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INTERIM REPORT

NRC Research and Technical
Assistance Report

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GENERAL ELECTRIC

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NUCLEAR ENERGY
ENGINEERING
DIVISION
Mail Code 583

May 21, 1980

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U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

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SUBJECT: BWR REFILL-REFLOOD PROGRAM
CONTRACT NO. NRC-04-79-184
INFORMAL MONTHLY PROGRESS REPORT FOR APRIL 1980

Gentlemen:

The following summarizes the subject matter covered in the attached report:

BWR/4 and 5 core spray distribution data evaluation continues and testing with an adiabatic bundle in the Single Heated Bundle Facility has been completed. These latter results will be used to assure the adequacy of steam injection planned to simulate heated bundles in the 30° Sector. Preliminary review of these data indicates a favorable outcome. Planning and design work continues on the 30°Sector facility modification. Additional progress in the model development area is reported including a review of the heat transfer correlations in TRAC and improvements to the numerics in the jet-pump model in TRAC.

Distribution of this report is being made in accordance with the "Monthly Distribution List" provided with W.D. Beckner's letter of September 6, 1979.

Very truly yours,

G.W. Burnett

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M/C 583, Telephone (408) 925-5375

cc: RG Bock

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NRC Research and Technical Assistance Report

BWR REFILL-REFLOOD PROGRAM

NINTH MONTHLY REPORT

APRIL 1980

Prepared For:

Division of Reactor Safety Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
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and

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General Electric Company

UNDER

Contract No. NRC-04-79-184

BWR REFILL - REFLOOD PROGRAM

APRIL -- 1980

SUMMARY

BWR/4 and 5 core spray distribution data evaluation continues and testing with an adiabatic bundle in the Single Heated Bundle Facility has been completed. These latter results will be used to assure the adequacy of steam injection planned to simulate heated bundles in the 30° Sector. Preliminary review of these data indicates a favorable outcome. Planning and design work continues on the 30° Sector facility modification. Additional progress in the model development area is reported including a review of the heat transfer correlations in TRAC and improvements to the numerics in the jet pump model in TRAC.

GENERAL

A PMG meeting was held in San Jose on April 16th and 17th, 1980. In addition to a number of administrative items technical review of progress was accomplished on each of the tasks listed below.

CORE SPRAY DISTRIBUTION

As reported last month, BWR/4 and 5 core spray distribution testing has been completed with good comparison to pre-test calculations. Data analysis and interpretation is continuing and the final test report is scheduled for completion in July.

SINGLE HEATED BUNDLE (TASK 4.3)

Stage 2 testing with the Lynn Adiabatic Bundle (LAB) has been completed. Tests were conducted to simulate the refill/reflood performance of average, high, and low power BWR fuel bundles with average ECC flows. At the request of the PMG, a LAB test was also included to simulate a high power, reduced ECC flow test to provide an alternate (extreme) set of conditions. Preliminary evaluation of the data indicates that adiabatic steam injection satisfactorily simulates the generation of steam resulting from heated bundles. The data show that the system refill/reflood response with the adiabatic bundle agrees well with that of a heated bundle, thus confirming the validity of using steam injection in the 30° Sector Steam Test Facility. Evaluation of the data is continuing.

The Stage 2 LAB test section is being disassembled and work is continuing on schedule for assembly of the Stage 3 Separate Effects Bundle (SEB). Appendix A discusses steam superheat measurements which have been added at the request of the PMG. A draft of the Stage 3 Task Plan will be available for PMG review during May. Stage 3 testing is scheduled to begin in July.

CCFL/REFILL SYSTEM EFFECTS [30° SECTOR] (TASK 4.4)

The task strategy and conceptual design approach were presented to the PMG at the April meeting. The facility design approach evaluation and optimization are continuing with respect to cost and schedule effectiveness. A preliminary calculation of the SSTF blowdown response was made using an existing drift-flux based system thermal hydraulic code. These predictions provide preliminary results for planning the initial fluid inventory and distribution within the system.

Preparation of a set of separate effect engineering calculations was initiated in support of the SSTF facility design and test matrix preparation. Preparation of data reduction specifications was also initiated. Design efforts continued in the areas of instrumentation (transducer selection and special probe design), process control (control valve sizing and selection), and loop design (process valve and sizing selection).

A reference design measurement plan for instrumentation in the vessel internals was defined and detail design work is in progress. Agreement was reached on coordinating design, fabrication, and procurement efforts between Lynn and San Jose.

MODEL DEVELOPMENT (TASK 4.7)

The Two-fluid version of TRAC with the CHAN component, which was developed by INEL, has been implemented on the CDC 7600 computer at GE.

BASIC MODELS AND CORRELATION (TASK 4.7.1)

The development and preliminary assessment of the constitutive correlations and basic models continued during this period, the main emphasis being on the heat transfer models. The subcooled boiling model for TRAC has been completed and a description of the model is being prepared. Enclosed as Appendix B is a review of the heat transfer correlations in TRAC. A modification to the radiation heat transfer model allowing for anisotropic reflections from the rod surfaces has been developed, and is being prepared for implementation into TRAC.

SINGLE CHANNEL CODE (TASK 4.7.2)

The development of the single channel code continued during this period. The effort was on the development of the storage capability of the boundary conditions for the single channel component. This feature is currently being debugged.

TRAC BWR SUPPORT (TASK 4.7.3)

The recent emphasis has been mainly on the development of a jet-pump model. For the intermediate jet pump model a modification to the momentum equations was developed, which gives a better calculation of pressure changes due to area changes. This allows the simulation of the jet-pump with fewer nodes. A description of this model is enclosed as Appendix C. The correlation of the mixing and other irreversible losses in the jet-pump continued during this period.

An analysis of the phenomena in the upper plenum has been initiated. The main effort is on the analysis of the penetration of a jet in a two-phase mixture and on turbulent shear in the upper plenum. The object is to determine the controlling phenomena for the macroscopic flow and temperature distributions in the upper plenum.

MODEL QUALIFICATION (TASK 4.8)

Some preliminary discussions were held with Creare to explore the potential for Creare to assist in data screening and preparation for utilization in the model qualification effort. A small subcontract to Creare is anticipated to evaluate this approach using one set of data identified for model qualification in the task plan draft.

G. W. Burnette

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/fs

APPENDIX A

STEAM SUPERHEAT MEASUREMENT IN STAGE 3 SEPARATE EFFECTS BUNDLE

L. L. MYERS

The possibility of measuring steam superheat temperature in the Stage 3 Separate Effects Bundle has been investigated. This study was undertaken at the request of the Program Management Group (PMG) during the April 17, 1980, review meeting for the Single Heated Bundle Task 4.3. Two thermocouples in each of the two water rods will be used to obtain data in the region between rods. This change in instrumentation was made since it has a minimum perturbation in the schedule and cost of the task. The documentation reviewed and the various alternatives considered are discussed below.

The accurate measurement of the steam temperature in the region between heater rods in a test bundle is subject to several uncertainties and the interpretation of the measurements is difficult. Experimental investigations to address measurement techniques are discussed in references 1 and 2.

The German study reported in Reference 1 deals with measurement uncertainties caused by the presence of thermal radiation fields and by wetting due to droplets. They used thermocouples to measure coolant phase temperatures and cited the requirements of a small heat capacity to diminish the response time and a small diameter to diminish the disturbance of the flow. They used 10- and 20- mil diameter Inconel sheathed Chromel-Alumel thermocouples in three different configurations:

1) Unshielded - the thermocouple was supported within 30- and 80- mil outside diameter sleeves extending perpendicularly into the flow stream with the thermocouple junction extending 120 mils beyond the sleeve.

2) Droplet and Radiation Shielded - the thermocouple was mounted the same way, but the tip extended into a 140-mil diameter hollow cylindrical radiation shield alinged with the axis parallel to the flow and with conical droplet deflectors attached to the ends of the cylinder, and

3) Radiation Shielded Only - the radiation shield was similar (120- mil inside diameter) without the conical droplet deflectors and with thinned ends to minimize droplet dispersion.

They observed that the response times of both diameters of unshielded thermocouples were sufficient to detect the superheat temperature during the first phase of reflood simulation. The smaller diameter thermocouple led to earlier quenching but permitted detection of superheat for a longer period due to repeated dryout of the probe. The droplet and radiation shielded thermocouples indicated approximately 90°F lower minimum temperature (out of a 1300°F) but also exhibited earlier quenching ($\sim$50 seconds earlier out of 300 seconds) and no dryout after the first quenching. Thermocouples with the radiation shield only were observed to dry out after quenching, but the effect was not as pronounced as for the unshielded thermocouples. After considering the advantages and disadvantages of the three configurations in the various flow regimes, it was concluded in Reference 1 that a probe with an axially open radiation shield is a reasonable compromise.

The Oak Ridge report (Reference 2) describes heated bundle PWR simulation tests in which the steam temperature within the bundle was measured by 40-mil diameter thermocouples which extended either 250 mils from the shroud wall or 120 mils from the surface of an unheated rod. For these tests, the thermocouple measurements were corrected for radiation by applying an energy balance and estimating the uncertainty in steam temperatures. In the data reported in Reference 2, an uncertainty of ± 50°F was applied to steam temperatures ranging up to 1048°F with a corresponding saturation temperature of 547.4 ± 2°F.

Instrumentation plans for the Stage 3 Separate Effects Bundle which were discussed with the PMG did not include measurement of the steam superheat temperature within the bundle. Temperature measurement and data utilization plans did include a thermocouple in the flow path both above and below the upper tie plate, twenty-eight thermocouples distributed between the four sides and various axial locations on the wall of the inner channel, and ten wall temperature thermocouples in each of the 62 heater rods and each of the two water rods at nine axial locations. At the request of the PMG, it was agreed to look into the possibility of routing thermocouples through the walls of the water rods at three or four elevations and to determine what the effect the incorporation of steam superheat thermocouples would have on the cost and schedule of the Stage 3 tests. The only thermocouples which were found to be available without significant schedule impact were two batches of 20-mil diameter thermocouples which were determined to be either too short or to have incompatible sheathing material for the intended use. It was therefore decided to use four of the existing water rod thermocouples. A method of attachment and placement was developed which had no significant impact on the shedule (the water rods and thermocouples were in the shop for fabrication and assembly at the time the decision was made). Alternatives considered included either extending the thermocouple into the flow path from one rod or extending the thermocouple across the distance between two rods with the junction centered in the flow path. The use of radiation shields was also considered, but was abandoned due to the time which would be required to design and fabricate a suitable shield and to develop a method of attachment. The final configuration utilizes a 63- mil diameter sleeve around the 32- mil diameter ungrounded Chromel-Alumel thermocouple. The sleeve is crimped to secure it to the 304 stainless steel thermocouple sheath and is secured to the wall of the water rod by peening or staking to produce an interference fit. The sleeve extends 50 mils beyond the wall of water rod and the tip of the thermocouple extends 50 mils beyond the end of the sleeve. The four thermocouples are located at elevations of 27, 69, 81, and 123 inches from the bottom of the heated length.

REFERENCES

1) "Experience with Steam Temperature and Water Detection Probes for Transient Mist Flow in Hot Rod Bundles", P. Ihle, St. Müller, Institut für Reaktorbauelemente.

2) "Report on Bundle Uncovery/Recovery Testing", J.D. White, Oak Ridge National Laboratory, letter dated 4/1/80.

APPENDIX B

January 16, 1980

KHC-02-80

TO: Distribution

FROM: K. H. Chu KHC
Thermal Hydraulic Methods

SUBJECT: REVIEW OF THE HEAT TRANSFER COEFFICIENT CORRELATIONS IN TRAC P1A

The purpose of this letter is to review the TRAC solid to liquid heat transfer coefficient correlations based on the listing of TRAC-P1A (CY 24).

NOMENCLATURE

c_p	Specifc heat at constant pressure
D_h	Hydraulic diameter
G	Mass flux
g	Gravitational constant
h	Heat transfer coefficient
h_{fg}	$h_g - h_l$ at saturation
k	Conductivity
P	Pressure
T	Temperature
v	Velocity
X	Flow quality
α	Void fraction
ρ	Density
μ	Viscosity
σ	Surface tension

SUBSCRIPT

g	Vapor
l	Liquid
s	Saturation
w	Wall

I. 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, Figure 1, are coded in a subroutine named HTC0R and in a series of subroutines called by HTC0R. This package of subroutines is used for all conditions and in all components where HTC's are required.

II. HTC CORRELATIONS SELECTION LOGIC

For a given set of conditions (i.e., α , X, T_w, T_1, and T_s), the HTC is found independent of the flow regime in the manner illustrated in the flow diagram of subroutine HTCOR (Figure 2). The flow quality X, is used in the correlation and the slip is set equal to 1.0 if $\alpha \leq .001$ or zero liquid velocity for counter current flow.

III. HTC CORRELATIONS

A. Regime 1 - Forced Convection to Single Phase Liquid

In this regime, one of the following conditions is satisfied:

1. $T_w < T_l$ and $\alpha < .05$
2. $T_w < T_s$ and $\alpha < .05$
3. $T_s \leq T_w < T_l$ and $.05 \leq \alpha < .9995$
4. $T_l \leq T_w < T_s$ and $.05 \leq \alpha < .9995$

The HTC's in this regime are given by:

$$h_g = 0$$

$$h_l = h_{FORC}$$

where:

$$h_{FORC} = \max \left\{ h_{lam}, h_{turb} \right\}$$

$$h_{lam} = 4 \frac{k_{TP}}{D_h}$$

$$h_{turb} = .023 \frac{k_{TP}}{D_h} \left[\frac{G(1-X) D_h}{\mu_l} \right]^{.8} \left[\frac{\mu_l C_{p.l}}{k_l} \right]^{.4}$$

$$k_{TP}^{-1} = (1-X) k_l^{-1} + X k_g^{-1}$$

COMMENTS

The two phase conductivity k_{TP} used in the correlations is possibly due to the fact that the high void two phase mixture is also included in this regime. Setting the HTC for vapor to zero might not be valid for high void mixture and mist flow situations.

B. Regime 2 - Nucleate Boiling or Forced Convection Vaporization

In this regime, one of the following conditions is satisfied:

1. $\alpha < .9995$, $T_w \geq T_1$, $T_w \geq T_s$ and steady state calculation (ISTDY = 1)
2. $\alpha < .9995$, $T_w \geq T_1$, $T_s \leq T_w \leq T_{CHF}$

The HTC for this regime are given by:

$$\left.\begin{aligned} h_g &= (1-W)\, h_{g,6} \\ h_1 &= W\, h_{CHEN} \end{aligned}\right\} \quad \text{for } .995 \leq \alpha < .9995$$

$$\left.\begin{aligned} h_g &= 0 \\ h_1 &= h_{CHEN} \end{aligned}\right\} \quad \text{for } 0 \leq \alpha < .995$$

where:

$W = 1 - (\alpha - .995)/(.0045)$

$h_{g,6}$ = HTC for vapor in regime 6 (free or forced convection to vapor)

$h_{CHEN} = F\, h_{FORC} + F_s\, h_{NUCL}$

F = Reynolds number factor defined in page 54 of the TRAC P1A manual

h_{FORC} = Defined in regime 1

F_s = Subcooled correction factor

$$= \begin{cases} 1 & \text{if } T_1 \geq T_s \\ (T_w - T_s)/(T_w - T_1) & \text{if } T_1 < T_s \end{cases}$$

$$h_{NUCL} = .00122 \frac{k_\ell^{.79} \, C_{P,\ell}^{.45} \, \rho_\ell^{.49}}{\sigma^{.5} \, \mu_\ell^{.29} \, h_{fg}^{.24} \, \rho_g^{.24}} \Delta T^{.24} \Delta P^{.75} S$$

$T = T_w - T_s$

$P = P_s - P$

P_s = Saturation pressure corresponding to T_w

$$= \left(\frac{T_w - 255.2}{117.8} \right)^{4.484305} 10^5$$

S = Suppression factor defined in page 54 of the TRAC P1A manual.

Nucleate boiling occurs as soon as T_w reaches T_s without including the boiling incipience phenomenon. Subcooled nucleate boiling has been included in the code though it was not reported in the TRAC P1A manual. Basically, the Chen correlation was used but a slight modification on the forced convection component of the correlation has been made to smooth out the transition of the HTC's between regimes 1 and 2.

C. Regime 3 - Transition Boiling

The conditions that $T_w \geq T_1$, $T_{CHF} \leq T_w \leq T_{min}$ and $\alpha < .9995$ are satisfied in this regime. The temperatures at critical heat flux, T_{CHF}, and minimum stable film boiling, T_{min} will be discussed later in Section V.

The HTC's for the regime are given by:

where:

$$w = \frac{T_w - T_{CHF}}{T_{min} - T_{CHF}}$$

h_{TB} = HTC for transition boiling

$$= \frac{\gamma q_{CHF} + (1-\gamma) q_{min}}{T_w - T_l}$$

q_{CHF} = Critical heat flux (will be discussed in Section IV)

q_{min} = Heat flux at minimum stable film boiling temperature

$$= (1-\alpha) h_B (T_{min} - T_l)$$

$$\gamma = \left(\frac{T_w - T_{min}}{T_{CHF} - T_{min}} \right)^2$$

h_R = HTC for radiation between wall and liquid

$$= \sigma \varepsilon \frac{T_w^4 - T_s^4}{T_w - T_s}$$

σ = Stefan-Boltzman constant

ε = Wall emissivity

$$h_s = \begin{cases} 0 & \text{if } T_l \geq T_s \\ .012 \rho_l c_{p,l} |v_g - v_l| & \text{if } T_l < T_s \end{cases}$$

= HTC for subcooled liquid

$h_{g,nc}$ = HTC for vapor natural convection
(will be discussed in regime 6)

$h_{g,DR}$ = Dougall-Rohsenow Correlation

$$= .023 \frac{k_g}{D_h} \left\{ \frac{\rho_g [\alpha v_g + (1-\alpha) v_l] D_h}{\mu_g} \right\}^{.8} \left(\frac{C_{p,g} \mu_g}{k_g} \right)^{.4}$$

h_B = Modified Bromley Correlation

$$= .62 \left[\frac{k_g^3 (\rho_l - \rho_g) g h'_{fg}}{\mu_g (T_w - T_s) \lambda} \right]^{.25}$$

$$h'_{fg} = h_{fg} + .5 C_{p,g} (T_g - T_s)$$

$$\lambda = 2\pi \left[\frac{\sigma}{g(\rho_l - \rho_g)} \right]^{.5}$$

The HTC for transition boiling, h_{TB} adopts the approach of Bjornard and Griffith* by constructing a curve interpolation of the boiling curve between CHF and minimum stable film boiling points. The HTC for subcooled liquid which is not documented in the

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* Symposium on Thermal and Hydraulic Aspects of Nuclear Reactor Safety, Vol. 1, p. 17-41.
Winter Annual ASME, Atlanta, Georgia Nov. 27 thru Dec. 2, 1977

manual is taken from J. H. Lineham and M. A. Grolmes. The shape factor for the radiation heat transfer although reported in the manual is not programmed in the code.

D. Regime 4 - Film Boiling

The conditions that $T_w \geqslant T_1$, $T_w > T_{min}$ and $\alpha < .9995$ are satisfied in the regime.

The liquid and vapor HTC in this regime are given by:

$$h_\ell = (1-\alpha)\left[\frac{T_w - T_s}{T_w - T_\ell} h_R + \frac{T_s - T_\ell}{T_w - T_\ell} h_s \right]$$

$$h_g = \begin{cases} (1-\alpha)\dfrac{T_w - T_s}{T_w - T_g} h_B + \alpha \max\{h_{g,nc}, h_{g,DR}\} & \text{if } T_w > T_g \\ \alpha \max\{h_{g,nc}, h_{g,DR}\} & \text{if } T_w \leq T_g \end{cases}$$

where:

h_R, h_s, h_B, $h_{g,nc}$, and $h_{g,DR}$ are defined in regime 3.

The heat flux at T_{min} calculated in this regime according to

$$q_{min} = h_1 (T_{min} - T_1) + h_g (T_{min} - T_g)$$

is found to be different from that calculated from the correlations in regime 3. This leads to the discontinuity of h_1 and h_g between regimes 3 and 4.

E. Regime 6 - Forced or Natural Convection to Vapor

The condition that $\alpha \geq .9995$ is satisfied in this region and the HTC's are given by:

$$h_l = 0$$

$$h_g = \max \left\{ h_{g,nc} , h_{g,turb} \right\}$$

where:

$h_{g,nc}$ = McAdam Correlation for natural convection

$$= .13 \frac{k_g}{D_h} \left[\frac{D_h^3 \rho_g^2 g \, |T_w - T_g|}{\mu_g T_g} \right]^{1/3} \left(\frac{c_{p,g} \mu_g}{k_g} \right)^{1/3}$$

$$h_{g,turb} = .023 \frac{k_g}{D_h} \left(\frac{\rho_g v_g D_h}{\mu_g} \right)^{.8} \left(\frac{c_{p,g} \mu_g}{k_g} \right)^{.3}$$

High speed correction is included when $v_g > 50 \, m/s$ and h_g is given by:

$$h_g = r \, h_{g,turb}$$

where

$$r = \frac{T_w - T_{aw}}{|T_w - T_g|}$$

$$T_{aw} = T_g + \left(\frac{c_{p,g} \mu_g}{k_g} \right)^{1/3} \frac{v_g^2}{2 c_{p,g}}$$

The high speed flow correction is not documented in the TRAC P1A manual.

F. Regime 7 - Forced Convection to Mixture

When the CHF calculation is not asked for by the user (ICHF = 0), the HTC for $\alpha < .9995$ is calculated in the following manner:

For $.995 < \alpha < .9995$

$$h_g = h_{m,g}$$

$$h_1 = W \max\{h_{m,1}, h_{m,turb}\}$$

where:

$$W = 1 - \frac{\alpha - .995}{.0045}$$

$$h_{m,1} = 4 \, k_l / D_h$$

$$h_{m,turb} = 0.023 \frac{k_l}{D_h} R_{em}^{.8} \left(\frac{C_{p,l} \mu_l}{k_l} \right)^{.4}$$

$$R_{em} = G D_h / \mu_m$$

$$\mu_m^{-1} = (1-x) \mu_l^{-1} + x \mu_g^{-1}$$

$$h_{m,g} = \begin{cases} (1-W) \max\{h_{g,nc}, h_{g,turb}\} & \text{if } V_g \le 50 \text{ m/s} \\ (1-W) \, r \, h_{g,turb} & \text{if } V_g > 50 \text{ m/s} \end{cases}$$

r, $h_{g,nc}$, $h_{g,turb}$ = Defined in regime 6.

For $\alpha \leq .995$

$$h_1 = \max \left\{ h_{m,1}, h_{m,turb} \right\}$$

$$h_g = 0$$

The high flow correction is not documented in the TRAC P1A mnaual. Modification has been made in the regime $.995 < \alpha < .9995$ to smooth out the transition of the HTC between regimes 1 and 7.

G. Regimes 11, 12, and 13 - Condensation

The conditions that $.05 \leq \alpha < .9995$, $T_w < T_1$ and $T_w < T_s$ are satisfied in these regimes. The HTC's are given as follows:

$$h_g = 0$$

$$h_1 = \max \left\{ h_{c,turb}, h_{c,lam} \right\}$$

where:

$h_{c,turb}$ = HTC for turbulent film condensation (regime 13)

= Carpenter and Colburn Correlation

$$= 0.65 \left(\frac{\rho_\ell k_\ell C_{p,\ell}}{\mu_\ell} \right)^{1/2} \tau^{1/2}$$

$$\tau^{1/2} = \frac{.046}{\left(\frac{G_g D_h}{\mu_g} \right)^{.2} \left(\frac{\rho_g v_g^2}{2} \right)}$$

$h_{c,lam}$ = HTC for laminar film condensation

$$= \begin{cases} \text{Horizontal film condensation, if} & |g\cos\theta| \leq .5 \\ \text{Vertical film condensation, if} & |g\cos\theta| > .5 \end{cases}$$

$$= \begin{cases} .296 \left\{ \dfrac{\rho_\ell(\rho_\ell-\rho_g) g h_{fg} k_\ell^3}{D_h \mu_\ell |T_w - T_s|} \right\}^{1/4} & \text{(Regime 11)} \\ 1.132 \left\{ \dfrac{\rho_\ell(\rho_\ell-\rho_g) g h_{fg} k_\ell^3}{D_\ell \mu_\ell |T_w - T_s|} \right\}^{1/4} & \text{(Regime 12)} \end{cases}$$

θ = Angle between the axis of the cell and the vertical.

The horizontal laminar condensation HTC is obtained from Chato while the vertical laminar condensation HTC is obtained by multiplying the original Nusselt formulation by 1.2 to account for the waviness of the film. However, in the original Nusselt formulation, the characteristic dimension was the axial length and not the pipe diameter.

IV. CRITICAL HEAT FLUX CORRELATIONS

The modified Zuber correlation for pool boiling CHF is used for $|g\cos\theta| \geq 0.1$ and $-600 < G < 100$ kg/m^2-sec. This is in line with the recommendation of Bjornard and Griffith*. However, they suggested a multiplier of 0.9 for vertical rod geometry in the modified Zuber correlation, which is missing in TRAC formulation. In TRAC code, a correction term for subcooled CHF has been added. But it is not reported in the TRAC manual. The modified Zuber correlation as appears in the code reads:

$$q''_{CHF} = (1-\alpha)\Big[0.131\rho_g h_{fg}\Big\{\frac{\sigma g(\rho_\ell-\rho_g)}{\rho_g^2}\Big\}^{1/4}$$

$$+ F_s(.696)\sqrt{k_\ell\rho_\ell C_{p,\ell}}\Big\{\frac{g(\rho_\ell-\rho_g)}{\sigma}\Big\}^{1/4}\Big\{\frac{\sigma g(\rho_\ell-\rho_g)}{\rho_g^2}\Big\}^{1/8}\cdot$$

$$(T_s - T_\ell)\Big]$$

where:

F_s = Subcooled correction factor

$$= \begin{cases} 1 & \text{for } T_s > T_1 \\ 0 & \text{for } T_s \leq T_1 \end{cases}$$

θ = Defined in Section IV.

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*Symposium on Thermal and Hydraulic Aspects of Nuclear Reactor Safety, Vol. 1, p. 17-41. Winter Annual ASME in Atlanta, Georgia November 27, thru December 2, 1977.

For high flow rates, i.e., $G > 200$ kg/m^2-sec. and $G < -700$ kg/m^2-sec., and $|g \cos\theta| < 0.1$ Biasi, et al correlation is used. The correlation described by Equations (127 and 128) of TRAC-P1A manual and will not be repeated here. However, the Biasi correlation appeared in the manual and the code is incorrect. The CHF for high quality should read:

$$q''_{CHF} = \frac{1.78 \times 10^7}{D^n G^{0.6}} h_p (1-X)$$

In the intermediate range of mass flux, i.e., $100 < G < 200$ kg/m^2-sec and $-700 < G < -600$ kg/m^2-sec, linear interpolation between $q''_{CHF,ZUBER}$ and $q''_{CHF,BIASI}$ is done. No particular reason for using Biasi correlation is given.

For loop components, i.e., one-dimensional formulation, the Bowring correlation, based on round tube and uniform heat flux data, is available to users by setting ICHF = 3.

The original Bowring correlation (Bowring 1972) was of the form:

$$q''_{CHF} = (A + B \Delta H_i)/(C + L)$$

where H_i and L were the inlet subcooling and the tube length, respectively. LASL, however, has modified the above form and used the following:

$$q''_{CHF} = (A - B h_{fg} X)/C$$

where X is the local quality.

The coefficients A, B, and C are complicated functions of pressure, mass flux, and diameter, and are given in the TRAC manual. They will not be repeated here. However, the definition of p_R as given in the TRAC manual is incorrect. It should be $p_R = 0.145\ p/10^6$. It has been coded correctly.

V. DETERMINATION OF T_{CHF} AND T_{MIN}

Chen correlation for nucleate boiling heat transfer coefficient is used to calculate the surface temperature corresponding to the CHF such that:

$$T_{CHF} = T_s + \frac{q''_{CHF}}{h_{CHEN}}$$

is satisfied. Since h_{CHEN} is a function of the wall temperature, the following iteration scheme is used to evaluate T_{CHF}:

$$T_{CHF}^{(0)} = T_s + q''_{CHF} / h_{CHEN}(T_W)$$

$$T_{CHF}^{(n+1)} = T_{CHF}^{(n)} + \Delta T_{CHF}^{(n)}$$

$$\Delta T_{CHF}^{(n)} = \frac{T_{CHF}^{(n)} - T_s - q''_{CHF} / h_{CHEN}^{(n)}}{1 + \frac{q''_{CHF}}{[h_{CHEN}^{(n)}]^2} \left(\frac{d h_{CHEN}}{d T_{CHF}} \right)^{(n)}}$$

where q''_{CHF} is limited to $q''_{CHF} \geqslant 10000\ W/m^2$ and $T_{CHF}^{(0)}$ to $T_s + 5 \leq T_{CHF}^{(0)} \leq T_s + 100$. The iteration terminates when $|\Delta T_{CHF}^{(n)}| < 1$ or $n = 10$; in the latter case, warning will be printed out and the whole calculation aborted. Finally, T_{CHF} is limited to $T_{CHF} \geqslant T_s + 5$.

The subcooled modification in Chen correlation is omitted in the determination of T_{CHF}. The expression for $(dh_{CHEN}/dT_{CHF})^{(*)}$ is also coded incorrectly.

T_{min} determines the boundary between the transition boiling regime and the film boiling regime. In TRAC, the homogeneous nucleation mechanism has been assumed to govern the minimum temperature as per recommendation of Bjornard and Griffith*. Therefore, T_{min} is given by:

$$T_{min} = T_{HN} + (T_{HN} - T_\ell)\left[\frac{\rho_\ell k_\ell c_{p,\ell}}{\rho_w k_w c_{p,w}}\right]^{1/2}$$

For simplicity, the homogeneous nucleation temperature, T_{HN} in TRAC is taken to be equal to T_{crit}. The subscript w stands for wall material properties which depend on the surface condition, i.e., oxidation, crud formation, aging, etc. However, these effects are not included in TRAC at present.

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* Symposium on Thermal and Hydraulic Aspects of Nuclear Reactor Safety, Vol. 1, p. 17-41. Winter Annual ASME in Atlanta, Georgia November 27, thru December 2,1977

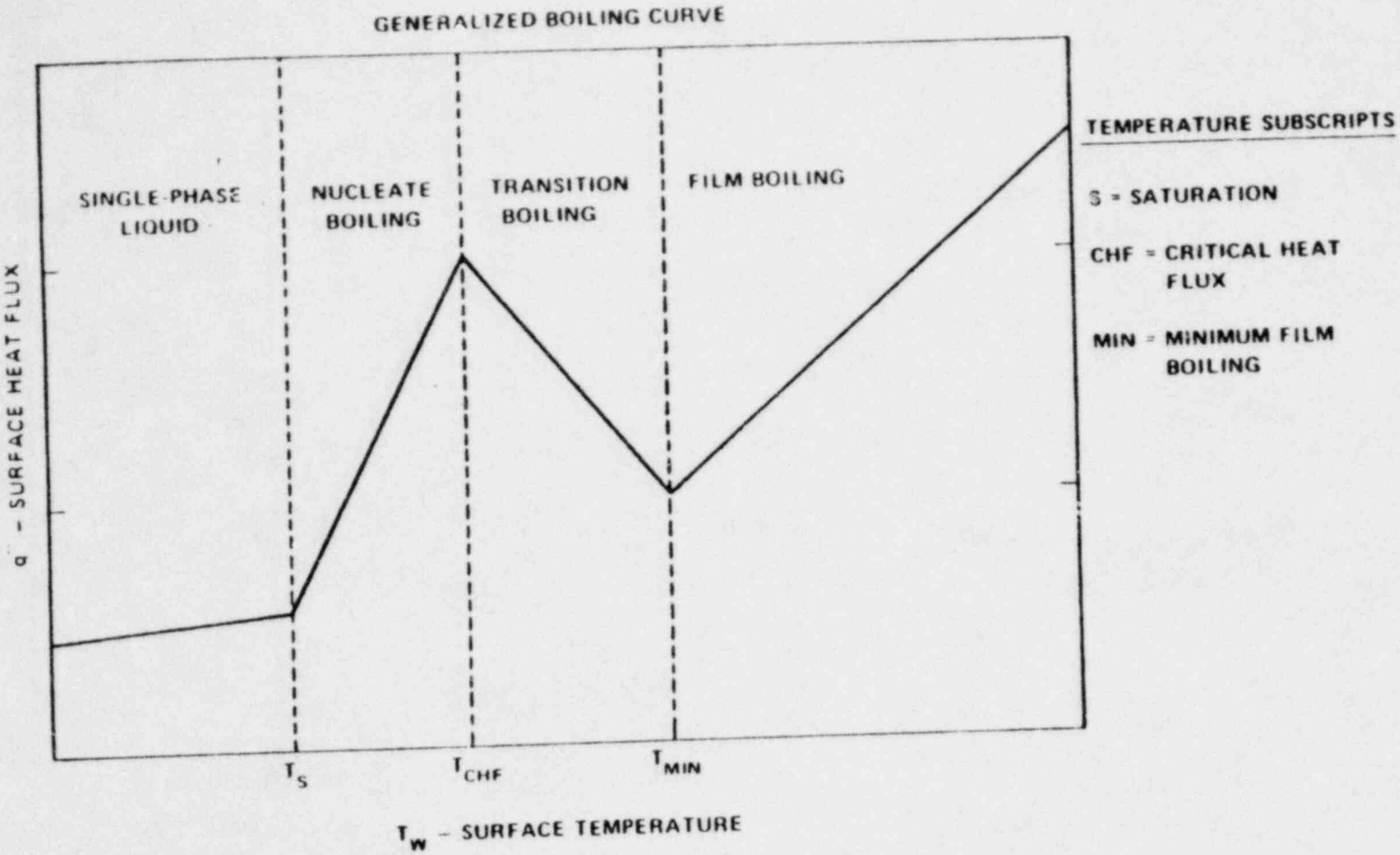


Fig. . 1
Generalized boiling curve.

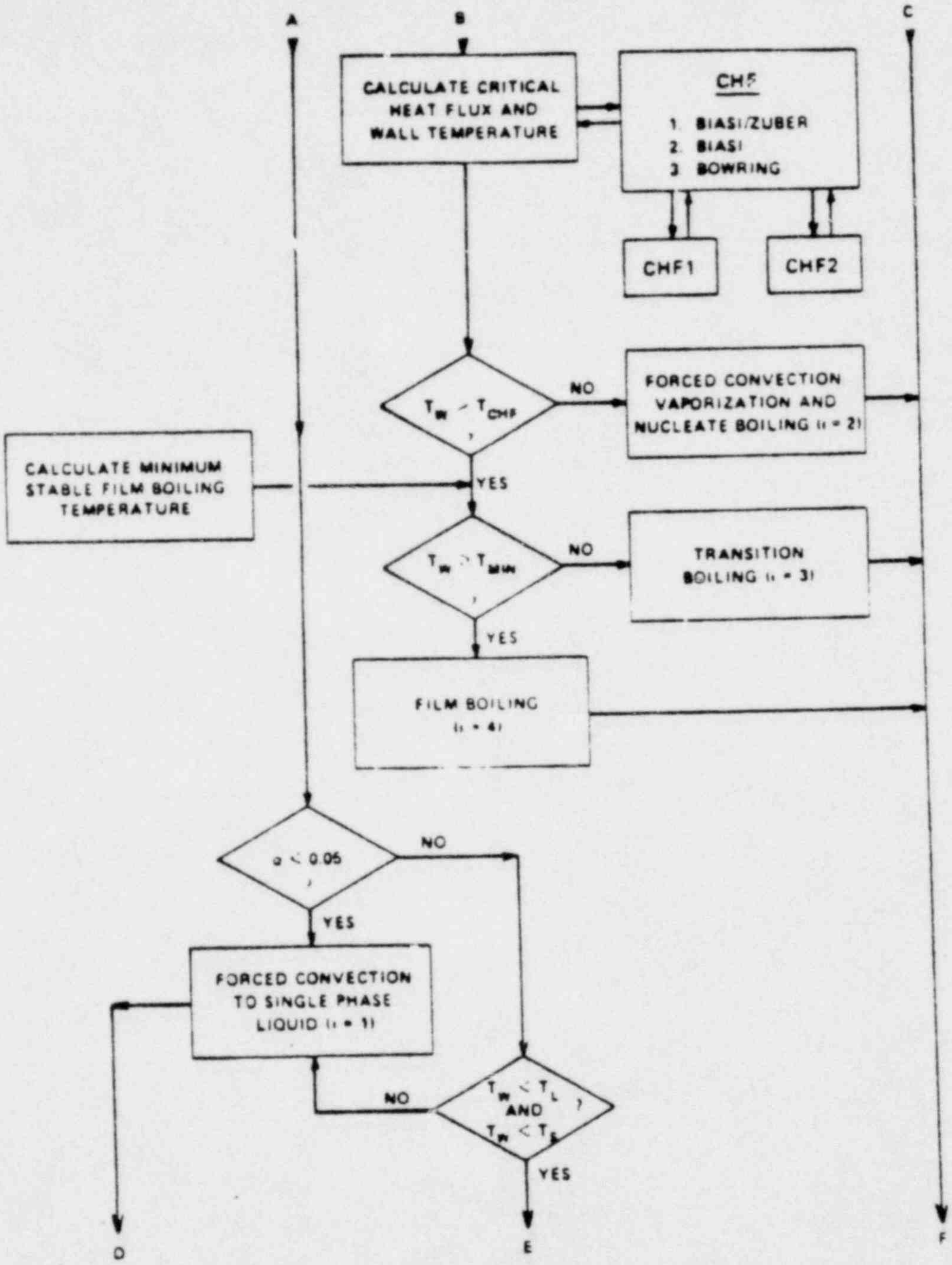


Fig. 2
Continued

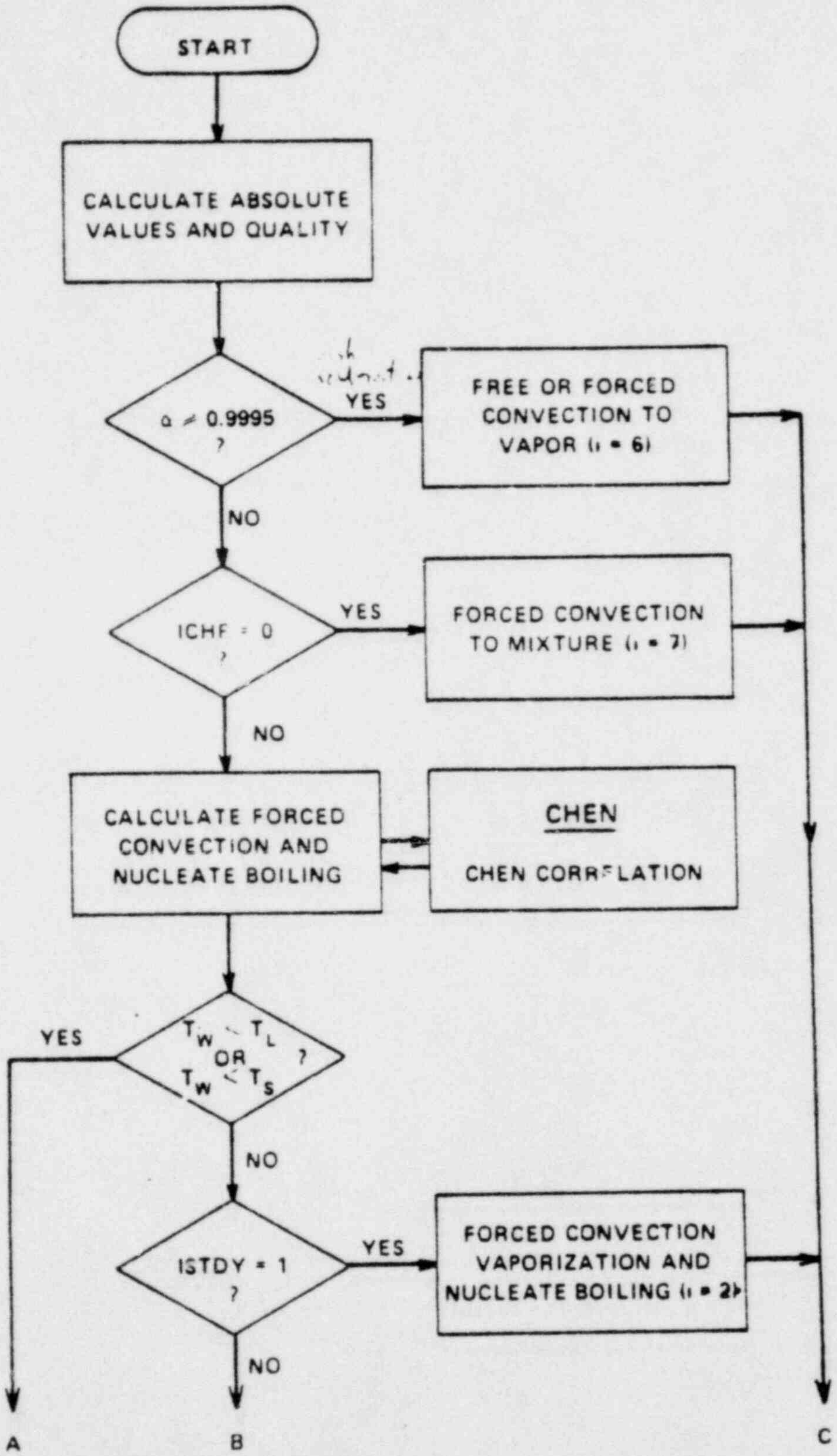
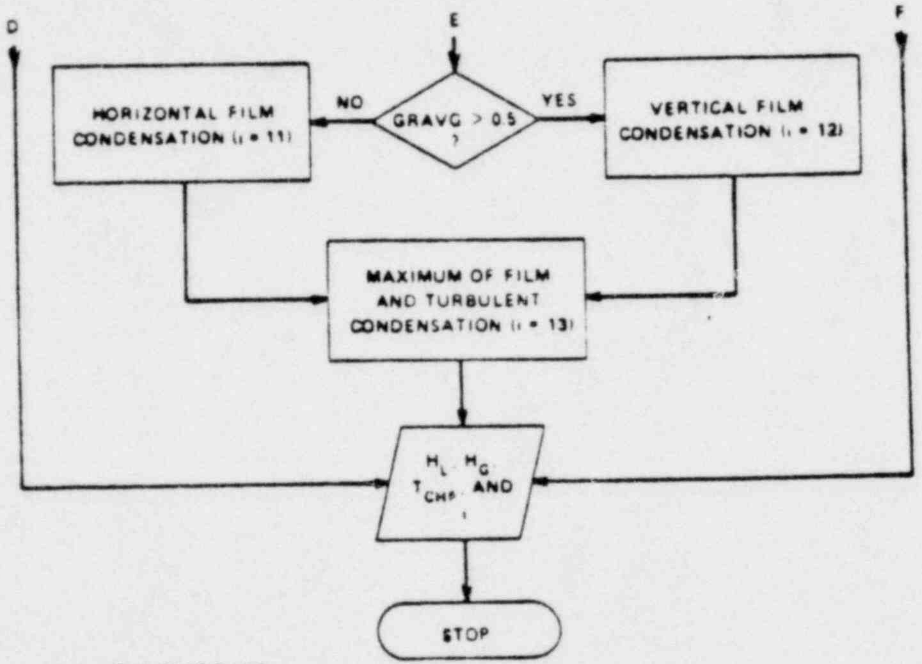


Fig. 2
Heat transfer regime and correlation selection logic.



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

Fig. 2
Continued

APPENDIX C

April 8, 1980 MMA-02-80

TO: Distribution

FROM: M. M. Aburomia, Senior Engineer
Thermal Hydraulic Methods

SUBJECT: MODIFICATION OF TRAC NUMERICS AND APPLICATION OF THE NEW SCHEME TO JET PUMPS

TRAC numerics for the fluid conservation of mass, momentum, and energy, do not conserve the fluid momentum in system configurations associated with area changes. This usually leads to the wrong prediction for the pressure distribution within such systems. The reason for the incorrect prediction of the pressure lies within the use of the back-difference approximation for the convective momentum terms in TRAC momentum conservation equations.

The analysis outlined below correct this dificiency by utilizing the central-difference technique for the convection momentum terms in TRAC. The analysis transforms this modification by introducing localized momentum correction terms in TRAC finite difference equations, to be called by TRAC users. TRAC subroutines are modified to include these correction terms. This technique would apply directly to fuel channels, tee components and pipes. Application of this technique to jet pumps under normal and flow reversal conditions have been performed. Comparison of TRAC results with experimental data is included.

MMA/dlp
Attachment

ANALYSIS

TRAC two-fluid momentum conservation equations for the liquid and vapor phases are:

$$\frac{\partial \vec{V}_\ell}{\partial t} + \vec{V}_\ell \cdot \nabla \vec{V}_\ell = \frac{C_i}{(1-\alpha)\rho_\ell} \vec{V}_r \left|\vec{V}_r\right| - \frac{1}{\rho_\ell} \nabla P + \frac{\Gamma}{(1-\alpha)\rho_\ell}\left(\vec{V}_\ell - \vec{V}_{i\ell}\right) - \frac{C_{w\ell}}{(1-\alpha)\rho_\ell} \vec{V}_\ell \left|\vec{V}_\ell\right| + \vec{g} \quad (1)$$

$$\frac{\partial \vec{V}_g}{\partial t} + \vec{V}_g \cdot \nabla \vec{V}_g = -\frac{C_i}{\alpha \rho_g} \vec{V}_r \left|\vec{V}_r\right| - \frac{1}{\rho_g} \nabla P - \frac{\Gamma}{\alpha \rho_g}\left(\vec{V}_g - \vec{V}_{ig}\right) - \frac{C_{wg}}{\alpha \rho_g} \vec{V}_g \left|\vec{V}_g\right| + \vec{g} \quad (2)$$

TRAC numerics utilize the back difference technique in its semi-implicit solution, to approximate the momentum convective terms of equations (1) and (2). (Refer to Figure 1).

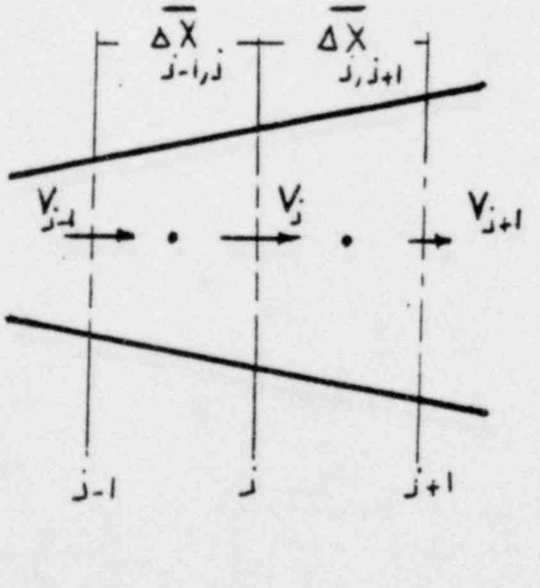


FIGURE 1. TRAC Fluid Cells

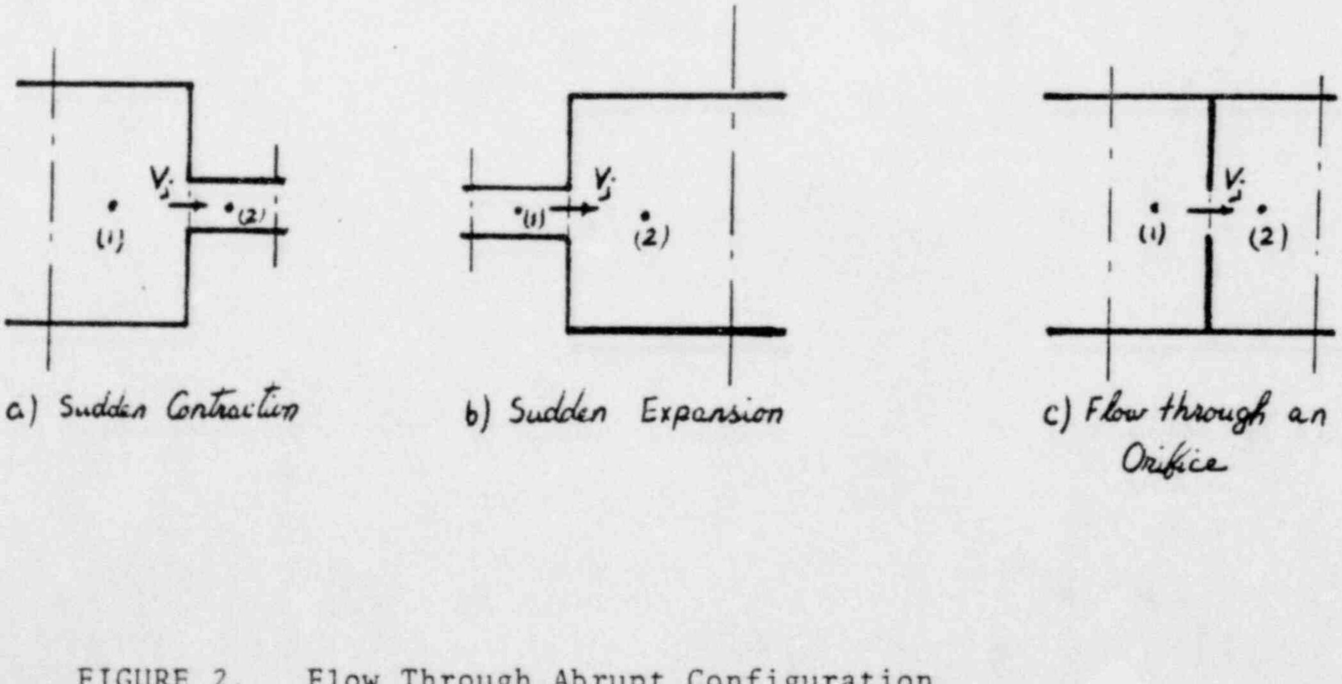
that is,

$$\vec{V}\cdot\nabla\vec{V} = V_j^n\left(V_j^n - V_{j-1}^n\right)/\overline{\Delta X}_{j-1,j} \qquad (3)$$

This approximation leads to the incorrect pressure distribution in equations (1) and (2). A more accurate expression for the convection momentum terms in TRAC is the central-difference approximation;

$$\vec{V}\cdot\nabla\vec{V} = V_j^n\left(V_{j+1}^n - V_{j-1}^n\right)/\left(\overline{\Delta X}_{j-1,j} + \overline{\Delta X}_{j,j+1}\right) \qquad (4)$$

this expression yields the correct pressure field for the cases of: sudden contraction, sudden expansion, and orifice flow, shown in Figure 2.



a) Sudden Contraction

b) Sudden Expansion

c) Flow through an Orifice

FIGURE 2. <u>Flow Through Abrupt Configuration</u>

To avoid any instability associated with the use of equation (4), TRAC equations were modified to include the difference between equations (4) and (3) in localized momentum correction terms, to be called by TRAC users, as shown below:

Liquid

$$\frac{\partial \vec{V}_\ell}{\partial t} + \vec{V}_\ell \cdot \nabla \vec{V}_\ell = \frac{C_i}{(1-\alpha)\rho_\ell}\vec{V}_r|\vec{V}_r| - \frac{1}{\rho_\ell}\nabla P + \frac{\Gamma}{(1-\alpha)\rho_\ell}(\vec{V}_\ell - \vec{V}_{i\ell}) - \left\{\frac{C_{w\ell}}{(1-\alpha)\rho_\ell} + C_\ell\right\}\vec{V}_\ell|\vec{V}_\ell| + \vec{g} \qquad (5)$$

Vapor

$$\frac{\partial \vec{V}_g}{\partial t} + \vec{V}_g \cdot \nabla \vec{V}_g = -\frac{C_i}{\alpha\rho_g}\vec{V}_r|\vec{V}_r| - \frac{1}{\rho_g}\nabla P - \frac{\Gamma}{\alpha\rho_g}(\vec{V}_g - \vec{V}_{ig}) - \left\{\frac{C_{wg}}{\alpha\rho_g} + C_g\right\}\vec{V}_g|\vec{V}_g| + \vec{g} \qquad (6)$$

where C_ℓ and C_g are the liquid and vapor momentum correction terms to be called by the user through specifying negative values for "NFF" parameter in TRAC input. C_ℓ and C_g have the expression (see Figure 1 for notation),

$$C_{\ell \text{ or } g} = \left\{\frac{1}{2}\frac{A_j}{A_{j+1}} + \left(R - \frac{1}{2}\right)\frac{A_j}{A_{j-1}} - R\right\} \qquad (7)$$

where A_j is the local area, A_{j-1} and A_{j+1} are the upstream and downstream flow areas, respectively. R is the length ratio of the nodes,

$$R = 0.5\left(\overline{\Delta X}_{j-1,j} + \overline{\Delta X}_{j,j+1}\right) / \overline{\Delta X}_{j-1,j} \tag{8}$$

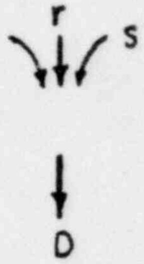
TRAC subroutines are modified to include these correction terms. The present scheme enables the user to use large nodes in TRAC system simulation, and therefore avoids the use of small time steps. Application of the present technique to jet pumps, with a single node simulating the drive line nozzle, has been performed. Comparison of TRAC results with experimental data, for jet pumps under normal and flow reversal conditions, is shown in Table I and Figure 3. As noted, TRAC with the present modifications yields the correct pressure and velocity fields.

TABLE I

COMPARISON OF TRAC (TF1D) JET PUMP MODEL PREDICTIONS WITH INEL JET PUMP DATA

(A) + ve Drive Flow

Input Parameters	INEL Jet Pump	TRAC JP Model Predictions
- Drive Line Flow	3.06 Kg/s (6.75 lb/s)	Same as INEL
- Suction Pressure (P_s)	7.528 MPa (1091.8 PSI)	Same as INEL
- Discharge Press. (P_D)	7.584 MPa (1099.9 PSI)	Same as INEL
- Temperature	555.3K (540°F)	Same as INEL
Output Values		
- Suction Flow	3.16 Kg/s (6.98 lb/s)	3.35 Kg/s (7.3 lb/s)
- Drive Pressure (P_r)	7.736 MPa (1121.9 PSI)	7.741 MPa (1122.7 PSI)
- M Ratio	1.03	1.09
- N Ratio	0.34	0.335



(B) - ve Drive Flow

Input Parameters	INEL Jet Pump	TRAC JP Model Predictions
- P_D - P_s	0.1335 MPa (19.36 PSI)	Same as INEL
- P_D - P_r	0.125 MPa (18.12 PSI)	Same as INEL
- Temperatures	555.3K (540°F)	Same as INEL
Output Values		
- Drive Line Flow	3.2 Kg/s (7.07 lb/s)	3.5 Kg/s (7.9 lb/s)
- Suction Flow	6.3 Kg/s (13.8 lb/s)	5.6 Kg/s (12.3 lb/s)
- M Ratio	1.97	1.6
- N Ratio	-1.12	-1.13

4/11/80

PRELIMINARY

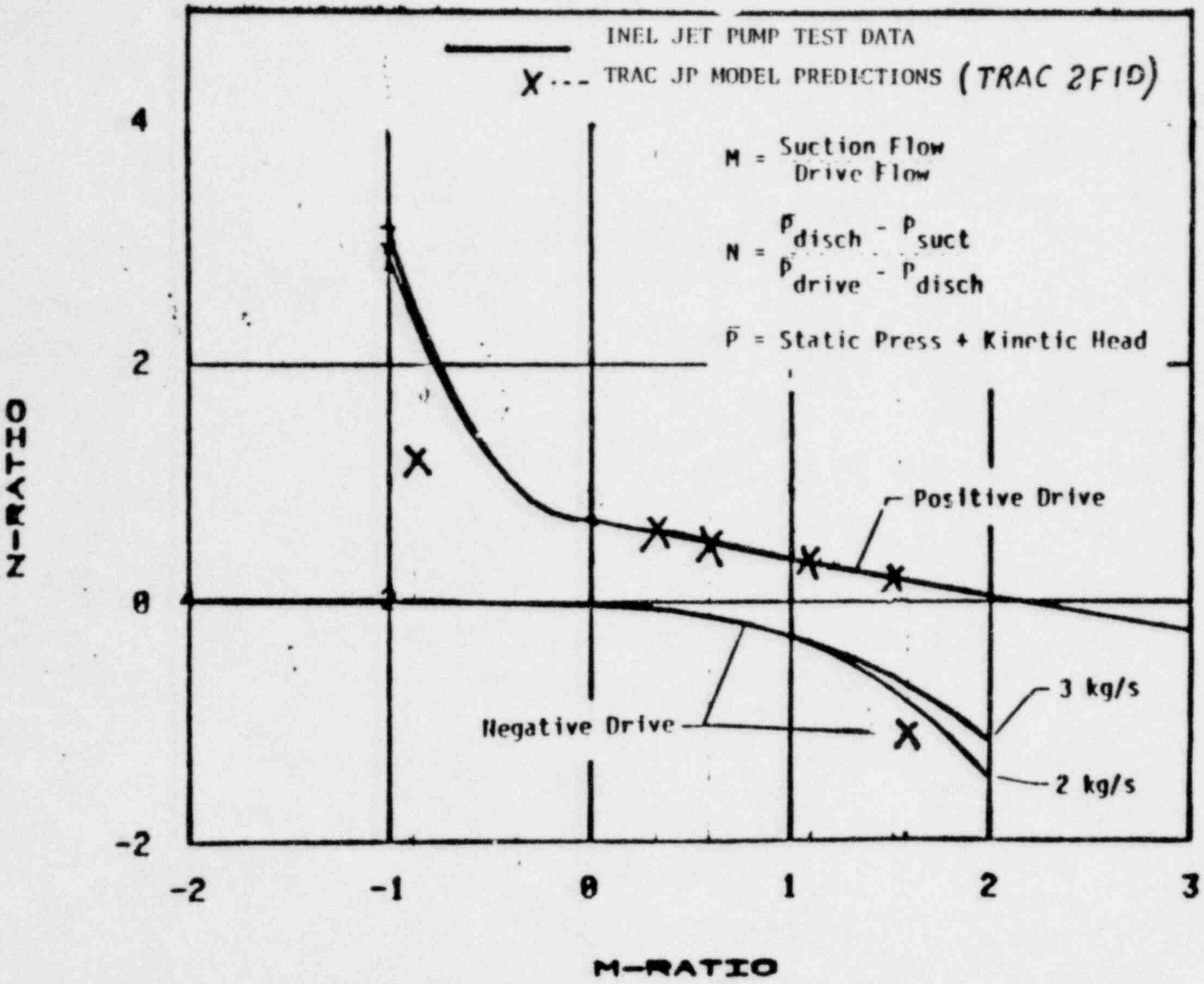


FIGURE 3: Comparison of TRAC Jet Pump Model Predictions with INEL Test Data