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Prof. Ivan Catton, Chairman
ACRS Subcommittee on
Thermal Hydraulic Phenomena
48-121 Engr. IV
University of California
at Los Angeles
Los Angeles, CA 90024-1597

Dear Prof. Catton:

Subject: Comments regarding the January 4-5, 1994 Meeting of the Thermal Hydraulic Phenomena Subcommittee of the ACRS, Review of RELAP5 T/H Computer Code, Bethesda, MD.

Enclosed are my comments on the subject meeting, written in response to your request at the end of that meeting. I have organized the comments in the order of the topics on the agenda.

It appeared to me that INEL was not prepared for the meeting, and I wonder whether the staff may have been forced into the position of defending indefensible work. I was very much impressed by the outstanding, three-part presentation of Mr. Kelly.

I hope that these comments are helpful. Please let me know if I can be of any further help.

Sincerely yours,

Wolfgang Wulff

Wolfgang Wulff

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1. **Modeling Issues** (R. Beelman)

1.1 There is no connection made between

(a) the ranking of important AP-600 phenomena in PIRT,

(b) the phenomena listed in PIRT and addressed in the experiments of the test matrix,

(c) the phenomena listed in PIRT and addressed by the planned instrumentation, and,

(d) most importantly, the phenomena listed in PIRT, and the phenomena to be modeled in the AP-600 version of RELAP5.

Aside from unsubstantiated claims that there is such a connection, there is nothing to show this connection. There are three test facilities supporting AP-600 licensing. Their test matrices and their instrumentation plans should be completed to show, how the high-ranking phenomena are addressed for code development on the one hand, and for code assessment on the other.

INEL should complete their list of "Currently Identified ALWR Models", to show which models address which high-ranking phenomena, and that all identified high-ranking phenomena are being addressed in RELAP5.

1.2 The "cross-flow model" in RELAP5 is in principle unable to predict two-dimensional flow in the downcomer and asymmetric flow distribution in the upper downcomer and upper plenum, because (a) the momentum balances are only one-dimensional and (b) the momentum balances lack the term for fluid internal shear, i.e. lateral turbulent momentum exchange due to lateral velocity gradients. The lateral exchange of turbulence in free spaces is not governed by the balance of pressure gradients, stream-wise and lateral wall shear.

The model described in Volume 1 of the RELAP5 documentation is intuitive, its assessment in the past is obfuscated by compensating errors (wall shear adjustments, for example).

2. Modeling of IRWST (D. Fletcher & W. Terry)

2.1 Cross Flow Pool Boiling Heat Transfer: On Fletcher's Viewgraph No. 11, the superposition of heat transfer coefficients has the wrong limit for $\alpha \to 0$.

2.2 The purpose of the planned sensitivity study for non-ADS transients is defined on Fletcher's Viewgraph No. 18: The reactor coolant system temperature variation is sought, as caused by the variations of the "pool-side boundary conditions" listed on the same viewgraph.

Clearly, this temperature variation is completely dictated by the variations of PHRH mass and enthalpy flow rates at the IRWST exit. One needs to vary only these two parameters to determine the associated coolant temperature variation. It is not clear that even that determination requires the RELAP5 code.

The thirty planned RELAP5 code calculations, estimated to take three months (as stated during the presentation), appear to be a waste of resources. All that the IWRST pool-side boundary conditions can affect, is the above exit enthalpy flow rate. Only steady-state calculations are needed for the bracketing sensitivity study pertaining to PRHR operation. The variation of the exit enthalpy flow rate can be computed for the listed parameters WITHOUT A CODE! Use some spreadsheet program and get done with it in a week!

2.3 IRWST plume modeling: INEL needs to acquire a basic background knowledge in standard boundary layer analysis, and to find out what governs the axial growths of boundary layer thickness, of displacement, momentum and energy thicknesses [Schlichting, 6th ed. p. 147]. Helpful references on buoyant plumes are: B. R. Morton, G. I. Taylor and J. S. Turner, Proc. Roy. Soc. (London) A234, 1 (1956); B. R. Morton, J. Fluid Mech. 8, 611 (1960); M. P. Murgai and H. W. Emmons, J. Fluid Mech. 8, 611 (1960); S. L. Lee and H. W. Emmons, J. Fluid Mech. 11, 353 (1961); H. J. Nielsen and L. N. Tao, Tenth Symposium (International) on Combustion, p. 965, The

Combustion Institute, (1965); J. R. Huntley, M.S. M.E. Thesis, Georgia Institute of Technology, (1972).

The boundary layer equations must be derived by standard integral methods, but starting with two-phase flow equations (mixture equations, i.e. drift flux equations, are recommended). One must eliminate small terms, based on the ratio of lateral to stream-wise dimensions being small. This leads to the boundary layer equations, which must be integrated along the lateral coordinate axis, to obtain the ordinary differential equations for the plume. INEL claims to model two-phase flow, yet they present only single-phase equations.

The axial variation of plume radius (or flow cross-sectional area) is determined by the balance equations and cannot be imposed, without contradicting the balance equations. A radial distribution of axial velocity can be imposed, and the useful choices are discussed in the above literature.

3. CMT Modeling (G. Johnsen)

3.1 The liquid-to-wall heat transfer coefficient on Viewgraph No. c027-rbn-1293-023b is incorrect; it must be computed with fluid thermophysical properties at $T_w + ½(T_w - T_\infty)$.

3.2 The heat transfer coefficient for the liquid side, "$(H_{if})_s$ is inappropriate for the conduction-controlled heat flux.

3.3 INEL needs to explain why they have compared RELAP5 results with seven measurements from G.E. Level Swell experiments, but not with level swell ($Z_L(t)$) measurements. What is wrong with the RELAP5 Z_L-predictions, that they cannot be shown?

INEL's claim that "most models appear applicable" to CMT simulation is premature.

4. Level Tracking (G. W. Johnsen)

<u>4.1 General Comments:</u>

4.1.1 The level <u>appearance</u> criteria presented by G. Johnsen are identical to the level <u>existence</u> (or locating) criteria previously published as part of INEL's "Vertical Stratification" model (see draft report, RELAP5/MOD3 Code Manual, Vol.4, p. 3.2-13). These criteria had been developed earlier for predicting the appearance of mixture levels in the interior of the core, during the blow-down phase of a Large-Break LOCA. They are based only on intuition.

INEL should select physically based level appearance and disappearance criteria for AP-600 components, where the levels either exist under normal steady-state conditions, or appear during the transient at the top of a vessel (CMT), at the time of steam valve openings, for example.

4.1.2 The ongoing implementation effort for the level tracking model should be discontinued, until it becomes clear which of the assumption made by G. Johnsen in his presentation, are in fact part of the level tracking model. The restrictions inherent in Johnsen's "consistency proof" (explicit as well as tacit assumptions) would limit the model's application to completely inconsequential transients, namely to transients with (for bases see 4.2.3 and 4.2.4 below):

(a) <u>time-invariant</u> volume-averaged void fractions $<\alpha>_{i-1}$ and $<\alpha>_{i+1}$ in the computational cells upstream and downstream of the cell which contains the mixture level.

(b) vapor void fractions α <u>independent of elevation z</u> in the cells adjacent to the level elevation Z_L; specifically, three void fractions, namely the one just below the level, $\alpha(Z_L^-)$, the one at the entrance to cell j with the level, $\alpha(z_{j-1})$, and the volume-averaged void fraction of the upstream cell (j-1), $<\alpha>_{j-1}$, all must be equal; three more void fractions, namely the one just above the level, $\alpha(Z^{+}_{L})$, the one at the exit from the cell j with the level, $\alpha(z_j)$, and the volume-averaged void fraction of the downstream cell (j+1), $<\alpha>_{j+1}$, must also be equal.

(c) no phase change Γ in the cell j which contains the mixture level.

(d) with constant vapor density; since the vapor below the level follows the saturation line, this implies time-invariant pressure.

Thus the model presented by INEL might be limited to the motion of only those levels which separate single-phase liquid from single-phase, incompressible gas, i.e. the only situation where the vapor void fraction and the vapor density are independent of space and time. The model does not take into account phase change, nor the kinematics of void propagation. There is no relevant reactor transient where these restrictions apply.

INEL's model for level tracking violates, according to the presentation, in a quantitatively significant way, first principles of physics, the rules of differential calculus and consistency with the vapor mass conservation equations in RELAP5. Any attempt at validating this model by experiments is futile.

4.1.3 Johnsen attempted to connect his "equation for the level motion", i.e. the second equation on Viewgraph CCMGJ09, with the correct equation of level motion, i.e. the last equation on Viewgraph No. CCMGJ16. The attempt failed, because (see 4.2.3 and 4 below):

(i) the derivation is in conflict with INEL's algorithm for level tracking; Equations (3) on Viewgraph No. CCMGJ15 violate the first two equations on Viewgraph No. CCMGJ08, since the volume averaged void fractions $<\alpha>_{i-1}$ and $<\alpha>_{i+1}$ are obtained in RELAP5 from transient vapor mass balances; they are computed as functions of time.

This conflict is at least one reason for INEL's compulsion for introducing the normally unnecessary "Bounding Limits".

(ii) the standard rule of calculus for differentiating integrals (Leibniz Rule) was ignored.

(iii) the wrong vapor mass balance has been used; the vapor generation term Γ/ρ_v and the vapor compressibility terms were omitted.

The nomenclature of the derivation shows that the distinction has been ignored between local and volume-averaged values of void fraction (notice that ignoring is not the same as neglecting on the basis of a quantitative argument of irrelevance!). Error estimates are needed to justify the implied deletion of void fraction differences.

The attempt of showing that the second equation on Viewgraph CCMGJ09 is equivalent to the last equation on Viewgraph No. CCMGJ16 reveals a shocking disintegration of minimal professional acceptance standards.

4.1.4 INEL should explain why they did not implement directly either the first equation on Viewgraph CCMGJ09, or the last equation on Viewgraph CCMGJ16; the latter being the equation that Johnsen so strenuously tried to match with his ill-fated Equation (2). When asked, Johnsen could not tell of any reason for not using the real thing directly.

INEL needs to clear up the confusion generated by Johnsen concerning the actual model in RELAP5: Is the level motion computed by the second equation on Viewgraph CCMGJ09 or Eq.(4) on Viewgraph CCMGJ15. If the latter is "consistent" with the former, why would INEL integrate the more complicated former one?

INEL should also complete their model description and address the continuity issues raised below in Item 4.2.5.

4.1.5 The NRC has funded level tracking model development intermittently for over ten years, in at least three laboratories (Pressurizer and Steam Generator levels in PWRs, Downcomer level in BWRs). Funding and time limitations are no plausible excuse for still not having a valid level tracking model implemented in RELAP5. The NRC needs the capability to review and assess the acceptability of the models that are developed by their contractors.

4.2 Specific Comments:

4.2.1 The first equation on Viewgraph CCMGJ09 is correct if and only if the three vapor void fractions in that equation are volume averages. One void fraction, $\langle\alpha\rangle_j$, is averaged over the entire cell j. The other two are averaged over the cell portions above and below the moving level:

$$\langle\alpha\rangle_j^+ = \frac{\int_{Z_L(t)}^{z_j} \alpha dz}{z_j - Z_L(t)}, \quad \langle\alpha\rangle_j^- = \frac{\int_{z_{j-1}}^{Z_L(t)} \alpha dz}{Z_L(t) - z_{j-1}}$$

One would conclude from the nomenclature that INEL is not aware of this and the following consequences:

RELAP5 computes (I hope!) the time rate of change of vapor mass in the entire cell (control volume), that contains the level, in terms of the vapor generation rate in the same cell and the vapor mass flow rates at the boundaries of the same cell. Whenever the first two equations given at the top of Viewgraph CCMGJ08 are invoked in conjunction with the first equation on Viewgraph CCMGJ09, then the time rate of change of vapor mass in the entire cell, that contains the level, becomes dependent also on the vapor mass fluxes across the remote boundaries of the neighboring cells and some vapor mass generation outside the control volume. This modeling conflict forces INEL to impose "Bounding Limits".

INEL should be required to determine by hand calculations whether a result is unexpected because of a conflict with conservation principles, discretization error or word length limitation of the computer, before they are permitted to impose "Bounding Limits" in the code. The bases for each "Bounding Limit" must be part of the code documentation.

4.2.2 The differentiation of the first equation on Viewgraph CCMGJ09, a static equation, for the purpose of getting a transient equation makes no more sense than the differentiation of a steady temperature distribution would make for the purpose of getting the transient conduction equation.

If INEL's model for level tracking is given by the second equation on Viewgraph CCMGJ09, then this question arises: What in the world can INEL expect from differentiating the first equation on Viewgraph CCMGJ09 analytically with respect to time, and then integrating the result numerically with respect to time? The best they could expect, without introducing some indefensible hocus-pocus, is the same equation they started out from, plus an unknown constant, which had to be set equal to zero, if the original equation had been valid.

4.2.3 Assumptions (3) on Viewgraph CCMGJ15 violate the first two equations on Viewgraph CCMGJ08. Assumptions (3) are therefore unacceptable. Recalling the conflict noted in Item 4.2.1 above, there may be two internal conflicts rendering the model, given by Eqs.(2) or (4) on Viewgraph CCMGJ15, worthless.

The two derivatives, that are arbitrarily set equal to zero, are of the same order of magnitude as the derivative that is retained; in fact, the cell-averaged void fraction $\langle\alpha\rangle_j$ is the sum of the void fractions $\langle\alpha\rangle^{+}_{j}$ and $\langle\alpha\rangle^{-}_{j}$, each weighted by its associated fraction of cell height. There is absolutely no defense for this cavalier and self-serving elimination of two inconvenient terms, and the retention of one convenient term.

INEL needs to state first the full vapor balance equation and then justify, on a quantitative basis, the deletion of every term that they ignore. Anything less is unprofessional. For the cell portion below the level:

$$\frac{d\langle\alpha\rangle_j^-}{dt} = \frac{j_v(z_{j-1}) - j_v(Z_L^-)}{Z_L - z_{j-1}} + \langle\frac{\Gamma_v}{\rho_v}\rangle_j^- - \frac{\langle\alpha\rangle_j^- - \alpha(Z_L^-)}{Z_L - z_{j-1}}\frac{dZ_L}{dt}$$

$$- \frac{1}{Z_L - z_{j-1}}\int_{z_{j-1}}^{Z_L}\left[\alpha\frac{\partial\rho_v}{dt} - j_v\frac{\partial\rho_v}{dt}\right]\frac{dz}{\rho_v} \quad .$$

A corresponding equation applies to the cell portion above the level.

4.2.4 The vapor mass balance, Equation (5), is also wrong, because two important terms are missing, neither of which will tend toward zero as the cell size tends to zero. The two terms arise from vapor generation and vapor compressibility.

$$\langle\frac{\Gamma_v}{\rho_v}\rangle_j - \frac{1}{z_j - z_{j-1}}\int_{z_{j-1}}^{z_j}\left[\alpha\frac{\partial\rho_v}{dt} - j_v\frac{\partial\rho_v}{dt}\right]\frac{dz}{\rho_v} \quad .$$

It is obvious that INEL did not start out from the standard vapor mass balance and that they did not apply standard rules of calculus, to arrive at Eq.(5) on Viewgraph No. CCMGJ16. It is also quite obvious from inspection of the above two terms, and from Item 4.2.3 above, that conditions 4.1.2(b) through (d) above must be met in order to render the terms ignored by INEL to be zero.

4.2.5 INEL failed to understand the last equation on Viewgraph No. CCMGJ16, which is the vapor mass jump condition for the case of no evaporation from, or condensation on, the interface. All values on the right-hand side of that equation must be taken just below and above the level at the time-dependent elevation $z = Z_L(t)$. The vapor volume fluxes on the right-hand side of Eq.(7), however, pertain to the stationary cell boundaries, at z_{j-1} and z_j.

A simple hand calculation, one that is routinely carried out as a part of code debugging, would have revealed at once that the vapor volumetric flux differences within a cell cannot be ignored in the presence of phase change.

4.2.6 INEL presented results from their level tracking model, but they never showed any direct result from integrating Eq.(4), that is, they did not present a plot of $Z_L(t)$. This result must have been obtained, before the plots on Viewgraphs kg006-rbn-1293-007 and -006 could have been produced. Why was the integral of Eq.(4) not presented?

The omission of such results from the presentation, and the incomplete model presentation lead to the conclusion that INEL has not yet solved the problems of discontinuity associated with the passage of the level through a cell boundary. What is done in the code, and what happens to the result, when the α-derivative and the two α-values in the denominator of Eq.(4) on Viewgraph CCMGJ16 are changed simultaneously, as the level passes upwards or downwards through a cell boundary?

5. **Film Condensation** (J. Kelly)

This three-part presentation was outstanding, forthcoming and competent. It should serve as an example for contractors' technical presentations and for setting professional standards of acceptability.

6. **Interfacial Heat Transfer** (G. Johnsen)

6.1 The PIRT results need to be related to the listed collection of heat transfer correlations, to show which heat transfer regimes are important.

6.2 INEL should provide the bases for the six "non-metastable" heat transfer correlations which have no bases, or else they need to show that correlations without bases are unimportant (via PIRT).

6.3 A scrutable reference citation is needed for the "suggested"? coefficients of 10^4 and $3 \cdot 10^6$, which appear fifteen times in the table of Johnsen's viewgraphs. The functions $f(\Delta T_{sf})$ and $f(\Delta T_{sg})$ need to be defined (Reference citation is ok.)

6.4 INEL needs to state <u>how</u> they intend to "validate RELAP5 interphase heat and mass transfer models". The tables show heat transfer coefficients. Are heat transfer coefficients computed from experimental results? Hardly! Maybe the products of interfacial area density times the heat transfer coefficients?

What can and will be evaluated from the experiments and then compared with the correlations in RELAP5? How are the needed phasic and interface temperatures measured? Are only global experimental results compared with global RELAP5 code calculations? Such a comparison would be inconclusive, because it obscures interphase heat transfer behind the effects from kinematic and thermal disequilibria, from compensating errors and possibly from wall heat transfer.

Viewgraph c026-rbn-1193-024 is such an inconclusive comparison, since the result is dominated not only by boundary conditions and inter-phase heat transfer, but also by the predictions of (a) the location of the point of net vapor generation, (b) the vapor generation rate, (c) the wall heat transfer coefficient and (d) all the parameters governing relative velocities. Viewgraph c026-rbn-1193-042 is another inconclusive comparison.

7. Critical Flow (W. Weaver)

I don't recall a presentation on this subject, and I did not receive any handout.

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8. Momentum Equations & Closure (W. Weaver)

8.1 The claim regarding the "[momentum flux discretization] errors of the same order" is misleading, because the errors are of two different types. Conservative momentum flux differencing means that for the momentum balance of a whole component with constant flow cross-section, the fluxes at internal cell boundaries cancel exactly, as they should, and without producing or destroying momentum at cell interfaces. Nonconservative differencing implies a gain or loss of momentum.

Both forms of differencing are affected by discretization errors (numerical mixing within the cell), which has been reduced successfully in other codes by quadratic, upwind-weighted differencing, instead of the zeroth-order donor-cell differencing in RELAP5.

8.2 The "several simple problems used to assess [the] accuracy of momentum flux term modeling" are misleading, because all the problems were restricted to nearly incompressible and frozen flows, and selected to produce insignificant changes in momentum flux across all the cells with the same fixed flow cross-sectional area. The sample problems fall into the category of Schmutzeffekte.

INEL should not generalize "for example proofs", done by selective code calculations. It is more convincing to compute (without RELAP5, integrating the phasic mass balances) the difference (or error) of exact momentum flux changes in terms of relevant vapor generation rates versus the momentum flux difference as obtained by RELAP5's differencing scheme.

9. Field Equations of RELAP5 (W. Weaver)

There is nothing to review here, and therefore nothing to comment on until INEL has completed the documentation. I trust that the "Internal Report" by V. H. Ransom has been peer-reviewed, before ACRS will be asked to work its way through yet another derivation of the two-fluid model. I trust that this new report does not trigger a new avalanche of rebuttal and review cycles.

Weaver states on his third viewgraph that "Most of RELAP5 documentation was directed towards code users". This statement is a self-serving attempt at lowering the standards for code documentation. We have heard it many times and rejected it every time (an earlier claim was that the code was written for the convenience of the code developer).

INEL must not reduce code users to second-class engineers by denying them the opportunity to scrutinize the models in RELAP5, to find out the capabilities and limitations of the code. Code users must be afforded the same rights as the readers have of archival documents in professional journals of engineering.