PROBLEMS IN MODELING

OF

SMALL BREAK LOCA

BY

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JUNE 26, 1980

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OUTLINE

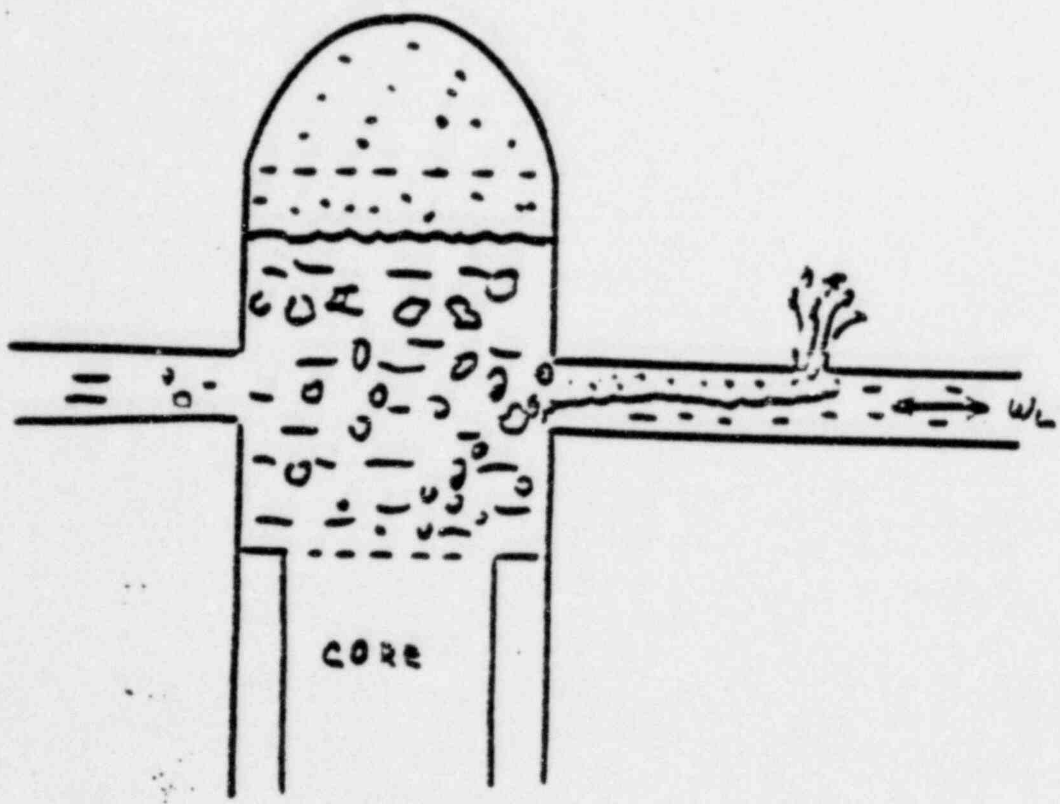
1. HORIZONTAL PIPE FLOW PHENOMENA OF INTEREST

2. CODE MODIFICATIONS

Anticipated Phase Separation During

Hot Leg Small Break with Main Coolant Pumps

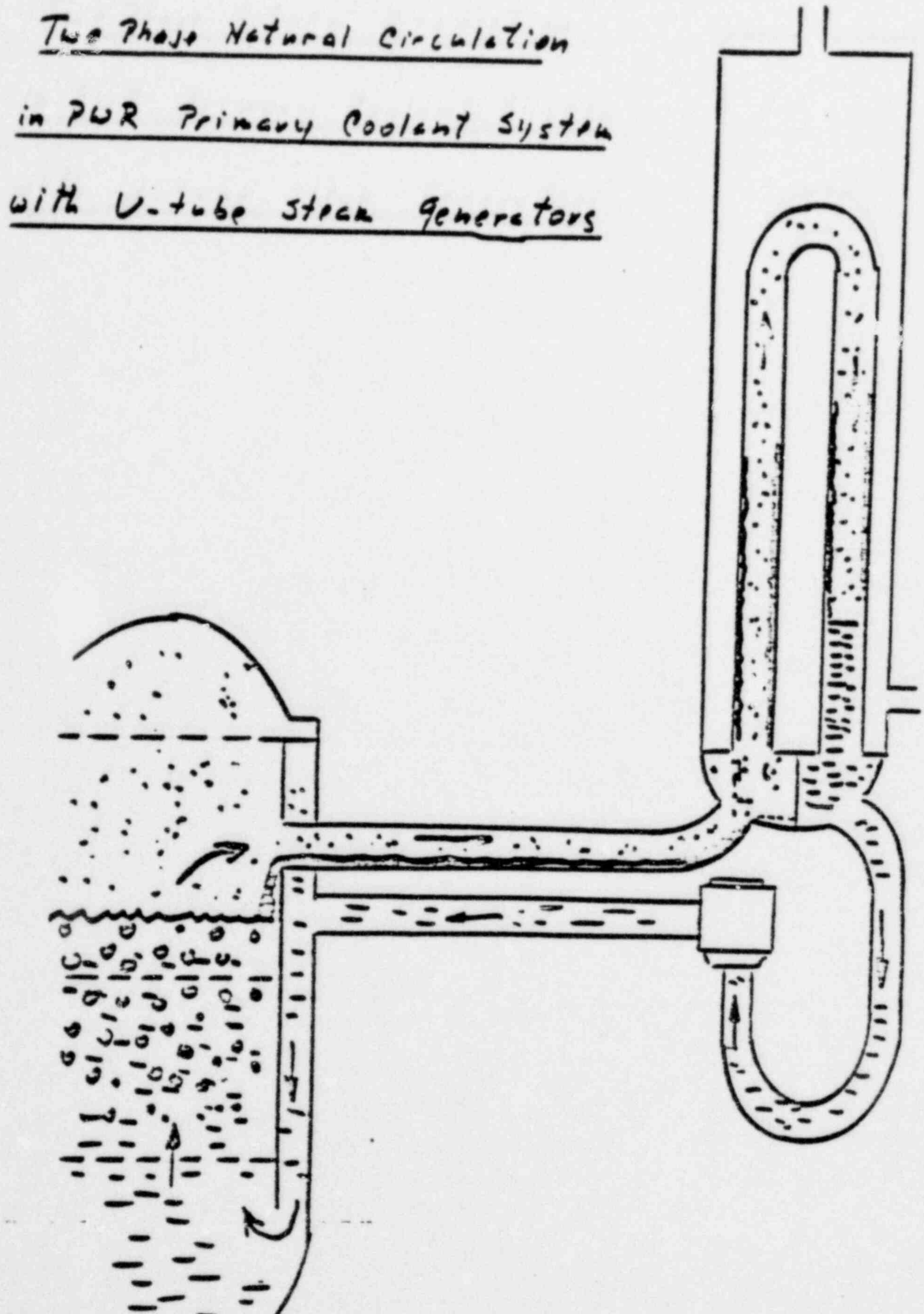
Tripped



Two Phase Natural Circulation

in PWR Primary Coolant System

with U-tube Steam Generators



TWO- PHASE FLOW PHENOMENA

IN

HORIZONTAL PIPES

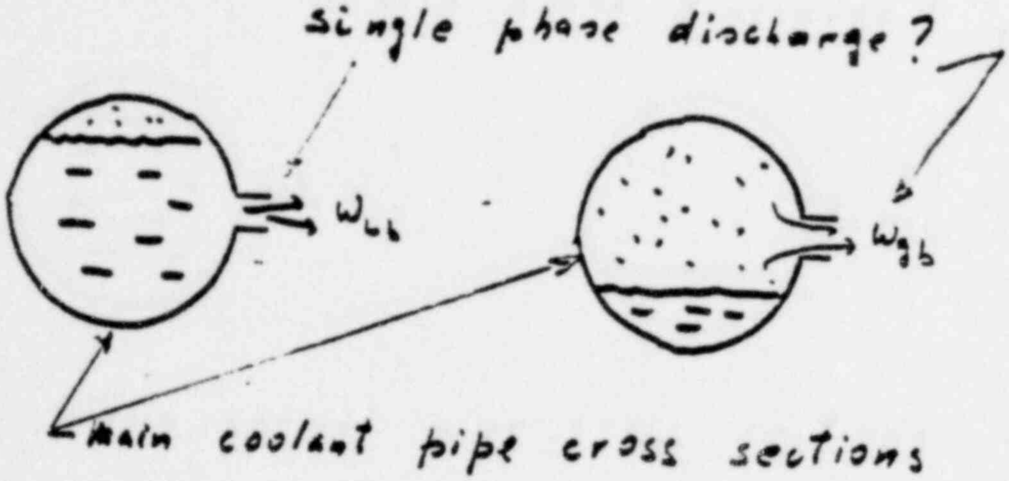
PHENOMENA:

1) TWO-PHASE FLOW REGIMES
2) ENTRAINMENT OF LIQUID IN BREAK FLOW
3) VAPOR PULL-THROUGH IN BREAK FLOW
4) CCFL

DETERMINE EFFECTS ON:

1) EVENTS IN EXPERIMENTAL FACILITIES VS. PLANT
2) TEST: SCALING
3) ANALYSIS: CODE SIMULATION AND
   BREAK FLOW CALCULATION

Separated Flow Regime



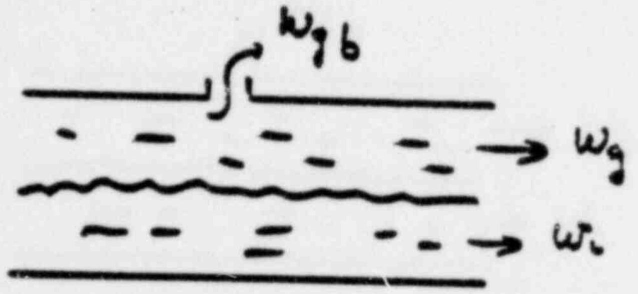
Questions:

1) What phenomena can induce two phase rather than single phase discharge?

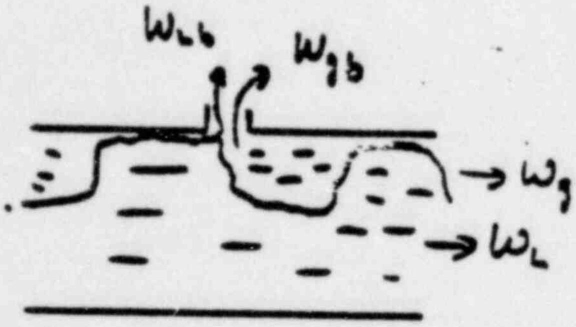
2) Can we scale these phenomena?

3) For a two phase discharge can we predict the mass flow rate?

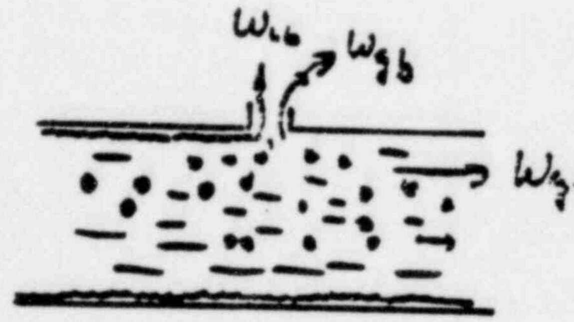
Flow Regime Effects on Discharge



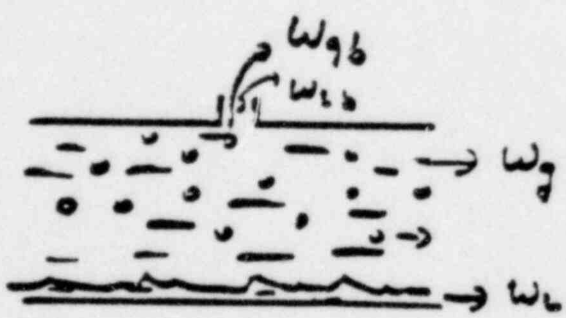
Separated



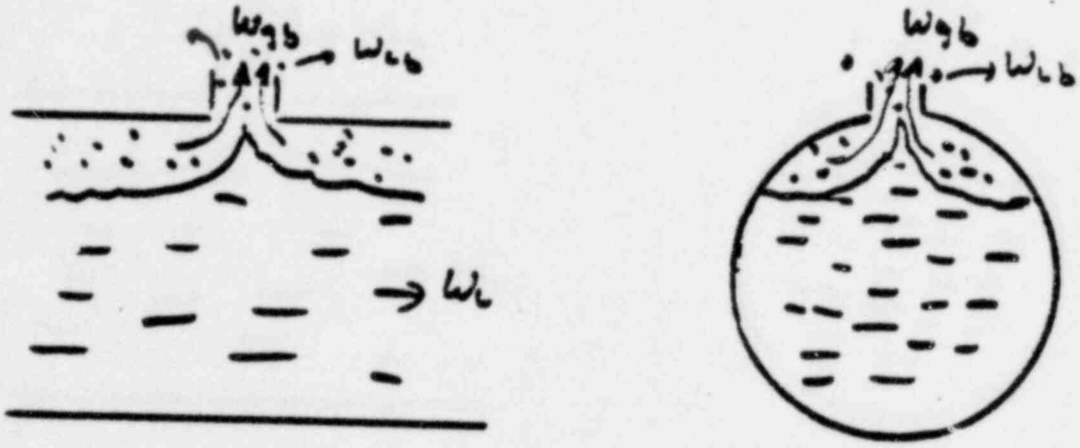
Slug



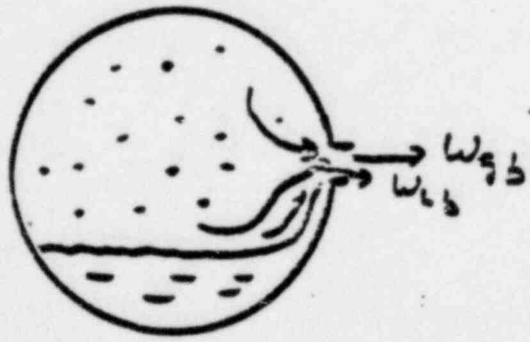
Annular - mist



Liquid Entrainment

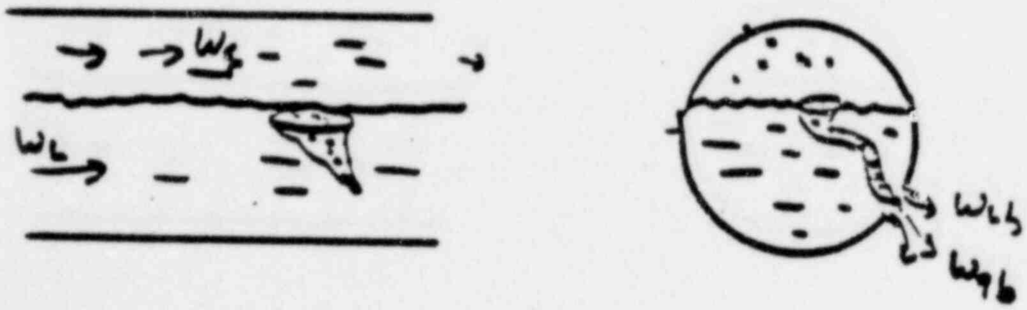


a)

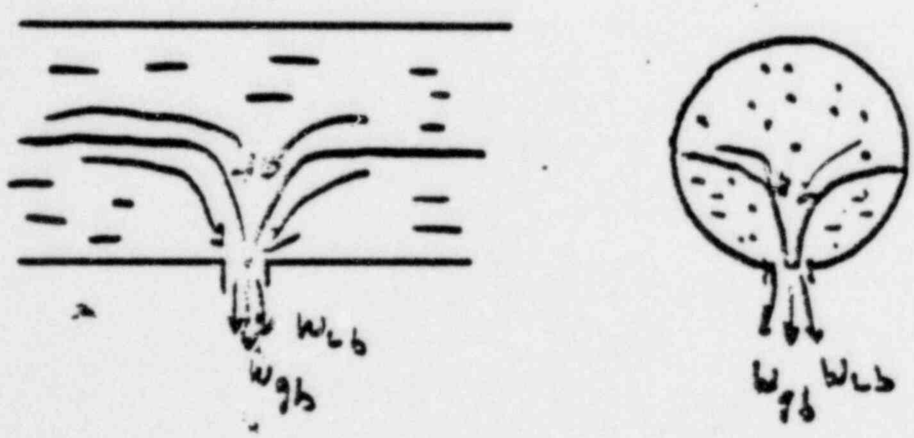


b)

Vapor Pull-Through

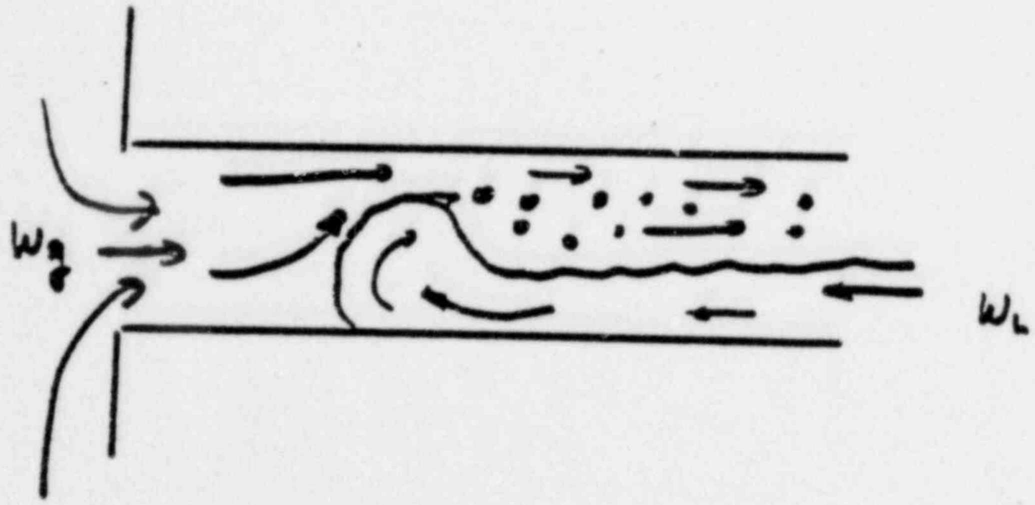


a) Vapor pull-through due to vortex formation

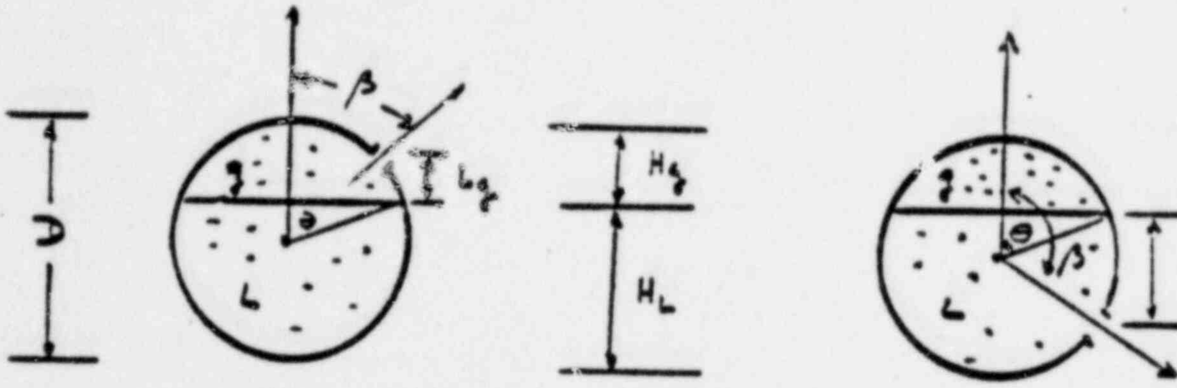


b) Vortex free flow

CCFL



Geometric Similarity



$$\alpha = \frac{1}{\pi}\left[\theta - \sin\theta\cos\theta\right] \quad ; \quad \frac{H_L}{D} = \frac{1}{2}\left(1+\cos\theta\right)$$

$$\frac{L_g}{D} = \frac{1}{2}\left[\cos\beta - \cos\theta\right] \quad ; \quad \frac{L_\ell}{D} = \frac{1}{2}\left[\cos\theta - \cos\beta\right]$$

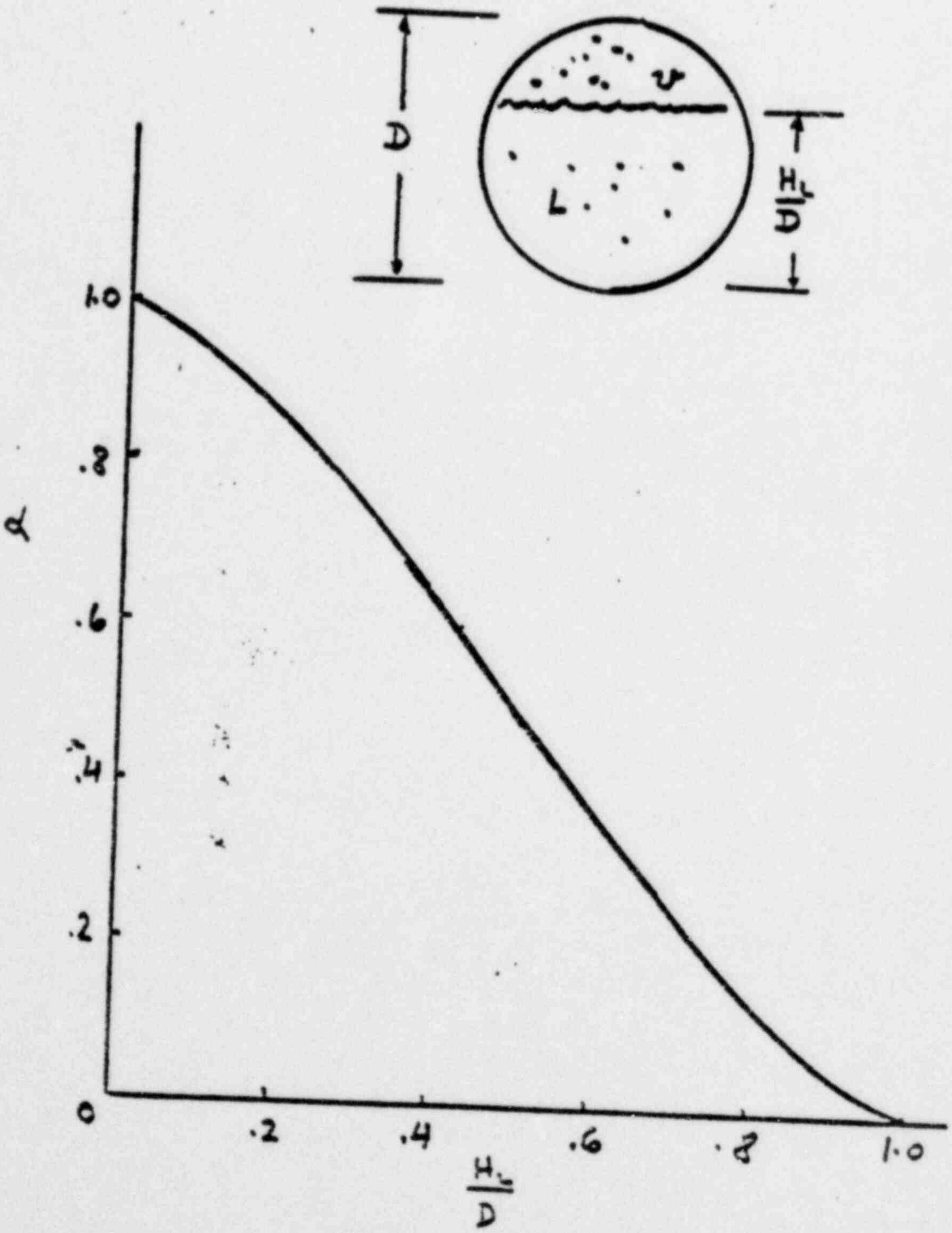
Consequently when:

$$\alpha_M = \alpha_R \quad \& \quad \beta_M = \beta_R$$

then:

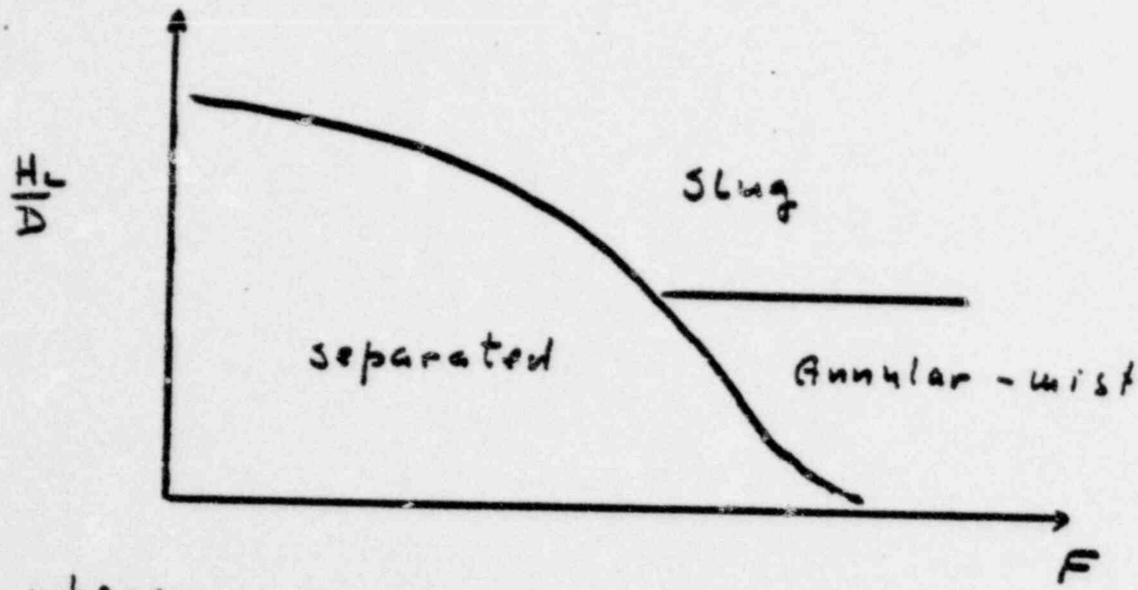
$$\theta_M = \theta_R \quad ; \quad \left(\frac{H_L}{D}\right)_M = \left(\frac{H_L}{D}\right)_R$$

$$\left(\frac{L_g}{D}\right)_M = \left(\frac{L_g}{D}\right)_R \quad ; \quad \left(\frac{L_\ell}{D}\right)_M = \left(\frac{L_\ell}{D}\right)_R$$



D
V
L
$\frac{H_L}{D}$
1.0
.8
.6
.4
.2
0
α
.2
.4
.6
.8
1.0
$\frac{H_L}{D}$

Dukler – Teitel Flow Regime Map



where:

$$F = \frac{j_g \sqrt{\rho_g}}{\sqrt{g \Delta\rho D}} = f\left(\frac{H_L}{D}\right)$$

if

$$\alpha_M = \alpha_R$$

then

$$\left(\frac{H_L}{D}\right)_M = \left(\frac{H_L}{D}\right)_R$$

and

$$F_M = F_R$$

If transitions occur at the same pressure then

$$\left(\frac{j_g}{\sqrt{D}}\right)_M = \left(\frac{j_g}{\sqrt{D}}\right)_R$$

Power to Volume Scaling

Power: $\dot{Q}$

Volume: V

Power to volume scaling:

$$\frac{\dot{Q}_R}{\dot{Q}_M} = \frac{V_R}{V_M} = S$$

Energy balance:

$$\dot{Q} = \rho_g h_{fg} j_g A_c$$

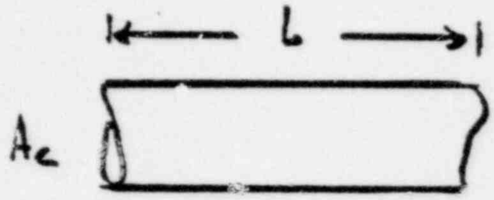
therefore:

$$\frac{j_{gM}}{j_{gR}} = \left(\frac{\dot{Q}}{A_c}\right)_M \left(\frac{A_c}{\dot{Q}}\right)_R = \frac{1}{S}\left(\frac{D_R}{D_M}\right)^2$$

Conditions for Isochronicity

Power to volume scaling:

$$\left(\frac{\dot{Q}}{V}\right)_M = \left(\frac{\dot{Q}}{V}\right)_R$$



using energy balance:

$$\left(\frac{\rho_g h_{fg}\, j_g A_c}{A_c L}\right)_M = \left(\frac{\rho_g h_{fg}\, j_g A_c}{A_c L}\right)_R$$

therefore

$$\left(\frac{j_g}{L}\right)_M = \left(\frac{j_g}{L}\right)_R$$

define vapor residence time by

$$\tau = \frac{L}{v_g} = \frac{L\alpha}{j_g}$$

therefore

$$\frac{\tau_M}{\tau_R} = \frac{\alpha_M}{\alpha_R}$$

if: $\alpha_M = \alpha_R$

then: $\tau_M = \tau_R$

Application to LOFT & Semiscale

Power to volume scaling:

$$\frac{j_{gM}}{j_{gR}} = \frac{1}{S}\left(\frac{D_R}{D_M}\right)^2 \qquad 1$$

Scaling of flow regime transition

$$F_M = F_R \qquad 2$$

where:

$$F_M = \left[\frac{j_g\sqrt{\rho_g}}{\sqrt{g\Delta\rho D}}\right]_M \qquad 3$$

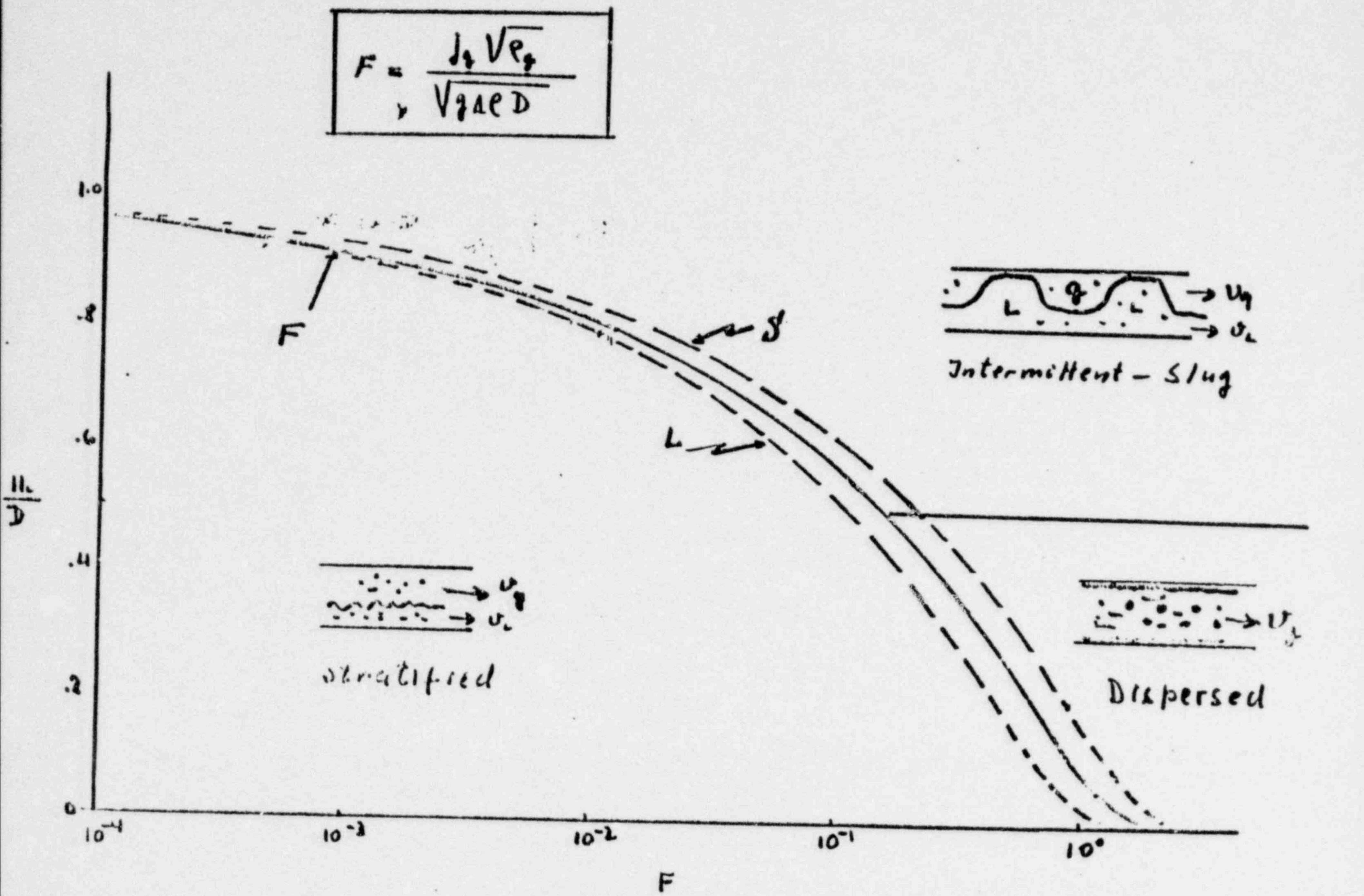
substituting Eq 1, in Eq 3:

$$\left(\frac{j_g\sqrt{\rho_g}}{\sqrt{g\Delta\rho D}}\right)_M = \underbrace{\frac{1}{S}\left(\frac{D_R}{D_M}\right)^2}_{\text{distortion}}\left(\frac{j_g\sqrt{\rho_g}}{\sqrt{g\Delta\rho D}}\right)_R \qquad 4$$

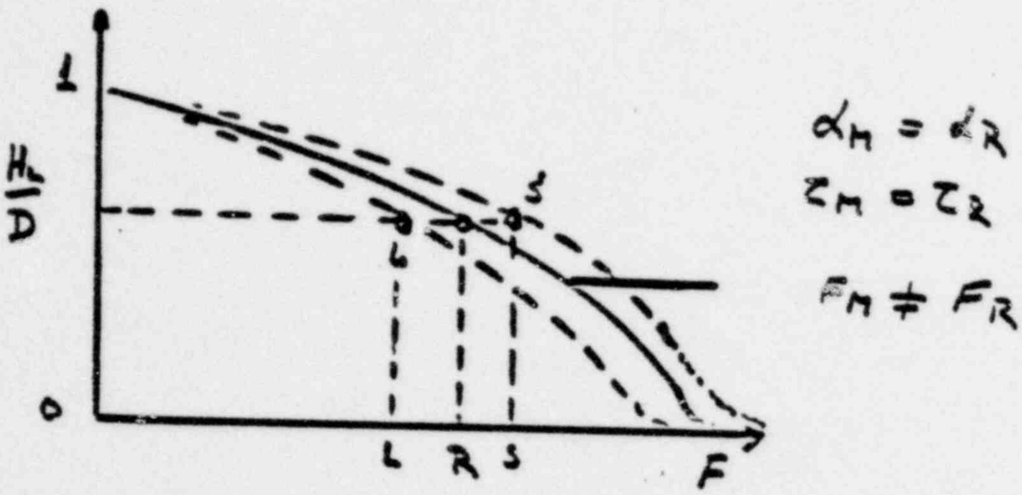
$$F_M = \frac{1}{S}\left(\frac{D_R}{D_M}\right)^{5/2} F_R$$

	D cm	S	$\frac{1}{S}\left(\frac{D_R}{D_M}\right)^{5/2}$
PWR	73.7	1	1
LOFT	28	64	0.175
Semiscale	3.4	1500	1.46

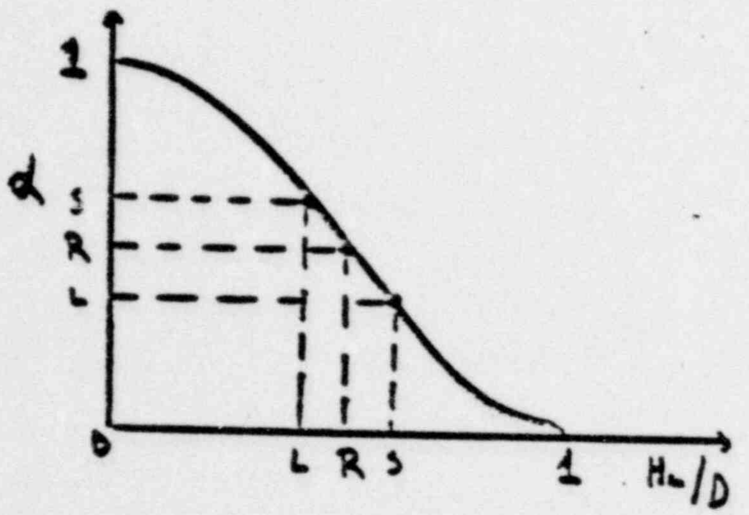
Conclusion: Flow regime transitions in a PWR are bounded by those in LOFT and Semiscale



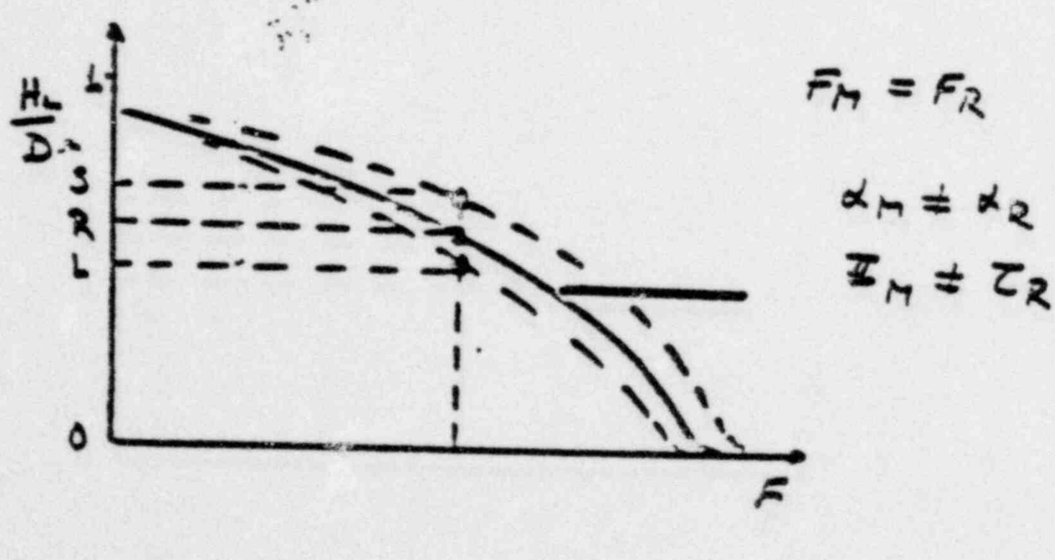
$F = \frac{j_g \sqrt{\rho_g}}{\sqrt{g \Delta\rho D}}$
1.0
.8
.6
.4
.2
0
$\frac{H_L}{D}$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
F
F
S
L
Intermittent - Slug
Stratified
Dispersed



1
H_L/D
0
L
R
S
F
$\alpha_M = \alpha_R$
$\tau_M = \tau_R$
$F_M \neq F_R$



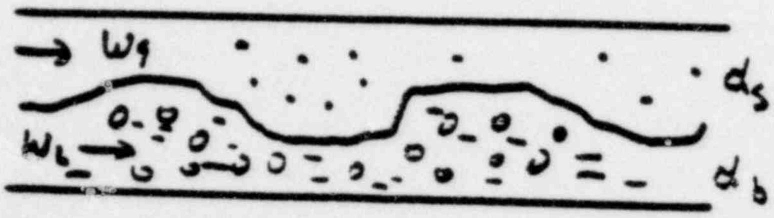
1
α
S
R
L
0
L R S
1
H_L/D



1
H_L/D
S
R
L
0
F
$F_M = F_R$
$\alpha_M \neq \alpha_R$
$\tau_M \neq \tau_R$

Effect of Flashing

1



$$\alpha_s + \alpha_b = \alpha$$

Flow transition criterion

$\alpha_b = 0$

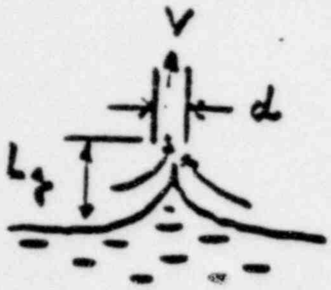
$$F = \frac{j_g \sqrt{\rho_g}}{\sqrt{g \Delta\rho D}} = f\left(\frac{H_L}{D}\right)$$

$\alpha_b \neq 0$

$$F = \frac{j_g \sqrt{\rho_g}}{\sqrt{g \Delta\rho (1-\alpha_b) D}} = f\left(\frac{H_L}{D}\right)$$

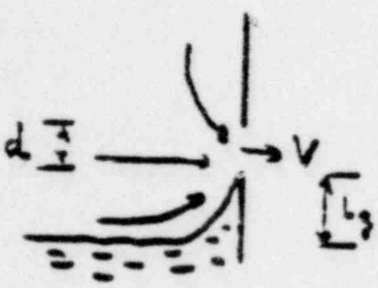
Liquid Entrainment

References: 1) Craya, A, Houille Blanche, 1949, pg 49-55
2) Gariel, P, " " ", pg 56-64
3) Rouse, H, Proc. ASCE, vol. 82, Aug 1956



Streeter Handbook of fluid Mechanics
ch. by Harlan

$$\frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho L_g}} \geqslant 5.7\left(\frac{L_g}{d}\right)^{3/2}$$



Orifice: $$\frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho L_g}} \geq 3.25\left(\frac{L_g}{d}\right)^{2}$$

Slot: $$\frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho L_g}} \geqslant 1.52\left(\frac{L_g}{d}\right)$$

$$\frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho L_g}} \geqslant c\left(\frac{L_g}{d}\right)^{m} \; ; \quad m = 1, \tfrac{3}{2}, 2$$

Application to LOFT and Semiscale

Power to volume scaling assuming same pressure and enthalpy increase:

$$\frac{\dot{Q}_R}{\dot{Q}_M} = S = \frac{v_R}{v_M}\left(\frac{d_R}{d_M}\right)^2$$

for choked flow at the break:

$$v_M = v_R$$

therefore:

$$\left(\frac{d_R}{d_M}\right)^2 = S$$

Entrainment correlations:

$$\frac{v\sqrt{\rho_L}}{\sqrt{g\Delta\rho L_g}} \geq \text{const}\left(\frac{L_g}{d}\right)^m$$

therefore:

$$\rightarrow \frac{D_R}{D_M}\frac{L_{gM}}{L_{gR}} = \left(\frac{d_M}{d_R}\right)^{m/m+1/2} = \left(\frac{1}{S}\right)^{\frac{m}{2m+1}}\frac{D_R}{D_M}$$

m	1	3/2	2
$m/2m+1$	1/3	3/8	2/5

Conclusion: Incipient liquid entrainment not scaled

However:

For PWR : $L_g < D = 73.7$ cm

for a 2.5% break: $d = 11.4$ cm

therefore:

$$\frac{L_g}{d} < \frac{D}{d} = \frac{73.7}{11.4} = 6.5$$

Assume choked flow: $V = 500$ m/sec at 1000 psia

then:

$$\frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho L_g}} > \frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho D}} = 187$$

for entrainment through orifice:

$$\frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho L_g}} \geq 3.25\left(\frac{L_g}{d}\right)^2 = 137$$

for PWR : 187 > 137

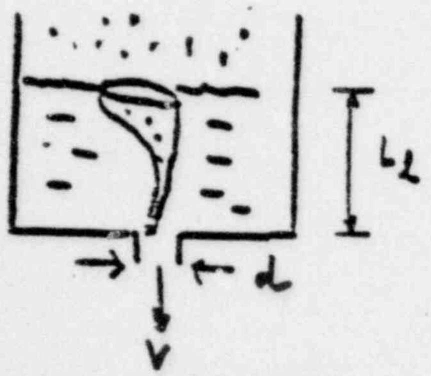
Conclusions: liquid entrainment probable in both facilities & PWR

Note: A more general correlation would be:

$$V\sqrt{\rho_g} \,/\, (g\Delta\rho L_g)^{1/2} = f\left(\frac{L_g}{d}\right)$$

Vapor Pull-through: Vortex Flow

Reference: L. Daggett and Keulegan G., "Similitude in Free Surface Vortex Formation," J. Hydr. Div. ASCE, v. 100, pg. 1506, 1974



$$\bar{R} = \frac{\pi}{2}\frac{Vd}{\nu} = \frac{\pi}{2} Re$$

Criteria for incipient vapor-pull-through:

$\bar{R} < 5\times10^4$:

$$\frac{L_l}{d} \le 17.5\times10^{-3}\ \frac{\Gamma}{\nu}$$ circulation

$\bar{R} > 5\times10^4$:

$$\frac{\Gamma}{V L_l} \geqslant \frac{\pi}{150}$$

Application to LOFT and Semiscale

Assume choked flow at the break

At $p = 1000$ psia : $V \simeq 20$ m/sec

then:

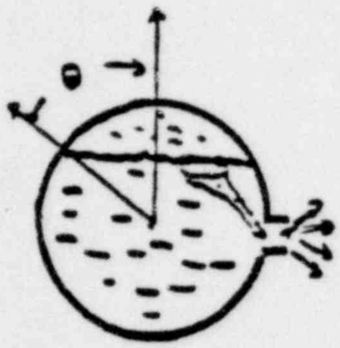
$$\left(\frac{Vd}{\nu}\right)_{g} = 4.25 \times 10^{5}$$

Therefore : incipient vapor pull-through is independent of break size

$$\frac{\Gamma}{V L_{e}} = \frac{\pi}{150}$$

or :

$$\frac{L_{eM}}{L_{eR}} = \frac{\Gamma_{M}}{\Gamma_{R}}$$



Assume:

$$\Gamma \sim v_L D \sin\theta$$

then:

$$\frac{(v_L D \sin\theta)_M}{(v_L D \sin\theta)_R} = \frac{L_{eM}}{L_{eR}}$$

For power to volume scaling:

$$\frac{v_{LM}}{v_{LR}} = \frac{1}{S} \frac{(1-\alpha)_R}{(1-\alpha)_M} \left(\frac{D_R}{D_M}\right)^2$$

therefore:

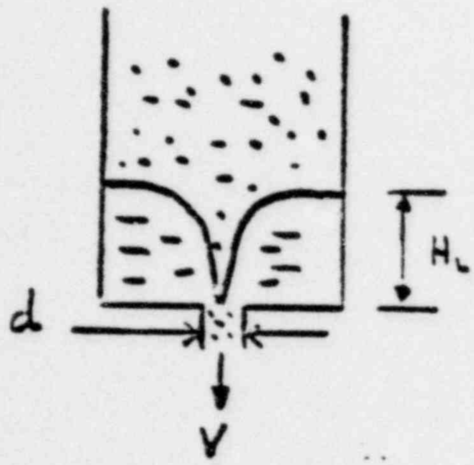
$$\frac{D_R}{D_M} \frac{L_{eM}}{L_{eR}} = \frac{1}{S} \frac{D_R}{D_M} \frac{(1-\alpha)_R}{(1-\alpha)_M} \frac{\sin\theta_M}{\sin\theta_R} \frac{D_R}{D_M}$$

$$\frac{1}{S}\left(\frac{D_R}{D_S}\right)^2 = 0.312 \quad , \quad \frac{1}{S}\left(\frac{D_R}{D_L}\right)^2 = 0.11$$

Conclusion: Incipient vapor pull-through not scaled

Vapor Pull-through : Vortex Free Flow

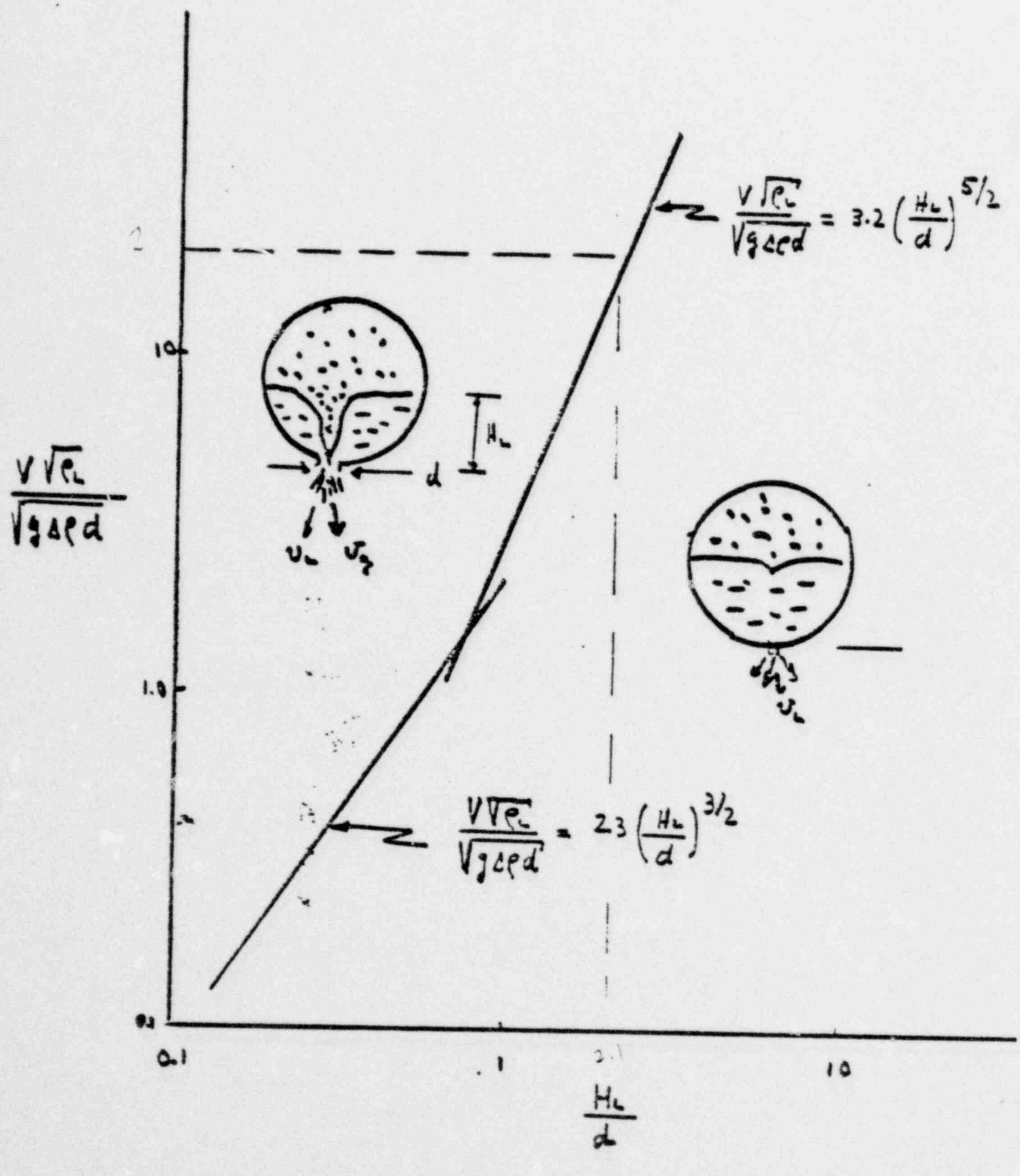
Reference: B. Lubin and M. Hurwitz: "Vapor Pull-through at a Tank Drain - With and Without Dielectrophoretic Baffling", Proc. Conf. Long Term Cryo-Propellant Storage in Space, NASA Marshall Space Center, Huntsville, Ala, Oct. 1966, pg. 173



Conditions for incipient vapor pull-through:

$$\frac{H_L}{d} < 1 \quad : \quad \frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho\, d}} = 2.3\left(\frac{H_L}{d}\right)^{3/2}$$

$$\frac{H_L}{d} > 1 \quad : \quad \frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho\, d}} = 3.5\left(\frac{H_L}{d}\right)^{5/2}$$



$\frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho d}} = 3.2\left(\frac{H_L}{d}\right)^{5/2}$
$\frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho d}} = 2.3\left(\frac{H_L}{d}\right)^{3/2}$
$\frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho d}}$
H_L
d
v_L
v_g
10
1.0
0.1
1
10
$\frac{H_L}{d}$

Application to LOFT and Semiscale

Power to volume scaling, assuming same pressure, enthalpy increase and choked flow:

$$\left(\frac{d_M}{d_R}\right)^2 = \frac{1}{S}$$

Correlations for incipient vapor pull-through:

$$\frac{L_I}{d} < 1 \quad : \quad \frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho d}} = 2.3\left(\frac{L_I}{d}\right)^{3/2}$$

therefore:

$$\frac{D_R}{D_M}\frac{L_{IM}}{L_{IR}} = \left(\frac{d_M}{d_R}\right)^{2/3} = \frac{1}{S^{1/3}}\cdot\frac{D_R}{D_M}$$

for:

$$\frac{L_I}{d} > 1 \quad : \quad \frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho d}} = 3.5\left(\frac{L_I}{d}\right)^{5/2}$$

therefore:

$$\frac{D_R}{D_M}\frac{L_{IM}}{L_{IR}} = \left(\frac{d_M}{d_R}\right)^{4/5} = \frac{1}{S^{2/5}}\frac{D_R}{D_M}$$

Conclusion: Incipient vapor pull-through is not scaled

For PWR and 2.5 % : $d = 11.4$ cm

$D = 73.7$ cm

therefore:

$$\frac{L}{d} < \frac{D}{d} = \frac{73.7}{11.4} = 6.5$$

Assume choked flow : $V = 20$ m/sec at 1000 psia

therefore:

$$F_R = \frac{V\sqrt{\rho_L}}{\sqrt{g\Delta\rho d}} = 20$$

From figure, at $F_R = 20$ vapor pull-through occurs at $H_L/d = 2.1$, that is at $H_L = 24$ cm

Conclusion page is missing

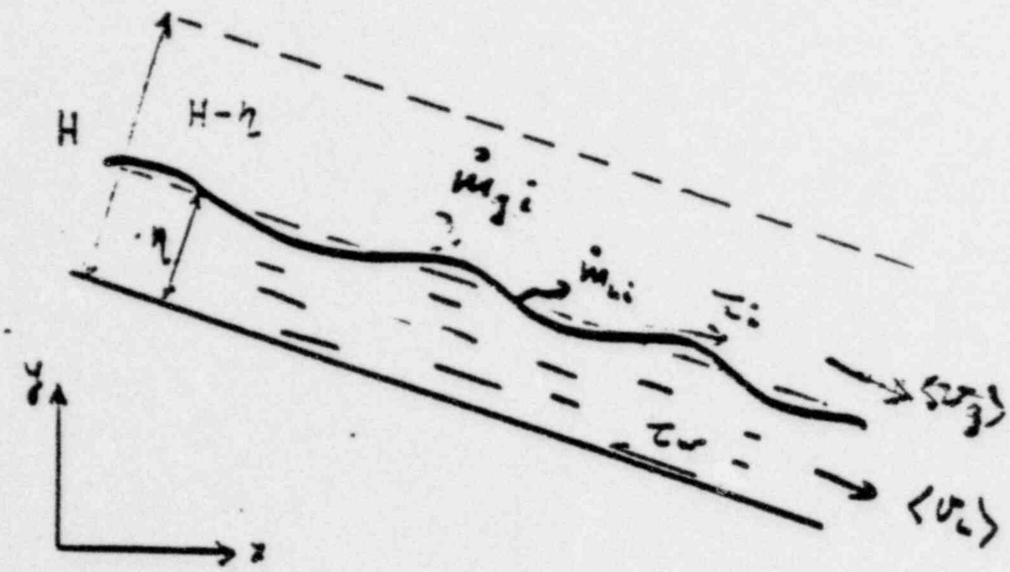
Always two phase flow discharge

Code Modifications

for

Horizontal Flow Phenomena

1-D Plane Flow



$$\frac{\eta(x,t)}{H} = 1 - \alpha(x,t)$$

Momentum Equations

Phase 1 : Liquid

$$\frac{\partial}{\partial t}\left[(1-\alpha)\rho_1\langle v_1\rangle\right] + \frac{\partial}{\partial x}\left[(1-\alpha)\rho_1\langle v_1\rangle^2\right] =$$

$$= -\frac{\partial}{\partial x}\left[(1-\alpha)\langle P_1\rangle\right] + (1-\alpha)\rho_1 g_x - \frac{\dot{m}_{1i}}{H} v_{1i} +$$

$$+ \frac{\tau_{2i}-\tau_{1w}}{H} + P_{1i}\frac{\partial}{\partial x}(1-\alpha) - \frac{\partial}{\partial x}\left[\mathrm{cov}(1)\right]$$

Phase 2 : Vapor

$$\frac{\partial}{\partial t}\left[\alpha\rho_2\langle v_2\rangle\right] + \frac{\partial}{\partial x}\left[\alpha\rho_2\langle v_2\rangle^2\right] =$$

$$= -\frac{\partial}{\partial x}\left[\alpha\langle P_2\rangle\right] + \alpha\rho_2 g_x - \frac{\dot{m}_{2i}}{H} v_{2i}$$

$$- \frac{\tau_{2i}}{H} - P_{2i}\frac{\partial(1-\alpha)}{\partial x} - \frac{\partial}{\partial x}\left[\mathrm{cov}(2)\right]$$

Present assumptions:

1) $\mathrm{cov}(1) = \mathrm{cov}(2) = 0$

2) $\langle P_1\rangle = P_{1i} \neq P_{2i} = \langle P_2\rangle$

Consequence:

$$-\frac{\partial}{\partial x}\left[(1-\alpha)\langle P_1\rangle\right] + P_{1i}\frac{\partial}{\partial x}(1-\alpha) = -(1-\alpha)\frac{\partial\langle P_1\rangle}{\partial x}$$

$$-\frac{\partial}{\partial x}\left[\alpha\langle P_2\rangle\right] - P_{2i}\frac{\partial(1-\alpha)}{\partial x} = -\alpha\frac{\partial\langle P_2\rangle}{\partial x}$$

$\therefore$ Ill posed problem

"Hydraulic" approximation:

$$\langle P_1 \rangle = P_{1i} - \frac{1}{2} \rho_1 (1-\alpha) g_y$$

$$\langle P_2 \rangle = P_{2i} + \frac{1}{2} \rho_2 \alpha g_y$$

Results in:

$$-\frac{\partial}{\partial x}\left[(1-\alpha)\langle P_1 \rangle\right] + P_{1i}\frac{\partial(1-\alpha)}{\partial x} = -(1-\alpha)\frac{\partial \langle P_1 \rangle}{\partial x} + \underline{\rho_1 (1-\alpha) g_y \frac{\partial(1-\alpha)}{\partial x}}$$

$$-\frac{\partial}{\partial x}\left[\alpha \langle P_2 \rangle\right] - P_{2i}\frac{\partial(1-\alpha)}{\partial x} = -\alpha\frac{\partial \langle P_2 \rangle}{\partial x} \underline{- \frac{1}{2} \rho_2 \alpha g_y \frac{\partial \alpha}{\partial x}}$$

Consequence: well posed problem

$\approx$ St. Venant eq. for channel flow

Note: The underlined terms are not present in Relap and TRAC codes.