ACRSR-1932

March 15, 2001

Dr. William D. Travers
Executive Director for Operations
U.S. Nuclear Regulatory Commission
Washington D.C., 20555-0001

Dear Dr. Travers:

SUBJECT: ELECTRIC POWER RESEARCH INSTITUTE RETRAN-3D THERMAL-HYDRAULIC TRANSIENT ANALYSIS CODE

During the 480th meeting of the Advisory Committee on Reactor Safeguards, March 1-3, 2001, we discussed the status of the Committee's review of the Electric Power Research Institute (EPRI) RETRAN-3D thermal-hydraulic transient analysis code. Our Subcommittee on Thermal-Hydraulic Phenomena most recently discussed this matter with representatives of the NRC staff, EPRI, and its contractors during a meeting on February 20, 2001. We also had the benefit of the documents referenced.

In early 1999, we reviewed the RETRAN code documentation. On July 14,1999, ACRS Member Dr. Graham Wallis presented a critique of the momentum equations in RETRAN to the ACRS. During 1999 and 2000, the staff raised several questions concerning the momentum equations, both informally and formally, through requests for additional information (RAIs). EPRI responded to these RAIs on April 27, 1999, October 22, 1999, and March 6, 2000. Additional written material was submitted by EPRI on February 15, 2001. During the February 20, 2001, Subcommittee meeting, EPRI representatives agreed to reconsider the justifications of the momentum equations in RETRAN and the example problems illustrating their use for modeling specific components.

The major concerns identified by the Thermal-Hydraulic Phenomena Subcommittee regarding the momentum equations are summarized by ACRS Member Dr. Graham Wallis in the attached documents.

Sincerely,

/RA/
George E. Apostolakis
Chairman

<u>Attachments</u>:

1. "Discussion on Momentum Equations," by ACRS Member Graham Wallis, dated February 25, 2001.
2. "Comments on EPRI Response to RAIs and Other Recent Submittals Concerning the RETRAN Code," by ACRS Member Graham Wallis, dated February 25, 2001.

References:

1. Safety Evaluation Report by the Office of Nuclear Reactor Regulation for EPRI NP-7450 "RETRAN-3D - A Program for Transient Thermal-Hydraulic Analysis of Complex Fluid Flow Systems," undated.
2. Letter dated February 15, 2001, from L. Agee, Electric Power Research Institute, to Graham Wallis, ACRS, Subject: Closure of the NRC RETRAN-3D Review.
3. Letter dated March 6, 2000, from G. Swindlehurst, Duke Power, to NRC Document Control Desk, Subject: Project No. 669 - Review of RETRAN-3D, Submittal of Additional Information.
4. Letter dated October 22, 1999, from G. Swindlehurst, Duke Power, to NRC Document Control Desk, Subject: Project No. 669 - Review of RETRAN-3D, Response to RAI Letter dated August 25, 1999.
5. Response to Office of Nuclear Reactor Regulation Request for Additional Information, EPRI Topical Report NP-7450, RETRAN-3D Project No. 669, dated April 27, 1999.
6. Office of Nuclear Reactor Regulation, U. S. Nuclear Regulatory Commission, "Staff Conference Call Follow Up," documenting results of NRR/EPRI conference call of August 29, 2000, pertaining to NRR review of RETRAN-3D.
7. Letter dated November 29, 2000, from Theodore Marston, EPRI, regarding ACRS Member Graham Wallis presentation to Commission regarding need for more realistic (best-estimate) thermal-hydraulic computer codes.
8. Comments by Graham Wallis on his review of RETRAN-3D, "Continuation of Review of RETRAN-3D," dated May 23, 1999.
9. Memorandum dated September 2, 1999, from P. Boehnert, ACRS, to ACRS Members, Subject: Supporting Documents - G. Wallis's Discussion on Status of EPRI RETRAN-3D Code Review - 465th ACRS Meeting, September 1, 1999.

<u>DISCUSSION ON MOMENTUM EQUATIONS</u>

By ACRS Member Graham Wallis, February 25, 2001

The momentum balance equation for a stationary control volume is (see any textbook)

$$d/dt \int (\rho\, \mathbf{v})\, dv \;=\; - \int p\, \mathbf{dA} \;+\; \int t\, \mathbf{.}\, \mathbf{dA} \;-\; \int \mathbf{v}\, (\rho\, \mathbf{v}\, \mathbf{.}\, \mathbf{dA}) \qquad (1)$$

For engineering purposes, this is usually reduced to the form

$$\mathbf{I}\, dW/dt \;=\; -\; \Sigma\, p_i\, \mathbf{A_i} \;+\; \mathbf{F_w} \;-\; \Sigma\, (\rho\, \mathbf{v_i}\, \mathbf{.}\, \mathbf{A_i})\, \mathbf{v_i} \qquad (2)$$

Equation (2) is a node/port description where the velocities, v, at each port, i, are assumed to be uniform. The usual idea is to compute the rate of change in flow rate, dW/dt, across some internal surface in the node and step forward in time. The flow rates, W, throughout the system modeled by a set of such nodes will be solution variables that are updated as the numerical transient proceeds. The coefficient, **I**, is the effective vector inertia of the fluid in the node, with units of length. It represents an approximation, particularly if the flow is not uniform. It is also a significant assumption that the momentum in the node is proportional to the flow rate, W, (which is a scalar quantity) across some defined surface in the node. This is not so bad for single phase incompressible flow with ports at the end of the nodal volume, because the flow is the same across any surface in the node that does not intersect the ports. For more general compressible or multiphase flows with many ports, the momentum in a nodal volume is not so easy to figure out. $\mathbf{F_w}$ is the force from the walls. The shear stress contribution to the forces at the ports is usually neglected.

To illustrate the importance of the wall force, consider a couple of parallel similar pipes in the x-direction joined by a 180-degree bend in the horizontal x-y plane and filled with an incompressible inviscid fluid. The momentum in the two pipes cancels and the total momentum in the system is all in the y-direction. The pressure and momentum flux terms on the right hand side of Equation (2) all act in the x-direction, so it is only the net wall force acting in the y-direction that is available to change the net fluid momentum in the system. This force may actually be

computed by first using mechanical energy conservation to get the acceleration and then using the y-component of the momentum balance to deduce the wall force.

There are several important features of Equation (2) that present difficulties to the code developer:

1. It is a vector equation. It can only be reduced to one-dimensional form if the flows and forces all act in a single direction, which is not the case for flow around a bend, for instance. If it is resolved in some direction to obtain a scalar component, then all terms must be resolved in a consistent way.

2. The force from the walls is unknown and cannot be determined from known quantities without invoking some new information, except in trivial cases which are probably limited to a straight pipe. This force is made up of resultants from both normal (pressure) and tangential (shear) components.

3. The pressures at the ports or junctions (node boundaries) act on areas. These areas cannot be made to disappear except when the flow is in a straight pipe and the equation can be divided through by the area. No amount of algebra can make the areas disappear in the general case, though the "momentum" equations in some codes are written without areas multiplying pressures at the junctions. To get an equation like Bernoulli's in which the pressures do not multiply areas and the formulation is one-dimensional, you have to integrate a differential form of the momentum balance along a streamline. This is strictly invalid when streamlines get mixed up in nodes, through turbulence or flow separation, but such an approach has also been tried as an alternative way to get usable equations for codes.

The biggest problem is Item 2. It is basically insurmountable in any general way. Attempts have been made to derive the force from the walls from another principle, such as conservation of mechanical energy. However, the forces from walls are usually imposed by stationary surfaces. They, therefore, do not work and do not contribute to the energy balance. Therefore, there is no way that the energy balance can be manipulated to solve for the wall force.

Conservation of mechanical energy is sometimes used in place of the momentum balance to provide an expression for dW/dt. Bird, Stewart, and Lightfoot [Reference 1] discuss the conditions for validity of such a balance (e.g., constant density or constant temperature). They solve the example of oscillations of a manometer this way. This method has not been developed as a general derivation that might apply to two-phase flows of the type that occur in reactor systems.

The approach taken in all codes is to derive a momentum balance for an extremely simple geometry, such as a long straight pipe. The result is then usually applied with little or no explanation or justification to other shapes and situations. I think it is true that the (long) straight pipe is the only case in which it is possible to overcome the three difficulties listed previously. With some allowances for "averaging," Equation (2) can then be expressed as

$$L\ dW/dt = p_1A - p_2A - \tau_w \pi DL + \rho_1 v_1^2 A - \rho_2 v_2^2 A \qquad (3)$$

Where L is the length of the pipe, subscripts denote the inlet and exit; A is the cross-sectional area, D the diameter (or effective diameter), and the velocities are all in the direction of the pipe axis. The wall shear stress is computed from the steady-flow friction factor, though friction is strictly not the same in unsteady flow. If Equation (3) is divided by A and the pipe is assumed to be circular, we get

$$L/A\ \ dW/dt = p_1 - p_2 - \tau_w 4L/D + \rho_1 v_1^2 - \rho_2 v_2^2 \qquad (4)$$

If the fluid is incompressible or suffers no change of density, the last two terms cancel each other and disappear. Similar equations can be deduced for each phase in the two-fluid model.

Even when applying these methods to straight pipes, care may need to be taken near ends or junctions where flow is not one-dimensional. The lengths, L, of nodes must be chosen to correspond to regions where the properties do not change too rapidly.

It is not directly evident from the documentation, but presentations from proponents of the RELAP and TRAC codes lead me to conclude that most of the reactor system is modeled as a series of straight pipes connected by nodes of zero length that contribute frictional losses but no inertia. Bends, for example, are

modeled as a series of these straight pipe segments and the additional losses contributed by the non-straight shape are added in between these segments. More complex nodes are modeled in an *ad hoc* manner that has evolved with time and experience.

RELAP and RETRAN also make use of a derivation for two coaxial straight pipes connected by a sudden change of area.   The pressure difference across the junction is taken as given by the steady flow loss coefficient and it is assumed that this all occurs in zero length. This is no different from the idea of joining two straight pipes with a valve or other “resistance” and there is no need for the pipes to be oriented in the same direction.

Denoting one pipe by the subscript “a” and the other by “b” we have two equations like Equation (4) as follows:

$$L_a/A_a \; dW_a/dt = p_1 - p_2 - \tau_w \, 4L_a/D_a + \rho_1 v_1^2 - \rho_2 v_2^2 \qquad (5)$$

$$L_b/A_b \; dW_b/dt = p_3 - p_4 - \tau_w \, 4L_b/D_b + \rho_3 v_3^2 - \rho_4 v_4^2 \qquad (6)$$

The pressure change across the junction is assumed to be given by the steady-state correlation, which could take the form,

$$p_2 - p_3 = k \; ½ \; \rho_2 v_2^2 \qquad (7)$$

with “k” being a loss coefficient for the junction.

There is nothing special going on here, just building up a composite piece of a circuit by combining two straight pipes and a junction.

Having read Bird, Stewart, and Lightfoot, the RELAP developers decided to express the empirical losses across the junction another way. The pressure change is expressed in terms of mechanical energy losses, or as a loss in Bernoulli head. This is strictly only valid for an incompressible fluid, though some workable derivations might be possible for other conditions, such as isothermal flow, if done carefully. Then Equation (7) is expressed as

$$p_2 - p_3 = -½ \; \rho_2 v_2^2 + ½ \; \rho_3 v_3^2 - k_e \; ½ \; \rho v^2 \qquad (8)$$

where k_e is a coefficient of mechanical energy loss. I have left the velocity and density in the last term without subscripts as the appropriate conditions have to be defined. This, of course, is part of the definition of the empirical loss coefficient k_e. I have also used subscripts on the "kinetic energy" terms, adding to the definition of the loss coefficient. I believe this loss coefficient is simply taken from single-phase flow tests, so it is something of a reach to apply it to an unsteady two-phase flow with density change.

If we use Equation (8) to eliminate the intermediate pressures, p_2 and p_3, from Equation (6) plus Equation (7) the result is

$$L_a/A_a \ dW_a/dt + L_b/A_b \ dW_b/dt = p_1 - p_4 + (- \tau_w \ 4L_a/D_a - \tau_w \ 4L_b/D_b - \tfrac{1}{2} \ \rho_2 v_2^2 + \tfrac{1}{2} \ \rho_3 v_3^2 - k_e \ \tfrac{1}{2} \ \rho v^2) + \rho_1 v_1^2 - \rho_4 v_4^2 \qquad (9)$$

In RETRAN, it is asserted that the two terms on the left hand side can be combined by assuming that both of the W's are the same as some "W" for the "junction". The term in parentheses is interpreted as some sort of total loss for the system, and the two last terms are interpreted as momentum fluxes in and out of the combined system. This is how the A's are made to disappear from what would be an equation resembling Equation (2) if written as the momentum equation for the whole works of two pipes plus junction. It then seems to be assumed, without argument, that a similar equation applies to any shape or component in the system, except when a special model is derived, as for a pump. RETRAN has sketches of more general shapes, but there is no proper derivation of a momentum balance for them, just an equation written down to look like the "two-pipe-plus- junction" (TP+J) case.

Note that Equation (9) is a scalar equation, unlike Equation (2). It does not represent a "momentum balance" for a control volume and it cannot be "resolved" in some direction. However, in RETRAN a modification is made to change the two final terms in Equation (9) to $\rho_1 v_1 v_{1,\psi} - \rho_4 v_4 v_{4,\psi}$ where the subscript is supposed to denote the "component that lies in the direction of the junction". I have yet to see a convincing derivation of this result. It seems to be a sort of hybrid between Equation (2) and Equation (9) in which the momentum flux terms are resolved in some chosen direction, as the ones in Equation (2) would have to be to obtain a scalar result. Since the direction is arbitrary, different results can be achieved, over a limited range, at the will of the user.

If the fluid is incompressible, or of constant density, then v_1=v_2 and v_3=v_4 so that Equation (9) reduces to a form of Bernoulli equation with losses (which the RETRAN version with “resolved” momentum fluxes does not, an indication that something is almost certainly wrong). This particular result can be deduced from the principle of mechanical energy conservation, as long as the density is constant, which is not the case in a general two-phase flow.

The TP+J model can also handle some aspects of momentum addition from side branches, as in ECC injection into a cold leg. If a flow W_{sa} is injected from a connection to the side of pipe “a” with velocity component v_{sa} in the direction of the pipe axis, then an additional source of momentum equal to $W_{sa}v_{sa}$ appears on the right hand sides of Equations (5) and (9). RETRAN also has such a term, but the definition of the velocity component is ambivalent. The example of the wye-junction in the RETRAN text (EPRI NP-1415 [Reference 2]) seems to indicate that this term was improperly evaluated in that case.

The RETRAN documentation at least acknowledges that there is a need to develop an equation describing a general shape with several connections to ports or junctions. There is just no good rationale for the result and no examples showing how to use the method for the sorts of nodes, other than straight pipes, that occur in models of nuclear systems. There are some other concerns with the documentation, including:

1. Derivations of momentum equations in various forms that appear questionable.

2. Examples of applications to bends, tee-junctions, wye-junctions that appear wrong at an elementary level, even if one accepts the basic equation used.

3. Strange features, such as resolving the scalar flow rate in each coordinate direction as if it were a vector and interpolating these components in ways that seem to defy physical reality. This shows up also in the worked examples, where some odd terms are derived.

4. Misplaced appearance of rigor, when it would be better to explain and justify assumptions.

5. A method of “resolving” the momentum flux terms that seems to be arbitrary and makes it possible to achieve a range of different results, depending on the user’s choice of the angle ψ.

These points are examined in more detail in the accompanying document “Comments on EPRI Response to RAIs and other Recent Submittals concerning the RETRAN code.”

Do these inadequacies or limitations or “assumptions” matter for the purposes of nuclear safety calculations? Perhaps. In some cases, the transients are so slow that the momentum balance collapses to the steady flow result and correlations for “pressure drop” suffice. Some transients appear to be dominated by the mass and energy balances, which are much easier to compute, as they deal with scalar quantities and the transfer from walls can be evaluated. In other cases, things may not be so simple. Because all the treatments of momentum balances are very rough approximations, it would seem a good idea to run sensitivity tests on all the coefficients, and perhaps on the structure itself, in these equations to explore if and when this makes any significant difference to safety conclusions and to provide explicit guidance for a user about possible problems or limitations.

In any case, it is not good for public confidence to have documentation that appears of doubtful validity to an informed observer.

<u>Nomenclature</u>:

A area
D diameter
F force
k loss coefficient
L length
p pressure
t time
v velocity
W mass flow rate

ρ density
τ shear stress
ψ angle defined in RETRAN

Bold symbols denote vectors or tensors

Subscripts:

a, b   Two pipes
e   energy
i   a general port or junction
s   from a side junction
w   at the wall
1,2   ends of the first pipe
2,3   before and after the junction
3,4   ends of the second pipe

References:

1. R. B. Bird, W. E. Stewart, and E. N. Lightfoot, "Transport Phenomena, John Wiley & Sons, New York, NY, 1976.
2. G. F. Niederauer, C. E. Peterson, E. D. Hughes, and W. G. Choe, "Application of RETRAN to Complex Geometries: Two-Dimensional Hydraulic Calculations," EPRI NP-1415, 1980.

COMMENTS ON EPRI RESPONSE TO RAIs AND OTHER RECENT SUBMITTALS CONCERNING THE RETRAN CODE
By ACRS Member Graham Wallis, February 25, 2001

ACRS reviewed the documentation of the RETRAN code in early 1999. On July 14, 1999, Dr. Wallis presented a critique of the momentum equations in RETRAN to the ACRS. During 1999 and 2000 the staff raised several questions concerning the momentum equations, both informally and as formal requests for additional information (RAIs). EPRI submitted responses to these RAIs on April 27 and October 22, 1999 and March 6, 2000. Additional written material was submitted by EPRI on February 15, 2001. On February 20, 2001 representatives of EPRI and their contractors met with the ACRS Subcommittee on Thermal-Hydraulic Phenomena at NRC headquarters in White Flint. At this meeting, EPRI agreed to reconsider the justifications of the momentum equations in RETRAN as well as the example problems illustrating their use for modeling specific components.

This document has been prepared to assist EPRI in identifying the major concerns of the ACRS and to facilitate their response. Since the uses of the momentum equations are pervasive in RETRAN, it is likely that some illustrations and derivations, resembling those cited in this report, have not been specifically identified. EPRI should therefore ensure that any proposed modifications or corrections to the RETRAN documentation and/or code content are comprehensively and consistently applied in any new versions.

Reference is made to the accompanying "Discussion on the Momentum Equations" prepared by Dr. Wallis.

REVISED DOCUMENTATION SUBMITTED WITH RAI RESPONSES

EPRI enclosed "Revision 5" [Reference 1] of their RETRAN documentation. The momentum equations are described in Section 3.

Figure II.3-1 shows a straight pipe, about which there is little disagreement.

Figure II.3-2 shows a bend. It is described as "a slight generalization." The bend looks rather gentle, but there is nothing in the text that says that the angle through which the flow is turned is small. No approximations seem to be made assuming

that the angle is small, so it appears that the method should apply to any bend, including a 180 degree one, for example. Section 3.1.2.1 is entitled "Constant Area Channels," yet the equations retain different areas A_k and A_{k+1} which appear later in the supposedly more general form Equation (II.3-27) which is written down with no additional explanation.

Equation (II.3-4) is the vector momentum balance. It should contain the resultant forces from normal and tangential stresses at the wall. Reference is made to Equation (II.2-34) to explain how the wall forces are divided up, but this equation (in Revision 1[Reference 2], which is what we have as the original basic document) only gives a very general form and does not explain the three terms appearing in Equation (II.3-4). F_{loc} later gets called the "form losses". It is presumably the resultant of normal stress components, because it gets combined with the surface pressures on the fluid surfaces later down the page. This combination does not help, as the components are later separated again.

"Assuming a uniform pressure along the surface within each region" to get Equation (II.3-7) is not useful because it throws out the important physics. If the fluid were subjected to uniform pressure, there would be no resultant force from that source. Even if true, it would not lead to the disappearance of the wall force due to normal stresses. In steady flow around a bend, the wall reaction is the force that turns the flow and enables the exit momentum to be in a different direction from the inlet momentum. This is especially evident for a 90 degree or 180 degree bend. When the flow accelerates, as in a transient, the wall force must also be considered. It is the only force providing the y-momentum change for a horizontal 180 degree bend with end faces in the x-direction, for example.

Equation (II.3-7) appears to be the component of a momentum conservation equation in the direction "i" and ψ is the angle between the directions k and i. The momentum fluxes are resolved in this direction. None of the friction forces, the gravitational forces or the pressure forces are resolved in this direction, therefore this cannot be the scalar component of a vector equation. Also, if this were based on a vector equation, the inertia terms on the left-hand side would have to be resolved in the chosen direction, so that the L's appearing in Equation (II.3-9) would have to be projected in that direction or redefined somehow.

The momentum flux terms contain different areas with subscripts k and k+1. The pressure terms do not. This is either an inconsistency or a sign of conceptual confusion.

The resultant of normal forces from the walls is omitted, though playing a key role in all bends that turn a flow through a significant angle.

The equation at the bottom of the page defines “a component of the volume centered flow.” Now, W is a scalar and does not have components. It is possible to define a variable by using the form at the bottom of the page, but it has to be used very carefully, as it has no direct physical interpretation and may well mislead (or itself be a symptom of misunderstanding).

(Many of these points were brought up in previous ACRS critiques of this work.)

Section 3.1.2.2 is entitled “Variable Area Channels.” Figure II.3-3 actually shows a very specific shape. It is analyzed in its one-dimensional form rather like the TP+J model discussed in the “Momentum Discussion,” though the figure should show two long pipes for this to be at all a good approximation. Equation (II.3-12) differs from the TP+J model in that the exiting momentum is resolved in the (mysterious) direction ψ which does not appear in the figure and should not be there if this is really a TP+J model. If this is supposed to be a momentum balance then all other terms, such as the pressure forces on the ends, must be resolved in this direction too. The gravitational terms should be resolved in appropriate directions along the pipe axes, and they are not, even if this is to be a TP+J model. This is another inconsistency. The equation is neither a true momentum balance nor representative of a true TP+J model but some sort of unjustified hybrid. The same is true of Equation (II.3-20), which is the more usual form of the RETRAN equation, containing those unusual “resolved” flow rates.

The idealization shown in Figure II.3-5 to represent “any junction” is so abstract and unexplained that it is hard to tell why it should be useful or how to use it without reference to worked examples. It seems unlikely that all configurations of interest can be forced into such a framework. There seems to be a leap of faith required to use Equation (II.3-27), which is merely a repetition of Equation (II.3-26).

It is stated that flow velocities are not necessarily normal to junctions, but have angles ϕ to them. This leads to discussions on Pages II-84 and II-85 of "Revision 5" in which the flow rates seem to be treated as vectors, which is unphysical. Figure II.3-5 is drawn with the end faces parallel to each other and normal to the direction "i" which seems to be defined by the junction around the middle of the picture. Are these features requirements of the model? What happens with less one-dimensional shapes? This figure is vague, and there is no derivation of the momentum equation for it, so there is really no way to check the validity of the result without looking at specific examples. However, it is probable that the momentum balance for a general control volume cannot always be idealized realistically in some arbitrary way like this.

Tee Example

The noding in Revision 5 is quite different from that in Revision 1. Does this mean that the "rules" for noding have changed in the code? How sensitive are the answers to the actual noding employed?

Equation (II.3-35a) is the x-direction momentum balance for the shaded volume in Figure II.3-7a. The contribution of W_4 in taking x-momentum out of the volume is ignored, though significant in reality, presumably because this flow is assumed to be all in the y-direction.

It seems to be being assumed that the zetas in Equation (II.3-28) are each 1/2. $W_{1,x}$(bar) (I can't figure out how to put a bar on the variable using this computer program, so I'll have to write them in) is set equal to $(W_1 + W_2)/2$. Because some flow is diverted to the side branch, it seems better to use $(W_1 + W_2 + W_4)/2$.

The use of $W_{1,y}$(bar) requires explanation as the flow appears to be perpendicular to the left-hand boundary of the control volume and not to have a y-component. Making it equal to $W_4/2$ is arbitrary and appears dubious. If one is going to reason this way, it should be considered that if only one half of W_4 comes in through the surface 1 (circled) then the other half must come in through the surface labeled 2 (circled) which is unlikely as flow is going out that way.

The arbitrary appeal to "applying the assumptions of steady-state conditions" is odd since the whole point is to develop methods for transients. Even more confusing is

the expression for “volume centered flow” at the bottom of the page. It doesn’t appear later, but would it somehow be used in the transient term in the momentum balance if this were to be shown in Equation (II.3-35b)?

Since $A_1=A_{2,}$ there is no need for two areas in Equation (II.3-35b). The loss term is presumably quite small, if evaluated for the steady flow going straight through from 1 to 2. If some flow goes out the side branch, then it will influence the losses. Then, e_2* must depend on W_4.

The momentum flux term for area 1 is incorrect in Equation (II.3-35b). If $W_2=0$ and flow is steady, then $W_1 = W_4$. The flow coming into the control volume is W_1; therefore, the first momentum flux term should not have the 4 in the denominator. This correction would make $p_2 = p_1+ W_1^2/\rho_1 A_1^2$. But this answer defies Bernoulli’s equation, if the fluid is inviscid and incompressible, which states that the maximum pressure rise is one half of this at the stagnation point somewhere on surface 2. The average pressure at 2 must be less than this maximum pressure. In reality a significant x-direction momentum is carried out of the cell by the flow W_4 , reducing the predicted pressure rise at 2 to reasonable values. This important physical mechanism is ignored in Equation (II.3-35b)

The sign of the term in square brackets in Equation (II.3-35a) and Equation (II.3-35b) is the opposite of what it is in the original general Equation, Equation (II.3-26).

Equation (II.3-36a) is odd. It cannot be the y-component of a momentum balance because the pressure acting on surface 1 is in the x-direction while that on surface 4 acts in the y-direction. The subscript ψ is supposed to signify the component in some specified direction (here unspecified). If ψ is y, as implied, then we should be multiplying W_1 by $W_{1,y}$ in the first momentum flux term and not getting a factor of 4 in the denominator in Equation (II.3-36b) but a factor of 2. The second momentum flux term does seem to correspond to a y-direction flux, but it is unclear why the “assumption of steady-state conditions” can be used in a transient.

The sign of the term in square brackets in Equation (II.3-36a) and in Equation (II.3-36b) is wrong. The area A_2 in the square brackets in Equation (II.3-36b) should be A_1.

If this were a real momentum equation in the y-direction, p_1 would not appear, but the forces on the bottom and top walls in the y-direction would have to be evaluated. There is also flow out of the 2 face; presumably it is assumed to carry no y-momentum, though the flow across the 1 face was assumed to have this capability.

This Equation cannot be an example of the TP+J approach because the control volume has three connections to the outside world and cannot be modeled by two pipes. In any case, the pipes are not "long" by any means, and that is the condition needed for this approximation to be good.

It is actually not easy to derive a valid transient motion equation for this control volume. It cannot be analyzed using the overall "momentum equation" because of wall forces, and it does not conform to a simplified model, such as the TP+J case. It really needs to be modeled by some special method, such as running a CFD code and/or conducting experiments and fitting the results for a range of flow splits (main branch versus tee-branch) with an empirical "three-port" model. However, this does not excuse what appear to be conceptual errors in the RETRAN documentation.

Elbow Example

At the bottom of Page II-91, the "steady-state assumption" appears to be being used. This obscures the understanding of how the method is to be used to represent a transient. It would help if Equation (II.3-37b) included the transient term so that we could see how it is to be evaluated (e.g., what L's and W's are to be used). This is not clear from any description in the text.

This solution has changed from the previous version in Revision 1. In that case, the second momentum flux term was evaluated as the square of $W_{2,x}$ so that the factor in the denominator in Equation (II.3-37c) was 4 and not $2\sqrt{2}$. Neither version reflects the physics. If this is a TP+J model (how does that work for a bend?), then the factor should be 1. If it is a momentum balance in the x-direction, then the total flow, W_2, should be multiplied by the velocity component in the x-direction, giving a factor of $\sqrt{2}$ in the denominator. In this latter case, the pressure force on the surface 2 would have to be resolved in the x-direction and the reaction from the wall somehow determined and resolved in the x-direction too.

The “flow rates in the x- and y- directions” in the middle of Page II-93 appear contrary to any physical interpretation. If some sort of numerical interpolation is going on, it does not seem to correspond even to the simple situation in which the flow rate in the pipe is constant, as in steady flow. The “magnitude of the volume-averaged flow” likewise cannot be $1/\sqrt{2}$ times the steady-state flow and there is no reason to make this the case in unsteady flow either.

Why are A_1 and A_2 being retained when the pipe has a constant cross-section? If it does not, then the pressure forces need to be multiplied by different areas if a true momentum balance is being performed.

If Equation (II.3-37c) is evaluated for constant area and steady frictionless flow, it turns out that there is an artificial pressure recovery in the bend because the first term on the right-hand side is bigger than the second. One would expect the pressure to stay constant. During the February 20, 2001 meeting, EPRI claimed that this did not matter much as this pressure recovery was canceled out by the pressure loss in the second half of the bend. This is not necessarily so. If the angle ψ for the second part of the bend is chosen in the same way as for the first part of the bend, being in the direction of the inlet face, then the same artificial pressure recovery occurs. In a coil of several 360-degree bends, this pressure could be used to build up as much pressure as desired and create a “pump” with no energy input.

In the previous paragraph, it was shown that the answer depended on the choice of the arbitrary angle ψ . This appears to be a general fault with the “vector” RETRAN momentum equation. One can change the momentum flux terms, without changing anything else in the equation, just by changing ψ and resolving them in a chosen direction. For frictionless steady flow in a bend, for example, the pressure difference can be made to take any value between some positive and negative limits, depending on the user’s choice of ψ. This is a very undesirable feature of what should be a deterministic method.

Wye-Junction Example

Dr. Wallis’ presentation to the ACRS in 1999 also included similar critiques of the way in which the wye-junction was analyzed in EPRI NP-1415 [Reference 3], which is the twenty-year old report out of which the present RETRAN documentation evolved. The conceptual problems appear similar to those

described above, though more extensive, partly because of the "cross-momentum" effects when flow crossing a surface introduces or removes momentum with a component in a direction parallel to the surface. If the documentation is to be modified to respond to the above points, then that example should probably also be corrected.

The Porsching Paper (The "old" one, dated October 15, 1999 [Reference 4], that came with the RAI responses)

This paper appears to be an attempt to justify the form of the RETRAN equation, such as Equation (II.3-26), apart from the "loss" terms.

Perhaps the first thing to note is that Porsching's Equation (10) is not compatible with Equation (II.3-26). Equation (10) is a momentum balance for the control volume, whereas the RETRAN equation is not. Dividing Equation (10) by A_o we find that the momentum flux terms have A_1A_0 and A_2A_0 in their denominators and not A_1^2 and A_2^2 as in Equation (II.3-26). The latter resembles the TP+J form, except for the (inappropriate) resolution of the momentum flux terms in the direction ψ. The RETRAN momentum flux terms are neither correct from the TP+J viewpoint nor from the "momentum balance resolved in a chosen direction" viewpoint. They are an invalid hybrid form.

The momentum flux terms in Equation (II.3-10) only have the same denominators because for this example all the areas are the same. The form in Equation (II.3-26) and Equation (II.3-27) has no physical basis, nor is one provided in the text.

Porsching's Equation (4) is acceptable if one is careful about the integration that enables the volume integral of momentum to be expressed in terms of an average flow rate across slices perpendicular to $\mathbf{n_0}$ throughout the volume. This is not spelled out in the paper. If the flow is incompressible or steady and the ends S_1 and S_2 are parallel to S_0, W_0 can be related to the flow rate across the particular surface S_0, but this is probably not possible in general. It is not correct that L_0 in Equation (4) is equal to V_Ω / A_0 for the incompressible or steady flow cases. It should be equal to the physical distance between S_1 and S_2 in the "0" direction, if the ends are perpendicular to this direction. Otherwise there are corrections for the pieces of volume that involve partial slices parallel to "0" that intersect the end faces. In a compressible or multiphase flow, it is quite possible for the flow rate across other

surfaces in the volume to be unrelated to that across S_0 so that L_0 in Equation (4) becomes a variable that is dependent on all the details of the flow. In any case, something like Equation (4) may be acceptable as an engineering approximation if careful definitions and restrictions are specified.

Porsching's Equation (5) is also in the form of a common engineering approximation. The final step in that equation is not exact, any more than the square of an average value of something is equal to the average of the square of something. This is well known in fluid mechanics and is the basis of correction factors for the momentum flux in a pipe with a velocity profile, for example. However, Equation (5) and the resulting Equation (6) are usually acceptable as engineering approximations which might require reevaluation if the velocity profiles are far from uniform.

The major error, or at least misleading derivation, in the Porsching paper concerns the pressure term in Equation (10). The integrals in Equation (7) are over all the areas of surfaces to the left and right of S_0. They include the walls of the duct as well as the areas for flow, S_1 and S_2. It is usual to separate out the net pressure forces on the flow areas, i.e., the ports or junctions connecting to other volumes, and the net pressure force on the walls. Porsching's mathematics in Equation (7) defines p_1 as the average pressure on components of surface in the "0" direction over both the area S_1 and all the area of duct walls on the left hand side of S_0. Physically, this has the effect of combining the forces on the fluid area and on the wall area into one average pressure times a reference area A_0. The quantities p_1 and p_2 used in RETRAN are averages over the fluid areas alone and are quite different from Porsching's average pressures in his Equation (8). Similarly, the pressures used by Bird, Stewart, and Lightfoot [Reference 5] in Porsching's Equation (13) are averages over the fluid areas and are quite different from those in Equation (8).

<u>New Material Submitted by EPRI on 2/15/01</u>

This consists of a letter from Lance Agee, a "new" paper by Porsching [Reference 6] (dated April 18, 2000), and a further revision (5b) to part of the RETRAN documentation. The letter claims that the concerns were suitably addressed in the RAI responses and by the Porsching papers. As mentioned above, they do not remove ACRS concerns and rather serve to reinforce previous conclusions.

The new version of the documentation addresses the momentum equation for a bend, illustrated in Figure II.3-2.   There is nothing about the bend being slight. Indeed the method is later applied to a 90-degree bend.

Here, for the first time, the authors consider the resultant of normal forces on the wall. [Actually also friction, if one wants to be exact. It is not true that the net friction and form forces are all taken care of by the steady-state pressure gradient, as claimed. A proper momentum balance for a general shape in steady flow will show that the net frictional force on the wall and the normal stresses associated with "form losses" do not just "balance the pressure difference" because the end forces have to be multiplied by the corresponding areas and resolved like vectors, while the pressure change does not. This is part of the continuing confusion in RETRAN between a true momentum balance and a "pressure difference" that crops up in a Bernoulli-like or "mechanical energy" or TP+J equation. To demonstrate this, consider a 180-degree bend of constant cross-section, with an incompressible fluid flowing through it in steady flow. The resultant of the wall shear stresses is in the diametral direction (0 degrees to180 degrees) while the pressure forces on the ends reinforce each other (rather than being in opposition) and act in the 90-degree direction, being balanced by the wall forces in that direction. The idea that friction forces and form losses balance pressure drop in the momentum equation is naïve and based on extrapolation of experience with a straight pipe].

There is an S_{tot} on the integral in Equation (II.3-5). Equation (II.3-5a) breaks this down into forces from the end faces and from the walls. Equation (II.3-6a) is similar to the derivation in the "old" Porsching paper. In this equation, the p_k and p_{k+1} are not average pressures over the junctions but are averages over the entire surface of the control volume including the walls. They are quite different from the average pressures over the ends. The math from Equation (II.3-6b) to Equation (II.3-6e) is essentially the same as was used by Porsching ("old" paper), except that in his more general case, the A in Equation (II.3-6e) would have the subscript 0. Equation (II.3-7) is essentially Porsching's Equation (10) with no allowance for the different subscripts on the areas, which confuses its later modification to a form in which the areas of the inlet and outlet and some characteristic area (A_0) of the volume are all different. (The earlier version of this derivation, Revision 1, contained an upstream area A_k and a downstream area A_{k+1}. These multiplied the

corresponding pressures in the momentum balance, Equation (II.3-9) but were not resolved in the direction ψ. These area factors were made to disappear in Equation (II.3-10) of Revision 1, the "RETRAN equation," by making the areas equal and dividing the equation by the area. When the areas are unequal this cannot be done and the RETRAN equation does not result. It is even stated in Revision 1 that Equation "(II.3-10) is valid only for the case of flow in a channel of constant cross-sectional area."

At the presentation on February 20, an argument was advanced that the pressures could be assumed to be uniform in the two regions before and after the "junction." In this case, there is no need to perform the integrations between Equation (II.3-5a) and Equation (II.3-6e). ACRS consultants opined that such sweeping assumptions in effect throw out the major physical phenomena and should not be made. In a more mathematical sense, there is no direct relationship between the average pressure over a volume and the average pressure over the surface area surrounding that volume. As an example, the force from the walls that turns the flow in a bend reflects the difference in the pressure forces on the inner and outer sides of the bend. If one applies the volume-average pressure over the whole surface, there is no force to prevent the flow from continuing straight ahead.

In sum, the critique of Porsching's "old" paper outlined above appears to apply equally well to the newest attempt to justify the RETRAN equation, albeit in a simplified form. Average pressures of various sorts should not be mixed up. There is also a sleight of hand in deriving a result in which all areas are equal and later generalizing it to cases where they are not.

The new Porsching paper (April 18, 2000) appears to recognize two of the basic problems outlined in the "Discussion," but his resolution of them seems inconclusive, merely suggesting that some sort of engineering approximation might be found.

His Option 1 is the old story. Equation (19) is the former Equation (10) with all the previous faults. The pressures appearing there are averages over the entire surface and not just over the ports or ends.

Option 2 is a new variation that appears essentially the same, but seems to involve resolving the total areas on each side of A_0 into two arbitrary directions. It is not clear how this helps to get rid of the net force from the wall (it is physically real and

cannot be excluded from a macroscopic momentum balance by mathematical juggling).

It is unclear if there is a problem with the orientation of surfaces, as discussed under “Remarks.” The area A_0 is equal to the area of any closed surface built on it, to the right or left, as long as one keeps track of the vector nature of surface elements. These surfaces can have any number of folds and wrinkles. That is not the problem.

Equation (26) seems to face up to the real problem. The total pressure force on one side is made up of the contribution from the walls and that from the end. The average pressure on the end is defined in Equation (27) as p_1 with a bar on it, recognizing that it is distinct from the p_1 that appeared in Equation (19). The effort now becomes to make the wall force, the last term in Equation (28), go away somehow. This is acceptable for a straight pipe [Case (a)], and perhaps as an approximation for a pipe with a slight bend or wrinkle in it [Case (b)]. But there is no justification for neglecting the term in general and none seems to be offered.

Section 2 of the “Remarks” admits another fundamental problem, how to relate the various W’s to each other. However, there appears to be nothing definite in this section that resolves the problem, just a discussion of how “averaging’ might be the way to do it.

RAI 1

This refers to Attachment 2 and is concerned with explaining how the RETRAN momentum equation applies to nodes of more complex shapes.

Figure 1 shows a straight pipe and is useful for defining the staggered grid approach and nomenclature.

Equation (3a) is said to be the ”one-dimensional mixture momentum equation.” As it involves two different areas, it cannot be a momentum balance equation because the pressure terms in Equation (3a) do not multiply areas. It must apply to a different shape than in Figure 1, probably a tapered pipe or two pipes joined together. It resembles Equation (9) in the “Discussion,” the “two-pipe-plus-junction” model (TP+J), yet does not contain the 1/2 ρ v^2 terms and does not

reduce to Bernoulli's equation (as it must) when there is no friction. So, this seems to be an equation that does not conform to any known pattern.

On page 5 (about the middle of the page), there is mention of "the component of the volume average flow which lies in the direction of the momentum cell." Now, there is no component of a scalar quantity like W, so it is unclear what this means. It is also uncertain what the "direction of a momentum cell" is when it has multiple inlets and exits or a complex shape.

The shapes shown in Figure 2 should be very useful for checking what the RETRAN momentum approach actually implies. "Junction 2 Cold Leg to Downcomer" is a bend, a classical sticking point for use of momentum conservation. Equation (5) is to be applied. It more closely corresponds to the TP+J model mentioned in the "Discussion" but (only) the momentum flux terms are resolved in a chosen direction. $W_{k,\psi}$ is said to be the "component (of the flow) that lies in the direction of the junction." As W is a scalar, it is unclear what this means and one has to look at the examples to figure out how to interpret the concept.

Tables 1 and 2 are intended to explain things. From Equation (3) and Equation (5), it appears that the W's with bars over them describe the flows at the boundaries of the momentum cells and the W's without bars are the flow rates in the cells that are part of the inertia term on the left hand side of the "momentum equation." What is meant by a "junction" is less clear, since the momentum and mass cells have different (staggered) boundaries. It looks as if the idea is that the numbers without circles on them in Figure 2 label "junctions" while the circled numbers label "volumes," so these must be the mass and energy nodes that are being described. (It looks as if the 1 above the cold leg in the lower figure should be circled.) These roles are reversed for the momentum cells.

The sketches at the bottom of Figure 2 help to show how the momentum cell is drawn. It appears that one takes a junction, such as 3, and adds together about one half of the volumes 2 and 3 (circled) in each side of it. In this way a piece, such as the top of the lower plenum, forms part of more than one momentum cell, as in the central and right-hand figures. The bottom part of the lower plenum apparently forms part of nothing and might as well not be there as far as the momentum balances go. It is difficult to relate these cells to the "generalized control volumes" on Page II-82 as that would seem to make the flow come out of the bottom of the

volumes in Figure 2 and go into the bottom of the lower plenum with no way to get out. The specific examples do not seem compatible with the "generalized" approach.

Tables 1 and 2 are baffling, apart from the directions associated with the arrows drawn at junctions which appear in the second column in Table 1. Because the momentum cells are staggered from the others, the momentum flux terms at the boundaries of a momentum cell do not correspond to these "junctions" but should be evaluated at the boundaries of the shaded volumes in the lower figures, where the Ws have bars and the "junctions" have circles. The Tables appear to contain a mixture of what appear to be Ws to be used to evaluate flux terms for the uncircled junctions and Ws to be used to describe the average momentum in the circled ones. The text below Table 1 states "The momentum flux terms are evaluated using the averaging model for the volume centered flows, where the volume centered flow is the arithmetic average of the inlet and exit flows." There is no explanation of how averaging led to the entries in Tables 1 or 2. "The actual equations implemented in RETRAN-3D to perform this task are given in Appendix A," but it is no help because it is not explained how the general equations are applied to the particular example.

It would be very desirable to have the actual momentum equations deduced from these tables presented in full. It should also be made clear what the specific values of all the terms actually are and how they are evaluated. This would help to clarify the procedures to be applied by a user and to remove ambiguities that remain in the present definitions and methods. It would additionally make it possible to evaluate the reasonableness of the results, as was done above for the bend and tee-junction.

Describing what appear to be some of the ambiguities and uncertainties with the existing documentation may help EPRI to respond more fully. For example, the W_k and W_{k+1} terms with bars are defined to be the flow rates into and out of a momentum cell. They seem to be resolved into a direction ψ, though scalars cannot be resolved. In Table 1, it seems that at Junction 2 W_2 goes in and $1/2W_2$ comes out. This does not correspond to any identifiable cell in Figure 2. One-half of W_2 is not the flow into or out of any region. One-half is not the cosine of any angle of relevance to the situation even if flows could be resolved. In the next line, Junction 3 has $1/2\ W_3$ going in and nothing coming out. This is probably another

example of the "interpolation" that gave strange results that defied the concept of continuity in the bend example.

In any case, there is no indication of how these values might be incorporated into the momentum equation for the shaded region called "Junction 2, cold leg to downcomer" in Figure 2. There is also no discussion of how to evaluate the "L" factor in the transient term and what appropriate "W" to use there. Therefore, this example does little to help the user understand the approach.

The text on Page 10 does not help either. If steady state conditions are assumed so that "W_1=W_2=$W_{3,}$" then how is this compatible with a "transient" analysis? Why is W_1 with a bar "simply W_2" and not something like (W_1+ W_2)/2? Flow rates do not have components so how can x- and y- components be defined, and how can they be deduced to be 1/2 W_2 which seems physically unreasonable?

The average orientation of the shaded volume is called theta and said to be 315 degrees (not a volume average) but this is not the same as ψ and anyway there is no theta in equation (5) so it is unclear what this is to be used for. At the end of the discussion of Junction 2 on Page 10 it is said that the factor 1/4 arises because of angular effects. Now, remember that the TP+J model is a scalar model (see the "Discussion") and the ρv^2 terms do not have to be "resolved" any more than the pressure terms do, so there are really no "angular effects" if this model is being used. During the meeting on February 20, a few examples were given to show how these hypothesized "angular effects" could give rise to significantly different results, for example at the tee-junction between the surge line and the hot leg, that might influence flow distribution during a transient.

Looking briefly at the other examples involving the lower plenum, it is unclear why the Junctions 5 and 6 are said to have no momentum flux when they have flows through them, why W_5 plays no role, and how W_4 can describe the momentum in the sum of the two shaded partial volumes for volume 4. In Table 2, it looks as if Volume 3, presumably the momentum cell around Junction 3, has no momentum in it; why? What pressure terms are to be used to describe Junctions 3 and 4? They have four boundaries that connect to regions containing other fluid. Equation (5) only has two pressures in it.

In reality, the lower plenum part of the reactor vessel is like a turbine bucket that turns the flow coming down out of the downcomer around in the direction of the core. A momentum balance would have to include the force from this structure. If, on the other hand, this is to be modeled as a TP+J, so that Equation (9) in the "Discussion" can be used to describe it, then it is unclear how the shaded volumes as drawn can be forced into such a conceptual framework. The various sketches of "general" volumes, such as Figures II.3-5 and II.3-6, do not help explain either the basis of the general RETRAN equation or how it is used to analyze a case like this.

<u>References</u>:

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3. G. F. Niederauer, C. E. Peterson, E. D. Hughes, W. G. Choe, "Application of RETRAN to Complex Geometries: Two-Dimensional Hydraulic Calculations," EPRI NP-1415, 1980.
4. T. A. Porsching, "A Scalar Macroscopic Momentum Balance for Multi-dimensional Fluid Flow," October 15, 1999.
5. R. B. Bird, W. E. Stewart, and E. N. Lightfoot, "Transport Phenomena, John Wiley & Sons, New York, NY, 1976.
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