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"Two-Phase Flow Phenomena in Full-Scale Reactor Geometry"

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Abstract

For the investigation of two-phase flow phenomena in full scale reactor geometry, a series of experiments were carried out at the Upper Plenum Test Facility UPTF, which represents the primary system of a 1300 MWe Pressurized Water Reactor with upper plenum, downcomer and primary main coolant pipes in 1 : 1 reactor scale.

UPTF was the German contribution to the international 2D/3D project established by the Japan Atomic Energy Research Institute (JAERI), the Nuclear Regulatory Commission (USNRC) of the United States of America, and the Federal Ministry for Research and Technology (BMFT) of the Federal Republic of Germany.

Large scale findings of the UPTF tests, related to two-phase flow phenomena in the downcomer, in the upper plenum, at the upper core tie plate, and in the main coolant pipes, will be discussed. The application of the UPTF test results for the validation of analytical models will be demonstrated.

1. Introduction

Contrary to single phase flow, where the flow consists of a uniform fluid, two-phase flow is characterized in general by large density and velocity differences between the water and the steam phases with various flow patterns, resulting from the interaction between surface tension, pressure drop, shear stress and gravity force.

An enormous number of experiments have been performed to investigate two-phase flow phenomena in the last two decades. However, the tests have mainly been executed at sub-scaled test facilities compared to full scale reactor geometry.

To provide required experimental data for the two-phase flow in reactor geometry, a test program at the full-scale test facility UPTF was executed [1].

2. The Upper Plenum Test Facility

The Upper Plenum Test Facility UPTF is an imitation of a four-loop 1300 MWe pressurized water reactor with upper plenum, downcomer and the main coolant pipes in full scale reactor geometry (Fig. 1 and 2).

The steam produced in a real core and the entrained water flow are simulated by a controlled steam and water injection through the core simulator. The steam generator behaviour is simulated by a controlled steam injection into the steam generator simulator.

The test facility has been designed in particular to study multi-dimensional two-phase flow effects in the upper plenum, at the upper core tie plate, and in the downcomer.

In the following, selected large scale findings from the UPTF experiments will be revealed [2]. Results of multi-dimensional flow in the downcomer, in the upper plenum, and at the upper core tie plate, as well as results related to flow phenomena in the hot and cold leg of the main coolant pipes, including studies of the reflux condenser mode, will be presented.

3. Downcomer Behaviour

Multi-dimensional flow phenomena in the downcomer have a strong impact on the overall system behaviour of a PWR during a loss-of-coolant accident. In particular the downcomer by-pass phenomena influences significantly the efficiency of the cold leg emergency core cooling (ECC) injection in case of an intermediate or large cold leg break.

To provide the required data base for full scale reactor geometry a test series of downcomer tests were performed at UPTF. Tests with steam and two-phase upflow and different ECC-injection locations were carried out to investigate downcomer behaviour during end-of-blowdown and refill phases as well as during the reflood phase of a large break loss-of-coolant accident.

Downcomer Behaviour during End-of-Blowdown and Refill Phases

During the end-of-blowdown and refill phases of a loss-of-coolant accident, steam from the core flows up the downcomer to the break. Due to flashing and entrainment in the lower plenum the downcomer upflow may be two-phase. The upflow can carry some or all of the ECC-water injected into the cold legs or the downcomer directly out of the broken cold leg and may limit or prevent the ECC-water downflow to the lower plenum.

The previous view of downcomer phenomena for cold leg ECC injection has been developed especially through the USNRC ECC By-pass Program. In this program, steam-water tests were performed at 1/30, 1/15, 2/15 and 1/5 scale at Battelle Columbus Laboratories [3] and at Creare [4]. Steady state counter current flow limitation (CCFL) tests with steam upflow and ECC-water downflow as well as transient tests involving lower plenum flashing and two-phase upflow were carried out.

Based on these experimental data of the sub-scaled test facilities empirical flooding correlations have been developed, using two dimensional groups, a modified

Wallis parameter

$$J_x^* = \frac{\dot{M}_x}{\rho_x A_{DC}} \frac{\rho_x^{1/2}}{\left[gW\left(\rho_w - \rho_s\right)\right]^{1/2}}$$

with W as average downcomer annulus circumference, and the Kutateladze number

$$K_x^* = \frac{\dot{M}_x}{\rho_x A_{DC}} \frac{\rho_x^{1/2}}{\left[g\sigma\left(\rho_w - \rho_s\right)\right]^{1/4}}$$

Though the tests have been carried out with a variation of the test facility scale between 1/30 and 1/5 scale the question, to what extent these findings can be extrapolated to full scale downcomer geometry, remained unanswered.

To provide CCFL and by-pass data for full reactor geometry, tests at UPTF were carried out.

In Fig. 3 UPTF results for steam upflow of 320 kg/s and ECC-injection (subcooling 115 K) in the three intact loops are illustrated. The contour plot shows isotherms of interpolated fluid temperatures (subcooling) in the unwrapped downcomer.

The two-dimensional presentation shows strongly heterogeneous flow conditions which were not obvious from small-scale experiments. The ECC-water delivered from the cold legs 2 and 3, which are located opposite the broken loop, penetrates the downcomer without being strongly affected by the upflowing steam flow. Most of the ECC-water delivered from cold leg 1, which is located near the broken loop, however flows directly to the break, bypassing the core.

The effect of ECC-injection location on downcomer phenomena is illustrated in Fig. 4. Results with slightly subcooled ECC-injection are presented in three diagrams.

In the upper diagram the established water delivery for ECC-injection rates of about 500 kg/s into each of the three intact cold legs is shown. The steam injection in the core simulator (M_{SC}) was varied between 30 kg/s and 450 kg/s. As the hot legs were closed in these tests, the steam had to flow via the downcomer to the break. Three regions regarding water penetration can be distinguished, characterized by the steam injection rate M_{SC}.

$M_{SC} > 300$ kg/s
Decreasing ECC delivery from cold legs 2 and 3 with increasing steam mass flow rate, no delivery from cold leg 1

100 kg/s $< M_{SC} <$ 300 kg/s
Complete ECC delivery from cold legs 2 and 3, no delivery from cold leg 1

$M_{sc} < 100$ kg/s
Complete ECC delivery from cold legs 2 and 3, partial delivery from cold leg 1

The diagram in the middle of Fig. 4 shows the water delivery for a ECC-injection rate of about 750 kg/s into cold leg 1 only. The data show a complete by-pass at steam injection rates above 100 kg/s and even partial bypass for the lowest investigated steam flow rate of 30 kg/s.

A different CCFL behaviour was observed by injecting ECC water into the cold legs 2 and 3. The data presented in the lower diagram of Fig. 4 indicate still partial by-pass at a steam injection rate of 100 kg/s. From the results of ECC-injection into the three cold legs 1 to 3, complete water delivery would be expected in the case of ECC-injection into two cold legs 2 and 3 at similar steam injection rates. Apparently, there is a synergistic effect in which the carry over from the cold leg 1 to the broken loop is increasing the delivery from cold legs 2 and 3 to the lower plenum.

To demonstrate the effect of scaling on downcomer CCFL the data obtained from UPTF and 1/5 scale Creare test facility for ECC-injection into three intact loops are compared in Fig. 5, using the Wallis parameter as defined in Equation 1. In order to compare data of slightly subcooled conditions from UPTF with CCFL results of Creare obtained with saturated ECC-injection, an effective steam flow (injected minus condensed steam) has been introduced.

Due to the strongly heterogeneous flow conditions in the full-scale downcomer of UPTF the water delivery curves of UPTF and Creare are significantly different. For dimensionless effective steam flow, $(J^*_{s,\,eff})^{1/2}$, greater than 0.2, the dimensionless water downflows of UPTF are much higher than the results of Creare. Note that the UPTF data at dimensionless effective steam flows smaller than 0.2 should not be directly compared to the Creare CCFL curve considering the lower scaled ECC-injection rate of UPTF compared to the Creare experiments. Higher water delivery rates can be expected below the CCFL curve if more ECC-water is injected into cold legs 2 and 3.

The main findings with respect to downcomer behaviour during the end-of-blowdown and the refill phases of an intermediate or large cold leg break with cold leg or downcomer ECC-injection can be summarized:

- there is a significant scale effect on downcomer behaviour
- the flow conditions in the downcomer are highly heterogeneous at full scale
- this heterogeneous or multi-dimensional behaviour increases the water delivery rates at full-scale relative to previous tests at sub-scale facilities
- the CCFL correlations developed from the sub-scale tests are not applicable to full scale downcomers
- the downcomer CCFL correlations for cold leg ECC injection based on sub-scale test results underpredict the water penetration to the lower plenum at full scale

- due to strong heterogeneity in a real downcomer CCFL correlations have to account for the location of the ECC injection relative to the break [5].

Downcomer Behaviour during Reflood Phase

During the reflood phase the water level in the downcomer increases and approaches the bottom of the cold leg nozzles. In case of a cold leg break, the steam generated in the core flows via intact loop towards the downcomer. In combined injection PWRs, essentially all of this steam is condensed by hot leg and cold leg ECC injection and there is no steam flow into the downcomer. In cold leg ECC injection PWRs, part of the steam is condensed. The steam not condensed, alongwith the steam generated in the downcomer due to superheated walls, flows circumferentially around the downcomer and out of the broken cold leg, entraining and carrying away a portion of the downcomer water. The downcomer entrainment decreases the available driving head for core flooding. This contributes in combination with the steam-binding phenomena to longer quench times and potentially results in higher fuel rod cladding temperatures.

Only few data of sub-scaled test facilities are available concerning the flow behaviour in a PWR downcomer during the reflood phase. Sub-scale CCTF II test results [6] indicated no significant reduction of the downcomer water level due to water entrainment through the broken cold leg. To provide the required full scale data, reflood tests at UPTF were carried out.

During testing, manometer oscillations between the downcomer and core were observed. As the downcomer level increased, water entrainment out of the break increased. An increase in entrainment caused a pressure increase in the downcomer which forced the downcomer level down and the core level up. Consequently, as the downcomer level decreased, entrainment out of the break and the pressure in the downcomer decreased. It has been found that for a given entrainment out of the broken cold leg the water level in the downcomer approaches a state of equilibrium. The water level measurements revealed that the water level in front of the broken cold leg was higher than that at other azimuthal positions. The local increase in water level depends on the steam/water flow at the broken cold leg and average downcomer water level. A maximum increase of 0.7 m was measured.

In Fig. 6 the downcomer water level versus water entrainment through broken cold leg for different steam flows is demonstrated. As shown in this figure, water entrainment through the broken cold leg increased with increasing steam flow and downcomer level.

The main findings with respect to downcomer behaviour during the reflood phase can be summarized:

- the water entrainment out of the break is a function of steam flow and downcomer level; water entrainment increases with increasing steam flow and increasing downcomer level

- the steam flow via the intact loops into the downcomer and therefore the entrainment out of the break is reduced by steam condensation on the ECC water, the steam flow reduction is strongly affected by ECC injection rates and ECC configurations
- in a PWR with combined ECC injection (into cold leg and hot leg) the ECC flow is sufficiently high (more than 170 kg/s per injection port) to condense all the loop steam flow during reflood, therefore no substantial entrainment occurs
- in a PWR with low ECC injection rates (80 kg/s per cold leg) the reduction of the driving head of downcomer level can be of significant importance
- the sub-scale CCTF tests showed less entrainment and level reduction than comparable tests at the large scale UPTF
- the water level is higher in front of the broken cold leg than at other azimuthal positions; the magnitude of this local increase in water level depends on the steam/water flow out of the broken cold leg and average downcomer level
- all ECC water injected through the nozzle near the broken loop is entrained directly out of the break, even at low downcomer levels

4. Tie Plate and Upper Plenum Behaviour

Dependent on the type of ECC injection systems, different flow phenomena occur at the tie plate and in the upper plenum of a PWR.

For PWRs with cold leg or downcomer ECC injection, countercurrent flow of steam/water upflow and saturated water downflow occurs. The water, which is entrained by the upflowing core steam flow, is either de-entrained at the tie plate, de-entrained in the upper plenum or carried over to the hot legs. The saturated water, which is de-entrained in the upper plenum, either form a pool in the upper plenum or flows countercurrently to the steam/water upflow back through the tie plate into the core.

For PWRs with ECC injection into the hot leg or the upper plenum, countercurrent flow phenomena at the tie plate involve steam/water upflow and local down flow of subcooled water.

The knowledge about tie plate and upper plenum behaviour was based in the past on results gained from small-scale test facilities. More recently elaborated experimental results and semitheoretical correlations for the vertical countercurrent flow of steam and ECC water through the upper tie plate of PWRs can be found in [7]. The tie plates were usually simulated by small perforated plates not exceeding the size of one fuel assembly. The Wallis parameter or the Kutateladze number were applied to correlate the data.

To study tie plate and upper plenum behaviour in full reactor geometry, tests at UPTF were performed. Tests with three different types of thermal-hydraulic boundary conditions were carried out (Fig. 7):

- countercurrent flow of saturated steam and water at the tie plate (Fig. 7 a), typical of PWRs with cold leg ECC injection
- countercurrent flow of steam and saturated water injected into hot legs (Fig. 7 b)
- countercurrent flow of saturated steam and water from the core and subcooled water injected into hot legs (Fig. 7 c), typical of PWRs with combined ECC injection

Countercurrent Flow of Saturated Steam and Water for uniform flow distribution

To study the countercurrent flow at the tie plate and the liquid hold up above the tie plate in case of saturated steam/water upflow a series of UPTF tests were carried out. Reactor-typical steam/water upflow was adjusted by the core simulator with controlled injection of steam and water.

In Fig. 8 data of these UPTF tests are plotted using the Kutateladze number for upflowing steam (K^*_g) and downflowing water ($K^*_{w,down}$). In addition corresponding data are presented from single fuel assembly tests performed at the Karlstein Calibration Test Facility [8] to determine potential scale effects. The figure clearly shows the information that countercurrent flow limitation at the tie plate occurred at the same Kutateladze numbers in the single fuel assembly test facility and in the full size facility UPTF with approximate 20 m^2 total cross section.

The test results indicate that:

- the steam/water upflow, the two-phase pool above the tie plate, and the water fall back through the tie plate is uniform across the vessel
- the flooding curves for both full-scale and sub-scale test facilities are similar
- the water downflow to each fuel assembly is scale-invariant
- for homogeneous flow conditions at the tie plate the flooding curve can be defined by applying the Kutateladze number as scaling parameter

Countercurrent Flow of Steam and Saturated Water injected into Hot Legs

The situation differs strongly from the one described above in that saturated ECC water is delivered to the upper plenum via the hot legs, while steam is injected through the core simulator flowing upward through the tie plate only. This boundary condition is not reactor typical, however tests with saturated water injection allow the investigation of heterogeneous flow distribution in the upper plenum and tie plate region without the influence of condensation effects.

A series of UPTF tests were carried out investigating two different configurations of ECC-injection. In Fig. 9 the results of tests with two loop injections (injection rates 2 x 100 kg/s) and single loop injection (injection rate 1 x 400 kg/s) are shown.

The main findings of the tests performed to investigate countercurrent flow of steam and saturated water injected into hot legs can be summarized:

- water breakthrough from the upper plenum to the core occurred in front of the injecting hot leg nozzles leading to heterogeneous flow conditions at the tie plate
- water downflow and steam upflow paths at the tie plate are separated
- there is no substantial time delay between start of ECC-injection and tie plate water breakthrough
- water breakthrough rate increased with decreasing core steam flow rate
- non-uniform distribution of vertical differential pressure in the upper plenum measured across the tie plate had been detected
- the water downflow is significantly higher than that of the flooding curve determined for homogeneous flow conditions at the tie plate
- the UPTF tests indicate clearly that "classical" Kutateladze-scaling can not be applied for heterogeneous flow conditions without modifications [5, 9]

Countercurrent Flow of Saturated Steam/Water Upflow and Subcooled Water Injected into Hot Legs

Compared to saturated hot leg injection the conditions for the water breakthrough at the tie plate become more favourable if highly subcooled ECC water is injected.

In Fig. 10 the results of an UPTF test with a very high water/steam ratio of the upflow rate of w/s = 4 are shown (a typical value for the reflood period of a PWR is w/s = 2). Additional results of tests, investigating the effect of the water/steam ratio of the two-phase upflow as well as the effect of transitory flow change with increasing and decreasing upflow rates are presented.

The UPTF tests have shown that:

- the ECC penetration to the core region always follows the ECC delivery to the upper plenum without substantial delay, and occurs in front of the hot legs with ECC injection
- the time-averaged water breakthrough at the tie plate is not significantly affected by intermittent water delivery to the upper plenum compared to continuous delivery
- the water breakthrough at the tie plate increases with decreasing steam flow rate

- for a given steam upflow rate the water breakthrough at the tie plate increases with decreasing water/steam ratio of the two-phase upflow
- a two-phase pool of saturated steam and water in the upper plenum at initiation of hot leg ECC injection has only a minor effect on the water breakthrough at the tie plate
- during the period of increasing core upflow rates the water downflow is higher than for decreasing upflow rates at the same steam upflow rates
- due to heterogeneous flow conditions at the tie plate, strongly dependent on scale, the "classical" Kutateladze scaling cannot be applied without modifications [5, 9].

General Conclusions related to Tie Plate and Upper Plenum Behaviour

In general the UPTF tests reveal that the tie plate CCF behaviour with hot leg ECC-injection is quite different from that without hot leg ECC-injection, even if saturated ECC-water is delivered to the upper plenum.

The classical Kutateladze type CCFL correlation can only be used to predict the tie plate water downflow rate if no ECC-water is injected into hot legs or upper plenum. Only in this case the tie plate CCFL test results elaborated in small scale test facilities can be applied to a large tie plate.

In case of hot leg ECC-injection the water downflow through the tie plate is much higher than predicted by the previous tie plate CCFL correlations which are based on small scale test data. The reason for this deviating CCF behaviour is the inhomogenous distribution of the water mass across a full size tie plate due to local ECC-water delivery to the upper plenum. These features guarantee a good core cooling with hot leg injection, because over the full range of typical reactor core outlet flowrates the injected ECC-water penetrates through the tie plate into the core without delay and leads in combination with the cold leg injection to a fast reflooding of the core.

5. Flow Behaviour in the Main Coolant Pipes

Flow Behaviour in the Main Coolant Pipes during ECC-Injection

Pressure and fluid oscillations as well as flow regime transition can occur in the main coolant pipes of a PWR during the end-of-blowdown, refill and reflood phases due to ECC-injection. These oscillations are mainly induced by direct contact condensation of steam and the injected subcooled ECC-water.

To investigate the flow behaviour in horizontal pipes with cold leg ECC-injection via a side tube, smallscale tests ranging from 1/20 to 1/3 scale were performed previously [10]. The experiments indicated that water plug formation and oscillations may occur.

To investigate the flow behaviour in horizontal pipes with hot leg ECC-injection via an axial injection nozzle, small scale tests with models at 1/5 and 1/10 scale were carried out in the past [11].

The tests indicated that complete ECC-water reversal can occur at high steam flowrates from the upper plenum to the hot leg.

UPTF tests were carried out to investigate loop flow patterns at full-scale and to quantify the thermal-hydraulic boundary conditions which leads to pressure and flow oscillations in the loop when ECC-water is injected into the cold leg or into the hot leg [12].

Three different flow patterns were identified:

- stable water plug
  refers to formation of a quasi-steady state water plug in the pipe adjacent to the ECC injection port
- unstable plug
  implies occurrence of an unstable water plug with large oscillation amplitudes in the pipe accompanied with water hammer events
- stratified flow
  stands for establishing of water flow at the bottom and steam flow at the top of the pipe, where temperature stratification can occur in the water flow.

The UPTF test data gained at different values of pressure and ECC subcooling are plotted in diagrams (Fig. 11 and 12) using the actual steam flow rate and the steam condensation potential of the ECC water. Consequently, the maximum steam condensation potential of the ECC water (thermodynamic ratio $R_T = \dot{M}_{S,\,cond.\,pot}/\dot{M}_S = 1$) is represented in these diagrams by a straight line indicating the interface between stratified flow and plug flow ranges.

For steam flows higher than the steam condensation potential of the ECC water ($R_T < 1$), stable stratified flow occurs because there has to be a flow path for the nearly saturated water at the bottom and the surplus steam at the top of the pipe. Stable stratified flow in the cold leg also occurs at steam flow rates slightly below the curve $R_T = 1$ (Fig. 11). The temperature stratification of the water flowing at the bottom of the pipe allows stable stratified flow to occur for $R_T > 1$. The extent of this region depends on the turbulence of the injected ECC water.

Fig. 11 and 12 reveal that stable water plug occurs only when the steam mass flow exceeds a certain threshold value. This threshold value is a function of the absolute pressure and also a function of the steam condensation potential of the ECC water in case of countercurrent flow in the hot leg. In this case the water plug formation in the hot leg pipe is linked to complete flow reversal of the injected ECC water.

When the actual steam flow is lower than the threshold value, i. e. the condensation potential of the ECC water is sufficiently higher than the actual steam flow, unstable plug flow with large oscillation amplitudes occurs in the cold leg or in the hot leg pipe. The steam flow condensing on the subcooled ECC oscillates strongly, while the water plug is expelled to the downcomer or upper plenum respectively. The intermittent formation of a new water plug can give rise to water hammer loads on the pipe walls.

At low steam flow and ECC injection rates, stable stratified flow can occur up to the vertical dot-dash line (drawn in Fig. 11 and 12) which marks the minimum condensation potential of the ECC water where the steam momentum flux is sufficiently high to form a water plug.

The UPTF tests reveal that:

- plug flow occurs when the condensation potential of the ECC-water exceeds the steam flow, typical for accumulator injection
- the flow is stratified when the condensation potential of the ECC-water is less than the steam flow
- plug flow results in intermittent ECC delivery into the downcomer or upper plenum respectively, while stratified flow causes continuous ECC delivery

Flow Conditions in Hot Leg during Reflux Condenser Mode

In the reflux condenser mode heat is transferred from the core to the secondary side of the steam generators by evaporation of water in the core and subsequent condensation of that steam in the U-tubes of the steam generators. A portion of this condensate flows countercurrently to the steam through the hot leg via the upper plenum back into the core. By momentum exchange between the upflowing steam and the downflowing water in the hot legs flooding may occur, which could prevent or at least deteriorate the water back flow to the core.

Countercurrent flow in PWR hot legs has been investigated at sub-scale facilities with pipe diameters up to 200 mm (see Fig. 13).

To provide CCFL data for full-size reactor geometry, UPTF tests were performed. The results are plotted in Fig. 14 using the Wallis parameter J^*. The data show that water runback to the test vessel decreases as the steam flow increases. At high steam flows ($J^*_g > 0.5$), there was complete turn-around of the water flow. The close agreement of the data at the two pressures indicates that the Wallis parameter adequately accounts for pressure effects.

In Fig. 14 the UPTF tests are also compared to CCFL correlations derived from sub-scale experiments. The Krolewski correlation [13] underpredicts UPTF water runback, on the other hand the Ohunki correlation [14] overpredicts runback. The Richter correlation [15], however, passes through the UPTF data, which is obviously due to the similar configuration of the flow channel.

The UPTF test No. 11 demonstrated that:

- a substantial margin exists between the flooding limit and the typical conditions expected in a PWR during reflux condenser mode of a small leak loss-of-coolant accident

6. Application of UPTF Test Results for Code Development and Code Assessment

The UPTF tests extended remarkably the experimental data base required to develop and validate analytical models used in the large thermal-hydraulic system codes for the description of phenomena in full scale reactor geometry.

To illustrate the application of the UPTF test results for model validation, the analysis of the UPTF test No. 11 [16], one of the essential tests in the ATHLET validation matrix due to the full scale reactor geometry of UPTF, will be shown.

In Fig. 15 the countercurrent flow situation during reflux condenser mode is characterized. Also the nodalization scheme of the hot leg, used in the analysis, is indicated.

In Fig. 16 the calculated CCFL mass flow rates together with the measured data are plotted in a Wallis diagram, using in contrast to Fig. 14 the cross-section of the hot leg outside the Hutze region as a characteristic dimension. Each symbol in the plot represents either one calculation or one test run.

Based on the measurement of the 3-beam-gamma densitometer, which is mounted in the hot leg at a position 6 m away from the pressure vessel, a water level height has been determined and compared with the ATHLET results.

Fig. 17 illustrates the calculated water level height along the hot leg at test conditions characterized by 15 bar system pressure and 24 kg/s vapour flow from the upper plenum to the steam generator. In this figure the Hutze region is indicated by an unshaded section. The calculated water level height can be compared with the value derived on the basis of the 3-beam-gamma-desitometer measurement. The analysis indicates that the CCFL in the hot leg occurs at the bend part of the hot leg. The accumulation of water reaches its maximum there. Consequently, the largest differences in phasic velocities are predicted for this position.

In Fig. 18 the water level heights at the position at the 3-beam-gamma-densitometer are plotted as function of the steam flow. It can be noticed that as far as the steam flow is less than the countercurrent flowlimit the water level height is kept on a low level of about 0.12 m. If the steam mass flow rate reaches the CCFL conditions the water level steeply increases to the highest level height of about 0.30 m. With further increase of the steam mass flow rate the water level height decreases gradually due to the start of entrainment from the water surface. At even higher steam flow the conditions of complete flooding are reached, the water downflow to the upper plenum is completely inhibited. In this situation a large amount of water still remains in the hot leg. The water level height at the measurement position is about 0.20 m.

The water level height, derived from the 3-beam-densitometer measurement, and the calculated data are in good agreement. The typical flow behaviour at the onset of flooding is predicted by the flow model implemented in ATHLET.

The UPTF test No. 11 confirms that:

- the flow model of ATHLET basing on Wallis parameter for steam and water, which has been validated previously on small-scale tests, predicts the countercurrent flow limitations also in case of a large diameter pipe of 0.75 m.

7. Conclusions

To investigate two-phase flow phenomena occurring in PWR primary systems during loss-of-coolant accidents with active emergency core cooling systems, a series of tests have been performed at the 1 : 1 scale test facility UPTF.

The UPTF tests have remarkably extended the data base required to develop and validate analytical models used in the large thermal-hydraulic codes for the simulation of two-phase flow phenomena in full scale reactor geometry.

Based on comparisons with test results from sub-scale facilities the following conclusions can be drawn with respect to the scalability of the two-phase flow phenomena:

- for two-phase flow conditions in horizontal and inclined pipes (1-D components) the classical J^* scaling can be applied successfully

- for inhomogeneous flow, e. g. in the upper plenum or downcomer, there is a need for improved multi-dimensional modelling

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NOMENCLATURE

A	cross section area, m²
D	diameter, m
F	condensation efficiency, [-]
g	acceleration due to gravity, m/s²
h	height, m
$K^* =$	$\rho^{1/2} \cdot j(g \cdot \sigma \cdot \Delta\rho)^{-1/4}$ Kutateladze number, [-]
$J^* =$	$\rho^{1/2} \cdot j(g \cdot D \cdot \Delta\rho)^{-1/2}$ Wallis parameter for pipes, [-]
$J^* =$	$\rho^{1/2} \cdot j(g \cdot W \cdot \Delta\rho)^{-1/2}$ Wallis parameter for downcomer, [-]
M	mass flow, kg/s
$M_{s,cond,pot}$	steam condensation potential of ECC, kg/s
p	absolute pressure, bar
R_T	thermodynamic ratio, [-]
T	temperature, K
W	average downcomer annulus circumference, m
$\Delta\rho = \rho_w - \rho_s$	difference of densities, kg/m³
ρ	density, kg/m³
σ	surface tension, N/m

Subscripts

C	core
cond	condensation
d	down; delivery
DC	downcomer
eff	effective
H	hydraulic
s	steam
w	water
x	water or steam

ABBREVIATIONS, ACRONYMS

BCL	broken cold leg
CCF(L)	countercurrent flow (limitation)
CL	cold leg
ECC	emergency core cooling (coolant)
MCL	main coolant line

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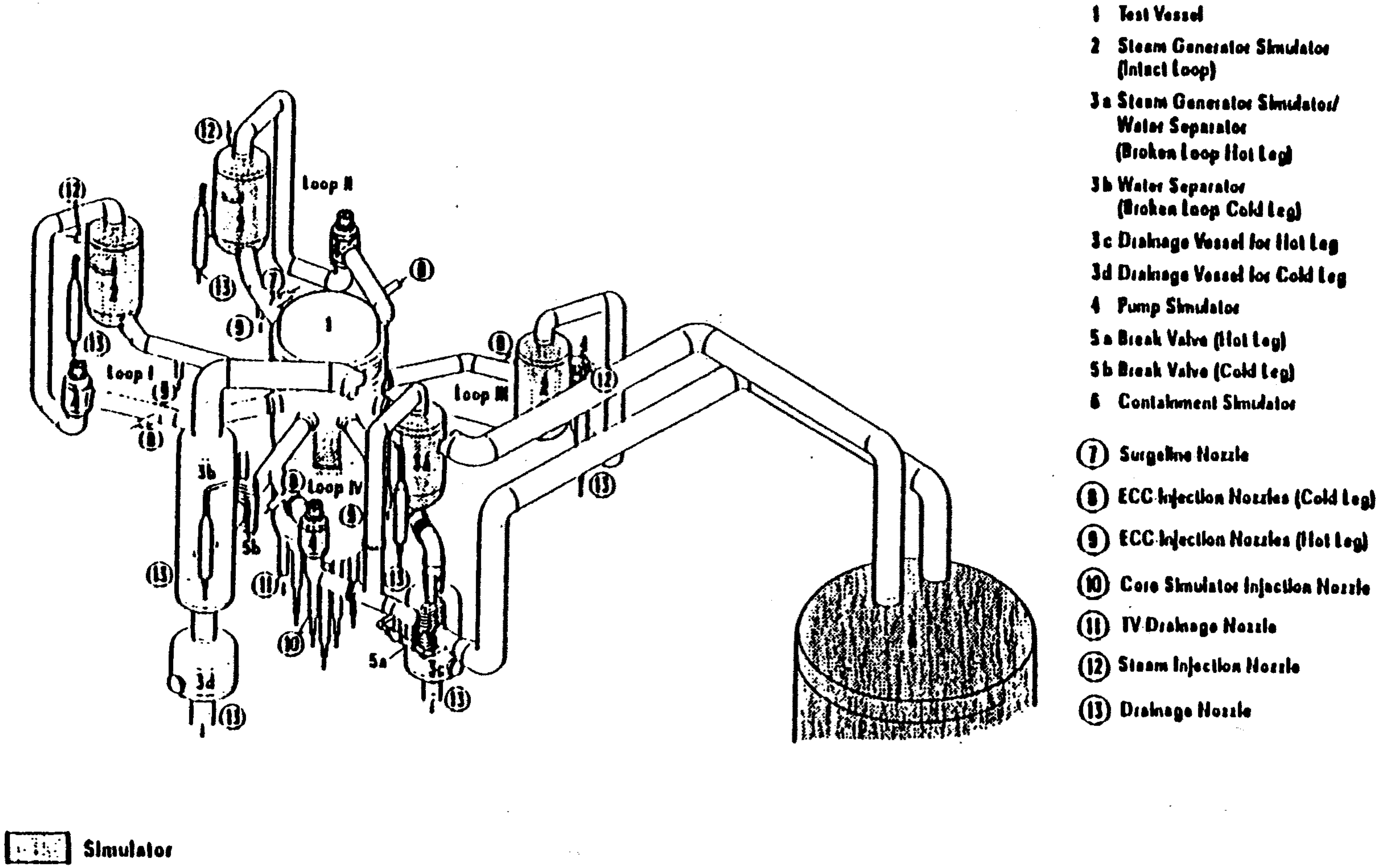
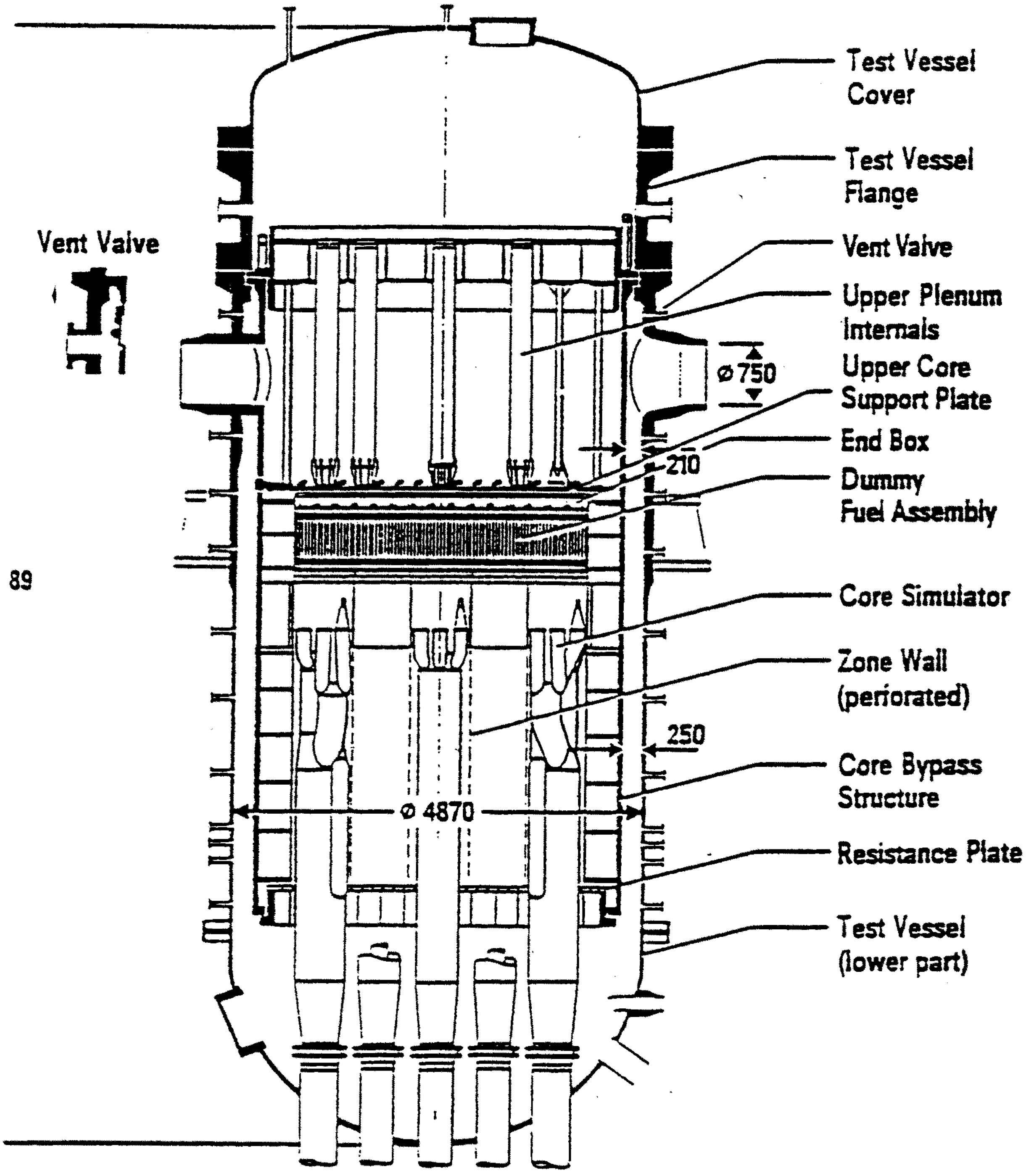


Upper Plenum Test Facility-Primary System

86 PWR 039e
UB KWU

Fig. 1 Upper Plenum Test Facility (UPTF) Primary System



TF-Test Vessel and its Internals 86 PWR 060e

2 Test Vessel of UPTF with Core Simulator, Downcomer, and Upper Plenum

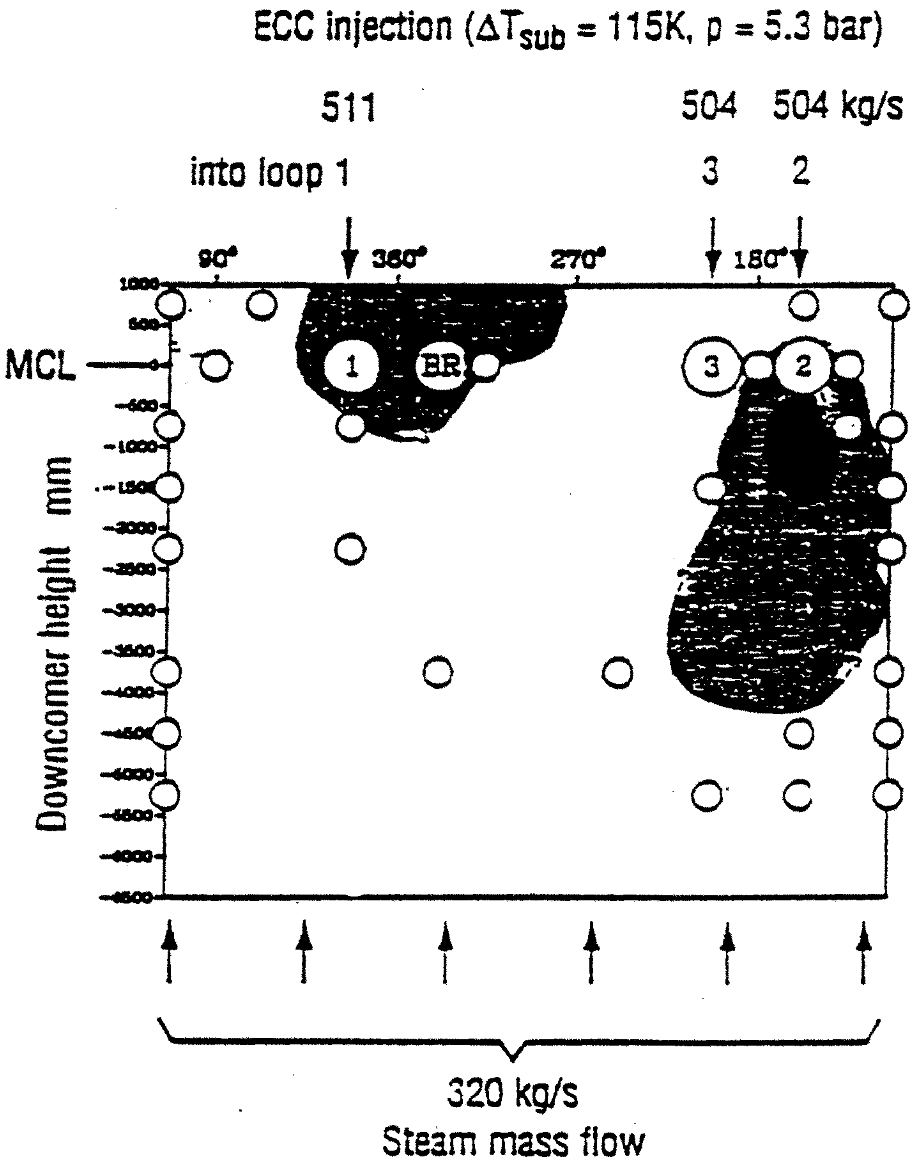


Fig. 3 Countercurrent flow conditions in full-scale downcomer for strongly subcooled ECC, distribution of subcooling

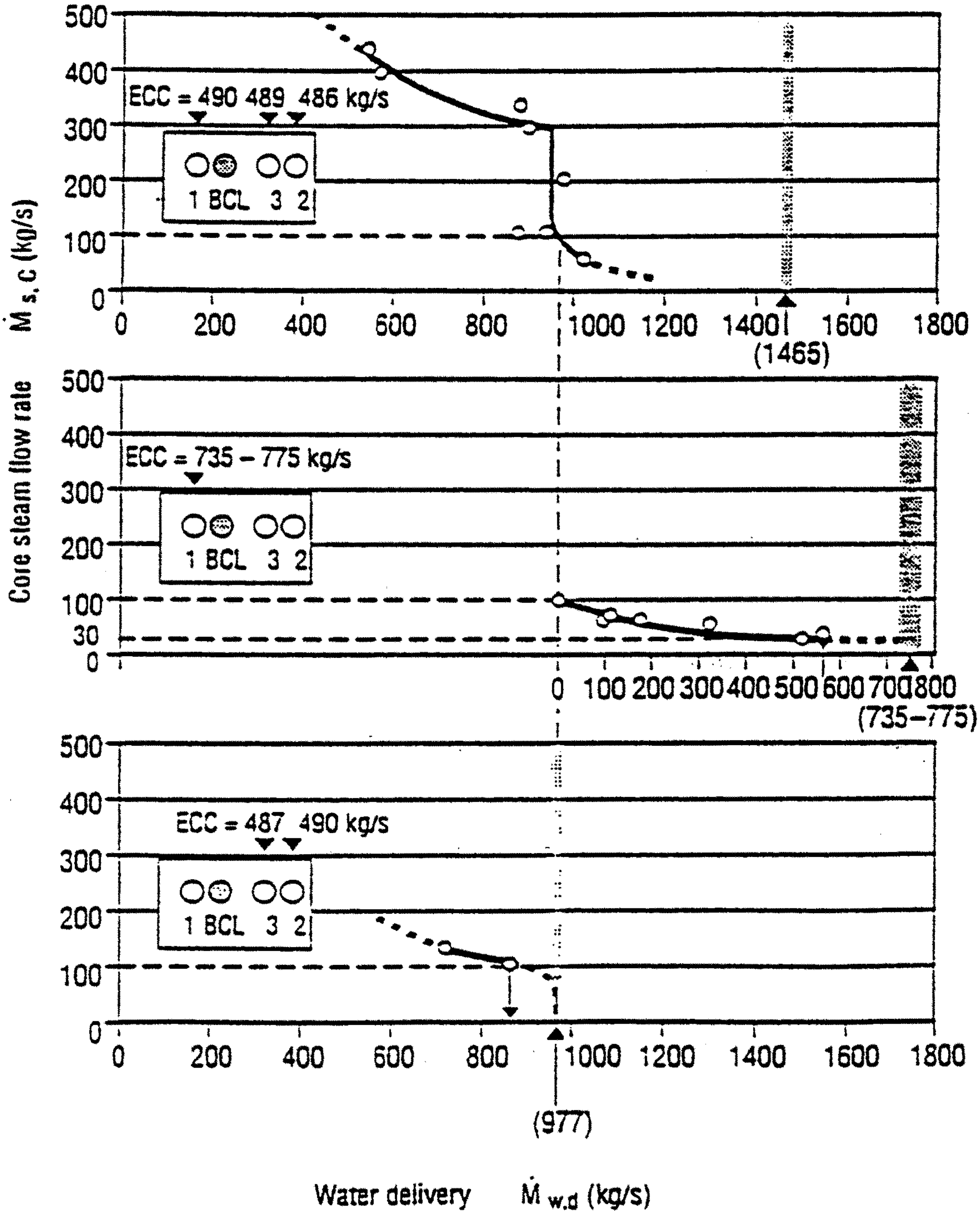


Fig. 4 Effect of loop arrangement on water delivery to lower plenum for nearly saturated ECC in countercurrent flow, UPTF tests 6, 7 and Z3B

91 UPTF 002 e

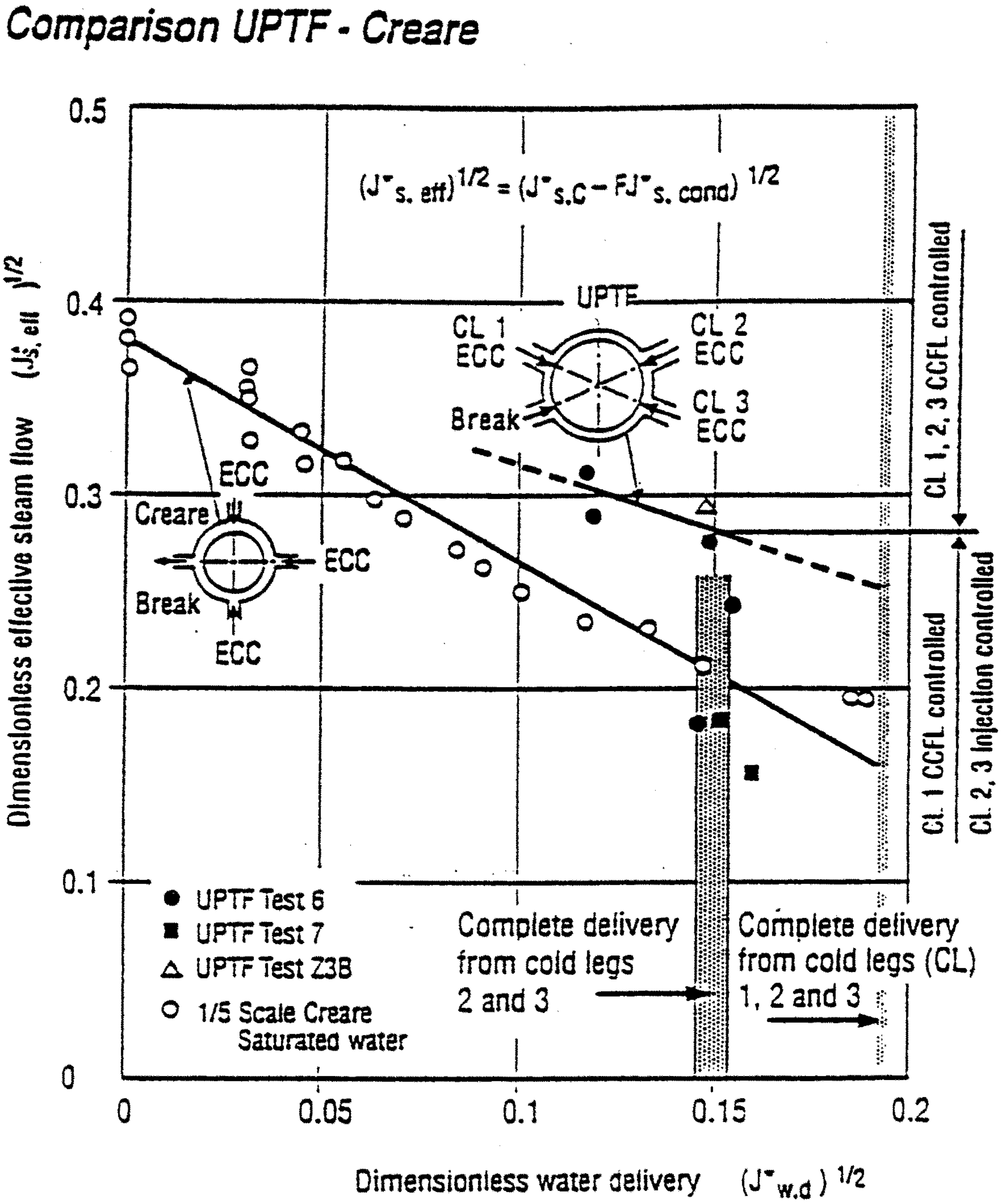


Fig. 5 Effect of geometrical scaling on water delivery to lower plenum for nearly saturated ECC in countercurrent flow, UPTF tests 6, 7 and Z3B

91 UPTF 007 e

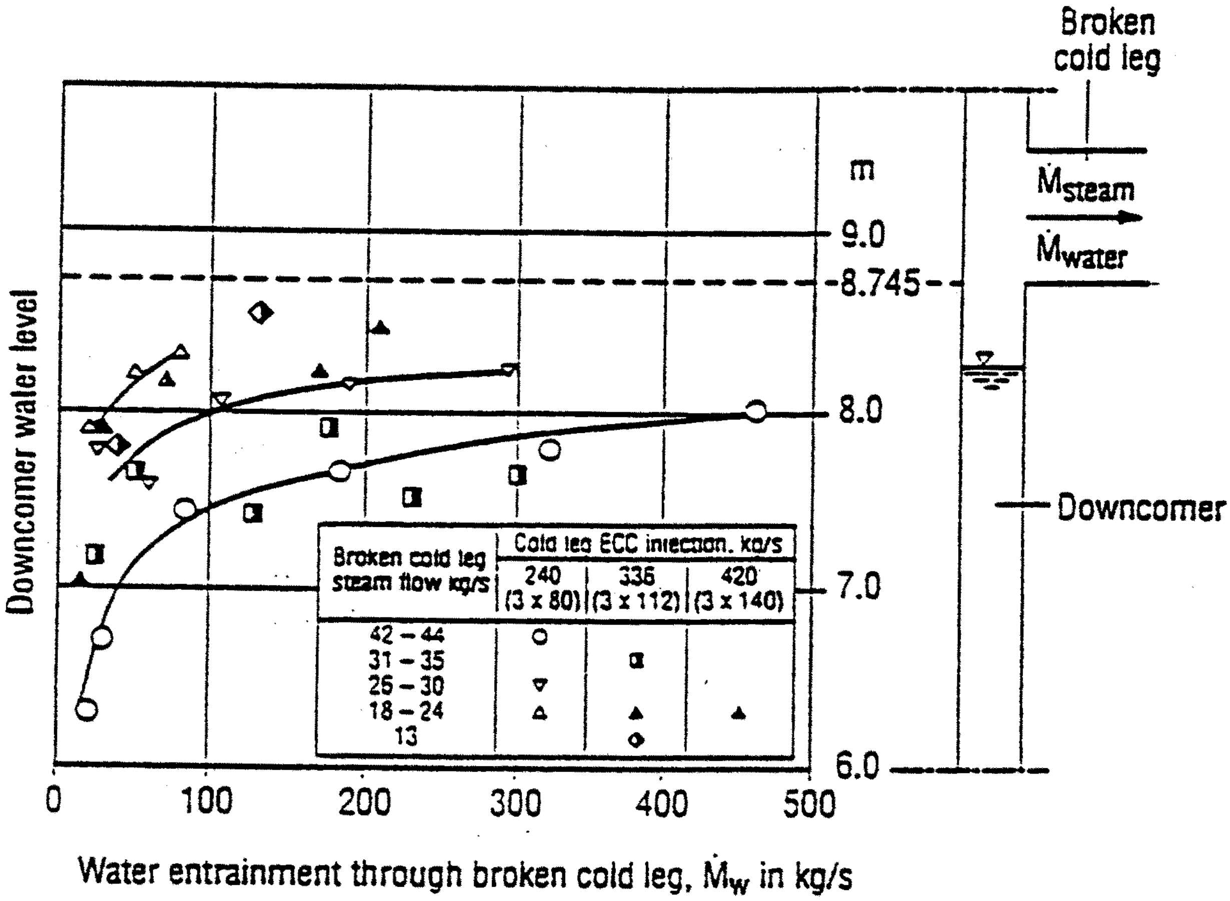
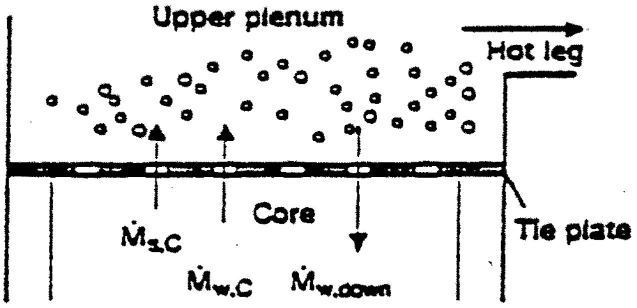
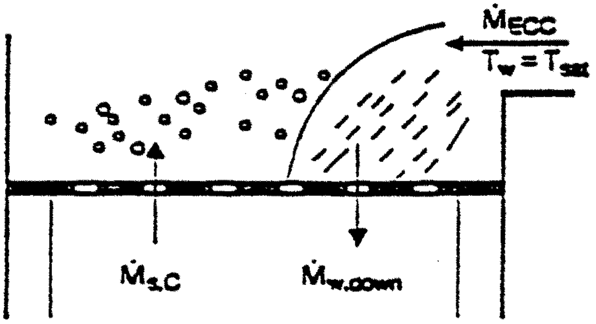


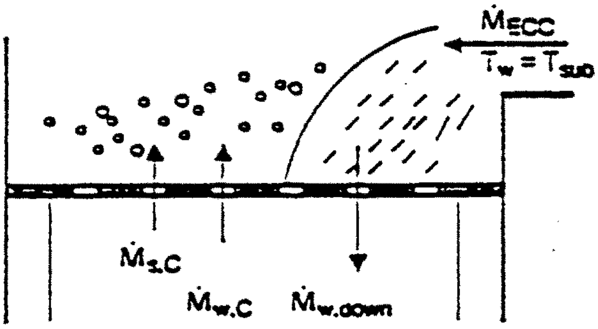
Fig. 6 Water entrainment through broken cold leg vs. downcomer for different water levels, steam flow and ECC injection rates



a. CCF of saturated steam and water with homogeneous water distribution at tie plate



b. CCF of steam from the core and saturated water from the hot leg with heterogeneous water distribution



c. CCF of saturated steam and water from the core and subcooled water from the hot leg with heterogeneous water distribution

Fig. 7 Countercurrent flow conditions at the tie plate addressed in UPTF tests

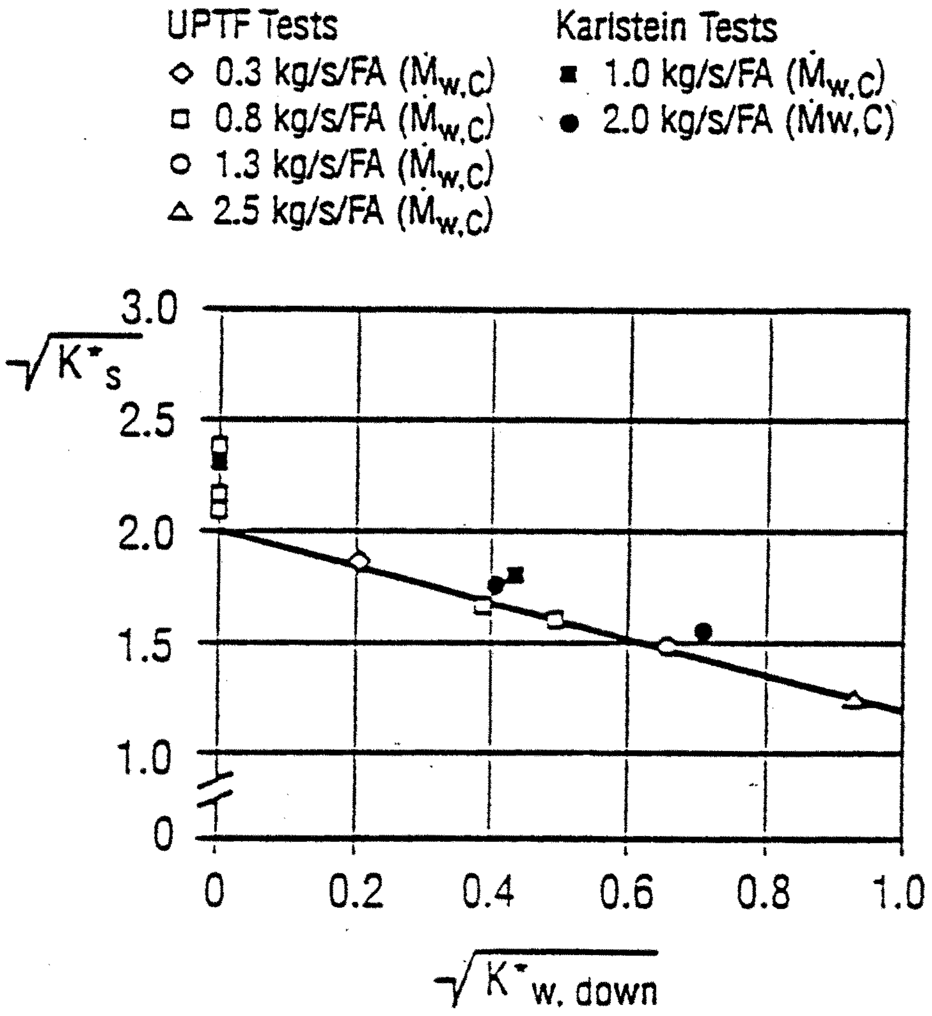


Fig. 8 Countercurrent flow of saturated steam and water at the tie plate

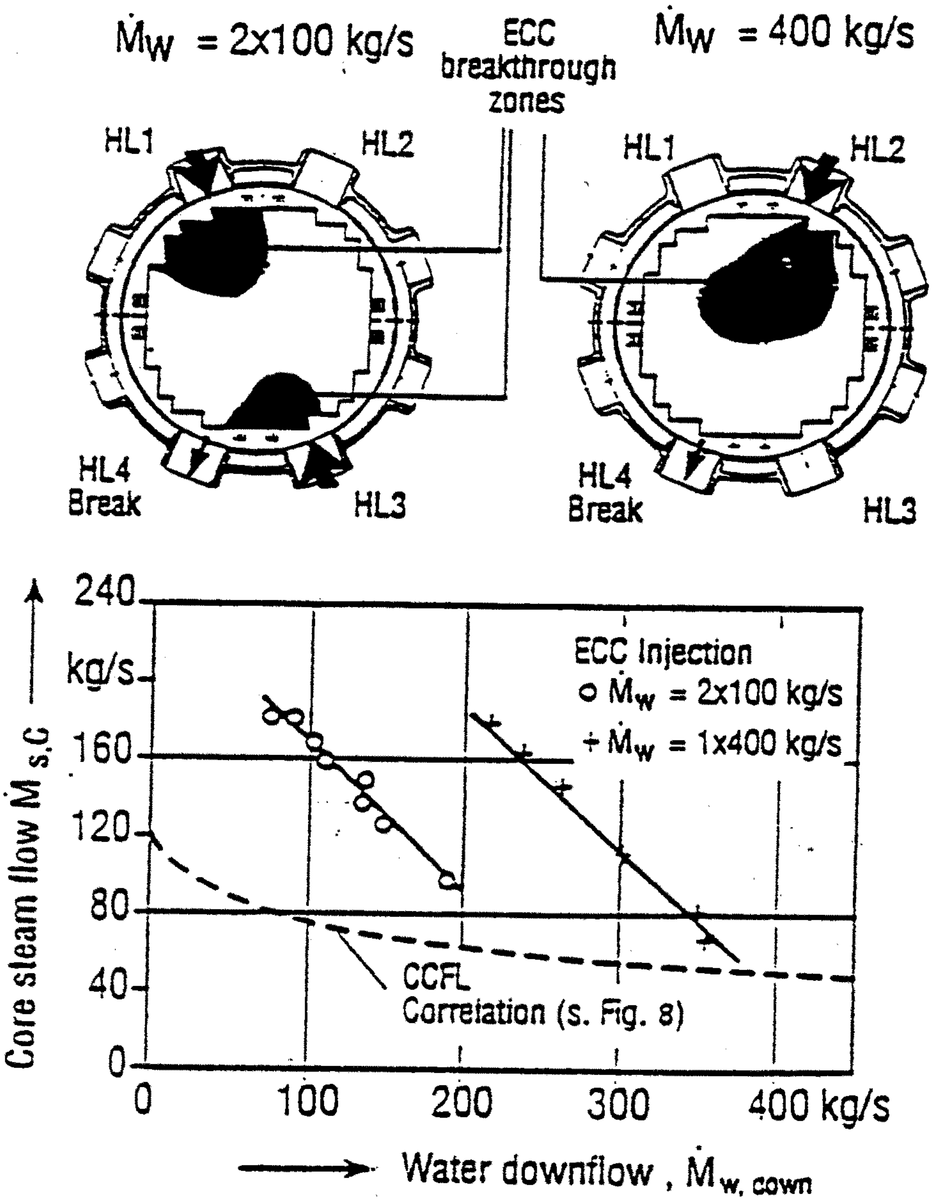


Fig. 9 Countercurrent flow of steam and saturated water injected into hot leg

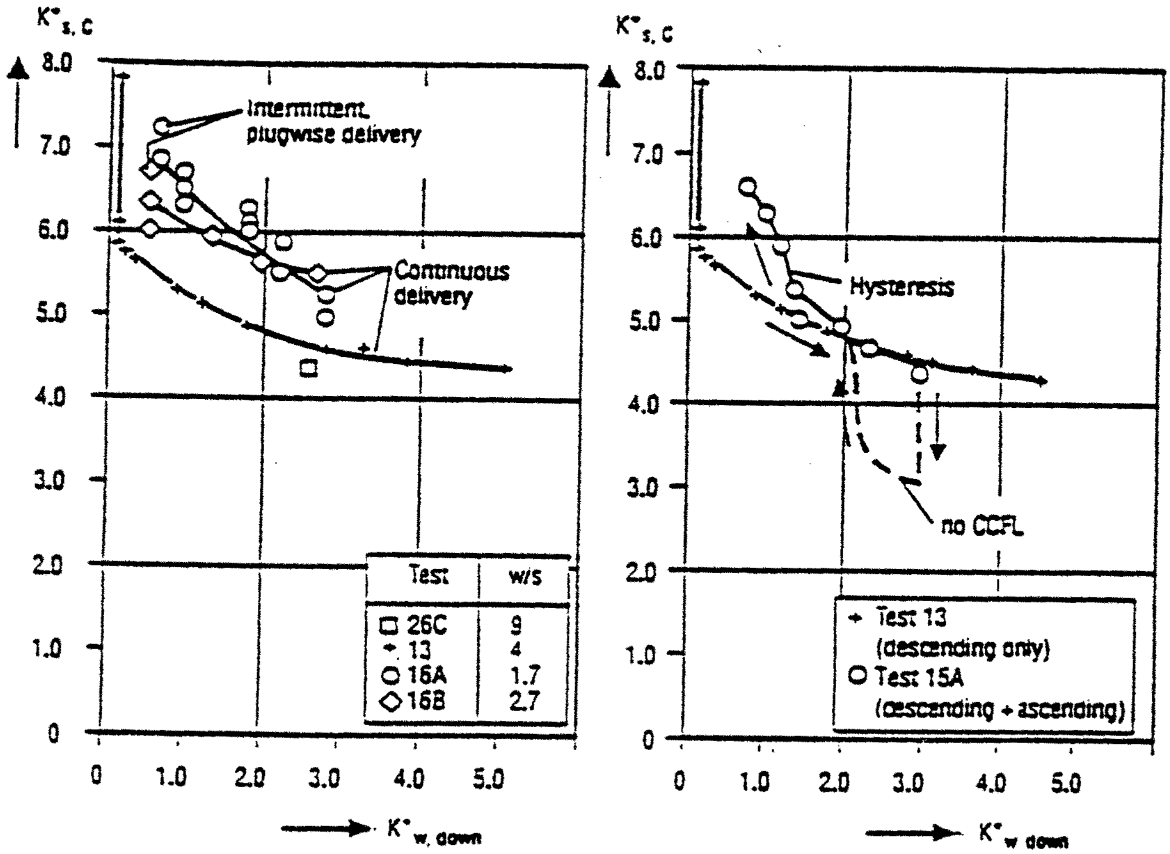


Fig. 10 Countercurrent flow of two-phase up-flow and subcooled water downflow during hot leg ECC injection

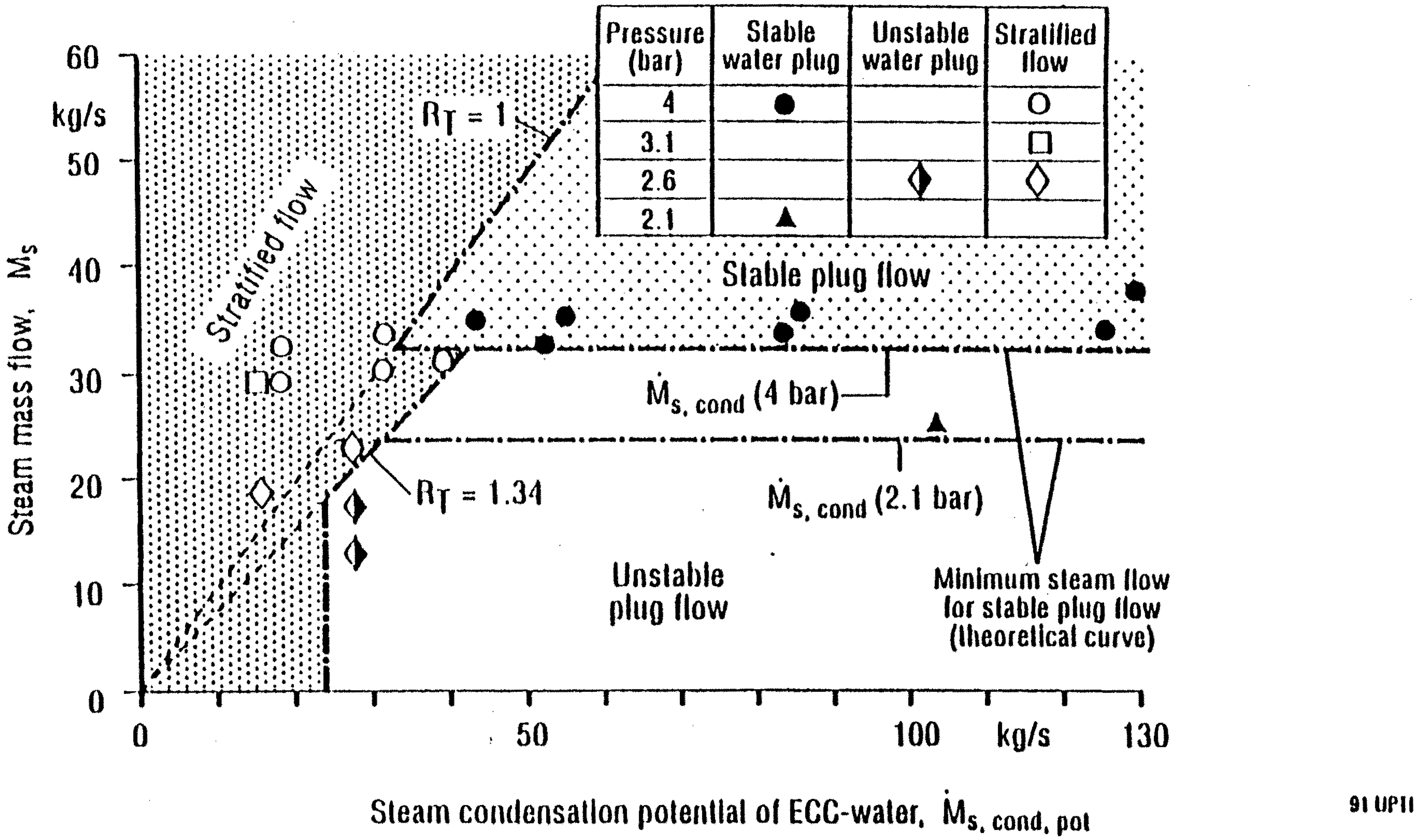


Fig. 11 Flow patterns for cocurrent flow in the cold leg

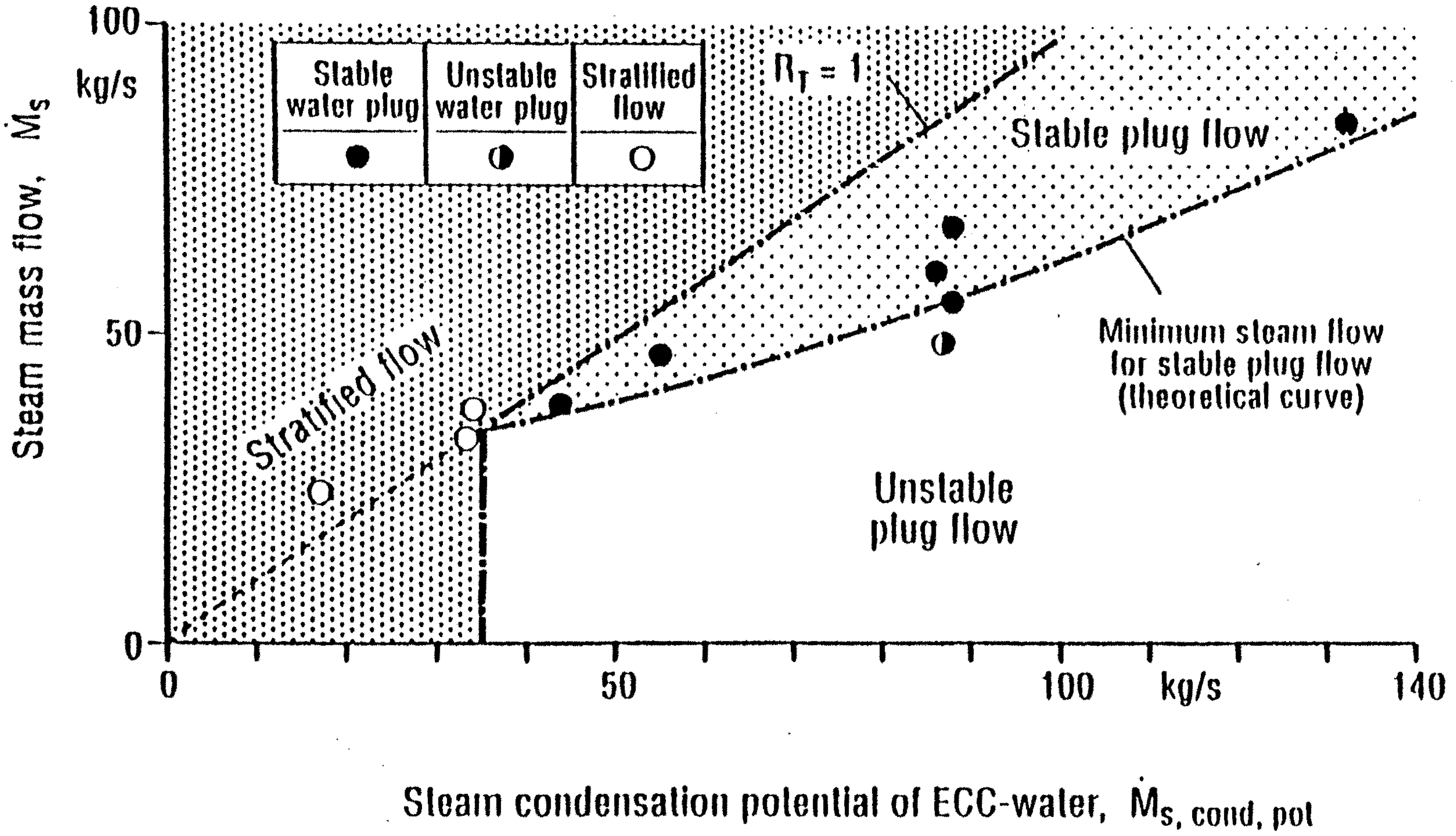


Fig. 12 Flow patterns for countercurrent flow in the hot leg

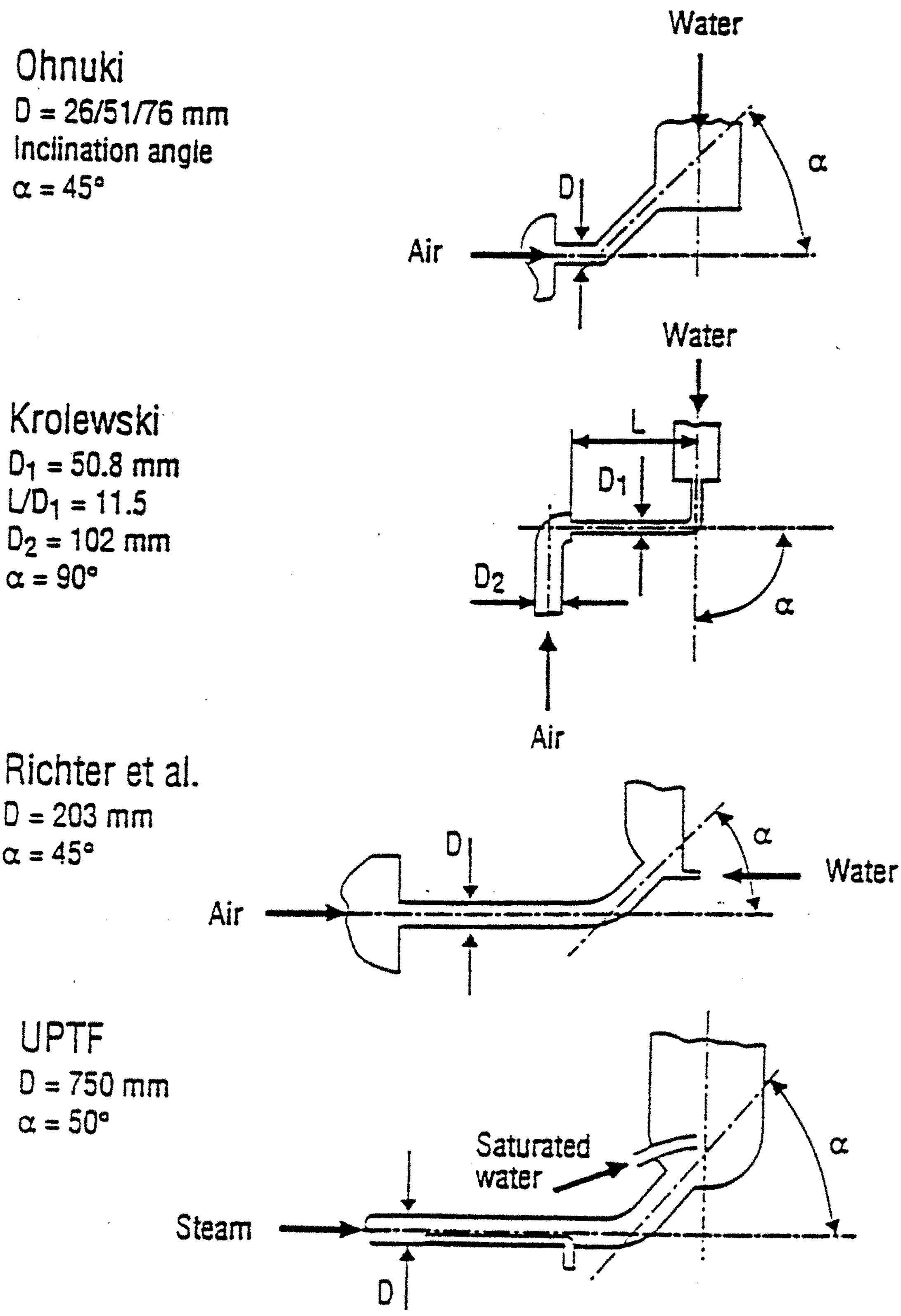


Fig. 13 Countercurrent flow studies in PWR hot legs

92 UPTF 024 e

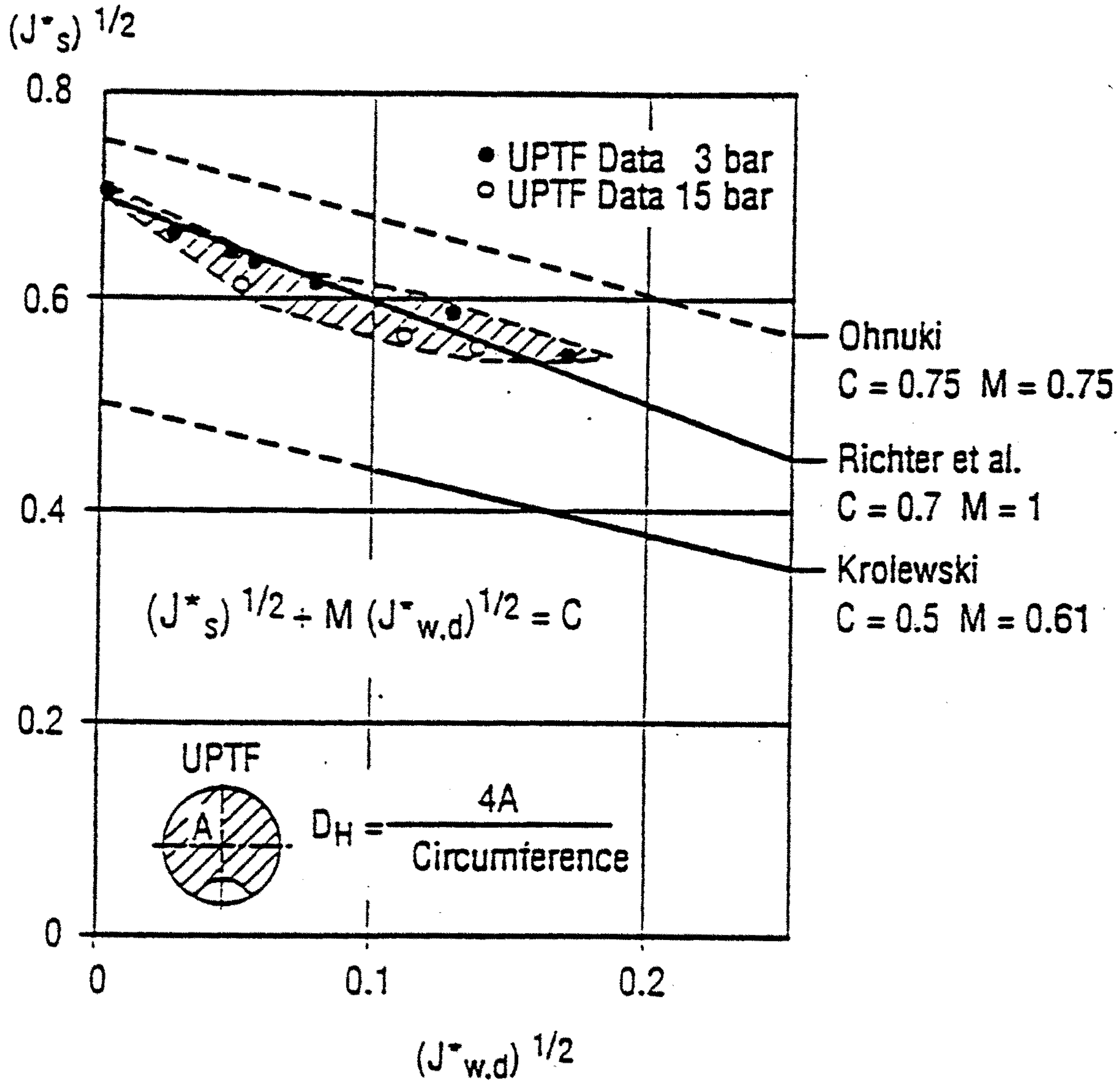


Fig. 14 UPTF test data compared to correlations derived from subscale tests

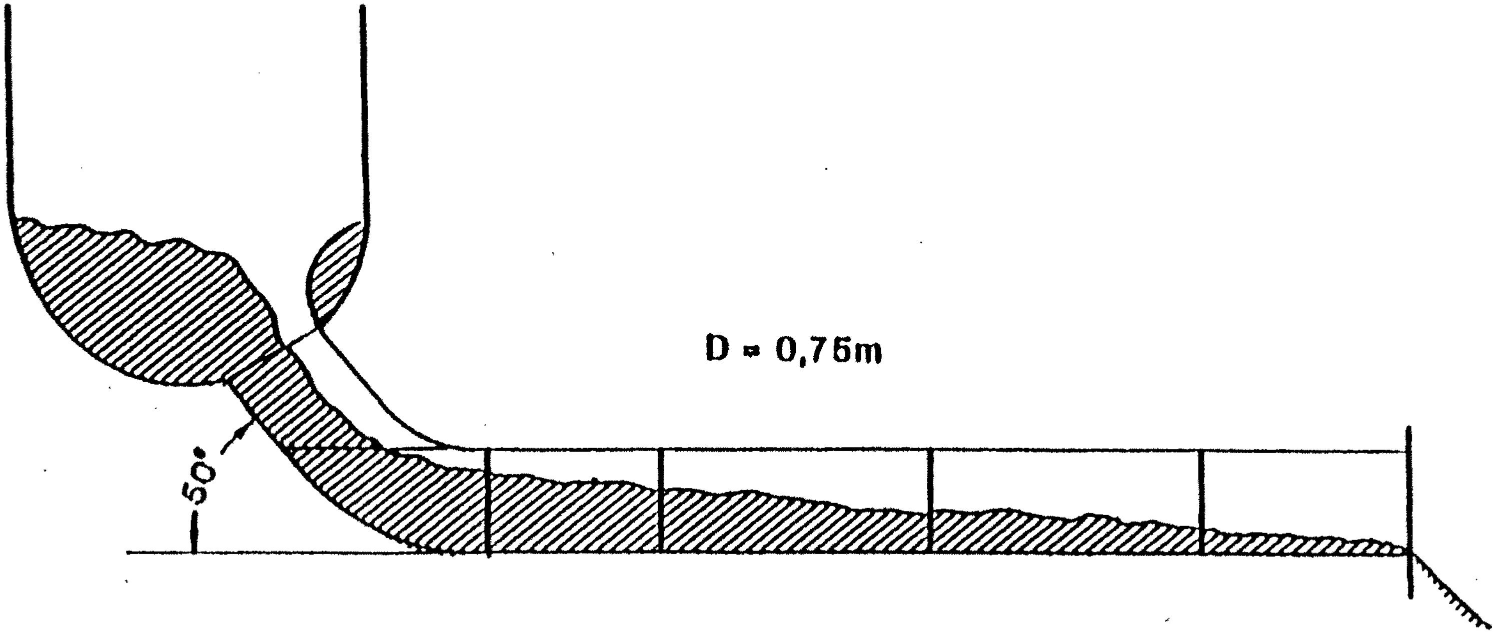


Fig. 15 Schematic View of Counter-current Flow and Nodalization of the Hot Leg

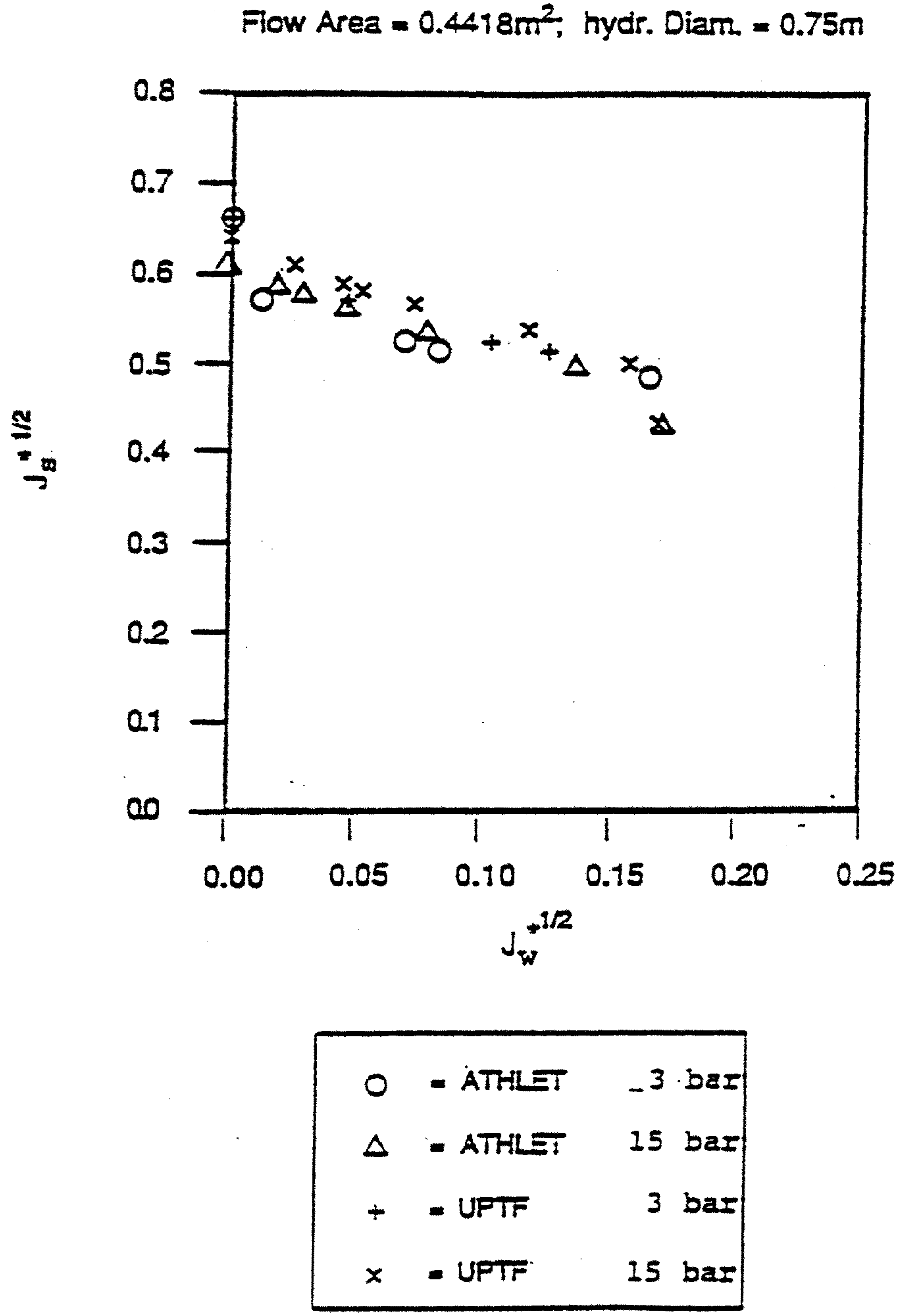


Fig. 16 UPTF and ATHLET data plotted in a Wallis diagram

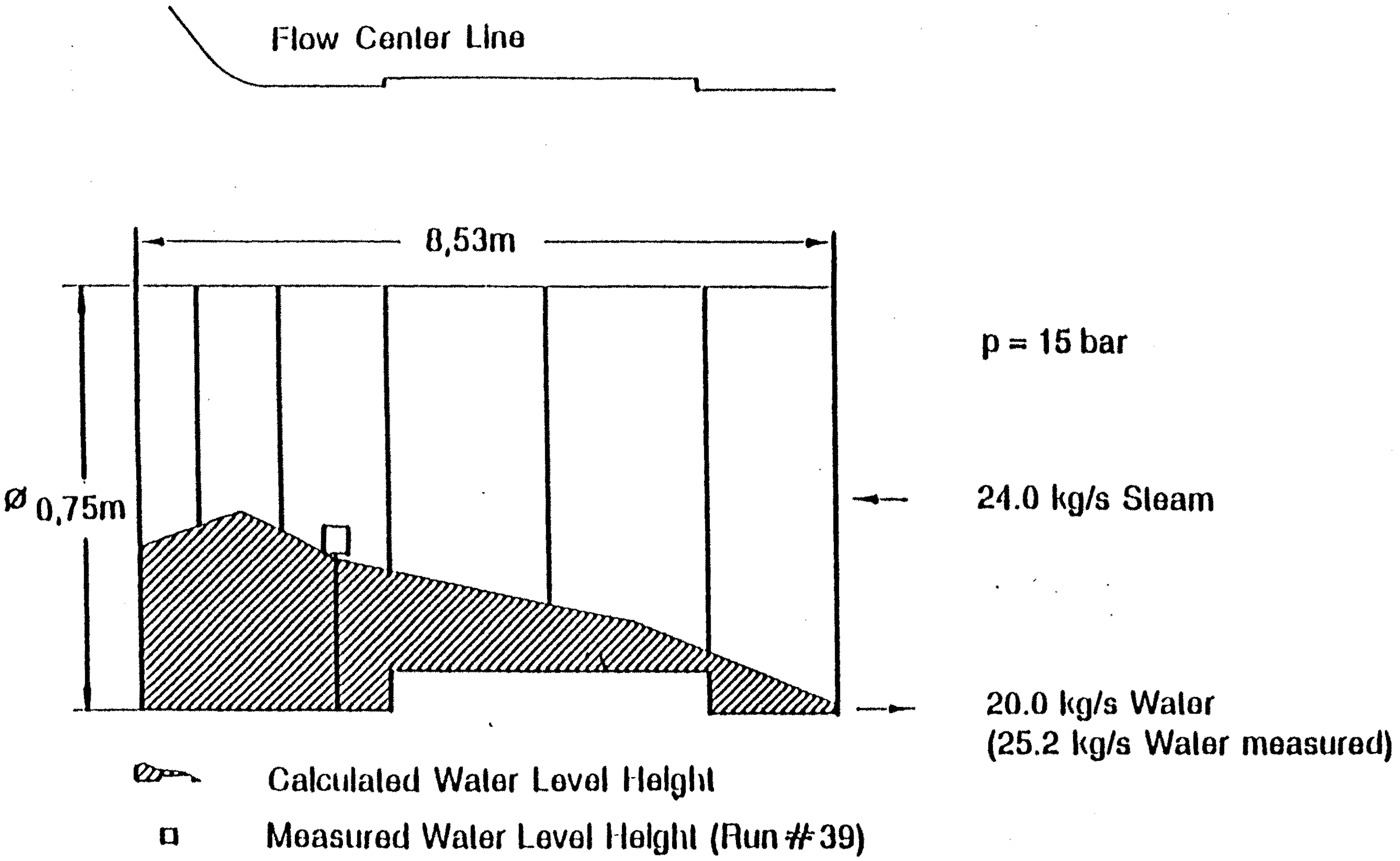


Fig. 17 Water level heights along the UPTF hot leg

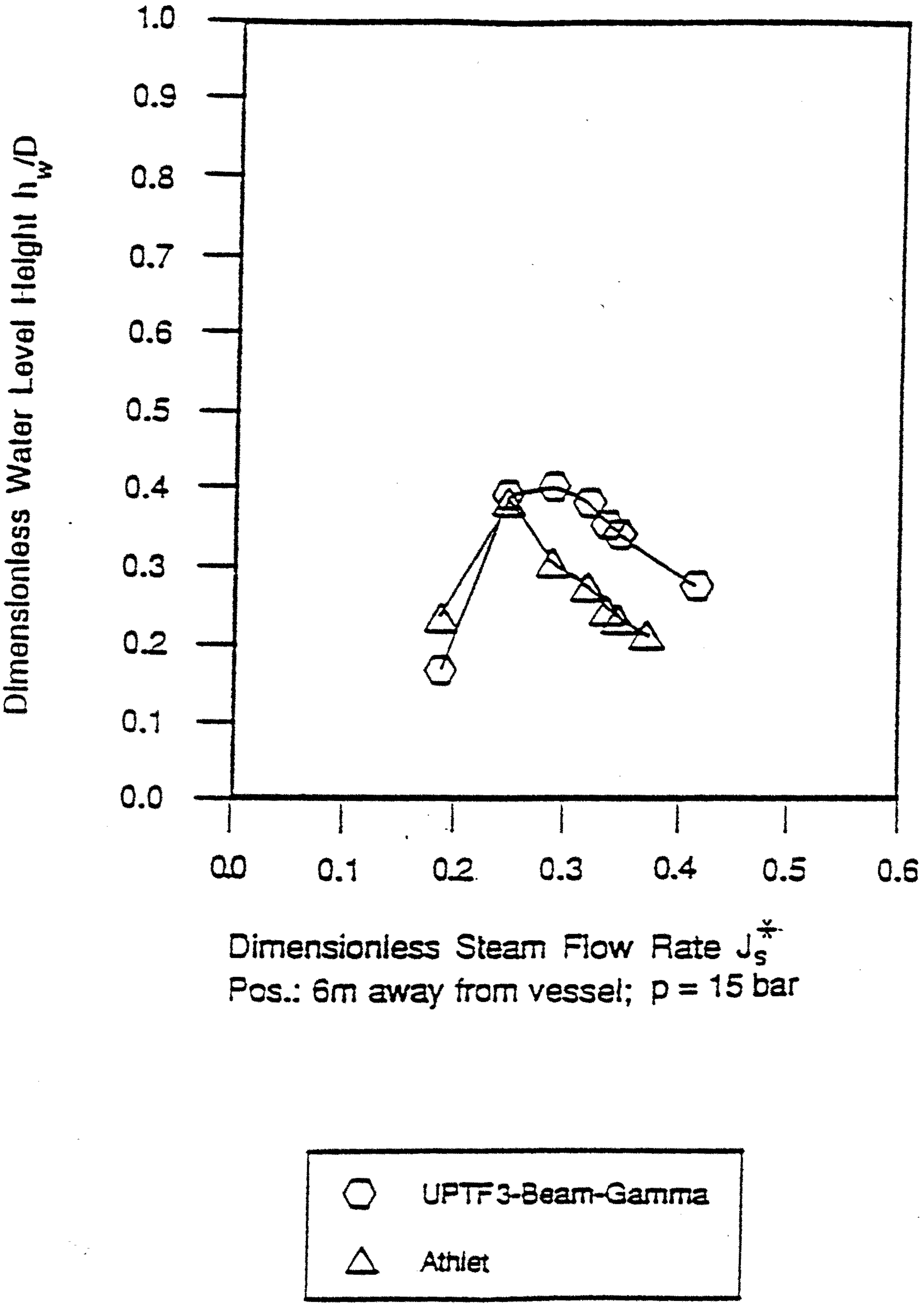


Fig. 18 Dimensionless water level height at 15 bar