WRITE(5,14) ROV,ROL
14    FORMAT(5X'VAPOR DENSITY',F10.4,5X'LIQUID DENSITY',F9.3/)
      WRITE(5,15) KL,CL,HFG,PR
15    FORMAT(5X'CONDUCTIVITY',F8.4,3X'SPECIFIC HEAT',F7.3,
     13X'LATENT HEAT',F8.3,3X'PR',F6.2//)
      WRITE(5,16)
16    FORMAT(2X,'X',5X,'DPF',10X,'DPM',7X,'DPT',8X,'RE',11X,'HZ',7X,
     1'HM',9X,'L',13X,'M',11X,'DP',5X,'MUSED'/)
      DO 21 I=1,19
      XL=.05*I
      X=1-XL
      A1=G*G/(GR*ROV*D)
      A2=0.09*((UV/(G*D))**0.2)
      A3=X**1.8
      A4=5.7*(RU**.0523)*(XL**.47)*(X**1.33)*(RRO**.261)
      A5=8.11*(RU**.105)*(XL**.94)*(X**.86)*(RRO**.522)
      DPF=-(A1*A2*(A3+A4+A5))
C     VOID FRACTION
      V=1/(1+(XL*RRO**.667)/X)
C     GRAVITY PRESSURE DROP
      DPG=((V*ROV+(1-V)*ROL)*A)/GR
      RE=(XL*G*D)/UL
C     MOMENTUM PRESSURE DROP
      B1=2*X
      B2=(1-2*X)*(RRO**.333)
```

```
      B3=(1-2*X)*(RRO**.667)
      B4=2*XL*RRO
1     DPM=-(A1*DDXDZ*(B1+B2+B3+B4))
C     TOTAL PRESSURE DROP
      DPT=DPF+DPM+DPG
C     DELTA PLUS
      IF(RE-50.) 30,30,31
30    DP=.7071*RE**.5
      GO TO 36
31    IF(RE-1125.) 32,32,33
32    DP=.4818*RE**.585
      GO TO 36
33    DP=.095*RE**.812
36    TAO=-(DPF*D/4.)
C     CALCULATE BETA
      IF(DP-90.) 37,37,38
37    BT=2.368-.259*ALOG(DP)
      GO TO 39
38    BT=1.2
C     CALCULATE FO
39    G1=RRO**.333/(1.-V)
      G2=(XL*(2.-BT)*RRO)/((1.-V)*(1.-V))
      FO=-DPT+(A/GR)*ROL-(A1*DDXDZ*(G1-G2))
C     CALCULATE F2
      M=(FO*DP*UL)/(TAO*SQRT(GR*TAO*ROL))
      MUSED=0
      IF(DP-5.) 40,40,41
40    F2=DP*PR
      K=0
      GO TO 44
41    IF(DP-30) 42,42,43
42    F2=5.*PR+5.*ALOG(1.+E*PR*(DP/5.-1.))/E
      K=0
      GO TO 44
43    Y1=((1+PR)**.1*(2.71828**(.1*PR)))/30.
      YDIS=(Y1*(DP**1.05)-DP)/((Y1*(DP**1.05))-2.5*Y1*(DP**.05)/PR-30
```

```
     1+2.5/PR)-M
      IF(YDIS) 60,60,61
60    C1=SQRT(1.+10.*M/(PR*DP*E))
      C2=60.*M/DP-1.-C1
      C3=60.*M/DP-1.+C1
      C4=2.*M-1.+C1
      C5=2.*M-1.-C1
      F2=5.*PR+5.*ALOG(1.+5.*E*PR)/E+(2.5*ALOG((C4*C2)/(C5*C3)))/(C1*E)
      MUSED=1
      GO TO 62
61    F2=5*PR+5*(ALOG(1+5*PR*E))/E+2.5*(ALOG(DP/30))
62    K=1
C     LOCAL HEAT TRANSFER COEFFICIENT
44    HZ=CL*SQRT(GR*TAO*ROL)/F2
      L=.05*HFG*G*D/(4.*HZ*DFT)
      IF(K) 3,3,4
4     DDD=.025*D/L
C     NEW QUALITY GRADIENT
      S=ABS((DDD+DDXDZ)/DDXDZ)-.01
      IF(S) 3,3,2
2     DDXDZ=-DDD
      WRITE(5,50) DDD
50    FORMAT (10X,E14.8)
      GO TO 1
C     MEAN HEAT TRANSFER COEFFICIENT
3     IF(I-1) 19,19,20
19    HM=HZ
      SH(I)=1/HZ
      GO TO 23
20    IR=I-1
      RH=1/HZ
      SH(I)=RH+SH(IR)
      HM=I/SH(I)
23    WRITE(5,17) X,DPF,DPM,DPT,RE,HZ,HM,L,M,DP,MUSED
17    FORMAT(F4.2,F9.3,E14.3,F9.3,E14.5,2F9.1,2E14.5,F9.3,I6)
```

```
21      CONTINUE
        END
```