WAPD-TM-213
AEC RESEARCH AND
DEVELOPMENT REPORT

MASTER

STDY-3, A PROGRAM FOR THE THERMAL ANALYSIS OF A PRESSURIZED WATER NUCLEAR REACTOR DURING STEADY-STATE OPERATION

JUNE 1960

CONTRACT AT-11-1-GEN-14

BETTIS ATOMIC POWER LABORATORY, PITTSBURGH, PA.,
OPERATED FOR THE U. S. ATOMIC ENERGY COMMISSION
BY WESTINGHOUSE ELECTRIC CORPORATION

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R. S. Pyle

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Contract AT-11-1-GEN-14

Price \$1.00

Available from the office of Technical Services,
Department of Commerce,
Washington 25, D. C.

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A digital program to perform a steady-state, parallel channel thermal analysis of a rectangular water channel nuclear reactor with a plate-type fuel element is described. Features that automatically vary certain input values to aid in parametric studies are included. The program was assembled by the FORTRAN compiler for a 16,000 word IBM-704 computer, including three tape units and one logical drum.

STDY-3, A PROGRAM FOR THE THERMAL ANALYSIS OF A PRESSURIZED
WATER NUCLEAR REACTOR DURING STEADY-STATE OPERATION

R. S. Pyle

I. INTRODUCTION

The digital code described herein was programmed for the IBM-704 computer with the aid of the FORTRAN compiler. This code is a composite of the best features of all the previous Bettis steady-state analysis codes. The present version is identified as STDY-3 and has been in general production since July 1, 1959.

STDY-3 performs a complete steady-state, parallel channel thermal analysis of a rectangular water channel core with a plate-type fuel element. The digital code performs enthalpy and temperature rise calculations for the core average channel from input parameters. Two-phase core pressure drop calculations are performed using the latest equations as described in Section II (Programmed Equations). These calculations include the pressure drop effects of acceleration, elevation, friction, and entrance and exit.

Hot channel pressure drop is computed by modifying the normal channel pressure drop by an input controlled plenum equation. To accurately compute the hot channel flow where the flow vs pressure drop curve may contain inflections, a table of hot channel flow vs pressure drop is constructed by a stepwise reduction of flow from 100% (times some optional input multiplier) of the average channel value to a flow producing excess steam quality ($>100\%$) in the hot channel. The flow vs pressure drop table is then searched and interpolated for a pressure drop value within two percent of the hot channel pressure drop as determined by the plenum effects on the normal channel. The flow corresponding to this pressure drop is considered the hot channel flow. Once the hot channel flow is determined, enthalpy, temperature, and steam quality values are printed. Maximum metal surface temperature, meat centerline temperature, and DNB ratio calculations are made for each axial point from input properties and design equations.

The program is capable of solving steady-state problems, including one and two pass cores, up to two hot channels per pass, and the parameter variations necessary for core safety margin calculations. For

safety margin calculations, up to five values each of system pressure, flow, inlet temperature, and power may be supplied for the same core. Each parameter is varied independently through the set of values supplied, and then returned to its original value while another parameter is varied.

II. PROGRAMMED EQUATIONS

A. Enthalpy Rise in an Axial Increment ΔZ

$$\Delta H_j = \left(\frac{\phi_{ave} F \phi_{ave} f'(z)_j}{G} \right) \left(\frac{A_h}{A_f} \right),$$

where

ϕ_{ave} is the average heat flux in the channel (Btu/hr-ft²),

$F \phi_{ave}$ is the average engineering hot channel factor (includes fuel density, thickness, and eccentricity), usually 1.0 for the average channel,

$f'(z)_j$ is the ratio of the average heat flux at the j_{th} elevation to the average heat flux in the channel,

G is the mass velocity in the channel (lb/hr-ft²),

A_h/A_f is the ratio of the effective heat transfer area to the effective flow area for the increment ΔZ (program assumes area widths are equal and $A_h/A_f = 2\Delta Z/\text{channel thickness}$).

B. Quality and Specific Volume

$$X_j = \frac{H_j - H_{sat}}{H_{fg}}$$

where

H_j is the average enthalpy at the j_{th} elevation,

H_{sat}, H_{fg} are the fluid physical properties (see Appendix III).

$$v_i = \frac{1}{\rho_j} = v_f + X_j v_{fg} \quad (\text{homogenous model})$$

$$v_j = \frac{1}{\rho_j} = \frac{1}{R_g \rho_g + (1 - R_g) \rho_f} \quad (\text{slip flow model})$$

where

ρ_j is the fluid density (lb/ft³),

$v_f, v_{fg}, \rho_g, \rho_f$ are the fluid physical properties (See Appendix III),

R_g is the Martinelli void fraction (See Appendix IV).

C. Pressure Drop

$$\Delta P_{\text{Total}} = \Delta P_{\text{acceleration (1)}} + \Delta P_{\text{acceleration (2)}} + \Delta P_{\text{elevation}} \\ + \Delta P_{\text{friction}} + \Delta P_{\text{entrance and exit}},$$

where

$$\Delta P_{\text{acc(1)}} = \frac{G^2}{g_c} (\text{SPT1} - \text{SPT2}), \quad (\text{spacial}) ,$$

$$\Delta P_{\text{acc (2)}} = \frac{G^2}{2g_c} \left[\left(\frac{\sigma_{\text{out}}^2}{\rho_{\text{out}}} - 1 \right) - \left(\frac{\sigma_{\text{in}}^2}{\rho_{\text{in}}} - 1 \right) \right] (\text{configuration change}),$$

$$\Delta P_{\text{elev}} = \sum_{j=1}^{j=j_{\text{bb}}} \rho_j \Delta Z + \sum_{j=j_{\text{bb}}}^{j=k} \frac{1}{v_j} \Delta Z ,$$

$$\Delta P_{\text{fric}} = \frac{G^2}{2g_c D_e} \sum_{j=1}^{j=j_{\text{bb}}} \left(\frac{f/f_{\text{iso}}}{\rho} \right)_j f_{\text{iso}j} \Delta Z \\ + \frac{G^2}{2g_c D_e} \sum_{j=j_{\text{bb}}}^{j=k} \Phi_{\text{LO}}^2 (f_{\text{iso, sat}})_j \Delta Z ,$$

$$\Delta P_{\text{E\&E}} = \frac{G^2}{2g_c} \left(\frac{K_c}{\rho_{\text{in}}} + \frac{K_e}{\rho_{\text{out}}} \right) ;$$

and where

G is the mass velocity in the channel (lb/hr-ft²),

g_c is the acceleration of gravity (32.2 ft/sec²),

$\rho_{\text{in}}, \rho_{\text{out}}$ is the density of fluid in or out of the channel (lb/ft³),*

ρ_j is the average density of fluid in section j, *

v_j is the average specific volume of fluid in section j, **

v_f is the fluid specific volume at saturation temperature,

ΔZ is the axial increment length (ft),

*Homogenous density or specific volume model always.

**Homogenous or slip flow specific volume model depending on pressure: (homogenous ≥ 1850 psia; slip < 1850 psia).

j is the specific axial increment,

k is the total number of axial increments,

j_{bb} is the increment number where bulk boiling begins,

K_c, K_e is the unrecoverable entrance or exit coefficient,

f_{iso, sat} is the isothermal friction factor at saturation temperature,

σ_{in}, σ_{out} is the area ratio at entrance or exit (ratio of the smaller to larger area),

De is the channel hydraulic diameter (2 x channel thickness),

f_{iso} is the isothermal friction factor from an equation of the type

$$f_{iso} = \frac{a}{Re^b},$$

f/f_{iso} is the friction factor ratio for heating and local boiling,

Φ_{LO}² is the ratio of two-phase frictional pressure drop gradient to corresponding isothermal liquid gradient,

$$\left. \begin{array}{l} \text{SPT1} \quad 1/\rho_{out} \\ \text{SPT2} \quad 1/\rho_{in} \end{array} \right\} \quad (\text{subcooled channel})$$

$$\text{SPT1, SPT2} = v_f + X_{out, in} v_{fg} \left(\text{boiling} \begin{array}{l} \text{exit} \\ \text{entrance} \end{array} \right) (\geq 1850 \text{ psia})$$

$$= \frac{(1 - X_{out, in})^2 v_f}{1 - R_g} + \frac{(X_{out, in})^2 v_g}{R_g} \left(\text{boiling} \begin{array}{l} \text{exit} \\ \text{entrance} \end{array} \right) (< 1850 \text{ psia}).$$

D. Criteria for the Existence of Local Boiling (Pressure Drop Only)

A channel is considered to be local boiling when

$$\theta_f \geq \theta_{J \& L},$$

where

$$\theta_f = \frac{\phi_{ave} F \phi_{ave} f'(z)}{h},$$

$$\theta_{J \& L} = T_{sat} + \frac{60 \left(\frac{\phi_{ave} F \phi_{ave} f'(z)}{10^6} \right)^{1/4}}{e^{P/900}} - T_j,$$

$$h = \text{HCO} \left(\frac{k}{De} \right) Re^{0.8} Pr^{0.4} \quad (\text{see Appendix IV}),$$

$$\begin{aligned}
\text{HCO} &= 0.023 \text{ at } < 1850 \text{ psia (design)} \\
&= 0.030 \text{ at } \geq 1850 \text{ psia (design)} \\
&= 0.030 \text{ at all pressures (best fit)}
\end{aligned}$$

T_{sat} is the saturation temperature,

T_j is the fluid temperature in section j ,

P is the system pressure (psia).

Local boiling is not considered for pressure drop purposes if it exists based on local factors only.

E. Hot Channel Pressure Drop and Plenum Factor

It is customary in parallel channel analysis to equate the pressure drop across channels in order to determine the distribution of flow. It is recognized that this may lead to some error if a point of exactly uniform static pressure common to all parallel channels is not chosen as a reference both up and down stream from the parallel channels. Thus, the inlet to outlet pressure drop of one channel may not equal the inlet to outlet pressure drop of another channel. This situation is generally referred to as "plenum maldistribution" and traditionally gives rise to a plenum hot channel factor:

$$(\text{F}\Delta T)_P = \frac{\text{average channel flow}}{\text{hot channel flow}}$$

This hot channel factor concept is obviously unsatisfactory since a reactor operates in the local and bulk boiling regions and the hot channel factor exists because of a difference in channel pressure drops; hence, the flow distribution is dependent upon the particular friction factors present. The friction factors may vary considerably as the amount of bulk and/or local boiling changes. Therefore, to account for the "plenum maldistribution," STDY-3 treats it as a reduction in the pressure drop across the hot channel.

STDY-3 uses a very general plenum equation to predict hot channel pressure drop. By the various algebraic manipulations illustrated below, this equation can be made to conform to most of the accepted methods of calculating hot channel pressure drop.

The general plenum equation programmed is:

$$\begin{aligned}
\Delta P_{\text{HC}} &= K_1 K_2 (\Delta P_{\text{AC}})_{\text{total}} + (1 - K_1 K_2) (\Delta P_{\text{AC}})_{\text{elevation}} \\
&\quad + [K_1 K'_1 K'_2 + K_2 K'_1 - K_1 K_2 (1 + K'_1)] (\Delta P_{\text{AC}})_{\text{acceleration}} ,
\end{aligned}$$

where

$$\begin{aligned}
(\Delta P_{\text{AC}})_{\text{total}} &= (\Delta P_{\text{AC}})_{\text{acceleration}} + (\Delta P_{\text{AC}})_{\text{friction}} \\
&\quad + (\Delta P_{\text{AC}})_{\text{elevation}} + (\Delta P_{\text{AC}})_{\text{entrance + exit}} ,
\end{aligned}$$

and where K_1, K_2, K'_1, K'_2 are input plenum factors.

By substitutions in the above equation, the following additional forms are possible:

If $K'_1 = K_1$ and $K'_2 = K_2 = 1.0$,

$$\Delta P_{HC} = K_1 (\Delta P_{AC})_{total} + (1 - K_1) (\Delta P_{AC})_{elevation}$$

If $K'_1 = K'_2 = 1.0$,

$$\Delta P_{HC} = K_1 (\Delta P_{AC})_{total} + (1 - K_1) (\Delta P_{AC})_{elevation} + (1 - K_1) (\Delta P_{AC})_{acceleration}$$

If $K_2 = K'_2 = 1.0$,

$$\Delta P_{HC} = K_1 (\Delta P_{AC})_{total} + (1 - K_1) (\Delta P_{AC})_{elevation} + (K'_1 - K_1) (\Delta P_{AC})_{acceleration}$$

This form is identical to the ART form (Ref 1) as follows: Let $K_1 = K_{pf}^{HC}$ and $K'_1 = K_{pa}^{HC}$; then

$$(\Delta P)^{HC} = K_{pf}^{HC} (\Delta P_f)^{NC} + K_{pa}^{HC} (\Delta P_{a2})^{NC} + (\Delta P_{el})^{NC}$$

F. Metal Surface Temperature (T_s), Metal Temperature (T_m), Departure from Nucleate Boiling Ratio (DNBR)

$$T_s = T_j + \theta_{loc}^*$$

where

$$\theta_{loc}^* = \theta_{f_{loc}} \text{ if } \theta_{f_{loc}} < \theta_J \text{ \& } L_{loc},$$

$$\theta_{loc}^* = \theta_J \text{ \& } L_{loc} \text{ if } \theta_{f_{loc}} > \theta_J \text{ \& } L_{loc},$$

$\theta_{f_{loc}}$ and $\theta_J \text{ \& } L_{loc}$ are defined in the local boiling section, except $F\theta_{loc}$ replaces $F\theta_{ave}$ and

$$HCO = 0.019$$

$$T_m = T_s + [\theta_{ave} F\theta_{loc} f'(z)] \left[\frac{THK_{clad}}{K_{clad}} + \frac{THK_{meat}}{4K_{meat}} \right]$$

where

THK_{clad} , THK_{meat} = clad and meat thickness

K_{clad} , K_{meat} = clad and meat conductivity

The five DNB equations are presently programmed into STDY-3; the particular equation used is controlled by the equation choice number, the j section enthalpy, the channel flow, and the system pressure.

$$DNB_1 = BOCN1 \left(\frac{H_j}{1000} \right)^{-2.5} e^{-0.0012 L/S (F_p)}$$

$$DNB_2 = BOCN2 \left(\frac{H_j}{1000} \right)^{-2.5} e^{-0.0012 L/S} \left(1 + \frac{G_{loc}}{10^7} \right)^2$$

$$DNB_3 = BOCN3 \left(\frac{H_j}{1000} \right)^{-0.72} e^{-0.0012 L/S}$$

$$DNB_4 = (0.37 \times 10^6) \left(\frac{H_j}{1000} \right)^{-(2.1 + 0.065L)} e^{-0.03L}$$

$$DNB_5 = (0.76 \times 10^6) \left(\frac{H_j}{1000} \right)^{0.497 - 0.0962L} e^{-0.0384L}$$

where L is the distance from the channel entrance to the center of the J_{th} section and S is the channel thickness.

The following chart illustrates the DNB equation used for each combination of problem parameters.

			DNB Equation					Equation Choice		
Eq Choice	System Pressure	Range	1	2	3	4	5	$x \times 10^5 \downarrow$	1	2
1 or 2	HP ≥ 1850 psia	$G_{loc} \leq 1.6 \times 10^6$	X					BOCN1	3.25	5.0
		$G_{loc} > 1.6 \times 10^6$		X						
	LP < 1850 psia	--		$\xleftarrow{\text{min value}} \xrightarrow{\hspace{1cm}}$	X			BOCN2	2.40	3.7
									BOCN3	8.90
3	HP ≥ 1850 psia	--					X	$F_p = 1.0$ at 1850–2000 to 800 psia		
	LP < 1850 psia	--					X	$F_p = 1.2$ at 1200 psia (linear between)		

The hot channel DNB ratio is calculated using one of the five DNB equations and the following:

$$DNBR = \frac{DNB_x}{\phi_{ave} F \phi_{loc} f'(z)}$$

G. High Pressure (≥ 1850 Psia) Heating and Local Boiling

$$f/f_{iso} = C_1 \left\{ 1 + \left[PD2 \left(\frac{3500-P}{1500} \right) \left(\frac{10^6}{G} \right)^{2/3} \right] \Psi \right\},$$

where

$$C_1 = PD1 (1 - 0.0025 \theta^*), \quad C_1 \text{ must be } < 1.0 \text{ or } C_1 \text{ is set to } 1.0,$$

$$\Psi = 1 - (\theta^*/\theta_f),$$

$$PD1 = 1.05 \text{ (design)}$$

$$= 1.00 \text{ (best fit),}$$

$$PD2 = 0.912 \text{ (design)}$$

$$= 0.76 \text{ (best fit).}$$

H. Low Pressure (< 1850 Psia) Heating

$$f/f_{iso} = 1.0 \text{ (design)}$$

$$= 1.0 - 0.001304 \theta_f \text{ (best fit)}$$

I. Low Pressure Local Boiling

$$f/f_{iso} = 1 + \frac{T_{ave} - T_{lb}^*}{T_{sat} - T_{lb}^*} \left[(f/f_{iso, sat}) - 1 \right]$$

where

$$T_{lb}^* = T_{sat} + \frac{60 (\phi/10^6)^{0.25}}{e^{P/900}} - \frac{\phi}{h},$$

$$f/f_{iso, sat} = \text{Martinelli value for } \Phi_{LO}^2 \text{ at 4.2\% quality.}$$

J. High Pressure (≥ 1850 Psia) Bulk Boiling

Basic Equations, Limited to $G \geq 0.7 \times 10^6$ and $X \leq 0.4$

$$\Phi_{LO}^2 = (ABO) (FAM) \quad 0 < X < 0.02$$

$$\Phi_{LO}^2 = (ABC) (FAM) \left(\frac{FMN \text{ at } P}{FMN \text{ at } 2000 \text{ psia}} \right) \quad 0.02 \leq X \leq 0.04$$

Extrapolation Equations

$$\Phi_{LO}^2 = \Phi_{LO}^2 \left(\frac{FAM \text{ at } X = 0.4}{FAM} \right) \left(\frac{FMN \text{ at } P}{4.75} \right) \quad 0.4 < X \leq 1.0$$

$$\Phi_{LO}^2 = \Phi_{LO}^2 \left(\frac{FAM \text{ at } G = 0.7 \times 10^6}{FAM} \right) \left[1 + 0.93 \left(0.7 - \frac{G}{10^6} \right) \right] \quad G < 0.7 \times 10^6$$

where

FAM is the family of curves representing Φ_{LO}^2 bulk boiling pressure drop data at 2000 psia (Appendix IV) (see Ref 2),

FMN are the Martinelli values of Φ_{LO}^2 for bulk boiling pressure drop (Appendix IV) (see Ref 3),

ABC = 1.1 design
= 1.0 best fit.

If $\Phi_{LO}^2 < 1$ in the above equations, Φ_{LO}^2 is set equal to one.

K. Low Pressure (< 1850 Psia) Bulk Boiling

For $G \leq 0.7 \times 10^6$,

$$\Phi_{LO}^2 = (ABC) (FMN) \left[1.36 + 0.0005 P + 0.1 \left(\frac{G}{10^6} \right) - 0.000714 P \left(\frac{G}{10^6} \right) \right].$$

For $G \geq 0.7 \times 10^6$,

$$\Phi_{LO}^2 = (ABC) (FMN) \left[1.26 - 0.0004 P + 0.119 \left(\frac{10^6}{G} \right) + 0.00028 P \left(\frac{10^6}{G} \right) \right].$$

If $\Phi_{LO}^2 < 1$ in the above equations, Φ_{LO}^2 is set equal to one.

L. Second-Pass Inlet Conditions

Second-pass inlet enthalpy is calculated by the following equations:

$$H_{in(2) AC} = H_{in(1)} + F_a (\Delta H)$$

$$H_{in(2) HC} = M [H_{in(1)} + F_a (\Delta H)] + (1 - M) H_{out(1) HC \#1}, \quad (1)$$

$$H_{in(2) HC} = M [H_{in(1)} + F_a (\Delta H)] + (1 - M) [H_{in(1)} + (\Delta H) (F \Delta T_{mix})] \quad (2)$$

where

ΔH is the first-pass AC enthalpy rise,

F_a is the fraction of flow heated,

M is the mixing factor,

AC is the average channel,

HC is the hot channel,

(1), (2) is the first or second pass.

Second-pass hot channel inlet enthalpy is calculated by Eq (1) if the input value $F\Delta T_{(mix)}$ is zero, and Eq (2) if $F\Delta T_{(mix)}$ is non-zero.

III. INPUT-OUTPUT OPTIONS

Three input options are available as follows:

- 1) Axial variation of channel roughness may be accomplished by entering a (1) in column 59 on the input control card (Card 2). A and B factors ($f_{iso} = A/Re^B$) must then be entered in pairs for each axial j point for each channel. These values are entered 5 pairs/card (format

	.		A			
--	---	--	---	--	--	--

.		B	
---	--	---	--

). Every card but the last of the set must contain 5 pairs of values. No card number should be included. This set of cards must be placed between the normal set of input cards and the blank card.
- 2) Axial variation of the heat transfer coefficient may be accomplished by entering a (2) in column 59 on the input control card (Card 2). Heat transfer coefficient multipliers must then be entered for each axial j point for each channel. These values are entered 10/card (format

	.				
--	---	--	--	--	--

). Every card but the last of the set must contain 10 values. No card number should be included. This selection also activates the axial variation of channel roughness option. Therefore, both sets of extra input cards must accompany this selection; roughness cards are followed by heat transfer multiplier cards. These card sets must be placed between the normal set of input cards and the blank card.
- 3) Convergence accuracy, the match of the true hot channel pressure drop (calculated by multiplying the average channel pressure drop by the plenum equation) to the actual hot channel pressure drop searched from the G vs ΔP curve, is programmed as 2%. This percentage may be altered by entering the desired value as a decimal in columns 60-63 as

.			
---	--	--	--

 (Card 2).

Three output options are available as follows:

- 1) A special hot channel edit* containing the following items may be obtained by entering a (1) in column 65 on the input control card (Card 2). This special edit contains:

a) f/f_{iso} , Φ_{LO}^2 , ρ , v_b , f_{iso} (for each j elevation),

b) T_{out} , X_{out} , H_{out} , ρ_{out} , $R_{g,out}$, $SPT1$, $SPT2$, H_{fg} , V_{fg} , ρ_{sat} , v_f , v_g , ρ_g , X_{in} , ρ_{in} , $R_{g,in}$,

and $f_{iso, sat}$ (for the channel);

and the parameters are defined as follows:

f/f_{iso}	Friction factor ratio for heating and local boiling
-------------	---

Φ_{LO}^2	Ratio of two-phase frictional pressure drop gradient to the corresponding isothermal liquid gradient
---------------	--

ρ Average density of fluid in a particular axial section

*See page 5 of the sample output.

v_b	Average specific volume of fluid in a particular axial section
f_{iso}	Isothermal friction factor
T_{out}	Temperature of fluid out of the channel
X_{out}	Quality of fluid out of the channel
H_{out}	Enthalpy of fluid out of the channel
ρ_{out}	Density of fluid out of the channel
$R_{g, out}$	Void fraction of fluid out of the channel
$\left. \begin{matrix} SPT1 \\ SPT2 \end{matrix} \right\}$	Spatial acceleration terms as defined previously
H_{fg}	Enthalpy of vaporization
v_{fg}	Specific volume of vaporization
ρ_{sat}	Saturation density
v_f	Specific volume of fluid at saturation conditions
v_g	Specific volume of gas at saturation conditions
ρ_g	Density of gas at saturation conditions
X_{in}	Quality of fluid into the channel
ρ_{in}	Density of fluid into the channel
$R_{g, in}$	Void fraction of fluid into the channel
$f_{iso, sat}$	Isothermal friction factor at the saturation temperature

- 2) An x-y plot of the hot channel G vs ΔP table may be obtained by entering a (1) in column 68 on the input control card (Card 2). (See page 3 of the Sample Output.)
- 3) A complete channel edit may be obtained for each flow step in the G vs ΔP table. The information at each step will be identical to that produced for the hot channel solution. This option may be activated by instructing the computer operator to depress sense switch 3. Using this option doubles the normal problem running time.

IV. INPUT FORM PREPARATION

The STDY input forms are shown in Appendix I. Any other form containing a similar format may be used to submit problems for computation. These forms are not interchangeable with input forms for previous versions of STDY. Instructions for completing the forms follow.

A. STDY Input Form (Page 1)

Title Card — Card 1 contains the eight-digit problem number and the code name STDY-3. Any alpha-numeric identification information may be placed in the center spaces (columns 13 to 65).

Control Card — Card 2 contains sixteen items of the following form:

- 1) #P Number of system pressures to be read from Card 3 (range: 1 through 5).
- 2) #G Number of normal channel flows to be read from Cards 4 and 5 (range: 1 through 5).
- 3) #T Number of first-pass inlet temperatures to be read from Card 6 (range: 1 through 5).
- 4) #Ø Number of channel heat flux variations to be read from Cards 71 to 75 as necessary (range: 1 through 5).
- 5) NP Number of passes (1 or 2).
- 6) N1C Number of first-pass channels (range: 1, 2, or 3).
- 7) N2C Number of second-pass channels. Must be zero for one-pass cores (range: 0, 1, 2, or 3).
- 8) J Number of axial sections for heat transfer purposes (range: 2 through 30).
- 9) K_{clad} Thermal conductivity of clad for meat temperature calculations (Btu/hr-ft-°F).
- 10) K_{meat} Thermal conductivity of meat for meat temperature calculations (Btu/hr-ft-°F).
- 11) Channel Length Channel length (in.).
- 12) Frac Flow Heated Fraction of flow heated for second-pass inlet enthalpy calculations only (see equation below).
- 13) $F\Delta T_{(\text{mix})}$ Hot channel factor to calculate alternate second-pass inlet enthalpy. Second-pass inlet enthalpy is calculated by Eq (1) if $F\Delta T_{(\text{mix})}$ is zero, and Eq (2) if $F\Delta T_{(\text{mix})}$ is non-zero.

$$H_{\text{in}(2) \text{ AC}} = H_{\text{in}(1)} + Fa (\Delta H)$$

$$H_{\text{in}(2) \text{ HC}} = M \left[H_{\text{in}(1)} + Fa (\Delta H) \right] + (1 - M) H_{\text{out}(1) \text{ HC}\#1} \quad (3)$$

$$H_{\text{in}(2) \text{ HC}} = M \left[H_{\text{in}(1)} + Fa (\Delta H) \right] + (1 - M) \left[H_{\text{in}(1)} + (\Delta H F \Delta T_{\text{mix}}) \right], \quad (4)$$

where

ΔH is the first-pass AC enthalpy rise,

Fa is the fraction of flow heated,

M is the mixing factor supplied separately for each second-pass hot channel on the plenum cards,

AC, HC is the average channel or hot channel, respectively,

(1), (2) is the first or second pass, respectively.

- 14) Starting HC Flow Multiplier applied to the average channel flow to obtain the starting flow for the G vs ΔP table (should be ≥ 1).
- 15) EQ Equation type (1), (2), or (3). (See Section II.)
 - (1) Design equations
 - (2) Best fit equations
 - (3) Design equations (special DNB equations)
- 16) SOL Hot channel solution selection (1, 2, or 3). A solution is defined as an intersection of the curve through the hot channel G vs ΔP points and the average channel pressure drop times the plenum factor line. This intersection may occur more than once for a particular problem.
 - (1) Prints the solution for the lowest flow.
 - (2) Prints the solution for the highest flow.
 - (3) Prints all solutions.

The first four numbers on the Control Card (Card 2) control the parameter variation provided for safety margin calculations. Each parameter will be varied independently through the set of values supplied, then reset to its initial value while any remaining parameters are varied. Only one parameter will be varied at a time; and once varied and reset, it will remain at its initial value for the remainder of the problem.

Pressure Card — Card 3 contains 1 to 5 pressures as indicated by the control card (psia).

Flow Card — Card 4 contains 1 to 5 first-pass G values as indicated by the control card (lb/hr-ft²).

Flow Card — Card 5 contains 1 to 5 second-pass G values as indicated by the control card (lb/hr-ft²). This card is not used for a one-pass problem.

T_{in} Card — Card 6 contains 1 to 5 first-pass inlet temperatures as indicated by the control card (°F).

q_{ave} Card — Cards 71 through 75 contain 1 to 5 sets of channel heat fluxes as indicated by the Control Card (Btu/hr-ft²). Card 71 contains the first set of fluxes, Card 72 contains the second, etc. One to six values are punched per card depending on the number of channels. If any of Cards 72, 73, 74, or 75 are not needed, they are not supplied.

B. STDY Input Form (Page 2)

Channel Description Cards — (Cards 81 through 86) One to six cards are supplied (equal to the number of channels) containing the following information:

THK_{ave} is the channel average thickness (in.).

THK_{loc} is the channel local thickness (in.). (May be left blank for normal channels.)

K_{con} is the contraction coefficient.

K_{exp} is the expansion coefficient.

The contraction and expansion coefficients are used to calculate entrance and exit unrecoverable pressure drop by the following equation:

$$\Delta P_{E\&E} = \frac{G^2}{2g_c} \left(\frac{K_{con}}{\rho_{in}} + \frac{K_{exp}}{\rho_{out}} \right),$$

where

G is the mass flowrate (lb/hr-ft²),

g_c is the acceleration of gravity (32.2 ft/sec²),

ρ is the bulk fluid density (lb/ft³).

a is a constant.

b is a constant.

These constants are used to describe the channel friction factor by the following equation:

$$f_{iso} = \frac{a}{(Re)^b},$$

where Re is the Reynold's Number.

THK_{clad} is the clad thickness (in.).

THK_{meat} is the meat thickness (in.) (g and h may be left blank for normal channels).

σ_{in} is the entrance area ratio.

σ_{out} is the exit area ratio.

These σ terms are used to calculate the configuration accelerations at the entrance and exit of the channel (smaller area/larger area).

$F_{\phi ave}$ is the average hot channel factor affecting heat flux (must be supplied for all channels).

$F_{\phi loc}$ is the local hot channel factor affecting heat flux (may be left blank for normal channels).

Plenum Cards — (Cards 91 through 94) Zero to four plenum cards must be supplied depending on the number of hot channels. These cards contain the K values as used in the following equation:

$$\begin{aligned} \Delta P_{HC} = & K_1 K_2 (\Delta P_{AC})_{total} + (1 - K_1 K_2) (\Delta P_{AC})_{elevation} \\ & + K_1 K_2' K_2' + K_2 K_1' - K_1 K_2 (1 + K_1') (\Delta P_{AC})_{acceleration}, \end{aligned}$$

where HC is the hot channel and AC is the average channel. These cards also contain the M factors necessary to the previously described second-pass inlet enthalpy equations.

Axial Flux Weighting Cards — (Cards 01 through 18) One to eighteen $f'(z)$ cards must be supplied as the last set of input. These values weight the average heat flux axially. One value for each axial point (J) for each channel must be supplied. These values are supplied up to ten/card; a new card is begun for each channel.

One blank card must follow each complete set of input data. This blank card is checked by the machine; if not supplied, the problem will be rejected. Successive problems may be submitted by stacking the sets of input data.

Certain input form blanks show a decimal point while certain others show a decimal and a sign. Values supplied in these spaces must go directly to the right or left of the decimal. The spaces to the right of a sign are available for powers of ten (e.g., 2.200 + 06 is interpreted as 2.2×10^6); blank spaces are interpreted by the machine to be zeros.

V. ESTIMATED RUNNING TIME

Problem running time, neglecting program loading, may be estimated by the following formula:

$$\text{Running time (minutes)} = 0.009 \left[(\#P - 1) + (\#G - 1) + (\#T - 1) + (\#\emptyset) \right] (N1C + N2C) - J$$

The above quantities are seven of the first eight values entered on Card 2 for the problem in question.

VI. SAMPLE INPUT AND OUTPUT

Sample input and output sheets are shown in Appendix II.

VII. MACHINE OPERATING INSTRUCTIONS

The STDY-3 code is designed to operate on an IBM-704 computer having a core storage of 16,384 words, an on-line card reader, an on-line 716 printer, one logical drum, and from one to three tape units. In addition, an off-line 717 printer is required.

- 1) The on-line printer board must be Share-2.
- 2) Tapes are normally only a blank 5 for problem output. If sense switch 3 option is requested, ready a blank 6.
- 3) Sense switches are normally all up. Switch 3 is down if requested.
- 4) Ready the card reader with the self-loading program deck followed by the data deck(s). One blank card must follow each data set.
- 5) Push the CLEAR and LOAD CARDS buttons.
- 6) End of run is signaled by a read select on the card reader and an "end of this problem" printed on line.
- 7) Output is normally only on tape 5. No rewind or end-of-file operations are programmed. A manual end-of-file should be written on the output tape before rewinding.

The code checks input cards for obvious errors. If an error is found, the substance of the error is printed on-line and the remainder of that particular problem input is run through the card reader. When a blank card is encountered, the erroneous problem is assumed to cease and a new problem to begin. A blank card at the end of each problem is therefore absolutely necessary to the proper functioning of this program.

To transfer computer control to the logical beginning of the program (to start a new problem or retry an old one), ready the data cards in the card reader and manually transfer to location $(00155)_8$ (program tape), or location $(00024)_8$ (program cards).

An estimated maximum running time is printed on-line for each problem. If a particular problem runs more than 5 minutes over the estimated time, an error should be assumed and the problem stopped.

ACKNOWLEDGMENTS

The writer is grateful to Mr. J. D. Wilde for his work on the original IBM-650 version of STDY and to Mr. G. J. Mohn for his assistance during the programming of STDY for the IBM-704. The curve fit equations for the "Heat Transfer Coefficient" and the "Family of Curves" representing bulk boiling pressure drop data were supplied by the Bettis Thermal and Hydraulics Section.

REFERENCES

1. J. E. Meyer, et al., "ART - A Program for the Treatment of Reactor Thermal Transients on the IBM-704," WAPD-TM-156 (November 1959).
2. N. C. Sher and S. J. Green, "Boiling Pressure Drop in Thin Rectangular Channels," Nuclear Engineering - Part VI, Chemical Engineering Progress Symposium Series, No. 23, Vol 55 (1959), Fig. 12, p 69.
3. R. C. Martinelli and D. B. Nelson, "Prediction of Pressure Drop during Forced Circulation Boiling of Water," Trans. ASME, Vol 70 (1948), p 695.
4. N. C. Sher, "Review of Martinelli - Nelson Pressure Drop Correlation," WAPD-TH-219 (July 1956), Table I, p 11.

STDY INPUT FORM

PAGE 1

APPENDIX I: STDY INPUT FORMS

TITLE CARD										10	20	30	40	50	60				
PROB. NO.										IDENTIFICATION INFORMATION									
1										S T D Y 3									
CONTROL CARD																			
2																			
PRESSURE CARD										10	20	30	40	50	60				
3																			
FLOW CARD																			
4										FIRST PASS									
FLOW CARD										10	20	30	40	50	60				
5										SECOND PASS (ONLY)									
T _{IN} CARD																			
6										FIRST PASS									
φ _{AVG} CARD										10	20	30	40	50	60				
7 1										1ST VARIATION									
7 2										2ND VARIATION									
7 3										3RD VARIATION									
7 4										4TH VARIATION									
7 5										5TH VARIATION									

DO NOT PUNCH CARDS WITHOUT HAND WRITTEN ENTRIES

CHAN

[illegible][illegible]

(START A NEW CARD FOR EACH CHANNEL)

[illegible]

APPENDIX II: SAMPLE PROBLEM

Sample Input (Hypothetical Reactor)

```

1 06269305      TEST PROBLEM      R.S. PYLE      STDY 3
2  1 1 1 1 1 2 0 10  7.4   7.4  41.   .84   1.   1 1   1 1
3  1800.
4  5.66 +06
6  473.8
71 2.5000+05 3.5000+05
81 .085          .323 .304 .1439 .169          .447 .447 1.
82 .078 .086 .333 .333 .1195 .150 .015 .081 .421 .421 1.12 1.17
91 1.0          .827 1.0   1.0
01 1.29  1.28  1.44  1.41  1.22  1.01 .82   .64   .46   .43
02 2.72  2.70  3.04  2.98  2.99  2.47  2.01  1.57  1.13  1.05

```

06269305

TEST PROBLEM

R.S. PYLE

STDY 3

STDY 3 *** PAGE 1

**** INPUT AS STORED IN MEMORY ****

CONTROL- 2 1 1 1 1 1 2 0 10 7.400 7.400 41.00 0.84 -0. 1.00 1 1
 PRESSURE- 3 1800.
 FLOW- 4 5.660E 06
 T(IN) 6 472.8
 FLUX 71 2.5000E 05 3.5000E 05
 CHAN. DESCRIPTION- 81 0.085 -0. 0.323 0.304 0.1429 0.169 -0. -0. 0.447 0.447 1.00 -0.
 CHAN. DESCRIPTION- 82 0.073 0.086 0.333 0.333 0.1155 0.150 0.015 0.081 0.421 0.421 1.12 1.17
 1ST PASS PLENUM- 91 1.0000 0.827C 1.0000 1.000C
 FLUX WEIGHTING- 01 1.2900 1.2800 1.4400 1.4100 1.2200 1.0100 0.8200 0.6400 0.4600 0.4300
 FLUX WEIGHTING- 02 2.7200 2.7000 3.0400 2.9800 2.9900 2.4700 2.0100 1.5700 1.1300 1.0500

Page 1 - Repeat of Input Data
 as Read from Input Cards

06269305

TEST PROBLEM

R.S. PYLE

STDY 3

STDY 3 *** PAGE 2

TAPE 5 AVERAGE CHANNEL VALUES (FIRST PASS)

PRESSURE=1800. AVERAGE CHANNEL- HEAT FLUX=2.5000E 05, THICKNESS=0.085, LENGTH=41.00, INLET TEMP.=473.8, H=457.5

J.	T AVE	H AVE	X
1	476.20	460.26	0.
2	480.99	465.74	0.
3	486.02	471.53	0.
4	491.27	477.61	0.
5	496.08	483.21	0.
6	500.14	487.96	0.
7	503.45	491.86	0.
8	506.08	494.97	0.
9	508.06	497.31	0.
10	509.66	499.21	0.

← Conditions Evaluated at the
Center of Each Axial Section

CHANNEL NUMBER= 1 CHANNEL MASS VELOCITY(G)=5.660E 06 ENTHALPY RISE(BTU/LB)= 42.61
 ACCELERATION DP= 0.444(1)+0.177(2) ELEVATION DP= 1.174 FRICTION DP=22.086 ENTRANCE + EXIT DP= 3.365
 CHANNEL TOTAL PRESSURE DROP= 26.890 AVERAGE CHANNEL PRESSURE DROP X PLENUM FACTOR= 22.487
 LOCAL BOILING STARTS J= 0 BULK BOILING STARTS J= 0
 T SAT= 621.15 H SAT= 649.12

Average Channel

MASS VELOCITY VERSUS PRESSURE DROP TABLE
 1ST HOT CHANNEL CHANNEL NUMBER= 2

Hot Channel

G=5.660E 06	DP= 34.896
G=5.377E 06	DP= 33.898
G=5.094E 06	DP= 32.767
G=4.811E 06	DP= 31.647
G=4.528E 06	DP= 29.502
G=4.245E 06	DP= 27.483
G=3.962E 06	DP= 26.137
G=3.679E 06	DP= 24.913
G=3.396E 06	DP= 24.481
G=3.113E 06	DP= 23.328
G=2.830E 06	DP= 23.144
G=2.547E 06	DP= 22.299
G=2.264E 06	DP= 21.968
G=1.981E 06	DP= 21.014
G=1.698E 06	DP= 20.397
G=1.415E 06	DP= 19.532

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TEST PROBLEM

R.S. PYLE

STDY 3

STDY 3 *** PAGE 3

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TEST PROBLEM

R.S. PYLE

STDY 3

STDY 3 *** PAGE 4

TAPE 5 HOT CHANNEL VALUES - SOLUTION NUMBER 1

0

PRESSURE=1800. HOT CHANNEL- HEAT FLUX=3.5000E 05, THICKNESS=0.078, LENGTH=41.00, INLET TEMP.=473.8, H=457.5

J	T AVE	H AVE	X	TS	TM	DNBR
1	492.91	479.52	0.	629.40	1071.55	1.314
2	529.70	523.37	0.	629.38	1068.28	1.167
3	566.53	569.80	0.	629.63	1123.80	0.915
4	602.52	618.51	0.	629.59	1114.00	0.721
5	621.15	666.80	0.035	629.60	1115.63	0.559
6	621.15	710.97	0.123	629.20	1030.71	0.541
7	621.15	747.22	0.195	628.80	955.53	0.551
8	621.15	776.18	0.253	628.34	883.55	0.603
9	621.15	798.02	0.296	627.77	811.46	0.733
10	621.15	815.66	0.331	627.65	798.33	0.702

← Conditions Evaluated at the
Center of Each Axial Section

CHANNEL NUMBER= 2 CHANNEL MASS VELOCITY(G)=2.547E 06 ENTHALPY RISE(BTU/LB)=366.64
 ACCELERATION DP= 5.949(1),-3.164(2) ELEVATION DP= 0.727 FRICTION DP=16.796 ENTRANCE + EXIT DP= 1.990
 CHANNEL TOTAL PRESSURE DROP= 22.299 AVERAGE CHANNEL PRESSURE DROP X PLENUM FACTOR= 22.487
 LOCAL BOILING STARTS J= 1 BULK BOILING STARTS J= 5
 T SAT= 621.15 H SAT= 649.12

06269305

TEST PROBLEM

R.S. PYLE

STDY 3

STDY 3 *** PAGE 5

* SPECIAL HOT CHANNEL EDIT *

J	FFISC	F2LO	RO	VB	FISO
1	1.06	0.	49.64	0.	0.0205
2	1.22	0.	47.46	0.	0.0203
3	1.43	0.	45.00	0.	0.0200
4	1.58	0.	42.34	0.	0.0198
5	1.58	1.31	42.34	0.031	0.0198
6	1.58	2.52	42.34	0.04*	0.0198
7	1.58	3.22	42.34	0.052	0.0198
8	1.58	3.82	42.34	0.058	0.0198
9	1.58	4.23	42.34	0.06*	0.0198
10	1.58	4.55	42.34	0.068	0.0198

← Conditions Evaluated at the
Center of Each Axial Section

TOUT	XOUT	HOUT	RGOUT	RGOUT	SPT1	SPT2	HFG	VFG	ROSAT	VF	VG	ROG	XIN	ROEIN	RGIN	FIOST
618.03	0.348	824.15	10.99	0.736	0.075	0.020	503.12	0.1911	40.84	0.0245	0.2155	4.638	0.	50.69	0.	0.0198

END OF THIS PROBLEM

This Page Only if Requested.

Key

FFISC = f/f_{iso}

F2LO = Φ_{LO}^2

RO = ρ

VB = V_B

FISO = f_{iso}

TOUT = T_{out}

XOUT = X_{out}

HOUT = H_{out}

ROUT = ρ_{out}

RGOUT = $R_{g, out}$

Key

SPT1 = SPT1

SPT2 = SPT2

HFG = H_{fg}

VFG = V_{fg}

ROSAT = ρ_{sat}

VF = V_f

VG = V_g

ROG = ρ_g

XIN = X_{in}

Key

ROEIN = ρ_{in}

RGIN = $R_{g, in}$

FIOST = $f_{iso, sat}$

APPENDIX III: WATER PROPERTY CURVE FITS

WATER DENSITY - POUNDS/CUBIC FOOT

$$\text{DENSITY} = 63.8 - .01781 T + 1.132 \times 10^{-5} T^2 - 6.786 \times 10^{-8} T^3$$

TEMPERATURE	DENSITY			
	SAT	2000 PSI	AVG	CURVE FIT
100	62.00	62.38	62.19	62.06
150	61.20	61.58	61.39	61.15
200	60.13	60.53	60.33	60.15
250	58.82	59.24	59.03	58.99
300	57.30	57.77	57.53	57.64
350	55.58	56.09	55.83	56.04
400	53.65	54.20	53.92	54.14
450	51.54	52.16	51.85	51.89
500	49.02	49.63	49.32	49.24
550	45.87	46.60	46.23	46.14
600	42.37	42.92	42.64	42.53
620	40.48	40.88	40.68	40.94

WATER DYNAMIC VISCOSITY - POUNDS/FOOT-HOUR

$$\text{DYNAMIC VISCOSITY} = (8.506 \times 10^{-3} T - .3643)^{-1}$$

TEMPERATURE	VISCOSITY			
	SAT	2000 PSI	AVG	CURVE FIT
100	1.650	1.658	1.654	2.056
150	1.050	1.068	1.059	1.097
200	0.738	0.757	0.748	0.748
250	0.568	0.587	0.578	0.567
300	0.452	0.468	0.460	0.457
350	0.378	0.390	0.384	0.383
400	0.327	0.335	0.331	0.329
450	0.287	0.293	0.290	0.289
500	0.256	0.260	0.258	0.257
550	0.230	0.235	0.232	0.232
600	0.210	0.212	0.211	0.211
620	0.200	0.202	0.201	0.204

SATURATION ENTHALPY - B.T.U./POUND

$$\begin{aligned} \text{LOG H(SAT)} &= .30934 \text{ LOG P} + 4.15695 & 2000 \text{ P } 1000 \\ &= .26452 \text{ LOG P} + 4.46708 & 1000 \text{ P } 100 \end{aligned}$$

PRESSURE PSI	ENTHALPY	
	ACTUAL	CURVE FIT
2000	671.7	670.6
1900	660.1	660.1
1800	648.3	649.1
1700	636.3	637.7
1600	624.1	625.9
1500	611.6	613.5
1400	598.7	600.6
1300	585.4	587.0
1200	571.7	572.6
1100	557.4	557.4
1000	542.4	541.2
900	526.6	526.6
800	509.7	510.5
700	491.5	492.7
600	471.6	473.0
500	449.4	450.8
400	424.0	424.9
300	393.8	393.8
200	355.4	353.8
100	298.4	294.5

WHERE* LOG= NATURAL LOGARITHM(BASE- 2.71828)

SATURATION TEMPERATURE - DEGREES F

$$\text{LOG T(SAT)} = .22151 \text{ LOG P} + 4.77123$$

PRESSURE PSI	TEMPERATURE	
	ACTUAL	CURVE FIT
2000	635.8	635.8
1900	628.6	628.6
1800	621.0	621.1
1700	613.1	613.3
1600	604.9	605.2
1500	596.2	596.6
1400	587.1	587.5
1300	577.5	577.9
1200	567.2	567.8
1100	556.3	557.0
1000	544.6	545.3
900	531.9	532.7
800	518.2	519.0
700	503.1	503.9
600	486.2	487.0
500	467.0	467.7
400	444.6	445.1
300	417.3	417.7
200	381.8	381.8
100	327.8	327.4

WHERE* LOG= NATURAL LOGARITHM(BASE- 2.71828)

ENTHALPY OF VAPORIZATION - H(FG) - B.T.U./POUND

$$H(FG) = 922.15 - .40516 P + 1.717 \times 10^{-4} P^2 - 4.219 \times 10^{-8} P^3$$

PRESSURE PSI	ENTHALPY	
	ACTUAL	CURVE FIT
2000	463.4	461.1
1900	482.4	482.8
1800	501.0	503.1
1700	519.6	522.3
1600	538.0	540.6
1500	556.3	558.3
1400	574.7	575.7
1300	592.2	592.9
1200	611.7	610.3
1100	630.4	628.1
1000	649.4	646.5
900	668.8	665.8
800	688.9	686.3
700	709.7	708.2
600	731.6	731.8
500	755.0	757.2
400	780.5	784.9
300	809.0	814.9
200	843.0	847.6
100	888.8	883.3

SPECIFIC VOLUME OF VAPORIZATION - V(FG) - CUBIC FEET/POUND

$$V(FG) = 524.0(P)^{-1} - .100 \quad 2000 \text{ P } 300$$

$$= 428.8(P)^{-1} + .126 \quad 300 \text{ P } 100$$

PRESSURE PSI	SPECIFIC VOLUME	
	ACTUAL	CURVE FIT
2000	0.1621	0.1620
1900	0.1769	0.1758
1800	0.1932	0.1911
1700	0.2111	0.2082
1600	0.2309	0.2275
1500	0.2530	0.2493
1400	0.2781	0.2742
1300	0.3066	0.3031
1200	0.3396	0.3367
1100	0.3781	0.3764
1000	0.4240	0.4240
900	0.4794	0.4822
800	0.5478	0.5550
700	0.6349	0.6486
600	0.7497	0.7733
500	0.9081	0.9480
400	1.1420	1.2100
300	1.5244	1.6467
200	2.2690	2.2700
100	4.4140	4.4140

TEMPERATURE - ENTHALPY

ACTUAL VALUES

TEMPERATURE F	ENTHALPY			
	SAT	1000 PSI	1500 PSI	2000 PSI
100	68.0	70.7	72.0	73.3
150	117.9	120.4	121.6	122.8
200	168.0	170.2	171.4	172.5
250	218.5	220.5	221.6	222.6
300	269.6	271.3	272.3	273.2
350	321.6	322.9	323.7	324.5
400	375.0	375.8	376.4	377.0
450	430.1	430.4	430.7	431.1
500	487.8	487.6	487.5	487.4
550	549.3		548.5	547.6
600	616.8			614.5
620	646.5			644.9

(CONTINUED)

TEMPERATURE - ENTHALPY

$$\text{TEMPERATURE} = (-1.98 \times 10^{-3} P + 31.57) + (-1.5 \times 10^{-5} P + 1.0027)H +$$

$$(.810 \times 10^{-7} P + .581 \times 10^{-4} H^2) + (-.857 \times 10^{-10} P - 2.978 \times 10^{-7} H^3)$$

$$\text{ENTHALPY} = (-1.18 \times 10^{-3} P - 30.06) + (.63 \times 10^{-4} P + .98)T +$$

$$(-2.719 \times 10^{-7} P - .106 \times 10^{-4} T^2) + (3.027 \times 10^{-10} P + 2.439 \times 10^{-7} T^3)$$

CURVE FIT VALUES

PRESSURE PSI	TEMPERATURE OR ENTHALPY	ENTHALPY BTU/LB	TEMPERATURE F
2000	100	73.5	126.6
2000	150	123.9	176.9
2000	200	173.4	227.2
2000	250	222.7	277.2
2000	300	272.4	326.6
2000	350	323.2	374.9
2000	400	375.6	421.9
2000	450	430.4	467.1
2000	500	488.1	510.3
2000	550	549.5	551.1
2000	600	615.0	589.1
1900	100	73.2	126.9
1900	150	123.6	177.2
1900	200	173.1	227.4
1900	250	222.5	277.4
1900	300	272.3	326.7
1900	350	323.1	375.0
1900	400	375.6	421.9
1900	450	430.4	467.2
1900	500	488.1	510.3
1900	550	549.3	551.1
1900	600	614.6	589.2

(CONTINUED)

1800	100	72.9	127.2
1800	150	123.2	177.4
1800	200	172.8	227.7
1800	250	222.2	277.6
1800	300	272.1	326.9
1800	350	323.1	375.1
1800	400	375.7	422.0
1800	450	430.5	467.2
1800	500	488.1	510.3
1800	550	549.2	551.1
1800	600	614.2	589.2
1700	100	72.7	127.4
1700	150	122.9	177.7
1700	200	172.5	227.9
1700	250	222.0	277.8
1700	300	272.0	327.0
1700	350	323.0	375.2
1700	400	375.7	422.0
1700	450	430.5	467.2
1700	500	488.1	510.3
1700	550	549.0	551.1
1700	600	613.0	589.2
1600	100	72.4	127.7
1600	150	122.6	178.0
1600	200	172.2	228.2
1600	250	221.8	278.0
1600	300	271.8	327.2
1600	350	323.0	375.3
1600	400	375.7	422.1
1600	450	430.5	467.2
1600	500	488.1	510.3
1600	550	548.8	551.1
1600	600	613.4	589.3
1500	100	72.1	128.0
1500	150	122.3	178.2
1500	200	171.9	228.4
1500	250	221.5	278.2
1500	300	271.7	327.3
1500	350	322.9	375.4
1500	400	375.7	422.1
1500	450	430.6	467.2
1500	500	488.1	510.3
1500	550	548.7	551.1

(CONTINUED)

1400	100	-71.9	128.3
1400	150	122.0	178.5
1400	200	171.6	228.7
1400	250	221.3	278.4
1400	300	271.6	327.5
1400	350	322.9	375.5
1400	400	375.7	422.2
1400	450	430.6	467.2
1400	500	488.0	510.3
1400	550	548.5	551.1
1300	100	71.6	128.5
1300	150	121.7	178.8
1300	200	171.3	228.9
1300	250	221.1	278.6
1300	300	271.4	327.6
1300	350	322.8	375.6
1300	400	375.7	422.2
1300	450	430.6	467.2
1300	500	488.0	510.3
1300	550	548.4	551.1
1200	100	71.3	128.8
1200	150	121.3	179.0
1200	200	171.0	229.1
1200	250	220.9	278.8
1200	300	271.3	327.8
1200	350	322.7	375.7
1200	400	375.7	422.3
1200	450	430.7	467.2
1200	500	488.0	510.3
1200	550	548.2	551.1
1100	100	71.1	129.1
1100	150	121.0	179.3
1100	200	170.7	229.4
1100	250	220.6	279.0
1100	300	271.1	327.9
1100	350	322.7	375.8
1100	400	375.7	422.3
1100	450	430.7	467.3
1100	500	488.0	510.3
1100	550	548.1	551.1

(CONTINUED)

1000	100	70.8	129.4
1000	150	120.7	179.6
1000	200	170.4	229.6
1000	250	220.4	279.2
1000	300	271.0	328.1
1000	350	322.6	375.9
1000	400	375.7	422.4
1000	450	430.7	467.3
1000	500	488.0	510.3
900	100	70.5	129.6
900	150	120.4	179.9
900	200	170.1	229.9
900	250	220.2	279.4
900	300	270.9	328.2
900	350	322.6	376.0
900	400	375.8	422.4
900	450	430.7	467.3
900	500	487.9	510.3
800	100	70.2	129.9
800	150	120.1	180.1
800	200	169.8	230.1
800	250	219.9	279.6
800	300	270.7	328.4
800	350	322.5	376.1
800	400	375.8	422.5
800	450	430.8	467.3
800	500	487.9	510.3
700	100	70.0	130.2
700	150	119.7	180.4
700	200	169.5	230.4
700	250	219.7	279.8
700	300	270.6	328.5
700	350	322.5	376.2
700	400	375.8	422.5
700	450	430.8	467.3
700	500	487.9	510.3
600	100	69.7	130.5
600	150	119.4	180.7
600	200	169.2	230.6
600	250	219.5	280.0
600	300	270.4	328.7
600	350	322.4	376.3
600	400	375.8	422.6
600	450	430.8	467.3

(CONTINUED)

500	100	69.4	130.7
500	150	119.1	180.9
500	200	168.9	230.8
500	250	219.2	280.2
500	300	270.3	328.8
500	350	322.4	376.4
500	400	375.8	422.6
500	450	430.9	467.3
400	100	69.2	131.0
400	150	118.8	181.2
400	200	168.7	231.1
400	250	219.0	280.4
400	300	270.1	329.0
400	350	322.3	376.5
400	400	375.8	422.7
300	100	68.9	131.3
300	150	118.5	181.5
300	200	168.4	231.3
300	250	218.8	280.6
300	300	270.0	329.1
300	350	322.3	376.6
300	400	375.8	422.7
200	100	68.6	131.6
200	150	118.2	181.7
200	200	168.1	231.6
200	250	218.5	280.8
200	300	269.9	329.3
200	350	322.2	376.7
100	100	68.3	131.8
100	150	117.8	182.0
100	200	167.8	231.8
100	250	218.3	281.0
100	300	269.7	329.4

HEAT TRANSFER COEFFICIENT

$$HT \text{ TRANSFER COEFF} = (C) (F) (G/10)^{6 \cdot 0.8} (DE)^{-0.2}$$

WHERE*

C = EQUATION COEFFICIENT .019, .023, .030, ETC.

G = MASS VELOCITY - POUNDS/HOUR-SQUARE FT

DE= HYDRAULIC DIAMETER OF CHANNEL - FT

$$F = 25391.0 + 64.78 H \quad H \text{ 600 BTU/LB}$$

$$= 20281.7 + 135.5 H - .10261 H^2 \quad H \text{ 600 BTU/LB}$$

APPENDIX IV: PRESSURE DROP AND VOID FRACTION CORRELATION CURVE FITS

FAMILY OF CURVES REPRESENTING BULK BOILING PRESSURE DROP DATA
 VERTICAL UP-FLOW AT 2000 PSI (PHI²_{LO})

CURVE FIT EQUATIONS

FOR MASS VELOCITY .7 G 5.0(10⁶)

FOR QUALITY 0 X .40

$$\text{PHI}_{\text{LO}}^2 = 1 + \frac{7(X)^{.75}}{6(1+X)^6 (G/10)^6}$$

(CONTINUED)

FAMILY OF CURVES REPRESENTING BULK BOILING PRESSURE DROP DATA

TABLE OF VALUES

MASS VELOCITY LB/HR-FT	QUALITY (X)											
	.010	.015	.020	.030	.040	.050	.070	.10	.15	.20	.30	.40
0.6(10) ⁶	1.27	1.42	1.55	1.79	2.00	2.23	2.65	3.25	4.20	5.08	6.70	8.20
*	1.37	1.50	1.63	1.85	2.07	2.27	2.65	3.18	4.04	4.86	6.51	8.20
0.7	1.23	1.34	1.45	1.65	1.83	2.00	2.36	2.87	3.62	4.30	5.65	6.85
*	1.32	1.43	1.54	1.73	1.91	2.08	2.40	2.84	3.54	4.21	5.51	6.80
0.8	1.20	1.29	1.38	1.55	1.70	1.84	2.14	2.55	3.20	3.80	4.85	5.80
*	1.28	1.38	1.47	1.63	1.79	1.94	2.21	2.59	3.18	3.74	4.79	5.81
1.0	1.16	1.24	1.32	1.45	1.57	1.69	1.91	2.23	2.70	3.11	3.84	4.50
*	1.22	1.30	1.37	1.50	1.63	1.74	1.95	2.24	2.69	3.09	3.84	4.52
1.5	1.10	1.15	1.20	1.30	1.37	1.45	1.58	1.77	2.05	2.27	2.67	3.00
*	1.15	1.20	1.25	1.33	1.41	1.48	1.62	1.80	2.06	2.29	2.68	3.00
2.0	1.07	1.12	1.16	1.23	1.30	1.35	1.46	1.60	1.79	1.95	2.20	2.40
*	1.11	1.15	1.18	1.25	1.30	1.36	1.45	1.58	1.76	1.91	2.15	2.33
5.0	1.05	1.07	1.10	1.13	1.16	1.19	1.24	1.30	1.38	1.44	1.55	1.62
*	1.04	1.06	1.07	1.10	1.12	1.14	1.17	1.21	1.27	1.30	1.35	1.37

* CURVE FIT VALUES

REF* 2

MARTINELLI - NELSON VALUES OF PHI_{LO}^2

CURVE FIT EQUATIONS

FOR QUALITY 0 X .02

$$\text{PHI}_{\text{LO}}^2 = 1.0$$

FOR QUALITY .02 X .20

$$\text{PHI}_{\text{LO}}^2 = \left(.9326 - .2263 \times 10^{-3} P \right) \times \left(1.65 \times 10^{-3} + 2.988 \times 10^{-5} P - 2.528 \times 10^{-9} P^2 + 1.14 \times 10^{-11} P^3 \right)$$

FOR QUALITY .20 X 1.0

$$\text{PHI}_{\text{LO}}^2 = \left(1.0205 - .2053 \times 10^{-3} P \right) \times \left(7.876 \times 10^{-4} + 3.177 \times 10^{-5} P - 8.728 \times 10^{-9} P^2 + 1.073 \times 10^{-11} P^3 \right)$$

P = PRESSURE - PSI

(CONTINUED)

2
MARTINELLI - NELSON VALUES OF PHI
LO

TABLE OF VALUES

PRESSURE PSI	QUALITY (X)											
	.010	.042	.10	.20	.30	.40	.50	.60	.70	.80	.90	1.0
100	3.0	12.0	26.5	51.5	82.0	111.	137.	167.	191.	211.	204.	153.
* 1.0	12.1	26.6	50.0	77.2	102.9	128.6	154.3	180.	205.8	231.5	257.2	
250	2.6	6.8	14.4	26.6	40.0	50.0	62.0	73.0	83.0	89.0	88.5	65.9
* 1.0	6.8	14.5	26.7	37.3	49.3	61.7	73.0	84.7	96.4	108.1	119.7	
500	2.0	4.3	8.6	15.4	22.3	27.9	33.7	39.5	44.5	48.0	48.0	34.0
* 1.0	4.3	8.7	15.4	20.9	27.2	33.4	39.5	45.5	51.5	57.3	63.2	
750	1.7	3.2	6.3	10.6	15.1	19.1	22.9	26.9	30.0	32.9	32.9	22.4
* 1.0	3.2	6.3	10.7	14.5	18.7	22.6	26.5	30.3	34.0	37.7	41.3	
1000	1.5	2.6	4.9	7.9	11.0	14.1	16.9	19.8	22.0	24.0	23.8	16.2
* 1.0	2.6	4.9	7.9	10.8	13.7	16.4	19.1	21.6	24.1	26.6	28.9	
1250	1.3	2.2	4.0	6.2	8.3	10.6	12.6	14.6	16.1	17.5	17.5	12.4
* 1.0	2.2	3.9	6.1	8.3	10.4	12.3	14.2	15.9	17.5	19.5	20.9	
1500	1.2	2.0	3.3	4.9	6.6	8.2	9.5	10.8	11.9	13.0	13.0	9.7
* 1.0	1.9	3.2	4.9	6.5	8.0	9.4	10.7	11.9	13.1	14.3	15.4	
1750	1.2	1.7	2.7	3.9	5.0	6.2	7.2	8.1	9.0	9.7	9.7	7.8
* 1.0	1.7	2.7	3.9	5.2	6.3	7.3	8.2	9.1	9.9	10.7	11.5	
2000	1.1	1.5	2.3	3.2	4.0	4.7	5.5	6.3	7.0	7.6	7.7	6.3
* 1.0	1.5	2.3	3.2	4.2	5.0	5.7	6.4	7.0	7.6	8.1	8.7	

* CURVE FIT VALUES

REF* 2

MARTINELLI VALUES OF VOID FRACTIONS (RG) INCLUDING MODIFICATIONS

CURVE FIT EQUATIONS

$$\text{VOID FRACTION (RG)} = A_0 + A_1 X + A_2 X^2 + A_3 X^3$$

WHERE*

FOR QUALITY 0 X .01

$A_0 = A_1 = A_2 = A_3 = 0$ (STDY3 PROGRAM USES FOG FLOW MODEL)
 (FOR DENSITY IN THIS RANGE)

FOR QUALITY .01 X .10

$$\begin{aligned} A_0 &= +.5973 - 1.275 \times 10^{-3} P + 9.019 \times 10^{-7} P^2 - 2.065 \times 10^{-10} P^3 \\ A_1 &= +4.746 + 4.156 \times 10^{-2} P - 4.011 \times 10^{-5} P^2 + 9.867 \times 10^{-9} P^3 \\ A_2 &= -31.27 - .5599 P + 5.580 \times 10^{-4} P^2 - 1.378 \times 10^{-7} P^3 \\ A_3 &= +89.07 + 2.408 P - 2.367 \times 10^{-3} P^2 + 5.694 \times 10^{-7} P^3 \end{aligned}$$

FOR QUALITY .10 X .90

$$\begin{aligned} A_0 &= +.7847 - 3.900 \times 10^{-4} P + 1.145 \times 10^{-7} P^2 - 2.771 \times 10^{-11} P^3 \\ A_1 &= +.7707 + 9.619 \times 10^{-4} P - 2.010 \times 10^{-7} P^2 + 2.012 \times 10^{-11} P^3 \\ A_2 &= -1.060 - 1.194 \times 10^{-3} P + 2.618 \times 10^{-7} P^2 - 6.893 \times 10^{-12} P^3 \\ A_3 &= +.5157 + 6.506 \times 10^{-4} P - 1.938 \times 10^{-7} P^2 + 1.925 \times 10^{-11} P^3 \end{aligned}$$

P = PRESSURE - PSI

FOR QUALITY .90 X 1.0

$A_1 = 1.0$ $A_0 = A_2 = A_3 = 0$ (STDY3 PROGRAM USES FOG FLOW MODEL)
 (FOR DENSITY IN THIS RANGE)

(CONTINUED)

MARTINELLI VALUES OF VOID FRACTIONS (RG) INCLUDING MODIFICATIONS

TABLE OF VALUES

PRESSURE PSI	QUALITY (X)										
	.010	.042	.10	.20	.30	.40	.50	.60	.70	.80	.90
100	.565	.717	.823	.887	.919	.939	.955	.968	.977	.986	.991
* .556	.714	.818	.877	.916	.942	.957	.967	.974	.982	.994	
250	.435	.656	.770	.849	.890	.914	.938	.953	.966	.977	.990
* .446	.665	.777	.845	.891	.921	.941	.954	.964	.975	.992	
500	.302	.595	.715	.808	.854	.887	.914	.934	.952	.968	.985
* .309	.586	.716	.798	.854	.893	.918	.936	.950	.966	.988	
750	.223	.513	.662	.768	.824	.864	.895	.921	.942	.962	.982
* .218	.512	.662	.757	.823	.867	.899	.920	.938	.958	.985	
1000	.170	.440	.617	.729	.797	.843	.878	.908	.931	.956	.978
* .162	.443	.614	.720	.794	.846	.882	.907	.928	.951	.982	
1250	.130	.375	.569	.690	.768	.820	.862	.894	.922	.950	.976
* .130	.379	.568	.684	.766	.824	.865	.894	.919	.945	.979	
1500	.106	.324	.514	.659	.739	.793	.843	.879	.912	.942	.972
* .111	.323	.521	.647	.737	.802	.847	.881	.909	.938	.976	
1750	.086	.270	.469	.621	.706	.767	.822	.864	.901	.936	.969
* .093	.273	.472	.608	.705	.776	.827	.865	.897	.931	.973	
2000	.068	.230	.415	.581	.670	.736	.796	.848	.890	.924	.965
* .064	.232	.417	.563	.668	.745	.802	.846	.884	.923	.970	

* CURVE FIT VALUES

REF* 2