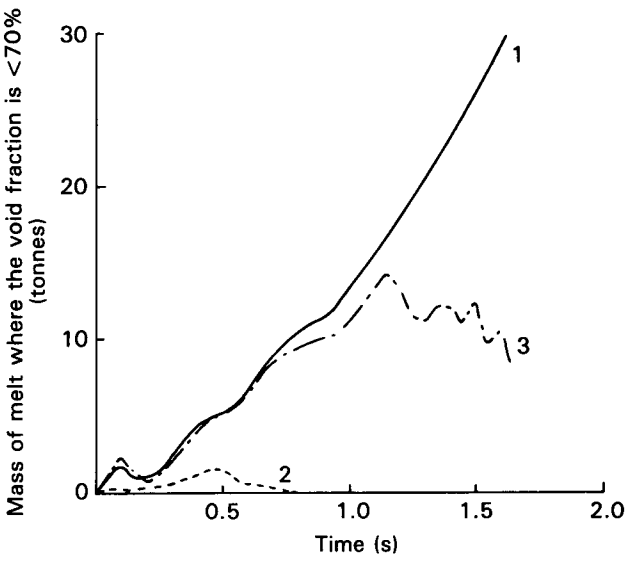

Fig. 2. Mass of melt where the void fraction is <0.7 as a function of time. Case 1 is for a standard version of CHYMES, case 2 for homogeneous flow, and case 3 for a modified vapor production term.

In all cases a fixed melt particle size of 20 mm was used. The following are evident from these calculations:

1. The homogeneous flow assumption ensures that there is little water present where there is melt, because as steam is produced and expelled it is forced to take the water out with it by design.
2. Making a modest change to the vapor generation term can have a very big effect on the predicted mass of melt in the premixture as defined by Theofanous et al.[1]; i.e., the predicted mass of melt in the "mixture" rises monotonically for a period of 1.5 s in case 1 and peaks at a value of ~15 tonnes in case 3. Thus, until we know more precisely what constitutes an explosive mixture, results of the type presented in Fig. 2 should only be used to examine the effect of varying parameters and initial conditions, etc., and should not be used as literal predictions of the "mass mixed." A detonation model is currently being developed for this purpose.[8]

To summarize, we have shown that there is also a U.K. model of premixing that has been used to perform reactor-scale simulations. However, it suffers from the same limitation as all the U.S. work: It is not yet a fully validated tool, and it can only be one if modelers and experimentalists work closely in a scientific manner. In this spirit, it should be feasible to develop validated models of all stages of the steam explosion process.

D. F. Fletcher
A. Thyagaraja

Culham Laboratory
General Physics and Theory Division
Abingdon
Oxon, OX14 3DB, United Kingdom

November 3, 1988

ACKNOWLEDGMENTS

The work described in this letter was funded by the General Nuclear Safety Research Program.

REFERENCES

1. T. G. THEOFANOUS et al., *Nucl. Sci. Eng.*, **97**, 259 (1987); M. A. ABOLFADL and T. G. THEOFANOUS, *Nucl. Sci. Eng.*, **97**, 282 (1987); W. H. AMARASOORIYA and T. G. THEOFANOUS, *Nucl. Sci. Eng.*, **97**, 296 (1987); and G. E. LUCAS et al., *Nucl. Sci. Eng.*, **97**, 316 (1987).

2. Letters to the Editor, *Nucl. Sci. Eng.*, **100**, 149–175 (1988).

3. A. THYAGARAJA and D. F. FLETCHER, *Comput. Fluids*, **16**, 59 (1988).

4. D. F. FLETCHER and A. THYAGARAJA, "Numerical Simulation of One-Dimensional Multiphase Mixing," CLM-P776, Culham Laboratory (1986).

5. D. F. FLETCHER and A. THYAGARAJA, "Numerical Simulation of Two-Dimensional Transient Multiphase Mixing," *Proc. 5th Int. Conf. Numerical Methods in Thermal Problems*, Montreal, Canada, June 29–July 3, 1987, Vol. 2, p. 945, Pineridge (1987).

6. D. F. FLETCHER and A. THYAGARAJA, "A Mathematical Model of Premixing," *Proc. Natl. Heat Transfer Conf.*, Houston, Texas, July 24–27, 1988, p. 184, American Nuclear Society (1988).

7. D. F. FLETCHER, "Large Scale Mixing Calculations," CLM-R282, HMSO, Culham Laboratory (1988).

8. D. F. FLETCHER and A. THYAGARAJA, "A Mathematical Model of Melt/Water Detonations," CLM-P842, Culham Laboratory (1988).

Response to "Comments on Fuel-Coolant Premixing Modeling"

There are two points being made by Fletcher and Thyagaraja.[1] The first challenges our statement that the only calculations available for large pours in reactor geometries and low pressures are ours. The other presents some results of their own and points out that very large premixtures can be obtained using their modeling approach and assumptions. We consider each point in turn.

On the question of the availability of reactor simulations other than ours, they claim that such have existed, but no evidence is provided to support this claim. Fletcher and Thyagaraja's Ref. 3 through 6 contain *no* such calculations. In fact, the *first and only, to this day*, calculation besides our own is the one presented in this letter by Fletcher and Thyagaraja. It may be interesting to the reader to know how this calculation came about.

I first learned of Fletcher and Thyagaraja's efforts in this area at a January 1987 meeting of a group of specialists on steam explosions at the Committee on Safety of Nuclear Installations (Organization for Economic Cooperation and Development) in Paris. In June 1987 I suggested to S. Board that it may be worthwhile to carry out a comparative exercise with Fletcher using our respective premixing models. Board supported the idea and talked to Fletcher, who accepted also, I thought, with enthusiasm. He agreed quickly with my specification for this exercise, which, in fact, is what is shown in Fig. 1 of Ref. 1. We both completed the exercise soon after that and were preparing to publish the results, except that Fletcher kept inventing reasons for postponement. We had agreed that we would *not* use these results until they were published together. In August 1988, Fletcher indicated to us that he was no longer interested in this

joint exercise. In his letter here, he put forth the bottom line of his results (curve 1 of his Fig. 2). Meanwhile, he documented most other aspects of this computation in a limited distribution report given as his Ref. 7. This brings us to his second point that pits these results against ours.

We address curve 1 of his Fig. 2. We disagree also with curve 2, but this two-fluid case is really more than 2-yr-old technology, and we will not waste time on it here, while curve 3 represents an arbitrary variation that does not capture the essence of the differences in the two models. These differences are indeed numerous and important, and as summarized below, they do not reflect favorably on Fletcher's modeling approach.

1. The interfacial drag was modeled by Fletcher, using an old formula by Harlow and Amsden, as follows:

$$D_{ij} = \frac{3}{4}\epsilon_i\epsilon_j\rho_i\rho_j C_{Di,j}\frac{L_iL_j}{\rho_iL_j+\rho_jL_i}\left(\frac{1}{L_i}+\frac{1}{L_j}\right)^2|V_j-V_i| \ ,$$

where

ϵ = volume fractions

L = length scales

V = velocities of phases i and j.

To our knowledge, this equation has not been used since, nor has it been compared to experimental data. In our model[2] we have adopted a flow-regime-dependent formulation due to Ishii and Zuber that has been experimentally verified and is in extensive use.

2. Fletcher assumes that the steam remains in saturation and allows no condensation. We emphasize that both steam superheating and steam condensation are seen to be very important in our computations.

3. Fletcher calculates the boiling rate $\dot{m}_s$ superposing radiation and film boiling heat transfer to the liquid by

$$h_{fg}\dot{m}_s = \epsilon_w\epsilon_p\frac{6}{D_p}\left[\sigma(T_p^4-T_w^4)+h_{FB}(T_p-T_w)\right] \ ,$$

where

ϵ_w, ϵ_p = water and melt volume fractions, respectively

T_p, T_w = melt particle and water temperatures, respectively

D_p = fuel particle diameter

h_{FB} = Bromley film boiling heat transfer coefficient

h_{fg} = steam latent heat of vaporization.

In contrast, we use a flow-regime-dependent formulation as follows.[2] For a steam void fraction (α, based on coolant volume) of <70% we assume we are in the bubbly or churn flow with sufficient water around each melt particle to maintain coolant saturation, to absorb all radiation emitted, and to yield film boiling in the sense of the Bromley correlation. For a steam void fraction >70%, we are in the dispersed water (droplet) regime with steam being the continuous phase. Thus, heat is transferred from fuel to steam by convection and from fuel to water by radiation. Thus, the steam is allowed to superheat and heat the suspended water droplets in it, which boil at saturation.

The impact of the above differences is illustrated in Fig. 1. Note that the curve marked "mimicking Fletcher's model" explains most of the discrepancy between Fletcher's high predictions and ours, although it does not quite match Fletcher's curve 1 in the latter portion of the transient shown. We will have to wait for the full documentation of his calculations before we can account for the remaining difference.

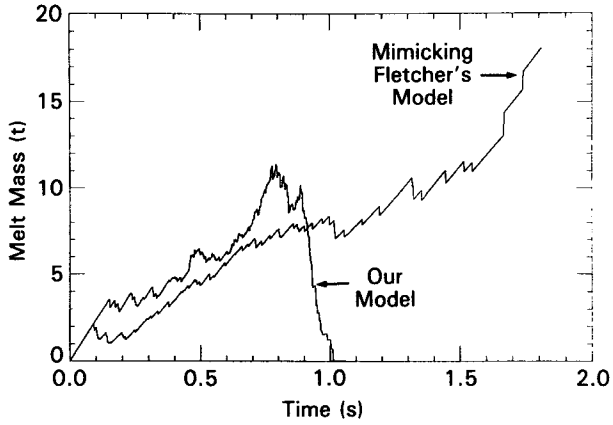

Fig. 1. The effect of constitutive law and model assumption limitations on Fletcher's predictions.

Much remains to be done, and we find it unfortunate that with such challenging tasks ahead we have to waste time in polemics.

T. G. Theofanous
W. H. Amarasooriya

University of California, Santa Barbara
Department of Chemical and Nuclear Engineering
Center for Risk Studies and Safety
Santa Barbara, California 93106

June 1, 1989

REFERENCES

1. D. F. FLETCHER and A. THYAGARAJA, *Nucl. Sci. Eng.*, **103**, 101 (1989).

2. W. H. AMARASOORIYA and T. G. THEOFANOUS, "Premixing of Steam Explosions: A Three Fluid Model," *Proc. Natl. Heat Transfer Conf.*, Houston, Texas, July 24–27, 1988, Vol. 3, p. 191, American Nuclear Society (1988).

Response to "Comments on Fuel-Coolant Premixing Modeling"

I want to provide some comments on the letters from Hopenfeld[1] and Fletcher and Thyagaraja[2] and relate them to the comments of Theofanous. I agree with some of the comments, but I want to focus on these comments in a particular order to emphasize how I think the fuel-coolant premixing issue can be investigated to move toward better agreement among researchers.

First, I agree with Fletcher that I should have included his model[3] in my summary Table I (see Ref. 4). If one were to do that and include the new mixing model incorporated into the IFCI code,[5] as well as the single calculation by Theofanous with his new model (ALPHA-PM, Ref. 6), then the table would look like Table I presented here.

If one reviews this table, it becomes immediately apparent