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THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

VAPOR-LIQUID CHANGE OF PHASE HEAT TRANSFER BEHAVIOR OF LIGHT HYDROCARBONS AND THEIR MIXTURES

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

BY

LUTHER DAVIS CLEMENTS, JR

Norman, Oklahoma

VAPOR-LIQUID CHANGE OF PHASE HEAT TRANSFER BEHAVIOR OF LIGHT HYDROCARBONS AND THEIR MIXTURES

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VAPOR-LIQUID CHANGE OF PHASE HEAT TRANSFER BEHAVIOR OF LIGHT HYDROCARBONS AND THEIR MIXTURES

By: Luther D. Clements

Major Professor: C. Phillip Colver

This work is a tripartite study of the effects of pressure and composition on vapor-liquid change of phase heat transfer in light hydrocarbons. The separate phenomena of natural convection and nucleate pool boiling in a saturated liquid, the burnout heat flux, and film condensation in a vertical reflux condenser were investigated. The pure components propane, n-butane, and n-pentane and the binary systems propane - n-butane and propane n-pentane were used.

The nucleate boiling data showed a pressure behavior consistent with that noted by previous investigators and a marked composition dependence of the boiling temperature difference. The natural convection data showed no particular pressure influence and a composition dependence analogous with that in nucleate boiling. A correlation which allows prediction of the nucleate boiling ΔT for a pure component using the desired heat flux and the critical properties of the material was developed. In addition, the composition dependence of the boiling temperature difference was related to the mixture relative volatility. A correction factor which accounts for mixture behavior in natural convection and nucleate boiling is proposed.

The film condensation data showed no strong influence of either pressure or composition. The latter result is consistent with other investigators. The data appear to be in the turbulent flow regime and a correlation for the film condensation data is presented.

The burnout data show the classic dependence on pressure and the pure component data agree well with the Moissis and Berenson correlation. There was a definite mixture effect present, with mixtures exhibiting burnouts as much as twice those of the pure components. It was found that the relative volatility also represented the composition dependence of burnout well. A modification of the Moissis and Berenson correlation is proposed for use in predicting mixture burnouts.

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Nomenclature

a	-	chemical activity
C	-	empirical constant
C _{co}	-	bulk concentration, 1b _m /ft ³
g	-	gravitational constant, ft/sec ²
g _c	•	unit conversion factor, lb _m -ft/lb _f -sec ²
h	-	heat transfer coefficient, Btu/ft ² hr F
k	-	thermal conductivity, Btu/ft hr F
1	-	dimensionless factor, $\lambda_2(\rho-c_{\infty})/\lambda_1c_{\infty}$
m	-	mass fraction
n	-	empirical exponent
q, q/A	-	heat flux, Btu/ft ² hr
t	-	time, sec
X	-	mole fraction; distance, ft
В	-	Laplace reference length, $(g_c \sigma/(g(\rho_1 - \rho_v)))^{\frac{1}{p}}$, ft
C _p	-	constant pressure heat capacity, Btu/lb _m F
D	-	diameter, ft
D ^O AB	-	infinite dilution diffusion coefficient, ft^2/hr
ð	-	mixture diffusion coefficient, ft ² /hr
E	-	electrical potential, volts
Gr	-	Grashof number, $(\rho^2 \beta g D^3 \Delta T / \mu^2)$; Gr' = Gr/ $\propto_{\mu}^{\frac{1}{2}}$
I	-	electrical current, amperes
K	•	vapor-liquid equilibrium constant
M	-	molecular weight
Nu	-	Nusselt number, (qx/koT)

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P	-	pressure, psia
Pr	-	Prandtl number, (#C _p /k)
R	-	radius, ft
Rg	-	gas constant
T	-	temperature, F
ΔT	-	temperature difference, Twall-Tsaturation, F
v	-	molar volume, ft ³ /lb-mol
α	-	thermal diffusivity, ft ² /hr
α	-	relative volatility, (K _{light} /K _{heavy}) _{T,P}
ß	-	growth constant; volumetric dilitation, ft ³ /F
δ	-	boundary layer thickness, ft
λ	-	latent heat of vaporization, Btu/lb _m
μ	-	viscosity, lb _m /ft hr
۶	-	density, lb _m /ft ³
σ	-	surface tension, lb _f /ft
۵ ^θ ۵	-	liquid superheat, F
Subscr	ipt	<u>8</u>
c	-	critical
В	-	referenced to the Laplace reference length
D	-	referenced to the diameter
1	-	liquid
r	-	reduced
sat	-	saturated
v	-	vapor
w,b	-	wall, boiling
1c	-	first critical or burnout

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VAPOR-LIQUID CHANGE OF PHASE HEAT TRANSFER BEHAVIOR OF LIGHT HYDROCARBONS AND THEIR MIXTURES

Chapter 1

Natural Convection and Nucleate Boiling Behavior

This portion of the study is specifically concerned with the effects of pressure and composition on the natural convection and nucleate boiling behavior of light hydrocarbons. Data for propane, n-butane, n-pentane, propane - n-butane, and propane - n-pentane mixtures are presented. The natural convection data were limited to those data points where no bubbles emanated from the heater surface. These data always fell below the breaks visible in some of the data plots.

Individual expressions, which relate the effect of pressure and the effect of composition on nucleate boiling ΔT , are developed and compared with experimental data. The natural convection data are compared with the McAdams correlation and to an empirical correlation developed in this work. Four commonly used nucleate boiling correlations are compared with the experimental data. A modification to compensate for the effect mixtures have on natural convection and nucleate boiling is proposed.

A. Pure Component Data

Figures 1-1, 1-2, and 1-3 present data for the pure components propane, n-butane, and n-pentane, respectively. Note that, as expected, in all cases there is a shift to a smaller ΔT with an increase in pressure. The propane and n-butane data agree closely with the data of Sciance, <u>et al.</u> (56) and the n-pentane data agree with those of Berenson (2).

The n-butane and n-pentane data show some tendency to combine into a single curve below the break between the natural convection and nucleate boiling regions. This tendency toward a minimal effect of pressure on natural convection has also been noted by Elrod, <u>et al.</u> (17), Gorenflo (22), and Danilova and Kupriyanova (14). There apparently are no data available for natural convection in light hydrocarbons.

B. Binary Mixture Data

Natural convection and nucleate boiling heat transfer data for the binary systems propane - n-butane are shown in Figures 1-4, 1-5, and 1-6, while data for the systems propane n-pentane appear in Figures 1-7, 1-8, and 1-9. Again it is apparent that an increase in pressure shifts the boiling curve to lower Δ Ts. Any effects due solely to composition are not immediately seen in the figures. It is necessary, then, to look for these effects in a cross-plot at a single reduced pressure. Figure 1-10 shows data for the propane n-butane system at a reduced pressure of 0.3. There is a definite compositional dependence. To illustrate further the















Figure I-6 63% Propane - 37% n- Butane Mixture Boiling Data





Mixture Boiling Data



Figure I-9 65% Propane - 35%n-Pentane Mixture Boiling Data



dependence of boiling heat transfer on composition, Figure 1-11 is a cross-plot of $\triangle T$ and composition. Similar results for the propane - n-pentane mixtures are shown in Figures 1-12 and 1-13. The natural convection data in Figure 1-14 also show a composition dependence similar to that found in nucleate boiling.

The relation between composition and ΔT (noted here for nucleate boiling) is not unique. Similar results have been reported by Cicelli and Bonilla (10), Huber and Hoehne (26), Wright, <u>et al.</u> (76), and Sternling and Tichacek (64). Under some circumstances, usually for partially misoible mixtures, van Wijk, Vos, and van Stralen (74) and van Stralen (70, 72) found that two maxima in the $\Delta T - x$ curve may be present. Two maxima, with a minimum at the azeotropic composition, were noted by Afgan (1). There appear to be no saturated liquid mixture data for natural convection in the literature.

C. The Effect of Pressure on Nucleate Boiling

The pronounced, regular effect of pressure on nucleate boiling has prompted a few analyses concerned specifically with predicting these effects. The earliest of these analyses resulted in the empirical relation

$$h = 5400 (P_r)^{0.44}$$
(1-1)

obtained by Cichelli and Bonilla (10). Data for propane, n-pentane, and n-heptane were used to calculate this expression.





PROPANE - n - PENTANE MIXTURES Pr 20.3





The corresponding states principle, combined with the maximum theoretical superheat calculated from the van der Waals equation of state, provided Lienhard and Schrock (35) a means of relating the system pressure and the nucleate boiling **AT**. The final result of the derivation was the expression

$$\frac{(\Delta T)_{\text{interest}}}{(\Delta T)_{\text{reference}}} = \frac{1.6 + 6.5(P_r)_{\text{interest}}}{1.6 + 6.5(P_r)_{\text{reference}}}, 0.01 < P_r < 0.65 (1-2)$$

Gorenflo (22) proposed the empirical relation

$$a = c q^{0.8} [0.74 + 2.2P_r]$$
(1-3)

where c is a function of the liquid being boiled. He used data for nucleate boiling refrigerants to determine the form of Equation 1-3.

A major shortcoming of Equations 1-1 and 1-3 is that both are based on very small data sets. Equation 1-2 is more general, but it does not seem to represent the data available in the literature well. It is apparent, then, that a simple, accurate relation between pressure and ΔT would be a distinct aid to the designer.

The approach taken in this work was to seek a direct relation between the nucleate boiling ΔT , the system pressure, and the nucleate boiling heat flux. Using the principle of corresponding states as a guide, the relative temperature difference

$$\Delta T_r = \Delta T / T_c^{\frac{1}{2}}$$
 (1-4)

and the reduced pressure

$$P_{\rm r} = P/P_{\rm c} \tag{1-5}$$

were defined as correlating parameters. A large body of nucleate boiling data for organic liquids and for water, summarized in Table 1-1, were used to obtain the relationship

$$\Delta T_r = 0.007 (q/A)^{0.3} (P_r)^{-0.65}$$
(1-6)

Equation 1-6, as shown in Figure 1-15, fit the composite data set with an average absolute deviation of 29.2%. Because of the wide variety of heater types and substances represented, the results indicate that a designer may use Equation 1-6 to estimate accurately the temperature difference required to transport a given amount of heat through a known area at a set operating pressure. Use of the correlation can lessen the requirement for large amounts of experimental data to support design calculations.

D. Effect of Composition on Nucleate Boiling

A major objective of this study was to obtain a quantitative representation of the effect of mixtures on nucleate boiling. It has often been noted that mixtures boil at ΔTs which are much higher than those of the individual pure components. Sternling and Tichacek (64) offered three possible explanations for this mixture boiling behavior:

Data Sources of Pressure Effects in Nucleate Boiling

Author	Substance	Reduced Pressures	Heater type
This work	Propane	0.3 - 0.7	0.811 in diam, horiz., gold plated cylinder
-	n-Butane	0.1 - 0.3	18
•	n-Pentane	0.05 - 0.2	••
Wright, <u>et al.</u> (76)	Ethane	0.03 - 0.2	••
Sciance, <u>et al.</u> (56,57) Methane	0.02 - 0.7	0.65 in diam, horiz., gold plated cylinder
••	Ethane	0.02 - 0.5	•
89	Propane	0.02 - 0.7	ан салаан бай <mark>н</mark> агаан ал
	n-Butane	0.03 - 0.3	10
Cichelli and Bonilla (10)	n-Pentane	0.13 - 0.64	3.75 in diam, horiz., chromium disc
	Benzene	0.02 - 0.65	11 · · · · · · · · · · · · · · · · · ·
**	Propane	0.28 - 0.6	
**	Heptane	0.04 - 0.29	•
	Ethanol	0.02 - 0.56	b0
Messler and Banchero (39)	Acetone	0.02 - 0.38	0.0643 in diam, horiz., stainless steel tube
•	Ethanol	0.02 - 0.56	
•	Benzene	0.02 - 0.51	
*	Freon 113	0.03 - 0.74	D
Huber and Hoehne (26)	Benzene	0.02 - 0.42	0.375 in diam, horiz., stainless steel tube



OF PRESSURE ON PURE COMPONENT AT
- 1. Changes in puncical properties due to changes in composition affect heat transfer.
- 2. Varying growth rates caused by a resistance to mass transfer of the more volatile component into the growing vapor bubble affect heat transfer.
- 3. Changing nucleation rates because of compositional differences affect heat transfer.

It is felt that compositional-induced effects based on physical property variations are a minor influence. With the exception of the critical properties, estimated mixture transport properties are essentially weighted averages of the pure component values. If the existing nucleate boiling correlations can be considered valid for mixtures, physical property variations of minor magnitude have a minimal effect upon the heat transfer characteristics.

Composition effects on nucleation rates could certainly affect heat transfer dramatically. Unfortunately, very little concerning nucleation in boiling, even for pure liquids, is presently known. Further investigation into the effects of mixtures on bubble nucleation is dependent upon an increased knowledge of the nucleation process in pure fluids.

One factor affecting nucleate boiling heat transfer which has received some previous attention is the bubble growth rate. Analytical studies in this area, particularly those of Scriven (58) and van Stralen (65, 66, 67, 68, 69, 71) have shown that the bubble growth rate, and, hence, the heat flux behavior, may be strongly influenced by liquid composition. As shown by van Stralen (67)

$$q_{w,b} \propto \beta \Delta T$$
 (1-7)

If we place Equation 1-7 into a form comparable with Figures 1-11 and 1-13, <u>i.e.</u>, conditions of constant reduced pressure and heat flux, we see

$$\Delta T_{q,P_r} \propto \frac{1}{\beta}$$
 (1-8)

It is of interest to determine the effectiveness of Equation 1-8 in representing experimental data for mixtures. Before this can be done, though, the form of the growth constant, β , for a mixture must be discussed.

A number of investigators have considered the problem of bubble growth in a binary liquid mixture. The results of Bruijn (7), Skinner and Bankoff (59, 60), Scriven (58), and van Stralen (65, 66, 67, 68, 69, 71) all have very similar origins and final forms. The expression

$$R(t) = \beta \Delta \theta_0 t^{\frac{1}{2}}$$
 (1-9)

which was shown to hold true for pure fluids (see Appendix D) was assumed to also be true for mixtures. In addition, it has been assumed that the thermodynamic equilibrium condition exists at the vapor-liquid interface, and that transport of the more volatile component in the liquid to the vapor interface is by way of diffusion. In addition to an exact value of β found from the simultaneous solution of two integral equations, Scriven (58) presented two limiting values of the growth constant for binary mixtures. In the limit of small superheat, <u>i.e.</u>, as $\beta + 0$, the growth constant is

$$\beta \approx (2k_1)^{\frac{1}{2}} \left\{ \Delta^{\theta} \circ \mathcal{P}_{v} \left(\overline{\lambda} - \frac{k_1 (m \rho_1 - c_{\infty}) R_g T_{\text{sat}}^2 (1-\alpha)}{\mathcal{O}_{c_{\infty} \lambda_1} (M_2 c_{\infty} + (\rho_1 - c_{\infty}) M_1 (1-\alpha 1))} \right) \right\}^{-\frac{1}{2}} (1-10)$$

At the other extreme, for high superheats,

$$\beta \approx \left(\frac{12\rho_{1}c_{p1}k_{1}}{\pi}\right)^{\frac{1}{2}} \left\{ \rho_{v} \left[\overline{\lambda} + \frac{(m\rho_{1}-c_{\infty})R_{g}T_{sat}^{2}(1-\alpha)}{c_{\infty}\lambda_{1}(M_{2}+(\rho_{1}-c_{\infty})M_{1}(1+\alpha))} \right] \left(\frac{\rho_{1}c_{p1}k_{1}}{\mathcal{D}}\right)^{\frac{1}{2}} \right\}^{-\frac{1}{2}}$$
(1-11)

van Stralen (65, 66, 67, 68, 69, 71) by an apparent analogy with Scriven's results suggested the somewhat simpler relation

$$\beta = \left(\frac{12}{\pi}\right)^{\frac{1}{2}} \frac{\alpha^{\frac{1}{2}}}{\rho_{1} \left[\frac{\chi}{c_{p}} + \left(\frac{\alpha}{D}\right)^{\frac{1}{2}} \frac{\Delta T}{C_{d}}\right]}$$
(1-12)

where

$$\frac{\Delta T}{G_{d}}(x_{o}) \approx -x_{o}(K(x) - 1) \left(\frac{dT}{dx}\right)_{x=x_{o}} = -x_{o}(K(x_{o}) - 1) \left(\frac{dT}{dx}\right)_{x=x_{o}}$$
(1-13)

The term $(\Delta T/G_d)$ may be evaluated either from Equation 1-13 or graphically.

Attempts to obtain a direct relation between the values for the pure component and mixture growth constants and their corresponding nucleate boiling Ts were unsuccessful. The very awkward form of the growth constant equations made it desirable to seek a simpler means of predicting mixture boiling behavior.

It has been noted by Wright, <u>et al.</u> (76) that the nucleate boiling behavior of a mixture is directly related to the mixture relative volatility. Inspection of the mixture growth constant equations shows that a form of the mixture relative volatility is an integral part of each expression. At a given pressure and composition the saturation temperature is fixed and the relative volatility defined by $(K_{light}/K_{heavy})_{T,P}$ is a unique value. It is suggested that this ratio of K-values, symbolized in this work by a_y , should be effective as a correlating parameter to take into account the contribution of relative volatility effects in boiling.

E. Natural Convection Correlations

The earliest mathematical description of natural convection heat transfer was presented by Nusselt (44). He used dimensional analysis to arrive at the realtion

$$Nu = f(Gr, Pr)$$
 (1-14)...

for a vertical wall configuration. Later Hermann (24)

solved the transport equations describing laminar natural convection in a diatomic gas from a horizontal cylinder with a constant wall temperature. The expression

$$Nu_{D} = 0.372 (Gr_{D})^{\frac{1}{4}}$$
 (1-15)

resulted. Hermann also found that a vertical wall of height 2.5D and a horizontal cylinder of diameter D have the same heat transfer coefficient. This equivalency was used by Eckert (15) to obtain an expression for all fluids

$$Nu_{D} = 0.539 \left(\frac{Pr}{0.952 + Pr} \right) \cdot (Gr_{D} Pr)^{\frac{1}{4}}$$
 (1-16)

This equation has also been suggested for use with liquid metals by Hyman, et al. (27). It should be noted that Eckert and Drake (15) suggest a constant of 0.508 for Equation 1-16 An empirical relation for laminar natural convection from a horizontal cylinder, which has found wide popularity, is the McAdams (37) correlation

$$Nu_{\rm D} = 0.53 \, (Gr_{\rm D} \, {\rm Pr})^{\frac{1}{4}}$$
 (1-17)

A number of numerical solutions for the Navier - Stokes equations for laminar natural convection from a horizontal cylinder have appeared recently. Of particular interest is the result

$$Nu_{D} = (Gr_{D} Pr)^{\frac{1}{4}} f(Pr)$$
 (1-18)

where

$$f(Pr) = \frac{Pr}{15.5 + 28.8 Pr^2 + 28.7 Pr}$$
(1-19)

obtained by Saville and Churchill (54) for a right circular cylinder. The functional form for f(Pr) was suggested by Lafevre's results for sharp-nosed bodies.

All of the results discussed above are based upon the assumption that the heater surface is at a constant temperature. The works of Chiang and Kaye (9) and Koh (29) helped to relax this assumption. They found that a prescribed, non-uniform heat flux or wall temperature had only a very small effect on the net natural convection heat transfer.

Turbulent natural convection has been modled by Eckert and Jackson (16). They integrated the equations of motion and energy to find

 $Nu_{x} = 0.0295 (Gr_{x})^{2/5} (Pr)^{7/15} (1 + 0.494 (Pr)^{2/3})^{-2/5} (1-20)$ or, alternatively

$$Nu_x = 0.021 (Gr_x Pr)^{2/5}$$
 (1-21)

The above results for both laminar and turbulent natural convection suggest that an empirical relation of the form

$$Nu_{x} = C (Gr_{x} Pr)^{n} \qquad (1-22)$$

should adequately represent data in both flow regimes. As noted in the discussion of the experimental data, there appears

to be a mixture effect in natural convection heat transfer in saturated liquids. For this reason the Grashof number for mixtures is modified by including the relative volatility parameter suggested in Section D. The parameter enters as $a_y^{-\frac{1}{2}}$, where the exponent $-\frac{1}{2}$ was found to give the best representation of the experimental data.

The natural convection data taken in this study were used in a least squares fit of Equation 1-22 in order to obtain the suitable empirical constants. The final relation, which is compared with the data in Figure 1-16, is

$$Nu_{\rm p} = 0.423 \, (Gr_{\rm p}^{*} \, {\rm Pr})^{0.312} \qquad (1-23)$$

This equation fit the data with an average absolute deviation of 42.2%. The slope of the data (roughly midway between that expected for laminar and turbulent flow) seems to indicate that these data lie around the laminar-turbulent transition. Indeed, the results of the investigation of Hyman, <u>et al.</u> (27) indicate that the laminar-turbulent transition for this data set would be at $Gr_DPr = 4 \times 10^7$, or slightly below the range of these data. Also shown in the figure is a line representing the McAdams correlation, modified for mixtures. The equation is somewhat conservative in its representation of these data, possibly also suggesting that the data are more nearly in turbulent flow than in laminar flow.



FIGURE I-16 NATURAL CONVECTION CORRELATION

F. Nucleate Boiling Correlations

The nucleate boiling data taken in this study were compared with four of the more popular correlations available in the literature. These correlations are the equations of McNelly (38), Kutateladze (32), Borishanskii and Minchenko (32), and the Rohsenow correlation as modified by Sciance, <u>et al.</u> (56). These expressions were selected because of their demonstrated effectiveness in representing pure component and mixture data (31, 76).

It is evident from Table 1-2 and Figure 1-17 that the correlations represent the pure component data well. However, the values in the table also show that the mixture results leave something to be desired. Again the relative volatility parameter, α_y , was used to take into account the mixture effects. It was found that inclusion of $\alpha_y^{-\frac{1}{2}}$ as a dimensionless parameter in the right hand side of each of the correlations substantially improved the results as seen in the table. The correlated mixture data are shown in Figure 1-18.

The modified correlations are: Modified Sciance-Rohsenow

$$\frac{\mathbf{q}\mathbf{B}}{\lambda \mathbf{H}} = 385.1 \left[\frac{\mathbf{c}_{pl} \mathbf{a}^{\mathrm{T}}}{\lambda \ \alpha_{p}^{\frac{1}{2}}} \left(\frac{\mathbf{T}_{r}}{\mathbf{P}r_{l}} \right)^{1.18} \right] \qquad (\text{all data}) \ (1-24)$$

Modified McNelly

$$\frac{hD}{k_{1}} = 0.225 \alpha_{\mu}^{-\frac{1}{2}} \left(\frac{qD}{\lambda \mu_{1}}\right)^{0.69} \left(\frac{PD}{\sigma}\right)^{0.31} \left(\frac{f_{1}-f_{v}}{f_{v}}\right)^{0.33} Pr_{1}^{0.69} \quad (1-25)$$

Table 1-2

Summary of Results:

Nucleate Boiling Correlation Testing

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Correlation	Percent Pure Component	Average Absolute Mixture, Unmodified	Deviation Mixture, Modified
Rohsenow- Sciance, Pure only	42.1		
Rohsenow- Sciance, Mixtures only		109.8	
Rohsenow- Sciance, All data	50.9		78.4
McNelly	33.1	101.3	30.3
Kutateladze	42.5	92.7	37.8
Borishanskii- Minchenko	37.3	302.0	99.4

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Comparison of Borishanskii-Mincheniko Correlation

Figure 1-17 Pure Component Nucleate Boiling Correlations (from Ref. 11)





10,000

1,000

100

10

10

8.7×10

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Comparison of Modified Kutateladze Correlation Comparison of Modified Borishanskii-Mincheniko Correlation

100

q B

1,000

 $\frac{\mathsf{PB}}{-}\right)^{0.7} (\alpha_{\nu})^{-0.5}$

10,000

Figure 1-18 Mixture Nucleate Boiling Correlations (from Ref. 11)

Modified Kutateladze

$$\frac{hB}{k_{1}} = 7 \times 10^{-4} \alpha_{\nu}^{-\frac{1}{2}} \left[\frac{qB}{\alpha_{1} \rho_{1} \lambda}\right]^{0.7} \left[\frac{PB}{\sigma}\right]^{0.7} Pr_{1}^{-0.3}$$
(1-26)

Modified Borishanskii-Minchenko

$$\frac{hB}{k_{1}} = 8.7 \times 10^{-4} \alpha_{\nu}^{-\frac{1}{2}} \left[\frac{qB}{\alpha_{1} \rho_{1} \lambda} \right]^{0.7} \left[\frac{PB}{\sigma} \right]^{0.7}$$
(1-27)

It should be noted that the results cited in Table 1-2 for the Sciance-Rohsenow equation in its unmodified form were obtained from a least squares fit of both the pure component and the mixture data. Figures showing the experimental data compared with the proposed correlations are given in reference 11.

G. Conclusions

1. The effects of both pressure and composition on nucleate boiling observed by previous investigators have been confirmed in this study.

2. There is a minimal pressure effect in natural convection to a saturated liquid.

3. Liquid composition seems to cause an increase in ΔT in the case of natural convection to a saturated liquid which is analogous to that noted in nucleate boiling.

4. Pure component nucleate boiling △Ts may be predicted accurately using the expression

 $\Delta T_{r} = 0.007 (q/A)^{0.3} (Pr)^{-0.65}$

The data used to develop this expression were represented with an average absolute deviation of 29.2%.

5. The values of $\alpha_{\nu}(x)$ may be used to represent the trend of $\Delta T_{mix}(x)/\Delta T_{pure 1}$. This means that the relative volatility forms a valid basis for predicting the increase in ΔT caused by the presence of a liquid mixture.

6. The expression

 $Nu_{\rm p} = 0.423 (Gr_{\rm D}^{\circ} Pr)^{0.312}$

fit the natural convection data with an average absolute deviation of 42.2%. The natural convection lata appear to be in the vicinity of the laminar-to-turbulent transition region, in agreement with the prediction from Hyman, et al.(27).

7. The term $a_y^{-\frac{1}{2}}$ in both natural convection and nucleate boiling correlations substantially improved the accuracy of the correlations in representing the experimental data from this work.

8. The modified McNelly nucleate boiling correlation best represented both the pure component and the mixture data.

Chapter 2

Film Condensation in a Vertical Reflux Condenser

The nature of the liquid film, primarily as it is influenced by condenser geometry, and the effects of noncondensibles have provided subjects for the bulk of the film condensation studies in the literature. There have been few investigations to study the effects of pressure or of mixture composition in film condensation. Hence, in this work the effects of pressure and of composition on the condensing behavior of light hydrocarbons are investigated. Data at several pressures for pure propane, n-butane, and n-pentane and for propane - n-butane and propane - n-pentane mixtures are presented and examined for indications of pressure or compositional influences. The data are compared with Nusselt's equation for laminar film condensation and a best-fit empirical equation which is suggested for turbulent film condensation.

A. Previous Studies

The first model of film condensation was the description of laminar film condensation presented by Nusselt (45) in 1916. His final expression was

$$h_{x} = 0.707 \left[\frac{g \rho_{1}^{2} k_{1}^{3} \lambda}{\mu_{1} x \Delta T} \right]^{\frac{1}{2}}$$
(2-1)

Here h_x is the local heat transfer coefficient, while x is the vertical distance the film has fallen.

Most subsequent studies in laminar film condensation have been directed toward relaxing or verifying Nusselt's original assumptions. Studies by both Minkowycz and Sparrow (40) and Poots and Miles (49) have shown that effects due to variable fluid properties are small. Momentum effects were investigated by Sparrow and Greg (61), while Chen (8), Koh (28), and Koh, <u>et al.</u> (30) showed condensing behavior is not strongly affected by interfacial shear. Subcooling in the condensate has been considered by Bromley (5). Rohsenow (52) allowed for the effect of non-linear temperature distribution in the condensate. It is worthy to note that all of these studies have tended to justify the original assumptions of Nusselt.

Film condensation of mixtures has enjoyed a small but steady interest through the years. The first formulation of the problem of condensing binary vapor mixtures was made by Colburn and Drew (12). They found that latent heat exchange is the dominant factor in the condensation process. Interfacial vapor-liquid equilibrium was assumed, and the main theme of the Colburn and Drew study was to determine the interfacial temperature.

Condensing data for the ethanol-water binary reported by Wallace and Davison (73) gave partial verification to the work of Colburn and Drew. A later investigation by Pressburg and Todd (50) found that the Colburn and Drew analysis allowed three reasonable choices for the condensing ΔT :

$$\Delta T_{BP} = T_{bubble point} - T_{surface}$$

$$\Delta T_{DP} = T_{dew point} - T_{surface} \qquad (2-2)$$

$$\Delta T_{V} = T_{vapor} - T_{surface}$$

Experimental results of Pressburg and Todd and of Mirkovich and Missen (41) showed that ΔT_{BP} is the correct choice for the mixture condensing ΔT . Recently, numerical calculations of Sparrow and Marschall (62) indicated the same conclusion.

Turbulence in the condensate film greatly enhances the heat transfer rate. Grigull (23) has shown that turbulent film condensation is a complex function of the dimensionless groups

$$\frac{h_{x}x}{k_{1}} \propto \left[\frac{x^{3}\rho_{1}^{2} \lambda g}{k_{1}\mu_{1}\Delta^{T}}\right]$$
(2-3)

which is simply a dimensionless form of Equation 2-1.

Thus it is suggested that an empirical relation of the form

$$\frac{h_{x} x}{k_{1}} = C \left[\frac{x^{3} \rho_{1}^{2} \lambda g}{k_{1} \rho_{1} \Delta T} \right]^{n}$$
(2-4)

should be adequate for correlation of film condensation data from a vertical surface, with the value of the exponent, n, and the coefficient, C, dependent on the condensate flow regime.

B. Results and Correlation

Pure component film condensation data for propane, n-butane, and n-pentane are shown in Figures 2-1, 2-2, and 2-3 respectively. The choice of the group h_X/x for the ordinate serves as a means of eliminating the position dependence of the heat transfer coefficient, h_X . Examination of the figures shows that in the cases of propane and n-butane there is definitely no systematic influence due to pressure; any possible pressure effect in the n-pentane data is not conclusive. Hence, these results indicate that there is, at most, a very minimal pressure effect in film condensation.

Data for the propane - n-butane and propane - n-pentane mixtures are shown in Figure 2-4. The ΔT used in calculating and plotting the heat transfer coefficients was the $\Delta T_{\rm BP}$. This fact was verified by comparing dew point and bubble point temperatures for the condensing mixtures with the calculated inner wall temperatures. The inner wall temperatures agreed with the bubble point temperatures at all times. A typical condenser temperature profile is shown in Figure 2-5.



FIGURE 2-1 FILM CONDENSATION DATA FOR PURE PROPANE



FIGURE 2-2 FILM CONDENSATION DATA FOR n-BUTANE







MIXTURES FOR LIGHT HYDROCARBON FIGURE 2-4 FILM CONDENSATION DATA

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DISTANCE FROM TOP OF CONDENSER, INCHES FIGURE 2-5 SAMPLE TEMPERATURE PROFILES FOR MIXTURE FILM CONDENSATION

The lack of a definite composition effect in Figure 2-4 is readily apparent. Further, it can be seen that the mixture data compare well with the pure component results. Mixture data of Wallace and Davison (73), Pressburg and Todd (50), and Mirkovich and Missen (41) also indicate that composition is not a major influence on film condensation. It is interesting to note that Onda, <u>et al.</u> (47) found that mixtures in a flow-through partial condenser can also be treated essentially as pure components.

As indicated earlier, examination of the relations for predicting film condensation behavior indicate that a dimensionless expression of the form of Equation 2-4 should be adequate for data representation. Data from this work are shown in Figure 2-6, and may be represented by the expression

$$\frac{h_{x} x}{k_{1}} = 1.88 \times 10^{-8} \left[\frac{x^{3} \rho_{1}^{2} \lambda g}{k_{1} \mu_{1} \Delta T} \right]^{0.75}$$
(2-5)

Best fit of the data shows an average absolute deviation of 35.7%. Comparison of the data with the Nusselt relation seems to indicate that the data were in the turbulent regime, because the slope is much larger than that of laminar condensation. It must be emphasized that Equation 2-5 was developed to represent turbulent film condensation data from a vertical reflux condenser. Use of this expression to predict turbulent film condensation in a flow-through type condenser is not warranted without further study.



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In general, with well behaved mixtures, film condensation of a binary mixture may be treated as condensation of a pseudopure component with the physical properties of the binary. This concept has been verified using a horizontal plate total condenser by several authors (41, 50, 73) and using a vertical reflux condenser in this work. Onda, <u>et al.</u> (47) also found that a mixture may be assumed to act like a pseudopure component in a vertical flow-through condenser.

There are two mixture types to which this notion of a pseudo-pure component does not apply. Obviously if one of the components is a noncondensible gas, the film condensation behavior will be affected. Also there can arise a peculiar situation when both vapors are condensible. In some binary systems, the surface tension gradients caused by the composition gradients present make the falling film unstable. The net result is a combination of dropwise and filmwise condensation. Mirkovich and Missen (41) have addressed the problem of condensation in the presence of an unstable film at some length.

C. Conclusions

1. System pressure has little, if any, effect on film condensation behavior.

2. Mixtures in film condensation tend to behave like pure components, exhibiting no unusual composition dependence.

3. Equation 2-5 adequately represents the film condensation data for both the pure components and the mixtures.

Chapter 3

Effect of Pressure and Composition on the First Critical (Burnout) Heat Flux

The first critical (burnout) heat flux is possibly the most intensely studied phenomenon in boiling heat transfer. The rapid, potentially destructive, increase in heater wall temperature associated with burnout makes a knowledge of the burnout heat flux behavior vitally important to exchanger design. Yet, there are a number of factors which influence burnout that are not well understood. In this work the effect of pressure and of composition upon burnout was of primary importance.

Most of the data presented here were taken with a 0.061 inch diameter carbon rod heater. Use of this heater instead of the gold cylinder used in the natural convection and nucleate boiling portion of this work was necessitated because the composite heater tended to break very soon after beginning to take burnout data. The heaters and the procedure for taking the data are described in Appendices A and B. The data are limited in the lower reduced pressure range because operation below room temperature was not possible. At the higher reduced pressures operation was limited by the difficulty in maintaining a very large apparatus at rather high

temperatures and by temperature limitations on some of the materials of construction.

A. Pure Component Burnout Data

The pure component burnout data for propane, n-butane, and n-pentane are shown in Figures 3-1, 3-2, and 3-3 respectively. In Figure 3-3 the n-pentane data should not be interpreted as always extending upward; physical limitations prevented taking data beyond the maximum of the burnout curve. Similar comments apply to a number of the other data sets presented here.

Also shown in Figures 3-1, 3-2, and 3-3 are predictions of burnout behavior based upon the equations of Moissis and Berenson (42)

$$q_{1c} = 0.18 \mathcal{L}\left[\left(\frac{\rho_{1}+\rho_{v}}{\rho_{1}}\right) / (1+2\frac{\rho_{1}}{\rho_{v}} + \frac{\rho_{1}}{\rho_{v}})\right] \qquad (3-1)$$

and Noyes (43)

$$q_{1c} = 0.144 \mathcal{L} \left[\frac{\rho_1 - \rho_v}{\rho_1} \right]^{\frac{1}{2}} \left(\frac{\mu_1 c_{p1}}{k_1} \right)^{-0.245}$$
(3-2)

where

$$\mathcal{L} = \lambda \rho_{v} \left[\frac{gg_{c}\sigma(\rho_{1} - \rho_{v})}{\rho_{1}^{2}} \right]^{\frac{1}{4}} \left(\frac{a}{g} \right)^{\frac{1}{4}}$$
(3-3)

These two expressions, out of the many burnout predictions in the literature, have been found to by previous investigators (13, 56, 57, 77) to be particularly effective for hydrocarbons.







The excellent agreement with the Moissis and Berenson expression is evident.

It is also of interest to note the excellent agreement between the n-butane data taken with the carbon rod heater and with the gold cylinder. This would seem to support the lack of a major surface dependence in burnout.

B. Mixture Burnout Data

Mixture burnout data for the propane - n-butane system are shown in Figure 3-4 and data for the propane - n-pentane system in Figure 3-5. Careful perusal of these figures shows that there is a definite composition dependence present. There is an increase in the burnout heat flux at a given reduced pressure which is roughly proportional to the liquid mole fraction of the lighter component.

The use of the reduced pressure in the exposition of the mixture data can lead to an ambiguity. There are two reduced pressures which can be defined for a given mixture. The true reduced pressure is the ratio of the system pressure to the true mixture critical pressure, while the pseudo-reduced pressure, P_r^* , is the ratio of the system pressure to the pseudo-reduced critical pressure, P_c^* , where

$$P_{c}^{*} = x_{1}P_{c1} + x_{2}P_{c2} \qquad (3-4)$$

For mixtures of nearly the same volatility $P_c \doteq P_c^*$, but for mixtures of widely different volatilities $P_c > P_c^*$.





PROPANE - n-PENTANE SYSTEM - 0.061 in. DIAM. CARBON ROD

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In this work the correlating reduced pressure is calculated using the pseudo-reduced pressure. This reduced pressure leads to maxima in the burnout curves in the region $0.2 < (P_r^*)_{max} < 0.3$ which is in agreement with the existing theories and correlations. Use of the true reduced pressure led to shifts in the burnout maxima for which there is no precedent.

C. Mixture Burnout Correlation

Although such a relatively dramatic composition dependence begs for an explanation, relatively little has been done with regard to correlating mixture burnout behavior. Kutateladze, et al. (33) used the relation

$$q_{1c} = \kappa_{P_{v}} \left[\frac{gg_{c}\sigma(P_{1} - P_{v})}{P_{v}^{2}} \right]^{\frac{1}{4}}$$
(3-5)

where $K = f(\Delta C/\Delta C_m)$. Here ΔC is the concentration difference of the more volatile component between the liquid and vapor and ΔC_m is the maximum value of this concentration difference. For the ethanol - benzene system $f(\Delta C/\Delta C_m)$ was nearly linear.

By contrast, van Stralen (71) used the bubble growth model described in Chapter 1 to obtain an expression for the burnout heat flux in mixtures. His final expression was

$$q_{1c,mix} = \left(\frac{\beta_{pure 1}}{\beta_{mix}}\right) \cdot q_{1c, pure 1}$$
 (3-6)

Equation 3-6 gave good results when compared with data at one atmosphere for 4.1% methylethyl ketone in water and for 1% 1-butanol in water.

The mixture burnout prediction of van Stralen did not prove effective for the mixtures investigated here. However, the work of Kutateladze, <u>et al.</u> (33) and the results in the nucleate boiling and natural convection portion of this work indicate that the mixture relative volatility does play an important role in all phases of boiling. Since the Moissis and Berenson correlation is so effective in representing the pure component data, a modification of this correlation using the relative volatility term, a_{μ} , was sought. It was found that the modified Moissis and Berenson relation

$$q_{1c} = 0.18 \ \alpha_{\nu}^{\frac{1}{2}} \mathcal{L}\left[\left(\frac{\rho_{1}+\rho_{v}}{\rho_{1}}\right)/(1 + 2\left(\frac{\rho_{v}}{\rho_{1}}\right)^{\frac{1}{2}} + \frac{\rho_{v}}{\rho_{1}}\right)\right]$$
(3-7)

is quite satisfactory in correlating all of the data from this work. The pure component data fit Equation 3-7 with an overall average deviation of 8.0% (propane - 7.0%; n-butane - 8.6%; and n-pentane - 7.7%). A comparison of experimental and calculated pure component data is given in Figure 3-6. The mixture burnout data, shown in Figure 3-7, were correlated with an average absolute deviation of 12.4% (9.6% for the propane - n-butane system and 15.1% for the propane - n-pentane system). By contrast, the unmodified equation gave an average absolute deviation of 27.2% (15.9% for the propane - n-butane system and 37.9% for the propane - n-pentane system). Equation 3-7 should also apply to other systems whose pure component data are represented well by the Moissis and Berenson relation.




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Figure 3-8 Comparison of Mixture Burnout Data with the Unmodified Moissis and Berenson Correlation

D. Conclusions

1. The pure component data are represented well by the Moissis and Berenson correlation.

2. There is a definite composition dependence of burnout behavior in the propane - n-butane and the propane n-pentane systems.

3. The correct reduced pressure to use in plotting mixture burnout data is the pseudo-reduced pressure.

4. The expression

$$q_{1c} = 0.18\alpha^{\frac{1}{2}} \left[\left(\frac{\rho_{1} + \rho_{v}}{\rho_{1}} \right) / (1 + 2 \frac{\rho_{v}}{\rho_{1}} + \frac{\rho_{v}}{\rho_{1}}) \right]$$

represents the experimental data for mixtures taken in this study with an average absolute deviation of 12.4%.

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Appendix A: Experimental Equipment

The experimental apparatus was a modification of the facility designed and built by Sciance (55) and used by Brown (6) and by Wright (75). The addition of an entirely new vertical condensing system permitted the investigation of film condensation. A schematic diagram of the entire apparatus is shown in Figure A1-1. A schematic diagram showing the autoclave and heater mounting is given in Figure A1-2, while Figure A1-3 shows the details of the heater construction. A detailed description of the procedure for constructing the heater was presented by Wright (75).

A. Boiling Vessel

The boiling vessel was a one gallon, stainless steel autoclave manufactured by Autoclave Engineers, Inc. The vessel was equipped with two $1\frac{1}{4}$ -inch diameter quartz sight glasses, oriented 180 degrees from each other. A special feature of this boiling vessel was that the body of the autoclave was mounted on a pneumatic jack, which allowed the vessel to be opened without disturbing the rest of the assembly.



FIGURE A I-I SCHEMATIC DIAGRAM OF EXPERIMENTAL APPARATUS



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DETAIL OF BORON NITRIDE INSULATOR



FIGURE AI-3 HEATER DESIGN DETAILS

openings for the liquid condensate return and for connection with the vapor by-pass line and the pressure measuring system.

The bulk liquid temperature in the autoclave was measured with four Conax grounded-tip, mineral insulated, stainless steel sheathed iron-constantan thermocouples. The thermocouples were arranged so that a temperature reading was made at twoinch intervals beginning at the heater and ascending.

Because all experiments were conducted above room temperature, it was necessary to provide auxiliary heating to insure that there would be no subcooling in the liquid pool. For runs PR3 and PR4, supplementary heating was provided by passing steam through a copper coil wrapped around the autoclave. This form of auxiliary heating proved to be inadequate for bulk temperatures in excess of 110 F. For runs PR5 through MX3, auxiliary heating was done with a single asbestos insulated nichrome resistance heater. Subsequent runs were performed using two asbestos insulated heaters.

The main body of the autoclave was insulated with a galvanized metal box containing perlite. The bus bar pressure glands, the liquid return line, and the lead to the vapor bypass line were all insulated with $\frac{1}{2}$ -inch thick fiberglass. The header and the sight glasses were also insulated with $\frac{1}{2}$ -inch fiberglass.

B. Test Heater

The test heater used in this work was of the same design as that used by Wright (75). It was a cylindrical, composite resistance heater, mounted horizontally. The body of the heater was a 13/16-inch diameter by 3¹/₂-inch long copper cylinder. The heat transfer surface was gold plated in an effort to achieve a stable and inert surface with which to study boiling behavior. The gold-plated surface proved to be remarkably stable throughout the course of the study. Electrical resistance heating was provided by using a 1/16inch diameter graphite electrode located in the center of the copper cylinder. The electrode was electrically insulated from the rest of the heater by a 0.02-inch thick boron nitride sleeve.

Temperature measurements were made in the heater with five iron-constantan thermocouples. These thermocouples were fabricated from 30 gauge Tem-Tex thermocouple wire. The thermocouples were inserted in 0.40-inch diameter by one-inch deep wells. The wells were set around a circle, at a distance of 5/64-inch from the heater surface. To eliminate any chance of thermal contact resistance at the thermocouple beads, a drop of mercury-indium solder was placed at the end of each well. The fact that the solder did not affect the thermocouple reading in any way was shown by the excellent agreement between readings of the heater thermocouples and the liquid thermocouples when the heater was off. The heater thermocouple

leads were connected to a screw-post terminal board inside the autoclave and from there to lead wires which passed out of the autoclave through the Conax pressure gland.

A second test heater was used for the bulk of the burnout tests. This heater consisted of a 0.061-inch diameter carbon rod, 2.80 inches long. The heater was clipped firmly to the same bus bar arrangement used for the other test heater.

C. Condenser

The condenser used was designed specifically for this study. A desire to study the effects of pressure and composition on film condensation necessitated a complete redesign of the original condenser system. The new condenser was fully instrumented with thermocouples for heat transfer measurements. To facilitate the installation and repair of the thermocouples, the condenser was made in three sections: the inner (condensing) tube, the outer (coolant) tube, and the mounting flange - liquid return line assembly. A diagram of the entire condenser assembly is shown in Figure A1-4.

The inside tube of the condenser was fabricated from a five and one-half foot long, 2-inch ID, schedule 80 stainless steel pipe. Welded to one end of the pipe was a $\frac{1}{2}$ -inch thick by one inch wide collar containing six equally spaced, $\frac{1}{4}$ -inch diameter, NF, bolt holes. This bolt collar provided a means of aligning the inner tube of the condenser during assembly and of securing the inner tube during operation.



A 1-inch wide by 3/8-inch deep groove was cut into the collar to allow the thermocouples set in the outer tube of the condenser room to slide through during assembly. The inside tube was capped by a 2-inch by 3/4-inch, schedule 80, stainless steel concentric reducer. The inside of the 3/4-inch diameter portion of the reducer was threaded to accept the fitting connecting the fill line and the condenser by-pass line. Also fitting over the top of the inside tube was a bell-like piece made up of a $2\frac{1}{2}$ -inch by $3\frac{1}{2}$ -inch, schedule 40, stainless steel reducer, a six inch long piece of 32-inch diameter, schedule 40, stainless steel pipe, and a $3\frac{1}{2}$ -inch ID, 300 pound stainless steel flange. The flange served as the upper mount for the outer jacket of the condenser. Two Conax MHM-125-A8-T thermocouple pressure glands, oriented 180 degrees from each other, were set into the six inch length of pipe.

The outer jacket of the condenser was a five foot by $3\frac{1}{2}$ inch ID, schedule 40, stainless steel pipe. A 300 pound stainless steel flange was welded to each end. The upper flange was faced and had a $5\frac{1}{2}$ -inch ID by 1/8-inch deep 0-ring groove cut into it. This 0-ring made a seal with the flange mounted on the top of the inside tube. At either end of the outer jacket, 180 degrees apart, $\frac{1}{2}$ -inch diameter holes were cut and $\frac{1}{2}$ -inch standard pipe nipples were welded on. The pipe nipples were the connections for the coolant supply.

The liquid return was a 10-inch long by 3/4-inch, schedule 80 stainless steel pipe topped by a 2-inch by 3/4-

inch, schedule 80, stainless steel concentric reducer, a 2inch long piece of 2-inch ID, schedule 80, stainless steel pipe, and a 9¹/₂-inch diameter stainless steel flange. The flange was faced and two 1/8-inch wide 0-ring grooves, one 21-inch ID and the other 42-inch ID, were cut into it. The smaller O-ring sealed the inside tube of the condenser with the liquid return line, while the larger O-ring sealed the outer jacket of the condenser. The liquid return line was threaded to fit into the header of the boiling vessel. Sciance (55) found that a condenser by-pass line was necessary for the apparatus to operate. This by-pass line was necessary to assure equal pressures at the top and the bottom of the condenser, thereby permitting liquid reflux to return to the boiling vessel. The addition of a much larger condenser greatly magnified the pressure equalization problem. The internal volume of the new condenser was large enough that the boiling vessel could be exhausted of liquid without developing sufficient head to cause the condenser to dump. The addition of a much larger by-pass line alleviated this problem to a great extent. The by-pass line used in this work was constructed of one-inch ID, schedule 40, stainless steel pipe. The fittings for this unusually large pressure line were fabricated in the Departmental Machine Shop. The unique problems presented in constructing fittings which would adequately hold pressure for a pipe this large required a special design,

The final pressure seal design combined an O-ring seal with a variable pressure compression ring. As shown in Figure A1-5, the outside wall of the tubing, the two walls of the compression ring, and the raised face of the pressure fitting completely enclose the O-ring. The resulting fourway compression is particularly suited for use with Teflon O-rings because it counteracts the marked tendency for Teflon to cold flow when subjected to elevated temperatures and pressures. The seal has been used in static service as high as 260 F and 400 psia without failure.

The condenser was instrumented at five points, ten inches apart, with twenty calibrated copper-constantan thermocouples. The thermocouples were arranged as shown in Figure A1-6 to give a measurement at the centerline of the coolant annulus, the outer surface of the condenser wall, inside the condenser wall, and the centerline of the coolant annulus. These four temperatures allowed calculation of local condensing coefficients at five points up the condenser.

Additional **measurements** on the coolant stream were used to make an overall heat balance on the entire boiling and condensing system. The coolant flow rate was measured with a calibrated Fisher and Porter Co. precision bore Flowrator rotameter. The coolant inlet and outlet temperatures were measured with a mercury-in-glass thermometer.

The main body of the condenser was insulated with four inches of Pittsburgh-Corning Foamglass insulation. The Foam-



FIGURE A1-5 SCHEMATIC DIAGRAM OF LARGE TUBE PRESSURE FITTING



Figure A1 - 6 Thermocouple Arrangement in Condenser

glass insulation was covered with 0.003-inch thick stainless steel foil. This foil acted both as a heat reflector and as protection for the Foamglass. The rest of the condenser and the by-pass line fittings were insulated with $\frac{1}{2}$ -inch thick fiberglass. The tubing in the by-pass line was insulated with 3/4-inch thick Armoflex foam rubber insulation.

D. Power Supplies

An Ultrasil, Model 2-IP2-10-01, "Udylite" direct current power supply was used during most of the experiments. This rectifier converted 208 volt, 60 cycle, 3-phase AC current to a variable direct current of 0-20 volts, 0-1000 amperes, with a maximum ripple of 5 per cent. In a few instances the voltage output from the "Udylite" was not adequate for the heat flux needed. The additional voltage was obtained by connecting a Sorenson, Model MA28-125, "Nobatron" power supply in series with the "Udylite". The combined power supplies had a capability of 14-56 volts and 0-125 amperes DC.

E. Experimental Measurements

All of the thermocouple measurements were made with a Hewlitt-Packard, Model 3460A, digital voltmeter. The Thermocouple readings were made against reference junctions kept in insulated ice baths. The autoclave thermocouples were connected through a Minneapolis-Honeywell 24-position rotary thermocouple switch. Temperatures are believed to be accurate to within 0.05 F.

The system pressure was measured using a Wallace and Tiernan, Model FA233 absolute pressure gauge in the range 0-150 psia. For runs through MX3 a 0-2000 psi Heise gauge was used for pressures in excess of 150 psia. Subsequent runs were made using a 0-1000 psi Heise gauge. A one-inch thick layer of rigid urethane foam insulated all pressure lead lines to minimize error due to heat leaks in the pressure measuring system. The Wallace and Tiernan gauge could be read to 0.2 psia; the 0-1000 psi Heise gauge could be read to 1 psi; and the 0-2000 psi gauge to 2 psi.

The boiling heat flux determination was made by measuring the voltage drop across the heater and the current passing through the heater. A Simpson Model 1700 multi-range voltmeter could give the voltage drop across the heater to $\frac{1}{2}$ per cent. The current reading was made with a Simpson Model 1701 multi-range millivolt meter and a Leeds and Northrup 0.001 ohm standard resistor. The accuracy of the current measurement was also $\frac{1}{2}$ per cent. The heat flux for the composite heater was calculated from

q/A = 55 E I

The dimensional constant, 55., is changed to 915. in the case of the carbon rod.

F. Experimental Chemicals

All chemicals used in this work were provided by the Phillips Petroleum Company. All were "Pure" grade. A gas chromatographic analysis of the chemicals is given in Table A1-1.

Table A1-1

Analysis of Pure Components

Primary Substance	Fractional Composition				
	°2	°3	C ₄	°5	с ₆
Propane	0.006	0.994	*	#	*
n-Butane	*	0.005	0.995	* :	*
n-Pentane	*	*	*	1.000	*

* None detected

Appendix B: Experimental Method and Data Reduction Experimental Method

A. Preliminary Steps

Before any series of experiments the autoclave and heater assembly were thoroughly cleaned with acetone. The system was then resealed, pressurized with dry nitrogen, checked for leaks, purged several times with nitrogen, and left sitting with a positive nitrogen pressure until ready for use.

Propane and n-butane were charged under their own vapor pressure. To do this, the vent line was opened slightly and the two valves on the gas line were opened. The vapor pressure of the liquefied gas forced liquid out of the inverted bottle, through the fill line, and into the system. The time required for the liquid level to pass the sight glass was measured with a stopwatch. The loading was continued for four times the length of time required to cover the sight glass, thus insuring at least five inches of liquid above the heater.

The n-pentane was loaded directly into the open autoclave. Then the system was sealed and pressure tested as described above. Following the leakage test, the nitrogen was vented and the n-pentane heated until it exhibited a vapor pressure of about 20 psia. Venting of the nitrogen and n-pentane continued until there was a correspondence between the

measured n-pentane vapor pressure and the vapor pressure calculated from the measured liquid temperature. In this manner all of the nitrogen could be flushed from the system.

The mixtures were made up in situ. This was done by first loading the heavier component until the liquid level was in approximate proportion to the desired mixture composition. That is, if a 50% mixture was desired, the autoclave would be filled about half way. Then the lighter component was added to the system. The mixture was boiled vigorously for one-half hour and allowed to sit over night to allow it to come to equilibrium. Before any series of mixture experiments, vapor pressure readings would be made to determine the approximate composition of the contents of the autoclave. The final composition determinations were made at each operating pressure by maintaining a steady-state vigorous boiling and taking liquid temperature and system pressure readings.

After the loading procedures had been completed, the test heater and, if necessary, the guard heaters were turned on. Before all nucleate boiling data runs the test heater was operated at 450-500 watts for a period of one hour. This conditioning period, combined with careful cleaning of the heater surface, was an attempt to maintain a stable and consistent heating surface.

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B. Taking Natural Convection and Nucleate Boiling Data

After the heater had been conditioned and the desired initial operating pressure attained, the power to the test heater was cut to nearly zero. The system was then allowed to equilibrate at the operating pressure. Once stable operation had been resumed, the first data point was taken by measuring the autoclave and heater thermocouples in rapid succession. Upon completing the readings, the heat flux was adjusted upward, the condenser and guard heater adjusted as necessary, and the system allowed to re-equilibrate.

In natural convection, stabilization occurred in a matter of 3-5 minutes, while at fairly high heat fluxes the system could be stabilized in 10-15 minutes. When operating at intermediate heat fluxes $(8,000-30,000 \text{ Btu/ft}^2\text{hr})$ the system was at times very difficult to control and would require as much as 30-45 minutes to achieve steady state. However, once a stable condition was achieved the apparatus remained at that condition indefinitely. It was necessary at very high heat fluxes (>85,000 Btu/ft²hr) to reduce the heat flux periodically to allow liquid which had accumulated in the condenser to drain back into the autoclave.

The bulk of the natural convection and nucleate boiling data reported here were taken with increasing heat flux. However, there was a check for hysteresis. At one convenient pressure in each run, data would be taken at both ascending and descending heat flux. In this manner a measure of the hysteresis effect was possible for each system studied. There was an observable hysteresis effect only once, in the case of the 63% propane - 37% n-butane mixture at 184 psia.

C. Taking Condensing Data

Condensing data were taken at the same time as the nucleate boiling data. The measurement of condensing coefficients was carried out by first taking a pressure reading, then voltage readings on all of the condenser thermocouples, then a water flow rate and temperature measurement, and finally a check on the system pressure. This entire process took 3-5 minutes. When the system stabilized, temperatures in the condenser showed basically no variation over as much as an hour.

It should be noted that a steady water flow through the condenser was not always necessary for stable operation. By carefully controlling the amount of cooling the condenser experienced, it was possible to achieve fairly stable operation without a continuous water flow. A minor problem encountered when the vapor condensing temperature was below about 90 F was that the condenser was not adequate to maintain a stable pressure at very high boiling heat fluxes.

D. Taking Burnout Data

When the gold plated heater was being used, burnout data were taken in the same manner as that used by previous investigators (6, 55, 75). The carbon rod heater called for a somewhat different method of data collection. The system

pressure was controlled mainly by guard heating because the net heat output of the carbon rod was so low. Once the desired pressure was attained, the heat flux in the carbon rod was increased in small steps until burnout occurred. Burnout was evidenced by an immediate increase in the amperage flowing through the heater. The burnout point would then be taken to be the last stable heat flux before the excursion. Duplicate measurements were made at each condition.

Data Reduction

E. Natural Convection and Nucleate Boiling Data Reduction

The reduction of natural convection and nucleate boiling data was performed by computer. Input for the data reduction program was the thermocouple voltage readings, the heater voltage and amperage readings, and the pressure measurement. The thermocouple measurements were converted to temperatures using a quadratic equation relating thermocouple voltage to absolute temperature. This temperature-voltage relation was obtained by a least-squares fit of the pertinent range of a standard iron-constantan thermocouple table. The heater inner temperatures were averaged and the heater wall temperature was calculated using the relation developed by Sciance (55). The heat flux was calculated as shown in Appendix A. All temperature calculations were performed in extended precision variables.

F. Condensing Data Reduction

The condensing data reduction was carried out in two parts. In the first part the thermocouple voltage readings were converted to temperatures. This was done by using a quadratic equation relating absolute temperature to the voltage for each of the twenty thermocouples. Twenty sets of coefficients were required in order to make the individual readings as accurate as possible. The temperature measurements, along with the nucleate boiling heat flux, the inlet and outlet water temperature, and the water flow rate served as inputs for the actual condensing data reduction program.

The condensing data reduction program used the condenser temperatures to calculate the local heat flux, inside wall temperature, condensing-side coefficient, and water-side coefficient at each of five points in the condenser. Four heat duties were calculated: the heat input from the nucleate boiling heat flux; the sensible heat change of the coolant water; the integral of the heat absorbed in the coolant water; and the integral of the heat transferred through the condenser wall. In most cases agreement between the four heat duties was within 10-20%.

Two items related to condensing data reduction bear special mention. The first is the location of the wall thermocouples and the heat transfer calculation. The wall thermocouple location was determined at each point by measuring the depth of the well and using the known inside

and outside diameters of the condensing tube to obtain the inside wall thickness by solving the right triangle. The radius to the thermocouple location was used in the actual calculation instead of the wall thickness to minimize the relative error engendered by the slight uncertainty in the wall thickness measurement. The heat transfer equations used to reduce the condensing data are presented in Bird, <u>et al.</u> (3).

A second important consideration was the individual calibration of the condenser thermocouples. All of the thermocouples used in the condenser were calibrated at the liquid nitrogen boiling point, solid CO₂ sublimation point, and water boiling point. These three points, plus the ice point, allowed construction of calibration curves for each thermocouple. These curves were then used to calculate "corrected" voltage readings for use in the quadratic fitting program.

Appendix C: Pure Fluid Bubble Growth Theories

Most of the bubble growth theories which have been proposed deal with the "asymptotic" growth period in the ebullition cycle. The asymptotic growth period is that time during which viscous, inertial, and surface tension forces are no longer controlling factors in bubble growth. The asymptotic growth period extends from roughly one to two microseconds after growth begins until bubble departure.

All of the models are based upon an idealization of a spherical bubble growing in a quiescent fluid medium. Other basic assumptions made by the initial investigator, Bosnjaković (4), are

- 1. The required latent heat of vaporization is supplied to the bubble boundary as a result of a slight superheating of the entire bulk liquid.
- 2. After a short initial period, the bubble is surrounded by a thin boundary layer, through which heat transfer is by conduction only.
- 3. There is a state of thermodynamic equilibrium at the bubble boundary.

Using these assumptions, Bosnjakovic was able to show

$$q/A = a\lambda = \frac{\Delta^{\theta}o^{k}}{\delta}$$
 (C-1)

where q/A is the heat flux density, a is the rate of evaporation per unit area, λ is the latent heat of vaporization, k is the liquid thermal conductivity, δ is the superheated boundary layer thickness, and \mathbf{A}^{θ}_{0} is the liquid superheating. For a spherical bubble a = $\mathbf{\rho}_{v}^{R}$ so

$$\rho_{\rm v}\lambda \dot{\rm R} = \frac{\Delta^{\theta} o^{\rm k}}{\delta} \qquad (C-2)$$

Take $\delta = (\alpha t)^{\frac{1}{2}} = (kt/\rho_v c_p)^{\frac{1}{2}}$, the thermal boundary layer thickness for transient conduction in a semi-infinite body with a plane boundary, and integrate Equation C-2 using R(0) = 0to get

$$R(t) = 2 \frac{\rho_1 c_p}{\rho_v \lambda} \Delta_0^{\theta} (\alpha t)^{\frac{1}{2}} = \beta \Delta_0 t^{\frac{1}{2}}$$
(C-3)

Before further utilizing Equation C-3, it is interesting to note the results of a few other investigators in the field of bubble growth. Forster and Zuber (20) used the extended Rayleigh equation to obtain the expression

$$R(t) + R_{0} \ln \frac{R(t)-1}{R_{1} - 1} = \frac{\rho_{1}c_{p}}{\rho_{v}\lambda} \Delta \theta_{0} (\pi \alpha t)^{\frac{1}{2}} = c_{1}\Delta \theta_{0} t^{\frac{1}{2}} \quad (C-4)$$

For the bubble radius here $R_0 = (2\sigma T/\lambda \Delta \theta_0)$ and R_1 is the radius at which growth resulting from the superheat term and evaporation term become equal. van Stralen (65, 67) has indicated that $(R(t)-1)/(R_1-1)$ tends towards zero, to give a result like that of Bosnjaković. A somewhat similar analysis by Plesset and Zwick (48) resulted in the expression

$$R(t) = \left(\frac{12}{\pi}\right)^{\frac{1}{2}} \frac{\rho_{1}c_{p}}{\rho_{v}\lambda} \Delta\theta_{0}(\alpha t)^{\frac{1}{2}} = c_{1}^{\prime}\Delta\theta_{0}t^{\frac{1}{2}} \qquad (C-5)$$

Appendix D: Thermo-Physical Property Estimation

With the exception of the saturated liquid and vapor densities, the pure component properties came from two sources. Saturated pure component data for propane and n-butane were taken from Sciance (55), while data for n-pentane were obtained from Gallant (21).

Saturated liquid and vapor densities were calculated using the modified Benedict-Webb-Rubin (MBWR) equation presented by Kwok (34). The pure component parameters and the parameter mixing rules suggested by Kwok were used for pure component and mixture calculations.

The vapor-liquid equilibrium data of Sage, <u>et al.</u> (46, 53) for both the propane - n-butane and the propane n-pentane systems were used to determine mixture critical properties. K-values calculated from these data were compared to K-charts in the NGPA Engineering Data Book (18), and the 800 psi convergence pressure charts were found to be adequate for use in predicting vapor-liquid equilibrium for these two systems. Temperature-composition diagrams were constructed for each of the pressures studied, and these diagrams were used to determine vapor and liquid compositions.

There is a complete lack of property data for the mixtures used in this study. For this reason, mixture property
data were estimated using pure component values. Mixture latent heats of vaporization and heat capacities were calculated using the linear mixing rules

$$\lambda_{\min} = x_1 \lambda_1 + x_2 \lambda_2 \qquad (D-1)$$

$$c_{p mix} = x_1 c_{p1} + x_2 c_{p2}$$
 (D-2)

Liquid mixture viscosities were calculated using the method of Huang, et al. (25) who proposed

$$\mu_{\rm m} = \frac{{\rm A}^{\prime}}{{\rm x}_1 \sqrt{{\rm M}_1} + {\rm x}_2 \sqrt{{\rm M}_2}}$$
(D-3a)

$$A' = x_1 \sqrt{M_1} \mu_1 + x_2 \sqrt{M_2} \mu_2 \qquad (D-3b)$$

Filippov and Novoselova (19) suggested the expression

$$k_{mix} = k_1 x_1 + k_2 x_2 - 0.72 | k_1 - k_2 |$$
 (D-4)

which applies only to calculating the liquid thermal conductivity for binary mixtures. The mixture surface tensions were calculated using the expression

$$\sigma_{\text{mix}} = \frac{\sigma_1 \sigma_2}{\sigma_1 x_2 + \sigma_2 x_1}$$
 (D-5)

which was developed by Stackorsky (63). Binary, infinite dilution diffusion coefficients were estimated with the relation

$$D_{12}^{0} = \frac{3.67 \times 10^{-8} \text{T}}{\mu_2 \text{ v}^{1/3}} (1.4(\text{v}_2/\text{v}_1)^{1/3} + (\text{v}_2/\text{v}_1)) \qquad (C-6)$$

suggested by Lusis and Ratcliff (36). The mixture diffusion coefficient \mathcal{A}_{AB} , was calculated by the method of Rathbun (51).

$$\mathbf{D}_{12} = (\mathbf{x}_1 \mathbf{D}_{21}^{\mathbf{o}} + \mathbf{x}_2 \mathbf{D}_{12}^{\mathbf{o}}) \frac{d(\ln a)}{d(\ln x_1)}$$
(D-7)

In this work $\frac{d(\ln a)}{d(\ln x_1)} \approx 1$. This is equivalent to the assumption of an ideal liquid solution, the validity of which was supported by the good comparison of fugacities calculated from ideal solution theory with those estimated from the MBWR equation. The stainless steel thermal conductivity was given by

$$k = 8.08 + 0.0052 T$$
 (D-8)

and the copper thermal conductivity was given by

$$k = 249.2 - 0.031 T$$
 (D-9)

Appendix E: Natural Convection and Nucleate Boiling Data

In this appendix the original experimental data for natural convection and nucleate boiling are summarized. For each datum the following items are listed: datum number, pressure, psia, heat flux, Btu/ft²hr, heater wall temperature, degrees R, and the temperature difference between the heater wall and the temperature of the saturated liquid bath, degrees R. The datum number PR1201 may be broken into the parts PR, which indicates propane, 12, for run number 12, and 01, for point number 1. Other descriptors used are NB for n-butane, NP for n-pentane, and MX for mixtures. The symbol * after a datum number indicates a point where no bubbles are visible on the heater.

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Propane

Data No.	Pressure psia	Heat Flux Btu/ft ² hr	Twall,R	∆T,R
PR1201 PR1202 PR1203 PR1204 PR1205 PR1205 PR1205 PR1207 PR1208 PR1209 PR1209 PR1210 PR1211 PR1212 PR1213	185. 186. 186. 186. 186. 187. 186. 183. 187. 186. 187. 187. 186.	113. 776. 1570. 2770. 3900. 5135. 6910. 8390. 12240. 16200. 21100. 27800. 36710	558.11 559.51 559.83 560.50 561.19 561.96 562.94 562.92 562.76 565.73 566.34 568.16 569.86	0.43 1.55 2.12 2.81 3.43 3.98 4.66 5.09 6.28 7.28 8.48 9.91
PR1214 PR1215 PR1216 PR1217 PR1218	189. 184. 183. 183. 185.	43580. 23050. 9380. 3850. 891.	571.97 566.48 562.24 560.54 559.30	13.17 9.29 5.87 3.52 1.71
PR1 301 PR1 302 PR1 303 PR1 304 PR1 305 PR1 306 PR1 307 PR1 307 PR1 308 PR1 309 PR1 310 PR1 311 PR1 312 PR1 313 PR1 314 PR1 315	186. 185. 184.5 184.5 185.5 185.5 185.	157. 368. 892. 1660. 2503. 3556. 5350. 7591. 9511. 13175. 17730. 23115. 27580. 37040. 48280.	558.13 558.36 559.31 560.26 560.77 561.42 562.28 561.76 562.59 563.02 562.79 563.13 563.76 566.20	0.52 0.98 2.236 4.62 5.36 5.66 5.09 5.002 6.61 78.74
PR1146 PR1147 PR1148 PR1149 PR1150 PR1151 PR1152 PR1153 PR1154	246. 247. 246. 248. 248. 247. 246. 245. 246.	117. 645. 2174. 5190. 8800. 15580. 24420. 31955. 68270.	580.20 581.28 582.31 583.13 585.04 586.33 587.91 588.99 596.16	0.50 1.22 2.32 3.40 4.69 6.48 8.23 9.84 16.70

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Data No.	Pressure psia	Heat Flux Btu/ft ² hr	Twall,R	∆ T,R
PR1134	308.	130.	599.51	0.75
PR1135	308.	718.	599.73	1.37
PR1136	307.	1689.	600.12	1.93
PR1137	308.	3110 . 4820	601 50	2.52
PR1130	308	7840	602 75	J.12 4 00
PR1140	309.	12350.	603.86	5,01
PR1141	308.	21100.	605.08	6.60
PR1142	308.	28070.	605.99	7.68
PR1143	302.	36710.	606.25	9.03
PR1144	308.	50490.	610.71	11.51
PR1145	308.	58150.	612.90	14.09
PR1119	370.	93.	615.71	0.47
PR1120	370.	167.	615.62	0.64
PR1121	370.	634.	616.28	1.06
PR1122	370.	1827.	617.08	1.72
PR1123	370.	3300 . 6050	017.21	2.41
PR1124	370	10180	610.27	J・4J 山 07
PR1126	370.	13810.	619.79	4.60
PR1127	371.	18200.	620.65	5.21
PR1128	370.	26260.	621.56	6.15
PR1129	370.	33490.	622.69	7.10
PR1130	372.	44170.	624.84	8.99
PR1131	370.	50400.	624.02	10.78
PR1132	369.	59020.	629.76	14.72
PR1133	367.	5 9 895.	630.77	16.18
PR1105	432.	348.	630.60	0.67
PR1106	432.	1347.	630.81	1.39
PR1107	432.	2652.	631.15	1.70
PR1108	432.	4250.	631.74	2.14
DP1110	4)2. 432	8810	632.60	2.56
PR1111	433	13300.	633.19	3.57
PR1112	433	18020.	633.78	4,10
PR1113	432.	24010.	634.56	5.11
PR1114	432.	29740.	635.96	6.00
PR1115	432.	34850.	639.02	9.14
PR1116	432.	45220.	639.87	9.94
PR1117	432.	51610.	639.89	10.36
PR1118	432.	55380.	640.31	10.15

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Propane - continued

Data No.	Pressure psia	Heat Flux Btu/ft ² hr	Twall,R	∆ T,R
PR1001	494.	10040.	646.96	4.28
PR1002	494.	15275.	647.79	5.14
PR1003	494.	21670.	648.12	5.48
PR1101	494.	12920.	647.35	5.09
PR1102	494.	19460.	647.66	5.29
PR1103	494.	33300.	647.80	5.40
PR1104	494.	40130.	647.98	5.36
		n-Butane		
ND0201#	ch a	1 /1 /2	£60 11	0.16
ND0201*	54•1 55 6	147. 750	502.11	0.10
NB0202*	55.0 511 0	21.07	507.05	11 00
NB0204	56 5	5200	577 20	13 76
NDULUT	JU • J	J2000	J// • 20	T J • {0
NB0301*	55.0	433.	566.51	4.04
NB0302 *	55.0	1703.	572.75	10.57
NB0303*	54.9	4177.	574.66	13.00
NB0304	55.4	7440.	577.20	14.99
NB0305	54.9	13095.	578.81	17.32
NB0306	54.5	19650.	580.12	19.15
NB0307	54.8	27730.	582.10	20.64
NB0308	55.2	35455	583.78	21.83
NB0309	55.2	47485.	585.46	23.50
NB0310	56.9	59700.	588.28	24.40
NBU311	54.8	37190.	583.23	21.81
NB0312	55.0	19620.	579.77	18.09
NB0313	54.8	8028.	575.33	13.95
NB0314*	55.0	2018.	571.13	8.89
NB0212*	110.	240.	612.63	1.11
NB0213*	110.	1056.	616.74	5.14
NB0214*	110.	2709.	619.31	7.63
NB0215	110.	4470.	621.05	9.62
NB0216	110.	9286.	622.51	10.98
NB0217	110.	14595.	624.27	12.67
NB0218	110.	25120.	626.47	15.24
NB0219	114.	43560.	632.02	18.10
NB0320	110.	47120.	628.48	17.27
NB0321	110.	67710.	631.60	19.97

Propane - continued

Data No.	Pressure psia	Heat Flux Btu/ft ² hr	Twall,R	∆T,R
NB0220*	137.	1986.	634.92	6.10
NB0221	137.	5270.	637.20	8.39
NB0222	137.	8576.	638.71	9.77
NB0223	137.	15470.	640.63	11.55
NB0224	137.	25690.	642.38	13.64
NB0225	137.	42100.	644.78	15.69
NB0322	137.	31300.	643.15	14.46
NB0323	136.5	47025.	644.37	15.72
NB0324	137.	65835.	646.26	17.32
NB0226	163.	8590.	651.93	8.42
NB0227	165.	16878.	654.93	10.25
NB0228	167.	27260.	657.54	11.56
NB0229	165.	39715.	657.95	13.07
NB0230	167.	61450.	661.07	16.07
NB0325	163.	30320.	656.04	12.62
NB0326	165.	47520.	658.70	13.39
NB0327	167.	68850.	661.00	15.25

n-Butane - continued

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n-Pentane

NP0101*	23.8	78.	580.09	0.29
NP0102*	23.8	213.	580.35	0.38
NF0103*	23.8	402.	581.12	0.69
NP0104*	23.9	865.	582.20	1.53
NP0105*	24.0	1824.	587.61	6.72
NP0106*	24.0	3038.	593.47	12.39
NP0107*	24.1	4453.	598.14	16.94
NP0108	24.3	5917.	600.23	18.62
NP0109	24.0	10760.	602.66	22.51
NP0110	24.0	16630.	605.97	26.19
NP0111	24.1	24490.	609.22	29.09
NP0112	24.2	33620.	612.63	32.22
NP0113	24.9	45140.	617.14	34.86
NP0114	25.4	55540.	620.78	37.24
NP0201*	36.6	109.	607.98	0.25
NP0202*	36.8	306.	608.70	0.74

Data No.	Pressure psia	Heat Flux Btu/ft ² hr	Twall,R	∆ T,R
NP0203*	36 .7	652.	609.60	1.78
NP0204*	36.6	1233.	611.90	4.31
NP0205*	36.5	2314.	618.23	10.86
NP0206*	36.5	3527.	621.20	14.01
NP0207	30.0	5135.	620.71	13.30
NP0200	36.6	12160	625 50	18 35
NP0210	37.0	18350.	629.26	21.66
NP0211	37.5	27440.	633.08	24.51
NP0212	36.8	34020.	634.39	27.16
NP0213	36.8	44000.	636.87	29.69
NP0214	36.0	55260.	638.21	32.25
NP0215	36.2	72930.	641.66	35.32
NP0115*	49.0	334.	628.46	0.78
NP0116*	48.6	702.	629.17	2.18
NP0117*	48.9	1315.	632.65	5.30
NPU118*	48.9	2342.	636.10 Kar 9a	8.05
NP0119*	40.9 48 o	5200	0JJ.0J 637 72	0.02 10 山0
NP0121	49.0	7377	639.72	12.31
NP0122	49.1	12150.	642.81	15.63
NP0123	48.8	18180.	644.81	18.15
NP0124	49.1	27065.	647.84	20.76
NP0125	49.0	34980.	649.45	22.59
NP0126	49.3	44740.	651.57	24.15
NP0127	49.7	50950.	655.20	27.14
NP0120	40.0	70220.	0)/+14	00,00
NP0301*	48.8	134.	627.58	0.58
NP0302*	48.8	182.	627.75	0.59
NP0303*	49.0	271.	628.25	0.84
NP0304*	40.9	410.	620.95	1.50
NP0306#	49.0	839.	631 20	3 90
NP0307*	48.9	1273.	633.53	6.28
NP0308*	48.9	1810.	636.09	8.66
NP0309*	49.0	2929.	639.23	12.12
NP0310	49.1	4110.	640.56	13.19
NP0311	49.1	6572.	642.02	14.69
NP0312	48.6	11240.	643.63	17.22
NPO 31 J	49.1 40 5	17040.	040.23	19.08
ND031 C	77·7	21/1.50	6/18 22	20.29

n-Pentane - continued

Δ T ,R	Twall ^{,R}	Heat Flux Btu/ft ² hr	Pressure psia	Data No.
22.86	650,64	44510	49.6	NP0316
21.54	649.00	28200	49.0	NP0317
20.36	648.65	20405.	49.6	NP0318
18.69	646.81	13020	49.5	NP0319
16.42	644.18	8593	49.3	NP0320
12.07	639.13	3896	48.8	NP0321
5.66	632.96	1386.	48.5	NP0322
2.99	629.56	557.	48.3	NP0323*
13.31	692.61	17030.	96.4	NP0129
14.59	694.82	22880	97.3	NP01 30
15.82	696.74	31140.	98.2	NP0131
17.32	697.99	42150.	97.9	NP0132
18.22	699.48	55800.	98.2	NP0134

n-Pentane	-	continued
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Propane - n-Butane Mixture 1 (43% Propane)

MX0101*	145.	81.	582.40	0.51
MX0102*	145.	1040.	586.81	5.76
MX0103*	145.	4503.	592.82	11.77
MX0104	147.	10070	272•72 500 17	15.22
MACIOJ	140.)	19070.	J77•17	10.20
MX0106*	174.	111.	599.52	0.98
MX0107*	174.	1018.	604.09	5.42
MX0108*	174.	4229.	609.60	10.62
MX0109	175.	10076.	613.05	13.58
MX0110	174.	19210.	614.66	16.63
MX0111	175.	28300.	617.38	18.79
MX0112	176.	47260.	622.38	22.70
MX0113	185.	74780.	632.63	26.96
MX0114	174.	36640.	618.70	20.62
MX0115	173.	13680.	611.17	14.17
MX0116	174.	1944.	602.97	4.74
MX0117*	204.	117.	614.30	1.24
MX0118*	203.	1072.	616.87	4.58
MX0119*	204.	4520.	623.33	9.84
MX0120	204.	9960.	626.19	12.61
MX0121	207.	18880.	629.64	15.14

Data No.	Pressure psia	Heat Flux Btu/ft ² hr	T _{wall} ,R	∆ T,R
MX0122 MX0123 MX0124 MX0125 MX0126 MX0126 MX0134 MX0127* MX0127* MX0128* MX0129 MX0120	206. 202. 204. 208. 215. 208. 227. 231. 232.	29260. 43960. 73430. 95290. 130000. 97300. 1067. 4186. 9533.	631.04 632.68 639.65 655.60 664.65 645.48 627.07 633.79 636.92 640.04	17.62 20.79 25.55 23.10 30.57 28.28 4.26 9.56 11.69
MX0130 MX0131 MX0132 MX0133 MX0135 MX0136 MX0137 MX0138 MX0139	235. 242. 232. 236. 262. 264. 263. 263. 267.	19900. 31370. 48070. 75030. 7743. 18160. 28700. 45140. 76100.	646.25 645.40 660.11 648.13 652.89 654.71 659.39 675.43	14.60 17.15 20.82 24.72 11.55 14.85 17.01 20.78 25.58

Propane - n-Butane Mixture 1 (43% Propane) - continued

Propane - n-Butane Mixture 2 (1% Propane)

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MX0201*	111.	76.	609.33	1.06
MX0202*	111.	683.	612.14	3.84
MX0203*	111.	3443	614.86	6.48
MX0204	111.	8821	616.82	8,58
MX0205	111.	17270.	618.39	10.70
MX0206	112.	29730.	621.72	13.06
MX0207*	130.	898.	631.11	3 18
MX0208*	139	3396	633.14	<u>й</u> .86
MX0209	139	8840.	635.14	6.67
MX0210	1 39	17120.	637.05	8.61
MX0211	1 39	27730	638.85	10.80
MX0212	140	45045	641.73	12.81
MX0213	140	75490	644.80	15.50
MX0214	139	32020	639.76	11.54
MX0215	139	12550.	636.82	8.28
MX0216*	139.	3285.	633.68	5.24

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Data No.	Pressure psia	Heat Flux Btu/ft ² hr	Twall,R	∆ T,R
MX0217	165.	10010.	650.43	6.70
MX0218	166.	18515.	653.20	8.02
MX0219	166.	29810.	654.35	9.71
MX0220	167.	46290.	657.09	11.38
MX0221	166.	75490.	659.27	14.20

Propane - n-Butane Mixture 2 (1% Propane) - continued

Propane - n-Butane Mixture 3 (63% Propane)

MX0301*	184.	109.	585.14	1.97
MX0302*	184.	430.	586.94	4.19
MX0303*	184.	1165.	589.29	6.77
MX0304*	185.	4348.	595.51	12.70
MX0305*	183.	9353.	598.44	17.67
MX0306	184.	18060.	604.80	22.04
MX0307	183.	28900.	605.58	24.75
MX0308	183.	57110.	614.21	32.32
MX0309	184.	25730.	603.48	22.39
MX0310	183.	12740.	597.05	16.36
MX0311	183.	5090.	592.09	10.69
MX0312	182.	2200.	587.63	6.82
MX0313	182	252.	584.39	3.28
MX0314*	245.	73.	610.06	2.44
MX0315*	243.	523.	610.92	4.00
MX0316*	243.	1228.	612.86	5.74
MX0317*	244.	4720.	619.99	12.09
MX0318	245.	11660.	625.72	18.06
MX0319	244.	25870.	629.64	22.20
MX0320	244.	48670.	636.52	28.94
MX0321	248.	76150.	648.61	32.11
MX0322*	304.	374.	632.42	3,23
MX0323*	303.	1 588	634 40	5 57
MX0324*	303.	5350	630.80	10.58
MX0325	306.	1 3870.	647.37	17,15
MX0326	302	31780.	651.47	22.28
MX0327	302	56330.	661.03	31,55
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Data No.	Pressure psia	Heat Flux Btu/ft ² hr	Twall,R	∆ T,R
MX0328*	362.	1303.	653.36	5.32
MX0329*	363.	6349.	659.16	10.62
MX0330	365.	17400.	666.27	16.87
MX0331	365.	37640.	672.49	23.70

Propane - n-Butane Mixture 3 (63% Propane) - continued

Propane - n-Pentane Mixture 1 (1% Propane)

And in case of the local division of the loc				and the second
MX0401*	49.0	197.	625.58	1.55
MYOLO2#	10.9	1102	621 24	J•/1 7 90
MYOLOL#	40.0	2021	625 87	12 64
MYOLOS#	40.9	3/110	640 13	17 04
MX0405*	40.3	5001	642 26	18 86
MYOLO7	49.J 40 5	6564	6li1 8li	17 57
MYOLO8	40 0	7017	643 60	18 86
MYOLOO	40 3	10360	646 36	20 53
MYOLIO	50.5	13840	640.50	23 36
M.Y.O.41.0	J1 • U	1)040.	049.30	<u>ار ، ر ،</u>
MX0411*	74.9	142.	659.81	1.98
MX0412*	74.9	196.	659.59	1.45
MX0413*	74.8	580.	662.08	3,90
MX0414*	74.8	1 590.	667.37	9,20
MX0415	74.8	2620.	670.20	12.23
MX0416	74.8	3832	670.49	12.37
MX0417	75.0	5608.	672.79	14.23
MX0418	75.1	7318.	674.53	15.54
MX0419	25.3	9660.	677.12	17.65
MX0420	75.7	1 5120.	680.20	19.84
MX0421	75.3	22347	681.70	22.16
MX0422	75.2	31090.	683.43	24.14
MX0423	75.1	39700.	684.66	25.66
MX0424	75.7	50700.	687.30	27.60
MX0425	75.0	40800.	684.35	25.86
MX0426	74.0	19140.	679.83	22.10
MX0427	73.9	6745.	672.46	14.82
MX0428*	73.5	2017.	666.77	9.39
MX0429*	73.2	668.	663.03	5.86

Data No.	Pressure psia	Heat Flux Btu/ft ² hr	Twall,R	∆ T,R
MX0430	97.8	21300.	697.85	17.68
MX0431	99.4	27510.	700.47	18.87
MX0432	100.0	37450.	702.44	20.34
MX0433	99.0	46475.	702.76	21.67
MX0434	100.3	59350.	705.45	23.14
MX0435	100.0	73980.	707.93	25.39

Propane - n-Pentane Mixture 1 (1% Propane) - continued

Propane - n-Pentane Mixture 2 (3% Propane)

and the second se			a submersion and a second s	
MX0518*	126.9	50.	689.86	1.95
MX0519*	126.3	510.	690.15	3.06
MX0520*	125.5	1248.	696.05	10.17
MX0521*	125.5	2402.	698.80	13.56
MX0522*	125.9	4220.	700.61	15.52
MX0523*	126.3	61 59.	702.18	16.98
MX0 524	127.3	9104	703.08	17.65
MX0525	128.5	12960	205.09	18 26
	100. 5	12/001		10.20
MX0 501*	153.	143.	716.34	1.64
MX0502*	153.	402.	717.14	2.16
MX0503*	153.2	1093.	719.68	4.39
MX0 504	153.5	21 51	721.63	5.90
MX0505	157.5	3465.	723.16	2.73
MX0506	153.8	5227	724 44	8.63
MX0507	154	7438	726.05	9,99
MX0508	155.	10650	727.67	11.00
MX0509	152.5	21980.	726.09	14.64
MX0510	155	35460	730.08	16 58
MY0511	152 5	<u>لا</u> 1080	730.08	10 62
MX0512	1 54	53020	732 50	21 03
MYOS13	1 57	68400	736 66	22 05
MYOELL	1 57	hh180	734.14	10 22
MYOSIS	1 57	24030	721 20	15.53
MYOKIA	156 5	2675 2675	777 05	
MYOELD		1224	(2(.0))	10.72
MAU JI /	エンフ・フ	エンフサ・	(41.04	5.50

Data No.	Pressure psia	Heat Flux Btu/ft ² hr	Twall'R	ΔT,R
MX0601 #	173.	51 .	631 - 59	2.10
MX0602*	172	245	631.65	4,22
MX0603#	171	586	633.76	6 14
MXOKOL	170.	976	636.19	9.26
MYOGOS	170.	1 542	638 70	11 74
MYOGOG	170	2713	642 70	16 48
MYOGOO	170 5	4770	647 40	20.05
MYOGOR	172	8012	652 11	20.95
MYOGOO	176.	11200	657 19	27.00
MYOSIO	172	16020	649 00	27.41
MXOCAA	172.	26620	662 20	30.49
MACOLL	176.	20370.		JJ. UJ
MXOCLC	172.	57590.	607.75	40.21
MYOOIJ	173.5	57040.	073.04	40.17
MX0614#	231.	48.	674.46	3.09
MX0615*	228.	273.	668.53	4.32
MX0616#	225.	825.	674.46	7.83
MX0617*	223.	1718.	677.14	11.62
MX0618	222.	2585.	678.82	14.22
MX0619	221.	4955.	683.72	19.58
MX0620	222.	8287.	687.64	23.79
MX0621	225.	17415.	694.84	28.05
MX0622	225.	28160	698.17	33.00
MX0623	226.	38390.	202.33	36.15
MX0624	221.	48845	702.20	30.78
MX0625	221	58510.	705.70	42 84
MX0626	210	32760	695.77	35 72
MX0627	223	9173	688.18	23 23
MX0628	220	2185	676 83	12 88
MX0629*	218.	197.	667.27	4.20
MY0630#	287	73	206 22	2 51
MY0621#	297.	()• 525	700.77	2.JI
MV0422#	207.	120/u	710.42	5.02
MY0622	202.	2724	(14.))	0.07
MYACAD	201.	4(Jヤ・ とのわり	713.37	14.00
MY0624	200.	7044.	710.09	10.02
MYACA	200.	10/07	720.05	10.32
WAVO JO	201.	16433.	724.24	21.54
MX0600	203.	10000.	127.12	23.90
MX0030	200.	27270.	731.08	26.76
WAU039	207.	30570.	734.43	28.01
WXU640	285.	48550.	736.22	34,48

Propane - n-Pentane Mixture 3 (38% Propane)

Data No.	Pressure psia	Heat Flux Btu/ft ² hr	Twall,R	∆ T,R
MX0701+	172.	100.	588-13	2.98
MX0702*	170.	342	587.88	4.25
MX0703*	169.	714.	589.99	7.09
MX0704*	169.	1436.	594.52	12.41
MX0705	168.	2282.	598.52	16.41
MX0706	169.	3603.	603.88	21.53
MX0707	170.	4829.	609.02	27.20
MX0708	171.	6550.	614.58	30.94
MX0709	171.	9068.	619.21	35.59
MX0710	170.	13580.	623.70	40.08
MX0711	172.	17640.	627.36	42.56
MX0712	170.	25570.	630.15	46.29
MX0713	170.	37670.	634.61	50.39
MX0714*	227.	94.	615.21	0.86
MX0715*	227.	502.	618.57	4.39
MX0716*	227.	1263.	623.51	9.89
MX0717*	226.	2159.	627.26	14.24
MX0718	225.	3051.	630.62	17.84
MX0719	225.	4601.	635.89	23.46
MX0720	225.	6441.	639.73	27.09
MX0721	226.	9178.	644.57	31.28
MX0722	225.	12720.	646.75	34.59
MX0723	226.	17360.	649.74	37.41
MX0724	226.	22850.	652.45	39.66
MX0725	225.	30400.	654.16	41.79
MX0726	225.	39585.	656.38	44.10
MX0727	226.	51420.	659.80	46.20
MX0728	226.	27350.	652.92	39.27
MX0729	224.	14870.	645.59	34.05
MX0730	226.	7199.	638.46	26.23
MX0731	224.	3276.	629.69	18.37
MX0732*	223.	1181.	620,46	9,36
MX0733*	290.	123.	646.63	1.89
MX0734*	290.	312.	647.32	2.94
WAU735*	290.	044.	049.52	5.08
WAU730	291.	1003.	053.10	8.49
MILOTI	290.	1900.	050.70	12.45
MAU7 JO	29U.	20jU.	059.55	15.27
MY0710	290.	4067.	002.90	10.55
いんし / やし かんし / やし かんし / やし /	290.	0676. Bhag	660 27	22.70
144.4.4.4.4.4.4.4.4.4.4.4.4.4.4.4.4.4.4	200. 200	0460.	604.67	24.00 00 00
MAU742	~YU.	TT 220.	071.13	27.02

Propane - n-Pentane Mixture 4 (65% Propane)

Data No.	Pressure psia	Heat Flux Btu/ft ² hr	^T wall' ^R	∆ T,R
MX0743	290.	16365.	673.24	29.06
MX0744	291.	21925.	675.68	30.84
MX0745	290.	29220.	677.69	33.05
MX0746	289.	38610.	679.98	35.50
MX0747	292.	48290.	683.09	38.68
MX0748	287.	56810.	694.01	44.09

Propane - n-Pentane Mixture 4 (65% Propane) - continued

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Appendix F: Burnout Data

In this appendix the original experimental data for the burnout heat flux are summarized. For each datum the following items are listed: datum number, burnout heat flux, system pressure, and reduced pressure. In the case of mixtures, the pseudo-reduced pressure is given in place of the true reduced pressure for the reasons cited in Chapter 3. The numbering system is the same as used with Appendix E. Datum numbers followed by the symbol * are indicative of points taken with the gold heater. All other points were taken using the carbon rod heater.

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	Reduced Pressure	0.238 0.238 0.248 0.287 0.2716 0.2716 0.2716 0.2718 0.2718 0.2718 0.2718 0.2718 0.2718 0.2718 0.2716 0.2716 0.2718 0.2716 0.2716 0.2716 0.2716 0.2716 0.2716 0.2716 0.2716 0.2716 0.2716 0.2716 0.2716 0.2716 0.2716 0.2718		0.365 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.1380 0.13800000000000000000000000000000000000
	Pressure psia	4444 4744	ω	
110 Propane	Heat Flux Btu/ft ² hr	153000. 153000. 1550000. 1550000. 1550000. 1550000. 1530000. 1530000. 1530000. 1530000. 1530000. 1530000. 11110000. 109000.	n-Butan	132400. 129400. 117400. 128600. 132600. 132600. 144600. 1564000. 164000.
	Data No.	PR1401 PR1401 PR1402 PR1403 PR1405 PR1405 PR14100 PR14110 PR14112 PR14115 PR14115 PR14116 PR14116 PR14119 PR14119 PR1420 PR1420		NB0328* NB0336* NB0335* NB04005* NB0406* NB0406* NB0410* NB04111* NB0412* NB0415* NB0415*

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Data No.	Heat Flux Btu/ft ² hr	Pressure psia	Reduced Pressure
NB0501	110000.	33.5	0.061
NB0502	113000.	35.0	0.064
NB0503	114000.	36.0	0.065
NB0 <u>5</u> 04	111000.	36.4	0.066
NB0505	111500.	36.9	0.067
NB0506	129000.	62.5	0.114
NB0507	129000.	62.7	0.114
NB0508	140000.	85.8	0.156
NB0 <u>5</u> 09	137000.	86.2	0.157
NB0510	143000.	105.0	0.191
NB0511	142000.	105.5	0.192
NB0512	150000.	119.8	0.218
NB0513	148000.	119.8	0,218
NB0514	149000.	120.1	0.219
NB0515	152000.	148.0	0.269
NB0516	149000.	147.8	0.268
NB0517	149000.	148.2	0.270
NB0518	148000.	171.	0.311
NB0519	150000.	171.	0.311
NB0520	149000.	171.	0.311
NB0521	151000.	192.	0.349
NB0522	150000.	192.	0.349
NBU 52 3	145000.	212.	0.300
NB0524	149000.	213.	0.387
NDOCO	150000.	213.	0.387
NBU 520	145000.	433. 00.0	0.420
NBOS28	146000	43 3 . 235	U.420 0 止28
NDV JEU	, T40000	~)].	V. 420

n-Butane - o	continued
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n-Pentane

	وببرج بالبديدين وجرعيا فيستنكب كالتائك فيزيك ومقاف كمتكرين والبافي والباف والمراجع والفريد	وبالمركب والمتحد والمتحد والمركب والمتحد والمركب والمتحد والمتحد والمتحد والمتحد والمتحد والمتحد والمتحد والمتح	
NP0401	114000.	15.0	0.036
NP0402	127000.	21.5	0.044
NP0403	134000.	30.7	0.063
NP0404	138000.	44.0	0.090
NP0405	137500.	44.2	0.090
NP0406	139000.	57.0	0,116
NP0407	146000.	57.0	0.116
NP0408	144000.	57.4	0.117
NP0409	148000.	70.3	0.144

Data No.	Heat Flux Btu/ft ² hr	Pressure psia	Reduced Pressure
 NPO41 0	1 51 000.	70.3	0,144
NP0411	156000.	92.1	0.188
NP0412	1 57000.	92.2	0.188
NP0413	160000.	106.2	0.217
NP0414	162000.	106.1	0.217

n-Pentane - continued

Propane - n-Butane Mixture 1 (43% Propane)

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MX0141*	204600.	143.	0.224
MX0142*	196600.	159.	0.250
MX0144*	197000.	161.	0.253
MX0145*	191200.	165.	0.259
MX0146*	188000.	164.	0.257
MX0148*	184400.	189.	0.297
MX0149*	177000.	219.	0.344
MX01 50*	167600.	251.	0.394
MX01 51*	159800.	271.	0.425
MX01 52*	157400.	286.	0.449
MX01 53*	151600.	301.	0.473

Propane - n-Butane Mixture 2 (1% Propane)

MX0222*	222400.	88.	0.158
MX0223*	206200.	89.	0.159
MX0224*	192200.	89.	0.159
MX0225*	166800.	93.	0.167
MX0226*	151400.	96.	0.172
MX0228*	150000.	100.	0.179
MX0229*	160800.	106.	0.190
MX0230*	157400.	114.	0.204
MX0231*	167200.	126.	0.226
MX0232*	167200.	128.	0,229
MX0233*	170000.	135.	0.242
MX0234*	163400.	140.	0.251
MX0235*	1 57800	142	0.254
MX0236*	151200.	144.	0.258
MX0238*	145600.	175.	0.314

Data No.	Heat Flux Btu/ft ² hr	Pressure psia	Reduced Pressure
MX0801	187000.	126.2	0.217
MX0802	187000.	127.2	0.218
MX0803	190000.	139.4	0.243
MX0804	188500.	139.3	0.242
MX0805	188000.	153.	0.267
MX0806	186000.	153.	0.267
MX0807	186000.	167.	0.292
MX0808	186000.	167.	0.292
MX0809	181000.	179.	0.314
MX0810	180000.	178.	0.312
MX0811	177000.	178.	0.312
MX0812	178000.	188.	0.331
MX0813	179000.	188.	0.331
MX0814	180000.	188.	0.331
MX081 5	176000.	195.	0.344
MX0816	179000.	195.	0.344

Propane - n-Butane Mixture 4 (35% Propane)

Propane - n-Butane Mixture 5 (22% Propane)

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MX0901	158000.	70.8	0.125
MX0902	161000.	72.4	0.127
MX0903	164000.	73.6	0.127
MX0904	166000.	86.0	0.152
MX0905	167000.	88.0	0.155
MX0906	168000.	89.0	0.157
MX0907	172000.	109.6	0.194
MX0908	· 1 72000.	110.4	0.196
MX0909	171000.	124.6	0.221
MX0910	172000.	125.0	0.222
MX0911	167000.	136.3	0.242
MX0912	170000.	136.2	0.242
MX0913	171000.	136.4	0.242
MX0914	171000.	145.4	0.260
MX0915	168000.	145.3	0.260
MX0916	166000.	152.	0.272
MX0917	166000.	152.	0.272

MX1001 175000. 131.6 0.21 MX1002 176000. 131.9 0.21 MX1003 184000. 142.5 0.23 MX1004 184000. 143.5 0.23 MX1005 186000. 143.7 0.23 MX1006 187000. 155. 0.26 MX1007 189000. 156. 0.26 MX1008 190000. 156. 0.26 MX1009 195000. 169. 0.28 MX1010 192000. 170. 0.28 MX1011 193000. 170. 0.28 MX1012 191000. 188. 0.31 MX1013 195000. 188. 0.31 MX1014 189000. 188. 0.31 MX1015 195000. 190. 0.31 MX1017 196000. 205. 0.34 MX1018 193000. 205. 0.34 MX1019 195000. 219. 0.37 MX1020 194000. 235. 0.39 MX1021 194000.	Data No.	Heat Flux Btu/ft ^c hr	Pressure psia	Reduced Pressure
MX1002176000.131.90.21MX1003184000.142.50.23MX1004184000.143.50.23MX1005186000.143.70.23MX1006187000.155.0.26MX1007189000.156.0.26MX1008190000.157.0.26MX1010192000.169.0.28MX1011193000.170.0.28MX1012191000.188.0.31MX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.235.0.39MX1021194000.234.0.39	MX1001	175000.	131.6	0.216
MX1003184000.142.50.23MX1004184000.143.50.23MX1005186000.143.70.23MX1006187000.155.0.26MX1007189000.156.0.26MX1008190000.157.0.26MX1010192000.169.0.28MX1011193000.170.0.28MX1012191000.188.0.31MX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.234.0.39MX1022190000.234.0.39	MX1002	176000.	131.9	0.216
MX1004184000.143.50.23MX1005186000.143.70.23MX1006187000.155.0.26MX1007189000.156.0.26MX1008190000.157.0.26MX1009195000.169.0.28MX1010192000.170.0.28MX1011193000.170.0.28MX1012191000.188.0.31MX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.235.0.39MX1021194000.235.0.39MX1022190000.234.0.39	MX1003	184000.	142.5	0.235
NX1005186000.143.70.23NX1006187000.155.0.26MX1007189000.156.0.26MX1008190000.157.0.26MX1010192000.169.0.28MX1011193000.170.0.28MX1012191000.188.0.31MX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1020194000.219.0.37MX1021194000.235.0.39MX1022190000.234.0.39	MX1004	184000.	143.5	0.236
NX1006187000.155.0.26MX1007189000.156.0.26MX1008190000.157.0.26MX1009195000.169.0.28MX1010192000.170.0.28MX1011193000.170.0.28MX1012191000.188.0.31MX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1020194000.219.0.37MX1021194000.235.0.39MX1022190000.234.0.39	MX1005	186000.	143.7	0.237
MX1007189000.156.0.26MX1008190000.157.0.26MX1009195000.169.0.28MX1010192000.170.0.28MX1011193000.170.0.28MX1012191000.188.0.31MX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.235.0.39MX1021194000.235.0.39MX1022190000.234.0.39	MX1006	187000.	155.	0.260
MX1008190000.157.0.26MX1009195000.169.0.28MX1010192000.170.0.28MX1011193000.170.0.28MX1012191000.188.0.31MX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.235.0.39MX1021194000.234.0.39	MX1007	189000.	156.	0.261
NX1009195000.169.0.28MX1010192000.170.0.28MX1011193000.170.0.28MX1012191000.188.0.31MX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.235.0.39MX1021194000.235.0.39MX1022190000.234.0.39	MX1008	190000.	157.	0.262
NX1010192000.170.0.28MX1011193000.170.0.28MX1012191000.188.0.31MX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.235.0.39MX1021194000.234.0.39	MX1009	195000.	169.	0.284
NX1011193000.170.0.28MX1012191000.188.0.31NX1013195000.188.0.31MX1014189000.188.0.31NX1015195000.190.0.31NX1016193000.205.0.34NX1017196000.205.0.34NX1018193000.205.0.34NX1019195000.219.0.37NX1020194000.235.0.39NX1021190000.234.0.39	MX1.010	192000.	170.	0.285
NX1012191000.188.0.31MX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.219.0.37MX1021194000.235.0.39MX1022190000.234.0.39	MX1011	193000.	170.	0.285
NX1013195000.188.0.31MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.219.0.37MX1021194000.235.0.39MX1022190000.234.0.39	MX1012	191000.	188.	0,318
MX1014189000.188.0.31MX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.235.0.39MX1021190000.234.0.39	MX1013	195000.	188.	0.318
NX1015195000.190.0.31MX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.219.0.37MX1021194000.235.0.39MX1022190000.234.0.39	MX1014	189000.	188.	0.318
NX1016193000.205.0.34MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.219.0.37MX1021194000.235.0.39MX1022190000.234.0.39	MX1015	195000.	190.	0.319
MX1017196000.205.0.34MX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.219.0.37MX1021194000.235.0.39MX1022190000.234.0.39	MX1016	193000.	205.	0.344
NX1018193000.205.0.34MX1019195000.219.0.37MX1020194000.219.0.37MX1021194000.235.0.39MX1022190000.234.0.39	MX1017	196000.	205.	0.344
MX1019195000.219.0.37MX1020194000.219.0.37MX1021194000.235.0.39MX1022190000.234.0.39	MX1018	193000.	205.	0.344
MX1020194000.219.0.37MX1021194000.235.0.39MX1022190000.234.0.39	MX1019	195000.	219.	0.370
MX1021194000.235.0.39MX1022190000.234.0.39	MX1020	194000.	219.	0.370
MX1022 190000. 234. 0.39	MX1021	194000.	235.	0,396
	MX1022	190000.	234.	0.395
MX1023 188000. 234. 0.39	MX1023	188000.	234.	0.395
MX1024 190000. 233. 0.39	MX1024	190000.	233.	0.393
MX1025 190000. 243. 0.40	MX1025	190000.	243.	0.409
MX1026 190000. 242. 0.40	MX1026	190000.	242.	0.408

Propane - n-Butane Mixture 6 (70% Propane)

Propane - n-Pentane Mixture 5 (5% Propane)

MX1101	155000.	41.8	0.084
MX1102	151000.	41.4	0.083
MX1103	141000.	49.0	0.097
MX1104	143000.	49.0	0.097
MX1105	155000.	58.8	0.119
MX1106	155000.	58.7	0.118
MX1107	171000.	92.0	0.185
MX1108	170000.	92.3	0,185
MX1109	176000.	110.3	0.222
MX1110	172000.	110.2	0.222
MX1111	174000.	110.5	0.222

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Data No.	Heat Flux Btu/ft ² hr	Pressure psia	Reduced Pressure
MX1201	216000.	99.4	0.191
MX1202	216000.	99.6	0.191
MX1203	210000.	113.0	0.219
MX1204	209000.	113.1	0.219
MX1205	216000.	133.0	0.266
MX1206	213000.	133.0	0.266
MX1207	208000.	143.0	0.276
MX1208	208000.	143.0	0.276
MX1209	207000.	142.0	0.274
MX1210	213000.	65.0	0.122
MX1211	212000.	66.0	0.124
MX1212	210000.	69.5	0.131
MX1213	213000	69.7	0,132
MX1214	216000.	79.2	0,151
MX1215	216000	79.2	0.151
MX1216	220000	94.0	0.178
MY1 21 7	221000	95 0	0 180
MX1218	219000	95.2	0.181
MULT OF O	~	7.5.~	0.101

Propane - n-Pentane Mixture 6 (27% Propane)

Propane - n-Pentane Mixture 7 (41% Propane)

	مخصوصي مرادي واطنعانه فالخوج أووجيه والمترجي والمترجي والمترجون والبراج والمراجع والمراجع والمراجع	والمحاجب والمتحد والمتحد والمتحد والمتحد والمتحد والمحاج والمحاج والمحاج والمحاج والمحاج والمحاج والمحاج والمح	and the second
MX1 301	254000.	119.0	0.216
MX1 302	252000.	118.0	0.214
MX1 303	252000.	121.4	0.221
MX1 304	248000	136.4	0.245
MX1 305	248000	136.8	0.246
MX1 306	244000	145.8	0.264
NX1 307	244000	147.0	0.270
MX1 308	244000.	157.	0.291
MX1309	244000	157.	0.291
MX1 31 0	238000	167.	0.310
MX1311	237000.	167.	0.310
MX1 312	234000.	177.	0.328
MX1 31 3	234000.	177.	0.328
MX1 314	232000.	186.	0.346
MX1 31 5	230000.	187.	0.348
MX1 316	228000.	196.	0.368
MX1317	226000.	195.	0.364
MX1 318	226000.	198.	0.370
MX1319	224000.	205.	0.387
MX1 320	224000.	204.	0.385
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Data No.	Heat Flux Btu/ft ² hr	Pressure psia	Reduced Pressure
 MX1401	256000.	145.0	0,252
MX1402	256000.	145.0	0.252
MX1403	259000.	141.0	0.247
MX1404	261000.	140.0	0.245
MX1405	253000.	158.	0.278
MX1406	252000.	159.	0.280
MX1407	249000.	175.	0.312
MX1408	248000.	175.	0.312
MX1409	243000.	187.	0.330
MX1410	244000.	189.	0.334
MX1411	241000.	205.	0.361
MX1412	241000.	205.	0.361
MX1413	234000.	215.	0.382
MX1414	235000.	215.	0.382
MX1415	230000.	225.	0.399
MX1416	232000.	225.	0.399

Propane - n-Pentane Mixture 8 (61% Propane)

Propane - n-Pentane Mixture 9 (88% Propane)

252000.	181.	0,300
251000.	181.	0.300
254000.	195.	0.323
254000.	195.	0.323
253000.	212.	0.350
254000.	216.	0.341
250000.	235.	0.389
248000.	234.	0.388
253000.	262.	0.434
250000.	261.	0.432
251000.	261.	0.438
252000.	274.	0.460
252000.	275.	0.461
252000.	289.	0.488
251000.	289.	0.488
249000.	301.	0.507
248000.	300.	0.506
	252000. 251000. 254000. 254000. 253000. 250000. 253000. 253000. 251000. 252000. 252000. 252000. 251000. 251000. 249000. 248000.	$\begin{array}{cccccccccccccccccccccccccccccccccccc$

Appendix G: Condensation Data

In this appendix the original experimental data for film condensation are summarized. For each datum the following items are listed: datum number, system pressure, film condensation heat transfer coefficient, the temperature difference between the condenser wall and the bubble point liquid, and the distance from the top of the condensing surface to the thermocouple location. The numbering system used is the same as in the previous appendices.

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Propane

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Data No.	Pressure psia	h _x . Btu/ft ² hr F	4T , F	x, ft
PR1201 PR1202 PR1203 PR1204 PR1205 PR1206 PR1207 PR1208 PR1209 PR1209 PR1210 PR1210 PR1211 PR1212 PR1213 PR1214 PR1215 PR1216 PR1217 PR1218 PR1219	185. 184. 184. 187. 186. 186. 186. 186. 186. 186. 186. 187. 187. 187. 187. 187. 187. 189. 189. 189. 189.	2234. 7386. 2864. 1791. 1945. 931. 1188. 1346. 988. 894. 1370. 1286. 747. 754. 1052. 601. 648. 757. 944.	0.97 0.14 0.51 1.47 0.78 1.88 2.52 0.90 2.93 2.82 1.34 2.94 3.67 3.21 4.26 4.43	4.17 2.50 4.17 2.50 3.33 4.17 2.50 3.17 0.53 4.18 0.53 4.18 0.53 4.17 0.53 4.17 0.53 4.17 0.53 4.17
PR1101 PR1102 PR1103 PR1104 PR1105 PR1106 PR1107 PR1108 PR1109 PR1110	245. 245. 245. 245. 245. 245. 245. 245.	1269. 764. 750. 2980. 542. 688. 2152 544. 653. 828.	0.93 1.65 5.03 0.50 2.90 5.49 1.81 5.98 7.42 8.56	2.50 3.33 4.17 2.50 3.33 4.17 0.83 2.50 3.33 4.17
PR1111 PR1112 PR1113 PR1114 PR1115 PR1116 PR1117	305. 302. 302. 302. 310. 310. 310.	813. 5423. 768. 771. 917. 457. 670.	4.78 0.24 1.78 5.78 2.46 5.32 8.59	4.17 2.50 3.33 4.17 2.50 3.33 4.17
PR1118 PR1119	365. 365.	1164. 387.	1.58 15.36	2.50 4.17
PR1120	495.	224.	6,86	4.17

Data No.	Pressure psia	h _x Btu/ft ² hr F	AT, F	x, ft
NB0301 NB0302 NB0303	54.4 54.4 54.7	1012. 1614. 1382.	1.34 1.92 1.10	3.33 4.17 2.50
NB0304	54.7	1101.	2.10	3.33
NB0305 NB0306	54.7	1221.	3.13	4.17
NB0307	55.1	754.	3.33	3.33
NB0308	55.1	1032.	3.69	4.17
NB0309	55.2	2130.	1.11	0.83
NB0310 NB0311	55.2	733.	3.59 ル 62	2.50
NB0312	55.2	911.	5.13	4.17
NB0313	56.9	2239.	1.55	0.83
NB0314	56.9	600.	5.11	2.50
NB0315 NB0316	50.9	580. 788	5.55	3.33 4 17
NB0317	54.9	2041.	0.47	0.83
NB0318	54.9	1484.	1.69	2,50
NB0319	54.9	690.	3.57	3.33
NB0320	54.9	1239.	3.59	4.17
NB0321	82.5	751.	1.10	3.33
NB0322	82.5	1163.	3.18	4.17
NB0323	82.0	1402.	1.33	2.50
NB0325	82.0	913. 756.	7.48	J. J. 4.17
NB0326	82.4	808.	2.02	0.83
NB0327	82.4	596.	4.84	2.50
NB0328 NB0320	82.4 82 L	500 . 636	7.04	3.33
N D0 J 2 9		• 0 (0	****	-+ • T (
NB0330	109.9	51 51.	0.27	2.50
NB0331 NB0332	109.9	824.	1.73	3.33
NB0333	110.0	1085.	1.73	2.50
NB0334	110.0	524.	5.10	3.33
NB0335	110.0	704.	9.81	4.17
NB0336	136.5	1597.	0.43	3, 33
NB0337	136.5	795.	5.11	4.17
NB0338	136.7	1752.	0.14	0.83
NB0340	130.7	2204.	0.61	2.50
NB0341	136.7	550.	11.70	4.17

119 n-Butane

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Data No.	Pressure psia	h _x Btu/ft ² hr F	∆ T, F	x, ft
NP0101 NP0102 NP0103 NP0104 NP0105	24.1 24.2 24.9 25.5 24.1	1419. 1143. 888. 1057. 1848.	3.58 5.89 9.57 9.08 1.27	4.17 4.17 4.17 4.17 3.33
NP0106 NP0107 NP0108 NP0109 NP0110 NP0111 NP0112 NP0113	37.2 37.2 36.7 36.0 35.9 35.9 35.9	3023. 1144. 1056. 920. 893. 2784. 747. 740.	0.17 2.21 3.43 1.44 7.36 0.44 3.05 9.05	2.50 4.17 4.17 3.33 4.17 2.50 3.33 4.17

120 n-Pentane

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Propane-n-Butane Mixture 1 (63% Propane--37% n-Butane)

Data No.	Pressure psia	h _x Btu/ft ² hr F	AT, F	x, ft
MX0101 MX0102 MX0103 MX0104	146.4 146.4 146.4 146.4 146.4	732. 167. 91. 186.	1.93 9.12 12.10 12.55	0.83 2.50 3.33 4.17
MX0105 MX0106 MX0107 MX0108 MX0109 MX0110 MX0111 MX0112 MX0113 MX0113 MX0115	174. 174. 176. 176. 176. 176. 175. 175. 175. 175.	272. 115. 271. 1346. 211. 231. 290. 1623. 221. 94. 244.	6.92 13.14 14.52 2.66 10.96 11.99 13.83 1.79 8.31 10.66 13.29	2.50 3.33 4.17 0.83 2.50 3.33 4.17 0.83 2.50 3.33 4.17
MX0116 MX0117 MX0118 MX0119	185. 185. 185. 185.	852. 333. 372. 438.	4.69 8.98 9.75 11.32	0.83 2.50 3.33 4.17

Data No.	Pressure psia	hx Btu/ft ² hr F	∆T, F	x, ft
MX0120 MX0121 MX0122 MX0123 MX0124 MX0125 MX0126 MX0127 MX0128 MX0129 MX0130 MX0131 MX0131 MX0132 MX0133 MX0134	207. 207. 203. 203. 203. 202. 202. 202. 202. 202	823. 202. 783. 137. 281. 1835. 182. 243. 327. 481. 340. 414. 443. 713. 427.	1.23 11.91 1.21 13.53 16.55 0.69 10.72 11.93 15.52 5.71 8.78 10.43 12.47 12.70 10.54	2.50 4.17 2.50 3.33 4.17 0.83 2.50 3.33 4.17 0.83 2.50 3.33 4.17 0.83 2.50
MX0135	203.	595.	10.25	3.33
MX0136	203.	691.	10.88	4.17
MX0137	242.	1167.	0.97	0.83
MX0138	242.	184.	6.19	2.50
MX0139	242.	187.	12.99	4.17
MX0140	264.	336.	4.11	2.50
MX0141	264.	246.	9.72	3.33
MX0142	264.	338.	14.68	4.17

Propane-n-Butane Mixture 1 (63% Propane--37% n-Butane)--Continued

Propane-n-Butane Mixture 2 (1% Propane--99% n-Butane)

Data No.	Pressure psia	h _x Btu/ft2hr F	AT, F	x, ft
MX0201	165.	753.	3.59	4.17
MX0202	168.	477.	3.03	3.33
MX0203	168.	575.	5.50	4.17

Data No.	Pressure psia	h _X Btu/ft ² hr F	AT, F	x, ft
MX0301	185.	1188.	2.69	0.83
MX0302	185.	366.	6.34	2.50
MX0303	185.	338.	7.88	3.33
MX0304	185.	486.	9.30	4.17

Propane-n-Butane Mixture 3 (43% Propane--57% n-Butane)

Propane-n-Pentane Mixture 1 (1% Propane--99% n-Pentane)

Data No.	Pressure psia	hx Btu/ft ² hr F	∆ T, F	x, ft
MX0401	75.3	129.	4.98	2.50
MX0402	75.3	11 <i>5</i> 2.	0.58	4.17

Propane-n-Pentane Mixture 3 (38% Propane--62% n-Pentane)

Data No.	Pressure psia	h _x Btu/ft2hr F	∆ T, F	x, ft
MX0601	223.	587.	2.26	0.83
MX0602	223.	151.	8.59	2.50
MX0603	223.	171.	12.03	3.33
MX0604	220.5	210.	8,39	2.50
MX0605	221.	315.	5.24	3.33
MX0606	221.	201.	9.88	4.17
MX0607	283.	387.	3,26	2.50
MX0608	283.	229.	8.69	3.33
MX0609	283.	257.	22.68	4.17

Data Nc.	Pressure psia	'n _x Btu/ft ² hr F	at, f	x, ft
MX0701	170.	3028.	0.33	2.50
MX0702	170.	6620.	0.21	3.33
MX0703	170.	514.	3.69	4.17
MX0704	170.	1537.	0.74	2.50
MX0705	170.	467.	4.57	4.17
MX0706	172.	945.	1.33	2.50
MX0707	172.	530.	2,68	3.33
MX0708	172.	429.	5.25	4.17
MX0709	169.	379.	4.96	2.50
MX0710	169.	911.	3.52	3.33
MX0711	169.	514.	5.83	4.17
MX0712	171.	302.	5.52	0.83
MX0713	171.	432.	5.19	2.50
MX0714	171.	484.	6.28	4.17
MX0715	225.	428.	3.83	2.50
MX0716	225.	1104.	3.61	3.33
MX0717	225.	490.	9.31	4.17
MX0718	227.	385.	5.49	2.50
MX0719	227.	1022.	4.75	3.33
MX0720	227.	460.	10.78	4.17
MX0721	291.5	472.	3.49	2.50
MX0722	291.5	1107.	4.11	3.33
MX0723	291.5	428.	13.32	4.17
MX0724	285,	431.	5.17	2.50
MX0725	285.	520.	7.73	3.33
MX0726	285.	449.	12.62	4.17

Propane--n-Pentane Mixture 4 (65% Propane--35% n-Pentane)