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TITLE: TRAC HEAT TRANSFER

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I. INTRODUCTION

The purpose of this talk is to describe three parts of the TRAC heat transfer package, as shown in Fig. 1. First, the wall to fluid heat transfer coefficient (HTC) correlations and their selection logic are described. Second, the current gap conductance model is described and short-term and long-term improvements are discussed. Third, an improved reflood heat transfer model is described.

The TRAC-P1A[1] HTC correlations and gap conductance models are described and then the model corrections and improvements for TRAC-PD2 (previously called TRAC-P1A/MOD1) and subsequent code versions is outlined. In addition, heat transfer corrections given in the first TRAC newsletter are discussed.[2]

The generalized boiling curve and the various TRAC-P1A heat transfer regimes are shown in Figs. 2 and 3. The logic used for the selection of each regime is shown in Fig. 4. Figures 5-12 show the individual correlations used in each regime and also the methods used in splitting the heat transfer coefficients into liquid and vapor components. The critical heat flux (CHF) and minimum stable film boiling (T_{min}) correlations are discussed in Figs. 13-17 and 19-22. Figure 18 shows LOFT L2-3 peak clad temperature results for two T_{min} correlations. Figure 23-25 show the HTC changes in TRAC-NEWS1[2] and TRAC-PD2. The gap conductance models are shown in Figs. 26-28 and the new reflood heat transfer model implemented into TRAC-PD2 is shown in Figs. 29-36.

These models are discussed in detail in the following sections.

II. GENERALIZED BOILING CURVE

The heat transfer coefficients (HTC's) used in TRAC are obtained from a boiling curve constructed for the given set of fluid and wall conditions. The HTC correlations used in constructing this curve, Fig. 2, are coded in a subroutine named HTCOR and in a series of subroutines called by HTCOR. This package of subroutines is used for all conditions and in all components where HTC's are required.

A. HTC Selection Logic

Figure 4 shows a flow diagram of subroutine HTCOR. Before discussing the detailed selection of the heat transfer regimes available in TRAC-P1A, Fig. 3, several general comments can be made:

1) HTCOR is independent of the TRAC flow regime map,
2) the flow quality is used in the correlations, and
3) in HTCOR, the slip is set equal to 1.0 if any of the following conditions occur: $\alpha \leq .001$, the liquid velocity is zero, or if the slip is negative; that is, the slip is set equal to one in counter-current flow.

For a given set of conditions, the heat transfer coefficient is found in the following manner (See Fig. 4):

1) if $\alpha \geq .9995$, HTC is forced convection to vapor, Regime 6, Fig. 9,
2) if $\alpha < .9995$, the ICHF flag is examined. ICHF is a TRAC input variable. If ICHF=0, no CHF calculation is made and the HTC is calculated by using mixture equations, Regime 7, Fig. 10,
3) if ICHF $\neq$ 0, the boiling curve is examined. First, the two terms of the Chen correlation[3] are calculated. If the wall temperature is less than the liquid temperature or the wall temperature is less than the saturation temperature, the void fraction is checked to see if single phase liquid is present (Fig. 5) or condensation is occurring (Figs. 11, 12). If $\alpha < .05$, forced convection to single phase liquid is exists. Otherwise condensation exists,
4) if the wall temperature inequalities discussed in #3 do not exist (that is if TW $\geq$ TL and TW $\geq$ TSAT), the steady state input flag, ISTDY, is next checked. For steady state conditions, ISTDY=1, only Regime 2 (nucleate boiling and forced convection vaporization) can occur if Regime 1 does not exist. For transient conditions, the critical heat flux temperature is next calculated. The correlation(s) used depend upon the input variable ICHF (Fig. 13), except that ICHF=1 is always used in the vessel. For ICHF=1, the Zuber and Biasi correlations are used in the mass flux regions shown in Fig. 14. These correlations, which calculate the heat flux at CHF, QCHF, are shown in Figs. 15 and 16. The CHF temperature, TCHF, is found by iteration -- using the Chen correlation and QCHF. It should be noted that these correlations include subcooled effects,
5) if the wall temperature, TW, is less than TCHF, nucleate boiling exists, otherwise the minimum stable film boiling temperature (TMIN) is calculated in order to determine if transition or film boiling exists,

6) if TW < TMIN (it is already known that TW > TCHF), transition boiling exists, and

7) if TW > TMIN, film boiling exists.

D. Minimum Stable Film Boiling Temperature (TMIN)

The minimum stable film boiling temperature has a significant effect on TRAC results since it controls return to nucleate boiling. This is shown in the LOFT Nuclear Test results of Fig. 18.[4] The Tmin correlation used in TRAC-P1A is shown in Fig. 20 and in this equation Tmin is only a function of the liquid and wall properties and the liquid temperature.

A Tmin equation proposed for TRAC-PD2 is described in Figs. 21 and 22.[5,6] In addition to the physical properties, the Iloeje correlation depends on the equilibrium quality and the mass flux. Since the Iloeje Tmin increases with increasing G, it was proposed at the NRC workshop on Rewet Phenomena in Denver[7] that for G > 100,000 $\mathrm{lbm/hrft^2}$, G = 100,000 be used.

III. HTCOR ASSESSMENT

After TRAC-P1A was released, a number of organizations made calculations for situations that had not been previously examined, and these results indicated that discontinuities existed in the TRAC-P1A boiling curve. In addition several constants were found to be incorrect. The coding changes needed to correct these errors are described in Ref. 2. These problems led to a detailed examination of the TRAC heat transfer package. The examination was conducted by removing the heat transfer package from TRAC and running a small stand-alone computer program for a wide range of conditions. Curves were generated for the liquid and vapor heat transfer coefficients vs. the wall temperature, for the HTC's vs. the void fraction and for the critical heat flux vs. mass flux.

It was found that at G = 300 $\mathrm{kg/m^2s}$, a discontinuity exists between the two equations used in the Biasi equation.[8] This discontinuity results from Biasi's recommendation to always use one of the two equations below G = 300 and the maximum of the results of the two equations above G = 300. The recommendation was due to the fact that Biasi considered both QCHF and X to be unknowns and he wanted to avoid calculating qualities greater than 1.0. In TRAC-PD2 the maximum QCHF from the two equations is used for all values of G.

1604 060

In addition, it was found that the heat transfer coefficients were discontinuous between several regimes. The heat transfer coefficient correlation changes made as a result of this investigation and model additions and improvements made because of greater experience with an increasingly wide range of TRAC calculations are discussed in the next section.

IV. TRAC-PD2 HEAT TRANSFER CHANGES

Wall to fluid heat transfer correlation changes made between TRAC-NEWS1 and TRAC-PD2 are listed in Figs. 24 and 25. The following changes were made:

1) Since the experimental data used in obtaining the Chen and CHF correlations generally involved equilibrium data, the quality used in evaluating these correlations was changed from the flow quality to the equilibrium quality,

2) TRAC users have identified problems with the condensation equations (Figs. 11 and 12), and several consultants have suggested replacing the current equations with the Chen correction as indicated in Fig. 24,

3) As discussed above, a discontinuity exists in the Biasi equations at $G = 300\ kg/m^2s$ and this discontinuity has been removed,

4) TRAC-P1A uses only the homogeneous nucleation Tmin equation and this equation is not adequate to predict LOFT rewets. Therefore, the maximum of this equation and the Iloeje equation will be used in TRAC-PD2 if further assessment calculations confirm the accuracy of the Iloeje correlation. The maximum of the two equations is used since the Iloeje equation gives unrealistically low values of Tmin at low pressures,

5) TRAC-P1A did not allow the user to specify ZrO_2 at the clad outside,

6) Previous versions of the code set the CHF temperature equal to $T_{sat} + 5.0$ if the calculated T_{CHF} was less than $T_{SAT} + 5.0$. Some calculations showed that the heat transfer was nucleate boiling, whereas the data indicated that dryout had occurred. Therefore this coding was changed,

7) The high speed flow correction to the vapor HTC resulted in incorrect HTC's and is being deleted,

8) The discontinuity in the vapor heat transfer coefficients between the transition and film boiling regimes was corrected,

9) The Lineham and Grolmes subcooled boiling equation does not apply to conditions in which it was used. In addition the subcooling is accounted for in the CHF correlations (see Fig. 15). Therefore this equation was removed from the code,

10) Liquid natural convection correlations were not included in the code and these correlations have been added,

11) The Biasi and Bowring correlations due not apply over the entire mass flux range of interest in a reactor; and, therefore, only the combination of the Zuber and Biasi correlations (ICHF=1) is now available (ICHF=0 is still allowed), and

12) The TRAC-P1A calculations for LOFT L2-2 showed that the transition to convection to vapor (Regime 6) should occur at a void fraction lower than 0.9995 (see Fig. 4). In RELAP/MOD6 this transition occurs at $\alpha = .96$, based on the work of Hsu and Beckner.[9] Therefore, in order to insure a smooth boiling curve, linear interpolation was used for the heat transfer coefficients between the values calculated at $\alpha = .96$ and the values for $\alpha = 1.0$.

These changes, except for the Iloeje correlation, have been implemented into TRAC and are being assessed. The Iloeje correlation will be implemented if further assessment shows that it gives good agreement with data.

V. GAP CONDUCTANCE

TRAC gap conductance plans are shown in Fig. 26. As indicated in the figure, TRAC-P1A has a constant, input radial gas gap and the gap conductance changes during a transient only through the temperature effects on the gas thermal conductivity and through the radiative heat transfer term[1] (see Fig. 27).

An improved gap conductance model is being implemented into TRAC-PD2, and the FRAPCON[10] and FRAP-T[11] codes are planned for future implementation. The model to be used in TRAC-PD2 is discussed in detail in Ref. 12. The basic equation, boundary conditions, and assumptions for this model are shown in Fig. 28. The uncoupled, quasi-static approximation for the fuel rod mechanical equations in which the mechanical coupling term in the energy equation and the inertial term in the mechanical force balance are omitted, is used. By neglecting these terms it is assumed that the influence of the strains in the fuel and clad on the temperature distribution are small and that no vibrations due to the thermal stresses occur.

The fuel clad gap system is modeled in three regions: solid fuel, cracked fuel, and cladding. This simplified model is an improvement over the constant radial gas gap in TRAC-P1A and it will be implemented into TRAC and used until more detailed models are available.

VI. CONCLUSIONS AND FUTURE WORK

The conclusions from the TRAC-PD2 heat transfer changes are shown in Fig. 37. As indicated several errors were corrected and the boiling curve was made more continuous. New models were added to reflect the results of data comparisons made after TRAC-P1A was released. It should be noted, that the Iloeje correlation has not yet been implemented into TRAC-PD2. This will only be done if comparisons with additional data indicate that the Iloeje correlation gives good results.

Heat transfer changes and assessment intended for the immediate future are listed in Fig. 38. These items are discussed above in detail.

1604 063

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3. T. Bjornard and P. Griffith, PWR Blowdown Heat Transfer, Symposium on "The Thermal and Hydraulic Aspects of Nuclear Reactor Safety, Vol. 1, Light Water Reactors," ASME, 1977.

4. D. A. Mandell, A. C. Peterson, K. A. Williams, J. L. Creel, "TRAC Pre-test Calculations of LOFT Nuclear Test L2-3," to be presented at ANS Winter Meeting, San Francisco, November, 1979.

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12. S. W. Hatch and D. A. Mandell "An Improved Gap Conductance Model for the TRAC Code," Topical Meeting on Thermal Reactor Safety, Knoxville, TN, April 8-11, 1980 (Submitted for presentation).

Appendix A. NOMENCLATURE

c, c_p	specific heat
D_H	hydraulic diameter
g	acceleration of gravity
g_c	constant of proportionality
G,GM	mass flux
Gr	Grashof Number
h_L	liquid heat transfer coefficient
h_v	vapor heat transfer coefficient
h_{fg}	latent heat of vaporization
k, k_L, k_V, k_{TP}	thermal conductivity
Nu	Nusselt Number
P	pressure
P_c	critical pressure
Pr	Prandtl Number
Re	Reynolds Number
Tmin	minimum film boiling temperature
ΔTmin	Tmin - Tsat
T_w	wall temperature
T_c, TCRIT	critical temperature
T_L	liquid temperature
Tsat, T_s	saturation temperature
St	Stanton Number
u	radial displacement
x	flow quality
Xe	equilibrium quality
μ	viscosity
ρ	density
$\Delta\rho$	$\rho_L - \rho_V$
σ	surface tension, Stefan-Boltzmann constant in Figure 7
α	void fraction, coefficient of thermal expansion on gap conductance slides
ε	emissivity
ν	Poisson's ratio

SUBSCRIPTS

L	liquid
v	vapor
w	wall
f	saturated liquid
g	saturated vapor
TP	two phase
NC	natural convection
D-R	Dougall-Rohsenow
LSC	subcooled boiling
R	radiation
BROM	Bromley

TRAC HEAT TRANSFER

A. WALL/FLUID HEAT TRANSFER COEFFICIENT CORRELATIONS

B. GAP CONDUCTANCE

C. REFLOOD

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F. L. ADDESSIO

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FIGURE 1. TITLE

FIGURE 2. BOILING CURVE

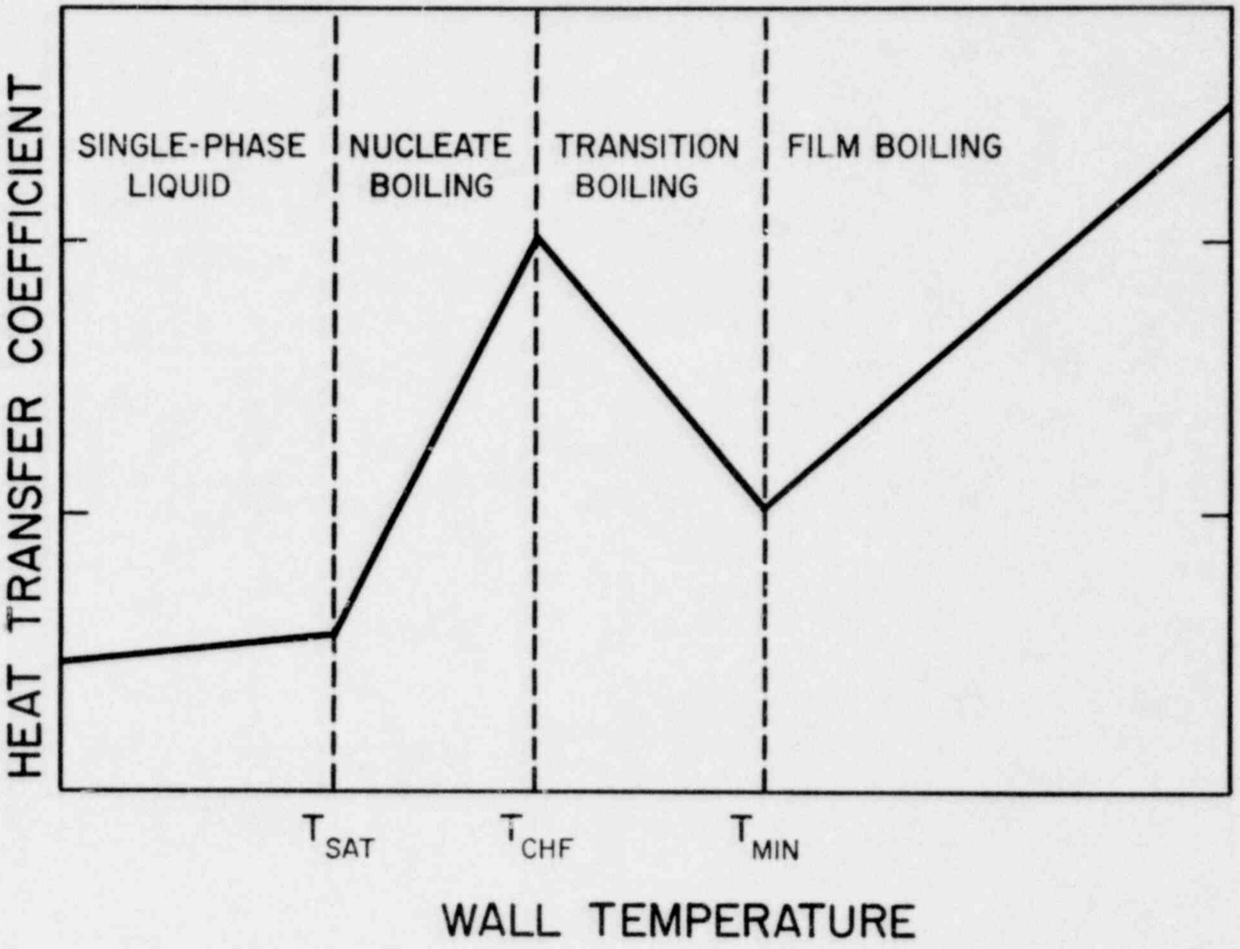

FIGURE 3. TRAC-P1A HEAT TRANSFER REGIMES

HEAT TRANSFER REGIME FLAG

IDREG (IDR)	HEAT TRANSFER REGIME
1	FORCED CONVECTION TO SINGLE PHASE LIQUID
2	NUCLEATE BOILING
3	TRANSITION BOILING
4	FILM BOILING
6	FORCED CONVECTION TO VAPOR
7	FORCED CONVECTION TO MIXTURE
11	CONDENSATION – HORIZONTAL
12	CONDENSATION – VERTICAL – LAMINAR
13	CONDENSATION – VERTICAL – TURBULENT

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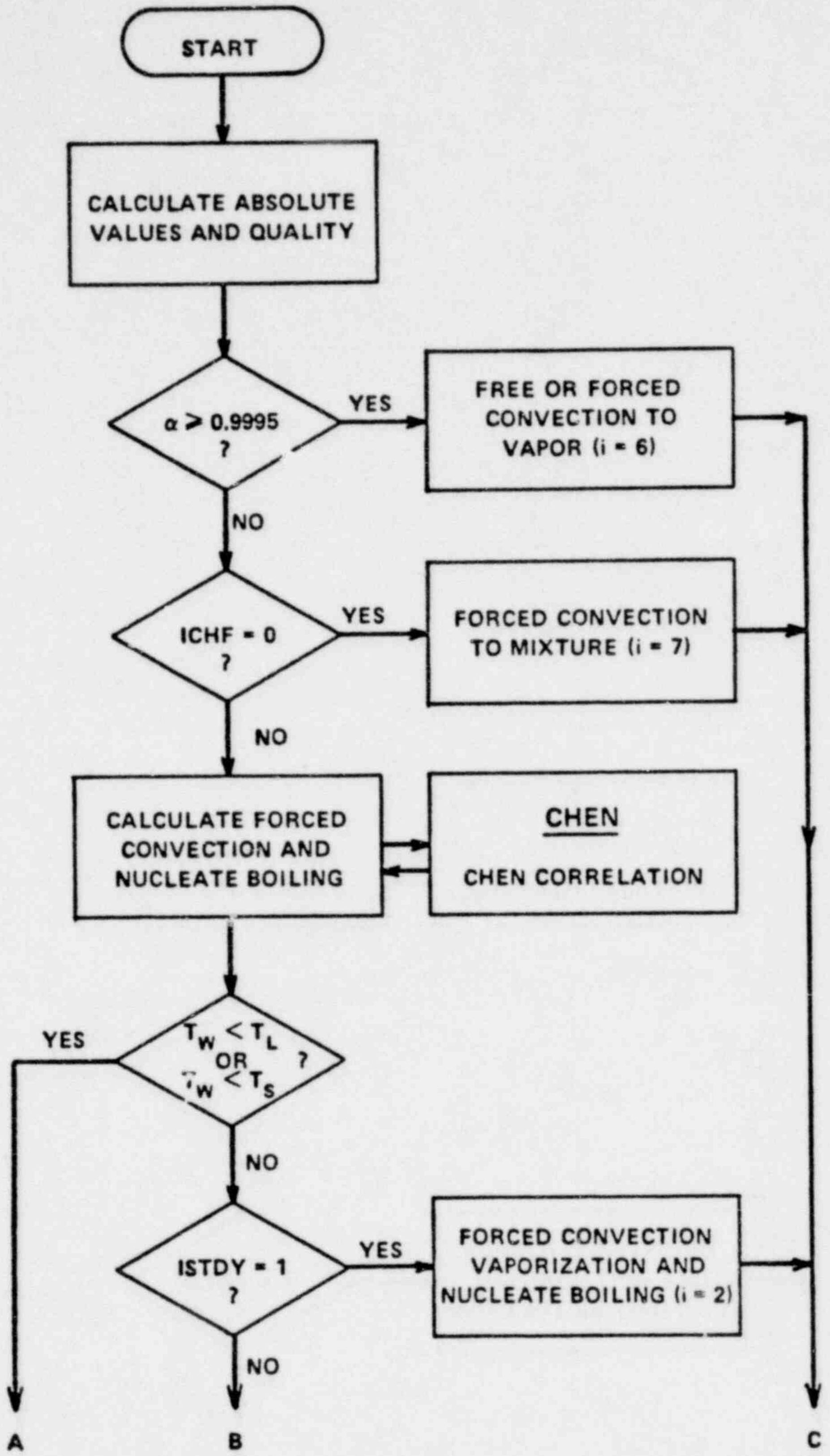


FIGURE 4. TRAC-P1A Heat transfer regime and correlation selection logic.

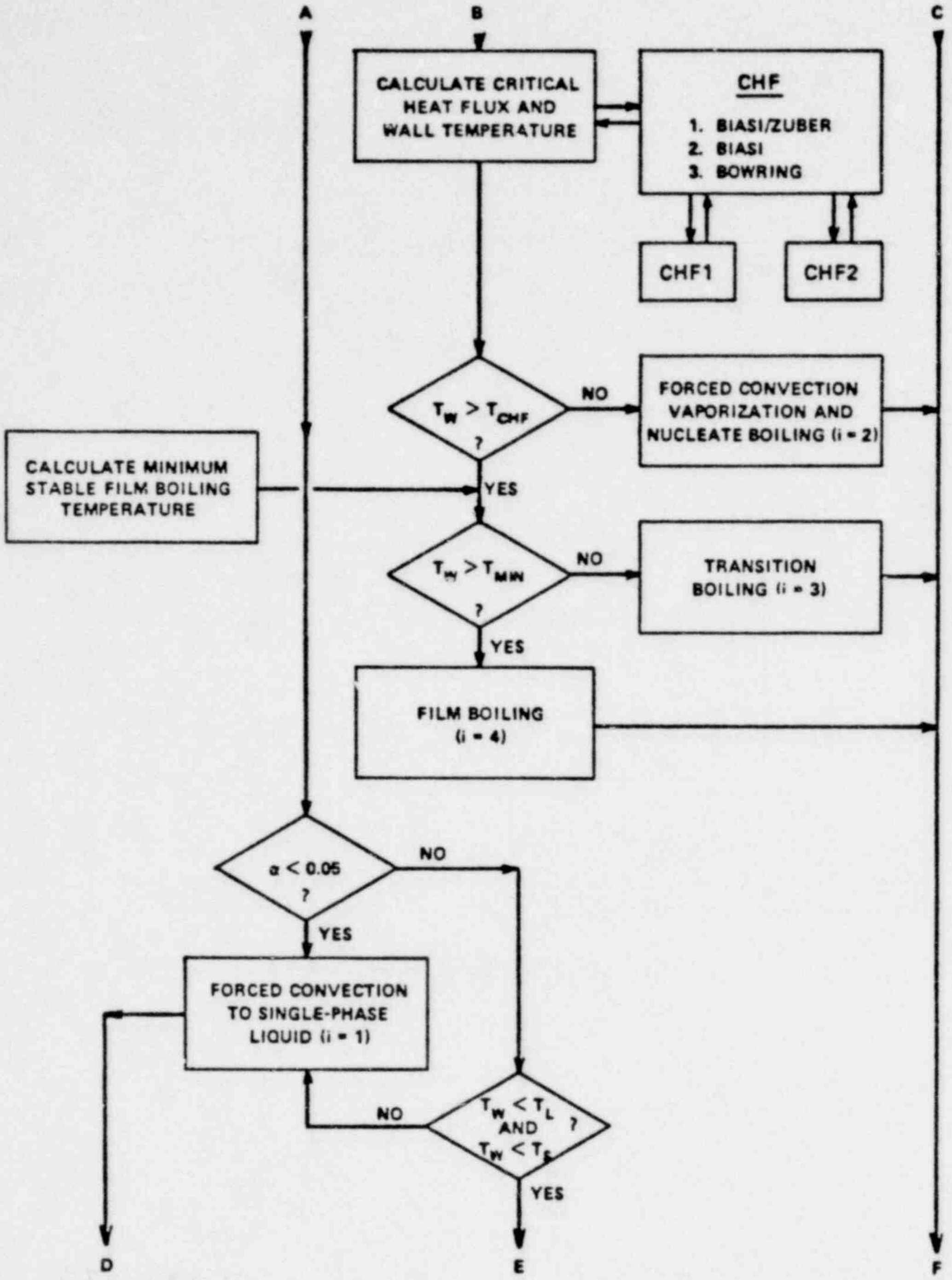
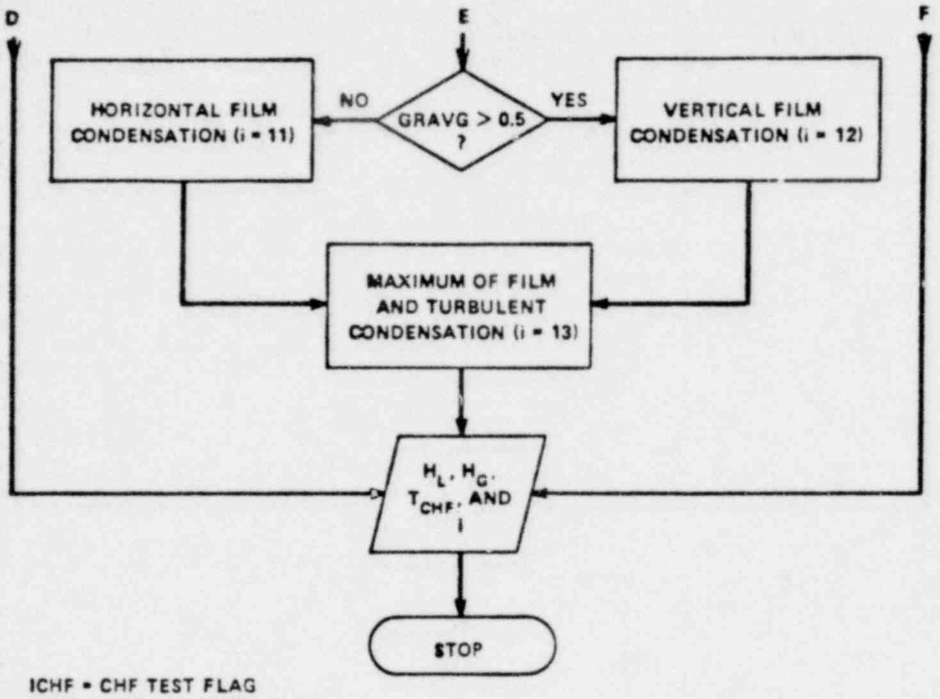


FIGURE 4. (CONTINUED)



ICHF = CHF TEST FLAG
ISTDY = STEADY STATE FLAG
GRAVG = $\overline{\cos\theta}$

FIGURE 4. (CONTINUED)

FIGURE 5. <u>HTCOR - REGIME 1</u>

FORCED CONVECTION TO LIQUID

$H_V = 0$

$H_L = MAX (H_{LAM}, H_{TURB})$

LAMINAR : NU = 4

TURBULENT: DITTUS - BOELTER

NOTES: 1) PROPERTIES EVALUATED AT T_L

2) NO NATURAL CONVECTION OPTION

FIGURE 6. HTCOR - REGIME 2

NUCLEATE BOILING - CHEN CORRELATION

$\alpha < .995$

$H_V = 0$

$$H_L = H_{FORC} + \text{MIN}\left(1, \frac{T_W - T_{SAT}}{T_W - T_L}\right) \cdot H_{NUCB}$$

$H_{FORC} = \text{MAX}\ (H_{LAM}, H_{TURB})$

RE INCLUDES CHEN F FACTOR

$$K_{TP} = \frac{1}{\frac{1-X}{K_L} + \frac{X}{K_V}}$$

ALL OTHER PROPERTIES AT T_L

FIGURE 6. (CONTINUED)

HTCOR - REGIME 2 CONTINUED

$\alpha \geq .995$

$$H_L = W_F \left[H_{FORC} + \text{MIN} \left(1, \frac{T_W - T_{SAT}}{T_W - T_L} \right) \cdot H_{NUCB} \right]$$

$$H_V = (1 - W_F) \text{ MAX } (H_{NC}, H_{TURB})$$

$$H_{NC} = .13 \, (GR_V \; PR_V)^{.333}$$

$$H_{TURB} = \text{DITTUS - BOELTER - VAPOR}$$

$$W_F = 1 - \frac{(\alpha - .995)}{.0045}$$

FIGURE 7. HTCOR - REGIME 3

TRANSITION BOILING

$$\gamma = \left(\frac{\mathrm{TW - TMIN}}{\mathrm{TCHF - TMIN}}\right)^2$$

$$H_{TB} = \frac{\gamma \cdot Q_{CHF} + (1 - \gamma) \cdot Q_{MIN}}{T_W - T_{SAT}}$$

$$H_L = H_{TB} + W_F(1 - \alpha) \left[H_R + H_{LSC} \, (T_{SAT} - T_L)/(T_W - T_L) \right]$$

$$H_V = W_F \, \alpha \, \mathrm{MAX} \, (H_{NC}, H_{D-R})$$

$$W_F = \frac{T_W - T_{CHF}}{T_{MIN} - T_{CHF}}$$

1604 076

FIGURE 7. (CONTINUED)

HTCOR - REGIME 3 CONTINUED

H_{LSC} = SUBCOOLED HTC

FROM: J. H. LINEHAN AND M. A. GROLMES, "CONDENSATION OF A HIGH VELOCITY VAPOR ON A SUBCOOLED LIQUID JET IN STRATIFIED FLOW", FOURTH INT. HEAT TRANS. CONF. PARIS, 1970

$$ST_L = \frac{NU_L}{RE_L\ PR_L} = .012$$

H_R = RADIATION HTC

$$= \sigma\varepsilon\ \frac{(T_W{}^4 - T^4{}_{SAT})}{T_W - T_{SAT}}\ .$$

FIGURE 8. HTCOR - REGIME 4

FILM BOILING

$$H_L = (1 - a)\left[H_R + H_{LSC}\frac{(T_{SAT} - T_L)}{T_W - T_L}\right]$$

$$H_V = (1 - a)\ \frac{(T_W - T_{SAT})}{T_W - T_V}\ H_{BROM}$$

$$+ a\ \text{MAX}\ (H_{NC}, H_{D-R})$$

IF $T_W - T_V > 0$

$$H_V = a\ \text{MAX}\ (H_{NC}, H_{D-R})$$

IF $T_W - T_V \leq 0$

1604 078

FIGURE 9. HTCOR - REGIME 6

FORCED CONVECTION TO VAPOR

$H_L = 0$

$H_V = \mathrm{MAX}\ (H_{NC}, H_{TURB})$

$NU_{NC} = .13\ (GR\ PR)^{.333}$

H_{TURB} = DITTUS - BOELTER - VAPOR

IF V_{VAPOR} 50 M/SEC

THEN HIGH-SPEED CORRECTION USED

$H_V = 0$ IF ADIABATIC WALL TEMPERATURE GREATER THAN T_W

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FIGURE 10. HTCOR - REGIME 7

OPTIONAL - USED IF ICHF = 0

FORCED CONVECTION TO MIXTURE

$\alpha < .995$

H_L = MAX (H_{LAM}, H_{TURB})

$NU_{LAM} = 4$

H_{TURB} = DITTUS - BOELTER

PROPERTIES EVALUATED AT T_L

EXCEPT $$\mu_M = \frac{1}{\frac{1 - X}{\mu_L} + \frac{X}{\mu_V}}$$

$H_V = 0$

FIGURE 10. (CONTINUED)

HTCOR - REGIME 7 CONTINUED

$\alpha \geq .995$

$H_L = W_F \text{ MAX } (H_{LAM}, H_{TURB})$

$H_V = (1 - W_F) \text{ MAX } (H_{NC}, H_{VTURB})$

$$W_F = 1 - \frac{(\alpha - .995)}{.0045}$$

IF $V_{VAPOR} > 50$ M/SEC, HIGH-SPEED CORRECTION

AGAIN USED

FIGURE 11. HTCOR - REGIMES 11, 13

FILM CONDENSATION IN HORIZONTAL PIPES

$$H_V = 0$$

$$H_1 = .296 \left[\frac{\rho_L \, (\rho_L - \rho_V) \cdot G \cdot H_{FG} \cdot K_L^3}{D_H \; \mu_L \, |T_W - T_{SAT}|} \right]^{.25}$$

IF $V_{VAPOR} = 0$ $\qquad H_L = H_1$

IF $V_{VAPOR} \neq 0$

$$H_2 = .065 \left[\frac{\rho_L K_L CP_L}{\mu_L} \right]^{\frac{1}{2}} \sqrt{T}$$

$$T = \frac{.046}{R_E^2} \; \frac{\rho_V v^2}{2}$$

$H_L = \text{MAX} \; (H_1, H_2)$

FIGURE 12. HTCOR - REGIME 12

LAMINAR FILM CONDENSATION IN VERTICAL PIPES

$$H_V = 0$$

$$H_L = 1.132 \left[\frac{\rho_L (\rho_L - \rho_V) G \cos\theta H_{FG} K_L^3}{D_H \mu_L \left| T_W - T_{SAT} \right|} \right]^{1/4}$$

FIGURE 13. CHF CORRELATIONS

ICHF = 0	NO CHF, REGIME 7 HTC'S USED
ICHF = 1	ZUBER/BIASI
ICHF = 2	BIASI
ICHF = 3	BOWRING

T_{CHF} FOUND BY ITERATING USING Q_{CHF} AND CHEN HTC CORRELATION

IF $T_{CHF} < T_{SAT} + 5.0$

T_{CHF} SET EQUAL $T_{SAT} + 5.0$

FIGURE 14. ICHF = 1, ZUBER/BIASI CHF

ALWAYS USED IN VESSEL
OPTIONAL IN OTHER COMPONENTS

VERTICAL FLOW ($\left|\overline{\cos\theta}\right| \geq .1$)

$-600 < G < 100 \ \frac{KG}{M^2S}$ ZUBER CHF

$G < -700$ OR $G > 200$
BIASI USED

G BETWEEN -600 AND -700
OR G BETWEEN 100 AND 200

LINEAR INTERPOLATION USED

NOTES: 1) ZUBER INCLUDES SUBCOOLED TERM
2) FLOW QUALITY USED

IF $\left|\cos\theta\right| < .1$, BIASI USED

FIGURE 15. ZUBER CHF CORRELATION

$$Q_{CHF} = (1-\alpha)\left[.131\ H_{FG}\ \rho_V\left(\frac{\sigma G(\rho_L-\rho_V)}{\rho_V^2}\right)^{.25} + Q_{SUB}\right]$$

$$Q_{SUB} = 2\ K_L\ \frac{(T_{SAT} - T_L)}{\left(\pi\ \mathbf{T}\ K_L/\rho_L C P_L\right)^{\frac{1}{2}}}$$

$$\text{IF } T_{SAT} - T_L > 0$$

$$Q_{SUB} = 0 \quad \text{IF } T_{SAT} - T_L \leq 0$$

$$\mathbf{T} = 2.625\left(\frac{\sigma}{G(\rho_L-\rho_V)}\right)^{\frac{1}{2}} \frac{1}{\left[\frac{\sigma G(\rho_L-\rho_V)}{\rho_V^2}\right]^{.25}}$$

FIGURE 16. BIASI CHF CORRELATION

$$Q_{CHF1} = F_1 \ (D,\ G) \ \left[F_2(P,G) - X\right]$$

$$Q_{CHF2} = F_3 \ (D,G,P) \ (1-X)$$

$$Q_{CHF2} = Q_{CHF} \quad \text{IF} \quad G \leq 300 \ \frac{KG}{M^2 S}$$

$$\text{OTHERWISE} \quad Q_{CHF} = MAX \ (Q_{CHF1},\ Q_{CHF2})$$

NOTE: X IS FLOW QUALITY

FIGURE 17. BOWRING CHF CORRELATION

$$Q_{CHF} = \frac{A - B\ H_{FG}\ X}{C}$$

$A = A\ (H_{FG}, D, G, P)$

$B = B\ (D, G)$

$C = C\ (D, G, P)$

NOTE: X IS FLOW QUALITY

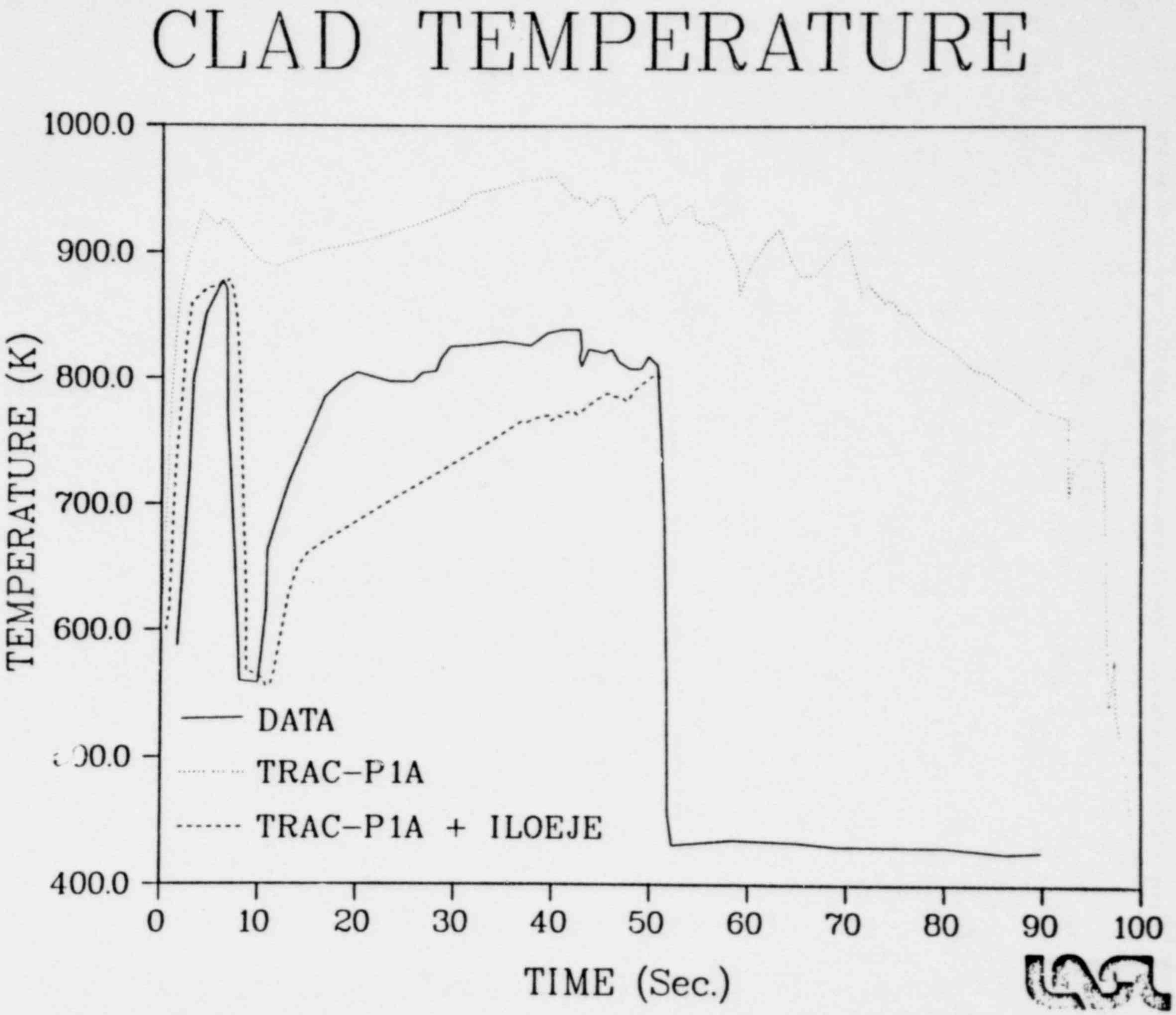

FIGURE 1 LOFT L2-3 Peak Clad Temperature

FIGURE 19.

MINIMUM STABLE FILM BOILING TEMPERATURE, T_{MIN}

TRAC–P1A CORRELATION: HOMOGENEOUS NUCLEATION

T_{MIN} = F (WALL AND LIQUID PROPERTIES)

ILOEJE CORRELATION :

T_{MIN} = F (PROPERTIES, G, X)

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FIGURE 20. MINIMUM STABLE FILM BOILING TEMPERATURE

TRAC - P1A:

$$T_{MIN} = T_{CRIT} + (T_{CRIT} - T_L) R^{.5}$$

$$R = \frac{K_L \rho_L CP_L}{K_W \rho_W CP_W}$$

FIGURE 21. MINIMUM STABLE FILM BOILING TEMPERATURE

ILOEJE, ET. AL.:

$$T_{MIN} = T_{SAT} + .29 \ \Delta T_{BER} \ \cdot$$

$$\cdot \ (1-.295 \ X_E^{2.45}) \left[1 + (G \ X10^{-4})^{.49}\right]$$

$$T_{BER} = .127 \ \frac{\rho_F}{K_F} \ H_{FG} \left(\frac{G(\rho_L - \rho_V)}{\rho_L + \rho_V}\right)^{2/3} \ \cdot$$

$$\cdot \left(\frac{G_C \ \sigma}{G(\rho_L - \rho_V)}\right)^{1/2} \left(\frac{u_F}{G(\rho_L - \rho_V)}\right)^{1/3}$$

PROPOSED T_{MIN}:

T_{MIN} = MAX (P1A, ILOEJE)

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FIGURE 22. ILOEJE et al. T_{min} CORRELATION

DATA BASE

$G = 40{,}000 - 100{,}000$ lbm/hr - ft^2

$= 54.2 - 135.6 \ \frac{kg}{m^2 s}$

$X_e = .3 - .8$

$P = 1000$ psia

$= 6.89 \times 10^6$ nt/m^2

Data Base for Iloeje Tmin Correlation

COMPARISON OF TRAC-P1A AND TRAC-NEWS1 HEAT TRANSFER

1) HTC BASED ON T_{SAT} SEVERAL PLACES INSTEAD OF T_L

2) ERRORS IN CONSTANTS IN CHF CORRELATIONS CORRECTED*

*TRAC NEWSLETTER NO. 1, JULY, 1979

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1604 094

FIGURE 23.

TRAC-PD2 HEAT TRANSFER CHANGES

1. USE EQUILIBRIUM QUALITY INSTEAD OF FLOW QUALITY IN CHF AND CHEN CORRELATIONS
2. REPLACE CONDENSATION HTC CORRELATIONS WITH CHEN CORRELATION, WITH THE SUPPRESSION FACTOR, S, ZERO
3. REMOVE 300 KG/M^{2}S EQUATION CUT-OFF IN BIASI
4. USE HOMOGENEOUS NUCLEATION AND ILOEJE T_{MIN}
5. ALLOW CLAD OUTSIDE TO BE ZRO_2
6. CHANGE $T_{CHF} = T_{SAT} + 5.0$ STATEMENT TO $T_{SAT} + 0.5$

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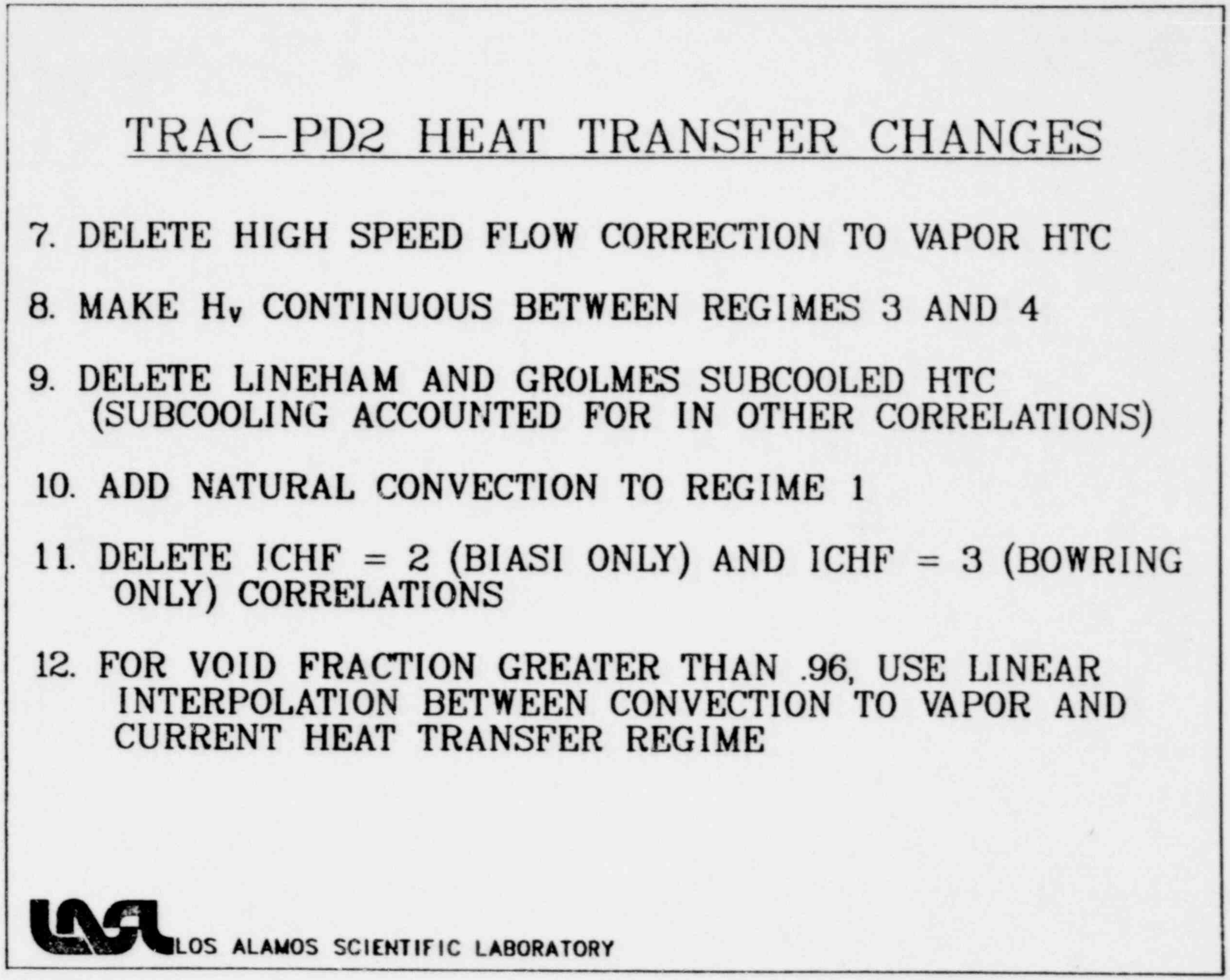
FIGURE 24.



TRAC-PD2 HEAT TRANSFER CHANGES

7. DELETE HIGH SPEED FLOW CORRECTION TO VAPOR HTC
8. MAKE H_v CONTINUOUS BETWEEN REGIMES 3 AND 4
9. DELETE LINEHAM AND GROLMES SUBCOOLED HTC (SUBCOOLING ACCOUNTED FOR IN OTHER CORRELATIONS)
10. ADD NATURAL CONVECTION TO REGIME 1
11. DELETE ICHF = 2 (BIASI ONLY) AND ICHF = 3 (BOWRING ONLY) CORRELATIONS
12. FOR VOID FRACTION GREATER THAN .96, USE LINEAR INTERPOLATION BETWEEN CONVECTION TO VAPOR AND CURRENT HEAT TRANSFER REGIME

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FIGURE 25.

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TRAC GAP CONDUCTANCE

TRAC-P1A:

- FUEL/CLAD GAP CONSTANT

SHORT-TERM:

- THERMAL EXPANSION MODEL
    - UNCOUPLED, QUASI-STATIC APPROXIMATION
    - TWO FUEL REGIONS - UNCRACKED AND CRACKED + CLAD

LONG-TERM:

- FRAPCON FOR STEADY STATE
- FRAP-T FOR THE TRANSIENT

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FIGURE 26.

TRAC-P1A GAP CONDUCTANCE MODEL

$$H_{GAS} = K_{GAS} / (\Delta r + \delta)$$

K_{GAS} = GAS THERMAL CONDUCTIVITY

δ = MEAN FUEL ROUGHNESS (4.4E-6)

Δr = RADIAL GAS GAP THICKNESS

THE RADIAL GAS GAP THICKNESS REMAINS CONSTANT THROUGHOUT A RUN.

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FIGURE 27.

SHORT–TERM SOLUTION
UNCOUPLED QUASI–STATIC EQUATION OF MOTION

$$\partial^2 u/\partial r^2 + r^{-1}\partial u/\partial r - u/r^2 =$$

$$\alpha(1. + \nu)/(1. - \nu)\ \partial T/\partial r$$

BOUNDARY CONDITIONS AND ASSUMPTIONS :

1. ZERO TRACTIONS AT BOUNDARIES
2. AXIAL EXPANSION IS ALLOWED
3. PLAIN STRAIN IS ASSUMED

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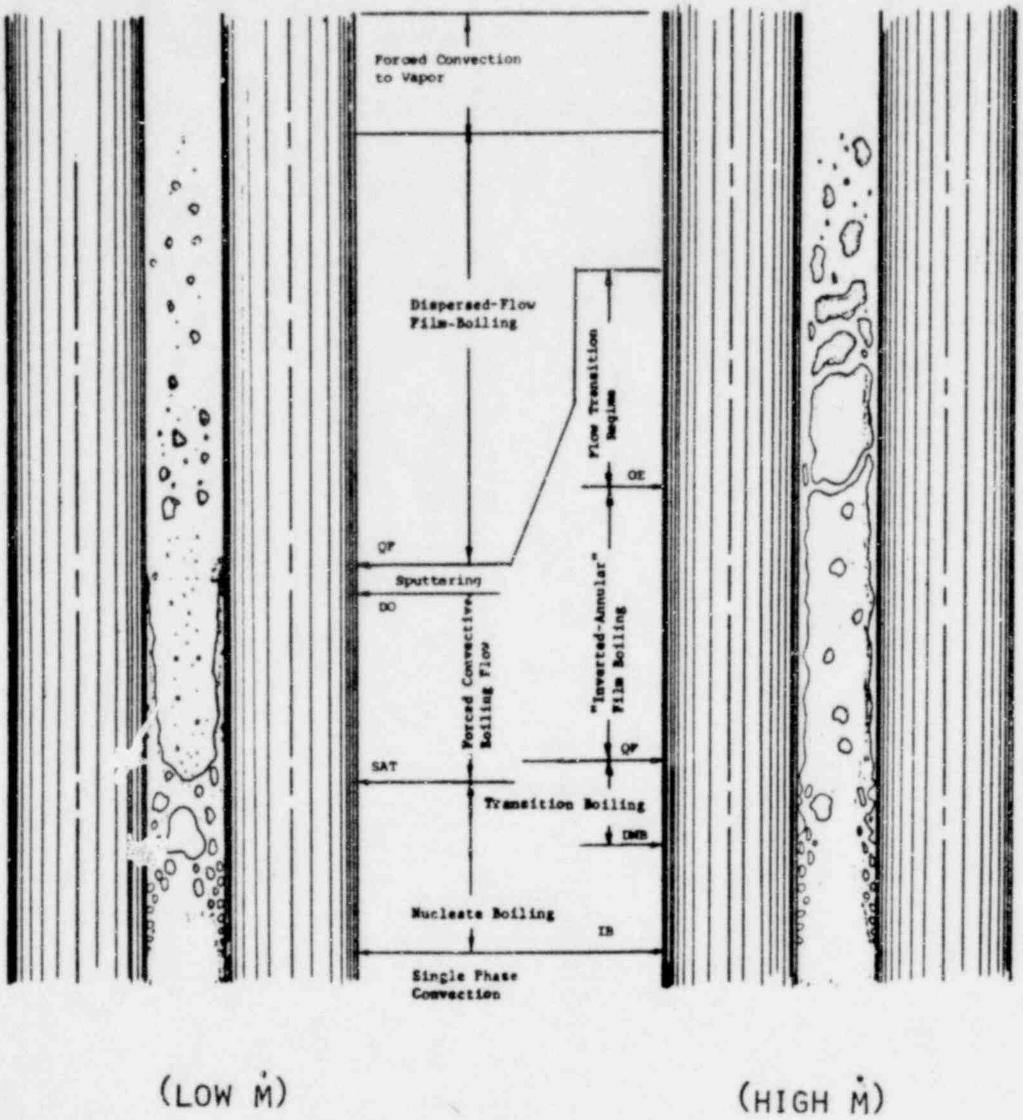
FIGURE 28.

FIGURE 29. QUENCH FRONT PROPAGATION



- NARROW REWETTING REGION (~1 MM)
- LARGE HEAT FLUXES
- AXIAL CONDUCTION
- QUENCH FRONT VELOCITY <u>NOT</u>, IN GENERAL, CONSTANT
- PRE-COOLING (I.E., CONVECTION & RADIATION TO DROPLETS)
- LAGRANGIAN QF MOTION
- MULTIPLE QUENCH FRONTS

FIGURE 30. TRAC MODIFICATIONS

- Improved Rod Conduction Model
- Removed QF Propagation Correlation
- Internal Fine Mesh Logic
- Multiple Quench Fronts

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FIGURE 31. CONDUCTION MODEL

- 2 - D (r, z) Conduction
- General Formulation
  - Internal Heat Generation
  - Metal-Water Reaction
  - Gap Conductance
  - Variable Rod Properties
- Difference Eqs. Conservative
- Axial-Differencing Explicit
- Radial-Differencing Implicit
- Coupling with Fluid Eqs. Semi-Implicit

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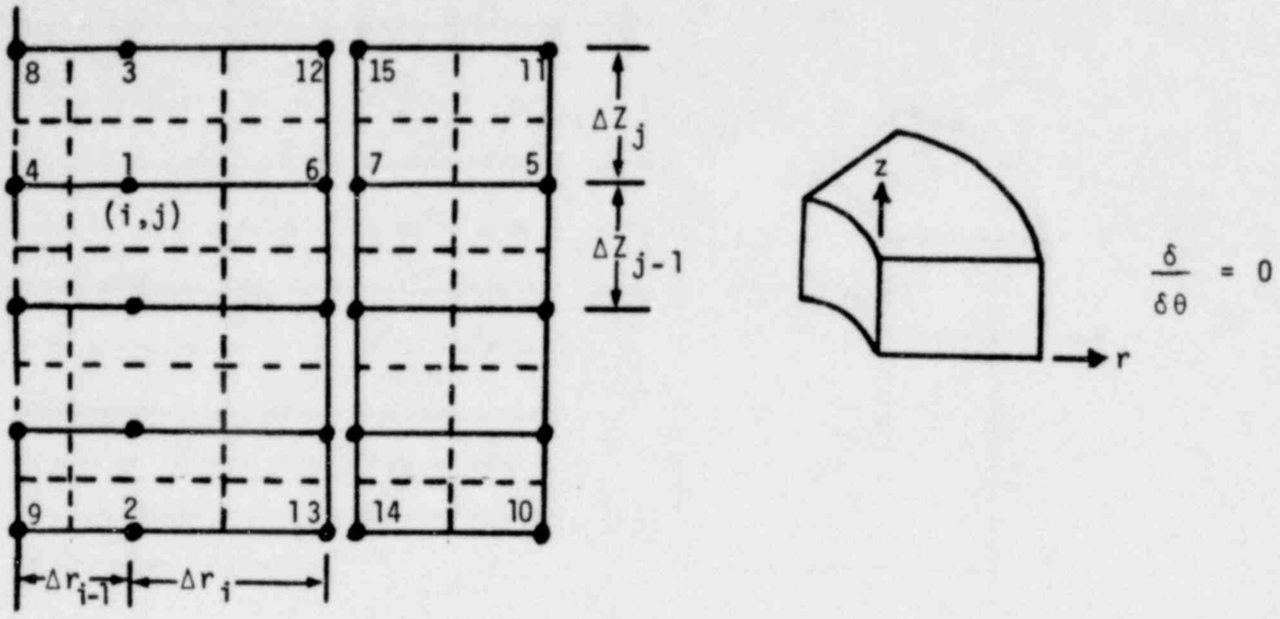
FIGURE 32. DIFFERENCE CONDUCTION RELATIONS



$$\iiint \frac{\delta(\rho e)}{\delta t}\, d\nu = \iiint \dot{q}'''\, d\nu + \oint\!\!\oint (\vec{n} \cdot \vec{q})\, dS$$

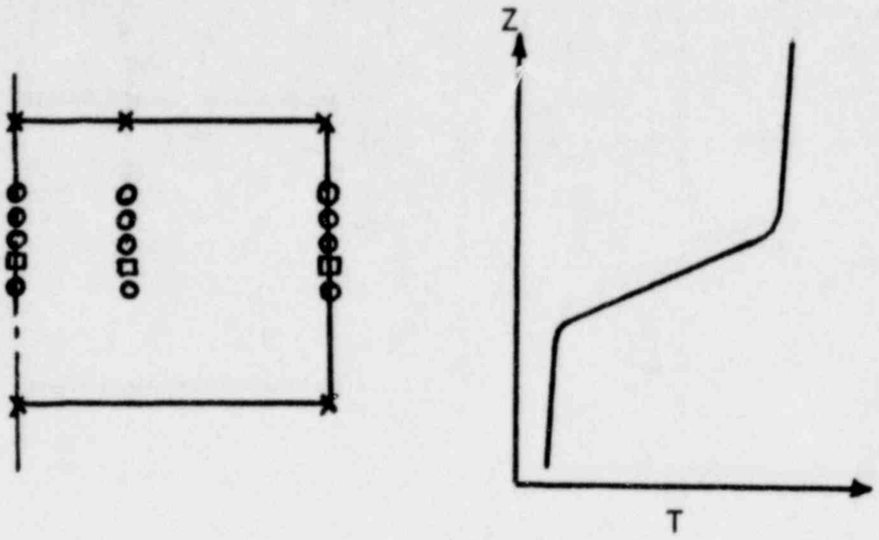
$$[\rho c]^n_{ij} \frac{T^{n+1}_{ij} - T^n_{ij}}{\Delta t} = \dot{q}'''^{\,n}_{ij}$$

$$+ \frac{r_{i+\frac{1}{2}}\, k_{i+\frac{1}{2}}}{r_i\, \frac{1}{2}(\Delta r_i + \Delta r_{i-1})} \; \frac{T^{n+1}_{i+1,j} - T^{n+1}_{i,j}}{\Delta r_i}$$

$$+ \frac{r_{i-\frac{1}{2}}\, k_{i-\frac{1}{2}}}{r_i \frac{1}{2}\, (\Delta r_i + \Delta r_{i-1})} \; \frac{T^{n+1}_{i-1,j} - T^{n+1}_{ij}}{\Delta r_{i-1}}$$

$$+ \frac{k_{j+\frac{1}{2}}}{\frac{1}{2}(\Delta z_j + \Delta z_{j-1})} \; \frac{T^n_{i,j+1} - T^n_{ij}}{\Delta z_j} + \frac{k_{j-\frac{1}{2}}}{\frac{1}{2}(\Delta z_j + \Delta z_{j-1})} \; \frac{T^n_{i,j-1} - T^n_{ij}}{\Delta z_{j-1}}$$

FIGURE 33. FINE MESH NODING



x Original Nodes (permanent)

□ Nodes Added at the Start of Reflood (permanent)

o Nodes Added to Resolve the QF

ADDED IF $\Delta T \geq \Delta T_{MAX}$

DELETED IF $\Delta T \leq \Delta T_{MIN}$

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FIGURE 34. ROD PROPERTIES

• k, c_p, ϵ, ...	Computed from Property Routines only at Fluid Cell Boundaries
• k, c_p, ϵ, ...	Obtained between Cell Boundaries by Linear Interpolation
• h_ℓ, h_v	Computed from HTCOR at ALL Surface Nodes

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FIGURE 35. TRAC COMPARISON WITH DATA

(UC-Berkley Reflood Test 114)

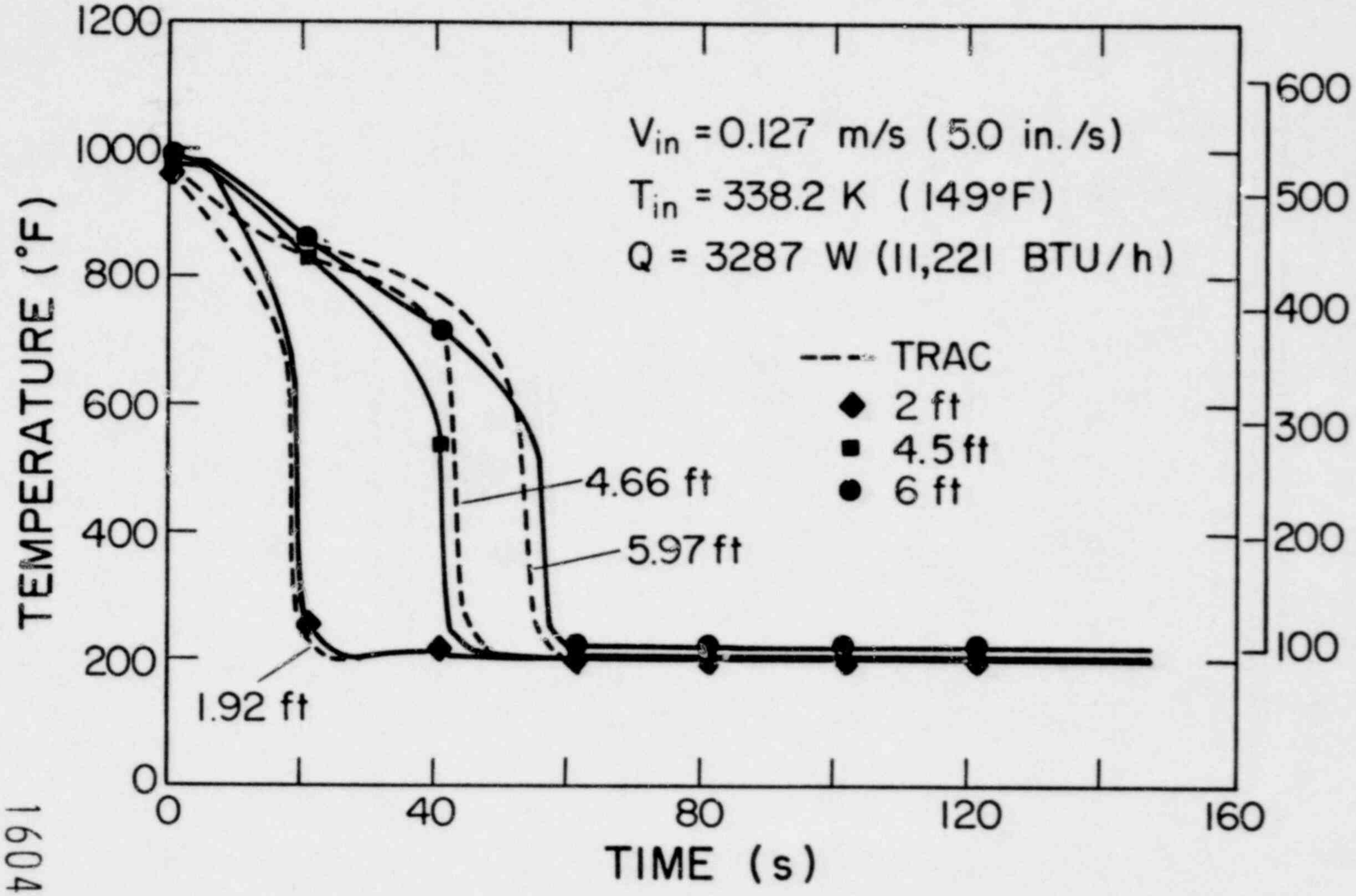

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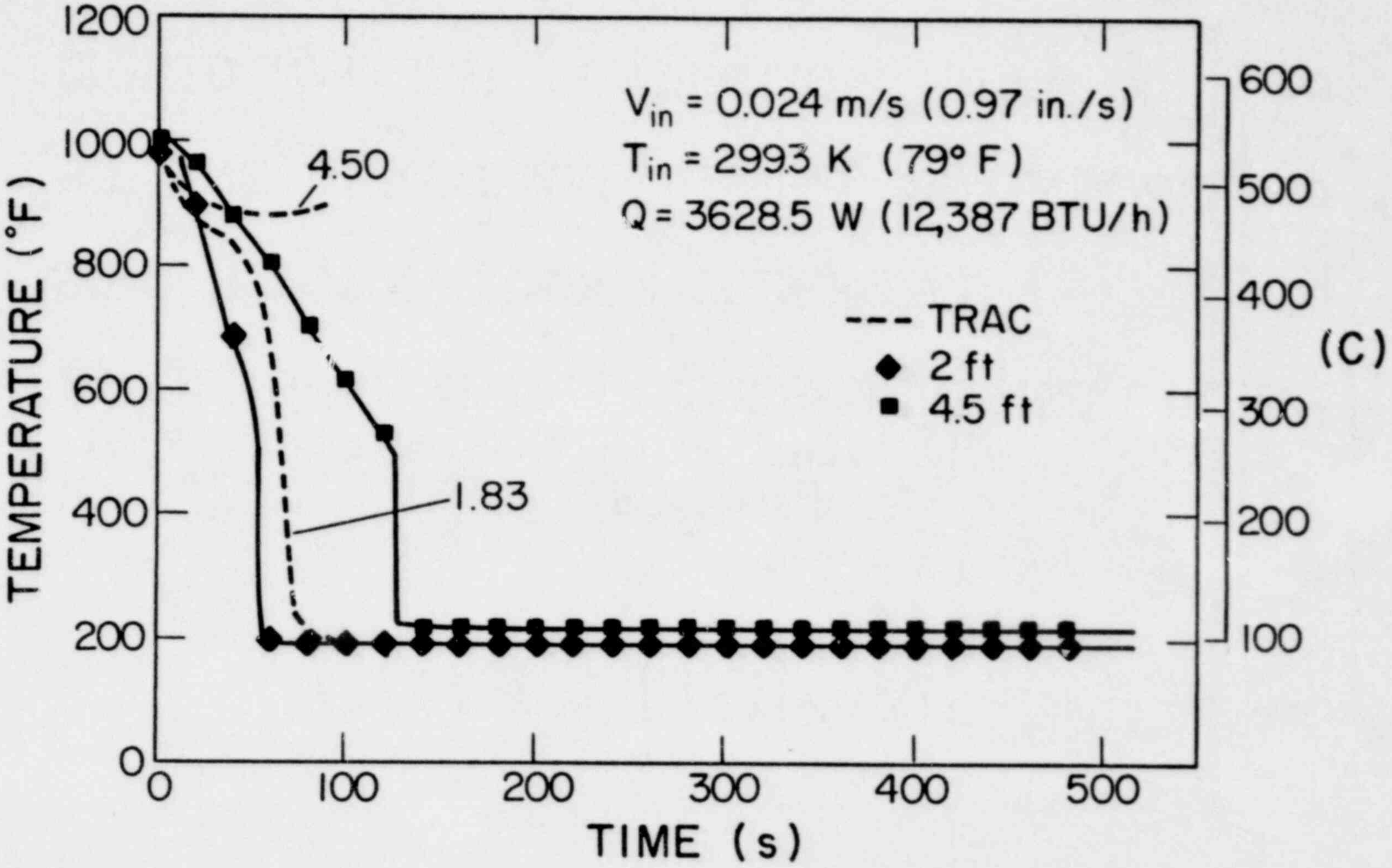
FIGURE 36. TRAC COMPARISON WITH DATA

(UC-Berkley Reflood test 187)



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CONCLUSIONS

* IOLEJE T_{MIN} IMPROVES LOFT DATA COMPARISON SIGNIFICANTLY (ADDITIONAL ILOEJE ASSESSMENT REQUIRED)
* SOME KNOWN ERRORS CORRECTED
* BOILING CURVE MADE MORE CONTINUOUS
* LIQUID NATURAL CONVECTION ADDED

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Fig. 37

FUTURE WORK

1. ADD BUNDLE CHF CORRELATION TO CODE

2. IMPROVE GAP CONDUCTANCE MODEL
    - * INTERIM MODEL
    - * FRAPCON/FRAP-T

3. ADDITIONAL ASSESSMENT
    - * ILOEJE CORRELATION
    - * NEW HEAT TRANSFER PACKAGE

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FIGURE 38.