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International Agreement Report

Numerics and Implementation of the UK Horizontal Stratification Entrainment Off-Take Model Into RELAP5/MOD3

Prepared by
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Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

June 1993

Prepared as part of
The Agreement on Research Participation and Technical Exchange
under the International Thermal-Hydraulic Code Assessment
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Numerics and Implementation of the UK Horizontal Stratification Entrainment Off-take Model Into RELAP5/MOD3

W M Bryce

SUMMARY

RELAP5/MOD3 is a computer code for the the analysis of fault transients in light water reactor systems. It has been subject to an international development exercise.

Among the fault transients which can be analysed using RELAP5/MOD3 is a loss-of-coolant accident (LOCA) in a Pressurised Water Reactor (PWR), in which a small break occurs in one of the large diameter horizontal pipes forming the reactor inlet or outlet legs. In this situation the steam and water in the pipe may separate to form a liquid level. The quality of fluid discharged from the break (proportion of the mass flow which is steam) then depends on whether the break is above or below the liquid level. RELAP5/MOD3 contains a special model to calculate discharge from an off-take connected to a large diameter horizontal pipe in which there is stratified flow, referred to as the horizontal stratification entrainment (HSE) model. Apart from small break LOCAs, such a model is also needed for analysing other abnormal conditions in PWRs.

Early in its development, the RELAP5/MOD3 HSE model was the same as that of the RELAP5/MOD2 code. This was assessed by Ardron and Bryce [1] who found that the model tended to under-predict significantly the discharge quality in many cases. They selected improved correlations for the off-take quality and implemented them in a modified version of RELAP5/MOD2 Cycle 36.04. The modified code was shown to give much improved agreement with separate effects test data.

This report describes the numerics and implementation details for the modification of RELAP5/MOD3 to use the same improved correlations. These details include the areas where the use of the HSE correlation set are extended outside of its range. The modifications, which were incorporated into pre-release code version 411, have been retained in the first "frozen" release of the code (version 5m5). Areas where changes have been made by EG&G in producing the release version which might affect the modelling are noted in the section on programming details. Particularly noteworthy is the restriction which apparently excludes the full control of the HSE model at the internal junctions of PIPE components.

A simple test problem is used to verify the RELAP5/MOD3 coding of the correlations, making use of the control system logic. This problem, run using the release code version, also

demonstrates that this version seems to be more prone to instability than the pre-release version 411. The problem is not believed to be associated with the HSE model.

Physics and Thermal Hydraulics Division
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Notation

A	area (m^2)
C	constant in Equation (5)
d	diameter of off-take pipe (m)
D	diameter of main pipe (m)
g	acceleration due to gravity (m/s^2)
G	mass flux ($\text{kg/m}^2/\text{s}$)
h	"height" of liquid level in main pipe with respect to centre of the off-take pipe entrance (m)

For a top off-take this is the distance of the liquid level from the top of the pipe cross-section

For a side off-take this is the distance of the liquid level above the off-take centre, it is negative if the liquid level is below the centre

For a bottom off-take this is the distance of the liquid level above the bottom of the pipe cross-section

h_b	critical value of h at which entrainment or pull-through commences (m)
K	empirical constant in Equation (1)
p	pressure (MPa)
R	non-dimensional height ($= h/h_b$)
S	slip ratio ($= v_g/v_f$)
S^*	modified slip ratio
v	velocity (m/s)
w	width of stratified liquid surface in pipe (m)
W	mass flow-rate (kg/s)
x	quality ($= W_g/W$)
\bar{X}	static quality ($= \alpha_g \rho_g / \rho$)
x_0	reference quality defined after Equation (4)
α	volumetric concentration or area fraction
ϕ	angle used in Equation (12)
ρ	density (kg/m^3)
$\Delta\rho$	density difference ($= \rho_f - \rho_g$)

Subscripts

- c associated with choked flow
- f property of liquid phase
- g property of gas phase
- j property of junction between main pipe and off-take pipe
- k property of continuous phase
- K property of donor volume

Superscripts

- n an old timestep value
- P an intermediate value
- (1) an intermediate value
- * an intermediate or modified value

1. INTRODUCTION

When a gas-liquid mixture discharges from a large diameter horizontal pipe into a small diameter off-take branch, the discharge flow quality depends on the liquid level in the main pipe. If the entrance to the off-take branch is submerged, the discharge flow is mainly liquid which may contain an entrained gas component. If the entrance is above the liquid level, the discharge is predominantly gas, which may contain an entrained liquid component.

The necessity for modelling this situation has been discussed previously [1]. Also, the RELAP5/MOD2 model to compute the quality discharged into a small off-take pipe when there is stratified flow in the main pipe (so called 'horizontal stratification entrainment (HSE) model') was assessed. The model was found to have a tendency to under-predict significantly the discharge quality over a wide range of conditions. An alternative set of discharge quality correlations were included in a modified version of RELAP5/MOD2 and shown to give considerably improved agreement with separate effects data.

This Report presents the numerics and implementation details to add the same improved discharge quality correlations into RELAP5/MOD3. In the light of experience with the modified RELAP5/MOD2 code, some of the numerics has been slightly changed for RELAP5/MOD3. The description is quite detailed in order to facilitate change by some future code developer. A simple test calculation was performed to confirm the coding of the correlations implemented in RELAP5/MOD3.

2. OFF-TAKE DISCHARGE QUALITY CORRELATION SET

To aid clarity, the correlation set used is repeated below. The reasons for its choice and the references to the originators are given in [1]. First there are correlations for the critical depth for entrainment and then correlations for the off-take discharge quality.

2.1. Critical Depth for Entrainment

The critical liquid height or depth h_b is a function of the off-take conditions. Its correlation has the same form for all orientations:

$$h_b = KW_k^{0.4}/(g\rho_k\Delta\rho)^{0.2} \quad (1)$$

where k refers to the 'continuous' phase, which is the gas phase for an upward branch, the liquid phase for a downward branch. For a horizontal side-branch, k is the gas phase when the liquid level is below the nozzle centre, and the gas phase otherwise. The values of K chosen are:

VERTICAL UPWARD BRANCH	K = 1.67	}	(2)
VERTICAL DOWNWARD BRANCH	K = 1.50		
HORIZONTAL SIDE BRANCH	K = 0.75: gas entrainment		
	K = 0.69: liquid entrainment		

2.2. Discharge Flow Quality

The correlations for discharge quality are given below according to off-take orientation. In these expressions R is the non-dimensional height of liquid level in the main pipe with respect to the centre of the off-take pipe entrance and is defined in the Notation:

2.2.1. Vertical Upward Branch

$$x = R^{3.25(1-R)^2} \quad (3)$$

2.2.2. Vertical Downward Branch

$$x = x_0^{2.5R} \left[1 - 0.5 R(1+R)x_0^{(1-R)} \right]^{0.5} \quad (4)$$

where

$$x_0 = 1.15/(1+\sqrt{\rho_f/\rho_g})$$

2.2.3. Horizontal Side Branch

$$x = x_0^{(1+CR)} \left[1 - 0.5 R(1+R)x_0^{(1-R)} \right]^{0.5} \quad (5)$$

where

$$x_0 = 1.15/(1+\sqrt{\rho_f/\rho_g})$$

and

$$C = \begin{cases} 1.09 & \text{for gas entrainment} \\ 1.00 & \text{for liquid entrainment} \end{cases}$$

For this case R is negative if the liquid level is below the main pipe centre.

3. EXTENSIONS OF THE CORRELATIONS

The correlations for off-take discharge quality are based on simple experimental situations whereas RELAP5 is a general purpose code and may have flow conditions different to the experiments. For example the main pipe flow may not be low or the off-take may have counter-current flow. All such aspects have to be allowed for in the implementation and are considered below.

3.1. High Flow-rate Limit

In the current RELAP5/MOD3 HSE model, homogeneous discharge conditions (that is normal donoring) are assumed in flow regimes other than stratified flow. This assumption fails to recognise that partial separation of the phases occurs in the slug, plug and annular flow regimes, in horizontal flow. As stated in [1], this is allowed for by applying the HSE model to all horizontal flow regimes except dispersed flow, which is assumed to be entered when $G > 3000 \text{ kg m}^{-2}\text{s}^{-1}$. A linear interpolation zone is defined between $G = 2500 \text{ kg m}^{-2}\text{s}^{-1}$ and $G = 3000 \text{ kg m}^{-2}\text{s}^{-1}$ in which the void fraction transitions from the value calculated from the quality given by the HSE correlations, to the donored value. The expression used for the mass flux G in this case is given below:

$$G = \text{Max} \left[\alpha_{gK} \rho_{gK} |v_{gK}| + \alpha_{fK} \rho_{fK} |v_{fK}|, (\alpha_{gj}^n \rho_{gj} v_{gj} + \alpha_{fj}^n \rho_{fj} v_{fj}) A_j / A_K \right] \quad (6)$$

This choice should suppress the HSE off-take model if there is high flow anywhere in the upstream volume.

3.2. Extreme Voids

The interpolation factor introduced in the previous section is reduced towards zero (such that the donor value for the off-take conditions is used) linearly if either of the phase area fractions (gas and liquid) of the donor volume approach zero. The boundaries of the two transition regions are

$$\left. \begin{aligned} \alpha_{gK} &= 10^{-5} \\ \text{and} \\ \alpha_{fK} &= \text{Max} \left[2 \cdot 10^{-7}, \text{Max} \left[2 \cdot 10^{-4}, 2 \cdot 10^{-3} \rho_{gK} / \rho_{fK} \right] \right] \end{aligned} \right\} \quad (7)$$

In the above equation, the subscript K denotes the upstream volume according to the phase flowing from the horizontal volume. These particular void limits are based on those used in the code flow regime package. These limits imply, for example, that if the donor volume gas fraction α_{gK} has the value $5 \cdot 10^{-6}$ then the interpolation factor is halved.

3.3. Allowing for Slip at the Take-off Junction

The correlations given above specify the flow quality in the off-take branch. RELAP5 requires the void fraction of the flow in the off-take. A desired flow quality can be obtained indirectly by converting the quality to a void fraction using a modified slip ratio as below:

$$S_j^* = \text{Max} \left[1.0, \text{Min} \left[\text{Max} \left[\rho_{fj} / \rho_{gj}, 10^{-7} \right]^{0.5}, \frac{|v_{gj}|}{|v_{fj}|} \right] \right] \quad (8)$$

The modifications in this expression restrict the range of slip ratio and use absolute velocities to maintain a finite positive result even when the flow becomes counter-current (this state is discussed further below) and to avoid discontinuities. The limits are arbitrary but are expected to be reasonable in most situations. In most cases S_j^* will be the actual junction flow slip ratio. (The release version 5m5 of RELAP5/MOD3 now has a junction flow quality defined but this extension has not been altered).

3.4. Allowing for Counter-Current Flow at the Off-Take Junction

For co-current off-take flow either α_g or α_f is calculated from the correlations as described above and manipulated into a junction value α_{gj} or α_{fj} . The other phase junction area fraction is obtained by requiring that the phase area fractions sum to unity.

For counter-current off-take flow the correlations are definitely outside their range of validity. However the code can enter this state. It was decided to use an ad hoc extension of the HSE model with the objective of minimising discontinuities in phase flow rates when the other phase off-take flow reverses. The junction phase area fractions calculated by RELAP5 in the absence of an HSE model do not normally sum to unity for counter-current off-take flow. Thus summing to unity was not taken as an objective. The ad hoc extension model is outlined below.

In this HSE extension model for counter-current flow, the gas area fraction is calculated on the basis of gas upwind conditions and the liquid area fraction is based on liquid upwind conditions, in line with the normal code practice. If the upwind volume for a phase is horizontal then the HSE correlations will be used for that phase. However four abnormal states may arise due to the flow being counter-current:

- (a) A gas flow from above the liquid level which could entrain liquid except that the liquid flows the opposite way.
- (b) A liquid flow from below the liquid level which could pullthrough gas except that the gas flows the opposite way.
- (c) A gas flow from below the liquid level which would normally be pulled through by a liquid flow except that the liquid flows the opposite way.

- (d) A liquid flow from above the liquid level which would normally be entrained by a gas flow except that the gas flows the opposite way.

For case (a)/(b) the reverse flow is ignored (the flowrate of the non-continuous phase does not appear in the correlations) and the gas/liquid area fraction calculated from the correlations. Cases (c) and (d) would not be expected to occur frequently. A fixup is required that will not introduce large discontinuities at phase flow reversals or when the level crosses a side off-take. For case (c)/(d) the gas/liquid area fraction is calculated from the correlations as if the liquid/gas flowrate was outwards but at the limit of zero. Thus there should be no discontinuity at phase flow reversals. For side off-take, at a void fraction of 0.5 in the horizontal volume Equation (5) gives a quality that is independent of flowrates so there is no discontinuity as the level passes the off-take for counter-current flow.

The RELAP5/MOD2 model has a partial implementation of this procedure. It fails to deal with two cases both involving two horizontally stratified volumes connected by a small orifice with counter-current flow. The two cases are where the orifice junction has been marked as an upward oriented off-take junction or a downward junction. In the first case the liquid is just given a donor calculated area fraction. Similarly in the second case the gas is given a donor value.

3.5. Treatment of Side Off-Take of Non-Negligible Area

The horizontal stratification entrainment model in RELAP5/MOD2 contains coding for treating the case where the liquid level in the main pipe is between the elevations of the top and bottom of the side branch entrance. The procedure used ensures that the junction void fraction tends to the void fraction in the main pipe when the side branch area tends to the area of the main pipe. Essentially there is an interpolation between the HSE model value and the donor value of void fraction. Virtually the same procedure is used in the implementation of the HSE model of [1] into RELAP5/MOD3.

To illustrate the procedure, consider the case where the liquid level is above the centre of the off-take branch ($\alpha_{gK} < 0.5$). Let α_g^* be the void fraction at which the liquid level would be at the elevation of the top of the side branch and let α_g^c be the void fraction calculated from the pull-through correlation. Then the liquid area fraction resulting from the procedure is calculated from the equations

$$\left. \begin{aligned} \alpha_f &= 1 - \alpha_g^c & \alpha_g^* &\geq \alpha_{gK} \\ \alpha_f &= 1 - \left[\left\{ \frac{\alpha_g^*}{\alpha_{gK}} \right\} \alpha_g^c + \left\{ 1 - \frac{\alpha_g^*}{\alpha_{gK}} \right\} \alpha_{gK} \right] & \alpha_g^* &< \alpha_{gK} \end{aligned} \right\} \quad (9)$$

where α_{gK} is the void fraction in the (gas) donor volume.

In fact, there is one additional complication. In the HSE model coding of RELAP5/MOD2 the void fraction is modified. Within the context of this new model, before α_g^* is used in Equation (9) it would be modified as follows:

$$\alpha_g^* \rightarrow \text{Min} \left[\alpha_g^*, 0.49 \right] * 0.85 \quad (10)$$

Documentation of the reason for this modification has not been seen by this author. It appears to extend the range of gas void fractions within which interpolation of the HSE and donor models may take place to a range of at least 0.4165 to 0.5835. It has been partially implemented in this new model with the factor 0.85 being omitted in Equation (10).

An analogous equation to (9) is used for $\alpha_{gK} > 0.5$ (entrainment). For the purposes of these calculations, the off-take orifice is assumed to have the diameter d_K^c given below:

$$d_K^c = D_K \sqrt{A_j / A_K} \quad (11)$$

In this implementation another modification is made. The critical depth h_b is given a minimum value of half of the estimated off-take diameter d_K^c . This helps avoid rapid changes as the level crosses the off-take for low off-take flow.

3.6. Treatment of Top and Bottom Off-Take of Non-Negligible Area

In the RELAP5/MOD2 coding, a procedure based on Equation (9) is also used for top and bottom off-takes. As noted in [1], this seems unreasonable since the liquid does not intersect the off-take entrance for these cases. However, some form of smoothing may be necessary when the liquid level approaches the level of the off-take. The correlations have not been demonstrated to be valid with large off-take area but the the implementation described here gives code users the option of using them or not.

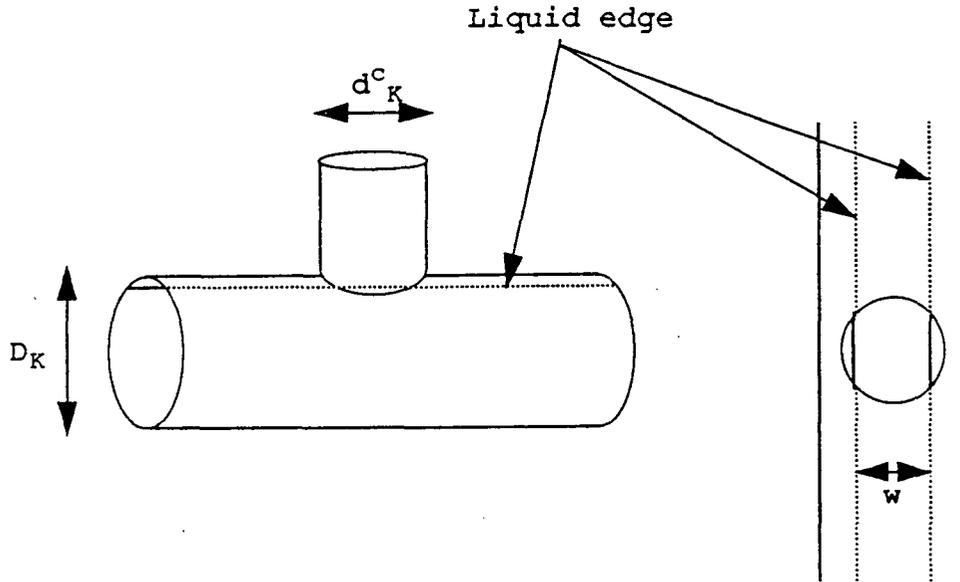
The smoothing used is based on a physical picture (see the next page). Looking at the main pipe through the off-take, if the liquid level is near the off-take and the edges of the liquid are in the field of view then the smoothing is applied. The smoothing is by interpolating to the donor void value according to the area of the field of view not occupied by liquid for a bottom off-take and according to that occupied by the liquid for a top off-take. The algorithm used is illustrated by the example of a bottom take-off:

$$\left. \begin{aligned} \alpha_f &= 1 - \alpha_g^c & \alpha_{gK} \geq 0.5 \text{ or } \sin\phi > 1 \\ \alpha_f &= 1 - \frac{2}{\pi} \left[\sin\phi \cos\phi + \phi \right] & \text{otherwise} \end{aligned} \right\} \quad (12)$$

where

$$\sin\phi = \frac{w}{\text{Min}[D_K, d_K^c]}$$

and w is the width of the liquid surface. This algorithm is slightly changed from that used in the RELAP5/MOD2 code version mentioned in Reference [1].



Schematic of View of Liquid Edge Through Top Off-take

3.7. Treatment of Large Critical Depths

It is conceivable that the critical entrainment depth h_b could imply a depth which is not contained within the main pipe. In this case the correlations (1)-(5) would predict gas pullthrough when the main pipe contains only liquid, or liquid entrainment when the pipe contains only gas. Such extreme values of h_b must take the correlations outside their range of validity. In this RELAP5/MOD3 model therefore it is assumed that the range of h_b is limited to the span of the main pipe diameter. This will imply less entrainment when the limit is in effect. This algorithm is different to that used in the RELAP5/MOD2 code version mentioned in Reference [1].

4. NUMERICS OF THE IMPLEMENTATION

A straightforward implementation of the correlations and extensions described above using old timestep values for all required properties is a recipe for disaster. Instead several improvements on this approach are used. These are described in the following Sections.

4.1. Time Level of Properties

The current values of almost all the property variables are used. (Current means the values at the time the HSE subroutine HZFLOW is called). The exceptions are the junction phase area fractions α_{fj} and α_{gj} used to evaluate the continuous phase flowrate W_k of Equation (1). For these the old timestep values α_{fj}^n and α_{gj}^n are used for two reasons. Firstly, the old timestep values will have been calculated with the HSE model (unless there has been a velocity reversal) and will be a better starting point than donor values from any intermediate calculation. Secondly, there is no change in values with this choice if a timestep is rejected and the calculation retried with half the timestep.

There is a special case however. If the flowrate W_k calculated from the old timestep junction phase area fraction would result in no entrainment then the flowrate W_k is recalculated using assuming the continuous phase area fraction α_{kj}^n was 1.0 corresponding to no entrainment. This helps to avoid large perturbations as entrainment starts and stops.

4.2. Condition the Correlations

Equations (4) and (5) for flow quality contain terms of the form

$$\left[1 - 0.5 R(1+R)x_0^{(1-R)} \right]^{0.5}$$

This term changes rapidly in the region of $R = 1$. To avoid numerical instabilities due to this behaviour the correlations are conditioned by replacing the term by a linear variation between its values at $R = 0.9$ and $R = 1.0$.

The non-dimensional height (or depth) R involves a division by h_b . To avoid problems when $h_b \rightarrow 0$ at zero off-take continuous phase flow W_k it is given a minimum magnitude of 10^{-6} m. The value of W_k is altered to the value $W_k^{(1)}$ which maintains the relationship Equation (1). (Such an alteration is also done if the minimum magnitude of h_b given for side off-takes, described just after Equation (11), is used).

To avoid other singularities, the density difference $\Delta\rho$ is given a minimum value of 10^{-7} kg/m³.

4.3. Improve Numerical Stability for Unchoked Flow

The explicit formulation described above is an invitation to instability. To try to overcome this a special procedure is applied. This is illustrated below for the calculation of liquid entrainment in co-current unchoked flow. Basically the procedure uses linear approximations of the non-linear functions. The resulting linear system is solved to give a better, more stable, calculation of the junction phase area fractions.

The entrainment is caused by the steam flow W_g (W_k is W_g in this case) from which a critical height h_b is calculated using Equation (1). This height may be modified if it is small as described above in which case it is associated with a modified gas flow $W_g^{(1)}$. Without the modification, $W_g^{(1)}$ is equal to W_g .

The appropriate entrainment correlation gives a flow quality which is converted into an off-take junction gas area fraction using the slip ratio S_j^* defined in Equation (8). Again this may be modified, by the finite area off-take modification or the high flow-rate modification for example, to give a gas area fraction which is denoted using the superscript P. This gas area fraction α_{gj}^P is unlikely to be the same value as that (α_{gj}^n) used to calculate W_g and this is the source of instability. The gas flow W_g may be considered as a function of the initial gas area fraction α_{gj}^n and the gas area fraction α_{gj}^P may be considered as a function of the gas flow. Then working to first order accuracy, the junction gas area fraction α_{gj} is set to the value which gives a gas flow which produces an entrainment giving rise to a self consistent gas area fraction.

This definition is represented by the following equations:

$$\alpha_{gj} = \alpha_{gj}^P + \frac{\partial \alpha_{gj}^P}{\partial W_g} \left[W_g^* - W_g^{(1)} \right] \quad (13)$$

$$W_g^* = W_g + \frac{\partial W_g}{\partial \alpha_{gj}^n} \left[\alpha_{gj} - \alpha_{gj}^n \right] \quad (14)$$

where in this case

$$\frac{\partial W_g}{\partial \alpha_{gj}^n} = A_j v_{gj} \rho_{gj} \quad (15)$$

and $\partial \alpha_{gj}^P / \partial W_g$ is non-positive. This partial derivative is evaluated assuming the slip ratio S_j^* and the degree of mixing of pure donor derived α_g are constant. The intermediate gas flow W_g^* is eliminated leaving the following expression for α_{gj} .

$$\alpha_{gj} = \frac{\alpha_{gj}^P + \frac{\partial \alpha_{gj}^P}{\partial W_g} \left[W_g - W_g^{(1)} - \alpha_{gj}^n \frac{\partial W_g}{\partial \alpha_{gj}^n} \right]}{1 - \frac{\partial W_g}{\partial \alpha_{gj}^n} \frac{\partial \alpha_{gj}^P}{\partial W_g}} \quad (16)$$

Under some circumstances the partial derivative $\frac{\partial \alpha_{gj}^P}{\partial W_g}$ is explicitly set zero:

- i. If the large critical depth modification was invoked.
- ii. If the flow was in counter-current cases (c) or (d).
- iii. If α_{gj}^P is 1.0 and α_{gj}^n is 1.0. (If α_{gj}^n is not 1.0 and the modified correlations give a non-zero derivative this is used to reduce perturbations as entrainment stops and starts.)
- iv. If α_{gj}^P is 0.0.

If the process is not calculated to be a negative feedback process, then the gas junction area fraction α_{gj} is left at the value α_{gj}^P .

Exactly the same form of procedure can be followed for counter-current flow for each phase flowing from a horizontal volume. For gas pullthrough the roles of gas and liquid are exchanged and the junction liquid area fraction is calculated by an expression like Equation (16):

$$\alpha_{fj} = \frac{\alpha_{fj}^P + \frac{\partial \alpha_{fj}^P}{\partial W_f} \left[W_f - W_f^{(1)} - \alpha_{fj}^n \frac{\partial W_f}{\partial \alpha_{fj}^n} \right]}{1 - \frac{\partial W_f}{\partial \alpha_{fj}^n} \frac{\partial \alpha_{fj}^P}{\partial W_f}} \quad (17)$$

Again under some circumstances the partial derivative $\frac{\partial \alpha_{fj}^P}{\partial W_f}$ is explicitly set zero:

- i. If the large critical depth modification was invoked.
- ii. If the flow was in counter-current cases (c) or (d).
- iii. If α_{fj}^P is 1.0 and α_{fj}^n is 1.0. (If α_{fj}^n is not 1.0 and the modified correlations give a non-zero derivative this is used to reduce perturbations as entrainment stops and starts.)
- iv. If α_{fj}^P is 0.0 and α_{fj}^n is 0.0. (If α_{fj}^n is not 0.0 and the modified correlations give a non-zero derivative this is used to reduce perturbations as liquid first appears.)

4.4. Improve Numerical Stability for Choked Flow

When the off-take flow is choked and co-current the assumption that only the dependence of the gas flow on the gas area fraction (Equation (14)) need be accounted for to obtain stability has been seen in practice to break down for liquid entrainment. Gas pullthrough with choked flow has also been seen to have problems. Procedures to improve stability for these two cases are described in the following two Subsections.

4.4.1. Liquid Entrainment

As stated above, the stability obtained by using the assumption of Equation (14) is not always satisfactory. Account has to be taken of the change in choked flow gas velocity v_g associated with a change in junction void fraction α_{gj} . Over a wide range of void fractions, an increase in junction gas area fraction results in an increase of choked gas velocity. This then would cause more entrainment of liquid in the next timestep reducing the junction gas area fraction. This is a negative feedback process which can cause oscillations.

The approximation used to take account of the change in choked flow gas velocity is to assume that $v_c \rho_j$ is a constant G_c and that the slip ratio S is also constant where

$$v_c = \frac{\alpha_{gj} \rho_{fj} v_g + (1 - \alpha_{gj}) \rho_{gj} v_f}{\alpha_{gj} \rho_{fj} + (1 - \alpha_{gj}) \rho_{gj}} \quad (18)$$

and

$$\rho_j = \alpha_{gj} \rho_{gj} + (1 - \alpha_{gj}) \rho_{fj} \quad (19)$$

Velocity v_c is used in the code's choked flow model. The assumed constant product G_c is evaluated with the old gas area fraction α_{gj}^n and current velocities. The assumptions then imply a relationship between v_g and α_{gj} and hence between W_g and α_{gj} . This latter relationship is linearised about α_{gj}^n and used to replace Equation (14). The derivative is constrained to be non-negative. The equations involved are Equations (20)-(25) below.

$$v_c = \frac{G_c}{\alpha_{gj}^n \rho_{gj} + \alpha_{fj}^n \rho_{fj}} \quad (20)$$

$$v_g = \frac{v_c (\alpha_{gj}^n \rho_{fj} + \alpha_{fj}^n \rho_{gj}) S}{\alpha_{gj}^n \rho_{fj} S + \alpha_{fj}^n \rho_{gj}} \quad (21)$$

$$W_g = A v_g \rho_{gj} \alpha_{gj}^n \quad (22)$$

where, because choked flow will be co-current, when calculating derivatives it is assumed that

$$\alpha_{fj}^n = 1 - \alpha_{gj}^n \quad (23)$$

The replacements for Equations (14) and (16) are

$$W_g^* = W_g + \frac{\partial W_g}{\partial \alpha_{gj}^n} \left[\alpha_{gj} - \alpha_{gj}^n \right] \quad (24)$$

and

$$\alpha_{gj}^P = \frac{\alpha_{gj}^P + \frac{\partial \alpha_{gj}^P}{\partial W_g} \left[W_g - W_g^{(1)} - \alpha_{gj}^n \frac{\partial W_g}{\partial \alpha_{gj}^n} \right]}{1 - \frac{\partial W_g}{\partial \alpha_{gj}^n} \frac{\partial \alpha_{gj}^P}{\partial W_g}} \quad (25)$$

where W_g and $\partial W_g / \partial \alpha_{gj}^n$ are evaluated from Equations (20), (21) and (22).

4.4.2. Gas Pullthrough

The situation is different for gas pullthrough. The negative feedback process described for liquid entrainment becomes a positive feedback. An increase in junction liquid area fraction results, for a wide range of void fractions, in a decrease in junction choked flow liquid velocity. The next timestep would then have less gas pullthrough (ignoring the countering effect of the increased liquid area fraction on the liquid mass flowrate) and hence there would be an increase in junction liquid area fraction. This may or may not give rise to instability. Using a procedure like that described above for liquid entrainment is likely to exacerbate any potential positive feedback instability because it could result in a reduced or negative denominator in the replacement expression for Equation (16) due to a small or negative value of $\partial W_f / \partial \alpha_{fj}^P$. This potential problem was not realised when the RELAP5/MOD2 code version of Reference [1] was developed.

Another problem observed in the RELAP5/MOD2 code version of Reference [1] is associated with the choked flow model transition between the subcooled and two-phase regimes. It is illustrated by considering a horizontal volume containing stratified gas and liquid with the liquid being subcooled. Consider a side off-take below the liquid level with the choked outflow liquid causing gas pullthrough. As the liquid level falls the equilibrium quality of the flow from a side off-take can change from subcooled to two-phase (the actual quality being two-phase throughout). As this happens the choked flowrate drops. This causes a drop in pullthrough resulting in a drop in off-take equilibrium quality to a subcooled value. If the choked flow routine is correctly coded (that is it uses junction equilibrium quality rather than upstream volume equilibrium quality) the next timestep will use the subcooled choked flow model giving an increase in off-take flow. This cycle can continue causing oscillations with period linked to the timestep size. This potential problem was not realised when the RELAP5/MOD2 code version of Reference [1] was developed. At the time of this development, it was expected that the released version of RELAP5/MOD3 would be based on the junction static quality and that this might also suffer from a similar instability.

In order to reduce such oscillations, a kind of damping is introduced by replacing the gas pullthrough version of Equation (14)

$$W_f^* = W_f + \frac{\partial W_f}{\partial \alpha_{fj}^n} \left[\alpha_{fj} - \alpha_{fj}^n \right] \quad (26)$$

by expressions involving an artificially large negative dependence of the choked liquid flowrate upon the junction gas area fraction.

Let \bar{X}^n be the static quality corresponding to α_{fj}^n and let \bar{X}^P be that corresponding α_{fj}^P (calculated from the extended correlations as used in previous Sections). The damping is applied if $\bar{X}^n < 2.5 \cdot 10^{-3}$ or $\bar{X}^P < 2.5 \cdot 10^{-3}$. In this case the junction liquid flowrate W_f^P is assumed to depend on \bar{X}^P according to

$$W_f^P = C (5 \cdot 10^{-3} - \bar{X}^P) \quad (27)$$

The "constant" C is chosen such that at the static quality \bar{X}^D the liquid flowrate calculated using the current liquid velocity v_f matches that given by Equation (27). The static quality \bar{X}^D is the minimum of $2.5 \cdot 10^{-3}$ and \bar{X}^n .

A partial derivative $\partial W_f^P / \partial \alpha_{fj}^P$ is evaluated from Equation (27) assuming that the only dependence is due to the \bar{X}^P term. This derivative is then used in Equation (26) in place of $\partial W_f / \partial \alpha_{fj}^n$.

5. PROGRAMMING DETAILS

5.1. New Variables

Six new global array variables have been added to the junction block:

VODFJO

This is the old junction liquid area fraction α_{fj}^n . The existing variable VOIDFJ cannot be used because it is overwritten before the HSE calculation is performed.

VODGJO

This is the old junction gas area fraction α_{gj}^n . The existing variable VOIDGJ cannot be used because it is overwritten before the HSE calculation is performed.

VDFJOO

This is the old junction liquid area fraction from the previous timestep. It is necessary because when a timestep is restarted the junction properties routine JPROP is called to recalculate the old junction variables from saved old volume variables.

VDGJOO

This is the old junction gas area fraction from the previous timestep.

VELFO

This is the old volume average liquid velocity.

VELGO

This is the old volume average gas velocity.

The number of junction variables in a parameter statement in the junction block is incremented by six.

5.2. Input Routines

No change. It should be noted that the release 5m5 has been changed compared to the pre-release version 411 for which this section applies. In particular it appears that pipe internal junctions are forced to have a value zero for the junction control flag "v" which denotes the junction orientation. The input data description does not state whether this means that the HSE model cannot be invoked (which is unduly restrictive) or whether it is invoked but as a central off-take orientation only.

5.3. Output Routines

No change.

5.4. Initialisation Routines

The changes described in this section were all made to the pre-release version 411. The release version 5m5 has changes to the input junction control flag "v" which denotes the junction orientation. The associated coding changes made by EG&G have not been studied by the author.

ICMPN1

For the original RELAP5/MOD2 HSE model, all junction geometries involving no significant area reduction between the horizontal volume and the off-take volume revert to the donor model for junction phase area fractions. For efficiency this is hardwired into subroutine ICMPN1. However for the new model described in this paper, upward and downward off-takes do not revert to the donor model in these geometries. Thus ICMPN1 was altered to allow these two types of off-take to use the new HSE model.

IJPROP

The new variables VDFJOO and VODFJO are initialised at the end of this routine to the initial junction value VOIDFJ (normally a donor value) calculated in the routine. Similarly VDGJOO and VODGJO are initialised to VOIDGJ. Currently RELAP5/MOD3 does not use any HSE model in the initialisation of junction conditions.

5.5. Transient Routines

MOVER

This routine is called when a timestep is accepted or rejected. If a timestep is rejected then the two junction variables VODFJO and VODGJO are reset to VDFJOO and VDGJOO respectively. Also the two volume variables VELF and VELG are reset to VELFO and VELGO respectively. If a timestep is accepted then VDFJOO and VDGJOO are updated to VODFJO and VODGJO, VODFJO and VODGJO are updated to VOIDFJ (α_{fj} at this stage) and VOIDGJ (α_{gj}) respectively. Also the two volume variables VELFO and VELGO are updated to VELF and VELG respectively.

HZFLOW

This is the routine that calculates the phase area fractions given by the HSE model for the junction phase flows that satisfy the model conditions. The new HSE model described in this report cannot be incorporated simply by following the existing routine logic because the new model can be in effect in flow conditions and geometries for which the old RELAP5/MOD2 model is not. The following pseudo-coding shows the essential part of the overall routine logic. The block IF levels have been numbered to aid in matching this logic to comments in the code source.

```

***This is a comment
***Enter routine with  $\alpha_{fj}$  and  $\alpha_{gj}$  set to donor volume values
IF ( HSE_model_not_allowed ) EXIT
***consider liquid entrainment
IF ( not_zero_gas_velocity ) THEN *** 0
  IF ( counter_current OR not_downward_off-take ) THEN *** 1
    LET off-take_volume = gas_downstream_volume
    LET upstream_volume = gas_upstream_volume
    IF ( upstream_volume_two-phase[ $\alpha_{gK} > 0$  AND  $\alpha_{fK} > 0$ ] ) THEN *** 2
      IF ( upstream_volume_horizontal ) THEN *** 3
        IF ( off-take_area_smaller OR not_side_off-take ) THEN *** 4
          IF ( counter_current OR upward_off-take OR
              ( side_off-take AND upstream_volume > half_empty ) ) THEN *** 5
            ***liquid entrainment section
            IF ( allowed_upstream_void_range ) THEN *** 6
              IF ( allowed_upstream_volume_mass_flux ) THEN *** 7
                { Calculate  $\alpha_{gj}$  using new model }
                IF ( co_current ) THEN *** 8
                  LET  $\alpha_{fj} = 1 - \alpha_{gj}$ 
                  EXIT
                ENDIF *** 8
              ENDIF *** 7
            ENDIF *** 6
          ENDIF *** 5
        ENDIF *** 4
      ENDIF *** 3
    ENDIF *** 2
  ENDIF *** 1
  IF ( co_current AND (upward_off-take OR
                      ( side_off-take AND upstream_volume > half_empty ) ) ) EXIT
ENDIF *** 0
***consider gas pullthrough
IF ( not_zero_liquid_velocity ) THEN *** 1
  LET off-take_volume = liquid_downstream_volume
  LET upstream_volume = liquid_upstream_volume
  IF ( upstream_volume_two-phase[ $\alpha_{fK} > 0$  AND  $\alpha_{gK} > 0$ ] ) THEN
    IF ( upstream_volume_horizontal ) THEN *** 2
      IF ( off-take_area_smaller OR not_side_off-take ) THEN *** 3
        ***gas pullthrough section
        IF ( allowed_upstream_void_range ) THEN *** 4
          IF ( allowed_upstream_volume_mass_flux ) THEN *** 5
            { Calculate  $\alpha_{fj}$  using new model }
            IF ( co_current ) THEN *** 6
              LET  $\alpha_{gj} = 1 - \alpha_{fj}$ 
            ENDIF *** 6
          ENDIF *** 5
        ENDIF *** 4
      ENDIF *** 3
    ENDIF *** 2
  ENDIF *** 1

```

ENDIF *** 3
ENDIF *** 2
ENDIF *** 1
ENDIF *** 0

6. PROGRAM TESTING

A simple test problem was used to verify the coding (in pre-release version 411) of the correlations. A time dependent volume was connected by a 1 sq cm test junction to a 206mm diameter horizontal volume. This volume discharged into a time-dependent volume at a fixed pressure of 0.1 MPa. The supplying volume fluid was kept at a fixed pressure of 0.7 MPa but its quality was swept from zero to unity in a sequence of ramps. The flow rate was determined by choking in the test junction. This simple three volume system was repeated three times to cover the three different possible orientations of the test junction: upwards, sideways and downwards. Thus the coded HSE correlations were swept over the complete range of liquid levels for co-current flow.

To automate the verification process, the RELAP5 control logic was used to calculate the code's values of the off-take flow qualities (flow quality was not an output variable for pre-release version 411 of the code for which the test input was developed) obtained with the HSE model enabled. The RELAP5 control logic was also used to calculate the off-take qualities directly by simulating the HSE correlations. This simulation took account of the modifications to the correlations to handle large critical depths and the critical depth modification for side off-takes given just after Equation (11). As such it will not give the off-take flow quality arising from the correlations alone. The modifications were included to minimise the differences to be expected in the comparison. The data is given in Appendix A. It has been modified to run on the release version 5m5 of the code. (The data needed changing because of a change in definition of the junction flags).

The two independent calculations, from the junction properties (determined by the HSE model) and from control system HSE simulation, of the off-take flow quality are compared graphically in Figures 1-6. These figures were produced by running the released code, version 5m5, on a Sun SPARCstation 1. Figures 1 and 2 show the up case, ie with upward oriented junction. Figure 1 shows the flow quality calculated from the junction properties, the control system simulated flow quality and the height ratio R (distance h of liquid level from off-take divided by the critical height h_b) plotted against time. Figure 2 shows the two flow qualities plotted against the height ratio R . The two qualities are indistinguishable despite transient effects. The plotting utility used to generate these figures was also used to calculate and plot the flow quality from the junction and volume properties assuming there was no HSE effect. During the period of interest, this quality was virtually zero.

Figures 3 and 4 show the side case, ie with side or central oriented junction. Figure 3 shows the flow quality calculated from the junction properties, the control system simulated flow quality and the height ratio R (height h of liquid level above the off-take divided by the critical height h_b) plotted against time. Figure 4 shows the two flow qualities plotted against the height ratio R . The two qualities are barely distinguishable except around the zero height ratio area. The difference here is due to the finite off-take area modification. Also plotted is the off-take flow quality calculated assuming there was no HSE effect. During the period of interest, this quality was virtually zero.

Figures 5 and 6 show the down case, ie with downward oriented junction. Figure 6 shows the flow quality calculated from the junction properties, the control system simulated flow quality and the height ratio R (distance h of liquid level from off-take divided by the critical height h_b) plotted against time. Figure 6 shows the two flow qualities plotted against the height ratio R. The two qualities were more distinguishable in this case than the up case. This is thought to be due to transient effects. The flow quality is changing significantly over a short time period. Also plotted is the off-take flow quality calculated assuming there was no HSE effect. In this case, during the period of interest, this quality was greater than that of the HSE model.

This test verified the coding of the correlations.

During this testing, a run was performed in which the flow area of the discharge junctions (downstream of the test junctions) was set to $5.0 \cdot 10^{-5}$. This showed numerical oscillations in the test junctions at high qualities. These oscillations persisted even when the test junction flow was single phase steam. It was also noticed that the slip was oscillating. This suggests that the problem is associated with a model other than the HSE model.

7. CONCLUSION

This report has described the numerics and implementation details for the modification of RELAP5/MOD3 to use the HSE correlation set described in Reference [1]. These details include the areas where the use of the HSE correlation set has been extended outside of its range. The modifications, which were incorporated into pre-release code version 411, remain in the first "frozen" release of the code (version 5m5). Areas where changes have been made by EG&G in producing the release version which might affect the modelling have been noted in the section on programming details. Particularly noteworthy is the restriction which apparently excludes the full control of the HSE model at the internal junctions of PIPE components.

A simple test problem was used to verify the RELAP5/MOD3 coding of the correlations, making use of the control system logic. This problem was run using the release code version. It was noted that this version seemed to be more prone to instability than the pre-release version 411. The problem is not believed to be associated with the HSE model.

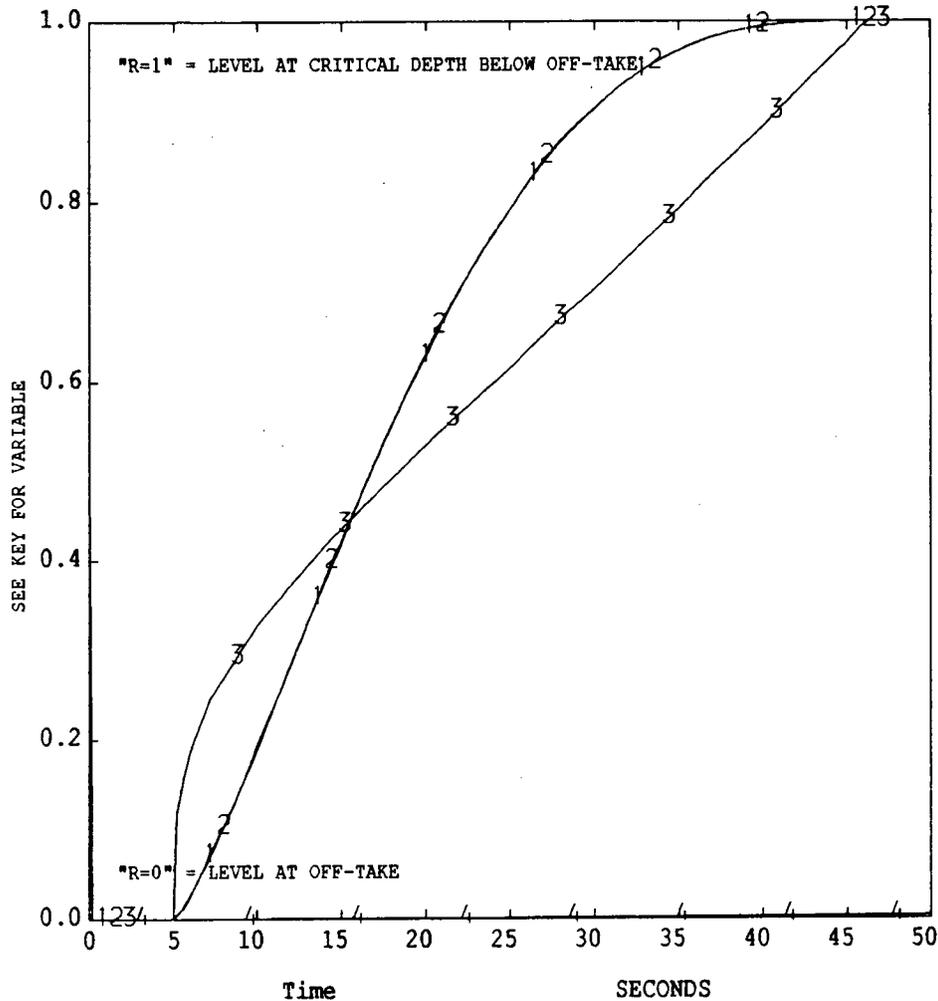
REFERENCES

1. Ardron, K H, Bryce, W M. Assessment of Horizontal Stratification Entrainment Model in RELAP5/MOD2. AEEW-R 2345. April 1988.



THE FOLLOWING ARE PLOTTED AGAINST Time
Control Component No, FROM VOL/JN PROPS

KEY		
SYM BOL	NAME	UNITS
1	Control Component No, FLOW X FROM JN. PROPS. LOC= 204/ 0/ 0 MNEM=CCNO INF=1	
2	Control Component No, FLOW X CONTROL SYS. HSE CALC. LOC= 255/ 0/ 0 MNEM=CCNO INF=1	
3	Control Component No, R ("HEIGHT" RATIO) LOC= 243/ 0/ 0 MNEM=CCNO INF=1	
4	FROM VOL/JN PROPS FLOW X WITH NO HSE MOD.	

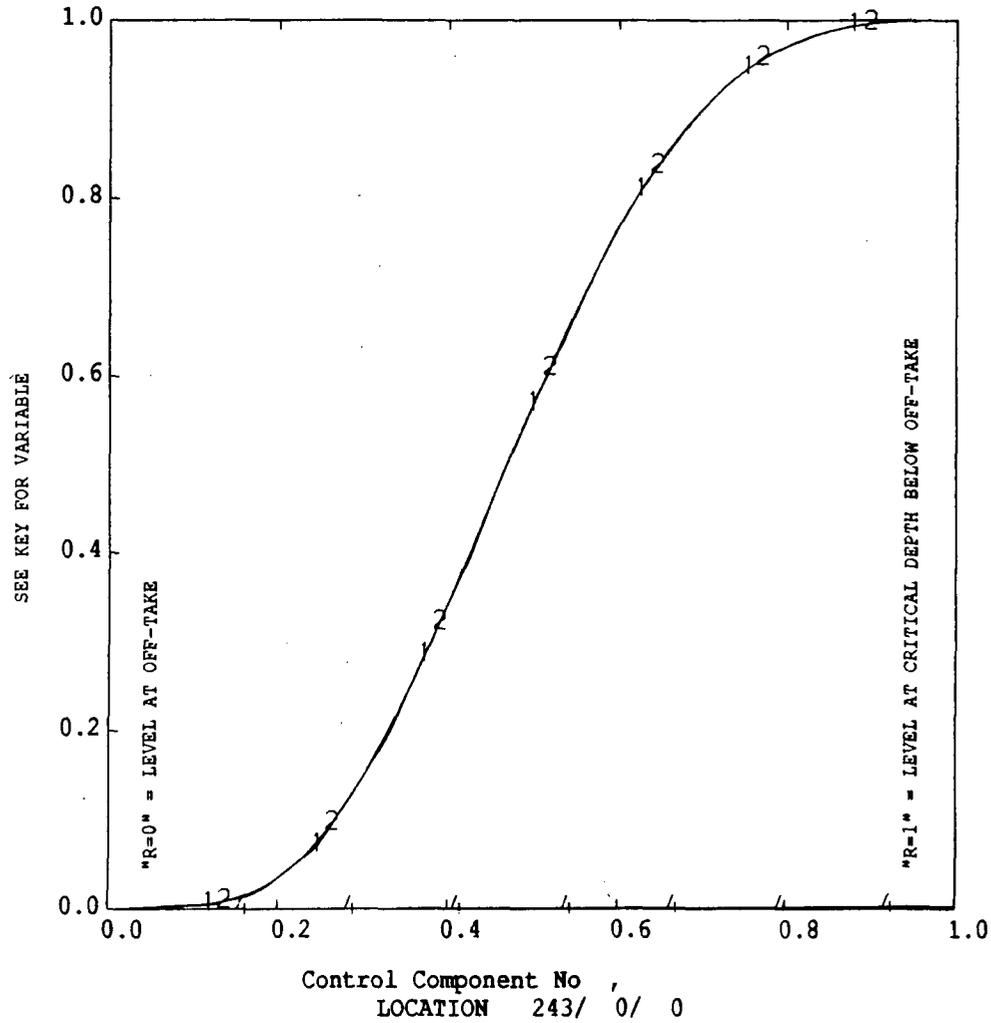


SIMPLE HSE TEST CASES RELAP5/MOD3 5M5 SUN SPARC 1
FIGURE 1 TEST ENTRALLC - UP CASE FLOW QUALITY



THE FOLLOWING ARE PLOTTED AGAINST Control Component No
Control Component No, FROM VOL/JN PROPS

KEY		
SYM BOL	NAME	UNITS
1	Control Component No, FLOW X FROM JN. PROPS. LOC= 204/ 0/ 0 MNEM=CCNO INF=1	
2	Control Component No, FLOW X CONTROL SYS. HSE CALC. LOC= 255/ 0/ 0 MNEM=CCNO INF=1	
4	FROM VOL/JN PROPS FLOW X WITH NO HSE MOD.	

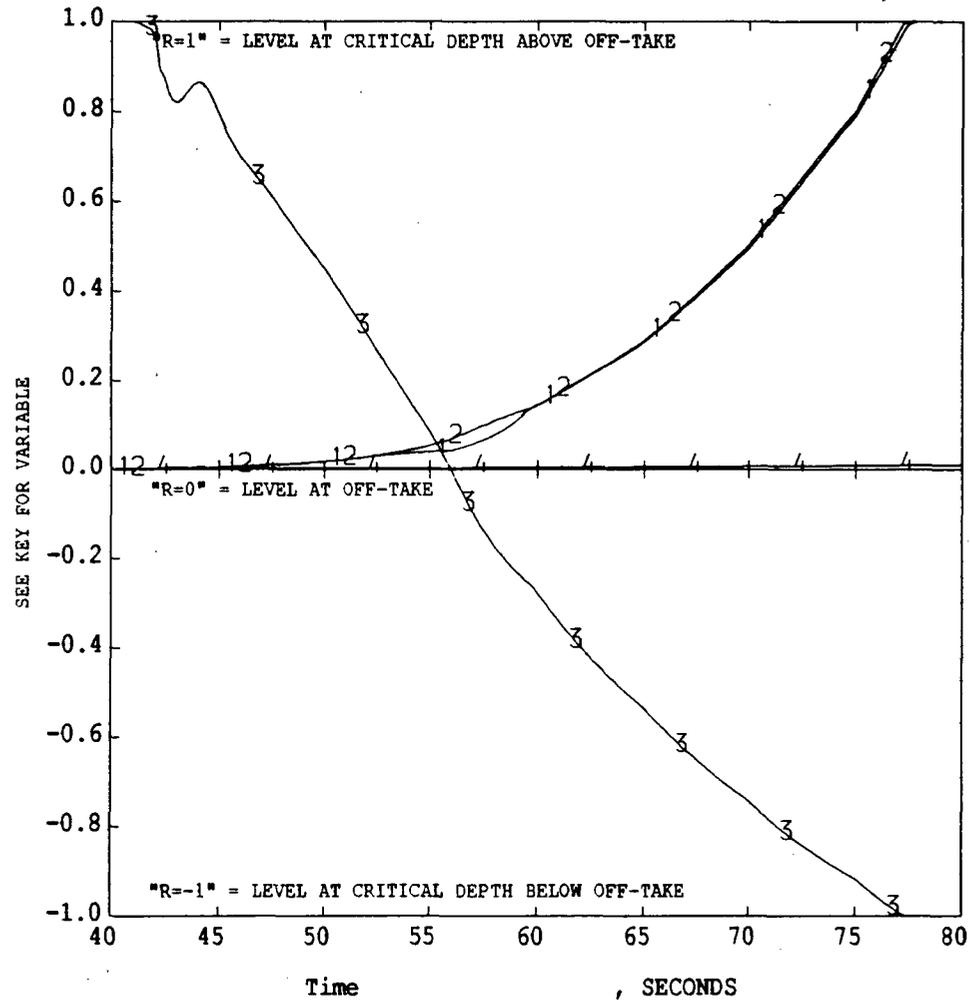


SIMPLE HSE TEST CASES RELAP5/MOD3 5M5 SUN SPARC 1
FIGURE 2 TEST ENTRALLC - UP CASE FLOW QUALITY



THE FOLLOWING ARE PLOTTED AGAINST Time
Control Component No, FROM VOL/JN PROPS

KEY		
SYM BOL	NAME	UNITS
1	Control Component No, FLOW X FROM JN. PROPS.	
	LOC= 212/ 0/ 0 MNEM=CCNO INF=1	
2	Control Component No, FLOW X CONTROL SYS. HSE CALC.	
	LOC= 270/ 0/ 0 MNEM=CCNO INF=1	
3	Control Component No, R ("HEIGHT" RATIO)	
	LOC= 247/ 0/ 0 MNEM=CCNO INF=1	
4	FROM VOL/JN PROPS FLOW X WITH NO HSE MOD.	

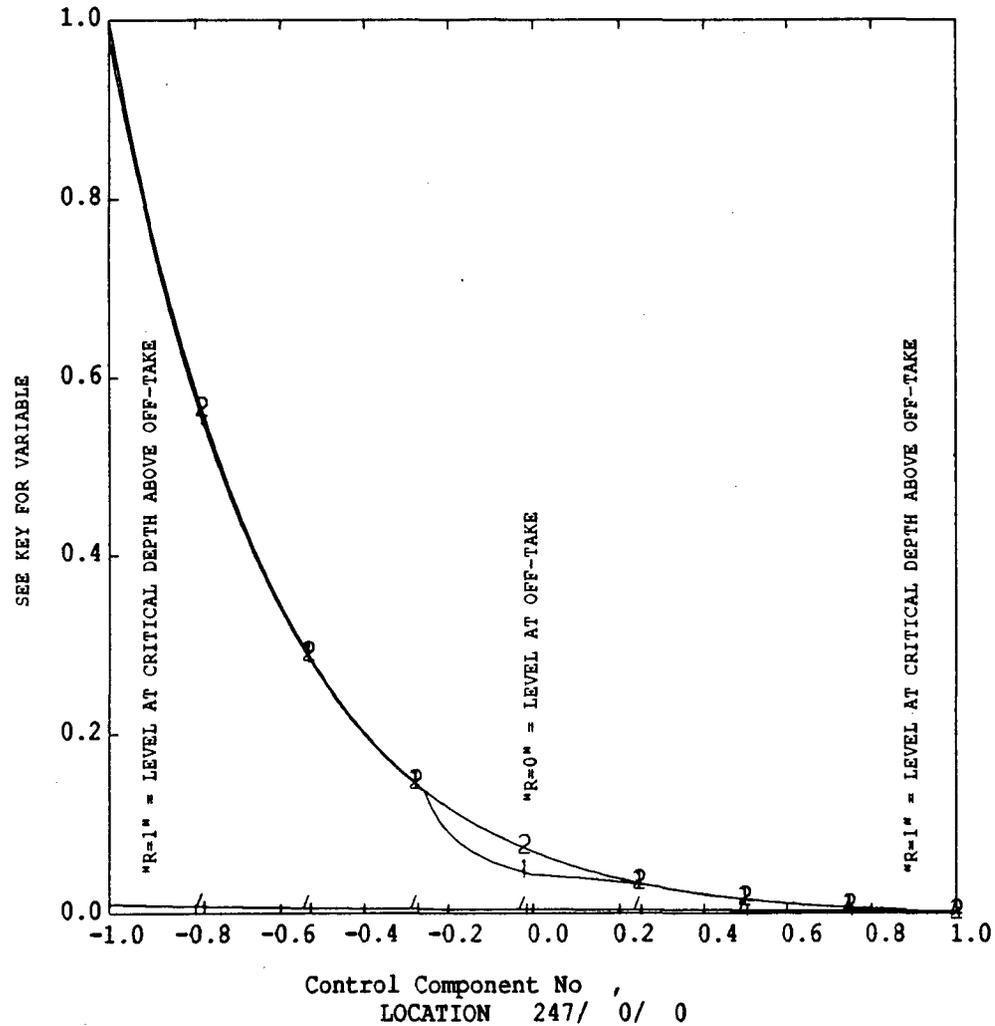


SIMPLE HSE TEST CASES RELAP5/MOD3 5M5 SUN SPARC 1
FIGURE 3 TEST ENTRALLC - SIDE CASE FLOW QUALITY



THE FOLLOWING ARE PLOTTED AGAINST Control Component No
Control Component No, FROM VOL/JN PROPS

KEY		
SYM BOL	NAME	UNITS
1	Control Component No, FLOW X FROM JN. PROPS. LOC= 212/ 0/ 0 MNEM=CCNO INF=1	
2	Control Component No, FLOW X CONTROL SYS. HSE CALC. LOC= 270/ 0/ 0 MNEM=CCNO INF=1	
4	FROM VOL/JN PROPS FLOW X WITH NO HSE MOD.	



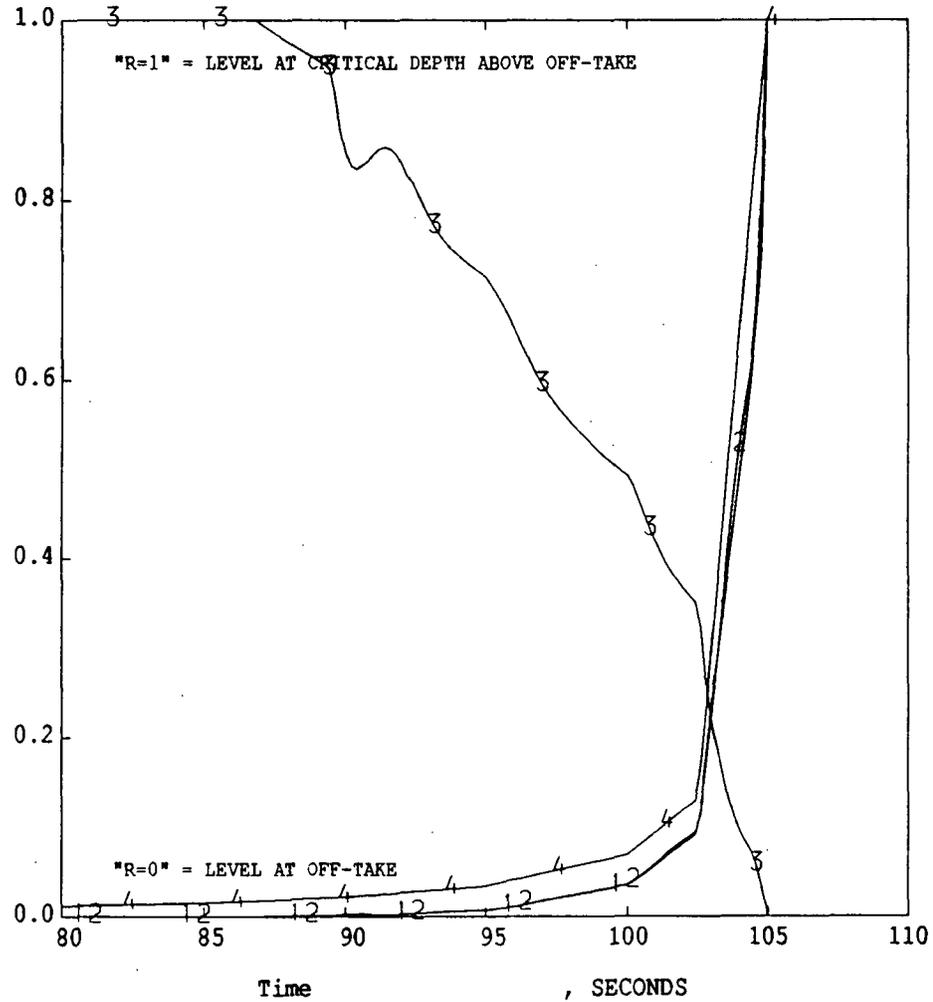
SIMPLE HSE TEST CASES RELAP5/MOD3 5M5 SUN SPARC 1
FIGURE 4 TEST ENTRALLC - SIDE CASE FLOW QUALITY



THE FOLLOWING ARE PLOTTED AGAINST Time
Control Component No, FROM VOL/JN PROPS

KEY		
SYM BOL	NAME	UNITS
1	Control Component No, FLOW X FROM JN. PROPS. LOC= 208/ 0/ 0 MNEM=CCNO INF=1	
2	Control Component No, FLOW X CONTROL SYS. HSE CALC. LOC= 283/ 0/ 0 MNEM=CCNO INF=1	
3	Control Component No, R ("HEIGHT" RATIO) LOC= 244/ 0/ 0 MNEM=CCNO INF=1	
4	FROM VOL/JN PROPS FLOW X WITH NO HSE MOD.	

SEE KEY FOR VARIABLE

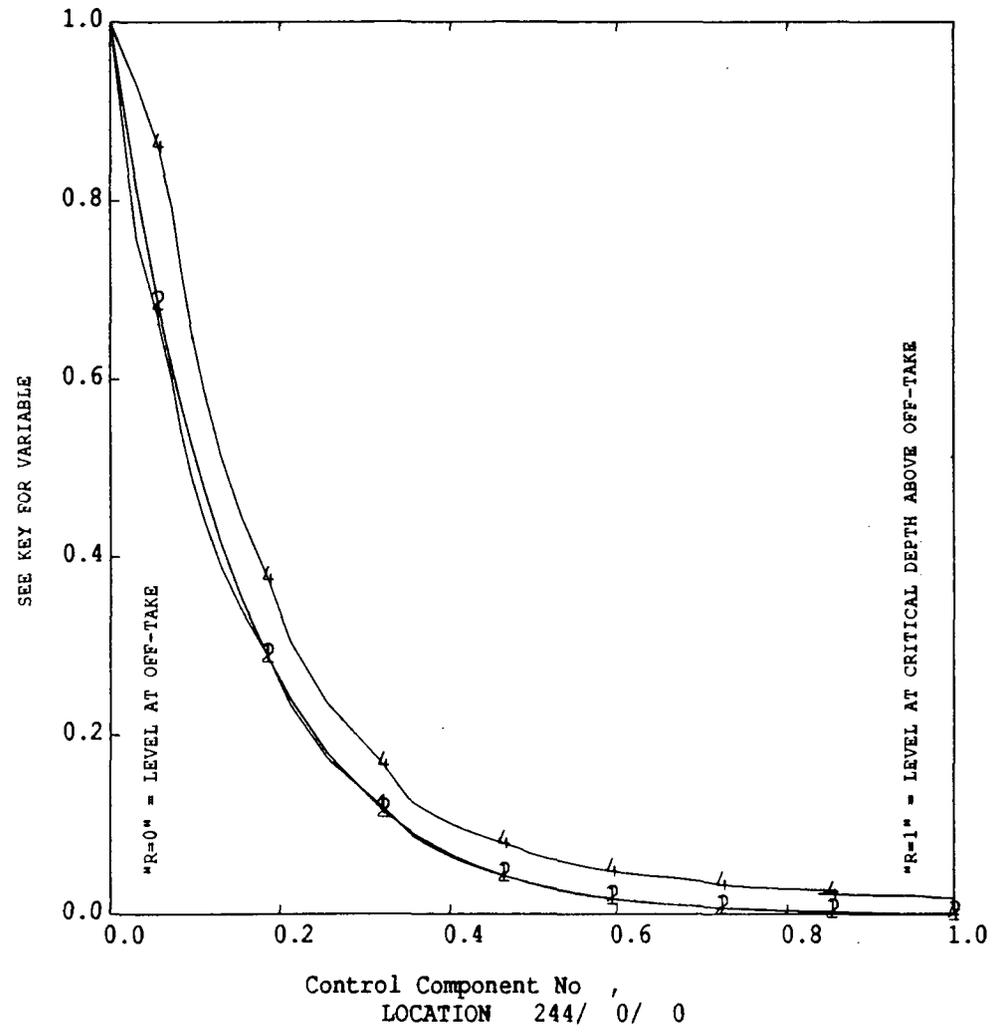


SIMPLE HSE TEST CASES RELAP5/MOD3 5M5 SUN SPARC 1
FIGURE 5 TEST ENTRALLC - DOWN CASE FLOW QUALITY



THE FOLLOWING ARE PLOTTED AGAINST Control Component No
Control Component No, FROM VOL/JN PROPS

KEY		
SYM BOL	NAME	UNITS
1	Control Component No, FLOW X FROM JN. PROPS. LOC= 208/ 0/ 0 MNEM=CCNO INF=1	
2	Control Component No, FLOW X CONTROL SYS. HSE CALC. LOC= 283/ 0/ 0 MNEM=CCNO INF=1	
4	FROM VOL/JN PROPS FLOW X WITH NO HSE MOD.	



SIMPLE HSE TEST CASES RELAP5/MOD3 5M5 SUN SPARC 1
FIGURE 6 TEST ENTRALLC - DOWN CASE FLOW QUALITY


```

20525100 "1+sqrt" sum 1.0 1.0 1
20525101 1.0 1.0 cntrlvar 250
*
20525200 x0 div 1.15 1.0 1
20525201 cntrlvar 251
*
* calculators for upward quality x
20525300 xu1 sum 1.0 0.0 1 3 0.0 1.0
20525301 1.0 -1.0 cntrlvar 243
*
20525400 xu2 mult 3.25 0.0 1
20525401 cntrlvar 253 cntrlvar 253
*
20525500 xup powerx 1.0 0.0 1 3 0.0 1.0
20525501 cntrlvar 243 cntrlvar 254
*
* calculators for side quality x
*
* calculators for x0 exponents
20525600 x0s1 sum 1.00 0.0 1 2 0.0
20525601 0.0 1.0 cntrlvar 245
*
20525700 x0s2 sum 1.09 0.0 1 1 0.0
20525701 0.0 1.0 cntrlvar 246
*
20525800 x0s sum 1.00 0.0 1
20525801 1.0 1.0 cntrlvar 256
20525802 1.0 cntrlvar 257
*
20526200 "1-rs" sum 1.0 0.0 1
20526201 1.0 -1.0 cntrlvar 247
*
20526300 xOp1-rs powerx 1.0 0.0 1
20526301 cntrlvar 252 cntrlvar 262
*
20526400 "1+rs" sum 1.0 0.0 1
20526401 1.0 1.0 cntrlvar 247
*
20526500 x0tm1s mult -0.5 0.0 1
20526501 cntrlvar 247 cntrlvar 264
20526502 cntrlvar 263
*
20526600 x0tm2s sum 1.0 0.0 1 1 0.0
20526601 1.0 1.0 cntrlvar 265
*
20526700 x0tm3s stdfctn 1.0 0.0 1
20526701 sqrt cntrlvar 266
*
20526800 x0tm4s powerx 1.0 0.0 1
20526801 cntrlvar 252 cntrlvar 258
*
20527000 xside mult 1.0 0.0 1 3 0.0 1.0
20527001 cntrlvar 267 cntrlvar 268
*
* calculators for downward quality x
*
* calculators for x0 exponent
20527500 x0d sum 2.5 0.0 1 3 0.0 2.5
20527501 0.0 1.0 cntrlvar 244
*
20527600 "1-rd" sum 1.0 0.0 1
20527601 1.0 -1.0 cntrlvar 244
*
20527700 xOp1-rd powerx 1.0 0.0 1
20527701 cntrlvar 252 cntrlvar 276

```

```

*
20527800 "1+rd" sum 1.0 0.0 1
20527801 1.0 1.0 cntrlvar 244
*
20527900 x0tm1d mult -0.5 0.0 1
20527901 cntrlvar 244 cntrlvar 278
20527902 cntrlvar 277
*
20528000 x0tm2d sum 1.0 0.0 1 1 0.0
20528001 1.0 1.0 cntrlvar 279
*
20528100 x0tm3d stdfctn 1.0 0.0 1
20528101 sqrt cntrlvar 280
*
20528200 x0tm4d powerx 1.0 0.0 1
20528201 cntrlvar 252 cntrlvar 275
*
20528300 xdown mult 1.0 0.0 1 3 0.0 1.0
20528301 cntrlvar 281 cntrlvar

```

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report presents the numerics and implementation details to add the same improved discharge quality correlations into RELAP5/MOD3. In the light of experience with the modified RELAP5/MOD2 code, some of the numerics has been slightly changed for RELAP5/MOD3. The description is quite detailed in order to facilitate change by some future code developer. A simple test calculation was performed to confirm the coding of the correlations implemented in RELAP5/MOD3.

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Robert C. Jones, Jr.
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