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A Unified Interpretation of One-Fifth to Full Scale Thermal Mixing Experiments Related to Pressurized Thermal Shock

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U.S. Nuclear Regulatory Commission

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ABSTRACT

Thermal mixing in relation to Pressurized Thermal Shock has been examined experimentally throughout the world in a variety of scales. These include the CREARE-1/5, the IVO/IVO(NRC)-2/5, the PURDUE(UCSB)-1/2, the CREARE-1/2, the HDR-1/1 and the UPTF-1/1 test facilities. The Regional Mixing Model and the associated computer programs REMIX and NEWMIX are used to interpret these data, in this report, in a comprehensive fashion. These interpretations indicate that cooldown transients and degree of stratification can be predicted with confidence. Universal stratification solutions are also provided, in graphical form, and a simple procedure for hand-calculation is also described.

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NOMENCLATURE

A_i	cross-sectional area of fluid stream i
A^*	$= A_c/A_{CL}$
D^*	$= D_{CL}/D_{HPI}$ diameter ratio
D_i	diameter of fluid stream, or system component i
d^*	$= d_c/D_{CL}$
d_i	depth of fluid stream i
Fr_i	$= U_i \{D_i g \Delta \rho / \rho\}^{-1/2}$, Froude number of stream i
$Fr_{HPI,CL}$	$= (Q_{HPI}/A_{CL}) \left\{ g D_{CL} \frac{\Delta \rho}{\rho} \right\}^{-1/2}$, superficial Froude number in the cold leg
g	acceleration due to gravity
h_i	enthalpy per unit mass of fluid stream i
$\dot{m}_{HPI}$	HPI mass flow rate
Q_i	volumetric flow rate of stream i
Q_o	volumetric flow rate out the system
Q^*	$= Q_e/Q_{HPI}$
Q_w	total heat flow into the system from walls
T	temperature
t	time
U_i	velocity of fluid stream i
V	volume of the whole system
V_i	volume of the fluid stream i
W	common width of contact between the two flowing streams
W^*	$W D_{CL}/A_{CL}$
y	vertical coordinate along a diameter of the cold leg, or down into the downcomer

Greek

α	flow regime parameter for back flow into the HPI line
β	fraction of entrainment from downcomer side
$\Delta \rho$	$\rho_i - \rho_j$ where i, j the two streams to which Fr is referred to.
κ	wave number
ρ	density
ρ^*	$= \rho_h/\rho_{HPI}$

Subscripts

c	cold stream
CL	cold leg
ϵ	center line
e	entrainment
HPI	high pressure injection
h	hot stream
m	well mixed or "ambient"
max	at the flooding limit
o	out flow
w	wall

Superscripts

$*$	nondimensional
-----	----------------

1. INTRODUCTION

The phenomena associated with High Pressure Safety Injection (HPI), and associated stratification/cooldown effects when this injection is under stagnated loop conditions, have received considerable attention since about 1981. The context of this interest is Pressurized Thermal Shock (PTS) and the stagnation conditions are peculiar to certain relatively narrow range of Small Break LOCAs [1]. The behavior cannot be described by systems codes (i.e., TRAC, RELAP), thus in addition to a large array of scaled experiments, considerable efforts have been expended in developing an associated analytical capability. These analytical directions ranged from large scale finite difference models (with a $k - \epsilon - \theta'$ description of turbulence) to empirically-oriented lumped parameter approaches. The Regional Mixing Model (RMM) and the associated computer programs REMIX and NEWMIX are based on a fundamentally-oriented zonal approach and have been successfully employed to the interpretation of all available experimental data, as well as to making reactor predictions for the Integrated Pressurized Thermal Shock (IPTS) study [2,3]. More recently, a number of utilities in this country as well as in Finland and Japan have requested and made use of REMIX/NEWMIX for similar purposes.

The description of the model, the computer program, and comparisons with experimental data have been extensively documented [4-16]. Although the comparisons with experimental data have been comprehensive in so far as encompassing all facilities and the key trends in each, space limitations in the usual "proceedings" or "archival publications" format did not allow these comparisons to include every single experimental trace available. The primary purpose of this report is to provide, under one cover, such a complete treatment. In addition, we provide a set of figures that encompass in a universal, i.e., scaled, fashion the complete solution to the stratification problem. That is, with the help of these figures (i.e., without ever running the computer program) the reader could predict the degree of stratification for any cold-leg/injector dimensions, injection rates, and fluid temperature combinations

All results are summarized in two appendices; the graphical solution of the stratification problem in Appendix A, and the comparisons with the experimental data in Appendix B. Because of the very large number of figures, special care has been exercised to make this report convenient to the reader. Toward this end, we have included:

- (a) a section on the theoretical development,
- (b) a section on the quick/graphical solution approach, and
- (c) "finder" tables at the beginning of each appendix.

In addition, the calculational bases, i.e., geometric data and experimental conditions, have been collected in convenient tabular form, and any special aspects of the REMIX/NEWMIX application or important features of the comparisons are summarized in the "discussion" section.

2. THE REGIONAL MIXING MODEL

Qualitatively, the physical situation may be described with the help of Figure 1. In the absence of loop flow, the relevant portions of the system include, as illustrated, the loop seal, pump, cold leg (and HPI line), downcomer and lower plenum. Dimensions and volumes typical for a 3,000 MW_{th} PWR are summarized in Table 1.

Figure 1. The temperature zones of the RMM.

Table 1. Geometric data of a typical 3,000 MW_{th} power plant[†]
Injector diameter: 21.6 cm

	Cold Leg	Vessel/ Downcomer	Lower Plenum	Pump	Loop Seal	Core Barrel	Thermal Shield
Inner Diameter (cm)	69.80	394.90	---	---	69.80	340.00	362.30
Length (cm)	704.00	634.30	---	---	444.30	634.30	466.30
Base Metal Wall Thickness (cm)	6.35	24.50	24.50	---	6.35	5.20	7.30
Clad Thickness (cm)	0.30	0.60	0.60	---	0.30	---	---
Insulation Thickness (cm)	8.90	8.90	8.90	8.90	8.90	---	---
Wall Heat Transfer Area to Water (cm ²) x 10 ⁻⁵	1.54*	7.87	3.30	---	0.97*	6.98	10.83**
Fluid Volume (cm ³) x 10 ⁻⁶	2.69*	12.56	13.80	2.00*	1.70*	---	---

[†] 3-loop Westinghouse Plant

* Per cold leg

** Both sides included

Initially, this whole portion of the primary system is filled with coolant (water) at a temperature near that of normal operation (~ 550 K). The cooldown transient is initiated by actuation of the HPI. Typical injection rates are ~ 10 to 15 kg/s although, depending on the system pressure, both lower and time-dependent injection rates are possible. Coolant exits at an equivalent rate through the reactor vessel, as indicated in Figure 1, and eventually out the break.

The ensuing flow regime, first established analytically by Theofanous and Nourbakhsh [4] is schematically illustrated in Figure 1. A “cold stream” originates with the HPI plume at the point of injection, continues toward both ends of the cold leg, and decays away as the resulting plumes fall into the downcomer and pump/loop-seal regions. A “hot stream” flows counter to this “cold stream” as indicated, supplying the flow necessary for mixing (entrainment) at each location. This mixing is most intensive in certain locations identified as mixing regions (MRs). MR1 indicates the mixing associated with the highly buoyant, nearly axisymmetric HPI plume. MR3 and MR5 are regions where mixing occurs because of the transitions (jumps) from horizontal layers into falling plumes. MR4 is the region of final decay of the downcomer (planar) plume. The cold streams have special significance since they induce a global recirculating flow pattern with flow rates significantly higher than the new flow through-put (Q_{HPI}). This keeps a major portion of the system volume in a well-mixed condition (at temperature T_m in Figure 1), so that the whole process may be viewed as the quasi-static decay of the cold streams within a slowly varying “ambient” temperature.

The quantitative aspects of this physical behavior were incorporated in the Regional Mixing Model (RMM) [4]. This model accounts for countercurrent flow limitations between the cold and hot streams at the cold leg/downcomer junction and incorporates plume mixing rates which are consistent with data from idealized single plume geometries. Subsequent system simulation tests confirmed the above described trends and began a data base against which the quantitative aspects of the RMM could be assessed.

The computation proceeds at two levels. The one is global and seeks to establish a “mean” system response, referred to as “ambient” in the discussion of the flow patterns above. The other is local and seeks to partition mass and energy into the cold and hot streams consistent with mixing rates and countercurrent flow requirements. The global computation proceeds from the initial conditions marching out in time. The local computation provides, at arbitrarily selected times, snapshots of detail constructed upon the global results. In practice, it is convenient that the two levels of computation proceed in parallel. The derivations can be followed with the help of Figure 1. The term “system” will refer to the assembly of components shown in Figure 1, with the following clarifications: (a) the outer vertical leg of the loop seal and the portion of the downcomer above the cold leg are not included, (b) the lower plenum volume is taken up to the lower edge of the core barrel, and (c) the downcomer and lower plenum volumes are partitioned equally among the available loops.

At the global level of the computation, we assume that the whole system is well mixed. It receives the mass and energy of the HPI flow and heat released from the walls and discharges a stream at the instantaneous, well-mixed density and energy levels. We therefore have

$$V \frac{d\rho_m}{dt} = Q_{HPI} \rho_{HPI} - Q_o \rho_m \quad (1)$$

$$V \rho_m \frac{dh_m}{dt} = Q_{HPI} \rho_{HPI} (h_{HPI} - h_m) + \dot{Q}_w \quad (2)$$

These are solved together with the water equation of state $\rho_m = f(h_m)$ to provide $Q_o(t)$, $h_m(t)$, and $\rho_m(t)$. The wall heat, $\dot{Q}_w$, is computed from co-currently run transient conduction calculations. The code can accommodate any number of such heat slab calculations, which can be specified to include such layered geometries as stainless steel clad, carbon steel vessel wall, insulation. At solid-fluid interfaces, boundary conditions are expressed in terms of prescribed heat transfer coefficients. For reactors, heat losses to the outside air are unimportant. On the water side, for reasonable choices in heat transfer coefficients, convection is sufficient to eliminate any sensitivity (i.e., conduction controls).

In the local calculation we seek to establish the flows, energies, and the volumes of the cold and hot streams. One of the more important features of the present model is that this volume partition is not chosen arbitrarily, but rather it is obtained as part of the solution. The mass and energy balances for a control volume around MR1 (see insert to Figure 1) then yield

$$Q_{HPI}\rho_{HPI} + Q_h\rho_h = Q_c\rho_c \quad (3)$$

$$Q_{HPI}\rho_{HPI}h_{HPI} + Q_h\rho_h h_h = Q_c\rho_c h_c \quad (4)$$

where Q_h and Q_c are the total hot and cold stream flow rates; that is, going to or coming from both directions as shown in the figure. The hot stream flow rate is equal to that entrained to the falling plume and depends on the injection Froude number, Fr_{HPI} , and the fall height $d_h = D_{CL} - d_c$

$$Q_h = Q_e(d_h, Fr_{HPI}) = 0.52 Q_{HPI} \left[\frac{d_h}{D_{HPI}} \right]^{1.236} Fr_{HPI}^{-0.414} \quad (5)$$

This entrainment function is valid for $0.1 < Fr_{HPI} < 3$. It was obtained by fitting the results of turbulence model, $\kappa - \epsilon - \theta'$, calculations and was shown to be in agreement with existing axisymmetric plume data [4]. Energy is partitioned into the hot and cold stream volumes such that the total energy remains equal to the mean value obtained from the global calculation

$$V_c\rho_c h_c + V_h\rho_h h_h = (V_c + V_h)\rho_m h_m \quad (6)$$

The cold volume is taken to be equal to that of the cold stream; that is, expressed in terms of the cold leg length and the height, d_c , of the cold stream in it. The hot volume is taken as the sum of the hot stream volume (in the cold leg) plus 25% of the pump volume, plus the volume of a horizontal downcomer slice with a height equal to 2 cold leg diameters.

Equations (3), (4), (5), and (6) are solved together with the counter-current flow requirement [15]

$$Fr_c^2 + Fr_h^2 = 1 \quad (7)$$

and the equation of state $\rho = f(h)$ to yield Q_e , Q_c , ρ_h , ρ_c , h_h , h_c , and d_h . The numerical procedure iterates on an assumed cold stream height. It calculates all other parameters from Equations (3) to (6) and repeats until Equation (7) is satisfied. The cost of such calculations is trivial.

Clearly, the Froude numbers in Equation (7) must be based on the actual cold stream and hot stream hydraulic diameters (stream cross-sectional area divided by the width of contact between the two streams), and respective flow rates exiting and entering the cold leg, rather than on the

total flows depicted in Equations (3) and (4). This is accomplished by the use of a parameter, β , that expresses the fraction of Q_e which mixes with the plume coming from the direction of the vessel. That is, the hot stream flow for use in Fr_h is βQ_e . Therefore, the portion arriving for entrainment from the loop seal side would be $(1 - \beta)Q_e$. Since the system is closed on that side, an equal volumetric rate of cold stream must flow in that direction. As a consequence, the net flow to be used in Fr_c of Equation (7) should be $Q_c - (1 - \beta)Q_e$ or $Q_{HPI} + \beta Q_e$. Even for an inclined injection, for the very low Froude numbers of interest, momentum effects are negligible and a symmetric behavior, i.e., $\beta = 0.5$ is adequate. This was confirmed by experimental visualizations. Furthermore, the results are insensitive to the choice of β [8].

There are two additional aspects of REMIX and NEWMIX which, because of their complicated nature, had to be treated empirically.

(a) Mixing within the HPI line. It was predicted [4] that for $Fr_{HPI} < 1$, backflow of the hot stream fluid and mixing within the injection line should be expected. Purdue's initial 1/2-scale experiments (Configuration-0) confirmed this prediction and provided the basis for taking this effect into account [16]. The approach is to define an effective HPI plume origin that moves into the injection line as the Fr_{HPI} decreases below the value of 0.6, as shown in Figure 2. In the calculations, this additional length, L_{eff} , is added to the d_h value to obtain the entrainment from Equation (5).

(b) Mixing at the cold leg-downcomer junction. A highly complicated three-dimensional mixing pattern occurs in MR3. In the original formulation of the RMM, the approach was to conservatively neglect this contribution to the mixing in the downcomer. Rather, the cold stream exiting the cold leg was assumed to form smoothly into a planar plume within the downcomer and to decay according to the $\kappa - \epsilon - \theta'$ turbulence model predictions [4]. Rapid decay was predicted, nevertheless. A refinement was possible on the basis of PURDUE's 1/2-scale data [7,16]. The planar plume is taken to form within a distance of $2D_{CL}$ below the cold leg centerline and to be fed in equal volumetric flow rates by the cold stream and surrounding hot volume fluid. The resulting temperature of the plume is used as initial planar plume temperature (T_j). Below this point, the decay is approximated to that of a planar plume of initial width equal to D_{CL} and $Fr = 1.0$, as shown in Figure 3. Note that decay here refers to actual heatup, and the temperatures so calculated are at the plume centerline, i.e., the lowest for any given distance from the plume origin. It should also be noted that since the cold stream, exiting the cold leg, always adjusts itself to a Froude number of ~ 0.5 , as was indeed the case in the experiments, this empirically determined entrainment at the junction (or cold stream "jump") should be generally valid. Clearly, the temperature outside the planar plume will be T_m . When $L/D_{CL} < 2$, the plume temperature is obtained as a linear interpolation between T_c and T_j .

Equation (7) is very interesting because it provides a natural control on the two streams. It expresses the condition of stationarity (on propagation rather than growth) of long, neutrally stable waves at the interface between the two counter-currently flowing streams as given by [17]

$$\rho_c U_c^2 \coth(\kappa d_c) + \rho_h U_h^2 \coth(\kappa d_h) = \frac{g}{\kappa}(\rho_c - \rho_h) \quad (8)$$

Accordingly, any flow conditions for which these equations apply cannot be changed gradually without leading to violent disruption of the flow by an internal hydraulic jump. As the flow rates and densities of the two streams are related by mass and energy conservation, Equations (3) and (4), Equation (7) expresses a single parameter family of flows — the cold stream depth being

Figure 2. Effective increase in HPI plume length used in RMM to represent mixing within the HPI line. For $Fr_{HPI} < 0.2$ behavior is very sensitive to the geometry

the parameter. That is, for a given primary fluid temperature, and HPI temperature and flow rate, each value of the cold stream depth specifies a corresponding value of the rate of entrainment (in the mixing plume of MR1). In particular, we have shown [9] that this relationship exhibits a maximum, and derived the position of this maximum in terms of the Froude number as

$$d_{max}^* = \frac{d_{c,max}}{D_{CL}} = 0.51 + 0.75 Fr_{HPI,CL} - 1.69 Fr_{HPI,CL}^2 + 2.86 Fr_{HPI,CL}^3 \quad (9)$$

We hypothesized that this maximum would, in fact, be obtained if the plume mixing conditions in MR1 were sufficiently intense as, for example, under very high Froude number injections (i.e., forceful jet impinging and splashing off the opposite wall in the cold leg). In this extreme Equation (5) becomes irrelevant and Equation (7) expresses the sole control of stratification.

The situation of combined control (that is, plume mixing and counter-current flow) is then pertinent to low Froude number injections from the top of the cold leg and can be computed with REMIX. The situation of sole counter-current flow control is pertinent to very high Froude number injections of any orientation and it can be computed with NEWMIX. In US reactor designs the HPI is typically 10–15 kg/s and what the situation is depends on the size of the injection nozzle. For example, typically Combustion Engineering and Westinghouse designs employ 25.7 and 21.6 cm nozzles (Calvert Cliffs and H.B. Robinson, respectively) and yield

Figure 3. Planar plume temperature as function of distance (L) from the cold leg centerline

Froude numbers of 0.3 and 0.5, while Babcock and Wilcox (i.e., Oconee) employs a 5.4 cm nozzle, which yields a Froude number of 16. This Oconee nozzle is on the side of the inclined (upward) portion of the cold leg which also helps maximize entrainment; in this case we have actually demonstrated experimentally the NEWMIX limit [9].

As a word of caution, there may be special cases with an intermediate behavior. These would involve top or side injections into a horizontal leg with not-so-high Froude numbers, or top injections with not-so-low Froude numbers. The latter case would produce somewhat higher temperatures than predicted by REMIX, but the former one could yield lower temperatures than the NEWMIX (i.e., non-conservative). From the point of view of poor mixing the worst are low Froude number injections (i.e., large nozzles) from the bottom or side of the cold leg. All such injections are outside the scope of this effort.

3. A SIMPLE GRAPHICAL SOLUTION

The plume entrainment rate, Equation (5) together with the relation of Figure 2, can be put in dimensionless form as

$$Q^* = 0.52 \{ 3\alpha D^{*-0.84} Fr_{HPI,CL}^{-0.33} - 5\alpha D^{*1.66} Fr_{HPI,CL}^{0.67} + (1-d^*) D^{*0.16} Fr_{HPI,CL}^{-0.33} \}^{1.236} \quad (10)$$

$$\alpha = \begin{cases} 1 & \text{for } Fr_{HPI,CL} < 0.6 D^{*-2.5}; \\ 0 & \text{for } Fr_{HPI,CL} > 0.6 D^{*-2.5}. \end{cases}$$

where $Q^* = Q_e/Q_{HPI}$, $d^* = d_c/D_{CL}$, $D^* = D_{CL}/D_{HPI}$ and

$$Fr_{HPI,CL} = (Q_{HPI}/A_{CL}) \left\{ g D_{CL} \frac{\Delta \rho}{\rho} \right\}^{-1/2} \quad (11)$$

The behavior is illustrated in Figures 4 and 5. Note in these figures that Q^* decreases as d^* goes up and that the whole family of lines is shifted downward as D^* increases. The first trend reflects the decreased exposure of the plume to the hot stream (as d_c increases). The second trend is primarily due to the regime change, in Equation (10), regarding backflow in the injection line. This transition occurs at

$$D_{tr}^{*2.5} Fr_{HPI,CL} = 0.6 \quad (12)$$

which yields D_{tr}^* values of 2.05 and 3.9 for $Fr_{HPI,CL}$ values of 0.1 and 0.02, respectively. For $D^* > D_{tr}^*$, at a given value of $Fr_{HPI,CL}$, the $\alpha = 0$ regime applies, there is no backflow in the injection line, and entrainment is considerably lower than for $D^* < D_{tr}^*$ (i.e., the $\alpha = 1$ regime with backflow). It is also clear that the $\alpha = 0$ regime is much less sensitive to the value of D^* than the $\alpha = 1$ regime.

Figure 4. Illustration of plume (jet) entrainment for $D^* = 2.0$. $Fr_{HPI,CL}$ is ranging from 0.02 to 0.30 in increments of 0.02

Figure 5. Illustration of plume (jet) entrainment for $D^* = 3.0$. $Fr_{HPI,CL}$ is ranging from 0.02 to 0.30 in increments of 0.02

Similarly, Equation (7) can be put in a dimensionless form [9], with the additional quantities defined by $\rho^* = \rho_h / \rho_{HPI}$, $W^* = W D_{CL} / A_{CL}$, and $A^* = A_C / A_{CL}$ to obtain

$$Q^{*3} + a Q^{*2} + b Q^* + c = 0 \quad (13)$$

where

$$a = \left\{ \frac{\rho^*}{(1 - A^*)^3} + \frac{1 + 2\rho^*}{A^{*3}} \right\} / \beta \rho^* \delta \quad (14)$$

$$b = \frac{\rho^* + 2}{A^{*3}} / \beta^2 \rho^* \delta \quad (15)$$

$$c = \left\{ \frac{1}{A^{*3}} - \frac{1}{W^* Fr_{HPI,CL}^2} \right\} / \beta^3 \rho^* \delta \quad (16)$$

and

$$\delta = \frac{1}{(1 - A^*)^3} + \frac{1}{A^{*3}} \quad (17)$$

Since W^* , A^* , and d^* are all geometrically related. Equation (13) provides a simple relationship of the form:

$$Q^* = f(d^*, \rho^*, Fr_{HPI,CL}, \beta) \quad (18)$$

In reactor applications ρ^* is initially at ~ 0.8 and approaches unity as the cooldown transient goes on. The effect of this variation on the results of Equation (18) is negligible. The $Fr_{HPI,CL}$ begins typically at a value of ~ 0.02 and increases gradually, through the cooldown transient. The relevant values of the parameter β are 0.5 and 1.0. The functional dependance of Equation (18) may be visualized, for the appropriate range of these parameters, with the help of Figures 6 and 7. The maxima in these figures corresponds to the NEWMIX limit of maximum entrainment. Over the ranges covered in Figures 6 and 7, the depth of the cold stream where this maximum occurs, d_{max}^* , could be fit by

$$d_{max}^* = \frac{d_{c,max}}{D_{CL}} = 0.51 + 0.75 Fr_{HPI,CL} - 1.69 Fr_{HPI,CL}^2 + 2.86 Fr_{HPI,CL}^3 \quad (19)$$

which is the equation actually used in NEWMIX. On the other hand, under low Froude number condition, the REMIX analysis procedure on stratification can now be seen as seeking the intersection between lines (of the same $Fr_{HPI,CL}$) in Figures 6 or 7 and a figure like Figure 4 drawn for the appropriate value of D^* . Moreover, the different states of stratification during a cooldown can be seen as trajectories (made up with points of such intersections) as illustrated in Figure 8 for the specific examples of Calvert Cliffs and H.B. Robinson (i.e., the IPTS plants).

Figure 6. Illustration of counter-current flow limited entrainment for $\rho^* = 0.8$ and $\beta = 1.0$. $Fr_{HPI,CL}$ is ranging from 0.02 to 0.30 in increments of 0.02.

Figure 7. Illustration of counter-current flow limited entrainment for $\rho^* = 0.8$ and $\beta = 0.5$. $Fr_{HPI,CL}$ is ranging from 0.02 to 0.30 in increments of 0.02

Using this simple superposition procedure, the stratification can be predicted, rather simply, for any conditions of interest. To make this easy full-page plots are provided in Appendix A for all conceivable ranges of dimensionless parameters.

In fact, even full cooldowns can be roughly predicted, by hand, since an estimate of h_m can be obtained from Equation (2) by assuming ρ_m to be a constant and using a rough estimate for $\dot{Q}_w(t)$. Having h_m as a function of time cold stream temperatures can be predicted, at any time, by the use of figures in Appendix A. With that initial plume temperatures and plume decay in the downcomer can be predicted as discussed already (use of Fig. 3). Finally, from the axial variation of the plume centerline temperature the azimuthal variation can be simply obtained by

$$T^* = \frac{T_m - T}{T_m - T_\infty} = \exp \{-41\eta^2\} \quad (20)$$

where

$$\eta = \frac{k}{n} \quad (21)$$

for any position with $y = nD_{CL}$ and $x = kD_{CL}$, where y is the distance along the downcomer and x is the distance in the azimuthal direction.

Figure 8. Trajectory of the REMIX solution for the case of the Calvert Cliffs and H.B. Robinson PWRs

As an illustrative numerical example of using this approach consider the Calvert Cliffs reactor under a safety injection of $\dot{Q}_{HPI} = 13.54$ kg/s. The mixing volume is 18.14 m^3 and initial, (0), and injection (HPI), temperatures, enthalpies and densities are given below.

$$T_{mo} = 548 \text{ K} \quad h_{mo} = 1220.84 \text{ kJ/kg} \quad \rho_{mo} = 754.8 \text{ kg/m}^3$$

$$T_{HPI} = 304 \text{ K} \quad h_{HPI} = 135.8 \text{ kJ/kg} \quad \rho_{HPI} = 996.5 \text{ kg/m}^3$$

Following the procedure in the previous paragraph we have

$$h_m = \left\{ h_{HPI} + \frac{\dot{Q}_w}{\dot{Q}_{HPI}\rho_{HPI}} \right\} - \left\{ h_{HPI} + \frac{\dot{Q}_w}{\dot{Q}_{HPI}\rho_{HPI}} - h_{mo} \right\} \exp \left\{ -\frac{t\dot{Q}_{HPI}\rho_{HPI}}{V\rho_m} \right\} \quad (22)$$

At $t = 500$ s with an estimate for $\dot{Q}_w = 2321$ kw, we obtain $h_m = 864$ kJ/kg. This corresponds to 474 K which compares with 480 K calculated with REMIX. Now, the Froude number can be obtained as

$$Fr_{HPI,CL} = 0.028 \quad (23)$$

and from Figures 5 and 7 (intersection of 0.028 lines by interpolation) we read

$$Q^* = 3.0 \quad \text{and} \quad d^* = 0.27 \quad (24)$$

Then T_c can be obtained from

$$T_c = \frac{\rho_{HPI} T_{HPI} + \rho_m T_m Q^*}{\rho_{HPI} + \rho_m Q^*} = 422 \text{ K} \quad (25)$$

and this compares to 435.6 K obtained from REMIX. Now, T_j can be estimated from

$$T_j = 0.5(T_c + T_m) = 448 \text{ K} \quad (26)$$

and with T_m and T_j at hand the centerline plume temperature can be determined easily from Figure 3. Finally the temperature at any position can be obtained using Eq. (20).

4. THE DATA BASE AND SPECIAL FEATURES OF THE COMPUTATIONS

A scaled representation of the world thermal mixing facilities, and their relation to a full PWR, is given in Figure 9. The scales and the identifying information on these facilities is summarized in Table 2. What was originally known as the PURDUE facility has been transferred to UCSB, hence the joint identification. The original IVO program was for the Loviisa reactor in Finland, while that identified as IVO(NRC) was an extension aiming to simulate US reactor conditions. In addition to their wide variation in scale, these facilities were operated under widely different conditions. They included both solute and/or thermally induced buoyancy and concentration or temperature measurements as an indication of mixing. In particular: the PURDUE (UCSB) experiments were run with room temperature water and brine (the HPI), and mixing was obtained from concentrations measurements; the CREARE-1/5, IVO, and IVO(NRC) experiments were run with solute buoyancy also, but mixing was inferred from temperature measurements; finally the CREARE-1/2, HDR, and UPTF were all run at pressure, i.e., thermally-induced buoyancy and temperature as the tracer. The HDR is a full pressure (temperature) facility of somewhat reduced scale of downcomer gap (1/2) and cold leg (1/4), the UPTF is a full-scale facility run at reduced pressure, and CREARE-1/2 is representative of a combination of both attributes. The IVO(NRC) tests are unique in involving multiloop injection, i.e., plume interactions in the downcomer (circumferentially 1/2). The HDR and UPTF experiments, on the other hand, involved single loop operation on a whole downcomer. Typical operating parameters for all are summarized in Table 3. The relevant geometric features of all the facilities have been collected in Tables 4 to 10. Run numbers and respective experimental conditions are given in Tables 11 to 15. More details about these facilities and their operation can be found in the references listed in Table 16.

In all calculations carried out for these comparisons the REMIX and NEWMIX programs were used in their established form [13]; however, some special features of individual facilities had to be considered as follows:

IVO/IVO(NRC) and CREARE Tests. The core side of the downcomer in these facilities was exposed to air. Heat losses were taken into account by an estimate of the insulation and natural convection to air. For the IVO/IVO(NRC) special consideration was given to the properties (heat capacity, etc.) of the CaCl_2 solution as functions of both temperature and concentration.

Figure 9. Scaled representation of the world thermal mixing facilities

HDR Tests. The reactor core space was filled with water which was free to recirculate within this region. The calculations allowed for heat transfer to the downcomer, through the core barrel, with natural convection coupling to the two fluids on either side of it. The letdown was from the bottom of the lower plenum, hence the core fluid was considered as a closed system.

UPTF Tests. Here the lower plenum contains 17 large (50–60 cm) pipes that contain trapped hot water whose temperature transient has been measured in the experiments. The total volume involved is $\sim 9 \text{ m}^3$, and the wall thickness is $\sim 1 \text{ cm}$ (stainless steel). This “extra” energy source was accounted for by a simple calculation of the thermal resistances involved and a driving force based on measured trapped-fluid temperature transient and computed lower plenum fluid transient.

To summarize the above it is important to emphasize that these special considerations arise from unique and non-prototypic aspects of these facilities, and their significance (or effect) to the comparisons is, in any case, very limited. For reactor calculations we have in the past neglected heat transfer from the core region to the downcomer. This is, of course, conservative, and we believe an appropriate step since all the rest of the computation is carried out on a best estimate basis. Eliminating this conservatism for reactor applications should carefully consider the actual geometry (baffle region, bypass flows, etc.).

Table 2. Key to the experimental facilities

FACILITY	SCALE	ORGANIZATION	SPONSOR	COUNTRY
CREARE	1/5	CREARE, Inc.	EPRI	USA
IVO	2/5	Imatran Voima Oy	IVO	Finland
IVO(NRC)	2/5	Imatran Voima Oy	USNRC	Finland
PURDUE(UCSB)	1/2	Purdue University (UCSB)	USNRC	USA
CREARE	1/2	CREARE, Inc.	EPRI/NRC	USA
HDR	1/1	Battelle Institute	BMTF	Germany
UPTF	1/1	KWU Kraftwerk Union	BMTF	Germany

Table 3. Typical operating parameters used in the various integral test facilities

Facility	$\dot{m}_{HPI}$ (Kg/s)	$\Delta\rho/\rho_{HPI}$	Fr_{HPI}	$Re_{HPI} \times 10^{-4}$
PWR	13.60	0.25	0.50	8.00
CREARE 1/5-Scale (Run 106)	0.13	0.02	0.57	0.25
IVO (NRC) (Test T111)	0.49*	0.16	0.40	0.71
PURDUE 1/2-Scale (0-1C)	0.71	0.09	0.23	0.84
CREARE 1/2-Scale (May 105)	5.17	0.12	1.42	4.92
HDR Full-Scale (T32.15)	0.99	0.28	1.30	2.50
UPTF Full-Scale (Run #025)	20.00	0.11	2.42	19.50

*Per cold leg.

Table 4. Geometric data of PURDUE(UCSB) 1/2-scale test facility
Injector diameter: 10.8 cm

	Cold Leg	Vessel/ Downcomer	Lower Plenum	Pump	Loop Seal	Core Barrel	Thermal Shield
Inner Diameter (cm)	34.30	12.50*	---	---	34.30	---	---
Length (cm)	409.00	192.00	---	---	265.00	---	---
Fluid Volume (cm ³) x 10 ⁻³	3.78	2.86	9.94	2.42	2.45	---	---

*Gap between vessel wall and core barrel.

Table 5. Geometric data of CREARE 1/5-scale test facility (MIX4)
Injector diameter: 5.08 cm or 0.7 cm

	Cold Leg	Vessel/ Downcomer	Lower Plenum	Pump	Loop Seal	Core Barrel	Thermal Shield
Inner Diameter (cm)	14.29	---	---	---	14.29	---	---
Length (cm)	157.98	121.16	---	---	121.90	121.16	84.46
Acrylic Wall Thickness (cm)	1.27	1.90	1.27	---	1.27	1.90	1.27
Wall Heat Transfer Area to Water (cm ²) x 10 ⁻³	7.09	8.16	7.90	4.76	5.47	8.16	11.37*
Fluid Volume (cm ³) x 10 ⁻³	25.34	30.48	42.30	32.54	19.55	---	---

*both sides included.

Table 6. Geometric data of IVO 2/5-scale test facility
Injector diameter: 2.7 cm

	Cold Leg	Vessel/ Downcomer	Lower Plenum	Pump	Loop Seal	Core Barrel	Thermal Shield
Inner Diameter (cm)	19.40	138.40	---	---	---	(117.40-129) [†]	---
Length (cm)	(110—255.80) [‡]	314.20	---	---	---	314.20	---
Acrylic Wall Thickness (cm)	0.61	1.00	0.61	---	---	2.00	---
Fluid Volume* (cm ³) x 10 ⁻⁴	14.06	43.75	13.15	---	---	---	---

[†]Core barrel inner diameter is 117.40 cm min. and 129.00 cm max.

[‡]Middle cold leg length is 225.80 cm and the other two are 110.00 cm each.

*Total volume.

Table 7. Geometric data of IVO(NRC) 2/5-scale test facility
Injector diameter: 6.5 cm

	Cold Leg	Vessel/ Downcomer	Lower Plenum	Pump	Loop Seal	Core Barrel	Thermal Shield
Inner Diameter (cm)	19.40	138.40	---	---	---	(117.40-129) [†]	---
Length (cm)	225.00	314.20	---	---	---	314.20	---
Acrylic Wall Thickness (cm)	0.61	1.25	0.61	---	---	1.25	---
Fluid Volume (cm ³) x 10 ⁻⁴	6.65 *	43.75	13.15	---	---	---	---

[†]Core barrel inner diameter is 117.40 cm min. and 129.00 cm max.
*Per cold leg, three legs.

Table 8. Geometric data of CREARE 1/2-scale test facility
Injector diameter: 11.43 cm

	Cold Leg	Vessel/ Downcomer	Lower Plenum	Pump	Loop Seal	Core Barrel	Thermal Shield
Inner Diameter (cm)	36.32	---	---	---	38.10	---	---
Length (cm)	377.60 ⁺	353.15	---	---	272.41	353.15	243.54
Base Metal Wall Thickness (cm)	2.10	7.00	0.60	---	2.10	7.00	3.81
Clad Thickness (cm)	---	---	---	---	---	---	---
Insulation Thickness (cm)	5.10	5.10	5.10	5.10	5.10	5.10	---
Wall Heat Transfer Area to Water (cm ²) x 10 ⁻⁴	4.30	5.71	3.70	---	3.26	5.71	7.88*
Fluid Volume (cm ³) x 10 ⁻⁵	4.07	6.38	6.05	2.72	3.11	---	---

⁺Including the length of cold leg nozzle.
*Both sides included.

Table 9. Geometric data of HDR full-scale test facility
Injector diameter: 5.0 cm

	Cold Leg	Vessel/ Downcomer	Lower Plenum	Pump	Loop Seal	Core Barrel	Thermal Shield
Inner Diameter (cm)	18.70	296.00	---	---	---	266.00	---
Length (cm)	600.00	694.26	---	---	---	694.26	---
Base Metal Wall Thickness (cm)	1.52	11.20	17.10	---	---	2.30	---
Clad Thickness (cm)	---	0.80	0.80	---	---	---	---
Insulation Thickness (cm)	10.00	10.00	10.00	---	---	---	---
Wall Heat Transfer Area to Water (cm ²) x 10 ⁻⁴	3.52	64.56	23.35	---	---	58.02	---
Fluid Volume (cm ³) x 10 ⁻⁵	1.65	78.47	129.80	---	---	---	---

Table 10. Geometric data of UPTF full-scale test facility
Injector diameter: 15.9 cm

	Cold Leg	Vessel/ Downcomer	Lower Plenum	Pump	Loop Seal	Core Barrel	Thermal Shield
Inner Diameter (cm)	75.00	(468.00-487.00) [†]	---	---	---	421.00	---
Length (cm)	948.10	702.00	---	---	---	702.00	---
Base Metal Wall Thickness (cm)	1.25	(5.50-15.00) [†]	6.50	2.40	---	8.00	---
Clad Thickness (cm)	---	---	---	---	---	---	---
Insulation Thickness (cm)	7.00	20.00	12.00	---	---	---	---
Wall Heat Transfer Area to Water (cm ²) x 10 ⁻⁵	2.23	10.74	10.61 [*]	0.68	---	9.28	---
Fluid Volume (cm ³) x 10 ⁻⁷	0.42	2.55	2.24	0.09	---	---	---

[†]Vessel inner diameter is 468.00 cm min. and 487.00 cm max.

⁺Base metal wall thickness is 5.50 cm min. and 15.00 cm max.

^{*}Area of core simulator pipes in lower plenum is included.

Table 11. Test conditions of CREARE 1/5 (MIX4) and 1/2-scale tests

Scale	Test #	Geometry	ρ_{loop} (kg/m ³)	ρ_{HPI} (kg/m ³)	$\dot{m}_{\text{HPI}}$ (kg/s)	Fr_{HPI}
1/5	100	CE	980.0	1164	0.441	0.68
	101	CE	979.4	999	0.126	0.60
	103	CE	978.9	1168	0.147	0.22
	104	W	978.9	1168	0.442	0.66
	106	W	978.3	998	0.126	0.57
1/2	May 105	W	878.0	1000	5.170	1.42
	May 106	W	877.0	1000	3.530	0.96

Table 12. Test conditions of PURDUE 1/2-scale experiments

Run #	ρ_{loop} (kg/m ³)	ρ_{HPI} (kg/m ³)	$\dot{m}_{\text{HPI}}$ (kg/s)	Fr_{HPI}
0-1C	998.2	1097	0.71	0.23
0-1C-R	998.2	1097	0.71	0.23
0-1V	998.2	1094	0.70	0.23
0-2C	998.2	1097	1.47	0.48
0-2C-R	998.2	1097	1.47	0.48
0-2V	998.2	1094	1.39	0.46
CE-1C	998.2	1096	0.69	0.22
W-1C	998.2	1096	1.40	0.46
B&W-1C*	998.2	1180	2.21	18.00
CE-2C	998.2	1185	0.97	0.22
W-1C-90	998.2	1096	1.39	0.46
CE-1C-PS	998.2	1096	0.69	0.22
CE-3C-0*	998.2	1095	1.24	15.00

*Injector diameter is 2.5 cm.

Table 13. Test conditions of IVO/IVO(NRC) 2/5-scale tests

Test #	Test Series	Injector(s) Used	ρ_{loop} (kg/m ³)	ρ_{HPI} (kg/m ³)	$\dot{m}_{HPI}^*$ (kg/s)	Fr_{HPI}
T9	IVO	B	977	1164	2.35	17.10
T10		B	977	1164	2.69	19.55
T12		B	978	1162	0.72	5.29
T16		B	978	1162	0.36	2.65
T44		B	975	1083	4.33	43.01
T45		B	975	1165	4.66	33.63
T47		B	975	994	3.98	98.23
T51		B	974	994	2.30	55.29
T106	IVO (NRC)	A & C	976	1172	0.49	0.388
T111		A, B & C	978	1166	0.49	0.395
T112		A & C	979	1166	1.21	0.980
T113		B & C	978	1168	1.73	1.385

*Per injector.

Table 14. Test conditions of HDR full-scale experiments

Test #	HPI nozzle #	T_{loop} (°C)	T_{HPI} (°C)	$\dot{m}_{HPI}$ (kg/s)	Fr_{HPI}
T32.11	1	300	20	0.12	0.1
T32.12		300	20	0.24	0.3
T32.13		300	20	0.37	0.5
T32.14		300	20	0.49	0.6
T32.15		300	20	0.99	1.3
T32.18		300	20	1.49	2.0
T32.19		300	20	2.37	3.2
T32.20		150	20	2.30	5.9
T32.21		300	20	5.56	7.4
T32.22		300	20	2.37	3.2
T32.31	2	300	20	0.12	0.1
T32.32		300	20	0.24	0.3
T32.33		300	20	0.37	0.5
T32.34		300	20	0.49	0.6
T32.36		300	20	0.99	1.3
T32.41		300	20	1.48	2.0
T32.51	3	300	20	0.49	0.6
T32.52		300	20	0.99	1.3
T32.57		300	20	1.48	2.0
T32.58		225	20	0.74	1.3
T32.61		150	20	0.52	1.3

Table 15. Test conditions of UPTF full-scale runs

Run #	T_{loop} (°C)	T_{HPI} (°C)	$\dot{m}_{\text{HPI}}$ (kg/s)	Fr_{HPI}
023	195	30	5	0.58
026	195	31	10	1.16
025	185	31	20	2.42
021	185	26	40	4.86
020	187	23	70	8.39

Table 16. Key reference documents for each facility

FACILITY	REFERENCE NUMBERS
CREARE-1/5	18, 19, 20, 21, 22
IVO/IVO(NRC)	23, 24, 25, 26, 27
PURDUE(UCSB)	6, 7, 8, 12, 16, 28
CREARE-1/2	29, 30
HDR	31, 32, 33, 34, 35
UPTF	36, 37, 38, 39, 40

We close this section by mentioning a major non-prototypicality in the UPTF experiments. Since the original geometry could only allow a low Froude number, side injection (i.e., very poor mixing as mentioned already in Section 2) a modification was made by an insert, as illustrated in Figure 10. Under high enough Froude numbers we expect that the conditions of the NEWMIX limit regime may be applicable. Unfortunately, the injector diameter was too large, and for the runs with “reasonable” injection rates (recall that ~ 10 kg/s is the upper range of our interest for most US reactors) the Froude numbers are too low for this limiting mixing regime to be applicable. We expect, therefore, a stratification (in the cold leg) much stronger than computed by NEWMIX. On the other hand, quite obviously, this peculiar injection geometry cannot be represented by REMIX either. Still, we proceeded with comparisons, using an artifi-

cially degraded entrainment in REMIX (by selecting an appropriate value for D_{HPI}) because it appeared interesting to interpret the system response and the behavior of the downcomer plume. Note that the system response does not depend on cold leg stratification in a significant way, and that the downcomer modelling approach can be independently checked once the conditions of the cold stream that feeds it (at the cold leg exit) have been specified. Further elaboration of these points is provided in Chapter 6 (Discussion) below.

Figure 10. Modified injection geometry in UPTF (dimensions in mm)

5. GUIDE THROUGH THE COMPARISON PLOTS

Since for the CREARE-1/5 data we could not obtain magnetic tapes, a selection only of typical comparisons are presented in the next section. In the next section we present also the comparisons for the PURDUE tests, which are quite special in their format. All other comparisons are collected in Appendix B, and discussed in the next section.

To locate a particular run, simply identify its name in one of the tables that summarize the operating conditions (Tables 11 to 15) and then the page numbers in Appendix B, that pertain to it, as found on Table B.1 (on the first page of Appendix B). To locate a particular temperature trace, locate the region according to the Regional Mixing Model and Figure 1 and identify it by the insert in each figure and the key in Table 17. With each prediction plot we show all experimental traces obtained within the zone corresponding to the region. In addition to the page numbers and Table B.1, all figures have been identified with the facility name and run number.

6. DISCUSSION

Typical comparisons for CREARE-1/5 facility data (MIX4) are shown for tests 100 and 106 in Figures 11 and 12. The agreement is excellent. It is interesting that in run 106, because of the very long time, heat release from the acrylic wall became important.

Table 17. Key to regions and insert schematics

Elevation of measurement position in the cold leg.
Elevation of measurement position in the downcomer, under the cold leg (i.e., in the plume).
Measurement position in the downcomer in relation to active (HPI) cold leg shown by the intersection of solid lines.
Measurement positions in pump simulator.
Measurement positions in lower plenum.
Measurement position in loop seal.

Typical comparisons for the PURDUE facility data are shown in Figures 13 to 17. Figures 13 and 14 are interesting because they show consistent comparisons also with the velocity distributions in the cold leg. Also, it is interesting to note that the measurement technique (continuously traversing concentration and hot-film probes) allowed an essentially continuous depiction of the concentration and velocity profiles, especially giving a measure of the gradient at the interface between the two streams. In all cases the predictions seem to properly represent what is being measured.

- T1: temperature of cold stream at the exit of cold leg;
- T5: temperature of hot stream at the exit of cold leg;
- T7: temperature of vessel wall at D_{CL} below cold leg center line;
- T8: temperature of core barrel wall at $1.3D_{CL}$ below cold leg centerline;
- T12: temperature of vessel wall at $1.5D_{CL}$ below cold leg centerline;
- T21: temperature of core barrel wall at $4D_{CL}$ below cold leg centerline;
- T24: temperature of vessel wall at $4.25D_{CL}$ below cold leg centerline;
- T103: temperature of fluid at lower plenum.

Figure 11. Typical interpretation of CREARE-1/5 scale experiments. Run 100 with REMIX (●)

- T1: temperature of cold stream at the exit of cold leg;
- T5: temperature of hot stream at the exit of cold leg;
- T7: temperature of vessel wall at D_{CL} below cold leg center line;
- T8: temperature of core barrel wall at $1.3D_{CL}$ below cold leg centerline;
- T12: temperature of vessel wall at $1.5D_{CL}$ below cold leg centerline;
- T21: temperature of core barrel wall at $4D_{CL}$ below cold leg centerline;
- T24: temperature of vessel wall at $4.25D_{CL}$ below cold leg centerline;
- T103: temperature of fluid at lower plenum.

Figure 12. Typical interpretation of CREARE 1/5-scale experiments. Run 106 with REMIX (●)

IVO Tests. These tests involved high Froude number injections from the bottom of the cold leg (vertically upward).^{*} The NEWMIX approach is appropriate for these conditions, although we expect some accumulation of cold water around the injection point in the cold leg, for high injection rates (high $Fr_{HPI,CL}$), and hence probably some tendency for the calculation to overpredict the cold stream temperatures. The comparisons bear out this expectation, which is especially evident in runs with $Fr_{HPI} > 20$ (i.e., T44, T45, T47 and T51). The overall cooldown is predicted very well in all cases.

IVO(NRC) Tests. For these tests the IVO facility was modified to match the low Froude number top injections of US PWRs. Our predictions with REMIX are seen to be excellent in all cases.

CREATE-1/2 Tests. Both tests were properly representing US PWR conditions—low Froude number top injection. The REMIX predictions are excellent in all respects.

HDR Tests. Comparisons with this rather large (detailed) experimental matrix quickly became repetitive, as the effect of nozzle position was negligible. We ended up choosing four runs for each nozzle position and, taken together, these choices covered well and more-or-less evenly the Fr_{HPI} over its complete range from 0.1 to 7.4. With the exception of run T32.21, the conditions are appropriate for REMIX, which was, therefore, utilized for all predictions. For run T32.21 ($Fr_{HPI} = 7.4$), we utilized NEWMIX. It should be emphasized, however, that although such an extended Fr_{HPI} range is excellent for testing both codes at the fringes of their limits, runs with Fr_{HPI} greater than ~ 1 create unrealistically strong plumes and are not relevant to large (3000 MW class) US reactors. All comparisons are uniformly excellent in all respects.^{**} It is worth noting also that for the first two runs the predictions were “double blind” [14].

UPTF Tests. As indicated above, we are not at all interested in the stratification behavior (in the cold leg) of the UPTF runs; however, the interpretation of what we refer to as a global response proved an interesting challenge. Initial REMIX calculations exhibited a behavior illustrated in Figure 18 for run 025 (20 kg/s injection). We observe a reasonably good comparison in the early portion of the transient and a gradual departure, after some time, to progressively larger deviations in the latter part of the transient. These trends, which could be observed in all five UPTF runs, are unique (among all other facilities), and they are indicative of a “heat source” coming into play some time in the transient. The timing of this departure decreased with increasing injection flow rate, but this was not in direct proportion. After exhaustive searching for leak paths to adjacent “hot” volumes, and with the help of MPR Associates’ personnel, we finally identified the source of the problem. It is a 4 mm gap in the hot leg nozzles that allows communication between the insides of the hot legs and the downcomer. The exact position is shown in Figure 19. The idea is that after some time the hot legs will participate in the mixing process, and this is evident in the hot leg temperature transient found in the complete data report

^{*} As mentioned already, this geometry simulates the Russian-designed reactor, Loviisa. From the US designs only the B & W involves high Froude number injections, but even there the behavior is substantially different because the injection occurs on the inclined portion of the cold leg which prevents accumulation of cold fluid around the injection location.

^{**} NOTE OF CLARIFICATION. Comparison plots such as those of pages B.292 (HDR T32.15) or B.349 (HDR T32.22) give the appearance of non-conservative discrepancies in the prediction of the off-the-plume-centerline temperature transients in the upper downcomer. This is purely the consequence of plume swaying, or random large scale lateral variations in the plume thermal structure, which is also apparent in the well-defined oscillatory character of the signal itself. Indeed, the lower boundary of these oscillations is well-enveloped by the prediction of the plume centerline temperature at the corresponding elevation, e.g., see pages B.280 and B.338 for runs T32.15 and T32.18, respectively.

[40] supplied to us by MPR associates during these special efforts. To represent this *pathological* behavior in REMIX we simply mixed-in the volume (and excess energy) of the hot legs, and of the inactive (i.e., no HPI injection) cold legs,* over a time period of 500 to 2000 s (depending on the run), the timing chosen to correspond to the first sign of hot leg participation, as indicated by the data. As shown in Figure 20, the global response could thus be well interpreted. On this basis our detailed comparison plots, in Appendix B, are given in "short-term" and "long-term" transients, the demarcation being where the hot legs began to participate. For each run the first 15 figures are the comparisons on the "short term" and include all aspects of the facility response, while the 5 figures that follow are comparisons on the "long term" and include only the global response. Since this behavior was discovered long after the digitized data were plotted (and discarded), the "short-term" plots were reconstructed from scanning the plotted traces (the early portion) and stretching the time axis. This produced merging of the oscillations, which, in cases where they were excessive, appear as large black areas. It thus became necessary to show the calculated results by special symbols, rather than continuous lines. This approach was followed for all UPTF runs, even those that exhibit "clean" experimental traces. From these comparisons we can draw the following conclusions:

- (a) Straight application of REMIX predicts well the global response in the "short term," i.e., prior to the "leaking" into the hot legs.
- (b) By accounting for the hot leg and inactive cold leg volume and energy, the global response is well predicted also for the remaining period of the transient. This shows the importance of "leak" volumes in moderating the cooldown. However, the potential role of particular leak paths in reactor calculations needs careful evaluation on the basis of the particular geometrical details.
- (c) The downcomer response is well predicted by REMIX once the cold stream behavior is reflected in the calculation. The cold leg stratification, itself, however, is peculiar to UPTF and of no interest to US designs.

In summary, despite the important UPTF unique and peculiar aspects, the interpretations provided above allow its effective use in a complementary role to the rest of the data base.

7. CONCLUSIONS

A comprehensive comparison of REMIX with data from facilities from 1/5 to 1/1 scale demonstrate an excellent predictive capability under all conditions of interest to US PWR, with large nozzle injections on top of the cold leg. High Froude number injections on the side of the inclined portion of the cold leg can be well predicted by NEWMIX according to the PURDUE (UCSB) data that remain unique in representing such injections. Bottom/upward injections, such as in the IVO and UPTF tests indicate that certain injection conditions can yield a higher degree of stratification than predicted by NEWMIX. However, NEWMIX was never intended for such geometries, which are irrelevant to US designs.

This report also contains a set of figures that can be used to predict stratification by a simple superposition step under any conditions of interest. In fact, a simple procedure is outlined for obtaining a first rough estimate of cooldown transient and stratification by simple hand calculations.

* Note that for reactor conditions, all cold legs are active and hence they participate in the mixing process right from the start.

Figure 13. Typical interpretation of PURDUE 1/2-scale data with REMIX

Figure 14. Typical interpretation of PURDUE 1/2-scale data with REMIX

Figure 15a. Transient concentration response at the exit of the cold leg for CE-1C compared with RMM predictions.

Figure 15b. Transient concentration response in the downcomer at $2D_{CL}$ below the cold leg centerline for Run CE-1C compared with RMM predictions.

Figure 15c. Spatial concentration profiles at the exit of the cold leg for Run CE-1C compared with RMM predictions.

Figure 16a. Transients concentration response at the exit of the cold leg for CE-2C compared with RMM predictions.

Figure 16b. Transient concentration response in the downcomer at $2D_{CL}$ below the cold leg centerline for Run CE-2C compared with RMM predictions.

Figure 16c. Spatial concentration profiles at the exit of the cold leg for Run CE-2C compared with RMM predictions.

Figure 17a. Transient concentration response at the exit of the cold leg for W-1C compared with RMM predictions.

Figure 17b. Transient concentration response in the downcomer at $2D_{CL}$ below the cold leg centerline for Run W-1C compared with RMM predictions.

Figure 17c. Spatial concentration profiles at the exit of the cold leg for Run W-1C compared with RMM predictions.

Figure 18. Illustration of predicted (REMIX) and experimental (UPTF) trends indicating a “hot source” coming into play sometime around 500 s into the transient. This is a typical behavior found for all UPTF runs.

Figure 20. Interpretation of the “hot source” problem of Figure 18 in terms of the hot and inactive cold leg volumes participating in the mixing process after some 500 s. The hot legs communicate with the downcomer fluid through the 4 mm circumferential gap found in all four hot leg nozzles, as illustrated in Figure 19. The four hot legs involve 13 m^3 of fluid volume and the three inactive cold legs another 15 m^3 .

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APPENDIX A

UNIVERSAL STRATIFICATION SOLUTIONS

This appendix contains in graphical form the functions

$$Q^* = f(d^*, \rho^*, Fr_{HPI,CL}; \beta) \quad (A.1)$$

and

$$Q^* = 0.52 \{ 3\alpha D^{*-0.84} Fr_{HPI,CL}^{-0.33} - 5\alpha D^{*1.66} Fr_{HPI,CL}^{0.67} + (1-d^*) D^{*0.16} Fr_{HPI,CL}^{-0.33} \}^{1.236} \quad (A.2)$$

$$\alpha = \begin{cases} 1 & \text{for } Fr_{HPI,CL} < 0.6 D^{*-2.5}; \\ 0 & \text{for } Fr_{HPI,CL} > 0.6 D^{*-2.5}. \end{cases}$$

The function of Equation (A.1) is shown in the first two figures corresponding to $\beta = 1.0$ and $\beta = 0.5$, respectively. The Q^* for ρ^* in the range $0.8 < \rho^* < 1$ varies by less than a few percent, hence the plots are applicable for this whole range. The function of Equation (A.2) is shown in the remaining figures of this appendix covering a broad range of D^* values, $2 < D^* < 10$, as indicated on each figure. The parameter on all these figures is $Fr_{HPI,CL}$, and it is covered in the range $0.01 < Fr_{HPI,CL} < 0.1$ in increments of 0.01. Universal stratification solutions may be obtained by the superposition of the applicable (A.1)-type plot with an (A.2)-type plot. The stable solution is with the smaller value of d^* .

Figure A.1. Illustration of counter-current flow limited entrainment for $\rho^* = 0.9$ and $\beta = 1.0$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.2. Illustration of counter-current flow limited entrainment for $\rho^* = 0.9$ and $\beta = 0.5$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.3. Illustration of plume (jet) for entrainment for $D^* = 2.0$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.4. Illustration of plume (jet) for entrainment for $D^* = 2.2$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.5. Illustration of plume (jet) for entrainment for $D^* = 2.4$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.6. Illustration of plume (jet) for entrainment for $D^* = 2.6$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.7. Illustration of plume (jet) for entrainment for $D^* = 2.8$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.8. Illustration of plume (jet) for entrainment for $D^* = 3.0$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.9. Illustration of plume (jet) for entrainment for $D^* = 3.2$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.10. Illustration of plume (jet) for entrainment for $D^* = 3.4$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.11. Illustration of plume (jet) for entrainment for $D^* = 3.6$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.12. Illustration of plume (jet) for entrainment for $D^* = 3.8$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.13. Illustration of plume (jet) for entrainment for $D^* = 4.0$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.14. Illustration of plume (jet) for entrainment for $D^* = 4.25$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.15. Illustration of plume (jet) for entrainment for $D^* = 4.5$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.16. Illustration of plume (jet) for entrainment for $D^* = 4.75$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.17. Illustration of plume (jet) for entrainment for $D^* = 5.0$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.18. Illustration of plume (jet) for entrainment for $D^* = 5.5$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.19. Illustration of plume (jet) for entrainment for $D^* = 6.0$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.20. Illustration of plume (jet) for entrainment for $D^* = 6.5$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.21. Illustration of plume (jet) for entrainment for $D^* = 7.0$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.22. Illustration of plume (jet) for entrainment for $D^* = 8.0$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.23. Illustration of plume (jet) for entrainment for $D^* = 9.0$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

Figure A.24. Illustration of plume (jet) for entrainment for $D^* = 10.0$. $Fr_{HPI,CL}$ is ranging from 0.01 to 0.10 in increments of 0.01.

APPENDIX B

DETAILED COMPARISONS OF REMIX/NEWMIX WITH DATA

Table B.1 Page numbers of detailed comparisons of
REMIX/NEWMIX with experimental data

FACILITY	TEST NO.	PREDICTION	PAGE NO.
IVO	9	NEWMIX-S	B.2
	10	NEWMIX-S	B.14
	12	NEWMIX-S	B.26
	16	NEWMIX-S	B.38
	44	NEWMIX-S	B.50
	45	NEWMIX-S	B.64
	47	NEWMIX	B.78
	51	NEWMIX	B.92
IVO(NRC)	106	REMIX-S	B.106
	111	REMIX-S	B.129
	112	REMIX-S	B.149
	113	REMIX-S	B.172
CREARE-1/2	MAY 105	REMIX	B.196
	MAY 106	REMIX	B.236
HDR	T32.15	REMIX	B.276
	T32.18	REMIX	B.296
	T32.21	NEWMIX	B.316
	T32.22	REMIX	B.334
	T32.31	REMIX	B.354
	T32.34	REMIX	B.373
	T32.36	REMIX	B.392
	T32.41	REMIX	B.411
	T32.51	REMIX	B.430
	T32.52	REMIX	B.447
	T32.57	REMIX	B.464
	T32.61	REMIX	B.481
UPTF	023	REMIX	B.498
	026	REMIX	B.518
	025	REMIX	B.538
	021	REMIX	B.558
	020	REMIX	B.578

B.70

B.100

B.108

B.110

B.112

B.115

IVO(NRC) 106

B.200

B.270

UPTF 023

UPTF 023

UPTF 023

UPTF 023

UPTF 023

UPTF 023

UPTF 023

UPTF 023

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UPTF 025

UPTF 025

UPTF 021

UPTF 021

UPTF 021

B.560

UPTF 021

UPTF 021

UPTF 021

UPTF 021

UPTF 021

UPTF 021

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UPTF 021

UPTF 021

UPTF 021

UPTF 021

UPTF 021

UPTF 020

UPTF 020

UPTF 020

B.580

UPTF 020

UPTF 020

UPTF 020

UPTF 020

UPTF 020

UPTF 020

UPTF 020

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