52-001

52-004

March 16, 1994

MEMORANDUM FOR: R. W. Borchardt, Director
Standardization Project Directorate
Associate Directorate for Advanced Reactors
and License Renewal

FROM: Timothy Collins, Acting Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

SUBJECT: RAI ON TRACG COMPUTER CODE REVIEW

Questions on GE Licensing Topical Reports NEDE-32176P, NEDE-32177P (Rev. 1) and NEDE-32178P are identified in the Enclosure, and these may be sent to GE. Review of TRACG containment models, its application and qualification for the SBWR is in progress, and a set of questions will be prepared on the subject.

SBWR testing issue has impacted certain areas of TRACG review, and therefore, review of those areas can not be completed until the issues are resolved with GE.

/s/

Timothy Collins, Acting Chief
Reactor Systems Branch
Division of Systems Safety and Analysis

Enclosure:
As stated

cc: R. Jones
M. Malloy

Contact: M. M. Razzaque, SRXB/DSSA
504-2882

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

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ENCLOSURE

REQUEST FOR ADDITIONAL INFORMATION (RAI) ON TRACG COMPUTER CODE REVIEW

The following set of questions cover some aspects of TRACG code models, application of the code to SBWR, and on code qualification. More specific questions on the Licensing Topical Reports NEDE-32176P, NEDE-32177P(Rev.1) and NEDE-32178P are provided in the following pages.

Questions on TRACG Models

1) Critical Flow: The design for the flow restrictors on the steamline and GDCS injection lines may make them efficient diffusers which may allow critical flow to occur at higher downstream to upstream pressure ratio than usually encountered. Is this taken into account in GE's critical flow modelling?

2) Two Phase Level Tracking: The original level tracking model developed under the refill-reflood had errors in the hydraulic head term and interfacial friction treatments. This caused significant errors in pressure calculations. What changes have been made to correct the original implementation?

3) Mixing Models: The turbulent mixing model is totally unmechanistic using a c=0.1 constant value. GE plant model nodalizations do not come close to resolving profiles to the degree of accuracy needed to use a mixing model of the form chosen by GE. Please explain.

4) Steam Separator: The GE steam separator model seems to be a steady state model. How slow do transients have to be for this model to be valid?

5) Numerical Methods: Mahaffy (see the attached paper) has shown that the GE implicit hydraulic solution method is inconsistent with the original differential equations at large Courant numbers and has the effect of adding a timestep size dependent inertia. This can affect things like flow coastdowns after a pump trip. What is the significance of this?

6) Control Blocks: The existence of feedback loops does not make implicit solutions impossible. TRAC-BF1 has an implicit control system solution. How can you ensure that your solution is not sensitive to the order chosen to evaluate the control blocks?

Questions on TRACG Application to SBWR

7) What is the adder for nodalization uncertainty?

8) The uncertainty of using 2D instead of 3D hydraulics has not been discussed. How are second order effects taken into account?

9) Table 3-2 in NEDE-32178P lists the core inlet temperature as 511°C. What is the correct core inlet temperature?

Questions on TRACG Qualification

10) Why there is no qualification data provided for the following phenomena?

a) Accumulator behavior for SLCS

b) Boron transport and mixing

c) Gas mixing in containment

d) Containment pressurization from beginning of high pressure blowdown.

11) Why there is no code qualification provided for separate effects condensation against any data?

12) Why there is no code qualification provided for horizontal stratified flow (hydraulic & thermal)?

13) Vierow-Shrock natural circulation condensation oscillation may occur with a stuck open vacuum breaker in containment. Can TRACG predict such phenomenon?

LIST OF QUESTIONS (NEDE-32176P & NEDE-32177P Rev.1)

A. Significant Questions

Thermal-Hydraulic Model

A.1 The conservation equations in Section 3.1 include mixing terms for mass, momentum and energy, but there are no expressions defining them.

A.2 What is the typical value of α_{tran} for the flow regime map? Why is it related to the stratified flow when the flow in the BWR vessel is predominantly vertical? Are you using the same flow regime map for both vertical and horizontal flow?

A.3 In the global flow regime of liquid continuous flow and vapor continuous flow, subflow regimes are used. What are the criteria for these subflow regime transitions?

A.4 Shouldn't the factor 2 be in the denominator in Eq.(3.2-12) for the wall friction? Is G^2 used instead of $G|G|$?

A.5 Is x in Eq.(3.2-15) a flow quality or an equilibrium quality?

A.6 Is the same loss coefficient C in Eq.(3.2-17) used for both the forward and reverse flow?

A.7 Section 3.2.2 states that the wall friction is distributed between the phases proportional to the void fraction. What is the basis of this statement ? Is this statement valid for all flow regimes? Is it in agreement with the wall heat transfer distribution between the phases?

A.8 The modified Chisholm correlation used for wall friction is a departure from the design method used in the past. Is there any assessment done to compare the two?

A.9 The homogeneous two-phase multiplier (3.2-18) is used for form losses. In view of its significant impact on thermal-hydraulic stability, has its adequacy been assessed? See the discussion on the subject in EPRI NP-1924-CCM, July 1981.

A.10 The equivalence between the two-fluid and drift flux models established for steady-state conditions are used for transient interfacial shear calculations. Is there any assessment done to show that this is still valid

under severe transient conditions such as large amplitude oscillations induced by thermal-hydraulic instability (e.g., LaSalle-2 event)?

A.11 How good is the approximation used for the velocity of dispersed phase in Eq.(3.2-59)?

A.12 Section 3.2.3.1 states that a value for k of 1.53 in Eq.(3.2-26) allows for fits with wide range of the data. Where is the reference for this?

A.13 What is the basis of selecting Weber number of 6.5 in Eq. (3.2-27)?

A.14 Why is maximum of Eq.(3.2-26) and (3.2-30) is used for drift velocity?

A.15 Why is k = 1.41 in Eq.(3.2-43) and k=1.53 in Eq.(3.2-26)?

A.16 What is the basis of interfacial density expression Eq.(3.2-46)?

A.17 In Section 3.2.7.2, why is Eq.(3.2-73) needed if the position of the level is known from Eq.(3.2-64)?. What is the basis of Eqs.(3.2-65) and (3.2-66)? What happened to the vapor generation rate above and below the level in the cell? The level velocity is generally derived from the jump conditions at the level. How is this formulation consistent with the vapor mass balance equation?

A.18 What is the basis of Eq.(3.2-84)?

A.19 What is the basis of Eq.(3.2-87) (Ref, range and validity)?

A.20 In Section 3.2.5.2, the liquid side heat transfer coefficient is given by Eq.(3.2-90) and the reference is older version of TRAC-PWR. The TRAC-PF1/MOD2 is now using a different expression. Are the data bases for these correlations valid for SBWR conditions?

A.21 Please provide the range and validity of Eqs.(3.2-91) and (3.2-92).

A.22 Eq.(3.2-95) describes the vapor side heat transfer coefficient and is based on TRAC-P1A (Ref 3-4). However, the later version of TRAC (TRAC-PF1, NUREG/CR-5069) states that this expression is very approximate and is based on the flow over a jet. What is the justification of Eq.(3.2-95)? Where does it apply in BWR?

A.23 What is the experimental basis for Eq.(3.2-98)? Is the degradation factor flow regime dependent? How does Eq.(3.2-98) match with the analysis of

Sparrow et. al. in Figure 3.2-4?

A.24 In Section 3.2.10.3, how is the wall heat transfer divided between the liquid and vapor phases in the transition boiling mode?

A.25 How applicable is the correlation for condensation (Section 3.2.10.5) based on low pressure tests for Isolation Condensers?

A.26 In Section 3.2.10.9, various pool boiling and forced flow correlations have been described. How valid are they for a natural circulation system with parallel channels? Are these correlations based on soft inlet or hard inlet conditions?

A.27 In Eq.(3.2-142), H_{chen} is not defined. What is it?

A.28 On page 3-15 reference is made to Subsection 3.3.7.3. Where is the subsection?

A.29 What is the value of α_{cut} used for level detection in Eq.(3.2-63)? and why?

A.30 What is the basis of using 0.999 for α^+ in Eq.(3.2-74)?

A.31 What are j_g^- and j^- in Eq.(3.2-75)?

A.32 How is flow reversal handled in the level tracking?

A.33 What is the expression for q_{evap}^* in Eq.(3.2-113)?

A.34 Why is Eq.(3.2-120) squared?

A.35 What is α_{min} in Eq.(3.2-130)? What is its typical value? How is it obtained?

A.36 What is the expression for ε_i in Eq.(3.2-147)?

A.37 What are F_{ji} in Eq.(3.2-151) and F_{ij} in Eq.(3.2-152)?

A.38 What are the definition and unit of P and T in Eq.(3.2-167)?

A.39 What is the basis for using Eq.(3.2-181) for the Leidenfrost temperature?

A.40 What is T in Eq.(3.2-185)? in what unit? Shouldn't 10^5 in this equation be 10^4 ?

A.41 Why is the boron transport model not presented? How is boron mixing treated?

Heat Conduction Model

A.42 Should the negative sign in Eqs.(4.1-2) and (4.1-3) be there?

A.43 What is the basis for using 0.96 in Eq.(4.2-7) for uncertainty?

A.44 What is R on the right hand side of Eq.(4.2-18)?

A.45 Is the temperature ratio on the right-hand side of Eq.(4.2-29) consistent with the volume to temperature ratios of the other two terms?

Component Models

A.46 There isn't a turbine model among the component models presented. How is a turbine modeled in TRACG?

A.47 Why is the mixture density ρ_m used in Eq.(5.2-1) instead of liquid density ρ_l?

A.48 Where is the assumption $v_v = v_l$ in Eq.(5.2-3) used in the pump model? How is this assumption justified?

A.49 Safety valves are of spring action type which has hysterisis effect. How is this handled by the valve model?

A.50 Is x in Eq.(5.5-8) a dynamic flow quality? How is it calculated?

A.51 Shouldn't the negative sign associated with R in Eq.(5.5-10) be positive? Consequently, the numerator of Eq.(5.5-11) for R should have a negative sign.

A.52 In view of question 6, is Eq.(5.5-12) correct?

A.53 What is the rationale for using Eq.(5.5-12) for transient CPR if TM(t) < TM(0) and using Eq.(5.5-13) if otherwise? Why is the linear

relationship valid?

A.54 Which test data were used to obtain the α^H curve in Figure 5.5-4?

A.55 Is Eq.(5.6-5) correct? Or is area ratio missing in the first term on the RHS of Eq.(5.6-2)? We can't get Eq.(5.6-5) from Eqs.(5.6-2) and (5.6-4).

A.56 Is the final expression for Eq.(5.7-5) correct? r_w is missing in the last term in the bracket. It should be a $r_w(r_w-r_f)$.

A.57 Why are the bypass fluid properties instead of hydraulic in-channel properties used in the kinetics calculations as stated on page 5-52?

A.58 What is the experimental basis for the steam dryer efficiency curves shown in Fig. 5.9-1? What are typical values of $v_{vd,l}$, $v_{vd,u}$ and Δx_d?

A.59 The transition from the spray regime to the submerged jet regime for the case of non-existent two-phase level in the upper plenum is not clear. How is the void fraction used for this transition?

A.60 Quasi-static momentum balance is used for the submerged jet model. How important is the temporal effect? Is there any assessment done?

A.61 What are ρ_∞ and h_∞ in the submerged jet model? What profiles are used for density η, velocity f, and enthalpy ϕ?

A.62 What is the basis for Eq.(5.11-1)? Any justification?

A.63 Why is it necessary to have only one cell for the steam shell in the heat exchanger model? What is the impact of this simplification?

A.64 Is the heat exchanger model adequate to represent the isolation condenser in the SBWR? How is the non-uniform temperature distribution in the tube bundle and IC pool taken into account?

Numerical Method

A.65 In the lumped heat slab model, the source term is neglected as in Eq.(6.1-5). How can the direct energy deposition (say, due to gamma ray) be accounted for in such a model? By the way, where are Eqs.(6.1-

1) through (6.1-4)?

A.66 The transition from Eq.(6.1-11) to Eq.(6.1-12) is not obvious. What is $\widetilde{T}_w^{n+1}$ on the right hand side of Eq.(6.1-12)? How are $\partial T_w/\partial T_l$ and $\partial T_w/\partial T_v$ evaluated?

A.67 Is Eq.(6.1-12) correct? Using it, one can not get Eqs.(6.1-13) and (6.1-14)..

A.68 Are Eqs.(6.1-15) and (6.1-17) correct? Δs should be associated with the first two terms on the RHS of these equations.

A.69 Why is Δt in Eq.(6.1-20)?

A.70 What has happened to $\Delta\widetilde{T}_w^{n+1}$ term of Eq.(6.1-19) in Eqs.(6.1-21) thru (6.1-25)?

A.71 What is Δs in the last term of Eq.(6.1-26)? Shouldn't the first two terms on the RHS of this equation have Δz associated with them?

A.72 What is Δs in Eq.(6.1-29)? Is it Δr_{N-1}? Shouldn't the first two terms on the RHS of this equation have Δz associated with them? Also the Δ_{N-1} in the first term associated with $\dddot{q}$ should be Δr_{N-1}.

A.73 Why is Δt in Eq.(6.1-34)?

A.74 What has happened to $\Delta\widetilde{T}_w^{n+1}$ term of Eq.(6.1-33) in Eqs.(6.1-35) thru (6.1-39)?

A.75 In the predictor-corrector method, the corrector step attempts to conserve precisely only the mixture mass. Isn't the precise energy conservation equally important? How can one be sure that energy is adequately conserved?

A.76 The boron conservation equations in Subsection 6.3.3.2 appear to have made the assumption that the boron solution is perfectly mixed with the liquid. This being the case, how can it model the imperfect mixing at low flow conditions and the potential boron stratification in the lower plenum?

Three-Dimensional Kinetics Model

A.77 Is there any assessment done for the acceptability of the assumptions (7.1-2) and (7.1-3)? Note that the spatial distributions of the fast and thermal neutrons are indeed very different and that the neutron spectrum does change a lot during a large amplitude power oscillation when the void fraction in the core changes between 0.1 and 0.99!

A.78 Is Eq.(7.1-7) correct? The product of $(1+M_2^2B^2+\tau/\Sigma_2v_2)$ & $(1+M_3^2B^2+\tau/\Sigma_3v_3)$, which can be approximated to $[1+(M_2^2+M_3^2)B^2 +(1/\Sigma_2v_2+1/\Sigma_3v_3)\tau]$, is missing in the last term of the equation. What is the impact of neglecting this?

A.79 What is the justification for neglecting the term involving τ in Eq.(7.1-11)?

A.80 The choice of neutron flux as the weighting function instead of the adjoint flux leads to a residual reactivity [see Trans. Am. Nucl. Soc., 24, 470 (1979)]. What is the impact of using self adjoint?

A.81 Is the expression for $\bar{\beta}_n$ correct? β_n is missing in the integrand and (k_∞/μ_0-1) should be k_∞/μ_0.

A.82 Is Eq.(7.1-20) correct? There seems to be an extra term and a dot is missing in the leakage term.

A.83 How is the factor 8 derived in Eq.(7.1-23)?

A.84 An average $\bar{\nu}$ is used in Eq.(7.1-26) with the assumption $\nu_1=\nu_2=\nu_3=\bar{\nu}$. How is the average $\bar{\nu}$ determined? What is the error on the nodal power from this assumption?

A.85 How is the spectral mismatch correction Δk_i calculated?

A.86 Why are M^2, D_1, Σ_1, and A_∞ treated as a function of U only?

A.87 Does the Doppler coefficient depend on exposure?

A.88 What is f in Eq.(7.3-2)? It is not defined.

A.89 Which experimental data were used to determine the decay heat parameters f_k and λ_k? What are their values?

A.90 Is the exponent 36 in Eq.(7.4-15) correct?

A.91 Is it sufficiently accurate to use the thermal-hydraulic time step for point kinetics calculations? Note that the TH time step can take 250 msec or more!

A.92 How often is the shape function recalculated in a typical transient? Is the update of the shape function automatically controlled?

Appendix B and C

A.93 What are the uncertainties on the thermodynamic properties? Is there any comprehensive assessment done to determine the accuracy of these property fits or correlations, especially at low pressures near the atmospheric pressure?

A.94 What are the uncertainties on the material properties? Is there any comprehensive assessment done on these material property correlations or data?

B. Minor Questions

B.1 In Section 3.1, the liquid energy balance equation (3.1-7) is given. However, in Section 6.2, the mixture energy equation (6.2-9) is used. Which one is actually used in the code?

B.2 Shouldn't the hydraulic diameter D_h be in the numerator in Eq.(3.2-14) for the Reynolds number?

B.3 Shouldn't ρ_l in Eq.(3.2-40) be ρ_v?

B.4 Shouldn't $<j>$ in Eq.(3.2-52) be $<j_v>$? What are m and K in Eq.(3.2-54)?

B.5 Is D_B in Eq.(3.2-91) d_b?

B.6 What is the correlation used for T_{min} in Eq.(3.2-120)?

B.7 Shouldn't H be H_i and the summation be over j in Eq.(3.2-148)?

B.8 What are α_d and d_d in Eq.(3.2-166)?

B.9 What is t_{ij} in Eqs.(3.2-171), (3.2-174) and (3.2-175)? Is it τ_{ij} ?

B.10 Shouldn't the summation over J be j in Eqs.(3.2-171) and (3.2-172)?

B.11 Shouldn't R_{co} in Eq.(4.2-17) be R_{fo} ?

B.12 The motor torque T_m in Eq.(5.2-14) is stated to be defined via the control system. How is this done? Automatically by TRACG or by the user?

B.13 Is H_d on page 5-40 the same as H_D?

B.14 Why is the steam line not connected to the steam dome in Fig. 5.8-3? As such, the wet steam will flow to the steam line.

B.15 What is the variable s in Eqs.(5.10-2) through (5.10-5)? It appears that s is the spatial variable of the trajectory and that the time dependency is neglected. How important is the temporal effect?

B.16 Is $V \cdot \nabla V$ on page 5-69 correct? Should it be $V \nabla V$?

B.17 Shouldn't the minus sign for the convective term in Eq.(6.1-15) be a plus sign?

B.18 Shouldn't $\Delta r_M^2/4$ on the left hand side of Eq.(6.1-31) be $\Delta r_{M+1}^2/4$?

B.19 Shouldn't the minus sign associated with the virtual mass term in Eqs.(6.2-6), (6.2-15), (6.2-16), (6.2-17) and (6.3-13) be a plus sign?

B.20 Shouldn't v_{dR} in the virtual mass term in Eq.(6.2-12) be v_{dZ}?

B.21 Shouldn't ρ_g associated with $\bar{F}_w$ in Eq.(6.2-17) be ρ_l?

B.22 Shouldn't the subscript j of the last term in Eq.(6.3-9) be j-1?

B.23 Shouldn't $\partial v_{gZ}/\partial R$ in Eq.(6.3-13) be $\partial v_{lZ}/\partial R$?

B.24 Shouldn't $\Delta^2 P_{IJK}$ in Eq.(6.3-52) be ΔP_{IJK}?

B.25 Shouldn't the minus sign associated with $\tau/\Sigma_2 v_2$ in the third term on RHS of Eq.(7.1-6) be a plus sign?

B.26 Shouldn't ϕ at LHS of Eq.(7.1-13) be ϕ_l?

B.27 Shouldn't v_l in Eqs.(7.1-16) and (7.1-18) be v^*?

B.28 Shouldn't λ_n in Eq.(7.1-19) be $\bar{\lambda}_n$?

B.29 Is the expression for total $\bar{\beta}$ correct? The subscript n on the LHS shouldn't be there.

B.30 Shouldn't β in the expression for M^{*2} be $\bar{\beta}$?

B.31 Shouldn't S' and C_n in the expression for S_t on page 7-13 be $\bar{S}'$ and $\bar{C}_n$, the spatial average over a cell?

B.32 Shouldn't Δ^2 in Eq.(7.1-24) be Δ_{ij}^2?

Significant Questions re NEDE-32178P

Question No	Page or Section	Question
S.3-1	Sect. 3.3	Sensitivity studies for the axial nodalization and for the fuel channel grouping are mentioned in Section 3.3, but no references are given. Please provide references, or include the results of these studies in NEDE-32178P. Some of the other nodalization decisions are justified in a qualitative way. These should be quantified, as appropriate.
S.3-2	Sect 3.6	The report states, that the SBWR is expected to operate generally more than 15% above the OLMCPR, but could theoretically reach its value, in particular under EOC conditions. However, with SSAR data of an OLMCPR value of 1.32, and with possible ΔCPR values of 0.25, it would appear, that no uncertainty or bias adders were used in the SSAR, suggesting either a reevaluation or a redefinition of the OLMCPR. Please comment.
S.3-3	Sect 3.7.2	There are apparently differences between the PIRTs of Ref.8 and Table 3.3 of NEDE-32178P, as shown in Table 3.1, here. Please explain. We feel, that, for a more consistent report, the underlying PIRT Tables should be included in the report, maybe as an appendix.
S.3-4	Sect 3.7.4	1σ uncertainties of the candidate parameters are included in Table 3.3. How have these been obtained ? For some this may be straight forward (SRV set point, manufacturers data would be expected to be the source), but how are, for instance the reactivity coefficients and decay heat parameters and the gap conductance values determined ? 4% on Doppler coefficient and 4.4% on decay heat would appear to be very small uncertainties??
S.3-5	Sect. 3.7.4	From the description of the parameter variation, it appears, that each parameter was varied separately from a base best estimate case; that is, joint variations were not conducted. Please explain, and if variations were done separately, please justify.

S.3-6	Sect 3.7&8	The method used, to establish the cumulative uncertainty is not clear from the description given. Please provide further detail, and preferably reference, to where it is described, and where else it has been used. It would appear, that this question is really connected also to Question S.3-5, above.
S.3-7	Table 3.3	PIRT # C1DX: what does "code qualification against plant integral test" refer to ? future proto-type experiments? was the implied current lack of knowledge considered in additional bias?

S.4-1	Sect. 4	We feel that a simple statement that results are satisfactory, as given, is not sufficient. While the statement is believed to be correct, the results of the ATWS simulations should at least be summarized here in quantitative form, with reference to report(s) containing more complete results. The acceptance criteria should be explicitly stated, and compared to the results of that accident simulations.
S.4-2	Sect 4.2.1	The second paragraph presents a qualitative argument for use of an analytical limit of the SRV set point, stating that the higher set point is of negligible effect on the long-term suppression pool temperature. This point should be supported by presenting quantitative results.

S.5-1	Sect. 5.2.2	The model description gives a brief qualitative reference to the nodalization used. As requested for Section 3, a quantitative justification with reference to any available nodalization studies should be supplied.
S.5-2	Sect. 5.4	Conformance to 10CFR50.46 Acceptance Criteria 1 to 3 is stated to follow directly from the "results". We assume, this means TRACG code predictions. We cannot find any reference to clad oxidation and metal/water chemical reactions in either of the three reports (NEDE32176P to 178P). If this is a simple, and possibly well justified, model, like "no oxidation at clad temperatures below xxx", then this should be stated here.
S.5-3	Sect. 5	There is no reference to any PIRTs for ECCS/LOCA scenarios, considering the in-vessel segment of the transients. The PIRTs referenced in Section 3 as Reference 8 of NEDE-32178P do include LOCA scenarios. Please confirm, that these are to be applied here, and if not, please provide alternate reference, or provide justification, why PIRTs are not required here. As requested with Section 3, the PIRTs should be reproduced here, possibly as an appendix.
S.5-4	Sect.5.4	Please comment, whether the decay heat of actinides is included in the analysis, as required by Reg Guide 1.157 (Sect. C-3.2.3).
S.5-5	Sect 5.4	For a self-consistent report, it is felt, that results of the LOCA analyses should be referenced, and there should be at least a table, summarizing the runs made, their break sizes and the most important output parameters, including peak clad temperature, with time of occurrence.
S.5-6	Sect 5.4.1	By comparing Tables 5.1 and 5.2 here, it appears, that many parameters were not included in the uncertainty analysis, which remains incomplete. Please expand or provide justification.

S.6-1	Sect 6.1	The restriction, of considering only a single scenario, a steam line break, should be justified.
S.6-2	Sect 6.2.2	In particular, since the containment design basis accident simulations, mentioned here, have not been reported in the SSAR, it would be strongly desirable, to include the results here, at least through summary tables, and with reference to the complete results.
S.6-3	Sect. 6.3.2	PIRTs for the containment analysis of ECCS/LOCA scenarios are mentioned here, but without any reference or details. Please confirm, that the PIRTs referenced in Section 3 as Reference 8 of NEDE-32178P were used here, and if not, please provide alternate reference. As stated before, the PIRTs should be made a part of NEDE-32178P.
S.6-4	Sect 6.3.2	The variation of three parameters, and comparison to a previous model cannot be considered to be a full uncertainty evaluation, corresponding to the CSAU process. For a complete uncertainty evaluation, at least all of the points of Section N of Table 5.1 should be addressed in full.

Minor Questions re NEDE-32178P

Question No	Page or Section	Question
M.1-1	Sect. 1	End of 3rd ¶: "so it can perform *any* transient or accident analyses"; it would appear preferable to be more specific here, for instance "most transient or accident analyses for current BWRs, with exceptions as noted in the report".
M.2-1	Sect 2.4	Again, TRACG is not used for *all* LOCA analyses. Note the "nearly all", at the beginning of Section 2.1.
M.3-1	Sect 3.5	Please include reference to GETAB (NEDO-10958) in report.
M.3-2	Sect 3.7.2	Considering over-pressure protection, the report refers to "the analysis submitted". We assume this means the analysis of Section 5.2 of the SSAR. Please confirm and clarify wording of report. If "submitted" always refers to the SSAR and not to this submittal, maybe this should be clarified in one general statement.
M.3-3	Sect 3.7.2	We assume, that PIRT parameters ranked 7 and higher were included with the candidate parameters in Table 3.3. Please clarify.
M.4-1	Sect 4.2.1	Please provide correct reference for "Reference 7-9."
M.5-1	Sect 5.4	2nd ¶: please confirm that you mean Section 5.3.1 instead of "5.1.5", which does not exist; please provide correction for "Reference 7-10", which also does not exist.
M.5-2	Table 5-1	Sect B.2: four flow rate entries are missing exponent on "10".
M.5-3	Fig. 5-2	The scale of Figure 5-2 makes it useless for any scaling of actual values used. A table, giving the power ratio (correct ordinate label), for instance at 1, 10, 100, 100 s, etc, would be significantly more useful.
M.6-1	Sect 6.2.2	Last sentence: please provide description or reference for the "special procedure" to account for thermal stratification in the suppression pool.

M.6-2	Sect 6.3.1	2nd sentence: "containment will maintain structural integrity....(excluding the blowdown peak)". We hope this is phrased misleadingly. Please clarify and/or revise wording. Blowdown peak determined by M3CPT ?, but we hope containment can survive that peak too!
M.6-3	Table 6.1	Entry (4): what does "internals stored energy added to decay heat" mean? The one is an initial condition, generally in units "work", the other is a heat generation rate, generally in units "work/time".

NEA/CSNI/R(92)12

PROCEEDINGS OF THE CSNI SPECIALIST MEETING ON TRANSIENT TWO-PHASE FLOW

"CURRENT ISSUES IN SYSTEM THERMAL-HYDRAULICS"

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Numerics of Codes: Stability, Diffusion, and Convergence

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ABSTRACT

The numerical methods used in the primary US reactor safety codes are summarized. The basic Courant-type stability limits for these codes are reviewed, and more subtle stability problems arising from the explicit evaluation of various friction and heat-transfer coefficients are discussed. Much of the stability and robustness of these codes has come at the expense of high numerical diffusion. The impact of numerical diffusion is illustrated. The question of convergence of solutions of the difference equations to those of the original differential equations is also addressed.

1. INTRODUCTION

Although the contents of this paper are applicable in varying degrees to a wide range of codes, specific remarks are limited to versions of the TRAC, RELAP, and (to a limited extent) the RETRAN code series. The stability properties of these codes, resulting from the choice of time level for pressure gradient and terms in the mass, energy, and momentum fluxes, have been well studied. Linearized stability analysis of the full set of two-phase flow equations provides only limited information, due to the complexity of the resulting algebraic equations. However, much has been learned from linearized analysis of the basic numerical methods applied to single phase flow, and detailed numerical trials of the full two-phase codes. Unfortunately, a large class of stability problems, resulting from the evaluation of various heat transfer and friction coefficients (wall and interfacial) at the old time level, has been inadequately addressed. Since these instabilities are generally manifested as bounded oscillations, it has been argued that they do not effect the mean predictions of system behavior. One example is presented of significant error in mean behavior caused by such an instability.

The questions of diffusion and convergence have not been as widely studied as stability. Since the inception of most reactor safety codes, it has been recognized that the chosen spatial and temporal difference methods introduce substantial numerical diffusion. However, for the vast majority of problems of interest this has not been a significant problem. Attempts to introduce less diffusive numerical schemes degraded the robustness of the methods to levels unacceptable in production codes. The recent importance of core oscillations in BWR's has resulted in renewed interest in the effects of this numerical diffusion and attempts to introduce improved methods.

The formal convergence of the difference equations used in reactor safety codes has generally been acceptable. However, in a less formal sense convergence problems can result from the use of a form

of the energy equation that is not fully conservative. For flow through an abrupt area change, the temperature change downstream will be predicted incorrectly regardless of the length selected for the mesh cells. This problem has been recognized for many years, but most recently became an issue as a result of an attempt to use RELAP to model the behavior of a reactor containment.

2. Basic Equations

Because of my background with the TRAC-PWR program, I will begin by discussing the numerical methods used in that code series, and then discuss key points of similarity and difference for other safety codes. To demonstrate these methods, only a simplified model for one-dimensional, single-phase flow in a pipe will be considered. References are provided for the full two-phase models and associated difference equations. The differential equations for this simple model are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho V = 0 , \tag{1}$$

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot \rho e V = - p \nabla \cdot V , \tag{2}$$

and

$$\frac{\partial V}{\partial t} + V \cdot \nabla V = - \frac{1}{\rho} \nabla p - K V |V| . \tag{3}$$

Here, K is a wall friction coefficient that may be a function of velocity and fluid properties.

TRAC-PWR codes beginning with TRAC-PF1 [1] employ the stability-enhancing two-step (SETS) method[2,3] to solve the flow equations. This is an extension to the standard semi-implicit methods found in earlier versions of TRAC [4] and versions of RELAP through RELAP5/MOD2 [5]. SETS has the advantage that it eliminates the material Courant stability limit of a semi-implicit method, and the computer time per cell per time-step is reduced by at least a factor of 5 over that of a fully implicit method.

A staggered spatial mesh is used for the finite-volume equations, with thermodynamic properties evaluated at the cell centers and the velocity evaluated at the cell edges. Only difference equations on the one-dimensional version of this mesh will be demonstrated, but the generalization to two- and three-dimensional versions is not difficult. To ensure stability and to maintain consistency with differencing in previous TRAC versions, flux terms at cell edges use donor cell averages of the form

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where

$$(YV)_{j+1/2} = \begin{cases} Y_j V_{j+1/2}, & V_{j+1/2} \geq 0 \\ Y_{j+1} V_{j+1/2}, & V_{j+1/2} < 0 . \end{cases} \tag{4}$$

Here Y may be any state variable. Other forms of this average may maintain stability with higher order spatial accuracy but they have not been carefully studied. With this notation the one-dimensional finite-difference divergence operator is

$$\nabla_j \cdot (YV) = (A_{j+1/2} (YV)_{j+1/2} - A_{j-1/2} (YV)_{j-1/2}) / vol_j , \tag{5}$$

where A is the area of the cell edge and vol_j the cell volume. The term $V \cdot \nabla V$ becomes

$$V_{j+1/2} \nabla_{j+1/2} V = \begin{cases} V_{j+1/2} (V_{j+1/2} - V_{j-1/2}) / \Delta x_{j+1/2}, & V_{j+1/2} \geq 0 \\ V_{j+1/2} (V_{j+3/2} - V_{j+1/2}) / \Delta x_{j+1/2}, & V_{j+1/2} < 0 , \end{cases} \tag{6}$$

where $\Delta x_{j+1/2} = 0.5 (\Delta x_j + \Delta x_{j+1})$. This momentum transport term is only directly relevant to TRAC-PF1/MOD1 [6] and earlier codes. TRAC-PF1/MOD2 [7] currently uses area and macroscopic density weighing within this expression, but these terms are still under study and will not be discussed here.

For the flow model given by Eqs. (1)-(3), the combination of basic and stabilizer equation sets can be written in several ways. One ordering that is always stable begins with the stabilizer step for the equations of motion, is followed by a solution of the basic equation set for all equations, and ends with a stabilizer step for the mass and energy equations. For this ordering, the SETS finite-difference equations for Eqs. (1)-(3) are:

STABILIZER EQUATION OF MOTION

$$\begin{aligned} (\hat{V}^{n+1}_{j+1/2} - V^n_{j+1/2}) / \Delta t &+ V^n_{j+1/2} \nabla_{j+1/2} \hat{V}^{n+1} \\ &- \beta (\hat{V}^{n+1}_{j+1/2} - V^n_{j+1/2}) \nabla_{j+1/2} \hat{V}^n \\ &+ \frac{1}{(\rho^n_{j+1/2} \Delta x_{j+1/2})} (p^n_{j+1} - p^n_j) \\ &- K^n_{j+1/2} (2 \hat{V}^{n+1}_{j+1/2} - V^n_{j+1/2}) |V^n_{j+1/2}| = 0 , \end{aligned} \tag{7}$$

where

$$\beta = 0, \ \nabla_{j+1/2}\tilde{V}^n < 0$$
$$1, \ \nabla_{j+1/2}\tilde{V}^n > 0 ; \tag{8}$$

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BASIC EQUATIONS

$$\begin{aligned}(V_{j+1/2}^{n+1} - V_{j+1/2}^{n}) / \Delta t \ &+ V_{j+1/2}^{n} \nabla_{j+1/2} \tilde{V}^{n+1} \\ &+ \beta \ (V_{j+1/2}^{n+1} - V_{j+1/2}^{n}) \nabla_{j+1/2} \tilde{V}^{n} \\ &+ \frac{1}{(\rho^{n}_{j+1/2} \Delta x_{j+1/2}} (\tilde{p}_{j+1}^{n+1} - \tilde{p}_{j}^{n+1}) \\ &+ K_{j+1/2}^{n} (2 \ V_{j+1/2}^{n+1} - V_{j+1/2}^{n}) \ |V_{j+1/2}^{n}| = 0 ;\end{aligned} \tag{9}$$

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$$(\tilde{\rho}_j^{n+1} - \rho_j^{n}) / \Delta t + \nabla_j \cdot (\rho^{n} V^{n+1}) = 0 ; \tag{10}$$

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$$\begin{aligned}(\tilde{\rho}_j^{n+1} \tilde{e}_j^{n+1} - \rho_j^{n} e_j^{n}) / \Delta t &+ \nabla_j \cdot (\rho^{n} e^{n} V^{n+1}) \\ &+ \tilde{p}_j^{n+1} \nabla_j \cdot (V^{n+1}) = 0 ;\end{aligned} \tag{11}$$

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STABILIZER MASS AND ENERGY EQUATIONS

$$(\rho_j^{n+1} - \rho_j^{n}) / \Delta t + \nabla_j \cdot (\rho^{n+1} V^{n+1}) = 0 ; \tag{12}$$

$\rho_j^{n+1} = \rho_j^{n}$

$$\begin{aligned}(\rho_j^{n+1} e_j^{n+1} - \rho_j^{n} e_j^{n}) / \Delta t &+ \nabla_j \cdot (\rho^{n+1} e^{n+1} V^{n+1}) \\ &+ \tilde{p}_j^{n+1} \nabla j \cdot (V^{n+1}) = 0 .\end{aligned} \tag{13}$$

A tilde above a variable indicates that it is the result of an intermediate step and is not the final value for the time step.

The material Courant stability limit is eliminated by treatment of the terms VVV, $\nabla \cdot \rho VV$, *and* $\nabla \cdot \rho eV$ during the two steps. Additional stability has been obtained with the particular form for the friction terms and the use of nonzero values of β in the VVV terms. These special terms for friction and VVV are obtained by linearizing similar terms that are fully implicit in velocity.

Equation (7) simply represents a tridiagonal linear system in the unknown $\tilde{V}^{n+1}$ and is solved first. Next, the coupled nonlinear system given by Eqs. (9) -(11) is solved. In practice this is accomplished by a Newton iteration in which the linearized equations are reduced to a linear system involving only pressure variations (see Ref. 6 or 7). Once these equations are solved, V^{n+1} is known; hence, Eqs. (12) and (13) are simple tridiagonal linear systems, with unknowns ρ_j^{n+1} and $\rho_j^{n+1} e_j^{n+1}$, respectively.

When this equation set is adapted to flow in complex piping networks, the pure tridiagonal structure is lost. However, the matrices are still sparse and easily solved.

Recent Boiling Water Reactor (BWR) versions of TRAC use a numerical method very similar to that described above. However, there are two significant differences in TRAC-BF1 [8] and later versions. Equation (7) is eliminated and Equation (6) as applied to the basic motion equation is replaced by

$$\begin{aligned} V_{j+1/2} \nabla_{j+1/2} V = \; & V^n_{j+1/2} \left(V^{n+1}_{j+1/2} - V^n_{j-1/2}\right) / \Delta x_{j+1/2}, \; V_{j+1/2} \geq 0 \\ & V^n_{j+1/2} \left(V^n_{j+3/2} - V^{n+1}_{j+1/2}\right) / \Delta x_{j+1/2}, \; V_{j+1/2} < 0 \; . \end{aligned} \tag{14}$$

This mixture of new and old time velocities in the velocity gradient can result in a failure of the solution of the difference equations to converge to the solution differential equations as the time-step and mesh length approach zero. This convergence problem is discussed in detail in Section 5.

Relap5/Mod3 contains options for either a semi-implicit method or a variation on SETS referred to as the Nearly-Implicit method [9]. The semi-implicit option is similar to applying Equations (9)-(11) with the tildes removed from the velocities. The key difference with TRAC is that a full solution of these nonlinear coupled algebraic equations is not attempted. The linearized equations are solved once. The resulting values for variables are substituted into the right hand side of the rearranged mass and energy equations.

$$\rho_j^{n+1} = \rho_j^n - \Delta t \, \nabla_j \cdot (\rho^n V^{n+1}), \tag{15}$$

$$\rho_j^{n+1}\, e_j^{n+1} = \rho_j^n\, e_j^n - \Delta t\, \nabla_j \cdot (\rho^n e^n V^{n+1}) + \Delta t\, \beta_j^{n+1}\, \nabla_j \cdot (V^{n+1}), \tag{16}$$

to obtain the final new time densities and energies. This method eliminates systematic mass errors that can result from the solution of linearized equations alone. This type of corrector method was abandoned in the TRAC program in the late 1970's as being significantly less robust than an iterative solution of the nonlinear difference equations. However, differences in flow equations and details of numerical techniques may have made this a good choice for RELAP5.

For the model equations in this paper the Nearly-Implicit approach involves the elimination of Equation (7) and the replacement of Equation (9) with

$$(V_{j+1/2}^{n+1} - V_{j+1/2}^n) / \Delta t + \bar{v}_{j+1/2}^n\, \nabla_{j+1/2}\, V^{n+1} + \beta\, (V_{j+1/2}^{n+1} - V_{j+1/2}^n) \nabla_{j+1/2}\, V^n + \frac{1}{(\rho)_{j+1/2}^n \Delta x_{j+1/2}} (\beta_{j+1}^{n+1} - \beta_j^{n+1}) + K_{j+1/2}^n\, V_{j+1/2}^{n+1} |V_{j+1/2}^n| = 0 . \tag{17}$$

In the actual RELAP implementation the $V\nabla V$ term is area and density weighted and central differenced. Equations (10) and (11) are linearized and solved to obtain intermediate values for new time pressure and specific internal energy as a linear function of cell face velocities. These relationships for pressure are substituted into Equation (17) and the resulting tridiagonal (for two-fluid equations a block tridiagonal) linear system is solved to obtain the new time velocities. Solution of Equations (12) and (13) follows as described for TRAC to obtain final new time densities and energies. At first thought, the conservative nature of the stabilizer mass equation should eliminate the need for anything other than a linearized solution of the basic equation set. Unfortunately, numerical experiments with TRAC indicate that stable behavior of the SETS method at high multiples of the material Courant limit requires a well converged solution of the nonlinear basic equation set.

The Nearly-Implicit method was originally described as a variant of SETS in reference [3], but rejected for use in TRAC because the use of separate stabilizer momentum equations actually requires less computational effort with TRAC's two-fluid equations. However, due to the presence of virtual mass terms in the RELAP two-phase momentum equations, the version of SETS found in TRAC is not feasible for RELAP and the Nearly-Implicit method is a natural choice.

RETRAN [10] is a third safety code series commonly used in the USA, although for a narrower range of transients than TRAC and RELAP. A significant reason for this restricted utility is the continued use of a drift-flux formulation for the flow equations. RETRAN-02 uses a fairly conventional semi-implicit technique, but with mass flow replacing velocity as an independent variable. RETRAN-03 removes the material Courant limit with a fully implicit treatment of all mass, energy and momentum

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flux terms [11], and applies advanced sparse matrix techniques to the resulting linear equations. It contains the option to solve only a single linearization of the equations as in RELAP, or to continue to solve the nonlinear equations with a Newton iteration. As is the case for TRAC and RELAP, RETRAN-03 and its predecessors evaluate all heat transfer and friction (wall and interfacial) coefficients at the old time level, and share the stability problems associated with this practice.

3. STABILITY

The original SETS method was constructed from information propagation arguments. It was observed that the semi-implicit approach eliminated the sound speed from the standard Courant limit of explicit schemes by transmitting sound wave information throughout the spatial finite-difference mesh in a single time step. The remaining material Courant stability limit ($\Delta t < \Delta x / |V|$) is accounted for by the argument that information on the material being convected is only propagated one cell per time step. Therefore, it was concluded that the remaining material Courant limit could be removed by adding to a semi-implicit method a step that propagates the necessary information on mass, energy, and momentum flux. This heuristic stability analysis is not always valid [12], and must be confirmed with more detailed linearized analysis and computational tests.

A more rigorous understanding of the stability of semi-implicit methods can be obtained by combining Equations (10) and (11) with the simple motion equation

$$\frac{V_{j-1/2}^{n+1} - V_{j-1/2}^{n}}{\Delta t} + V_{j-1/2}^{n} \frac{V_{j+1/2}^{n} - V_{j-1/2}^{n}}{\Delta x} + \frac{1}{(\rho)_{j-1/2}^{n}} \frac{P_{j+1}^{n+1} - P_{j}^{n+1}}{\Delta x} = 0 . \tag{18}$$

For a standard linearized stability analysis, the eigenvalues of the amplification matrix are

$$\lambda = \frac{\beta - \eta}{\beta \pm i \frac{c}{V} \chi^{1/2}} , \tag{19}$$

and

$$\lambda = \frac{\beta - \eta}{\beta} . \tag{20}$$

where

$$\beta = \frac{\Delta x}{V \Delta t} , \tag{21}$$

$$\eta = 1 - e^{-ik\Delta x} , \tag{22}$$

and

$$\chi = \eta\eta^* = 4 \sin^2\left(\frac{k\Delta x}{2}\right) . \tag{23}$$

Also note that $V > 0$ has been assumed.

For the first pair of eigenvalues stability requires

$$\lambda\lambda^* = \frac{\beta^2 + \chi(1 - \beta)}{\beta^2 + \frac{c^2}{V^2}\chi} < 1 . \tag{24}$$

This condition is clearly met for any Δt when the flow is subsonic, and as the velocity becomes much greater than the sound speed monotonically approaches the condition that $\Delta t < \Delta x/V$. For the final eigenvalue the condition for stability becomes

$$1 + \chi \frac{(1 - \beta)}{\beta^2} < 1 , \tag{25}$$

which is only true if $\Delta t < \Delta x/V$.

Extension of this type of stability analysis to the SETS Eqs. (7)-(13) is not as simple as in the preceding cases. The algebra becomes more complicated and the eigenvalues of the amplification matrix are given by

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$$\lambda = \frac{\beta}{\beta + \eta} \tag{26}$$

and

$$\lambda = \frac{2\beta(\beta + \eta) + r\eta(2\beta + \eta) \pm (r^2\eta^2(2\beta + \eta)^2 + 4r\beta(\eta^3 + 2\beta\eta^2 - \beta^3))^{1/2}}{2(r + 1)(\beta + \eta)^2} . \tag{27}$$

The magnitude of this eigenvalue is difficult to evaluate. However, it is instructive to take the limit of time steps much greater than the material Courant limit. For this case, β approaches zero and the eigenvalues in Eq. (27) go to zero and

$$\lim_{\beta \to 0} \frac{r}{r+1} < 1 , \tag{28}$$

suggesting unconditional stability.

In practice, the SETS equations are not unconditionally stable because heat transfer and friction coefficients are evaluated at the old time level. At very large time steps, functional forms for the friction factor containing a strong velocity dependence can drive instabilities, as can a strong void-fraction dependence for interfacial friction in the two-fluid model. This is why the method is referred to as stability enhancing rather than unconditionally stable.

One simple illustration of the instabilities that can arise from explicit coefficients is the problem that initially prompted the peculiar linearized implicit friction terms (wall and interfacial) in TRAC versions later than PD2. Consider a test problem consisting of a 5 foot high vertical column with a stream of air bubbles injected at the bottom. The problem is started in a pure liquid state and run to a steady state two-phase bubble rise flow. For this example the column is divided into 20 equal length cells. When run with the standard release version of TRAC-PF1/MOD2, it runs stably at all time steps tested (.001 - .5 s). A second series of runs has been made with a special version of TRAC-PF1/MOD2 in which the interfacial drag terms are the product of an explicitly evaluated coefficient, the absolute value of the relative velocity evaluated at the old time, and the relative velocity evaluated at the new time level. This is the form found in the vessel component of TRAC-PD2 and in all know versions of RELAP5.

Figure 1 shows the vapor velocity at the bottom face of the top cell in the column for a stable run with a time-step of .001 seconds, and for an unstable run with a time step of .02 seconds. For this problem the material Courant limit is about .5 seconds. The instability onset appears at about .01 seconds, and time-step control in TRAC will not permit execution of the problem with step values

consistently much above .02 seconds. When examined in detail the vapor velocity is switching between two extreme values from one step to the next.

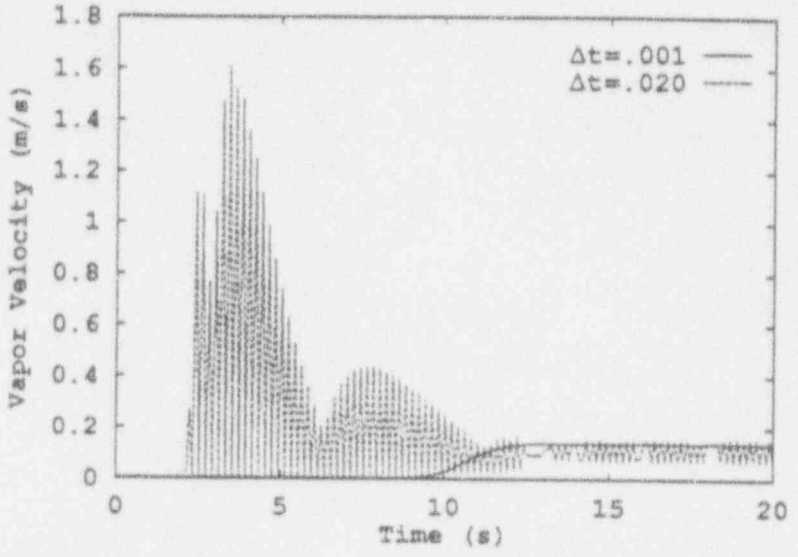

Figure 1. Bubble Rise Velocity

Figure 2 illustrates an important feature seen consistently in problems containing this type of interfacial drag instability. The mean void fraction in the column attains a steady value below that of the stable case. The average value of the bubble rise velocity in the unstable regime is larger than the actual bubble rise velocity. This oscillating instability has affected the accuracy of the prediction of the mean behavior of the system. Although the fix introduced in TRAC-PF1 appears to have solved the problem for all interfacial drag correlations used in the code. One could imagine correlations with more dependence on relative velocity introducing further instability due to old time level evaluation.

Other instabilities are clearly present in these codes due to explicit evaluation of various coefficients. Both TRAC and RELAP have had long term problems with time-step sizes being forced down to unexpectedly low values during the modeling of reflood. I believe that the prime cause in this situation is an unstable subcooled boiling model, but old time evaluation of wall and interfacial heat transfer coefficients are probably also playing a role. Even in seemingly stable conditions there is evidence [13] that fully explicit evaluation of wall heat transfer coefficients can lead to slow growth instability that significantly affects results, but is difficult to detect.

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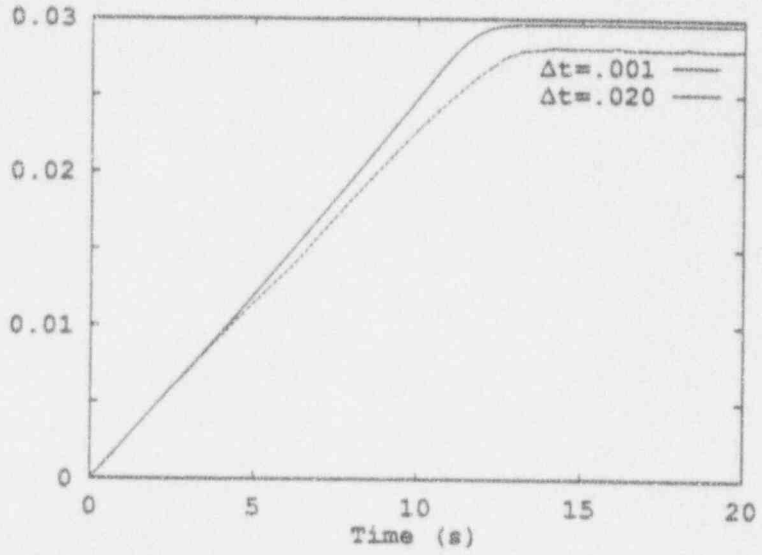

Figure 2. Mean Column Void Fraction

Although various forms of formal stability analysis are useful, only careful numerical experiments provide to final answers on numerical stability limits and the sources of some subtle instabilities. A common test is to drive a simple one dimensional channel with either two pressure boundary conditions or a combination of a mass flow and a pressure boundary condition. This is often fruitful, as in the above example. However, one should recognize that certain instabilities can be swept out of the exit pressure boundary condition. A more sensitive test is to construct a closed loop with either constant initial velocity and no wall friction or wall friction and a momentum source in one or more cells.

4. DIFFUSION

Because SETS was treated simply as an addition to the semi-implicit method, no attempt was made to modify the original spatial and temporal differencing procedures. As a result, the current form of SETS is first-order accurate in time and space and in some instances can produce excessive artificial diffusion. Fortunately, this diffusion is not often a problem in modeling reactor transients. The positive side effect of this low-order accuracy is that the method is extremely robust.

The existence of this strong numerical diffusion in codes with donor-cell differencing is well known. To provide a specific example, a test problem has been run using the boron field in TRAC-PF1/MOD2. A Boron solution is injected at time zero into a 10 meter pipe containing liquid moving at 1 meter per second. The boron mass fraction in the solution is 0.002. The pipe is initially modeled with 20 cells 0.5 meters in length. Figure 3 shows boron concentrations profiles at various times for a calculation with constant time steps of 0.250 seconds (half of the material Courant limit). Much of the numerical diffusion in this example is due to the implicit nature of the SETS method. In fact for

this problem with a constant velocity, the numerical diffusion is the same as that for a fully-implicit method using the same spatial differencing. Figure 4 contains the results of the same run with the stabilizing mass and energy equations eliminated. The code is running in semi-implicit mode, and has significantly less numerical diffusion. Numerical diffusion in this case is equivalent to that of a standard explicit method running with constant velocity.

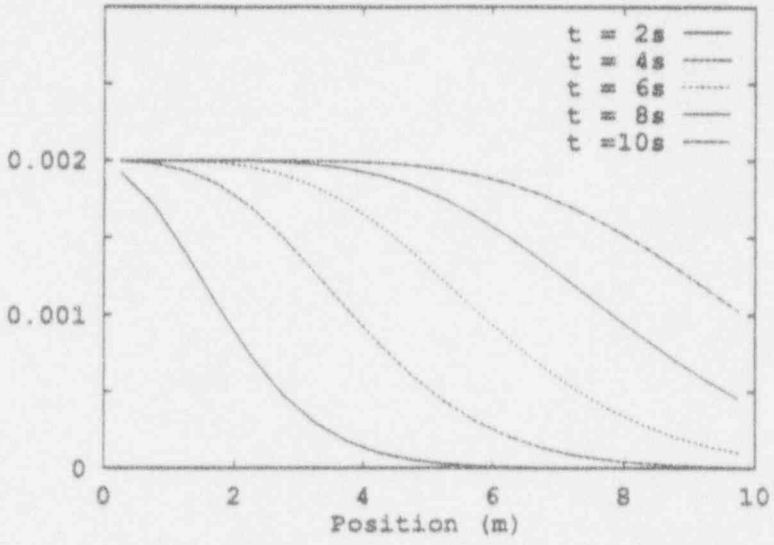

Figure 3. Implicit Diffusion Test, Time Step = .250s

Figures 5 and 6 illustrate the time-step size sensitivity of the implicit (SETS) and explicit (semi-implicit) time differencing scheme. As should be expected, the diffusion in the implicit method increases monotonically with time-step size. For the explicit numerical scheme, truncation terms associated with old time level evaluation of density in the mass flux tend to cancel the diffusive terms associated with donor-cell differencing. As should be expected, the boron profiles approach the same limit for the implicit and explicit methods as time-steps become small. For the explicit flux terms, diffusion decreases with increasing time-step size until a step function is propagated perfectly at the material Courant stability limit. In practice this non-diffusive propagation can not be achieved due to the standard use of a non-uniform mesh and the use of a variety of controls on time-step size.

Figure 4.

Figure 7 illustrates the effect of mesh size on diffusion for implicit and explicit fluxes. These results can also be predicted from the knowledge of the time and time-step dependence, and a remap of a given profile to half the time value on a mesh with half the cell length.

Figure 5.

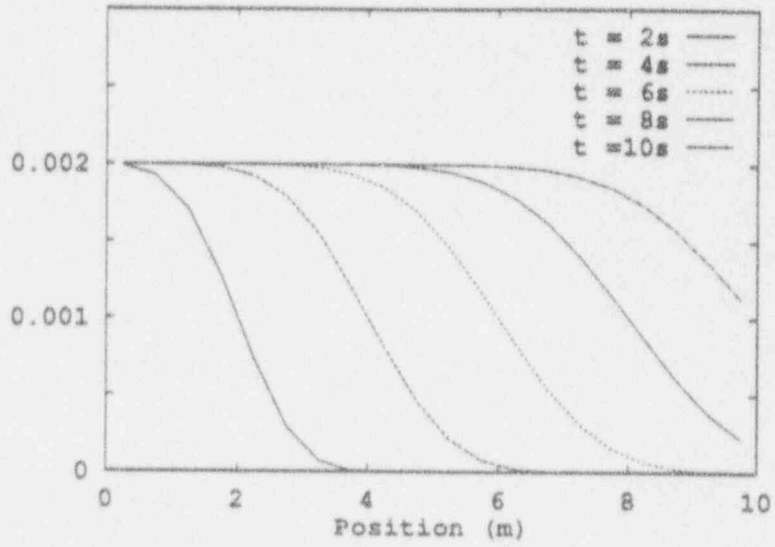

Figure 4. Explicit Diffusion Test, Time Step = .250s

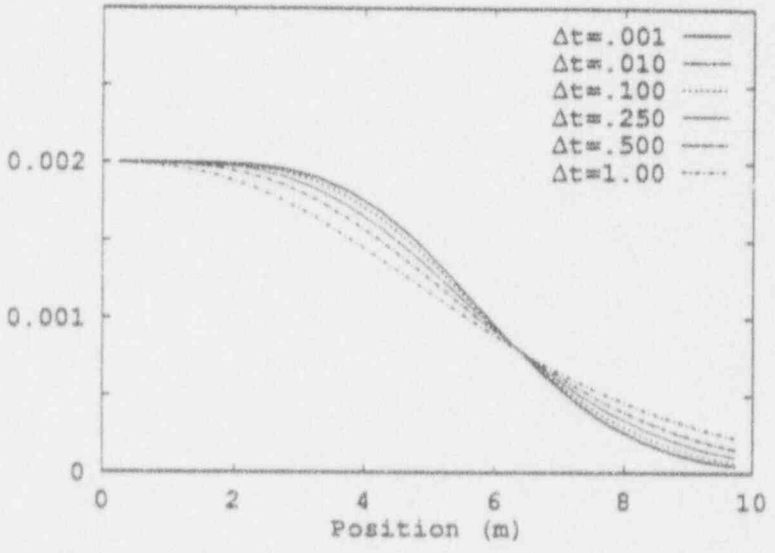

Figure 5. Implicit Diffusion Test, t = 6s

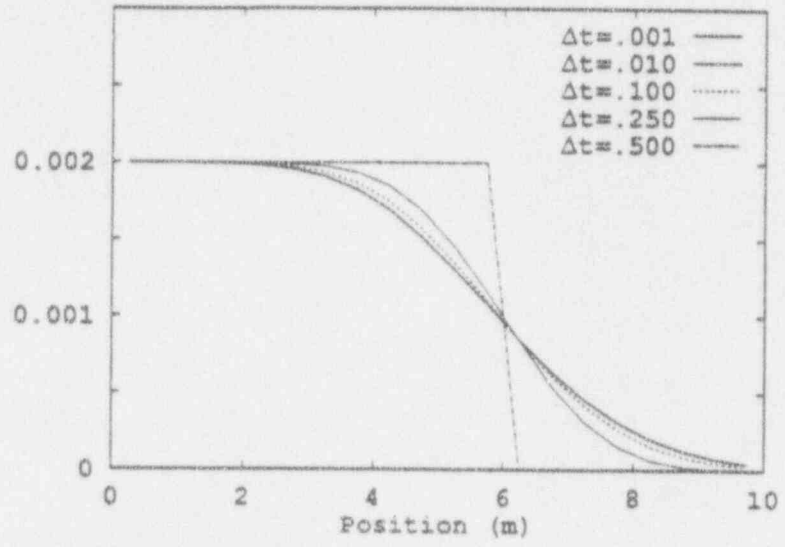

Figure 6. Explicit Diffusion Test, t = 6s

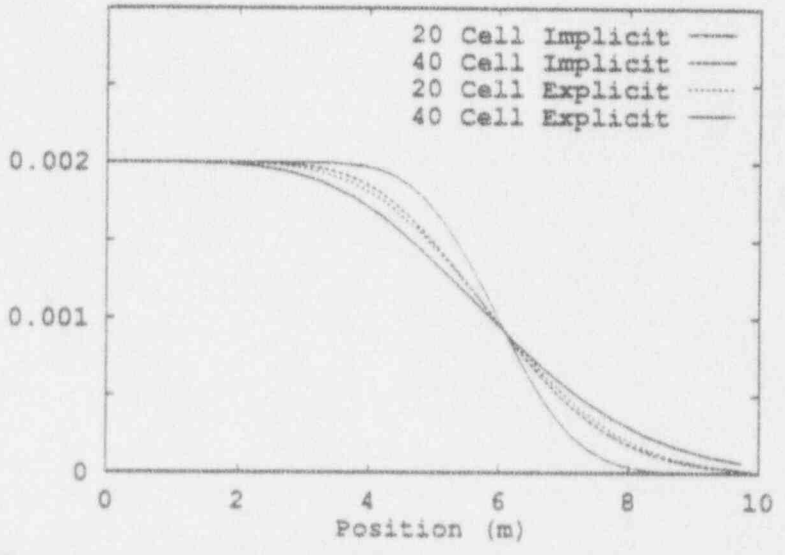

Figure 7. Diffusion Test, t = 6s, Time Step = .100s

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A misconception exists with some people that the numerical diffusion in a donor-cell method will damp out oscillations, making it inappropriate for the analysis of phenomena such as BWR core oscillations. Figure 8 presents a counter example to this assumption, plotting the time-history of the liquid level in a manometer. The manometer is modeled with 40, .05 meter cells. In fact Borkowski [14] has produced some very useful BWR predictions using TRAC-BF1. Numerical diffusion can act to damp high amplitude manometer oscillations down to a lower level that is maintained without further damping. However, the most frequent phenomena in codes like TRAC that act directly to suppress oscillations are related to water-packing [15]. Problems in thesis research by B. Boyer on flow instabilities in condensers [16] were traced to this source.

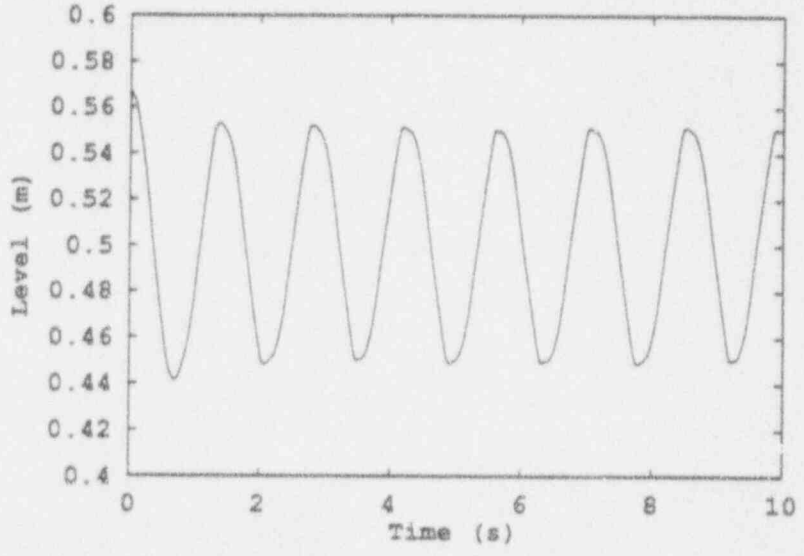

Figure 8. Manometer Liquid Level

Numerical diffusion can have an effect in the modeling of problems such as BWR core oscillations through another source. If a liquid front is artificially spread beyond it's true location in a core rod region, the underlying driving force may be incorrectly modeled to the extent that oscillations are never seen. These spreading effects tend not to be as severe in TRAC and RELAP as those spreading a boron front in a uniform velocity. The action of gravity combined with the non-uniform effects of interfacial drag on the liquid drop and vapor bubble velocities tend to keep fronts sharper than might be expected. The bubble rise stability test in Section 3 is a good example of this lowered amount of diffusion. The correct time for vapor arrival in the top mesh cell is 10.4 seconds. The first vapor is seen in this cell with a full SETS calculation at about 10.0 seconds for all time steps used (.001 - .5 s). In the case of the manometer oscillation presented in this section, no significant spreading of the liquid interface is seen.

At this time the basic versions of these system analysis codes continue to employ donor-cell spatial differencing. However, modifications to RETRAN-03 have been published that include a special

difference method to reduce numerical diffusion [17]. This method is applied to the full set of difference equations in RETRAN-03 and shows significant promise. An in-house version of TRAC includes a second-order Godunov method [18] to remove diffusion from the boron equation, but continues to use a standard full donor-cell difference in all other equations. This is scheduled for release in TRAC-PF1/MOD3. Similar improvement to the boron field in RELAP5 should be expected.

5. CONVERGENCE

There are actually two different convergence problems faced by these codes. The first is simply the convergence of the iteration required to solve the nonlinear coupled difference equations, and only is an issue for the TRAC series and the non-linear option in RETRAN. The Newton iteration in TRAC has always converged well provided that excessive changes in independent variables are limited by time-step control and tests are included to deal with transitions across the saturation line and between single and two-phase states. The second convergence problem is the question of whether the solutions to the difference equations converge to those of the differential equations as the time-step and mesh length approach zero. This property is also referred to as consistency.

The first thing to note regarding TRAC and RELAP5 is that it is not desirable to operate in a state where the difference equations are too close to full consistency with the differential equations. It is well known that the two-fluid model used in these codes is formally ill-posed [19]. Fortunately, at any practical time-step or mesh size, non-physical solutions are suppressed by the current difference equations. This issue should be reconsidered by anyone developing higher-order difference methods for reactor safety codes. It may be necessary to use a set of partial differential equations that are well-posed.

The most obvious occurrence of a consistency problem is in the TRAC-BWR motion equation. The difficulty can be illustrated with a simple flow equation

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} = 0 . \qquad (29)$$

The corresponding difference equation (assuming positive flow) in the BWR numerical method is

$$\frac{V^{n+1}_{j+1/2} - V^{n}_{j+1/2}}{\Delta t} + V^{n}_{j+1/2} \frac{V^{n+1}_{j+1/2} - V^{n}_{j-1/2}}{\Delta t} + \frac{1}{(\rho)^{n}_{j+1/2}} \left(\frac{P^{n+1}_{j+1} - P^{n+1}_{j-1}}{\Delta x} \right) = 0 . \qquad (30)$$

Now apply a standard truncation error analysis to Eq. (30), using Taylor series expansions about time level n and space point j+1/2. The result is

$$\left(1 + \frac{\Delta t\, V}{\Delta x}\right) \frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} + O(\Delta t) + O(\Delta x) + \ldots = 0 . \qquad (31)$$

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Consistency with the original partial differential equation clearly requires a time step size substantially below the material Courant limit.

The developers of TRAC-BWR were aware of this situation when the method was installed, but after careful consideration concluded that analysis of transients for which the code was designed would not be significantly affected. In most instances the velocity field is in a quasi-equilibrium state, or other conditions such as reflood or ECC injection limit the time-step well below the Courant limit. However, a user should always be aware of the limitations of this hybrid method. For example, it should not be applied to problems where the rate of coast-down after a pump trip or the time for establishing full natural circulation is important. In cases such as these, a standard SETS approach is clearly preferable.

A more subtle consistency problem is related to the modeling of discontinuities. One example of this is the classic water-packing problem [15]. If a water-packing pressure spike occurs on a given mesh, reduction of the time-step actually increases the magnitude of the spike. A second example is modeling of flow through an abrupt area change. Given the non-conservative form of the energy equation in TRAC and RELAP5, it is not possible to simultaneously obtain correct values for both the pressure and temperature change across an abrupt area change regardless of how small the time-step and mesh size. This is at the root of recent safety concerns, regarding the use of RELAP5/MOD3 to model both the reactor and containment (a job it was never meant to perform). This form of the energy equations also prevents the codes from correctly modeling the propagation of shock waves, but they have never been intended for that task.

6. CONCLUSIONS

The numerical methods in TRAC and RELAP5 have evolved to the point that they are very similar and share many advantages and flaws. The RETRAN series has followed a different path and now contains more implicit difference equations, and better options to counter numerical diffusion. Unfortunately RETRAN has continued to use a drift-flux formulation for it's basic equation set, limiting the range of transients that it can validly model.

Even after 15 years of development the TRAC and RELAP programs have numerical stability problems that should be resolved. The explicit treatment of friction and heat transfer coefficients is undoubtedly increasing the computer time required for simulating many transients. It may also be affecting the accuracy of these simulations.

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