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Docket No.: STN-52-003

December 18, 1995

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ATTENTION: T. R. QUAY

SUBJECT: WESTINGHOUSE AP600 NOTRUMP VERIFICATION AND BENCHMARK ACTIVITIES

Dear Mr. Quay:

Westinghouse has received from the NRC a number of requests for additional information (RAI) on the AP600 NOTRUMP computer code. These RAIs included requests to provide additional verifications and benchmarks of the NOTRUMP coding modifications performed as part of the verification and validation of the computer code for the AP600.

Westinghouse has provided responses to many of these RAIs which indicated that the scope and schedule for any additional code assessments would be provided to the NRC by December 31, 1995. The attached information summarizes the Westinghouse plan and schedule of work to be provided in this area. Included in the plan are additional NOTRUMP separate effects test simulations and additional NOTRUMP model assessments. These items are summarized in the attachment. The RAIs that each of these items relate to is included in the summary.

Please contact John C. Butler on (412) 374-5268 if you have any questions concerning this transmittal.

Brian A. McIntyre, Manager
Advanced Plant Safety and Licensing

/nja
Attachment

cc: W. Huffman, NRC
T. Collins, NRC
R. Landry, NRC
G. D. McPherson, NRC (w/o Attachments)
P. Boehnert, ACRS
N. J. Liparulo, Westinghouse (w/o Attachments)

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Westinghouse plan and schedule for additional NOTRUMP separate effects test simulations and additional NOTRUMP model assessments.

ADDITIONAL NOTRUMP SEPARATE EFFECTS TESTS

(Related to RAIs 440.468, 440.474, and 440.515)

In order to provide additional validation of the SIMARC Drift Flux Methodology, Modifications to Drift Flux Correlations, and the implicit treatment of Bubble Rise, Westinghouse will perform analysis of the G-2 level swell experiments given in EPRI report EPRI-NP-1692. Tests will be simulated over the full pressure range given in the test data at different bundle powers. Comparisons of the mixture height as a function of time, void distributions, vapor temperatures, and heater rod temperatures will be provided.

The results of these G-2 experiments are scheduled to be provided to the NRC in early March, 1996. Westinghouse intends to meet with the NRC staff before this date to discuss progress on modeling these tests.

ADDITIONAL NOTRUMP MODEL ASSESSMENT

A) Main Coolant Pump Model (related to RAI 440.475):

To assess the new coding a sample problem will be run with the AP600 plant model. The problem will be run twice, once with the old pump model and once with the new one. The problem will be run through the pump coastdown since the coastdown is what may be affected by the coding changes. Included in the NRC transmittal will be a brief description of the test problem and the resulting plots of flow rate through the pumps as a function of time. This work is currently scheduled for completion and transmittal to the NRC by the end of March, 1996.

B) Region Birthing Logic (related to RAI 440.478):

To demonstrate this logic the AP600 plant cases will be examined and a portion of a run will be identified that shows how a region is "birthed". After the appropriate case and time period is identified, the case will be rerun to capture the necessary detailed information to show the birthing of a region. Included in the NRC transmittal will be a brief description of the case performed and the appropriate figures to show the behavior of the model. This work is currently scheduled for completion and transmittal to the NRC by the end of March, 1996.

C) Horizontal Flow Drift Flux Model - Levelizing (related to RAI 440.477)
and Horizontal Stratified Flow Model (related to RAI 440.470):

To assess the validity of these models, calculations will be performed which will be similar to that performed using WCOBRA/TRAC by Takeuchi, et al in References 1 and 2 (Attachments 2 and 3). The same calculation will be done twice, once with each of the two models. The calculation is basically a computation of horizontal CCFL. This work is currently scheduled for completion and transmittal to the NRC by the end of March, 1996.

D) Implicit Treatment of Gravitational Head (related to RAI 440.476):

To verify the implicit treatment of gravitational head, a simulation of an oscillating manometer will be provided and analyzed both with and without the implicit treatment of gravitational head. The analyses will quantify the pressure imbalance produced by the explicit treatment of gravitational head, and they will verify that this pressure imbalance is virtually eliminated by the implicit treatment. This work is currently scheduled for completion and transmittal to the NRC by the end of March, 1996.

E) Fluid Node Stacking Logic (related to RAI 440.483):

To demonstrate this logic, two drain and fill problems will be performed, one single-phase and one two-phase. The single-phase problem will be a manometer similar to the one used to verify the implicit treatment of gravitational head (see item D). The two-phase problem will be a constant pressure boil-off problem similar to the one used to verify the implicit treatment of bubble rise (see item H). These problems will be done to highlight the operation of the fluid node stacking logic. This work is currently scheduled for completion and transmittal to the NRC by the end of March, 1996.

F) Net Volumetric Flow-Based Momentum Equation (related to RAI 440.469):

To assess this logic a portion of an AP600 plant calculation will be used. The calculation will be performed with the new logic turned on, and then will be performed again with the new logic turned off. Multiplots will be provided for the two cases for system pressure and mass flow rates in the flow links connecting the loops to the vessel. In addition, a simple problem will be performed to verify that the volumetric flow-based flow link model calculates the correct mass flow when the volume flow is specified. This problem will be a horizontal, frictionless pipe through which flow is maintained at a constant velocity (constant volumetric flow) as the density of the inlet steam/water mixture is varied. This work is currently scheduled for completion and transmittal to the NRC by the end of March, 1996.

G) Transient Two-Phase Level Swell (related to RAI 440.468)

To investigate flooding phenomena, calculations will be performed which will be similar to those performed using WCOBRA/TRAC in Reference 3. These calculations will demonstrate that the SIMARC methodology, the modified drift-flux correlations, and the changes to the distribution parameter properly treat flooding phenomena. They will basically be computations of vertical CCFL. This work is currently scheduled for completion and transmittal to the NRC by the end of March, 1996.

H) Bubble Rise (related to RAI 440.474):

To verify the implicit treatment of bubble rise, a constant-pressure boil-off problem will be simulated and analyzed both with and without the implicit treatment of bubble rise. The model will consist of a two-node stack connected at the top to a constant-pressure boundary node. Heat will be applied to the bottom of the stack, and the froth level will be initialized well into the upper node. The boil-off transient will be simulated until the froth level is well into the lower node. The simulations and corresponding analyses will demonstrate the implicit method's ability to exceed the material courant limit. This work is currently scheduled for completion and transmittal to the NRC by March 29, 1996.

REFERENCES

1) Takeuchi, K., Bajorek, S. M., Hochreiter, L. E., Kemper, R. M., "Horizontal Stratified Flow in Hot and Cold Legs at a Small Break LOCA of a PWR," ASME Paper 93-HT-1, Presented at the National Heat Transfer Conference, Atlanta, Georgia, August 8-11, 1993.

2) Takeuchi, K., Bajorek, S. M., Hochreiter, L. E., Kemper, R. M., "Horizontal Stratified Flow in a Small Break LOCA," Transactions ANS 64, 1991, pp. 638, 639.

3) Westinghouse Code Qualification Document for Best Estimate Loss of Coolant Accident Analysis, Volume 3, Hydrodynamics, Components, and Integral Validation, Section 15-1-2 (CCFL in a Vertical Channel), WCAP-12945-P.

ATTACHMENT 2

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

93-HT-1

HORIZONTAL STRATIFIED FLOW IN HOT AND COLD LEGS AT A SMALL BREAK LOCA OF A PWR

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ABSTRACT

The WCOBRA/TRAC code has been used extensively for the analysis of a large break loss of coolant accident (LOCA), and is now being developed to examine best estimate small break LOCA scenarios. Horizontal counter current flow limit (CCFL) and the transition from horizontal stratified flow to slug flow are important phenomena that a small break LOCA code must predict and calculate correctly. As a test for the WCOBRA/TRAC code's capability to predict these phenomena, counter flow in a horizontal channel was examined and code predictions of flooding in the horizontal channel were made. These predicted flooding points were compared to expected flooding points based on correlations for horizontal stratified to slug flow regime transition. A method of estimating the flooding point based on regime transition models is described. The code's prediction on flooding behavior was found to be in good agreement with the flow regime transition based flooding curve. Calculated water levels in the channel were found to agree well with the weir flow prediction.

INTRODUCTION

The WCOBRA/TRAC code[1-3] is a best estimate thermal hydraulic code for analyzing a PWR design basis large break loss-of-coolant accident (LBLOCA). WCOBRA/TRAC is a combination of the COBRA-TF and TRAC-PD2 computer codes. TRAC-PD2 is used to mol the loops with one dimensional components, and COBRA-TF is used for three dimensional modeling of the vessel internals. Efforts have been made to use the same code for a small break LOCA analyses.

In small break LOCA (SBLOCA) analyses, problems in predicting two phase flow phenomena have been summarized by Zuber[4]. Vapor pull through, or mixture quality at a break located at the top, the side, or the bottom of a horizontal pipe cannot be determined automatically without having a specific model. The same problem exists at the hot leg and the pressurizer surgeline junction. In addition, a problem exists in prediction of stratified flow and the counter current flow limit (CCFL) in the hot leg and cold leg. Indeed, flow slowly injected into the middle of a horizontal pipe modeled by a one-dimensional TRAC-PD2 component remains in the injected cell and does not flow into the neighboring cells. Improvement of the TRAC modeling was found important to such problems as gravity driven flows as opposed to pressure or momentum flux driven problems. All of the SBLOCA problems identified by Zuber are three dimensional by nature. Application of the COBRA-TF three dimensional cells to the piping components conceptually resolves the problem, however performance evaluation tests are necessary. In this paper, the code capability to predict horizontal CCFL is tested against CCFL correlations and the computed steady state liquid level is compared with the level of weir flow model.

The CCFL in a horizontal pipe was originally considered by Wallis[5]. He defined the flooding curve as a bounding condition of the Long's equation for existence of a solitary wave[6]. On a similar basis of an instability condition of a solitary wave, flow regime transition from a stratified flow to a slug flow was studied by Taitel and Dukler[7], and also by Wallis and Dobson[8]. The conditions for these two events are mathematically the same. But the expressions given

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to the phase transition are different from the flooding curves. In this paper, the two events are related and the formulae for the flow regime transitions are translated to the flooding curves for the stratified flow in a circular pipe and a square channel. These translated flooding curves and the Long / Wallis's flooding curve are also mutually compared in the next section. Tested in section 3 are the CCFL transitions computed with the COBRA three-dimensional pipe model, as a square channel. The computed results are compared with the above flooding curves. The water levels computed for steady states are compared with the weir flow model[9], in section 4.

HORIZONTAL CCFL CORRELATIONS

Wallis derived a flooding correlation for a horizontal stratified flow in search of the bounding condition of the Long's equation for a stratified wave in a channel. In order to accommodate other correlations and theories, we assume the more general form,

$$\frac{j_f^{*2}}{(1-\alpha)^{\nu}} + \frac{j_g^{*2}}{\alpha^{\nu}} = c^2 \tag{1}$$

as the drift flux relation, where dimensionless volumetric flux for steam is defined by

$$j_g^* \equiv j_g\left[\frac{\rho_g}{gD\Delta\rho}\right]^{1/2} \tag{2}$$

corresponding to volumetric flux j_g (m/sec) for steam, D is the hydraulic diameter, g is the acceleration of gravity, ρ_g is the steam density, and $\Delta\rho = \rho_f - \rho_g$. The dimensionless volumetric flux j_f^* for liquid is similarly defined with the liquid density ρ_f. Equation (1) with c=1 and m=3 becomes the Long / Wallis equation (see p.139-141 of Ref. 5). This Equation (1) represents a family of ellipses in the (j_f^*, j_g^*)-plane. The derivative of this equation with respect to void fraction α,

$$\frac{j_f^{*2}}{(1-\alpha)^{\nu+1}} - \frac{j_g^{*2}}{\alpha^{\nu+1}} = c^2 \tag{3}$$

yields a family of curves tangent to the above family of ellipses.

The flooding curves are obtained from these two equations by eliminating the void fraction, α. In the process an interesting relationship comes out. Eliminating j_f^* from Eqs.(1) and (3) yields the expression:

$$j_g^* = c\alpha^{(\nu+1)/2} \tag{4}$$

The flooding curve is

$$(j_f^*)^{2/(\nu+1)} + (j_g^*)^{2/(\nu+1)} = c^{2/(\nu+1)} \tag{5}$$

The drift flux relation of a vertical flow in the (j_g^*, j_f^*) coordinate system is a straight line for a given void fraction. The drift flux of a horizontal flow is given by Eq.(1) and forms an ellipse, as shown in Figure 1. The first quadrant is for the cocurrent flow and the second quadrant for counter-current flow. The envelope in the first quadrant is the flow regime transition. The flow regime beyond this part of envelope can no longer be a horizontal stratified flow but a slug, intermittent, or annular dispersed flow. The envelope in the second quadrant is the flooding curve beyond which no flow state exists. Both conditions for the flow regime transition and the flooding have been derived mathematically on the same ground that the solitary wave grows indefinitely. The flow regime transitions have been expressed in the form of Equation (4). Once the phase transition is identified, the coefficients of c and m are determined for the flooding relationship of Eq.(5).

EXAMPLE 1: Taitel-Dukler with A Circular Pipe

The Taitel-Dukler phase transition[7] from horizontal stratified flow to intermittent and annular dispersed liquid flow regimes is conditioned by

$$j_g^* > C_2\alpha^{3/2}\left[(4/(\pi D))\frac{dA_L}{dh_L}\right]^{-1/2} \tag{6}$$

where A_L and h_L are liquid flow area and the level. This is a complicated expression of α which can be approximated by

$$j_g^* = \alpha^3 \tag{7}$$

In Eq.(4), c = 1 and m = 5. Therefore, the flooding curve of Eq.(5) becomes

$$(j_f^*)^{1/3} + (j_g^*)^{1/3} = 1. \tag{8}$$

EXAMPLE 2: Taitel-Dukler with A Circular Pipe And C_2 = 0.5

In the Taitel-Dukler phase transition formula, the factor C_2 can be 0.5, just as Wallis-Dobson. In this case, the transition condition can be approximated by,

$$j_g^* = 0.55\alpha^2 \tag{9}$$

Because c = 0.55 and m = 3, the flooding curve of eq.(5) becomes,

$$(j_f^*)^{1/2} + (j_g^*)^{1/2} = 0.742 \tag{10}$$

EXAMPLE 3: Wallis-Dobson with A Square Channel

After a series of tests, Wallis-Dobson[8] derived the flow regime transition formula in a similar expression.

$$j_g^* = 0.5\alpha^{1.5} \qquad (11)$$

Therefore, c = 0.5 and m = 2 and the flooding curve of Eq.(5) becomes

$$(j_l^*)^{2/3} + (j_g^*)^{2/3} = 0.707 \qquad (12)$$

These obtained flooding curves are shown in Figure 2. The three flooding curves are approximately the same, especially at the middle point, $\alpha = 0.5$.

The phase transition and the flooding curves are symmetric, consistent with the Taitel-Dukler approximation for the interfacial force to be dependent only the steam velocity, ignoring the interface velocity.

The Long / Wallis's flooding curve in Reference 5 is shown as case (4) in Figure 2. His flooding curve is derived from Long's wave equation which is based on the classic velocity potential theory for a stratified flow. Taitel-Dukler phase transition correlations takes into account the interphasic forces as well as fluid wall forces. Therefore the two phases are more strongly coupled in Taitel-Dukler correlation than they are in the Long / Wallis correlation. The Wallis and Dobson correlation in example 3 is the test data and obviously these forces are in effect.

COMPUTATION OF HORIZONTAL CCFL

A horizontal pipe was modeled by COBRA-TF three dimensional cells, forming a square channel. The CCFL is obtained with saturated steam and liquid under a counter-current state. As steam flow rate is gradually increased, liquid flow direction is eventually reversed. The flow states obtained through out the process of computation will be compared with the flooding correlations obtained in the previous section.

A horizontal 5.486 m (18 ft.) long pipe of 0.91 m by 0.91 m (3 ft. by 3 ft.) square cross section is modeled with six horizontal channels and 3 cells in each channel, as illustrated in Figure 3. These dimensions approximate a PWR hot leg. The channels are connected laterally by "gaps". Channel 10 has a dead end at the left and a pressure boundary condition at the top. A 1D pipe component is connected at the bottom of channel 9 to supply liquid. Steam is injected at the top of channel 5. The right hand end of channel 5 is connected to a region simulating a large volume.

Initially, the entire system is assumed filled with saturated steam, at 1000 psia. A transient calculation begins with injection of saturated liquid at a constant rate. After a steady state of liquid flowing into the container is established, saturated steam is injected. The injected steam flows out of the system at the pressure boundary, forming a counter-current state. The steam injection rate is gradually increased so that a quasi steady state is maintained throughout the computation.

With a constant liquid injection rate ranging from 31.75 to 442.3 kg/s (70 to 650 lb_m/sec), the computed flow states are shown in Figure 4 by circles in the coordinates of square roots of dimensionless volumetric fluxes for steam and liquid. For a given liquid flow rate, computed states are linked by lines. The lowest point shows a finite steam flow rate, while the steam injection rate is still zero. This steam flow is due to the steam in the large vessel volume displaced by the liquid flowing into the vessel. As the steam injection rate increases, the circles move up-wards, turn along the flooding curve. Eventually, the liquid flow direction is reversed and both liquid and steam flow out of the system through the pressure boundary at the top of channel 10. The computed flow states agree well with the flooding constraints.

WATER LEVEL

Before steam was injected, a steady state liquid flow was established through the square channel into the vessel. The liquid fractions computed in each cell are shown in Table 1. The equivalent water levels are also shown. First, realization of horizontal stratified flow is evident. Next, the water levels are compared with the weir flow level, n_0, given by

$$q_T = Dg^{1/2}((2/3)\,n_0)^{3/2} \qquad (13)$$

for the total volumetric flow rate, q_T, the width of the crest, D, and the acceleration of gravity, g. The weir flow levels are computed for each flow rate in Table 1 and the results are shown. The water levels computed with the WCOBRA/TRAC code agree well with the weir flow prediction over the entire range of flow rates in consideration.

The Taitel-Dukler equilibrium levels are expressed as a function of X defined in Eq.(8) of Ref. 7:

$$\chi^2 = \frac{C_l(j_l(D/\nu_l))^{-0.2}\rho_l(j_l)^2}{C_g(j_g(D/\nu_g))^{-0.2}\rho_g(j_g)^2} \qquad (14)$$

where C_l is the friction factor, ν_l is the dynamic viscosity, and ρ_l is the density of liquid phase and the quantities subscripted by g are similarly defined for the gas phase. This formula is applied to our computational steady state situation: that is, the injected liquid flows into the vessel and displaces steam in the vessel. The displaced steam flows through the pipe in the opposite direction to the liquid flow and exits to a constant pressure boundary. Thus, in the steady state, steam and liquid forms a counter current flow and $j_g = j_f$. With the application of the last relationship to Eq.(14) the value of X is found to be 3.36 (or water level = 1.86 ft.). It is clear from Equation (14) that this condition is independent of the liquid flow rate. Equation (14) was originally derived assuming equilibrium conditions. In this situation, close to the weir, however, this assumption may not hold.

DISCUSSION AND CONCLUSION

The horizontal stratified flow was modelled with three-dimensional cells of WCOBRA/TRAC code. The computed water levels were found to agree with the weir flow model for all the tested cases of liquid flow rates ranging from 31.75 to 442.3 kg/s (70 to 975 lb_m/sec).

A drift flux relation of a horizontal stratified flow is bordered by both the flooding curve and the flow regime transition curve. Thus, the drift flux relation determined by the correlation for the flow regime transition specifies the flooding curve, as described in the text. The domains of these flow regime determined flooding curves are smaller than those of the original Wallis flooding curve. The former forbids two phase counterflow at lower velocities than the latter. This indicates a stronger coupling of the two phases with the flow regime transition based flooding curve than with the Wallis flooding curve. This is the result of the interfacial forces which have been taken into account in the flow regime transition correlation, but not in the Wallis flooding curve.

The computed CCFL agree well with the flooding curves. To find stability of the above results, a sensitivity study was conducted by varying the number of cells per channel, by changing the length of the pipe, and then changing the channel length. The computed results were quite stable as long as the number of cells is greater than one and the channel length (or horizontal cell spacings) remains approximately the size of the pipe diameter.

An interesting future work would be establishing a relationship between the horizontal and vertical drift flux relations. For a vertical pipe, the drift fluxes of the liquid and the vapor phases form a straight line in a (j_g^*, j_f^*)-plane for a constant void fraction. It becomes an ellipse in a horizontal pipe as illustrated in Figure 1. It is of interest to find out how the transition between the two extremes takes place in an inclined pipe.

REFERENCES

1. T. E. Guidotti and M. J. Thurgood, "COBRA/TRAC Large Break LOCA Calculations", ANS-tr-46 (1984) 469.

2. M. J. Thurgood, et. al., "COBRA/TRAC: A Thermal Hydraulics Code for Transient Analysis of Nuclear Reactor Vessels and Primary Coolant Systems", NUREG/CR-3046 (1983).

3. L. E. Hochreiter, et. al., "The Westinghouse Best-Estimate LOCA Model: WCOBRA/TRAC", ANS-tr-55 (1987) 458.

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5. G. B. Wallis, "One-Dimensional Two Phase Flow", McGraw-Hill, N. Y. (1969).

6. R. R. Long, "Solitary Wave in the One- and Two- Fluid Systems", Tellus, vol. 8, pp.460-471 (1956).

7. Y. Taitel and A. E. Dukler, "A Model for Predicting Flow Regime Transitions in Horizontal and near Horizontal Gas-Liquid Flow", AIChE Journal 22, (1976) 47.

8. G. B. Wallis and J. E. Robson, "The Onset of Slugging in Horizontal Stratified Air-Water Flow", Int. J. Multiphase Flow, Vol. 1 (1973) 173.

9. I. H. Shames, "Mechanics of Fluids", McGraw-Hill, New York, N. Y. (1982).

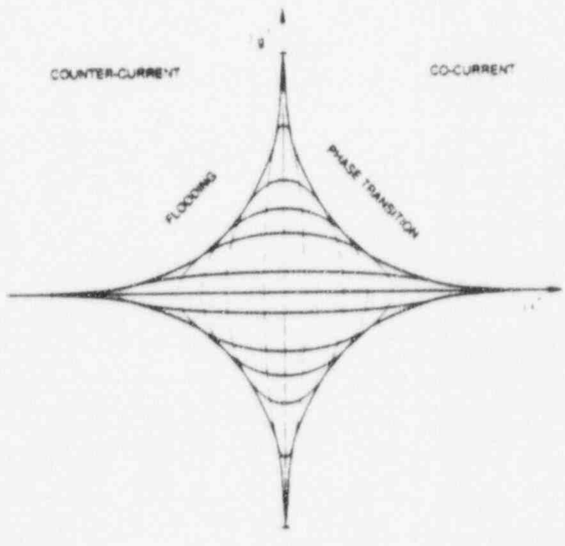

Figure 1. The Drift Flux in a Horizontal Stratified Flow and The Flooding Curves

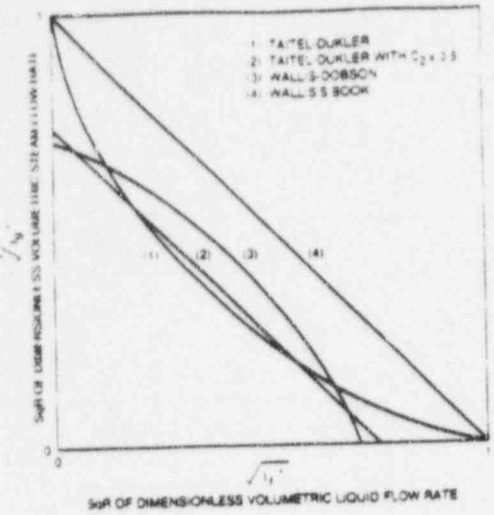

Figure 2 The Flooding Curves for Horizontal Stratified Flow

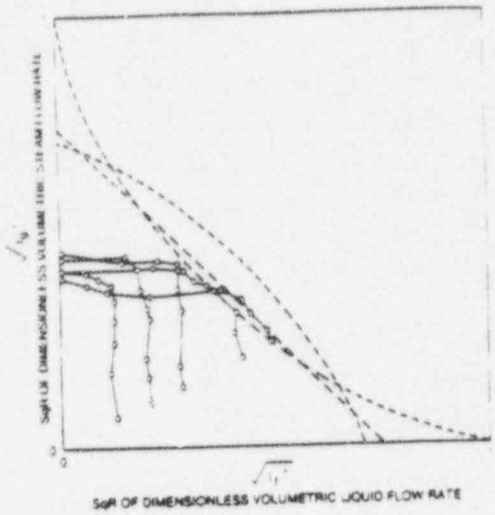

Figure 4 The Computed Horizontal Flow State and The Flooding Curves.

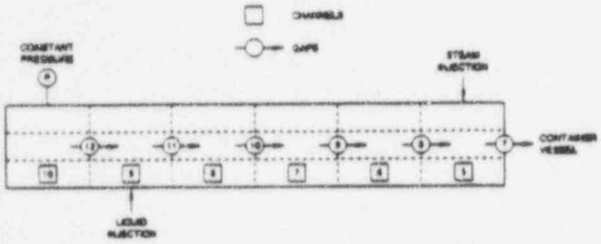

Figure 3 A Three Dimensional Model for A Horizontal Pipe

TABLE I

THE COMPUTED WATER LEVELS AND THE WEIR MODEL

Channel	10	9	8	7	6	5
W_L=70 lb_m/sec						
α_L cell 2	0.	0.	0.	0.	0.	0.
cell 1	.674	.617	.494	.424	.359	.160
water Level (ft.)	.674	.617	.494	.424	.359	.160
	weir flow Level = 0.30 ft.					
W_L=170 lb_m/sec						
α_L cell 2	0.	0.	0.	0.	0.	0.
cell 1	.993	.923	.988	.876	.763	.321
water Level (ft.)	.993	.923	.988	.876	.763	.321
	weir flow Level = 0.54 ft.					
W_L=325 lb_m/sec						
α_L cell 2	.030	.104	.030	0.	0.	0.
cell 1	.992	.992	.994	.942	.892	.499
water Level	1.022	1.096	1.024	.942	.892	.499
	weir flow Level = 0.83 ft.					
W_L=650 lb_m/sec						
α_L cell 2	.733	.988	.525	.351	.222	0.
cell 1	.992	.999	.969	.991	.980	.581
water Level	1.725	1.987	1.514	1.342	1.202	.581
	weir flow Level = 1.32 ft.					
W_L=975 lb_m/sec						
α_L cell 3	.134	.016	.040	.023	0.	0.
cell 2	.992	.990	.846	.683	.528	.296
cell 1	.995	1.0	.993	.992	.992	.746
water Level	2.121	2.006	1.879	1.698	1.120	1.042
	weir flow Level = 1.72 ft.					

AP600

ATTACHMENT 3

VOLUME 64
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1991 WINTER MEETING

SAN FRANCISCO, CALIFORNIA

NOVEMBER 10–14, 1991

AMERICAN NUCLEAR SOCIETY

TRANSACTIONS

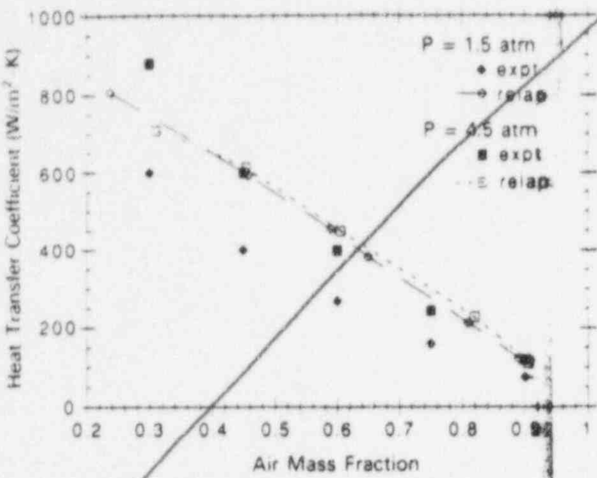

Fig. 3. Heat transfer variation with air fraction.

2. K. E. CARLSON, R. E. RIEMKE, S. Z. ROUHANI, R. W. SHUMWAY, W. L. WEAVER, "User's Guide and Input Requirements, RELAP5/MOD3 Code Manual," Vol. 2, Idaho National Engineering Lab. (June 1990).

3. Horizontal Stratified Flow in a Small-Break LOCA, *K. Takeuchi, S. M. Bajorek, L. E. Hochreiter, R. M. Kemper (Westinghouse)*

A major concern in the analysis of a small-break loss-of-coolant accident (LOCA) is the modeling of countercurrent flow limit (CCFL) conditions in horizontal pipes.[1] Normally, this is modeled using two momentum equations, one each for the vapor and liquid, and a flow regime map that chooses the interfacial area. A novel approach was taken with the WCOBRA/TRAC code by extending the vessel channels outward to model the hot and cold legs. In this case, three momentum equations, one for each field (liquid, vapor, and entrained liquid), are solved. The use of vertical cells in these channels permits a natural modeling of the physical flow in the piping. A horizontal pipe corresponding to the hot leg was modeled by a three-dimensional vessel model in the WCOBRA/TRAC code. The code capability in CCFL prediction was tested by comparing the computed flooding curve with Wallis's correlation.[2] Computed liquid levels are compared with Taitel-Dukler's equilibrium level[3] and the Weir flow model.

A horizontal 18-ft-long pipe of 3-ft- × 3-ft-square cross section is modeled with six horizontal channels and three cells in each channel, as illustrated in Fig. 1. The channels are connected laterally by gaps. Channel 10 has a dead end at the left and a pressure boundary condition at the top. A one-dimensional pipe component is connected at the bottom of channel 9 to supply liquid. Steam is injected at the top of channel 5. The right-hand end of channel 5 is connected to a large vessel container.

Initially, the entire system is filled with saturated steam at 1000 psia. A transient calculation begins with injection of saturated liquid at a constant rate. After a steady state of liquid flowing into the container is established, saturated steam is injected with gradually increasing rate until the liquid flow is reversed, and both liquid and steam flow out of the system through the pressure boundary condition at the top of channel 10.

With a constant liquid injection rate ranging from 70 to 650 lb_m/s, the computed flow states are shown in Fig. 2 by closed rectangles in the coordinates of square roots of dimensionless volumetric fluxes for steam and liquid. It is of interest to see a clear flooding limit in the computation. From the envelope, the flooding relation in WCOBRA/TRAC is estimated to be

$$(j_g^*)^{1/2} + (j_f^*)^{1/2} = c \,, \tag{1}$$

with $c = 0.59$. The Wallis flooding theoretical model for a horizontal pipe[2] is $c = 1$. Taitel-Dukler's flow regime transition can be translated to a CCFL. In this case, $c = 0.707$ so that the computed CCFL is also quantitatively good.

At a 170 lb_m/s liquid injection rate, a steady state was computed. The liquid level was computed to be $0.37 * D$, where D is the pipe height. On the other hand, the Taitel-Dukler equilibrium level would be $0.62 * D$. According to the Weir flow model, the level would be $0.18 * D$. Probably, the effect of the

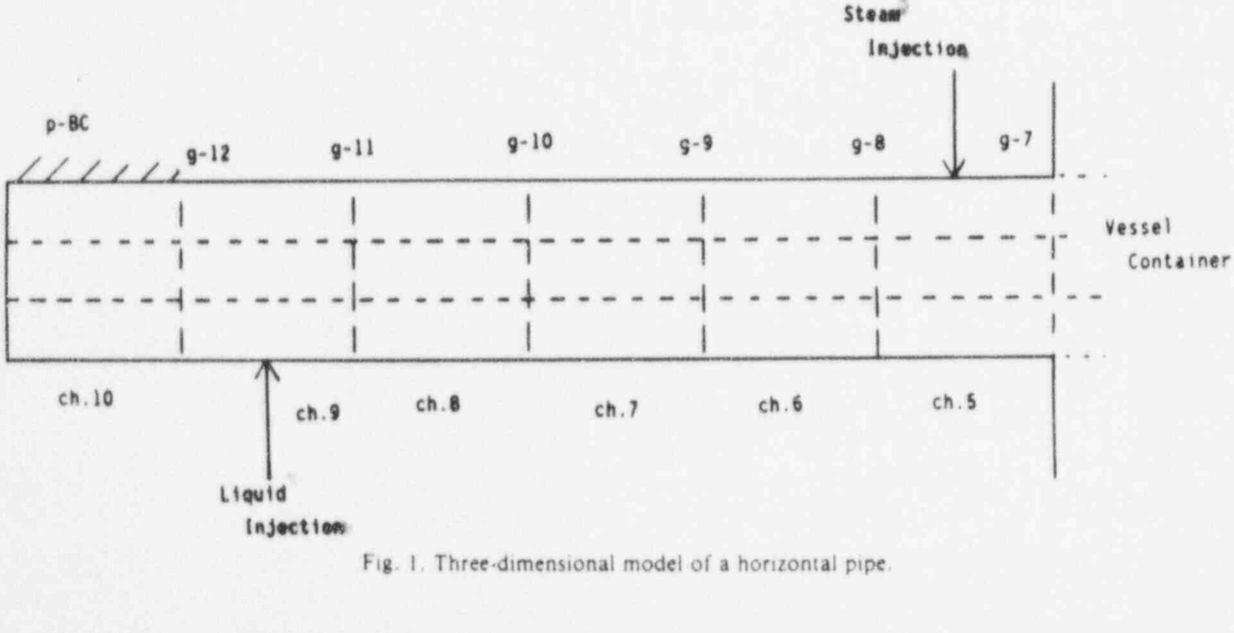

Fig. 1. Three-dimensional model of a horizontal pipe.

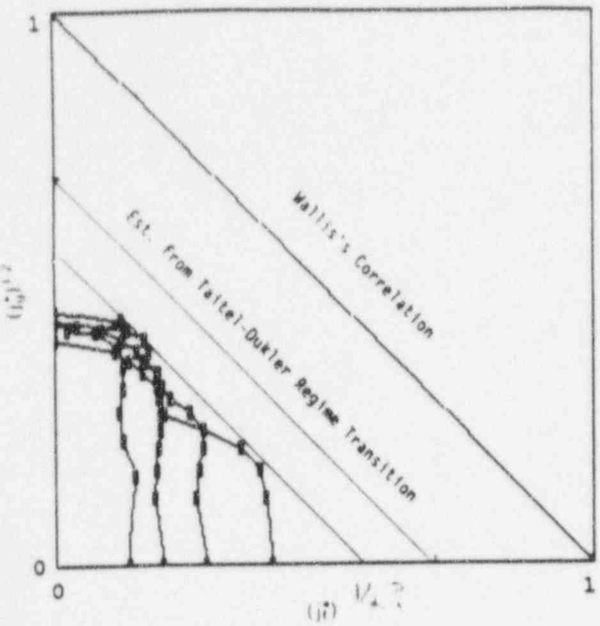

Fig. 2. Flooding limit in a horizontal pipe computed by WCOBRA/TRAC versus Wallis's correlation and estimate from Taitel-Dukler flow regime transition.

boundary condition is too strong in the short pipe model to be comparable to the theories.

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3. Y. TAITEL, A. E. DUKLER, "A Model for Predicting Flow Regime Transitions in Horizontal and near Horizontal Gas-Liquid Flow," *AIChE J.*, **22**, 47 (1976).

4. Microgravity Phase Separation of Rotating Fluids in a Fixed Cylinder, *Igor Carron, Frederick Best (Texas A&M)*

INTRODUCTION

The management of gas-liquid flow in a reduced gravity environment is subject to engineering characteristics different from those applied on Earth. The significance of surface tension effects compared with reduced buoyancy caused by the very low gravity levels experienced in spacecraft makes it compulsory to revise engineering considerations with regard to the design of gas-liquid separation devices. A preliminary experiment was performed by the interphase transport phenomena laboratory at Texas A&M University to assess the different needs required for a better comprehension of the stability of gas-liquid interfaces in rotating fluids under microgravity conditions.

PREVIOUS WORK

Although separation by stratification is easily achieved under normal gravity, it becomes a challenge when the stratification due to gravity is comparable to other forces, e.g., surface tension. The concept of separation by centrifugal forces has therefore arisen. Leslie[1] performed experiments aboard the National Aeronautics and Space Administration (NASA) KC-135 reduced-gravity aircraft on rotating bubbles in a low-gravity environment. His experiments and calculations show that the centrifugal effect positions the gas at the center of a rotating liquid, as expected. The liquid in Leslie's experiment is dragged along by the wall of the rotating container. He also shows the specific parameter that needs to be taken into account for the stabilizing effect of rotation. The perturbational influence of gravity jitters on a rotating liquid is assessed in the analysis of Hung et al.,[2] which tracks the time-dependent axisymmetric interface. However, this approach to phase separation requires a rotating container with attendant mass and reliability penalties that are undesirable in spacecraft systems.

CONCEPT DESCRIPTION

Since phase separation by fluid rotation in a stationary container seemed advantageous, a simple preliminary experiment to investigate relevant phenomena was developed. The air-water experiment described here, although very close to the previous experiments, has the particular feature of examining the behavior of the gas-liquid interface for a complex rotating fluid. Fluid motion is induced by a rotating stirrer at the (1-*g*) bottom of a cylindrical tank. The experiment was flown aboard the NASA KC-135 reduced-gravity aircraft. Fluid angular velocity was high enough to produce a vortex under 1-*g* conditions and a reorientation to an annular geometry under 0-*g* conditions. Tests were run with various stirring speeds and with the stirrer on or off during the 30-s 0-*g* periods. The interface shape was continuously recorded using a standard-speed video camera.

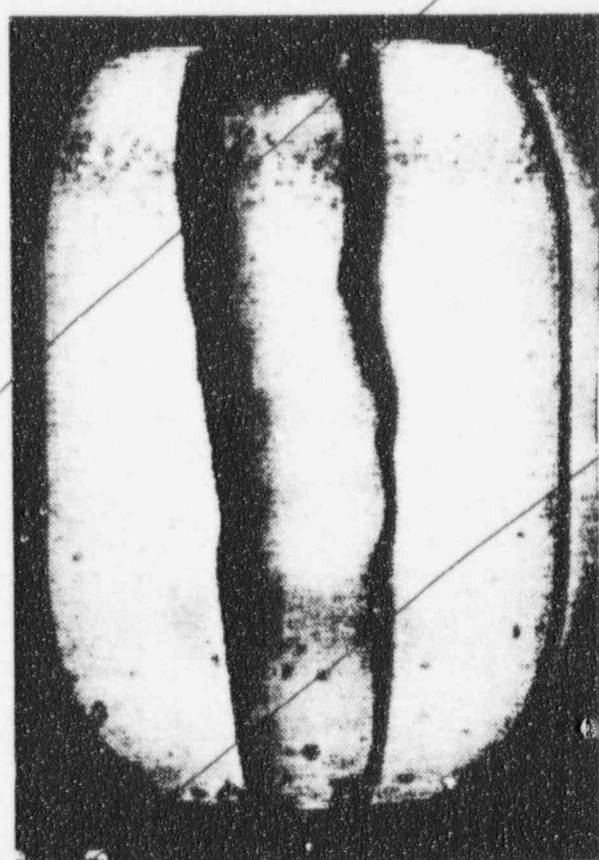

Fig. 1. Stable gas column in a rotating fluid under microgravity.