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Analysis of the UPTF Separate Effects Test 11 (Steam-Water Countercurrent Flow in the Broken Loop Hot Leg) Using RELAP5/MOD2

Prepared by
M. J. Dillistone

Winfrith Technology Centre
United Kingdom Atomic Energy Authority
Dorchester, Dorset, DT2 8DH
United Kingdom

Office of Nuclear Regulatory Research
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Washington, DC 20555

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NOTICE

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SUMMARY

RELAP5/MOD2 predictions of countercurrent flow limitation in the UPTF Hot Leg Separate Effects Test (test 11) are compared with the experimental data. The code underestimates, by a factor of more than three, the gas flow necessary to prevent liquid runback from the steam generator, and this is shown to be due to an oversimplified flow-regime map which does not allow the possibility of stratified flow in the hot leg riser. The predicted countercurrent flow is also shown to depend, wrongly, on the depth of liquid in the steam generator plenum.

The same test is also modelled using a version of the code in which stratified flow in the riser is made possible. The gas flow needed to prevent liquid runback is then predicted quite well, but at all lower gas flows the code predicts that the flow is completely unrestricted - i.e. liquid flows between full flow and zero flow are not predicted. This is shown to happen because the code cannot calculate correctly the liquid level in the hot leg, mainly because of a numerical effect of upwind donoring in the momentum flux terms of the code's basic equations. It is also shown that the code cannot model the considerable effect of the ECCS injection pipe (which runs inside the hot leg) on the liquid level.

CONTENTS

1 INTRODUCTION 1

2 MODELLING THE TEST 2

3 RESULTS 3

3.1 Failure of RELAP5 to predict the flooding point gas flow 3

3.2 Behaviour of the code with stratified flow allowed in the riser 4

4 THE LIQUID LEVEL IN THE HOT LEG

4.1 Introduction 7
4.2 Momentum flux terms 8
4.3 Effect of the Hutze 9

5 EFFECT OF THE LIQUID LEVEL IN THE STEAM GENERATOR INLET PLENUM 11

6 CONCLUSIONS AND RECOMMENDATIONS 13

Acknowledgements 14
References 14

Appendix 15

List of Figures

Figure 1	UPTF broken loop hot leg	17
2	RELAP5 nodalisation scheme	17
3	Experimental and predicted flooding curves	18
4	Predicted distribution of void in hot leg	19
5	Prediction of flooding using more realistic liquid levels in the hot leg	20
6	Liquid level in the hot leg before flooding, calculated by program TEST and taking into account the effects of the Hutze	21
7	Hot leg dimensions	22
8	Steady stratified flow in the hot leg	23
9	Cross-section through the hot leg showing Hutze	22
10	Situation envisaged in steam generator plenum before start of test	24

1. INTRODUCTION

Among the tests carried out at the Upper Plenum Test Facility (UPTF) in Germany was a Hot Leg Separate Effects Test (test 11) which measured the runback of saturated liquid from the steam generator inlet plenum to the reactor vessel against a countercurrent flow of steam.

The UK does not have direct access to either the results or the experimental details of the test, except for what are published in the open literature. The analyis in this report is based on the results as described in [1].

Section 2 of the report describes the modelling of the test using the best-estimate thermal hydaulics code RELAP5/MOD2 cycle 36.05. The results are discussed in Section 3; the main conclusion from these results is that the inability to predict stratified flow in the hot leg riser was crucial to the code's overall prediction of flooding in the hot leg. In the light of this, a small modification was made to the code's horizontal flow-regime map to allow stratified flow in inclined pipes generally, and the tests were rerun with the modified code. The results of these runs are also discussed in Section 3.

It was found that the modified version of the code predicted the liquid flow considerably better than the standard version, but it still didn't do very well because it got the liquid level in the hot leg completely wrong. Reasons for this are discussed in Section 4; they are, firstly, that the way the code models the momentum flux terms in the momentum equations leads it to predict the liquid level to slope the wrong way under certain conditions, and, secondly, that the irregular shape of the hot leg cross-section where the ECCS injection pipe ("Hutze") runs has a considerable effect on the liquid level which the code is quite unable to model.

Finally, it was noticed in a particularly long run using the standard version of the code that the predicted liquid flow was affected by the liquid level in the steam generator inlet plenum, something which other similar experiments indicate is not a physical effect. This is discussed in Section 5, and is shown to be a consequence of the code's "Reverse Void Profile" model, which reduces interphase friction whenever it detects a low void above a high void.

2. MODELLING THE TEST

The UPTF facility is a full-scale simulation of a four-loop German PWR which is similar to a 4-loop Westinghouse. In this test only the broken loop was used, and figure 1 shows the relevent part of the loop. In the German design the ECCS injection pipe penetrates the hot leg and runs along inside it for most of its length, effectively reducing the flow area in the hot leg by about 10%. This section of the ECCS pipe is known the "hutze".

According to [1], the test was conducted as follows. Saturated water was injected into the steam generator inlet plenum as a spray, at a constant flow-rate of 30 kg/s. It collected at the bottom of the plenum and ran down the riser, along the hot leg and into the reactor vessel. Once the flow was steady, steam was injected into the reactor vessel, from which it flowed along the hot leg, up through the steam generator simulator and eventually out through a valve into a containment simulator. The flow of liquid into the reactor vessel was measured, and two gamma densitometers measured the average void fraction at two places along the hot leg. The experiment was repeated with nine different steam flow-rates at an overall pressure of 15 bar, and with six different flow-rates at 3 bar.

In the RELAP5 exercise only the 15 bar tests were modelled, and Figure 2 shows the nodalisation scheme used. The dimensions of the reactor vessel and the hot leg are taken from [1], but the dimensions of the steam generator plenum are pure guesswork. The section of the hot leg where the Hutze runs cannot be modelled exactly with RELAP5, which assumes that all pipes have a circular cross-section, but the reduction in flow area was achieved simply by specifying a smaller (but still circular) pipe.

The junction between the hot leg and the pressure vessel was modelled with an abrupt area change. Changing to a smooth area change was found to have about the same effect on liquid flow as reducing the gas flow by 1 kg/s. Supplying form loss coefficients altered the liquid velocity quite dramatically at the junction, but has no appreciable effect on liquid mass flow-rate.

The RELAP5 simulations followed the experimental procedure of allowing the liquid flow to settle down before the steam was introduced. With RELAP5 10 seconds was allowed for this, and that was found to be enough to let the initial oscillations in the system die away. After that time the steam supply to the reactor vessel was increased from zero to its final value over a period of 2 seconds, and the run continued for a further 53 seconds, making 65 in all.

3. RESULTS

The two main conclusions from the RELAP5 modelling of the test are summarised below, and then enlarged upon.

1. Standard RELAP5/MOD2 fails to predict the flooding curve even reasonably well, underestimating the steam flow-rate needed to prevent liquid drainback by a factor of more than three, and allowing either complete drainback or practically none, but nothing in between. This is principally because there is no suitable flow-regime for the riser, where the flow should be stratified but is forced to be either slug or annular, in both cases with far too much interphase friction. The transition from complete to zero drainback happens at the steam flow-rate which causes the transition from slug to annular flow in the riser, a transition which should be irrelevant in this test.

2. If the flow-regime map is changed to allow stratified flow in the riser, the code predicts well the point of zero drainback, but again the only other possibility allowed is complete drainback. The transition from complete to zero drainback happens when the gas velocity reaches the value which marks the start of the interpolation region between stratified and slug flow in the horizontal pipe (ie at about half the gas velocity predicted by Taitel and Dukler for the transition to slug flow to be complete). The predictions of unrestricted flow at lower gas flow-rates happen because the code does not correctly predict the liquid level along the hot leg, on which the Taitel and Dukler criterion depends.

3.1. Failure of RELAP5 to predict the flooding point gas-flow

The experimental flooding curve, or plot of steam flow-rate against liquid flow-rate, is reproduced from [1] in figure 3. The two points on the right of the graph, corresponding to a liquid flow-rate of 30 kg/s, are not part of the flooding curve: there, all the liquid available is flowing along the hot leg, and the flow is not being limited by the steam.

Also shown on figure 3 is the flooding curve predicted by RELAP5, and it is clear that the prediction is wrong in two ways: flooding is predicted to happen at steam flow-rates more than three times lower than in the experiment, and no 'intermediate flows' are allowed between complete flow and practically no flow.

Both errors occur simply because RELAP5 has no suitable flow-regime for the flow in the riser, the section of pipe which connects the hot leg to the steam generator inlet plenum.

The obvious behaviour for the liquid flowing down into the riser is to emulate a mountain stream on a windy day - which means, as far as a code is concerned, stratified flow. Mukherjee and Brill [7] observed in studies of cocurrent downflow that, if liquid and gas flow rates were not too high, stratified conditions persisted at all pipe inclinations up to and including the vertical. However, stratified flow is not permitted in RELAP5 except in pipes sloping at less than 15 degrees to the horizontal, and the riser slopes at 50 degrees. The code is forced to choose from bubbly, slug or annular flows, in all of which the interphase friction is much higher than would be the case in stratified flow; thus the code predicts flooding to happen at a much lower gas flow-rate than was observed in the experiment.

In fact the code chooses slug flow. At low gas flow-rates the slug regime covers the range of void fractions from 0.25 to roughly 0.96, and the voids predicted for the riser are towards the top of this range (see Figure 4 for a typical void profile). In practice, the presence of liquid slugs in the riser would mean that flooding had already occurred - it is hard to imagine counter-current slug flow in such a situation, particularly with the liquid free to run out at the end of the hot leg. Nevertheless, at low enough gas flows, the code calculates the interphase friction to be insufficient to prevent counter-current flow, even in the slug regime.

For gas flow-rates higher than a certain critical value, the upper limit on void fraction for the slug regime changes abruptly from being 0.96 to being 0.75, which means in the case of the riser that the flow regime switches from slug to annular as the gas flow reaches the critical value. As is reported elsewhere [2], the interphase friction rises very rapidly as this point is reached, because the i/f coefficient calculated by the code is typically three times greater in the annular regime than in the slug regime at the same void. It is this sudden increase in interphase friction which causes the abrupt change from complete liquid flow to zero flow.

3.2. Behaviour of code with stratified flow allowed in riser

The third curve in Figure 3 is the flooding curve predicted by RELAP5 when the flow-regime map is modified to allow stratified flow in the riser (specifically, in any pipe inclined at less than arcsin 0.8 to the horizontal). The point of zero liquid flow is now predicted much better, mainly because the correlation which determines it is the correct one physically, i.e. the transition from horizontal stratified to slug flow. However, the liquid flow is increasingly overpredicted as the gas flow increases from around 50% of its flooding-point value, and there is still an abrupt change from complete to zero liquid flow at the flooding-point. The reason for this is that, except at gas flows at or above the flooding-point, the code gets the liquid level in the hot leg quite wrong, and this delays the onset of flooding, as explained below. Reasons why the code gets the liquid level wrong are discussed in the next section.

The onset of horizontal flooding is brought about, in RELAP5, by the rapid and very large increase in interphase friction which happens as the flow regime changes from stratified to slug flow. The correlation used to decide when the transition from stratified to slug flow occurs is the Taitel & Dukler criterion, which is essentially a relationship between the flooding-point gas superficial velocity J_G and the void fraction:

$$J_{G\,fl}^{\ *} = 0.5\, \alpha^{3/2}(1-\cos\theta)\sqrt{\frac{\tilde{A}}{D^2 \sin\theta}} \qquad (1)$$

($J_G^{\ *}$ is a dimensionless superficial velocity defined in Section 4.1, α is the void fraction and θ is defined in Figure 7.) For a given gas flow rate, this criterion defines a void fraction[1] which corresponds to a liquid level that might be called a "maximum stable level" (MSL). While its level remains below this MSL the liquid will be able to flow along the hot leg and into the pressure vessel, unhindered by the gas flow; if the level rises significantly above the MSL in any cell the interphase friction in that cell will increase dramatically and the liquid will be swept towards the riser.

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[1] In fact, flooding in RELAP5 occurs at *half* the flow rate given by (1); see the last paragraph in this section.

RELAP5 predicted a maximum void fraction of around 0.9 in the hot leg, more or less independently of the gas flow; theory (as outlined in the next section) suggests a minimum void fraction as low as 0.75 at low gas flows. (The experimental measurements are not helpful here, because they give only the fraction *after* flooding had occured, and the liquid profile would probably have looked quite different just before flooding). Thus the liquid level predicted in the hot leg was lower than it should have been, and the code was able to combine a liquid flow of 30 kg/s with a liquid level below the MSL defined by (1), right up until the gas flow reached 40 kg/s. At this point a small "ripple" on the surface (probably just caused by numerical "noise") was enough to raise the liquid level in one cell above the MSL, and the ripple grew and was blown back along the hot leg and into the riser, taking with it most of the liquid in the hot leg. This caused a transition to slug flow in the riser, and the flow there became unstable and began to slosh up and down, with large surges of liquid alternately being blown up into the steam generator and running back down into the riser. They could not penetrate into the hot leg, however, because they involved liquid levels much bigger than the MSL; as soon as they reached the stratified region they caused a massive increase in interphase friction, and were blown straight back into the riser. Thus no liquid at all could flow into the hot leg and the net liquid flow into the pressuriser fell to zero. The hot leg was acting rather like an inductance coil in an electrical circuit: it offered no resistance to steady flow (provided the liquid level was below the MSL), but prevented unsteady flow with the same mass flow-rate because it would have meant a liquid level much higher in places than the MSL.

To put this into perspective, compare (Figure 5) the RELAP5 flooding curve with that generated by a stand-alone FORTRAN program. This program uses the same correlations as RELAP for wall and interphase friction, but it integrates the momentum equations backwards along the hot leg from the pressure vessel to the riser, taking into account the effects of the "Hutze" region, and getting a liquid level in the hot leg which is much more realistic than the level predicted by RELAP5 (Figure 6). The closeness of the resulting flooding curve to the experimental one is not very significant (it is quite sensitive to changes in the Taitel Dukler criterion (1)); the important thing is that it has the same *shape* as the experimental curve, because this suggests that RELAP5 might do a lot better if it were able to calculate reasonable liquid levels in the hot leg. If RELAP predicted these levels correctly, flooding would occur at lower gas flows, which would mean that the MSL in the hot leg might be high enough to allow some of the surges in the riser to break into the hot leg and produce a non-zero net flow, thus getting rid of the abrupt change from complete to zero flow. However, this is a matter of speculation at the moment, and will remain so unless some way is found of improving the code's predictions of liquid level.

Two final points should be made. Firstly, it is probably fortuitous that RELAP5, modified to allow stratified flow in the riser, predicted the point of zero liquid flow very well. The prediction depends on the predicted maximum liquid level in the hot leg; since the code wrongly predicted a level that was more or less independent of the gas flow rate, it was presumably chance that the gas flow rate for which this level gave the right answer was also the flow rate which in the experiment corresponded to zero liquid flow.

Secondly, although the transition from stratified to slug flow is made to happen when the flow rate reaches the value given by the Taitel & Dukler criterion (1), in RELAP5 the interphase friction does not jump suddenly from its stratified to its slug value when this happens. Instead, it begins to increase towards the slug value when the gas flow rate is only half of that given by (1), and reaches its full slug value when the flow is equal to (1). But the total increase in interphase friction is so great (typically three orders of magnitude) that only a very small part of it is needed to produce flooding (by which is meant here the sweeping of the liquid in the hot leg into the riser), and flooding is therefore predicted to happen at flow rates just over *half* those given by (1). Thus, in these tests, horizontal flooding (as distinct from stratified-slug transition) occurs when the void fraction is given, not by the Taitel & Dukler criterion (1), but by half of it, i.e.

$$J_{G,fl}^{*} = 0.25\ \alpha^{3/2}(1-\cos\theta)\sqrt{\frac{A}{D^{2}\sin\theta}} \tag{2}$$

(TRAC, although it uses the same correlation, begins to weight the interphase friction towards the slug value only at the full Taitel and Dukler gas flow (1), and the interphase friction reaches its full slug value only when the gas flow reaches twice the Taitel and Dukler value.)

4. THE LIQUID LEVEL IN THE HOT LEG

4.1. Introduction

The liquid level in the UPTF hot leg could not be observed directly. The average void fraction at two places could be inferred from the readings of gamma densitometers placed at the centre of the hutze section and at a point just downstream of the riser, and from these liquid levels could be deduced. However, most of the readings were made in tests where the gas flow was sufficient to reduce the liquid flow but not enough to prevent it altogether, and as already described RELAP5 did not predict conditions like that - the liquid flow was either full or zero.

To understand why RELAP5, modified to allow stratified flow in the riser, predicted flooding to occur at gas flows which were too high, it would have been useful to know what the liquid level looked like in the hot leg just before flow limitation. This information is not available (because void measurements were made at two places only, and those were not close to the point of greatest liquid level), but to a limited extent it can be deduced from theory and other similar experiments. When this is done, it is clear that that the liquid levels predicted by RELAP5 are nothing like what they could have been in the experiment.

The rate of change of liquid level l is related to the rate of change of void fraction α by

$$\frac{dl}{dx} = -\frac{W}{A}\frac{d\alpha}{dx} \qquad (3)$$

where W is the width of the liquid surface, A is the flow area of the pipe and the liquid flows in the positive x direction (see Figure 7). The rate of change of void fraction is given by

$$Dg\,\Delta\rho\cdot\frac{d\alpha}{dx} = \frac{WALL\ \ FRICTION + INTERPHASE\ \ FRICTION}{\dfrac{A}{WD} - \left\{\dfrac{(J_G{}^*)^2}{\alpha^3} + \dfrac{(J_L{}^*)^2}{(1-\alpha)^3}\right\}}$$

$$= \frac{F}{Q - P} \qquad (4)$$

where D is the pipe diameter, $J_G{}^* = J_G\sqrt{\rho_G/gD\,\Delta\rho}$ is a dimensionless superficial gas velocity and $J_L{}^*$ is similarly defined. This equation can be derived by eliminating the interface pressure gradient between the one-dimensional phasic momentum equations for steady horizontal stratified flow, and then using the mass conservation equations to express velocity gradients in terms of void gradients (for details see for example [3]).

The friction terms (F) are always positive for countercurrent flow, so the sign of the liquid gradient depends on $Q-P$. If this is positive the liquid level falls in the direction of liquid motion, the liquid accelerates and the flow is said to be subcritical, if it is negative the liquid level rises and the liquid decelerates in the direction of motion, and the flow is said to be supercritical.

At a point where the liquid discharges freely into a large open space, such as at the pressure-vessel end of the hot leg, the flow is critical (i.e $P = Q$). The flow upstream arranges itself so that this is possible: if conditions at the other end of the horizontal section are subcritical, this leads to a liquid level like that shown in Figure 8a; if on the other hand the entry conditions are supercritical, the liquid level will rise for some distance and then jump suddenly to a subcritical value (Figure 8b), after which the flow is the same as in the purely subcritical case.

At non-CCFL gas flows (i.e. when the gas flow was too low to cause a reduction in the liquid flow) the flow in the UPTF hot leg probably looked something like Figure 8b[2], because in the one or two non-CCFL tests which were made, the void fraction readings showed that the conditions at the riser end were just supercritical. RELAP5's predicted liquid level for this situation is shown in Figure 8c; it is much lower than it should be, all the way along the hot leg, because the level at the inlet continues to fall even though conditions there are (and are predicted to be) supercritical. The reason for this is not completely understood, but almost certainly is connected with the form of the momentum flux terms used in the code, as outlined briefly below. However, in these particular tests the presence of the hutze has a considerable effect on the liquid level, and it is shown in section 4.3 that RELAP5 would still get the level wrong quantitatively even if it were able to predict correctly its qualitative behaviour, simply because it cannot model the irregular cross-section in the pipe where the hutze runs. Finally, it is worth noting that in RELAP5/MOD2 there is an error in the momentum equations of a factor of two in the term which gives the pressure difference between neighbouring horizontal cells due to the difference in their liquid levels, and this error would lead to the code underestimating the level gradient. Fortunately, the UK version of the code on which these tests were run has an option (no. 14) which corrects the error, and that option was enabled throughout the tests.

4.2. Momentum flux terms

The main reason why the code makes the liquid level slope the wrong way seems to be that the particular form of the momentum flux terms used in the momentum equations makes this happen. Details are given in the Appendix, but briefly, the form of the finite difference approximation to the momentum flux gradient used in RELAP5 means that the liquid level gradient cannot change sign until P is roughly equal to 4Q (instead of Q, as it should be). This is equivalent to saying that if the liquid flow is supercritical (so that the flow should be slowing down and the level rising in the direction of flow) the liquid will continue to accelerate and the level will continue to fall in the direction of the flow until the velocity is roughly twice the critical velocity. This leads in general terms to a liquid level which is on average much lower than it should be, if the liquid is "mildly" supercritical on entry to the horizontal section (as was the case in the UPTF model).

There does not seem to be an easy way around this difficulty. The problem lies in the upwind differencing of the momentum flux (and also the mass flux) terms, and should disappear if a simple

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[2] At gas flows close to flooding the flow in the hot leg would not have been truly steady, because of roll waves developing on the surface; the Figures still probably give a reasonable impression of the mean depth.

central differencing scheme were used. Unfortunately, central differencing schemes are not inherently stable under these circumstances, which is why the more complicated upwind scheme is used. Possibly an alternative upwinding scheme may exist which does not lead to the same error in liquid level gradient, or at least reduces the error. Unless the code can correctly predict at least the qualitative behaviour of the liquid level, there doesn't seem to be any point in trying to improve the finer points, such as wall or interphase friction.

4.3. Effect of the Hutze

The effect on the liquid level of the upwind differencing of momentum flux was so great that any attempt to study the effect of the Hutze using RELAP5 was pointless. However, use was made of a FORTRAN program, written for the purpose, which calculated the liquid level all along the hot leg by integrating (4) along the pipe, starting from the pressure vessel end and assuming that the flow there was exactly critical (i.e. $P=Q$). The program, called TEST, used the same correlations as RELAP5 for wall and interphase friction, but it was possible to include the effects of the Hutze region as well. The results suggest that, even if RELAP5 did not have the problems with the momentum flux terms described above, it would still have underpredicted the liquid level by as much as 50% because it could not model the irregular cross-section in the Hutze region of the hot leg.

The cross section of the Hutze is elliptical, takes up about 10% of the total flow area in the hot leg and runs along the bottom of the hot leg for the middle half of its length (see Figure 9). Its effects on the liquid level gradient are principally:

i. It means that the void fraction corresponding to a given liquid level is higher in the hutze region than elsewhere, because the hutze occupies space that would have been full of water.

ii. It reduces the flow area by about 10%. This increases the phase velocities and hence the friction term F in (4). It also increases the superficial velocities J_G and J_L and so affects P.

iii. It increases the surface area of the wall in contact with the liquid, and so increases the wall friction component of F.

iv. It alters the way in which the liquid surface area changes with depth, which affects the calculation of the level difference term Q.

v. The constriction of the channel has the same effect as a low weir laid right across the pipe. As a consequence of (i), if the liquid level in the hutze were the same as that just downstream of it, the flow in the hutze would be supercritical. This cannot happen; instead, the level in the hutze region has to be high enough so that the flow in it is subcritical. At the downstream end of the hutze the liquid level drops as at a weir, and the flow there is just critical. The liquid level upstream of that point is then determined by the level there, rather than the level at the hot leg outlet, and is higher as a result.

The relative importance of these effects can best be seen by an example. According to the program TEST, a gas flow-rate of 25 kg/s is just below the value needed to produce flooding. (If the experimental data are extrapolated, it would have been just *above* the flooding value.) Working on the assumption that the flow is just critical at the pressure vessel end of the hot leg (which means the void there is 0.90), TEST predicts that with that gas flow-rate and a full 30 kg/s liquid flow the void fraction at the riser end would be around 0.75. If the hutze were not there, the program predicts the void fraction at the riser end would be about 0.85. Thus the hutze decreases the void fraction by around 0.1

Of that decrease, 60% is due to (v) above, the "weir effect" at the entry to the hutze. A further 15% occurs because the surface is still sloping quite steeply just upstream of the hutze entry, where the flow is nearly but not quite critical. Thus 75% of the hutze effect is *directly* attributable to the effect of the irregular geometry, and could not be calculated by RELAP5. The remaining 25% is mostly due to (ii) above, the reduction in the flow area, and this can be modelled by RELAP5. The effects of the additional wetted wall and altered relationship between surface area and liquid level are negligible.

To summarise, even if RELAP5 were generally able to calculate the liquid level gradient correctly in qualitative terms, in the particular case of the UPTF experiments it would only be able to calculate about 25% of the expected change in void fraction caused directly by the hutze, leading to an error of around 50% in its prediction of the total change in liquid level along the hot leg.

5. EFFECT OF THE LIQUID LEVEL IN THE STEAM GENERATOR INLET PLENUM

One of the things not included in the report of the UPTF experiment on which this analysis is based was a description of the liquid level in the vessel used to simulate the Steam Generator Inlet Plenum. Ralph et al. [4] found that the gas flow needed to prevent liquid flow through a short horizontal pipe was different depending on whether or not the end of the pipe was submerged, and a similar difference might be expected in the UPTF test, depending on whether or not there was a substantial liquid level in the plenum. On the other hand, if there was such a liquid level, other similar experiments indicate that the height of the level does not affect the liquid flow - it is a simple "either/or" situation.

In the absence of definite expermental detail, it was assumed in all the tests described in this report that the plenum started nearly empty, with a void of 0.9 in the lowest cell and 1.0 in all the others. This was consistent with the situation depicted in one of the diagams in the report, in which the liquid level in the plenum was shown as just coming up to the bottom of the riser entry (see Figure 10). In tests where the gas flow was low enough for there to be no reduction in the liquid flow, the liquid drained away as fast as it was supplied, and the level remained constant; in tests where the liquid flow in the hot leg *was* limited by the steam flow, the level in the plenum rose so slowly that it had not changed appreciably by the end of the run.

However, it was noticed in one much longer run made with standard RELAP5 (i.e. no stratified flow permitted in the riser) that as the void in the bottom cell in the plenum became appreciably less than that in the riser, liquid flow in the hot leg began to increase slowly (from zero). It reached a plateau at about 6 kg/s, and then began to rise again, reaching another plateau at about 11 kg/s. It seems that the standard code's predictions of the liquid flow depend on the depth of liquid in the plenum, *which should not be the case*.

The reason for this is that when there is an appreciable amount of liquid in the plenum, the void in the bottom cell is lower than the void in the top of the riser. This means that at the junction between riser and plenum (and, in fact, in the other two junctions in the riser) there is what RELAP5 knows as a "reverse void profile", i.e. a low void over a high void. Under these conditions the code reduces the interphase friction at the junction quite dramatically, by a factor (typically of the order 10-100) proportional to the difference in void across the junction. Since the predictions of liquid flow made by the standard code were determined by the erroneously high interphase friction in the riser caused by the wrong choice of flow-regime, it is clear that reducing this interphase friction would affect the liquid flow.

The plateaus in the liquid flow rate may correspond to different cells in the plenum starting to fill. The cells do not fill completely with liquid (because the escaping steam which passes through them occupies a finite volume), and the void in one cell affects the void in its neighbours. A change of level in any cell in the plenum can alter the void in the bottom cell and hence, by changing size of the void difference across the junction with the riser, can influence the liquid flow.

No long run was made with the modified version of the code (allowing stratified flow in the riser). If the above explanation is correct, the liquid level in the plenum would then have had no effect, since with stratified flow in the riser the liquid flow was eventually restricted by interphase friction in the horizontal pipe, where the Reverse Void model does not operate. The only situation in which the level might have had an effect is one in which the plenum had begun full of liquid. Under those circumstances a reverse void at the junction between riser and plenum, existing from the beginning, might allow enough liquid into the riser to destroy the stratified flow there and produce the turbulent conditions that tended to result in flooding, leading to an early reduction in the liquid flow. It might even remove the "all or nothing" flow and turn the flooding-curve in Figure 3 into a passable imitation of the experimental data. This would not give too much cause for rejoicing, however, as it would still leave the flow dependent on the liquid level in the plenum, and in any case it would be giving the right answer for entirely the wrong reasons.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

1. Standard RELAP5/MOD2 predicted badly the countercurrent liquid flow in the UPTF Hot Leg Separate Effects Test, underestimating by a factor of more than three the steam flow-rate needed to prevent liquid flow, and not allowing any situation in which the liquid flow was other than full (unrestricted) or zero.

2. The code understimated the flooding-point gas flow because its flow-regime map did not allow the possibility of stratified flow in the riser between hot leg and steam generator, and so the interphase friction there was greatly overestimated.

3. The liquid flows predicted depended, wrongly, on the level and distibution of liquid in the steam generator plenum. In some cases liquid flow was predicted when there was a high level in the plenum, but not when the plenum was empty. This was due to the code's "Reverse Void Profile" model reducing interphase friction in the riser when the plenum was full but not when it was empty.

4. When the code was modified so as to allow stratified flow in the riser, the code predicted quite well the gas flow at which liquid flow was prevented, but overpredicted the liquid flow badly at lower gas flow rates, and still allowed only either full or zero liquid flow.

5. Crucial to the predictions of the modified code was its inability to predict correctly the liquid level in the hot leg. This failure was probably a consequence of the way the code models the momentum flux terms in the momentum equations. Even if this could be corrected, however, in this particular experiment an error of up to 50% would still be expected in the predicted maximum liquid level, because the code cannot model the effects of the irregular cross-section in the hot leg caused by the presence of the ECCS injection pipe ("hutze").

6. If RELAP5 could correctly predict the hot leg liquid level, the Taitel and Dukler criterion for the transition from horizontally stratified flow, *as presently coded*, should enable it to predict the flow limitation in the UPTF test reasonably well.

6.2. Recommendations

1. It is recommended that RELAP5's flow-regime map be altered so as to allow the possibility of stratified flow in inclined pipes. (Presently it is only allowed in pipes inclined at less than 15 degrees to the horizontal.) Theoretical flow-regime maps have been published which predict the stratified flow boundary in inclined pipes. and one of these might be suitable for inclusion in RELAP5 (possibly that of Barnea et al. [5,6] for example).

2. It is also recommended that some attempt be made to improve RELAP5's prediction of liquid level behaviour in stratified flow.

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APPENDIX: EFFECT OF UPWIND DONORING ON THE LIQUID LEVEL GRADIENT

In steady, horizontal, stratified two-phase flow, the area-averaged one-dimensional momentum equations can be combined by elimination of the interface pressure gradient to give

$$\frac{Ag\,\Delta\rho}{W}\cdot\frac{\partial\alpha}{\partial x} + \rho_G u_G \frac{\partial u_G}{\partial x} - \rho_L u_L \frac{\partial u_L}{\partial x} = \mathit{FRICTION\ TERMS} \qquad \text{(A1)}$$

where the terms on the left represent, respectively, hydrostatic pressure gradient (due to change in liquid level), and gas and liquid momentum flux gradients. For countercurrent flow the friction terms are always positive.

Using the continuity equations, (A1) can be written

$$Dg\,\Delta\rho\cdot\frac{\partial\alpha}{\partial x}\left\{\frac{A}{WD} - \frac{(J_G{}^*)^2}{\alpha^3} - \frac{(J_L{}^*)^2}{(1-\alpha)^3}\right\} = \mathit{FRICTION\ TERMS} \qquad \text{(A2)}$$

where A is the pipe flow-area and D its diameter, and W is the width of the liquid surface. If the expression in brackets is positive the flow is subcritical (and $\partial\alpha/\partial x$ is forced to be positive), while if it is negative the flow is supercritical.

If the RELAP5 finite-difference form of the momentum equations is treated in the same way, (A2) looks like

$$\frac{1}{\Delta x}\cdot\left\{g\,\Delta\rho(-\Delta y_n) + \Delta(\mathit{gas\ mom.\ flux}) - \Delta(\mathit{liquid\ mom.\ flux})\right\} = \mathit{FRICTION\ TERMS} \qquad \text{(A3)}$$

where Δy_n is the change in liquid level between mesh cells n and n+1, and hence is negative when the level is falling.

The RELAP5 liquid momentum flux gradient term consists of a basic term and a "viscous-like correction". When the code's finite-difference form of the continuity equations are used to replace Δu_L's with $\Delta\alpha$'s and the result is reduced to first order in small quantities, the overall liquid term looks like

$$\frac{1}{4}\cdot\rho_L\cdot\frac{1-\dot{\alpha}_n}{1-\bar{\alpha}_n}\left[\frac{\Delta\alpha_n}{1-\alpha_{n+1}} + \frac{3\Delta\alpha_{n-1}}{1-\alpha_{n-1}}\right]\cdot u_{L_j}^2 \qquad \text{(A4)}$$

where $\Delta\alpha_n = \alpha_{n+1} - \alpha_n$, u_{L_j} is the junction liquid velocity, $\bar{\alpha}_n = 0.5\,(\alpha_n + \alpha_{n+1})$, and $\dot{\alpha}_n$ is donored according to the sign of the square bracket term:

$$\begin{aligned} \dot{\alpha}_n &= \alpha_{n+1} && \textit{if the bracket is positive} \\ &= \alpha_n && \textit{if the bracket is negative} \end{aligned}$$

Substituting this into (A3), ignoring the gas and friction terms which are negligible by comparison, and replacing $-\Delta y_n$ with $(A/W)\Delta\alpha_n$, gives an equation of the form

$$K\,\Delta\alpha_n = M\,\Delta\alpha_n + N\,\Delta\alpha_{n-1} \qquad \text{(A5)}$$

This equation, which is effectively the RELAP5 form of (A1), couples the void gradient at one junction to the gradient at the upstream junction. The coupling is due to the upwind donoring of void fraction in the momentum and continuity equations, which brings α_{n-1} into equation A4.

The condition that the liquid level gradient change sign between junctions is that $\Delta\alpha_n$ and $\Delta\alpha_{n-1}$ have opposite signs, i.e. $K - M \le 0$, which is roughly equivalent to

$$\frac{4A}{WD} - \frac{J_L^{*2}}{(1-\alpha)^3} \le 0 \qquad \text{(A6)}$$

Comparing this with the equation for supercritical flow

$$\frac{A}{WD} - \frac{J_L^{*2}}{(1-\alpha)^3} \le 0 \qquad \text{(A7)}$$

it can be seen that RELAP5 will not allow the liquid level gradient to change sign until the liquid velocity is roughly twice the critical velocity.

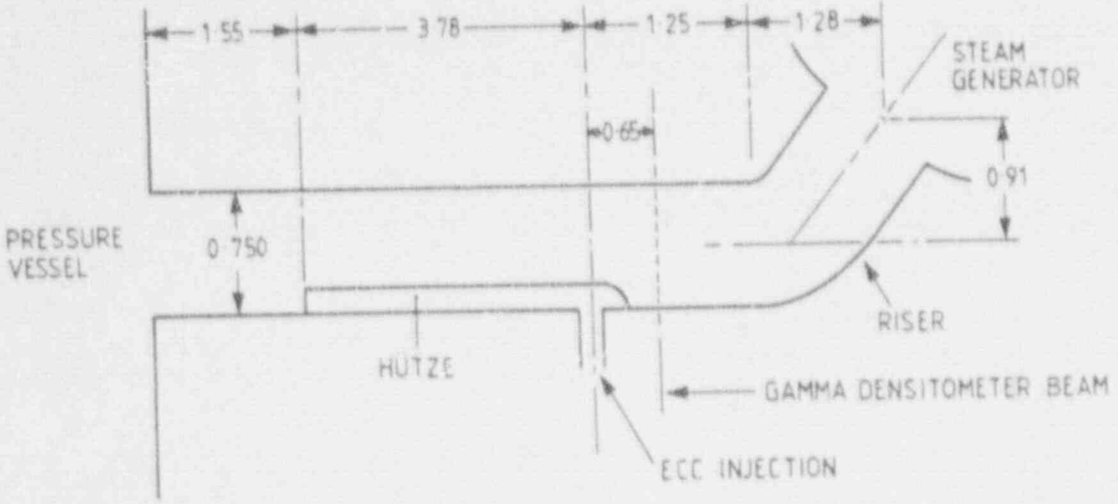


FIG. 1 UPTF BR[illegible]N LOOP HOT LEG

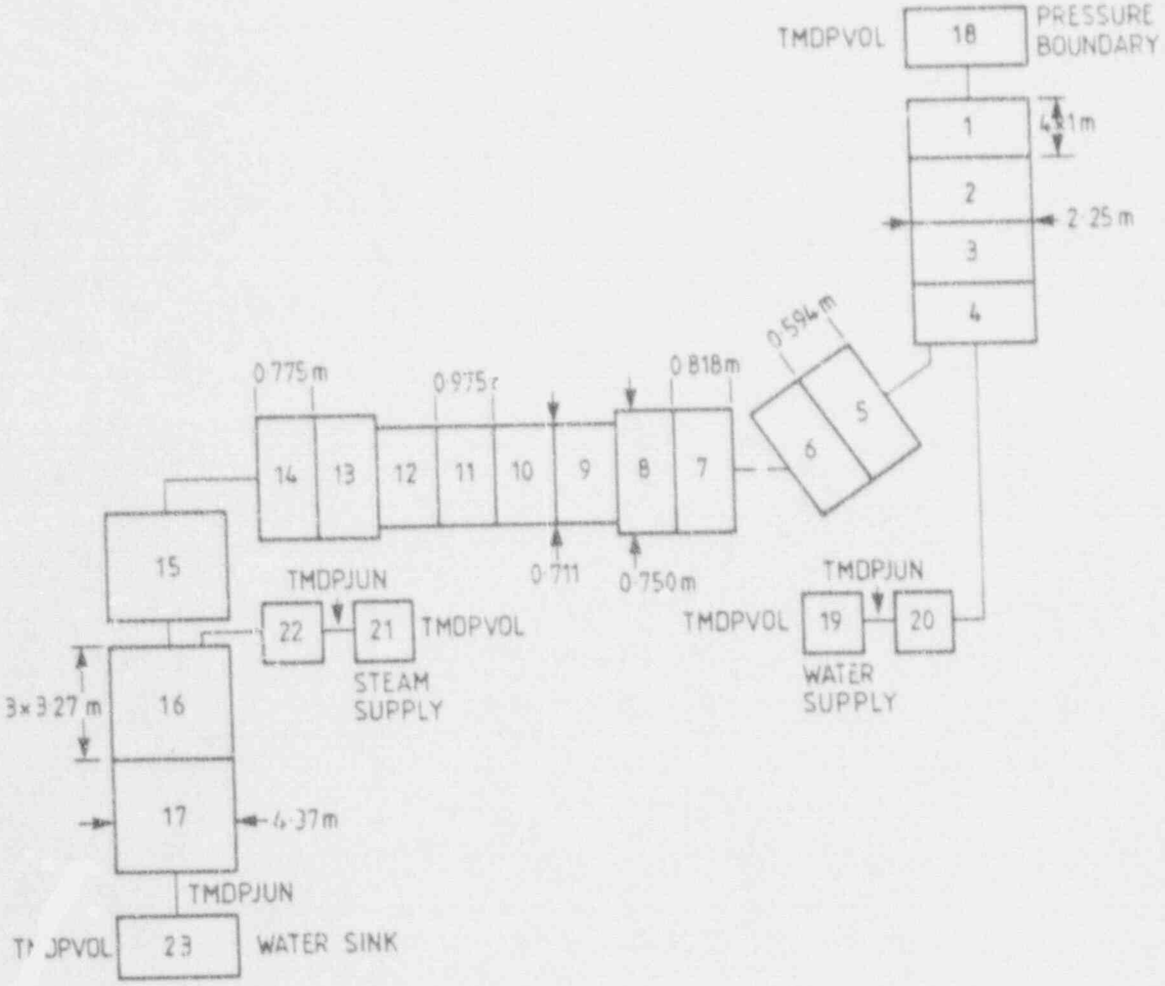


FIG. 2 RELAP5 NODALISATION SCHEME

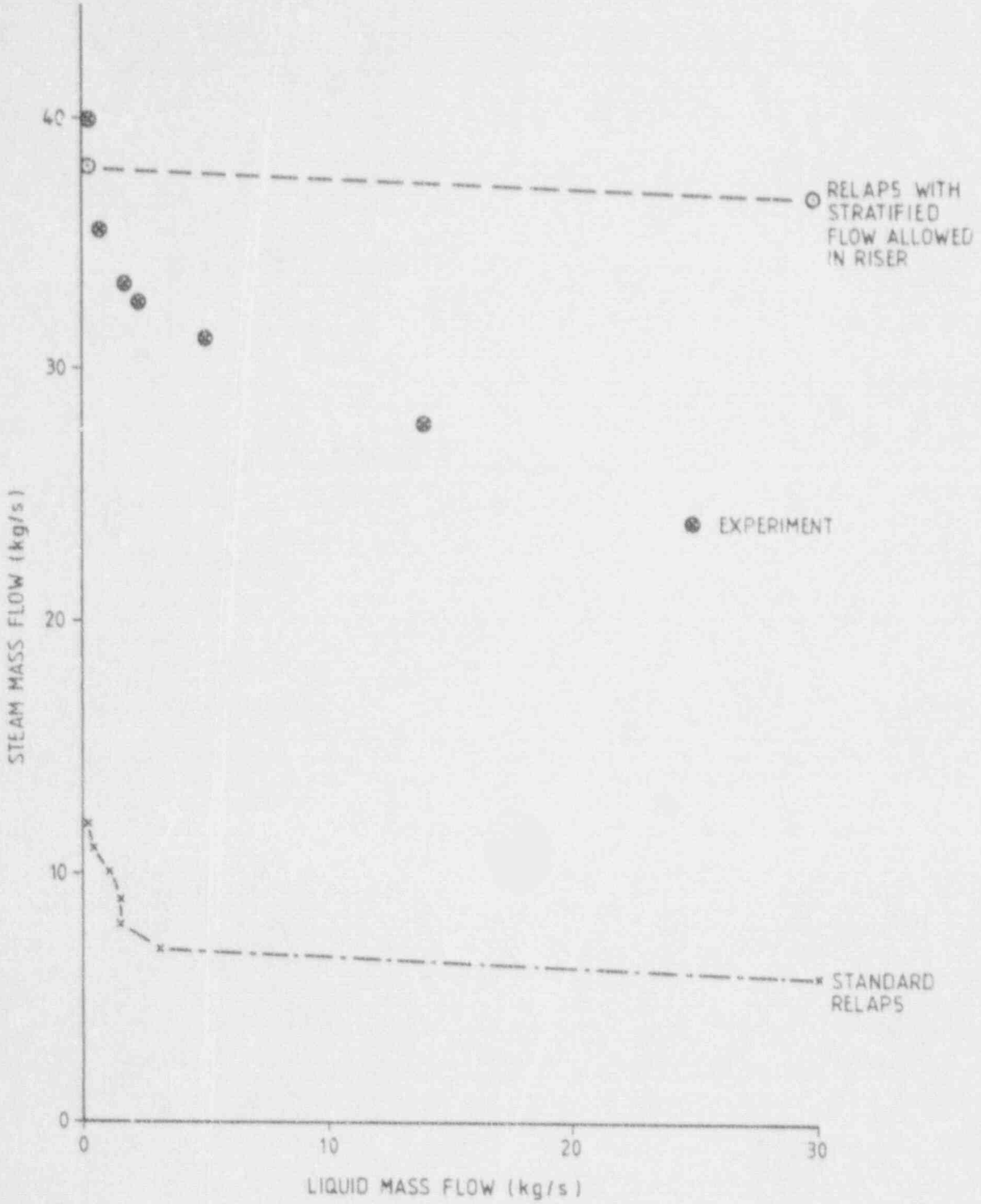
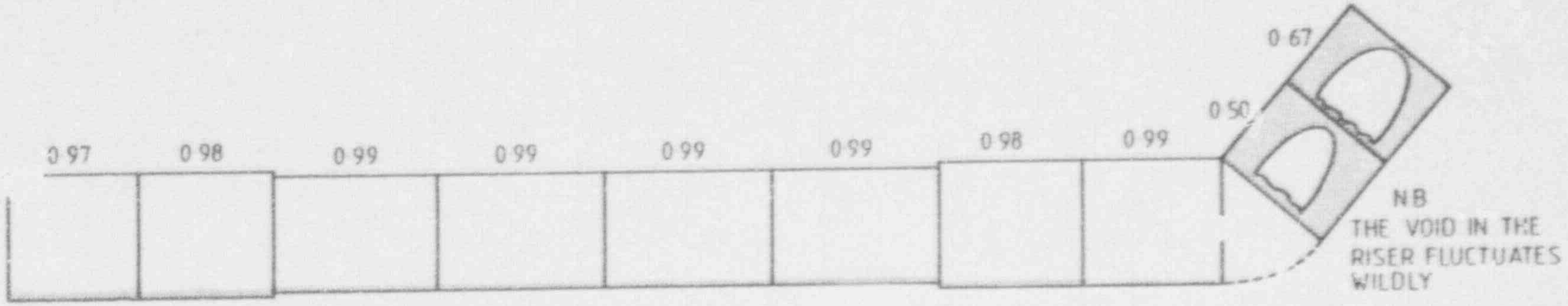


FIG. 3 EXPERIMENTAL AND PREDICTED FLOODING CURVES



(STEAM FLOW 10 kg/s, LIQUID FLOW 0, t = 25 secs, STANDARD RELAP5)

FIG. 4 PREDICTED DISTRIBUTION OF VOID IN HOT LEG

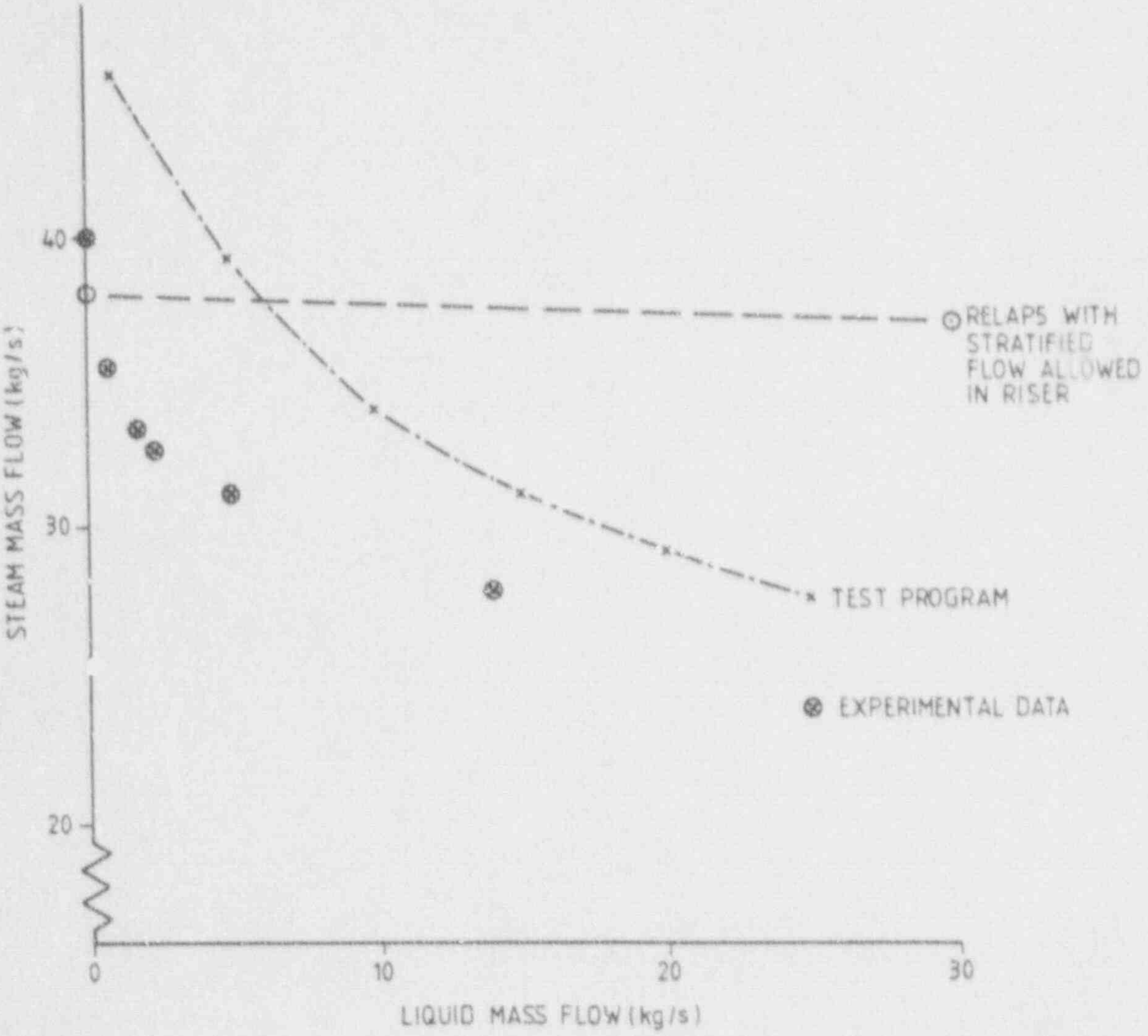
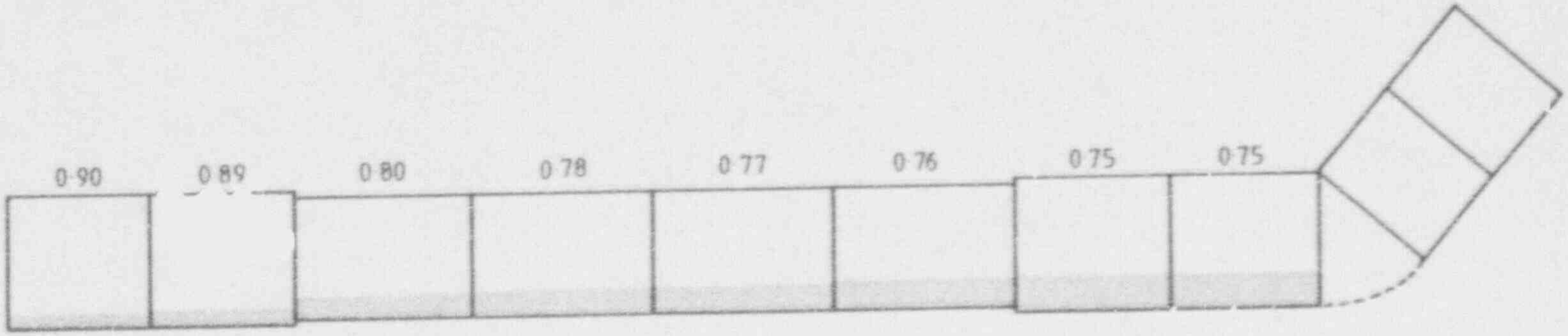


FIG. 5 PREDICTION OF FLOODING USING MORE REALISTIC LIQUID LEVELS IN THE HOT LEG



(STEAM FLOW 25kg/s, LIQUID FLOW 30kg/s)

FIG. 6 LIQUID LEVEL IN HOT LEG BEFORE FLOODING, CALCULATED BY PROGRAM "TEST" AND TAKING INTO ACCOUNT THE EFFECTS OF THE HÜTZE

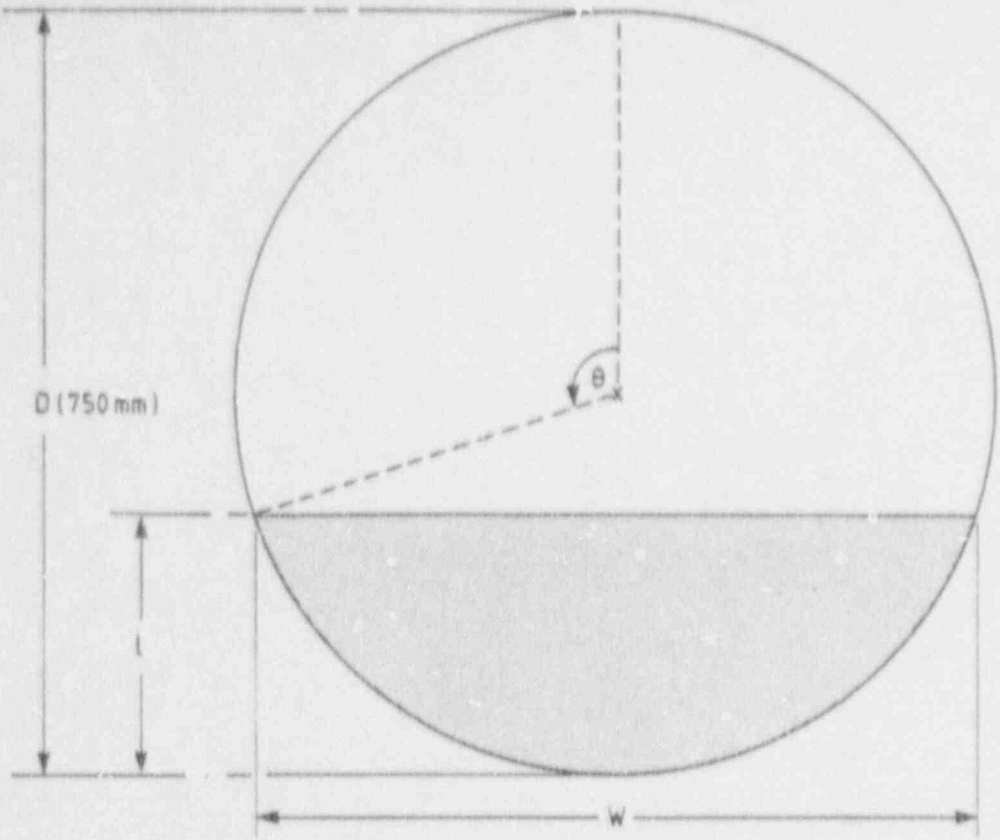
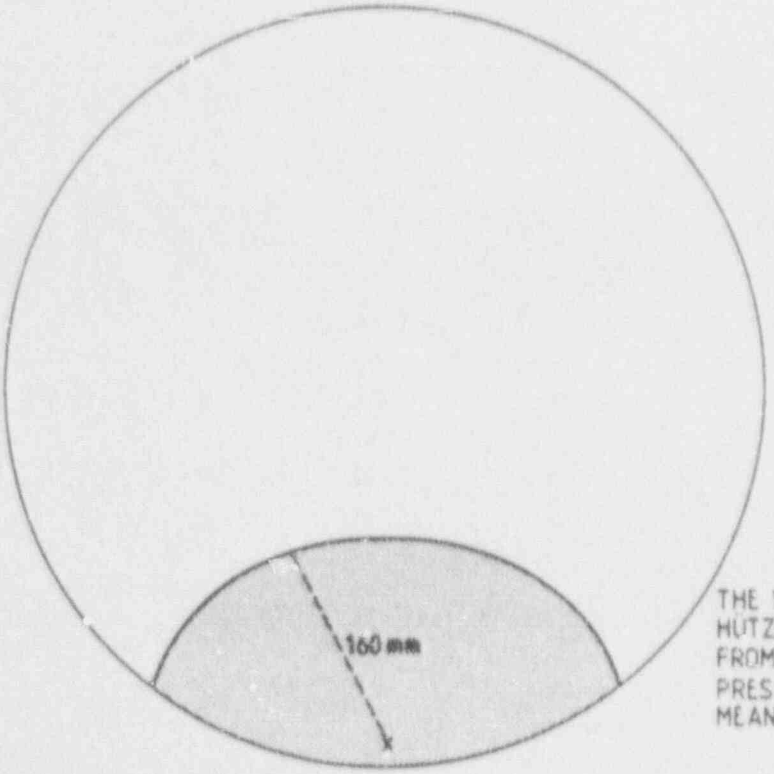
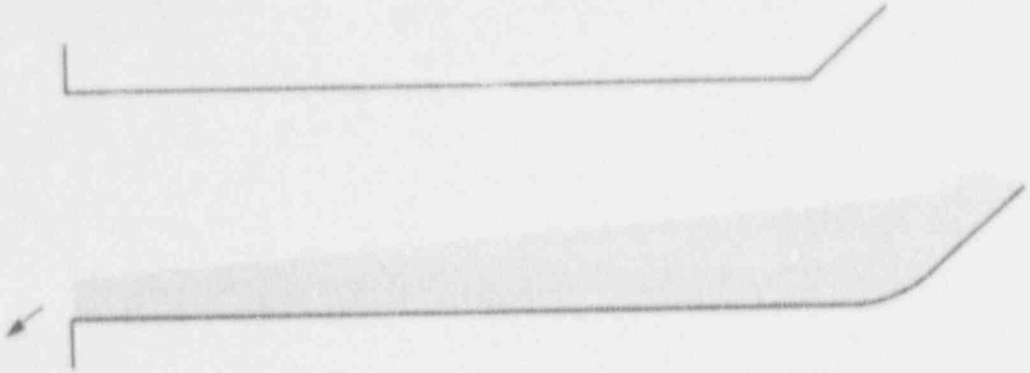


FIG.7 HOT LEG DIMENSIONS

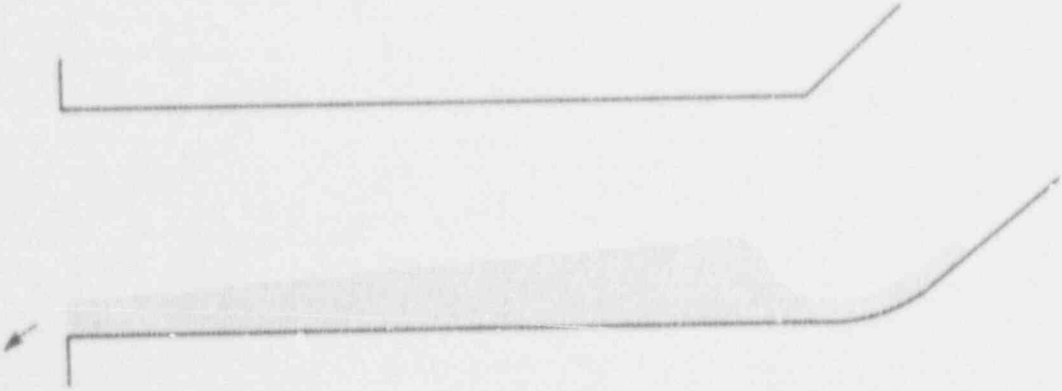


THE VALUE FOR THE HÜTZE RADIUS IS TAKEN FROM REFERENCE [1]; PRESUMABLY IT IS MEAN RADIUS

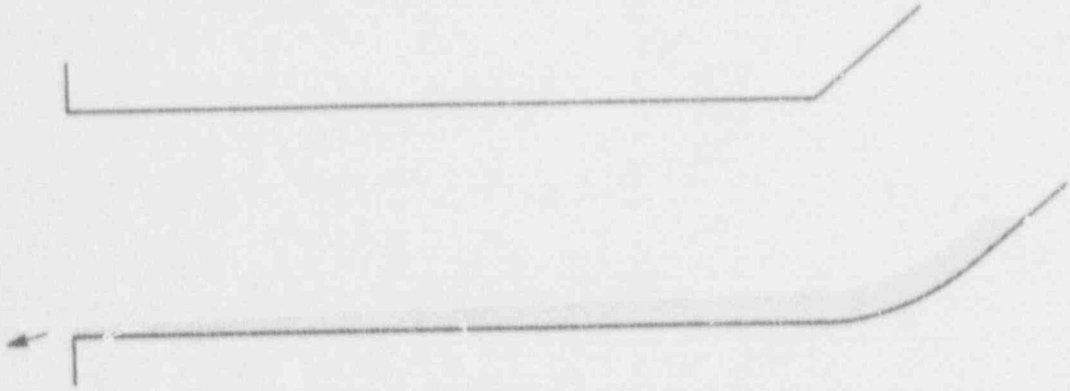
FIG. 9 CROSS-SECTION THROUGH HOT LEG SHOWING HÜTZE



a) THEORETICAL : SUBCRITICAL CONDITIONS AT UPSTREAM END



b) THEORETICAL : SUPERCRITICAL CONDITIONS AT UPSTREAM END



c) RELAP5 PREDICTION (SHOULD LOOK LIKE b)

FIG. 8 STEADY STRATIFIED FLOW IN THE HOT LEG

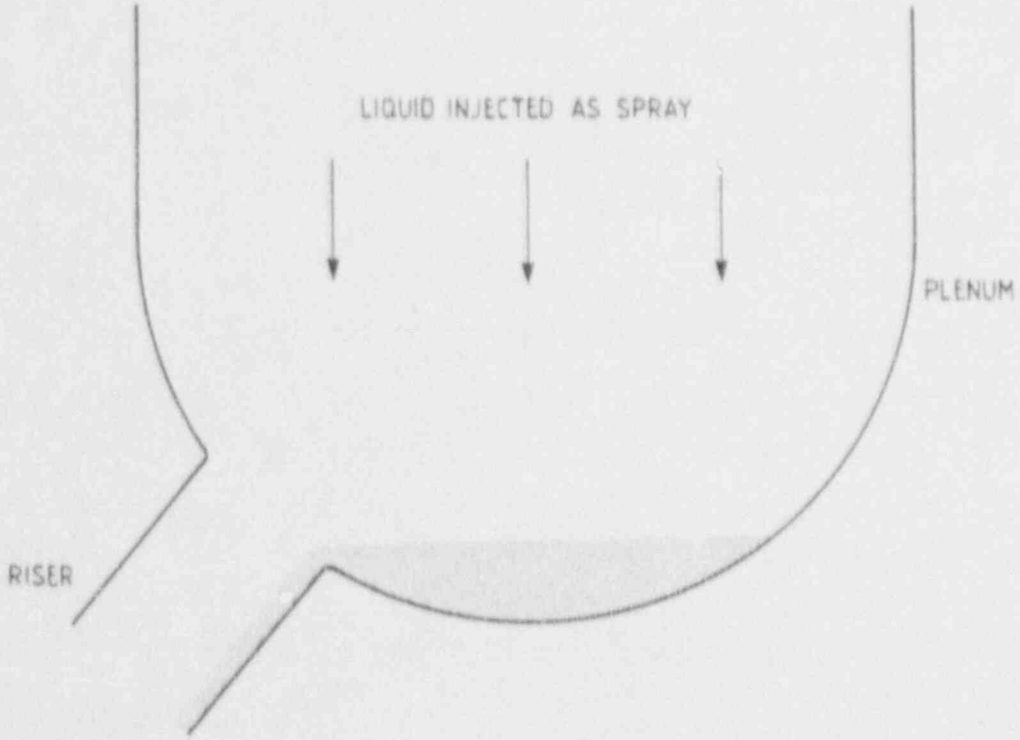


FIG. 10 SITUATION ENVISAGED IN STEAM GENERATOR PLENUM BEFORE START OF TEST

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(2-89)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

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11. ABSTRACT (200 words or less)

RELAP5/MOD2 predictions of countercurrent flow limitation in the UPTF Hot Leg Separate Effects Test (test 11) are compared with the experimental data. The code underestimates, by a factor of more than three, the gas flow necessary to prevent liquid runback from the steam generator, and this is shown to be due to an oversimplified flow-regime map which does not allow the possibility of stratified flow in the hot leg riser. The predicted countercurrent flow is also shown to depend, wrongly, on the depth of liquid in the steam generator plenum. The same test is also modelled using a version of the code in which stratified flow in the riser is made possible. The gas flow needed to prevent liquid runback is then predicted quite well, but at all lower gas flows the code predicts that the flow is completely unrestricted - i.e. liquid flows between full flow and zero flow are not predicted. This is shown to happen because the code cannot calculate correctly the liquid level in the hot leg, mainly because of a numerical effect of upwind donoring in the momentum flux terms of the code's basic equations. It is also shown that the code cannot model the considerable effect of the ECCS injection pipe (which runs inside the hot leg) on the liquid level.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

ICAP, RELAP5/MOD2, AEEW-M2555, analysis, UPTF, Steam-Water Counter-Current Flow, Broken Loop Hot Leg

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