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DEVELOPMENTAL ASSESSMENT OF RELAP 5/MOD 3 CODE AGAINST ROSA-IV/TPTF HORIZONTAL TWO-PHASE FLOW EXPERIMENTS

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Yutaka KUKITA, Hideaki ASAKA, Yuichi MIMURA*, Yoshinari ANODA
Misako ISHIGURO, Toshiyuki NEMOTO** and Kanji TASAKA

日本原子力研究所
Japan Atomic Energy Research Institute

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Developmental Assessment of RELAP5/MOD3 Code Against ROSA-IV/TPTF Horizontal Two-phase Flow Experiments

Yutaka KUKITA, Hideaki ASAKA, Yuichi MIMURA*
Yoshinari ANODA, Misako ISHIGURO+, Toshiyuki NEMOTO**
and Kanji TASAKA

Department of Reactor Safety Research
Tokai Research Establishment
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken

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A developmental version of the RELAP5/Mod3 code (as of June 1989) was assessed for accuracy using experimental data taken for high-pressure (7 MPa) steam-water two-phase flow in a large-diameter (0.18 m) horizontal-pipe test section of the ROSA-IV Two-Phase Flow Test Facility (TPTF). The agreement between the measured and calculated test section void fractions was much better than that for the previous generation of RELAP5 (MOD2). The improvement was achieved primarily due to the code changes with respect to the flow stratification criterion and interfacial-drag calculation scheme.

Keywords: Two-Phase Flow, Flow Regime Transition, Horizontally Stratified Flow, Interfacial Drag, Computer Code, RELAP5, ROSA-IV, TPTF.

+ Computing Center
* ISL Co.
** Fujitsu, Ltd.

ROSA－Ⅳ／TPTF水平二相流データによるRELAP5／MOD3コードの開発的性能評価

日本原子力研究所東海研究所原子炉安全工学部
久木田　豊・浅香　英明・三村　裕一*・安濃田良成
石黒美佐子+・根本　俊行**・田坂　完二

（1990年2月16日受理）

現在開発の途上にあるRELAP5／MOD3コードの性能評価のため，ROSA－Ⅳ／TPTF装置による高圧（7MPa），大口径（0.18m）水－蒸気水平二相流実験の解析を行った。試験部内のボイド率に関する解析結果と実験結果の一致は，既存のRELAP5コード（MOD2）にくらべ著しく改善された。これは，層状流の発生限界に関するモデルならびに相間摩擦の計算方法がMOD2にくらべ改良された結果である。

東海研究所：〒319－11 茨城県那珂郡東海村白方字白根2－4
＋　計算センター
＊　㈱アイ・エス・エル
＊＊　㈱富士通

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1. INTRODUCTION

A developmental version of the RELAP5/MOD3 code [1], as of June 1989, was assessed at the Japan Atomic Energy Research Institute (JAERI) by analyzing horizontal two-phase flow experiments conducted at the ROSA-IV Two-Phase Flow Test Facility (TPTF) [2]. These experiments are characterized by a high system pressure (7 MPa), a large test section diameter (0.18 m) and a wide range of mass flux (40 to 1000 kg/m^{2}s) obtained in the test section for concurrent saturated two-phase flow.

The present assessment calculations were conducted as part of the research cooperation between JAERI and the United States Nuclear Regulatory Commission (USNRC) under an agreement between JAERI and USNRC on the USNRC participation in the JAERI ROSA-IV Program. Under this agreement, the USNRC is providing JAERI with successive versions of the RELAP5 code.

Previously, similar assessment calculations were performed by JAERI for the RELAP5/MOD2 code (cycle 36.02) [3]. These calculations indicated several deficits of the code as described in [4-6]. The three major problems found in these calculations are:

(1) The Taitel-Dukler flow stratification criterion [7] used in RELAP5/MOD2 is inconsistent with TPTF flow regime transition data. However, satisfactory agreement between the criterion and data can be obtained by simply replacing the vapor velocity term in the criterion by the vapor-to-liquid relative velocity [8, 9].

(2) Non-physically large interfacial drag coefficients are calculated for a junction through which a stratified two-phase flow discharges into a liquid-filled vessel. This occurs since RELAP5/MOD2 calculates the junction interfacial drag by taking an average of the interfacial drag coefficients calculated for the upstream and downstream volumes adjacent to the junction.

(3) For a stratified flow discharging into a vapor region of a vessel, the calculated liquid velocity in the test section downstream region exceeds the hydraulic critical velocity [10]. This occurs even when the vapor velocity at the subject region is smaller than the liquid velocity, i.e., even when the interfacial drag is decelerating the

liquid phase.

These problems in MOD2 and the code changes made by JAERI to fix the problems were communicated to the USNRC. The current version of MOD3 includes code changes to resolve (1) and (2) above. The stratification criterion was modified [11] as suggested by JAERI. The interfacial drag calculation scheme was modified such that the interfacial drag coefficient as well as flow regime are calculated at the junction points (volume boundaries) rather than at volume centers. However, no code changes have been made to fix (3) above.

At the writing of this report, JAERI has not been fully informed of the detailed code changes between MOD2 and MOD3. Their understanding of the MOD3 models is based primarily on [11] and [12].

As such, performing MOD3 assessment calculation against the TPTF experiments became of interest to both JAERI and USNRC. Thus, an arrangement [12] was made between the two parties so that JAERI could obtain a developmental version of MOD3 and conduct calculations before the end of September 1989. This schedule was defined such that the JAERI work could be included in the MOD3 developmental assessment efforts primarily conducted at the Idaho National Engineering Laboratory.

A developmental version of MOD3 (called MOD2.5 Version 4) [1] was released by the INEL to JAERI late June 1989. However, for JAERI it took about two months after receiving the code to make it usable on the JAERI computer (FACOM VP-100) which is an IBM-type machine. Since this was the first time for MOD3 to be used on an IBM-type machine, several problems were found in the code which had to be resolved for implementation into the JAERI computer. These are listed in Appendix A of this report. The assessment calculations were initiated on September 8, 1989.

The short time available before the calculation deadline allowed JAERI to make only a brief review of the analytical results. The review results as well as calculational procedure and analytical results are documented in this report. Results for eight representative cases are presented in this report although more than forty cases were actually analyzed.

2. TEST DESCRIPTION

The TPTF 8-inch horizontal flow test section (Fig. 1) [2] consists of a 0.18 m i.d., 10-m long circular pipe discharging into a large (1.3 m i.d.) vessel. The test section can be replaced with one having a smaller diameter (0.09 m). Tests are conducted in steady states by providing a concurrent saturated two-phase flow from a mixer connected to the test section inlet.

The present assessment calculations were conducted for those tests which used a "homogeneous flow" type mixer consisting of a bundle of perforated tubes through which steam was injected into water to create a well-mixed two-phase flow. The two phases separated quickly after exiting the mixer, due to the density difference, forming a stratified flow at the test section inlet. When this homogeneous-flow type mixer was used for the 0.18-m i.d. test section, the flow in the test section was always in smoothly-stratified or wavy-stratified flow regimes, i.e., no transition to intermittent (slug) flow regime was observed.

The test section was instrumented with gamma-ray densitometers and a conduction probe rake to measure the liquid level. Two fixed 3-beam densitometers, located 17 and 48 diameters downstream the test section inlet, respectively, were used for the tests which were analyzed.

The test boundary conditions for the eight tests analyzed in the present assessment calculations are shown in Table 1. These tests cover the whole range of experimental mass flux available in the TPTF test section, and includes both high and low vessel level cases. The data set used for the present assessment consists of data developed by Kawaji [13] and data recently obtained by Anoda for similar test conditions to those of Kawaji.

The tests were conducted at system pressures of about 7 MPa. The test variables were mass flux, ranging from 40 to 1000 kg/m^{2}s, and flow quality, ranging from 0.1 to 0.6. Also the effects of the test section outlet water level was studied by setting the vessel water level both above and below the test section outlet. For the high-level cases the vessel level was about 0.4 m higher than the top of the test section, and was about 0.4 m lower than the test section bottom for the low-level cases. For the high and low-level cases, the test section flow discharge into the liquid-filled and vapor-filled regions of the vessel, respectively.

3. RELAP5/MOD3 INPUT MODEL

The same input model as used for the MOD2 assessment calculations [4-6] were used (Fig. 2). Fifteen horizontally-oriented volumes of the same size were used to represent the TPTF test section downstream the first densitometry location (L/D=17). Vertical volumes are used to model the vessel. The cross-flow junction option was used to model the junction between the test section and the vessel.

The calculations were run to obtain a steady state for experimental boundary conditions which were imposed at the test section inlet side (L/D = 17) and at the vessel. To obtain a steady state, each calculation was run for 500 s physical time.

The inlet-side boundary conditions were imposed by using a time-dependent volume and a time-dependent junction in terms of steam and water velocities, void fraction, water and steam saturation enthalpies. The velocities were derived from the phasic flow rates and void fraction (measured at L/D = 17 using the gamma-ray densitometer). The vessel boundary conditions were imposed in term of pressure. A horizontal junction discharging from the vessel was used to establish a liquid level at a desired elevation in the vessel. This junction discharged into a time-dependent volume which was used to impose the system pressure.

4. RESULTS AND DISCUSSION

The calculated void fraction profiles along the test section are shown in Figs. 3 through 6, 8 through 12, and 14 and 15, together with calculational results obtained with MOD2 (Cycle 36.05). The axial profiles of volume-center void fractions are indicated in comparison with experimental void fraction measured at L/D=48.

The CPU time spent to run 500-s (physical time) steady-state calculation with MOD3 on the FACOM VP-100 computer is listed on Table 2. The maximum time step specified in the input data was 0.125 s for all the cases except for the two cases which required a smaller time step (0.0625 s) for convergence to a steady state. For certain cases, CPU time spent by the comparable MOD2 calculation is also shown for comparison. Generally, the MOD2 calculations were faster than the MOD3 calculations probably because the MOD2 calculations used a JAERI-developed vectorized version and the present MOD3 calculations did not. The required core memory size was 3988 KB for MOD3 and 5464 KB for the JAERI vectorized version of MOD2.

4.1 High-Level Cases

The deficit in the MOD2 interfacial drag calculation scheme (due to calculating flow regime and interfacial drag coefficient at the volume center) was most clearly seen for the low-flow high vessel level cases (Runs 722 and 728, Figs. 3 and 4, respectively). For these cases, MOD2 largely overpredicted test section void fractions because of overpredicting the interfacial drag at the test section outlet junction [3, 4]. This deficit is resolved in MOD3 by calculating flow regime and interfacial drag coefficients at the volume boundary (junction) rather than at the volume center. The prediction of test section void fractions is improved considerably over the MOD2 calculations. This improvement is major for analyses of small-break loss-of-coolant accident (LOCA) in a pressurized water reactor (PWR) where flow rates in horizontal legs are generally small.

The flow regime indicated on the output listing was horizontally stratified flow (HST) for all the volume points inside the test section, for all the cases calculated, including both high-level and low-level cases. However, for all the high-level cases, the calculated local conditions (vapor-to-liquid relative velocity vs. void fraction) falls, at least for the test section downstream region, actually in the transitional regime as defined by MOD3. The transitional regime is represented by a range of void fraction, dependent on mass flux and flow quality, for which the stratification interpolation factor "FSTRAT" takes values between 0.0 and 1.0. The lower bounding void fraction of the MOD3-defined transitional regime agrees approximately to the modified Taitel-Dukler criterion. This definition of the transitional regime seems arbitrary. In the TPTF 7 MPa experiments, the flow regime transition condition was closely represented by the modified Taitel-Dukler criterion. The range of transitional void fractions are compared to the calculated void fraction profiles in the figures.

In the transitional regime, the interfacial drag coefficient is calculated by interpolating the constitutive relations for stratified and non-stratified (slug) flow regimes. Thus, the interfacial drag coefficients calculated for these cases were greater than what may have been calculated for a purely-stratified flow.

For a concurrent, horizontal two-phase flow to discharge into a liquid-filled region, the flow needs to be "flooded", i.e., the interfacial drag must be large enough, at least at the downstream end of the horizontal channel, to prohibit countercurrent flow from occurring. For low-pressure steam/water or air/water two-phase flows in a small-diameter pipe, flow regime transition from stratified to non-stratified flow needs to occur for the flow to be flooded. It is uncertain, however, whether or not this is the case for high-pressure steam-water flows in a large diameter pipe; there is a potential for such cases that the interfacial drag in stratified flow is large enough to cause the flow to be flooded. Although this is an interesting problem, the present TPTF tests do not provide detailed information on flow regime at the test section outlet because of lack of instrumentation.

Both MOD2 and MOD3 calculated the flow regime transition to occur. It is noteworthy that the RELAP5 interfacial drag coefficient for stratified flow is calculated using a Blasius-type correlation. This implies that a purely-stratified flow, with no influence of interfacial disturbances, is assumed, whereas stratified flow observed in the present tests included small interfacial disturbances. Some other codes, for instance TRAC-PF1/MOD1 [14], use stratified-flow interfacial drag models based on wavy flow data. These models give larger interfacial drag coefficients than predicted by the RELAP5 model. TRAC analysis of the TPTF high-level experiments [15] predicted no flow regime transition in the test section making a clear contrast to the RELAP5 calculations.

The relationship between the void fraction and interfacial drag in the transitional regime depends on the interpolation function "FSTRAT" defined in the code, in addition to the interfacial drag models used for stratified and non-stratified flow regimes. Thus, the predicted void fraction depends on the defined functional form of FSTRAT. There is a tendency that the test section void fractions are overpredicted for low-flow cases whereas both the predicted and measured void fractions are within the RELAP5 transitional regime. This may be related to the fact that the range of the transitional void fractions is wider for lower mass velocities, and also that the lower bound of the RELAP5 transitional void fraction agrees approximately to the modified Taitel-Dukler criterion. Namely, MOD3 may tend to overpredict interfacial drag for these cases.

For the intermediate mass flux case (Run 785, Fig. 5), the agreement between the MOD3 calculation and data was almost perfect.

For the high-flow cases (Run 749, Fig. 6), the difference between MOD3 and MOD2 calculations were less significant than for the low-flow cases, however, the agreement with data was always better with MOD2 than with MOD2.

For this high-flow case, the MOD3-predicted void fraction shows peculiar behavior at the test section volume points close to the outlet, peaking at the downstream end volume point. This seems to be related to an undulation in the axial variation of the interfacial drag coefficient, FIJ (Fig. 7). The value of FIJ took a minimum at the outlet junction. For this case, the transition between the stratified and non-stratified flow regimes was calculated to occur within a narrow range of void fraction (Fig. 6). Thus, the value of FIJ was sensitive to the calculated value of void fraction.

The void fraction distribution for the downstream-end region of this case has been found to be noding sensitive. Figure 8 shows results for a sensitivity calculation where the downstream-end test section volume in the standard calculation was further divided into five subvolumes. A lower peak value of void fraction was obtained with this fine nodalization than with the standard input model.

Sensitivity calculations have been performed also for the modeling of the test section outlet junction. While the standard calculation used the single junction option for the upstream-side (test section side) of this junction and the cross-flow junction option for the downstream side (vessel side), two sensitivity calculations were performed using single junction-to-single junction and cross-flow junction-to-single junction representation of this junction, respectively. As shown in Figs. 9 and 10, the sensitivity calculations predicted smooth change in void fraction at the downstream end of the test section.

4.2 Low-Level Cases

The disagreement between data and MOD2 calculations observed for the low-level low-flow cases was related to non-physically large liquid velocities at the test section downstream end. Although the liquid velocity should not exceed the hydraulic critical velocity [10] at the test section outlet, unless the interfacial drag forces the liquid velocity to be supercritical, MOD2 calculated liquid velocities factors of up to 5 higher than the critical velocity. To resolve this problem, the basic equations needs to be rewritten, however, this was not done in developing MOD3 from MOD2. Thus, this problem remains with MOD3, and supercritical liquid velocities are calculated even for low-flow cases (Runs 2541 and 2535, Figs. 11 and 12, respectively).

The overprediction of the test-section-outlet liquid velocity is responsible, at least partly, for the over prediction of the test section void fractions for the low-flow cases.

The calculated void fraction at the test section outlet junction are compared to the conditions for critical flow, i.e., the conditions for stationary infinitesimal disturbance on the interface, in Fig. 13. The calculated results are shown for both MOD2 and MOD3 calculations. The reason for the difference between the MOD2 and MOD3 calculations may be related to the code change regarding the void gradient term [11].

For the high-flow cases (Runs 2514 and 2508), the test section void fractions are independent from the vessel water level, being determined by the balance between the wall friction and interfacial friction forces in the test section. Transitional flow was calculated for these cases, and the agreement between the measured and MOD3-calculated void fractions are satisfactory. Better agreement than with MOD2 was obtained because of the updated flow stratification criterion.

5. CONCLUSIONS

The RELAP5/MOD3 code was developmentally assessed against the TPTF experimental data, taken for saturated, concurrent, horizontally-stratified two-phase flow in a 0.18 m i.d. pipe under a system pressure of about 7 MPa. Mass flux (40 to 1000 kg/m2s), quality (0.1 to 0.6) and water level in a vessel to which the test section discharges were the test parameters. The calculated results are compared to predictions with the RELAP5/MOD2 (CY 36.05) calculations conducted using the same input model.

The axial profile of the test section void fraction was calculated by imposing experimental boundary conditions at the test section inlet side and at the downstream vessel.

The present assessment calculations confirmed the effectiveness and adequacy of the code changes made between MOD2 and MOD3. The major observation from the present calculations are as follows.

<u>High Level Cases</u> For the experimental cases with the vessel water level higher than the test section outlet, significant improvement over the MOD2 calculation was obtained with MOD2. This was achieved mainly because of the change in the interfacial drag calculation scheme, from the volume-based to junction-based calculation of interfacial drag. For high-flow cases, the change in the flow stratification criterion also contributed to the improved agreement.

<u>Low Level Cases</u> For the experimental cases with the vessel water level lower than the test section outlet, the liquid velocity at the test section outlet was overpredicted by both MOD2 and MOD3, because of inability to deal with the critical flow phenomenon in a gravity-driven flow. This resulted in overpredicting the test section void fractions for low-flow cases. For high-flow cases, the experimental flow was supercritical due to interfacial drag, and the prediction of void fraction was improved due to the update in the stratification criterion.

Acknowledgment

The authors gratefully acknowledge the comments given by the US participants to the 11th ROSA-IV Program Review Meeting held at the Idaho National Engineering Laboratory on November 22-24, 1989, where a preliminary version of this report was presented.

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Table 1 Summary of Test Boundary Condition

RUN NO.	Mass Flux (kg/m^2s)	Flow Quality (-)	Vessel Water Level
722	39.7	0.590	Above Test Section Outlet
728	100	0.596	
785	410	0.039	
749	1004	0.048	
2541	43.7	0.562	Below Test Section Outlet
2535	123	0.146	
2514	453	0.366	
2508	1043	0.103	

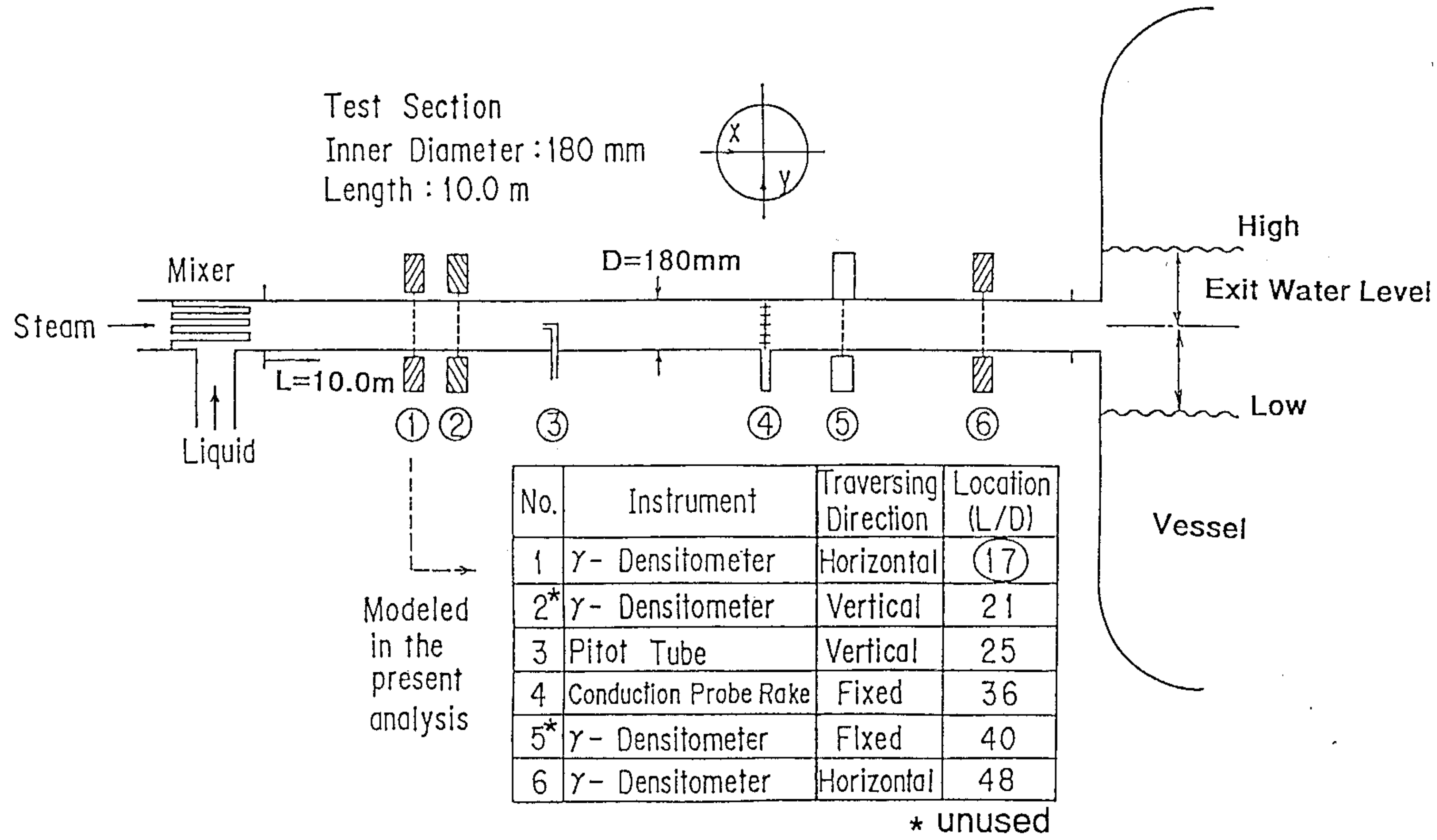
Pressure: 7.3 - 7.5 MPa

Table 2 CPU Time Spent for 500-s (Physical Time) Steady-State Calculation

Run No.	CPU Time/MAX. Time Step (s)	CPU Time Spent by MOD2 (s)
722	121/0.125	42
728	123/0.125	43
785	121/0.125	42
749	121/0.125	42
2541	115/0.125	80
2535	122/0.125	80
2514	223/0.0625	165
2508	213/0.0625	163

Used Machine : FACOM/VP100

Used Core Memory : 3988 KB (cf. MOD2 Vector Version 5464 KB)



No.	Instrument	Traversing Direction	Location (L/D)
1	γ- Densitometer	Horizontal	(17)
2*	γ- Densitometer	Vertical	21
3	Pitot Tube	Vertical	25
4	Conduction Probe Rake	Fixed	36
5*	γ- Densitometer	Fixed	40
6	γ- Densitometer	Horizontal	48

* unused

Fig. 1 Schematic View of Two-phase Flow Test Facility (TPTF).

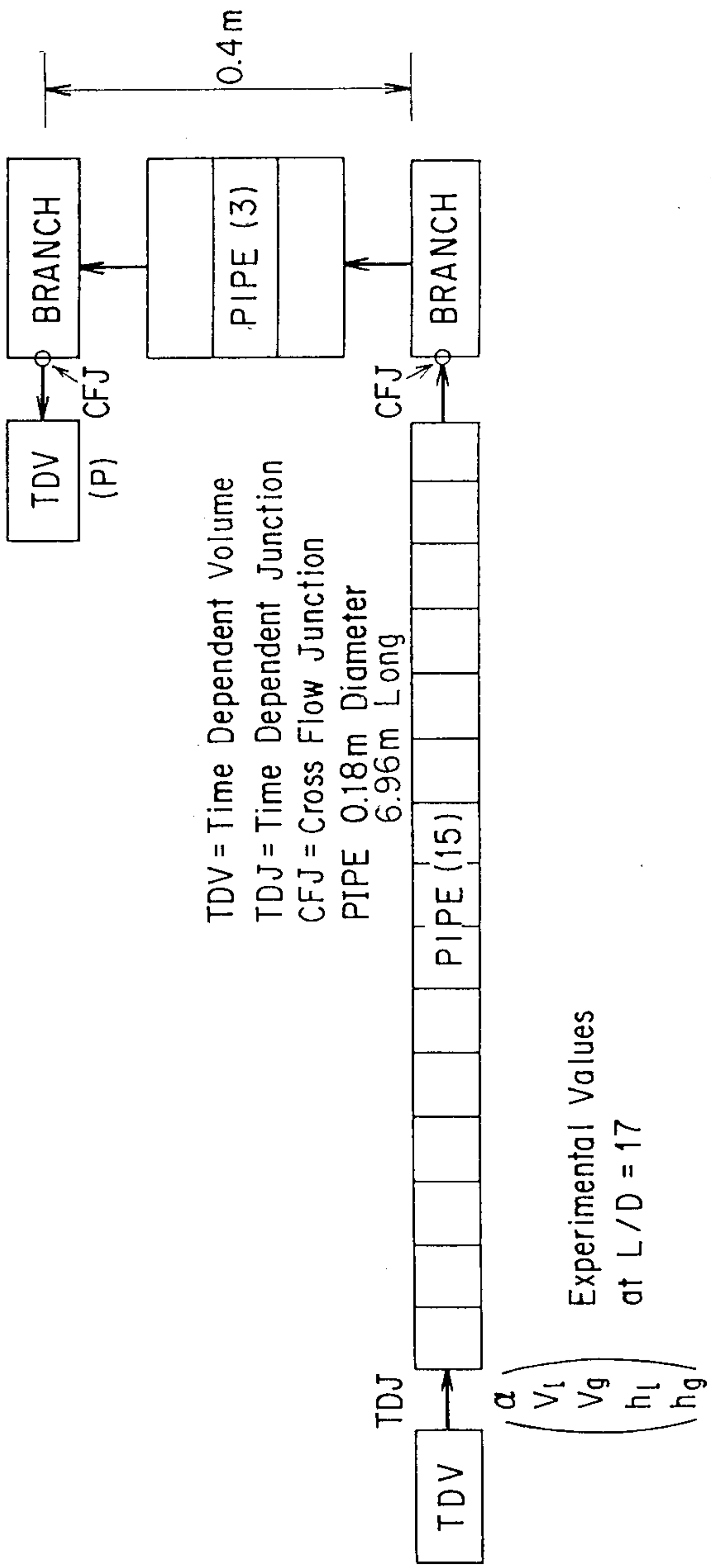


Fig. 2 RELAP5 Model for TPTF Horizontal Flow Test.
(shown for high-exit-level geometry)

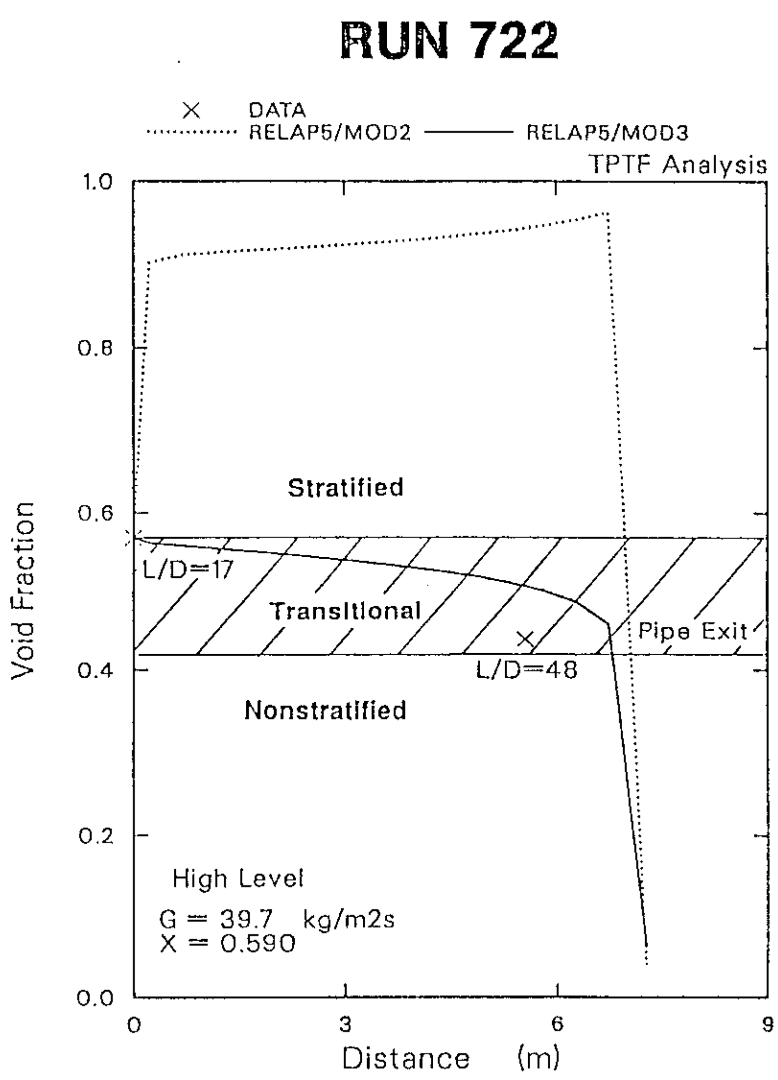


Fig. 3 Comparison of Measured and Predicted TPTF Void Fractions. (High Exit Water Level, Run 722)

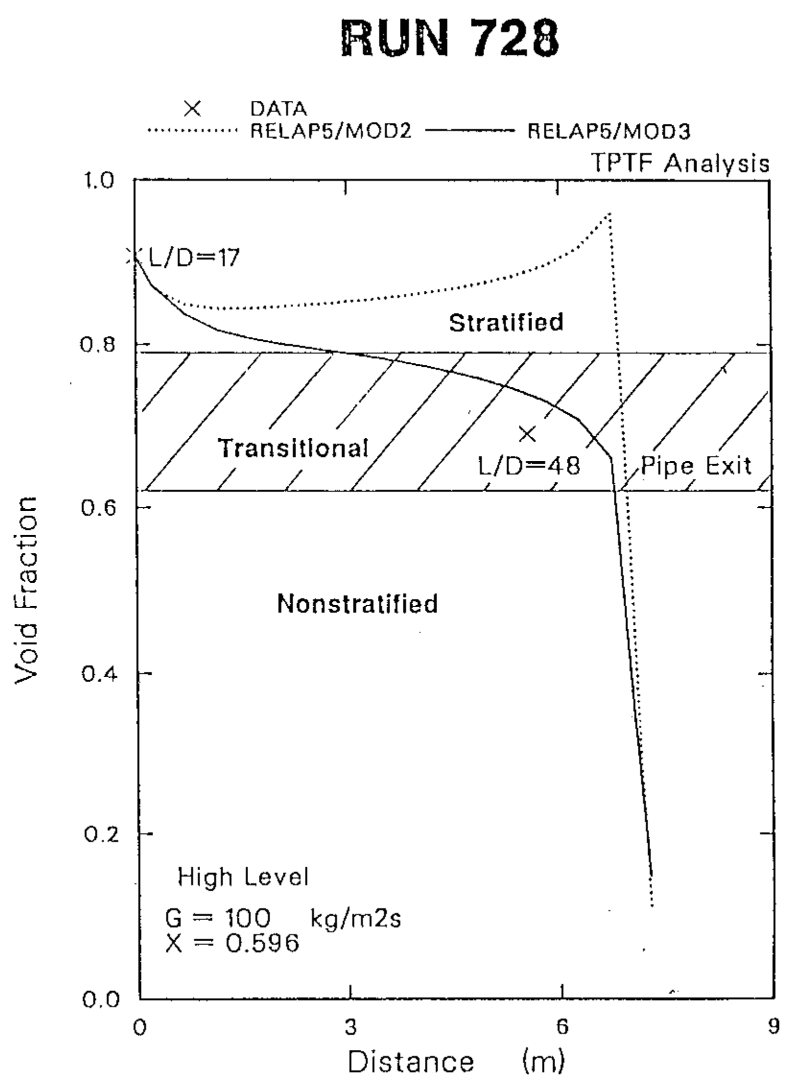


Fig. 4 Comparison of Measured and Predicted TPTF Void Fractions. (High Exit Water Level, Run 728)

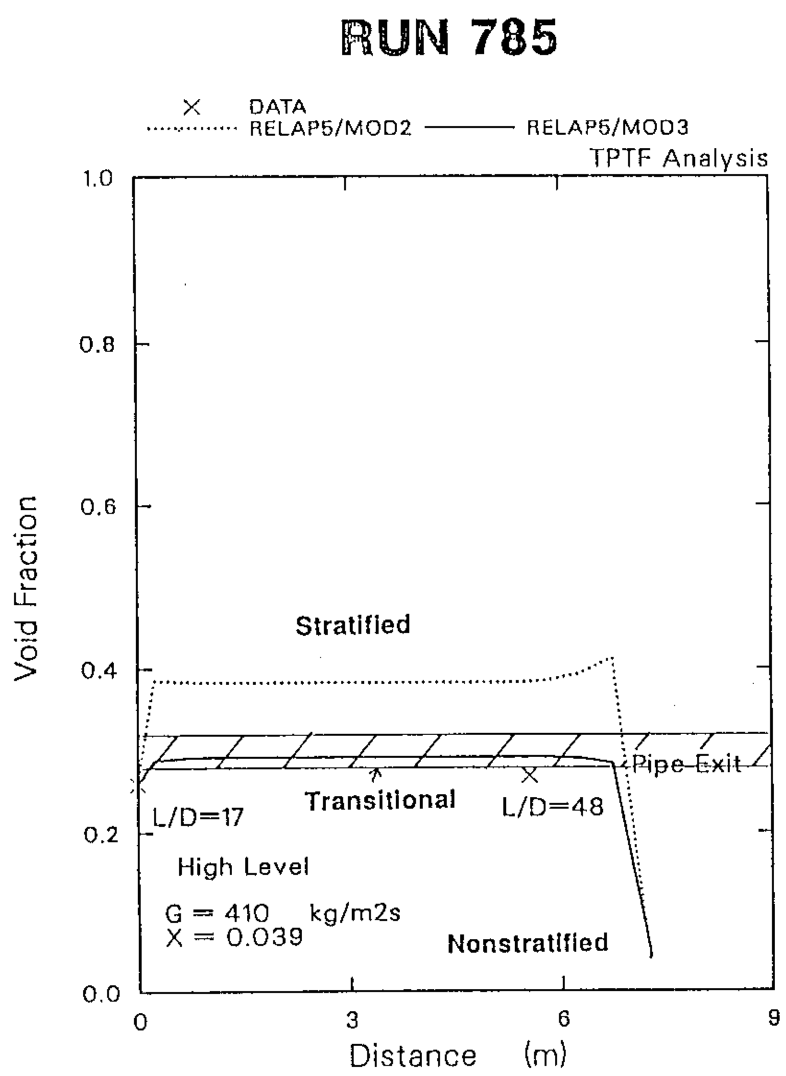


Fig. 5 Comparison of Measured and Predicted TPTF Void Fractions. (High Exit Water Level, Run 785)

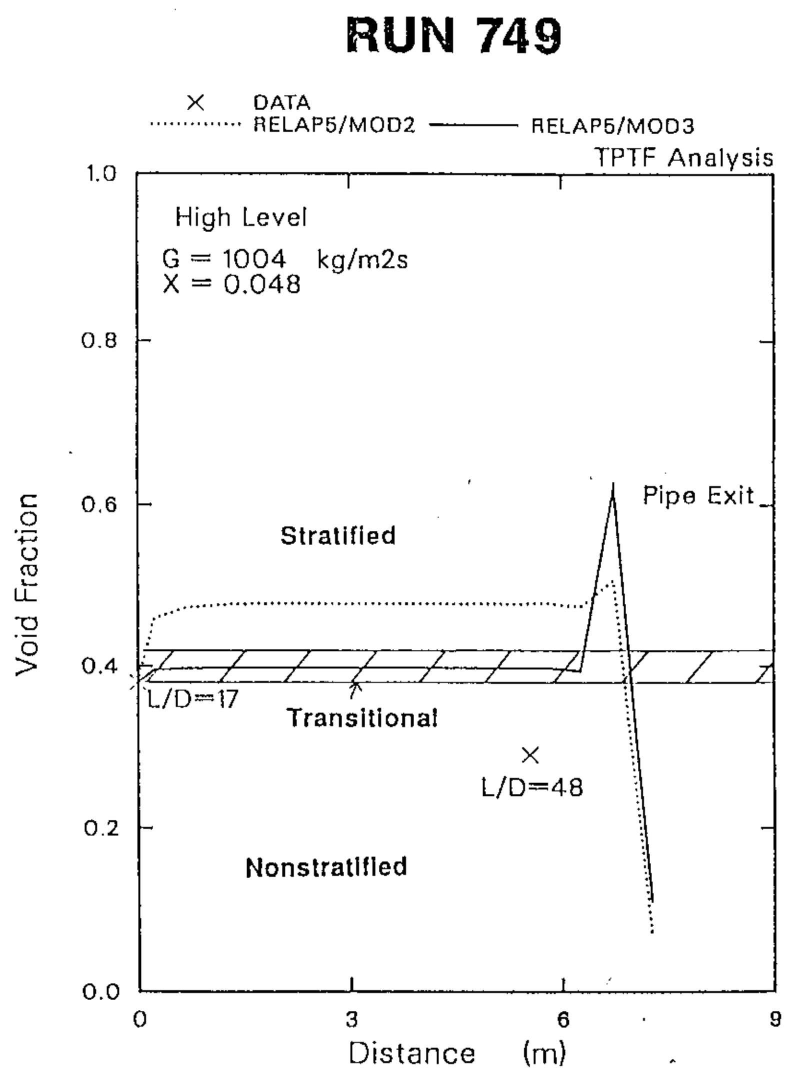


Fig. 6 Comparison of Measured and Predicted TPTF Void Fractions. (High Exit Water Level, Run 749)

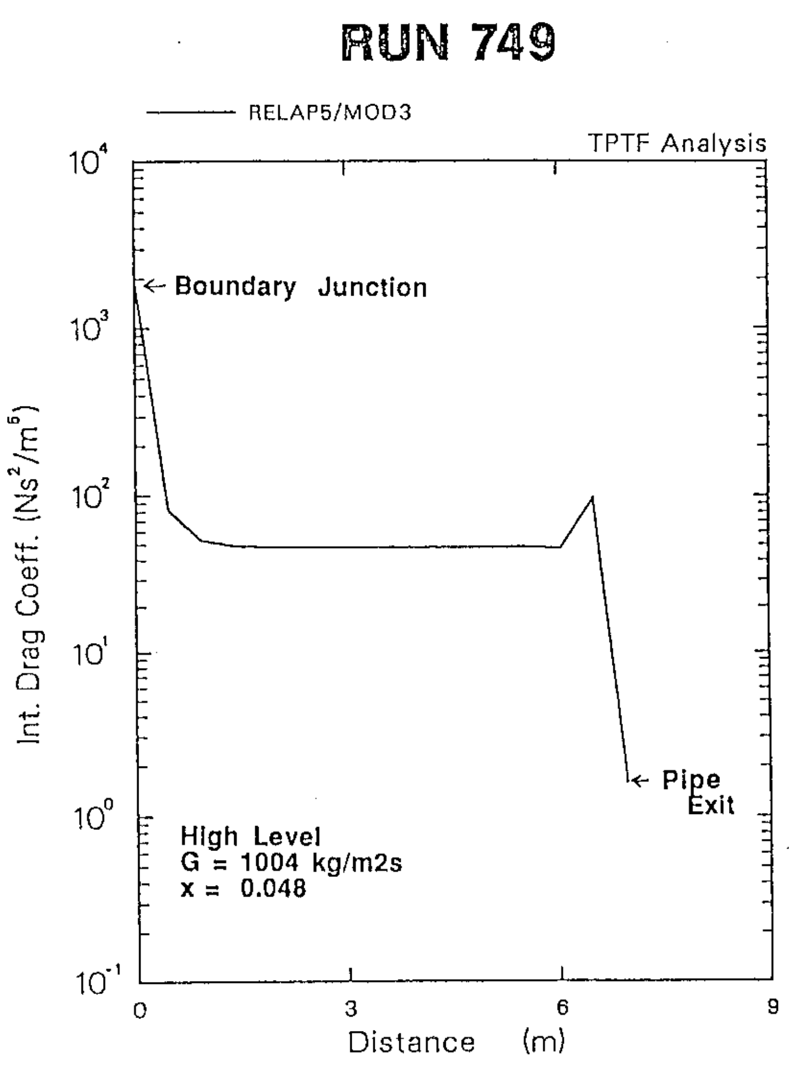


Fig. 7 Interfacial Drag Coefficient calculated with RELAP5/MOD3. (High Exit Water Level, Run 749)

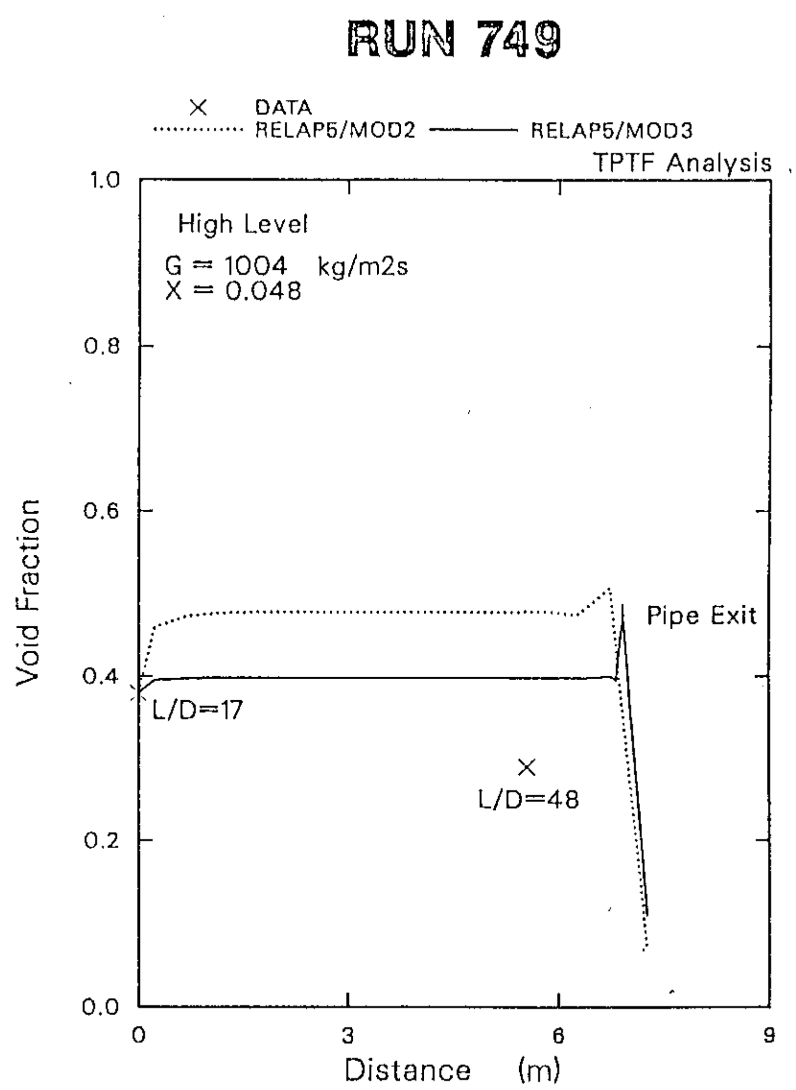


Fig. 8 Noding Sensitivity Calculation with the Last Test-Section Volume in the Standard Calculation Divided into Five Subvolumes. (High Exit Water Level, Run 749)

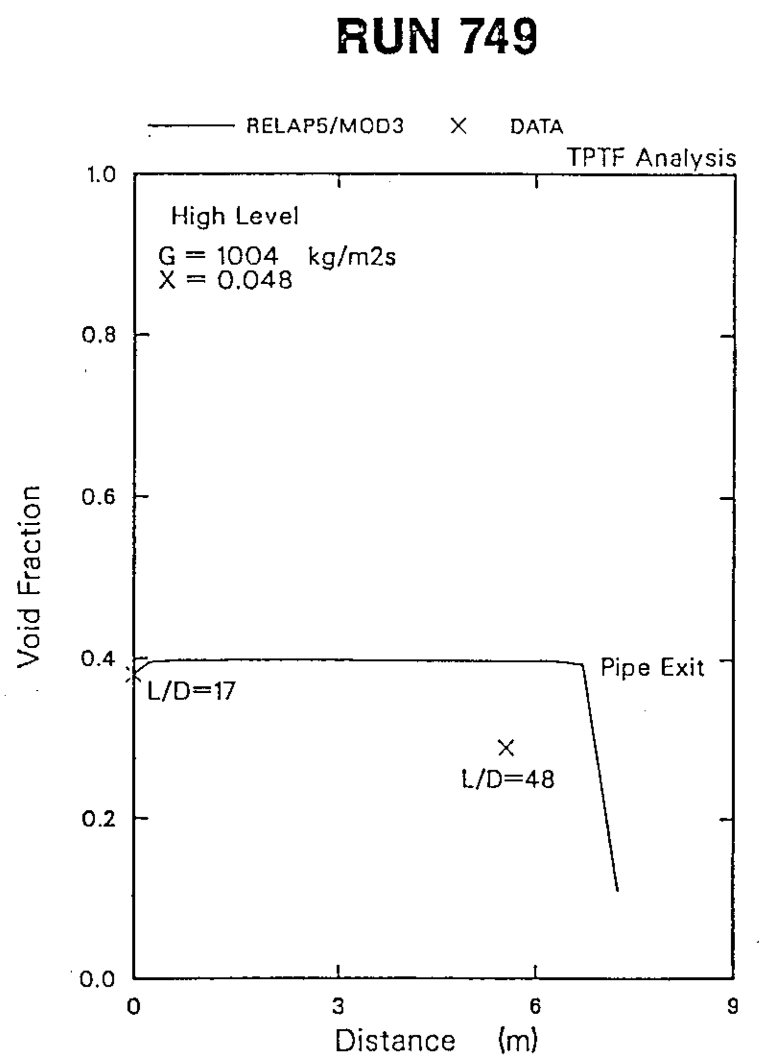


Fig. 9 Sensitivity Calculation with the Test Section Exit Junction Represented Using the Single Junction Option for Both the Test-Section Side and Vessel Side of the Junction (High Exit Water Level, Run 749)

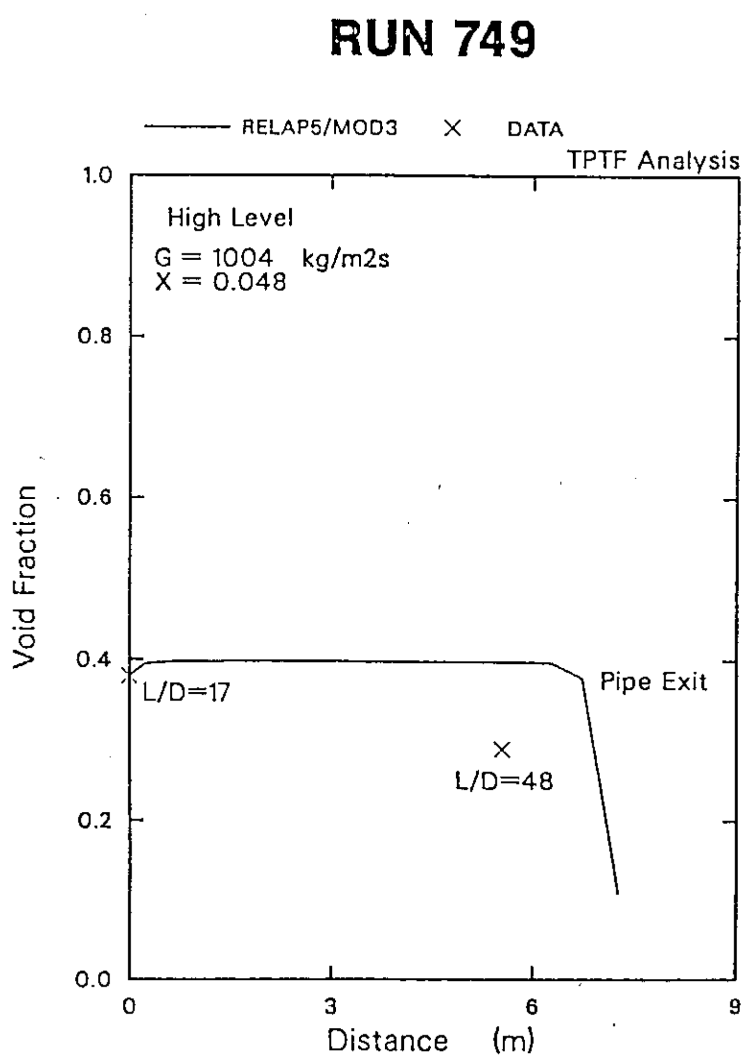


Fig. 10 Sensitivity Calculation with the Test Section Exit Junction Represented Using the Cross-Flow Junction Option for the Test Section Side of the Junction and the Single-Junction Option for the Vessel Side of the Junction, Respectively (High Exit Water Level, Run 749)

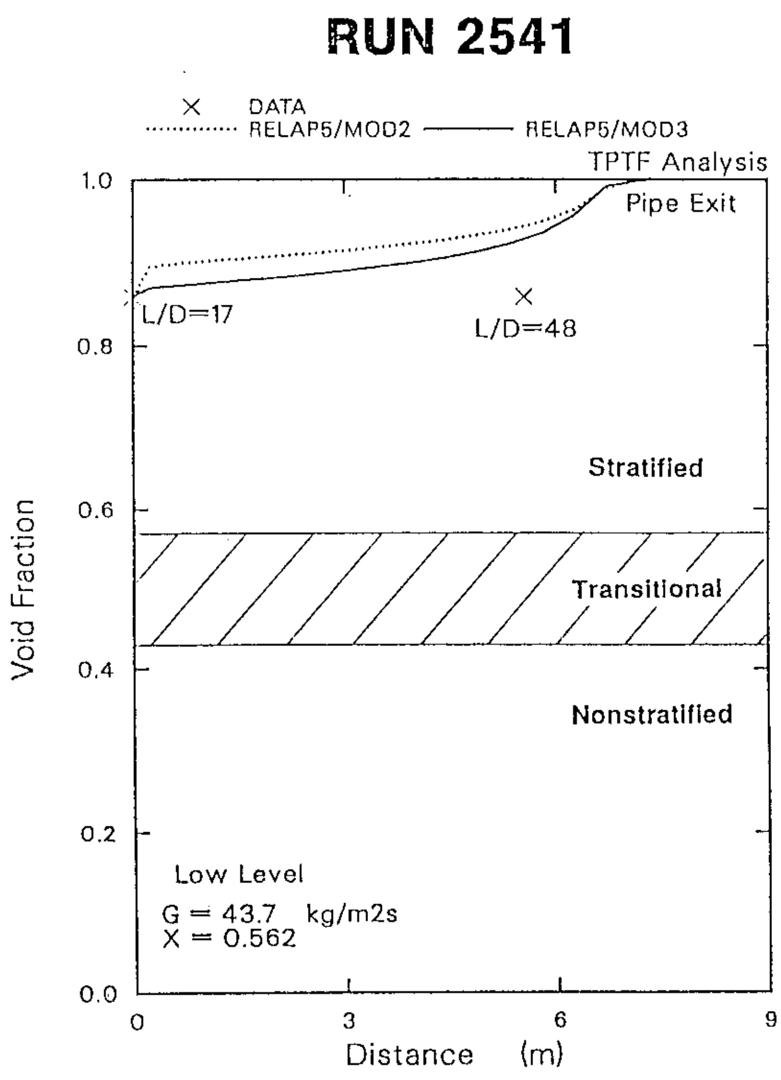


Fig. 11 Comparison of Measured and Predicted TPTF Void Fractions. (Low Exit Water Level, Run 2541)

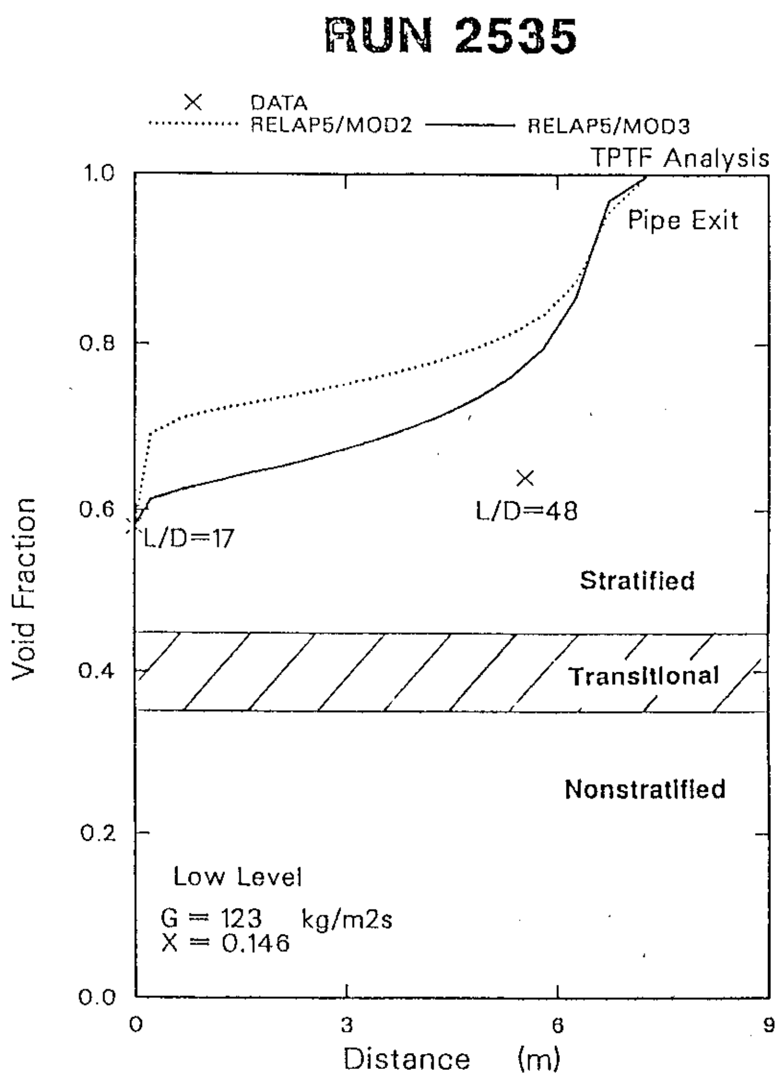


Fig. 12 Comparison of Measured and Predicted TPTF Void Fractions. (Low Exit Water Level, Run 2535)

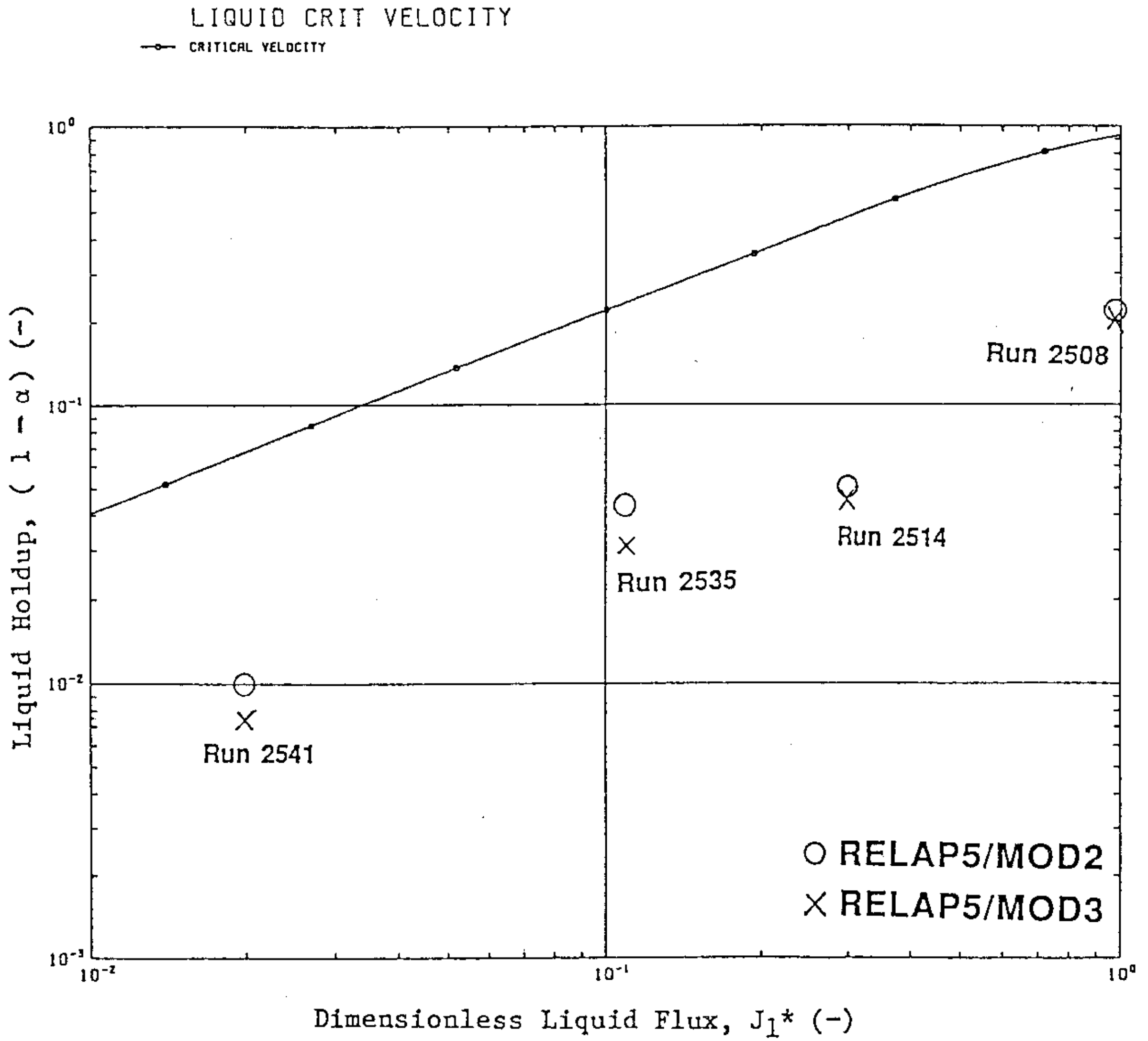


Fig. 13 Pipe Exit Liquid Fraction (L/D=56) Calculated with RELAP5/MOD2 and MOD3. (Low Exit Water Level, Runs 2508, 2514, 2535 and 2541)

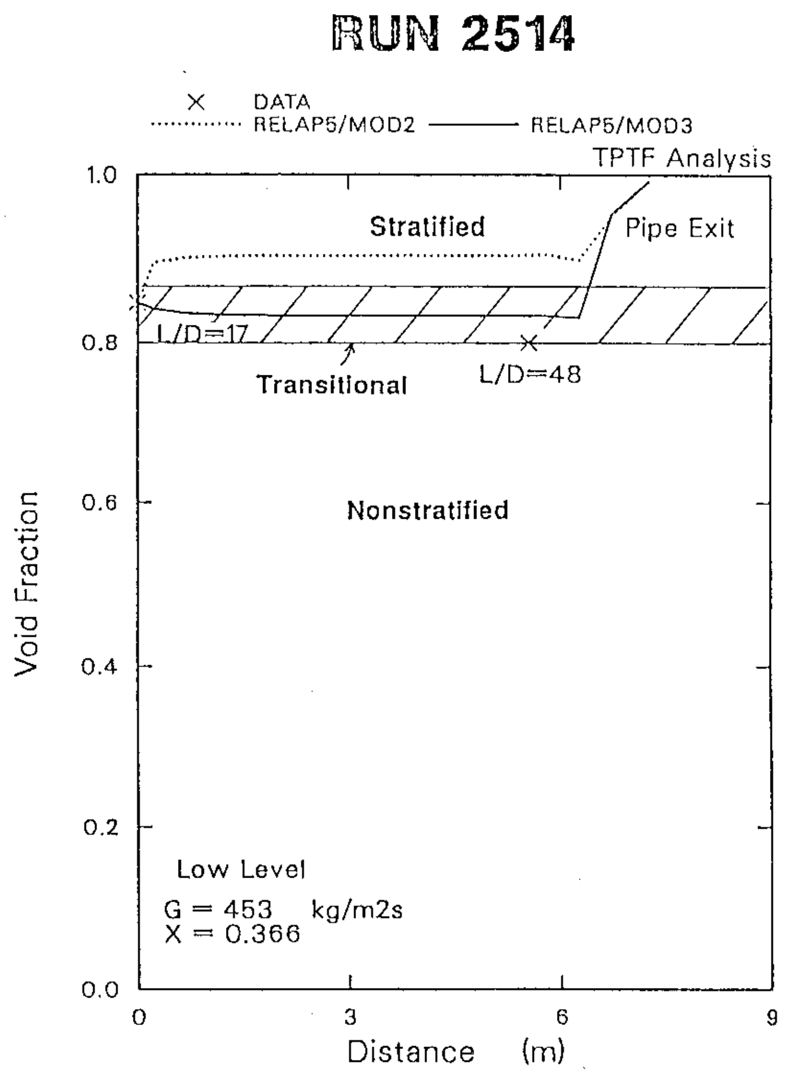


Fig. 14 Comparison of Measured and Predicted TPTF Void Fractions. (Low Exit Water Level, Run 2514)

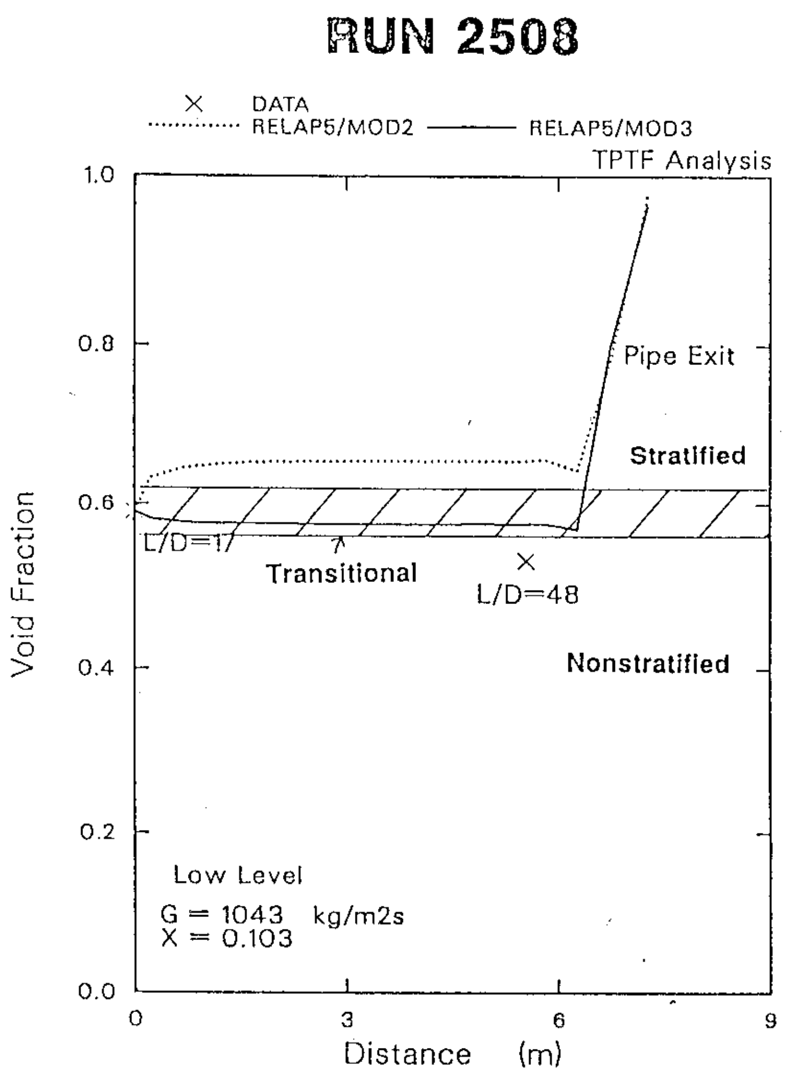


Fig. 15 Comparison of Measured and Predicted TPTF Void Fractions. (Low Exit Water Level, Run 2508)

Appendix Error Correction to RELAP5/MOD2.5 by JAERI

JAERI modifications are classified into three categories as follows:

(1) Correction of Bugs of the original code.

(2) Modification for 32-bit machine which includes miscoding for 32-bit machine in the original program.

(3) Modification for plotter (DISPLA) and its JAERI extended use.

Here the modification of category (1) is described.

(1) DTSTEP

IBM option was missing.

(2) SYSSOL

Addition of actual arguments FA( ). This addition became necessary when PMINVD and PMINVF routines are automatically converted by CONV32.

(3) IPLOAD

Miscoding of LOCSAV and other miscoding.

(4) WRITPL

LTEST was undefined and other miscoding.

(5) CHRINT

CHRINT subroutine was removed by SUPD12 but this routine is necessary.

(6) FTBOPN, FTBPR1, STH2X6, FTBGET (Environmental Library)

Miscoding was found.

(7) PHAINT (PHANTV in RELAP5/MOD2.5)

Variable VCRIT is sometimes undefined when used at the statement below the Stn. 140 (which is one of newly added statements in a recent version). At that time, a previously calculated value of VCRIT is incorrectly used. This error was found for the Problem TYPPWR in the previous SELAP code. In the present RELAP5/MOD2.5 this statement is skipped by a secret input parameter and not effective, but the situation will be same if executed.