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ABSTRACT

This paper presents the results of a study of mixing phenomena related to boron dilution during small break loss of coolant accidents (LOCAs) in pressurized water reactors (PWRs). Boron free condensate can accumulate in the cold leg loop seals when the reactor is operating in a reflux/boiler-condenser mode. A problem may occur when subsequent change in flow conditions such as loop seal clearing or re-establishment of natural circulation flow drive the diluted water in the loop seals into the reactor core without sufficient mixing with the highly borated water in the reactor downcomer and lower plenum. The resulting low boron concentration coolant entering the core may cause a power excursion leading to fuel failure. The mixing processes associated with a slow moving stream of diluted water through the loop seal to the core are examined in this paper. Bounding calculations for boron concentration of coolant entering the core during a small break LOCA in a typical Westinghouse-designed four-loop plant are also presented.

1. INTRODUCTION

A small-break LOCA is characterized by slow RCS depressurization rates and low fluid velocities within the reactor coolant system (RCS) as compared to a design basis large-break LOCA. Because of the slow depressurization rate, various phase change/separation phenomena dominate the thermal hydraulic characteristics of small-break LOCAs. One aspect of this behavior which has been recognized more recently [1] is the existence of an inherent boron dilution mechanism in the course of SBLOCAs that involves decay heat removal by phase-separating natural circulation (i.e. reflux/boiler condenser mode operation). The steam that is generated in the core is largely devoid of boric acid. Due to subsequent condensation in the

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steam generators, a portion of boron-free condensate can run down the downflow side of the steam generator tubes and accumulate in the loop seals between the steam generator outlet plena and the reactor coolant pumps (RCPs). A subsequent change in flow such as loop seal clearing or re-establishment of natural circulation flow, may provide an effective mechanism to drive the slug of diluted water into the core. However, the buoyancy and turbulent mixing process between the loop seal and the core may sufficiently increase the boron concentration of the diluted stream to prevent a power excursion leading to fuel failure.

The mixing processes associated with a slow moving stream of diluted water through the loop seal to the core are examined in this paper. The quantitative aspects of different mixing mechanisms and a simplified, yet physically based, methodology for their integration into an overall prediction of dilution boundary will be presented. Bounding case analyses of the boron concentration in the coolant entering the core due to loop seal clearing or reestablishment of natural circulation flow in a typical Westinghouse designed 4-loop plant will be also provided.

2. MIXING PROCESSES AND PHENOMENA

2.1 Mixing in the Loop Seals

During reflux condensation the loop mean flow rate is virtually null. The safety injection of cold and highly borated water into a stagnant loop leads to stratification accompanied by counter-current flows and a global recirculating flow pattern with flow rates significantly higher than the net flow through the system. This keeps a major portion of the system volume including the loop seals (vertical leg below the pump and bottom horizontal leg), the downcomer (excluding the region above the cold leg) and the lower plenum in a well mixed condition. The ensuing flow regime was first established analytically by Theofanous and Nourbakhsh [2,3] as part of the work supporting an NRC sponsored study related to Pressurized Thermal Shock (PTS). This work predicted overcooling transients due to high pressure safety injection into a stagnant loop of a PWR. The quantitative aspects of this behavior may be found in the regional mixing model [2-4]. This model has been successfully employed to interpret all available thermal mixing experimental data obtained from the system simulation tests performed in support of the PTS study [5].

Similar thermal stratification and mixing behavior may even exist in the presence of very low loop mean flow. In the presence of thermal stratification and effective natural recirculating flows, the dilution transient can be represented by a simple global boron mass conservation equation:

$$\rho V \frac{dC_m}{dt} = q_{SI}(C_{SI} - C_m) + q_L(C_L - C_m) \tag{1}$$

Where ρ is the density (the effect of density variation is neglected); V is the system volume; C_m, C_{SI} and C_L are boron concentrations of flow entering the core, safety injection and loop flow (entering the bottom horizontal leg of the loop seal), respectively; and q_{SI} and q_L are the safety injection and loop flows, respectively. It should be noted that the volume V includes the cold leg, pump, lower plenum, downcomer (excluding the portion above the cold leg) and the vertical leg below the pump and bottom horizontal leg of the loop seal. The downcomer and lower plenum volumes should be partitioned equally among the available loops.

Equation 1 can be integrated analytically to:

$$C_m = \frac{C_{SI} + RC_L}{1+R} + \left[C_o - \frac{C_{SI} + RC_L}{1+R}\right] e^{\frac{(1+R)t}{\tau}} \tag{2}$$

where

$$\tau = \frac{\rho V}{q_{SI}} \tag{3}$$

and

$$R = \frac{q_L}{q_{SI}} \tag{4}$$

Assuming that initially, the system is filled with borated water with a boron concentration of 1500 PPM, the time variation of boron concentration, Cm, due to the loop flow of unborated water ($C_{LS} = 0$) for $q_{SI} = 7$ Kg/sec, $C_{SI} = 2200$ PPM and different values of R is illustrated in Figure 1. For example at a pressure of 8.MPa and with the assumption that three steam generators stay active, $q_L = 7$ Kg/sec and $R \approx 1$[6]. With a flow ratio of $R = 1$, the boron concentration would be more than 1100 PPM. However, the vertical downflow leg (and steam generator outlet plenum) may remain full of pure condensate.

2.2 Mixing at the Safety Injection Point

For a well mixed condition there must be sufficient loop flow not only to break up the safety injection plume (jet) but also to produce stable flow into the downcomer. Nourbakhsh and Theofanous[7] used the boundary of stability and developed a criterion for the existence of perfect mixing in the presence of loop flow, their stratification/mixing boundary can be expressed by:

$$Fr_{SI,CL} = \left[1 + \frac{Q_L}{Q_{SI}}\right]^{-7/5} \tag{5}$$

where Q_{SI} and Q_L are the volumetric flow rates of the safety injection and the loop, respectively. The Froude number, $Fr_{SI,CL}$ is defined as:

$$Fr_{SI,CL} = \frac{Q_{SI}}{A_{CL}}\left\{gD_{CL}\frac{(\rho_{SI} - \rho_L)}{\rho_{SI}}\right\}^{-1/2} \tag{6}$$

where A_{CL} and D_{CL} are the flow area and the diameter of cold leg respectively.

This stratification criterion should be considered as providing a high estimate of the flow ratio, R, necessary for ignoring stratification. For perfect mixing, the concentration of diluted flow stream after mixing with the safety injection flow, C_{pm} can be easily quantified by the boron mass balance at the mixing point:

$$C_{pm} = \frac{C_{SI} + RC_L}{1+R} \tag{7}$$

Typically, natural circulation flows are in the 110 to 250 Kg/sec range. For a RCS pressure of 4.2 MPa, the safety injection flow is ~ 10 Kg/sec. In terms of stratification criterion parameters, these values correspond to $Fr_{SI,CL} \approx 0.02$ and $R = 15$, indicating perfect mixing except for the lower range of natural circulation flow.

2.3 Mixing in the Downcomer

A highly complicated three dimensional mixing pattern occurs at the cold leg-downcomer junction. This contribution to mixing is conservatively neglected and the dilute stream exiting the cold-leg is assumed to form smoothly into a planar plume within the downcomer. Under low loop flow conditions, the diluted stream entering the downcomer would be colder due to mixing with the safety injection, than the downcomer coolant. The resulting positively buoyant planar jets decay rapidly, enhancing the mixing and global flow recirculation. However, in the presence of relatively high natural circulation loop flow, the temperature of condensate, even after the mixing with the safety injection flow, would be higher than the downcomer temperature and thus the inlet flow into the downcomer would constitute a negatively buoyant jet (Inverted Fountain).

Except for limited data on maximum penetration distance,[8] there have been no experimental or analytical studies on the behavior of negatively buoyant planar jets reported in the open literature. In order to be able to quantify the mixing of a negatively buoyant planar jet of the diluted water with the highly borated downcomer ambient, an extensive analytical study of negatively buoyant jets was performed as a part of the present work.[6] The jet model of Chen and Rodi[9] was adopted for this purpose. The model utilizes the standard equations for natural convection boundary layer type flows with a vertically oriented buoyant force and a K-E-$\bar{T}^{-2}$ differential turbulence model to evaluate the transport terms in the equations.

The integration was carried out using the Patankar-Spalding method.[10] In order to achieve high computational efficiency this method invokes a coordinate transformation, which utilizes a normalized Von Mises variable; and thus instead of the y coordinate, a nondimensional stream function is used in the transverse coordinate.

Results for the range of small Froude numbers of interest here are presented in Figures 2 through 5. It should be noted that the nondimensional axial and transverse direction X^*, Y^*, Froude number, Fr, nondimensional temperature (or concentration), T^*, and nondimensional velocity U^* are defined as follows:

$$X^{*} = \frac{x}{2B_o} \tag{8}$$

$$Y* = \frac{Y}{2B_o} \tag{9}$$

$$T* = \frac{T-T_a}{T_o-T_a} = \frac{C-C_a}{C_o-C_a} \tag{10}$$

$$U* = \frac{U}{U_o} \tag{11}$$

$$Fr = \frac{U_o}{\sqrt{2B_o g(\rho_a-\rho_o)/\rho_o}} \tag{12}$$

The results of the turbulent jet model illustrate that at low Froude number, the negatively buoyant planar jets spread rapidly in the lateral dimension with much lower entrainment or mixing as compared to positively buoyant planar jets. For example a negatively buoyant planar jet with a Froude number of 1.5 deaccelerates to less than 50% of its initial velocity, without any significant entrainment or mixing, within less than one initial width of the jet ($X^{*} < 1$). In a negatively buoyant jet, due to the buoyancy force which acts against the flow direction, the flow penetrates to a finite distance in the ambient environment before reversal occurs. It should be noted that the present Parabolic turbulent jet model neglects the effect of return flow. Furthermore, the validity of boundary layer assumptions is questionable near the stagnation point where the axial velocity approaches zero and significant lateral spreading of the jet occurs.

The turbulent jet model was also utilized to predict the maximum penetration distance for negatively buoyant planar jets. If the source is small compared with the maximum penetration distance, the flow will depend only on the buoyancy flux, F_o, and momentum flux, M_o, at the jet source. In this case the flow will not depend explicitly on the volume flux, Q_o. Following an approach similar to the one used by Turner for the case of a circular fountain,[11] the maximum penetration distance of a negatively buoyant planar jet, H_{max}, can be defined by the dimensional consistency requirement as:

$$H_{max} = \text{constant} \times \left[\frac{M_o}{\rho_o}\right] \left[\frac{F_o}{\rho_o}\right]^{-2/3} \tag{13}$$

where

$$M_o = 2B_o \rho_o U_o^2 \tag{14}$$

$$F_o = 2B_o \, \rho_o \, U_o \, g \, (\rho_a - \rho_o) \, / \rho_a \tag{15}$$

Combined with the definition of the densimetric Froude number, (Eq. 12), the maximum penetration distance (Eq. 13) can be expressed by:

$$\frac{H_{\max}}{2B_o} = \text{constant} \times F_r^{4/3} \tag{16}$$

The proportionality constant evaluated by the turbulent jet model predictions is 2.42 as shown in Figure 6. Due to computational difficulty, it was not possible to predict the maximum penetration distance for low Froude number jets (Fr<3). Assuming that at low Froude number the flow depends on momentum flux and volume flux only, based on the dimensional consistency requirement, the maximum penetration distance, Hmax/2Bo, should be a constant. This is also supported by the experimental data reported by Goldman and Jaluria[8] which indicate a finite value of penetration distance as the Froude number decreases to a very low value. Thus the maximum penetration distance can be correlated by:

$$\frac{H_{\max}}{2Bo} = 2.42 \; Fr^{4/3} \; for \; Fr > 2 \tag{17}$$

A comparison of the present correlation with the data reported by Goldman and Jaluria is also presented in Figure 6.

Assuming that the ambient to the negatively buoyant planar jet in the downcomer behaves as though it is well mixed, the global boron mass conservation equation can be expressed as:

$$\rho V_a \frac{dC_a}{dt} = q_{ent}(C_{mj} - C_a) \tag{18}$$

$$C_{mj} = \frac{C_o + \frac{q_{ent}}{q_o} C_a}{1 + \frac{q_{ent}}{q_o}} \tag{19}$$

Where ρ is the density (effect of density variation is neglected); C_o, C_a and C_{mj}; are boron concentrations of flow entering the downcomer, the ambient, and mean jet flow entering the lower plenum; respectively; V_a is the volume of ambient; and q_o and q_{ent} are the inlet flow to downcomer and entrainment flow into planar jet, respectively. It should be noted in the case of symmetric flow of diluted water from different loops, the low Froude number negatively buoyant jets entering the downcomer grow rapidly in lateral direction and thus would occupy the whole downcomer circumference before reaching to lower plenum. In this case the volume of ambient would be reduced accordingly.

Equations 18 and 19 can be integrated analytically to:

$$\frac{C_a - C_o}{C_a^o - C_o} = e^{-\frac{\alpha}{1+\alpha}\frac{q_o}{\rho V_a}t} \tag{20}$$

$$\frac{C_{mj} - C_o}{C_a^o - C_o} = \frac{\alpha}{1+\alpha} e^{-\frac{\alpha}{1+\alpha}\frac{q_o}{\rho V_a}t} \tag{21}$$

where

$$\alpha = \frac{q_{ent}}{q_o} \tag{22}$$

The numerical values of α are obtained from the results of jet model.

2.4 Mixing In The Lower Plenum

The diluted stream of water leaving the downcomer will experience some mixing with the highly borated water of the lower plenum before entering the core.

In the presence of thermal stratification (very low loop flow), due to entrainment, the positively buoyant planar wall jet entering the lower plenum carries a flow which is at least one order of magnitude higher than the HPI flow. Thus the highly borated water in the lower plenum is drawn continuously to the downcomer and cold leg resulting in a very intensive mixing and recirculation in the lower plenum. Indeed the results of thermal mixing experiments related to pressurized thermal shock[5] (under stagnated flow condition) indicate no thermal stratification in the lower plenum (i.e. a well mixed lower plenum).

Under the relatively high natural circulation loop flow (even in the presence of stratification), the loop flow accommodates a significant portion of entrainment and thus there may not be significant recirculation (if any) from the lower plenum back to downcomer. However, the negatively buoyant wall jet of diluted water entering the lower plenum will penetrate to some finite depth before it reaches to a stagnation point and then reverses direction upward toward the core region. The highly borated ambient water in the lower plenum will be entrained into this flow, resulting in a higher boron concentration in the flow entering the core compared with that entering the lower plenum. The detailed quantification of mixing in the lower plenum is beyond the scope of the present study. Some bounding calculations to show the impact of lower plenum mixing are presented in the following section.

3. BOUNDING ANALYSES

Many thermal hydraulic aspects of boron dilution, except the mixing effects, can be analyzed by using system codes such as TRAC and RELAP. The mixing processes underway from the loop seal to the core involve multidimensional one-phase flow effects which typically are not modelled in system codes. Furthermore, these codes exhibit far too much numerical diffusion to be useful for tracking a relatively sharp concentration gradient around the system.[1] Simulation of dilution transients using one of the system codes to provide the thermal hydraulic conditions needed for both the mixing analysis and the reactor physics calculations is beyond the scope of the present study. In this section bounding calculations for boron concentration of coolant entering the core due to subsequent change in flow conditions such as loop seal clearing or re-establishment of natural circulation flow in a typical Westinghouse design 4-loop plant (RESAR3S) are presented. Summaries of some pertinent data for the reference plant are shown in Figure 7.

3.1 Boron Dilution Due to Loop Seal Clearing

Loop seal clearing has been suggested as a potential mechanism for driving an accumulated slug of diluted water from the loop seals into the core.[1] The experimental evidence on loop seal clearing [12] indicate that the loop seals are cleared only after the liquid level in the vertical leg below the steam generator outlet plenum reaches the top of the bottom horizontal section.

During this period of gradual reduction of liquid level in the vertical leg the loop flow entering the bottom horizontal leg of the loop seals is relatively low. As discussed in section 2 (under low loop flow conditions) the safety injection of cold, highly borated water into the cold leg leads to stratification accompanied by counter-current flows and recirculation. For example at a pressure of 8.MPa, and with the assumption that three steam generators stay active, the safety injection flow, q_{SI}, is 7 Kg/sec. The flow of condensate entering the bottom horizontal leg, q_L, based on condensation rate and the TRAC results of loop seal level change for a 3 in. break reported in Reference 13, is estimated to be $\approx$ 11.9 Kg/sec. Under these conditions $Fr_{SI,CL}$ = 0.013 and R $\approx$ 1.7, indicating flow stratification. Thus the resulting boron concentration of flow entering the core, Cm, can be estimated by using Equation 2 (see also Figure 1). Assuming that initially the system is filled with borated water with a boron concentration of 1500 PPM, the boron concentration after 350 seconds (based on the time duration of level reduction before loop seal clearing reported in Reference 13) is more than 1200 PPM.

3.2 Boron Dilution Due to Reestablishment of Natural Circulation Flow

The reestablishment of natural circulation flow may occur during the refill phase of small break LOCAs as long as the secondary heat sink is available. The magnitude and timing of the natural circulation flow depends on plant geometry, break size and location, ECCS capacities, equipment failure criteria and operational actions, all of which differ considerably in various designs. In the absence of detailed system code simulation results during the refill phase of small break LOCAs, bounding estimates of the needed thermal-hydraulic conditions for mixing calculations was used to predict the dilution boundary.

If the RCS refill and reestablishment of natural circulation proceed at low pressure (a characteristic of relatively large SBLOCAs) high flow of cold, highly borated water injected into the cold legs, via accumulators or low pressure safety injection system, mixes with the natural circulation flow of unborated water. This leads to a significant increase in boron concentration of the resulting flow before entering the core region. For example for a typical Westinghouse designed 4-loop plant, the low pressure safety injection flow is on the order of 115 Kg/sec per loop. The natural circulation flow by conservatively assuming 2% core decay power is about 4% of the nominal flow or 175 Kg/sec per loop.[6] Neglecting the potential for thermal stratification and conservatively assuming perfect mixing, the boron concentration of the resulting flow entering the downcomer estimated by using Equation 7 is 872 PPM. Even without considering any mixing in the downcomer and lower plenum, this level of boron concentration does not result in a power excursion leading to fuel failure.

For the present bounding analyses, it was also assumed that the reestablishment of natural circulation occurs at a RCS pressure higher than accumulator injection setpoint (a characteristic of relatively smaller SBLOCAs). Assuming an RCS pressure of 4.8 MPa ($\approx$ 700 Psia) and a

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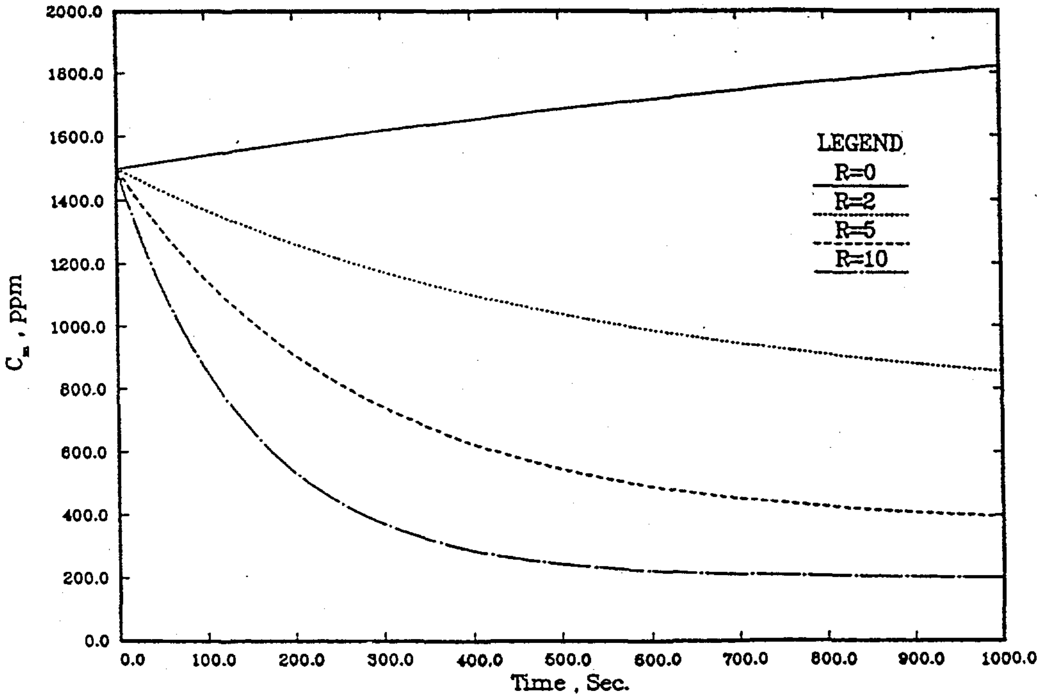

Figure 1 Dilution transient under stratified and recirculating flow regime

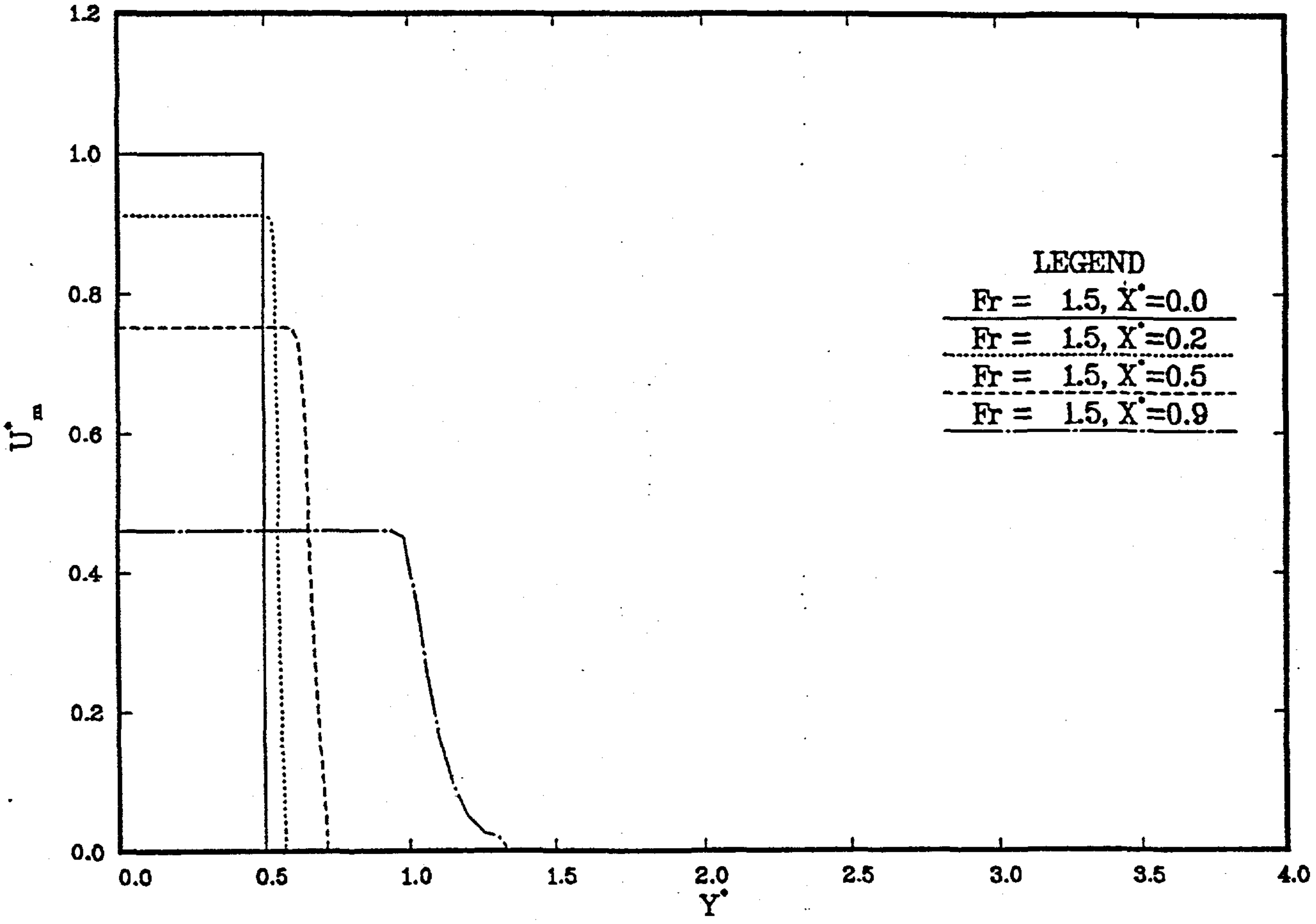

Figure 3 Calculated results of velocity profiles for a negatively buoyant planar jet (Fr=1.5)

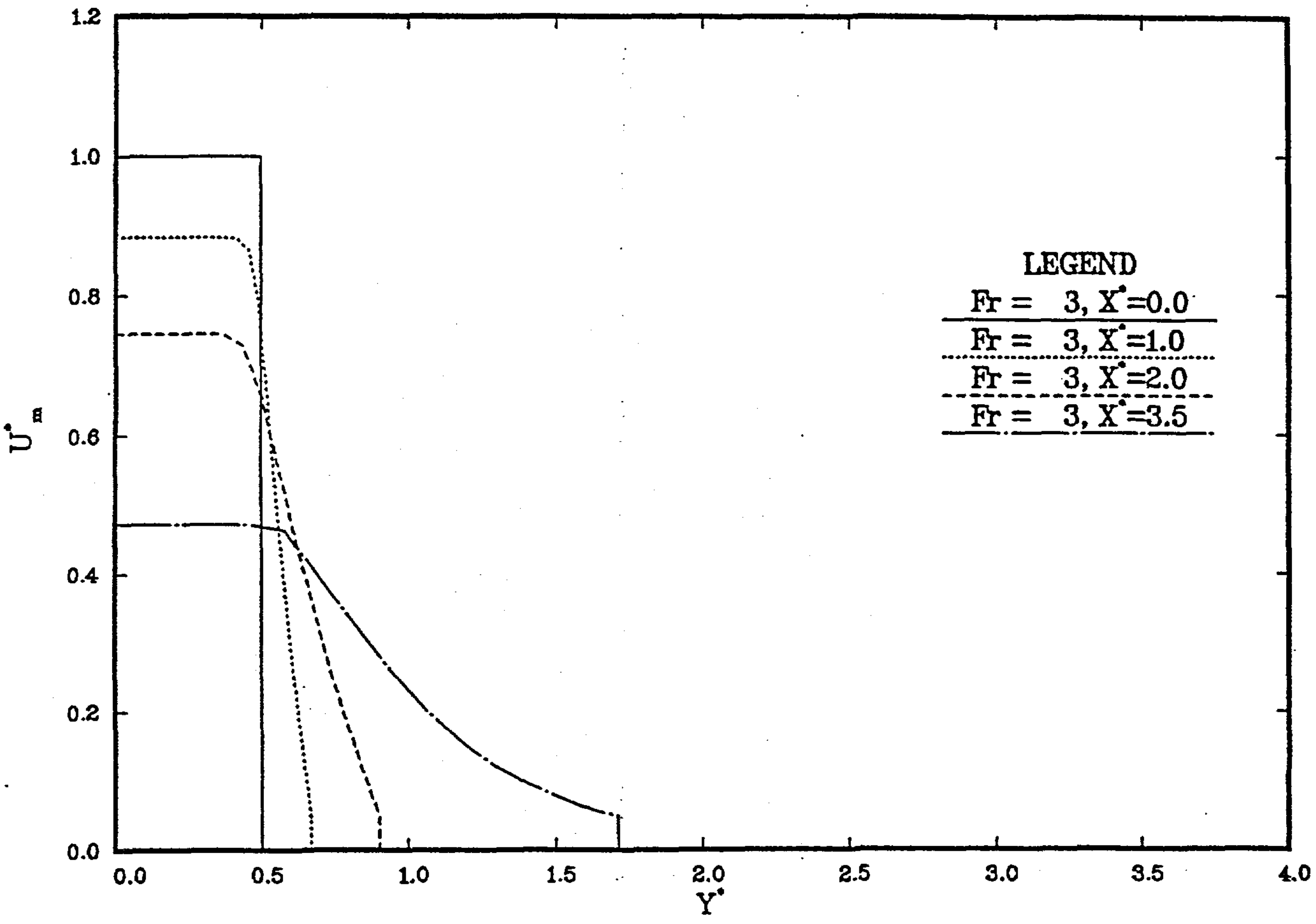

Figure 5 Calculated results of velocity profiles for a negatively buoyant planar jet (Fr=3)

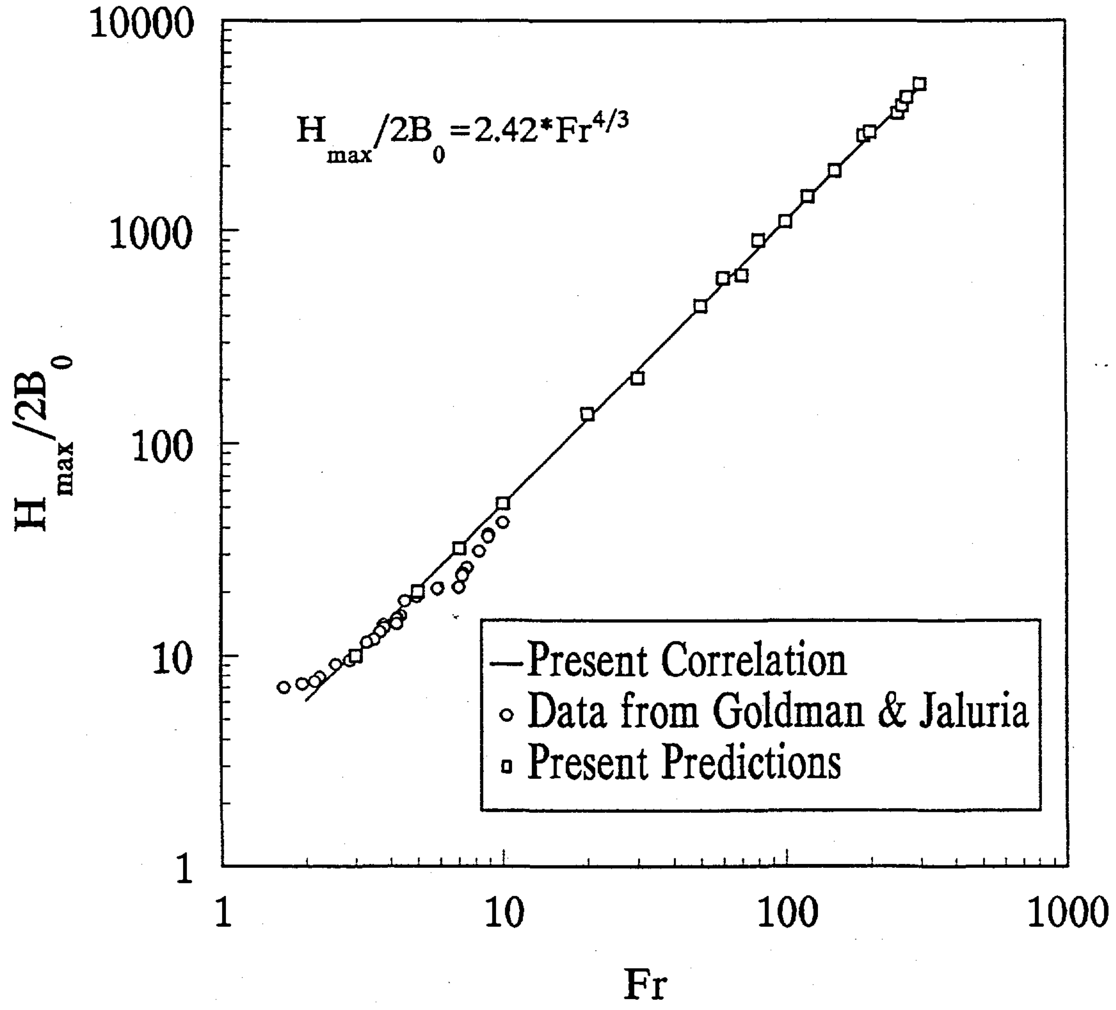

Figure 6 Comparison of Predicted Maximum Penetration Distance of Negatively Byoyant Vertical Planar Jets with Experimental Data

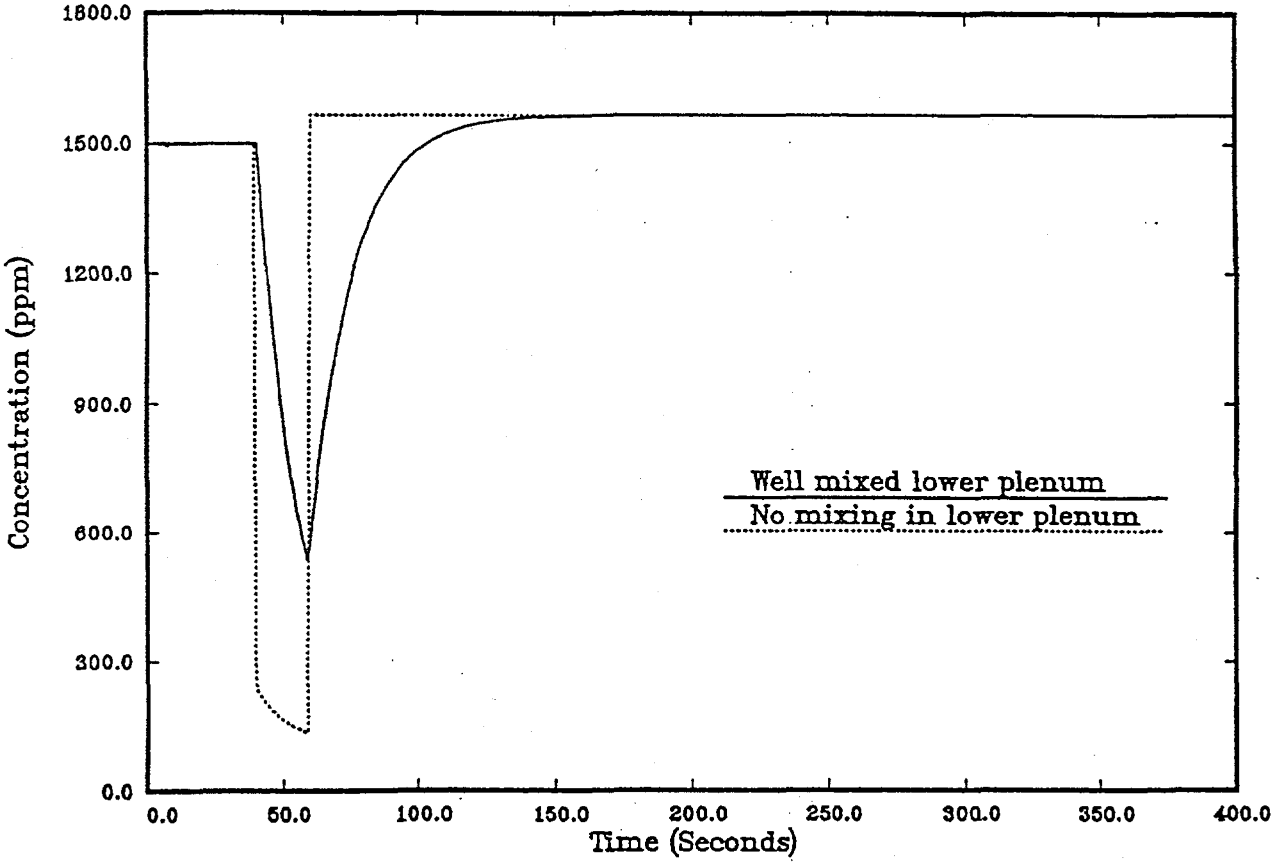

Figure 8 Transient boron concentration entering the core (condensate volume = 4m^3, natural circulation flow = 225 Kg/sec)