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15

MASTER

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PROGRAM No. 302

A BOILING WATER ANALYSIS ON THE IBM - 650

ALCO

ALCO PRODUCTS, INC.
POST OFFICE BOX 414
SCHENECTADY, N. Y.

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ABWAC - MNC

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A BOILING WATER ANALYSIS CODE ON THE IBM - 650

AEC Contract No. AT(30-3)-326

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I. Beretsky
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ABSTRACT

A method has been developed for using the IBM 650 Electronic Data Processing Machine to obtain detailed information concerning thermal and hydraulic conditions within a plate type reactor channel when the coolant in the channel is present in both vapor and liquid phases.

I INTRODUCTION

The basic equations presented within this report are used to evaluate steady state thermal and hydraulic conditions that are present in a channel which has steam leaving the exit of such a channel. Equations are developed predicting the water temperature and surface temperature profiles along the axial length of the channel. Provision is made for determining the increased frictional resistance encountered in nucleate and bulk boiling. Property values of the coolant which are functions of temperature are evaluated as point functions, thus eliminating the use of average values. Finally, burnout equations as presented in reference (B) are used for obtaining the burnout ratios in this report.

II DESCRIPTION OF EQUATIONS

A. Water Enthalpy:

The water anthalpy at an axial position J is represented by

$$H(J) = Hw + \frac{q_{av} F_{q-eng} F_{cpp}(J)}{W} \qquad (1)$$

where Hw is the inlet enthalpy

B. Water Temperature:

1. For the condition when $H(J) \leq Hsat$, $Tw(J)$ is taken from supplied table of $T_W(J)$ vs $H(J)$. The table is made by supplying up to 20 pairs of temperature and enthalpy; the first entry being that of inlet conditions, the final entry saturation conditions.

2. For the condition when $H(J) > Hsat$, the water temperature equals Tsat. Therefore, a calculation of quality is made where

$$X = \frac{H(J) - Hsat}{H_{fg}} \qquad (2)$$

C. Mass Flow Rate:

$$G = \frac{144\ W}{dY} \qquad (3)$$

D. Forced Convection Single Phase Heat Transfer Coefficient:

$$H(J) = M \cdot F(J) \cdot K(J) \cdot \frac{(G)^{0.8}}{(d/6)^{0.2}} \qquad (4)$$

$$\text{where } K(J) = Kw \left\{ 1 + \alpha_1 \left(Tw(J) - Tw \right) \right\} \quad Tw \leq Tw(J) \leq Tsat \qquad (5)$$

and $Kw = \left(\frac{C_p \mu}{k}\right)^{0.4} \frac{k}{\mu^{0.8}}$ evaluated at the inlet water temperature, Tw. Therefore, the property values of water that effect the film coefficient are represented by a linear equation as shown in equation (5). M is a constant that would normally appear in the Dittus-Boelter equation. F(J) is a factor that can be used to account for increased values of the film coefficient along the axial position (J).

E. Surface Temperature:

General equation for Ts(J);

$$Ts(J) = Tw(J) + \frac{\phi(J)}{h(J)} \qquad (6)$$

$$\text{where } \phi(J) = q''_{av} \, Fq''_{eng} \, F_{RLP}(J) \qquad (7)$$

The value of $T_s(J)$ as calculated by equation (6) is constantly compared to a critical temperature represented by

$$Tc(J) = Tsat + Kcr \cdot \left\{ \phi(J) \right\}^{1/4} \qquad (8)$$

$$\text{where } Kcr = \frac{60}{10^{1.5}} \exp\left(-\frac{P}{900}\right) \qquad (9)$$

When the value of $Ts(J) < Tc(J)$, the surface temperature is given by equation (6). When the value of $Ts(J) \geq Tc(J)$, the value of the surface temperature is given by equation (8).

F. Isothermal Friction Factor:

The isothermal friction factor is described as $fiso = C_1 \left(\frac{dG}{6\mu}\right)^{-C_2}$ (10)

and μ is represented by a linear approximation as shown

$$\mu(J) = \mu_w \left\{ 1 + \mu_1 \left[T_w(J) - T_w \right] \right\} \quad T_w \leq T_w(J) \leq T_{sat} \qquad (11)$$

where μ_w is the viscosity of the coolant at temperature T_w.

G. Increase of Frictional Resistance:

1. Nucleate Boiling: (Subcooled Liquid)

This method uses the value of 1, e.g. $f(J) = fiso$, for subcooled liquid unless nucleate boiling is present and the bulk water temperature is greater than a fixed value.

$$\frac{f(J)}{fiso} = \begin{cases} 1 \; ; & T_w(J) < T_1 \\ 1 \; ; & T_w(J) \geq T_1 \text{ and } T_s(J) < T_c(J) \\ 1 + f_1 \left(\frac{T_w(J) - T_1}{Tsat - T_1} \right); & T_w(J) \geq T_1 \text{ and } T_s(J) \geq T_c(J) \end{cases} \qquad (12)$$

2. Bulk Boiling: (Saturated Liquid)

This method for computing bulk boiling friction forms a continuous function with the subcooled liquid calculations when a value of $1 + f_1$ is assigned to $(f(J)/fiso)$ for zero quality. This friction factor is used up to the quality at which the Martinelli-Nelson[(A)] two-phase friction factor becomes greater. Three linear approximations are then used to describe the variation of f(J)/fiso with quality:

$$f(J)/_{fiso} = \begin{cases} K_1 & 0 \leq X(J) < X_1 \\ K_2 + K_3X & X_1 \leq X(J) < X_2 \\ K_4 + K_5X & X_2 \leq X(J) < X_3 \\ K_6 + K_7X & X_3 \leq X(J) < X_4 \end{cases} \qquad (13)$$

H. Water Density:

Water density is represented by linear approximations as shown for temperatures below saturation and as a function of quality for a temperature at saturation. The approximation used is:

$$\rho(J) = \begin{cases} \rho_w \left\{1 - \epsilon_1 \left(T_w(J) - T_w\right)\right\} & T_w(J) \leq T_2 \\ \rho_2 \left\{1 - \epsilon_2 \left(T_w(J) - T_2\right)\right\} & T_2 < T_w(J) \leq T_{at} \\ (v_f + X v_{fg})^{-1} & H(J) \geq H_{sat} \\ & T = T_{sat} \end{cases} \qquad (14)$$

where ρ_w and Tw are the inlet water density and temperature, respectively.

I. Pressure Drop Equations:

1. The entrance loss is expressed as

$$\Delta P_{ent} = \frac{G^2(10^{-9})}{2g\,(1.867)} \frac{Ke}{\rho_w} \qquad (15)$$

where Ke is the entrance loss coefficient.

2. The exit loss is expressed as

$$P_{exit} = \frac{G^2 (10^{-9})}{2g\,(1.867)} \quad \frac{K_c}{\rho(L)} \qquad (16)$$

where Kc is the exit loss coefficient and $\rho(L)$ is the density $\rho(J)$ @ J = L, L being the total channel length.

The remaining pressure drops to be evaluated are that due to elevation, acceleration and frictional losses.

3. <u>Elevation Loss</u>:

$$\Delta P_e = \pm \int_0^Z \frac{\rho(Z)\, dZ}{1728} \qquad (17)$$

where Z is the channel length in inches up to a particular height. (+) is taken for up flow, (-) for down flow).

4. <u>Acceleration Loss</u>:

$$\Delta P_a = \frac{G^2(10^{-9})}{g(1.867)} \left\{ \frac{1}{\rho(Z)} - \frac{1}{\rho_w} \right\} \qquad (18)$$

which is the acceleration loss at same height Z.

5. <u>Frictional Pressure Drop</u>

a. $H(J) \leq H_{sat}$

$$\Delta P_f = \frac{G^2(10^{-9})}{4g\,d(1.867)} \cdot \int_0^{Z_1} \frac{(fiso)\left(\frac{f(Z)}{fiso}\right)}{\rho(Z)}\, dZ \qquad (19)$$

where Z_1 is the height where the water temperature is at saturation conditions.

b. $H(J) > H_{sat}$

$$\Delta P_f = \frac{G^2 f_{sat}\, v_f (10^{-9})}{4gd(1.867)} \cdot \int_{Z_1}^{Z} \left(\frac{f(Z)}{fiso}\right) dZ \qquad (20)$$

J. Burnout Equations (Burnout Ratio)

$$B = \frac{\phi_{b.o.}}{\phi(J)} = \begin{cases} \dfrac{F_c(J)\, R_1 \, \left(H(J)\right)^{\gamma_1}}{\phi(J)} \; ; & G < G_1 \\[2ex] \dfrac{F_c(J)\, R_2 \, \left[H(J)\right]^{\gamma_1}}{\phi(J)} \cdot \left\{1 + \dfrac{G}{10^7}\right\}^{\gamma_2} & G \geq G_1 \end{cases} \qquad (21)$$

where $F_c(J)$ is used to include local corrections for L/D_e effects present in these burnout equations.

III PROGRAM INSTRUCTIONS

A. Input Format

All input is in floating point form,* using the notation as shown on page 11.

The card sequence of the input deck must be maintained as shown in Tables Ia - Id.

Succeeding sets of imput will be operated on by the computer, provided each set is separated by a blank card.

The Enthalpy versus temperature table is entered on six cards according to the following format. A maximum of twenty entries is allowed. If less than twenty entries are used, the remaining fields in the table must be punced as zeroes. Entries must be listed in ascending order.

One complete input set will consist of cards 1 through 15 plus cards 16 through card number (15 + J) where J equals the number of axial positions taken along the channel length, and finally one blank card.

* Except as noted.

Table 1-a

BASIC PARAMETERS

Card No.	Word 1[1]	Word 2[2]	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
1	02 0091 0007[3]	W	d	Y	Ke	ρ_w	q_{av}	Kcr
2	02 0098 0007	F_{qeng}	Hw	Hsat	Hfg	Kw	α_1	μ_1
3	02 0105 0007	M	q"av	Fq"eng	ν_f	ν_{fg}	ρ_2	ϵ_2
4	02 0112 0007	ϵ_1	f_1	K_1	K_2	K_3	K_4	K_5
5	02 0119 0006	K_6	K_7	γ_1	γ_2	ΔZ	K_c	—

(1) A 12 punch required in columns 2 and 10 of every card.

(2) The sign of each entry must be punched, a high X for plus and a low X for minus.

(3) Word 1 of each card is fixed and must not be changed.

Table 1-b

ENTHALPY VS. WATER TEMPERATURE

Card No.	Word 1[1]	Word 2[2]	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
6	02 0051 0007[3]	H(J) 1	2	3	4	5	6	7
7	02 0058 0007	H(J) 8	9	10	11	12	13	14
8	02 0065 0007	H(J)15	16	17	18	19	20	Temp 1
9	02 0072 0007	Temp 2	3	4	5	6	7	8
10	02 0079 0007	Temp 9	10	11	12	13	14	15
11	02 0086 0005	Temp 16	17	18	19	20	—	—

Table 1-c

ADDITIONAL PARAMETERS

Card No.	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
12	02 0013 [4] 0000 [7]	Tsat [6]	02 0016 0000	Tw	02 0018 0000	μ_w	02 0020 0000	C_1
13	02 0021 0000	C_2	02 0029 0000	T_2	02 0030 0000	X_1	02 0032 0000	X_2
14	02 0033 0000	X_3	02 0034 0000	T_1	02 0036 0000	Flow [8]	02 0043 0000	G_1
15	02 0045 0000 [5]	R_1	02 0046 0000	R_2	01 0002 0000	J**	00 0000 0000	—

(4) A high X punch required in column 3 of every card.

(5) A low X required in column 10 of card number 15.

(6) Only the sign of negative values need be punched.

(7) Words 1, 3, 5 and 7 are fixed and must not be changed.

(8) If flow is up, this entry must be punched as 10 0000 0051 +

If flow is down punch entry as 10 0000 0051 -

** J must be entered in fixed point form i.e., 00 0000 00XX

A card, with the following format, must be punched for each axial position:

Table 1 -d

PARAMETERS DEPENDENT ON AXIAL POSITION (J)

Card No.	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
16	02 0010 0000	$F_{cpp}(1)$	02 0023 0000	$F_c(1)$	02 0025 0000	FRLP (1)	02 0042 0000	$F_c(1)$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
15+J		$F_{cpp}(J)$		$F_c(J)$		FRLP (J)		$F_c(J)$

(9) A low X punch required in every card in column 10.

(10) Only the sign of negative values need be punched.

(11) A high X punch required in column 3 of every card.

B. Output Format

All output is in floating point form as shown below.

Output can be in either one of two forms, dependent on the option desired.

(1) With the sign switch set to (+), output will be in the form shown in Table II-a.

(2) With the sign switch set to (-), output will be in the form shown in Table II-b.

C. Floating Point Number Form

Number form

.XXXXXXXXPP

XXXXXXXX - mantissa

PP - exponent, i.e. the power of 10 with 50 added.

Examples + .000345 = 3450000047 +

- 34.5 = 3450000052 -

D. Operating Instructions

1. Input Deck

(a) ABWAC program deck

(b) Input cards, each set followed by a blank card

2. 533 Read-Punch Unit

(a) Ready read feed with input deck

(b) Ready punch feed with blanks

(c) Insert IT-SOAP 533 Panel

3. 650 Console

(a) Set programmed switch to STOP

Set half-cycle switch to RUN

Set control switch to RUN

Set display switch to PROGRAM REGISTER

Set overflow switch to SENSE

Set error switch to STOP

(b) Set (70 1952 9999) $\pm$ in storage entry switches

(c) Set (1999) in Address selection switches

(d) Press computer reset key

(e) Press program start key on console

(f) Press start key on Read unit

(g) When read hopper empties, press end of file key

When the problem is completed, the machine will stop with (70 1976 1898) on the console.

To restart program, transfer manually to 1999

4. Calculation Time

Option 1

Time (minutes) $= \frac{13}{60}$ (N), where N = number of axial positions taken along the channel length.

Option 2

Time (minutes) $= \frac{16}{60}$ (N)

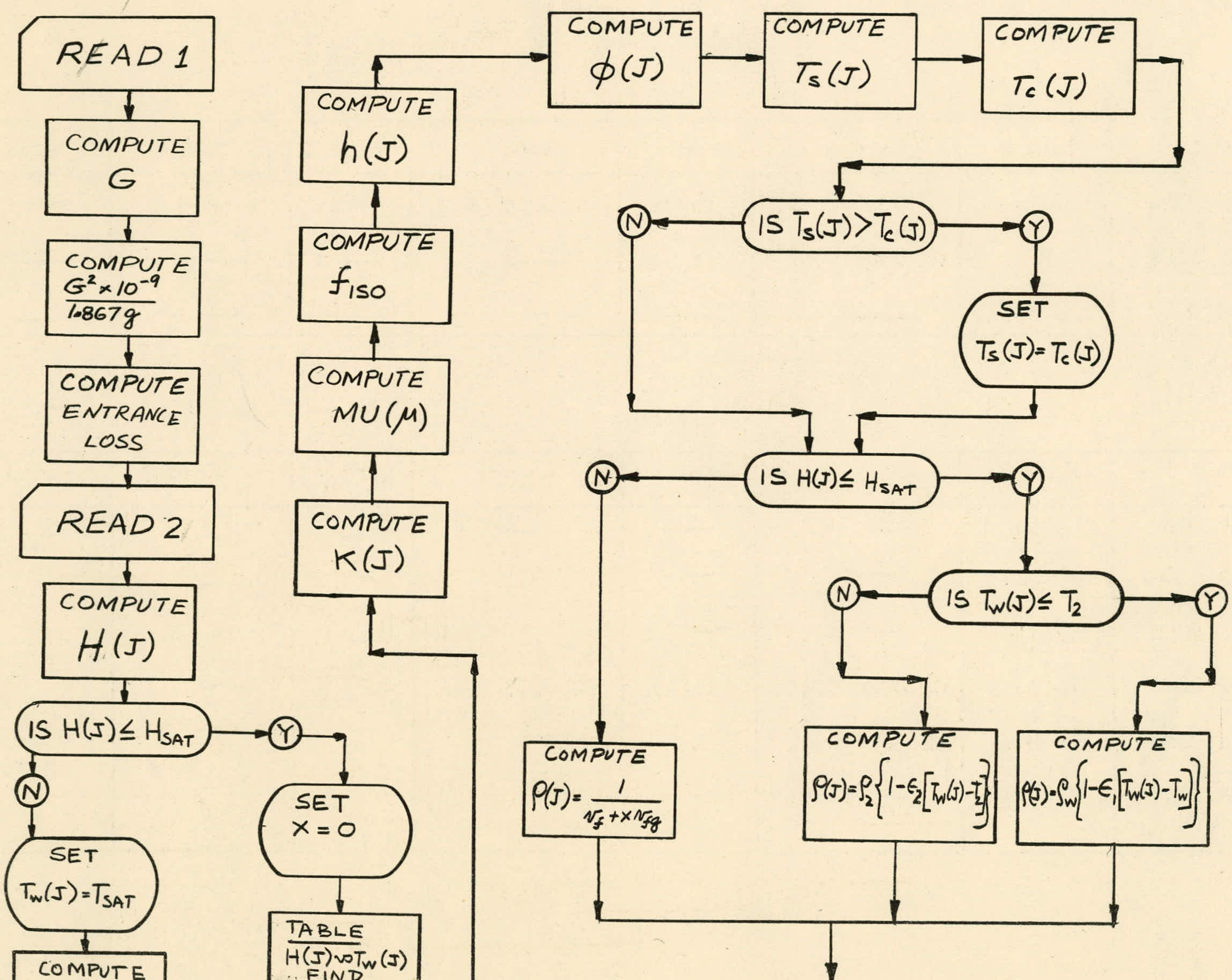
Table II-a

Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
02 0012 0044	Tw(J)	02 0026 0044	Ts(J)	02 0008 0044	Δ Ps	—	—
02 0044 0044	B	02 0007 0044	X	—	—	—	—
02 0008 0047	Δ P total	—	—	—	—	—	—

Table II-b

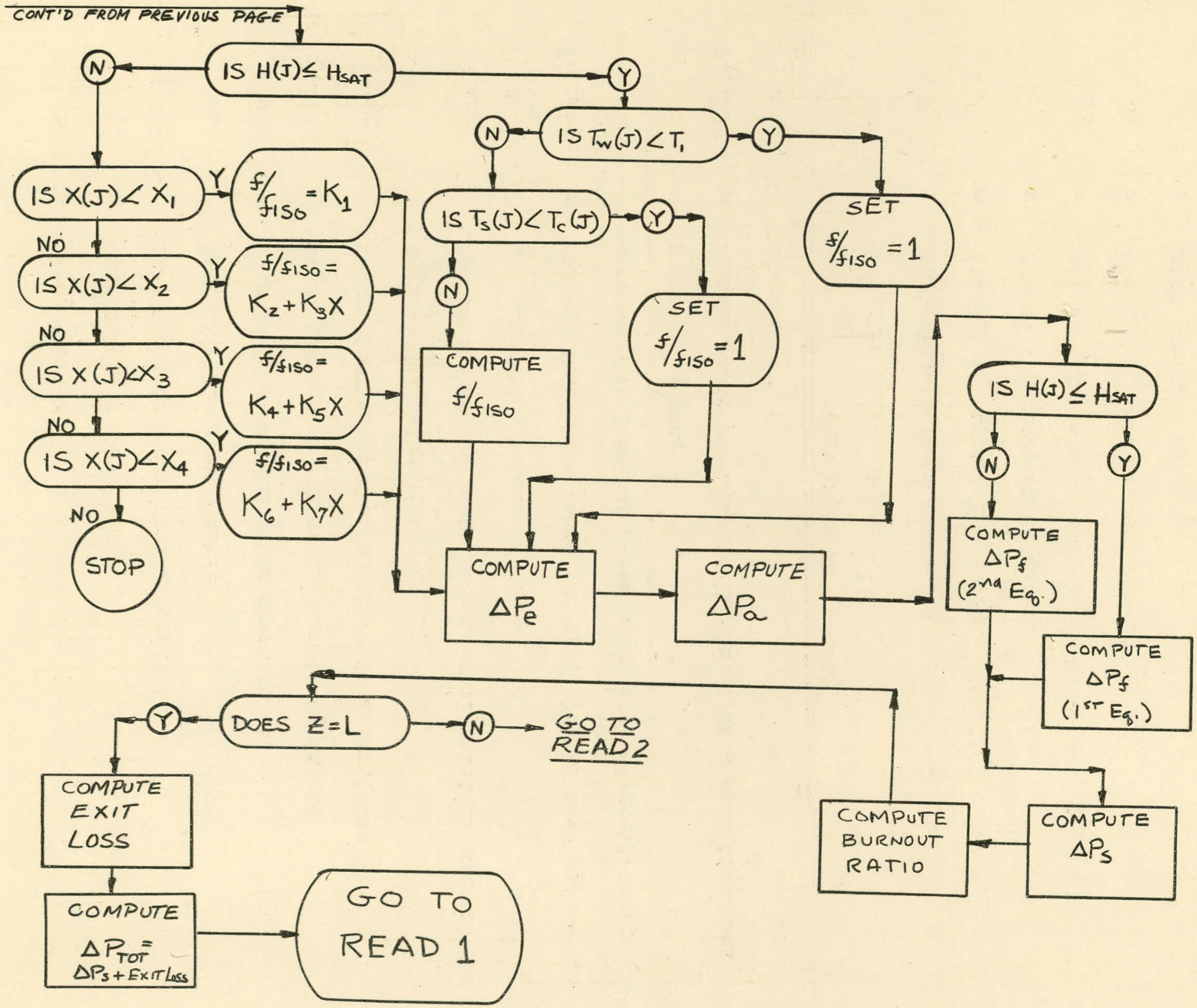
Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
02 0019 0000	fiso	—	—	—	—	—	—
02 0028 0000	ρ(J)	—	—	—	—	—	—
02 0031 0000	f/fiso	—	—	—	—	—	—
02 0012 0044	T_w(J)	02 0026 0044	Ts(J)	02 0008 0044	Δ P_s	—	—
02 0044 0044	B	02 0007 0044	X	—	—	—	—
02 0008 0047	Δ P total	—	—	—	—	—	—

FLOW CHART



CONTINUED ON NEXT PAGE

FLOW CHART


CONT'D FROM PREVIOUS PAGE
IS H(J) ≤ HSAT
N
Y
IS TW(J) < T1
IS X(J) < X1
f/fISO = K1
NO
IS X(J) < X2
f/fISO = K2 + K3X
IS X(J) < X3
f/fISO = K4 + K5X
IS X(J) < X4
f/fISO = K6 + K7X
STOP
IS TS(J) < TC(J)
SET f/fISO = 1
COMPUTE f/fISO
SET f/fISO = 1
IS H(J) ≤ HSAT
COMPUTE ΔPe
COMPUTE ΔPa
COMPUTE ΔPf (2nd Eq.)
COMPUTE ΔPf (1st Eq.)
DOES Z = L
GO TO READ 2
COMPUTE EXIT LOSS
COMPUTE BURNOUT RATIO
COMPUTE ΔPS
COMPUTE ΔPTOT = ΔPS + EXIT LOSS
GO TO READ 1

APPENDIX 1

NOMENCLATURE

B	=	Burnout Ratio
C_p	=	Specific heat Btu/lb°F
C_1, C_2	=	Isothermal friction factor constants
D_e	=	Hydraulic diameter, inches
$F(J)$	=	Film coefficient factor in equation (4)
$F_c(J)$	=	Local correction factor in Burnout equations
F_{qeng}	=	Factor applied to heat addition to channel due to engineering tolerances
Fq''_{eng}	=	Factor applied to heat flux at local point in channel due to engineering tolerances
$F_{cpp}(J)$	=	Maximum cumulative power per unit length developed up to a particular level of a specified fuel element/average power of reactor
$F_{RLP}(J)$	=	Maximum power at a particular level of a specified fuel element / Average power of reactor
G	=	Mass flow rate, lb/hr-ft^2
G_1	=	Constant in Burnout equations
$H(J)$	=	Enthalpy at any axial position, Btu/lb
H_{fg}	=	Heat of vaporization of water, Btu/lb
H_{sat}	=	Enthalpy of fluid at saturated conditions, Btu/lb
H_w	=	Enthalpy of inlet water, Btu/lb
J	=	Axial position notation
$K(J)$	=	Point value of film coefficient property values as indicated in equation (5)

NOMENCLATURE (Con't)

K_W	=	Constant in equation (5)
K_{CR}	=	Constant in equation (8)
K_e	=	Entrance loss coefficient
K_c	=	Exit loss coefficient
K_1-K_7	=	Constants in bulk boiling friction factor equations
L	=	Total channel length, ft.
M	=	Constant in equation (4)
P	=	Pressure, lb/in^2
ΔP	=	Pressure drop, lb/in^2
R_1, R_2	=	Constants in burnout equation
T_1	=	Constants in nucleate boiling friction factor equation, °F
T_2	=	Constants in density equation, °F
$T_W(J)$	=	Water temperature, °F
$T_s(J)$	=	Surface temperatre, °F
$T_c(J)$	=	Critical temperature, °F
W	=	Flow rate, lb/hr
Y	=	Channel width, inches
Z	=	Channel height at any particular level, inches
ΔZ	=	Basic increment for division of channel for finite difference calculation (Node Length), inches
d	=	Channel gap, inches
exp	=	Denotes exponent to base e
f(J)	=	Friction factor
fiso	=	Isothermal friction factor

NOMENCLATURE (Con't)

f_{sat}	=	Isothermal friction factor at saturated liquid conditions
f_1	=	Constant in friction factor equation
g	=	Gravitational constant, ft/sec^2
$h(J)$	=	Film coefficient, single phase $Btu/hr\text{-}ft^2\text{-}^oF$
k	=	Thermal conductivity of water, $Btu/hr\text{-}ft\text{-}^oF$
q_{av}	=	Average heat addition to channel, Btu/hr
q''_{av}	=	Average heat flux to channel, $Btu/hr\text{-}ft^2$
v_f	=	Specific volume of liquid at saturation, ft^3/lb
v_{fg}	=	Difference in specific volume of liquid between vapor and liquid, ft^3/lb
X	=	Steam quality
$X_1\text{-}X_4$	=	Constants in bulk boiling friction factor equations
α_1	=	Constant in equation (5)
ϵ_1, ϵ_2	=	Constants in density equation (14)
γ_1, γ_2	=	Constants in burnout equation (21)
$\mu(J)$	=	Viscosity of liquid, lb/ft-hr
μ_w	=	Viscosity of liquid at T_w, lb/ft-hr
μ_1	=	Constant in equation (11)
$\rho(J)$	=	Density of liquid, lb/ft^3
ρ_w	=	Density of liquid at inlet conditions, lb/ft^3
ρ_2	=	Constant in equation (14)
$\phi(J)$	=	Actual heat flux, $Btu/hr\text{-}ft^2$
$\phi_{b.o.}$	=	Burnout heat flux, $Btu/hr\text{-}ft^2$

APPENDIX 2

SAMPLE PROBLEM

A sample problem is presented showing both output and input. It should be noted that both are purely fictitious and merely indicate the format for input and output.

INPUT (In consistent units) See Format in Tables Ia - Id.

$W = 2 \times 10^4$	$v_f = 0.02485$	$T_{sat} = 635.8$
$d = 0.1$	$v_{fg} = 0.02$	$T_w = 510.0$
$Y = 2.88$	$\rho_2 = 47.5$	$\mu_w = 0.333$
$K_e = 0.1$	$\epsilon_2 = 0.002$	$C_1 = 0.5$
$\rho_w = 50$	$\epsilon_1 = 0.001$	$C_2 = 0.25$
$q_{AV} = 1 \times 10^6$	$f_1 = 0.6$	$T_2 = 560$
$K_{CR} = 1.5$	$K_1 = 1.6$	$X_1 = 0.04$
$F_{qeng} = 1.725$	$K_2 = 1.1875$	$X_2 = 0.2$
$H_w = 499.2$	$K_3 = 10.3125$	$X_3 = 0.9$
$H_{sat} = 671.7$	$K_4 = 1.8357$	$T_1 = 560$
$H_{fg} = 463.5$	$K_5 = 7.0714$	$Flow = +1.0$
$K_w = 1$	$K_6 = 25.03$	$G_1 = 1 \times 10^6$
$\alpha_1 = 0.001$	$K_7 = -18.7$	$R_1 = 4 \times 10^9$
$\mu_1 = 0.001$	$\gamma_1 = -1.0$	$R_2 = 2 \times 10^9$
$M = 0.023$	$\gamma_2 = 2.0$	$N = 5$
$q''_{av} = 4 \times 10^5$	$\Delta Z = 0.5$	
$Fq''_{eng} = 2.00$	$K_c = 0.1$	

ENTHALPY VS. WATER TEMP. TABLE

	H(J)	Tw(J)
1	442.2	460
2	453.3	470
3	464.6	480
4	476.0	490
5	487.4	500
6	499.2	510
7	511.0	520
8	523.0	530
9	535.2	540
10	547.7	550
11	560.4	560
12	573.4	570
13	586.6	580
14	600.3	590
15	614.5	600
16	629.3	610
17	645.0	620
18	661.4	630
19	671.7	635.8
20	0	0

This particular problem N was equal to 5, and therefore, five axial position cards must be supplied.

(J)	F_{cpp}	F	F_{RLP}	F_c
1	0	2	5	1
2	1.125	1	4	0.9
3	2	1	3	0.8
4	2.625	1	2	0.7
5	3.00	1	1	0.6

OUTPUT See Format in Tables IIa - IIb.

J	T_w	T_s	ΔP	B	X	ρ	fiso	f/fiso
1	510.0	606.3	1.663	4.01	0	50.0	0.0187	1.000
2	587.03	669.2	6.358	3.77	0	44.9	0.0191	1.213
3	635.82	694.8	11.97	3.97	0	40.29	0.01936	1.600
4	635.82	689.2	17.90	4.82	0.1163	36.79	0.01936	2.386
5	635.82	670.0	22.98	7.91	0.1861	34.99	0.01936	3.106

P Total = 25.34 (Includes ΔP @$(J = 5) + \Delta P_{exit}$)

APPENDIX 3

BIBLIOGRAPHY

A. "Prediction of Pressure Drop During Forced Circulation of Water", R.C. Martinelli and D.B. Nelson. Trans. of ASME, Aug. 1948

B. WAPD-T-188 Westinghouse Electric Corp. January 31, 1958