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Potential for Boron Dilution During Small-Break LOCAs in PWRs *

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ABSTRACT

This paper documents the results of a scoping study of boron dilution and mixing phenomena 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 the 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 were examined in this report. A bounding evaluation of the range of boron concentration entering the core during a small break LOCA in a typical Westinghouse-designed, four-loop plant is also presented in this report.

1 INTRODUCTION

Boric Acid is used as a soluble neutron absorber for long-term reactivity control in pressurized water reactors (PWRs). A reduction in the boron concentration (i.e., boron dilution) in the core region may result in a reactivity accident with the potential to cause a power excursion and fuel damage.

Boron dilution events have always been of concern in PWRs. The required safety analyses for PWRs include events in which positive reactivity is added to the core due to inadvertent boron dilution. For these boron dilution events, it is assumed that the dilution flow is injected to a continuously flowing reactor coolant which leads to homogenous dilution of all the primary coolant inventory. For homogenous dilution events a large volume of diluted water is required and the boron concentration in the core changes slowly which leaves plenty of time for the identification of the problem and operator intervention.

The accident at the Chernobyl Nuclear Power Plant provided an impetus for renewed interest in reactivity accidents in PWRs. Studies by several European organizations (mainly in France, Sweden and Finland) have postulated numerous new boron-dilution-induced reactivity transients in PWRs. These scenarios assume accumulation of diluted water in a stagnant part of the reactor coolant system (RCS) during a period when there is very little circulation. Due to subsequent change in flow conditions such as start of a reactor coolant pump (RCP), the depleted zone will be transported to and through the reactor core and cause a reactivity transient. Most of these heterogeneous (local) dilution events assume the addition of boron-free coolant from an external source, such as the chemical and volume control system (CVCS), erroneously diluted accumulator, reactor coolant pump seal injections or a reversed steam generator leak.[1]

Recently, a mechanism has been identified that leads to heterogeneity in boron concentration without any external source of diluted water.[2-3] This dilution mechanism is via accumulation of

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boron free condensate in the cold leg loop seals due to reflux/boiler-condenser mode operation during certain accidents, such as small break loss of coolant accidents (LOCAs). The subsequent change in flow conditions, 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 along the way from the loop seal to the core may sufficiently increase the boron concentration of the diluted stream to prevent a power excursion leading to fuel failure.

The general objective of the work presented in this paper is to improve the understanding of the boron dilution mechanism and the mixing phenomena during small break LOCAs in PWRs.

The mixing processes associated with a slow moving stream of diluted water through the loop seal to the core are examined in this paper. A preliminary evaluation of the range of boron concentration entering the core during a small break LOCA in a typical PWR is also presented in this paper. It must be recognized that the focus of this study is limited to a Westinghouse-designed, four-loop plant. The reactor design studied is the RESAR-3S. No attempt is made to extrapolate the results to other Westinghouse designs or to Combustion Engineering or Babcock & Wilcox reactor designs.

2 THE THERMAL HYDRAULICS OF SMALL-BREAK LOCAs RELEVANT TO BORON DILUTION

There has been significant research activity related to small-break loss-of-coolant accidents (LOCAs) following the accident at Three Mile Island Unit 2 (TMI-2). The experimental and analytical results from these research programs have provided a better understanding of the important physical phenomena relevant to small break loss of coolant accidents.

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 (SBLOCAs). One aspect of this behavior is the existence of an inherent boron dilution mechanism in the course of SBLOCAs that involves the 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 steam generators, a portion of boron-free condensate can run down the downflow side of steam generator tubes and accumulate in the loop seals between the steam generator outlet plena and the reactor coolant pumps (RCPs). A problem may occur when the subsequent change in flow condition such as loop seal clearing or re-establishment of natural circulation flow drive the diluted water in the loop seals to 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 result to a power excursion leading to fuel failure. The phenomena and processes of interest to boron dilution issue during small-break LOCAs are summarized in Figure 1.

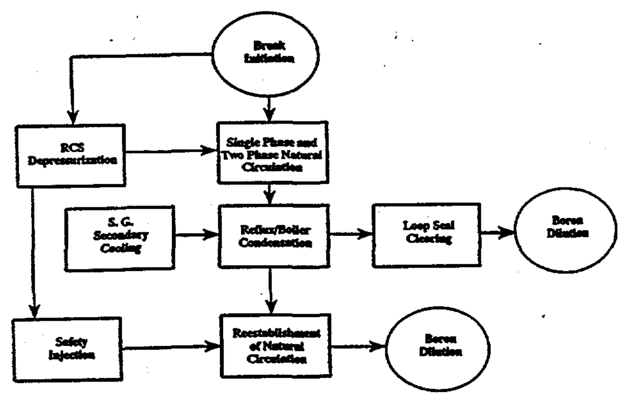

Figure 1 Phenomena and processes of interest to boron dilution issue during small break LOCAs

DISCLAIMER

In this section, a general discussion of the small-break LOCA phenomenology relevant to the boron dilution issue is presented. In particular, this chapter discusses the conditions under which boron dilution occurs. The mixing processes associated with a moving stream of diluted water through the loop seals to the core are discussed in Section 3.

2.1 Characteristics of Small Break LOCA Scenarios

The small-break LOCAs as generally defined, include any break in the PWR pressure boundary with an area less than 4.65 x 10^{-2} m^2 (0.5 ft^2). This range of break areas encompasses all small lines that penetrate the RCS pressure boundary[4].

The emergency core cooling system (ECCS) is the principal PWR design feature for mitigating the consequences of a small-break LOCA. The purpose of the ECCS is to restore the water inventory in the RCS, thus provide for sufficient core cooling. The major subsystems of a typical US PWR ECCS are the high pressure safety injection (HPSI) system, the safety injection tanks (SITs) or accumulators and the low-pressure safety injection (LPSI) system. Because of the need for heat removal by the steam generators, the auxiliary feed water system is also important for small-break LOCA mitigation.

The major characteristics of the transient response to the small-break LOCAs are similar for all U.S. PWR designs. The magnitude and timing of the physical phenomena as functions of break size depend on plant geometry, break and injection locations, emergency core cooling (ECCS) capacities and equipment failure criteria, all of which differ considerably in various designs. For the present study, the results of TRAC and RELAP calculations for cold leg small break LOCAs in a Westinghouse-designed, four-loop plant (RESAR-3S) reported in Reference [5] are utilized. These calculations are based on the minimum availability of ECCS equipment required by licensing regulations in the United States; particularly, credit is taken for one HPSI and one charging pump. Only one motor-driven auxiliary feedwater pump was assumed to be available. Summaries of pertinent Westinghouse plant data for a four-loop design are shown in Figure 2.

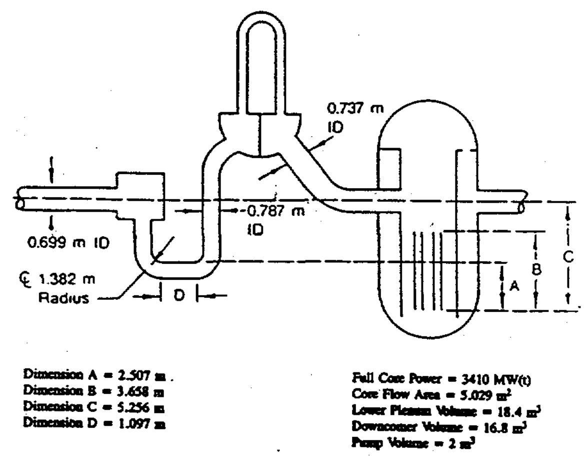

Figure 2 Pertinent data for a typical Westinghouse design Four-Loop Plant (RESAR-3S)

If the break area is large enough (0.95 cm diameter in the reference plant) that the charging pumps cannot maintain the reactor coolant inventory, the RCS will depressurize. The depressurization causes a reactor trip signal, a reactor coolant pump trip signal and a safety injection actuation signal at ~ 12 MPa (~ 1750 Psia). The reactor coolant pumps are stopped to reduce coolant loss through the break. Natural circulation is thus required to provide the heat removal from the core to the steam generators.

The rate of RCS depressurization following high pressure safety injection depends on the break size. Three major classes of small-break LOCAs are commonly identified:[4,6]

(1) breaks that are large enough to depressurize the RCS to the set-point pressure of the accumulators, (2) smaller breaks that lead to a quasi-steady pressure plateau, and (3) even smaller breaks that may lead to RCS repressurization due to injection

via the HPI pumps. The range of break areas in each class depends on the PWR design parameters, including the physical layout of the loops, core power, HPSI pump capacity and accumulator set point pressure[4].

For relatively large small-break LOCAs, the RCS depressurize to the accumulator injection setpoint pressure. For the reference PWR design these breaks have an area of $>2x10^{-3}m^2$ (>2 in diameter break). For breaks in this range, the reactor coolant flow through the break is sufficient to remove core decay heat load without any additional cooling through the steam generators. The pressure drops very rapidly with a short interval pressure plateau above the secondary side safety valve setpoint before loss of natural circulation occurs. A halt in depressurization occurs because the energy removal through the break, which is limited by the critical flow, is less than the core decay heat. The excess energy is removed to the secondary water in the steam generators. However, after break uncovery, the rate of energy removal through the break increases and the RCS continues to depressurize until accumulator injection.

A second class of small-break LOCAs is defined as those in which the net rate of reactor coolant inventory loss is arrested before the RCS depressurizes to the accumulator setpoint pressure. For breaks in this range (1 to 2 inches in diameter for the reference PWR) of the small-break LOCA spectrum, the initial RCS depressurization is similar to that for larger breaks, including rapid initial depressurization and a pressure plateau dictated by secondary-water temperature. However, when the break is uncovered and steam is discharged, only a short period of rapid depressurization occurs. This is followed by very slow depressurization, which continues so long as heat is being removed by the steam generators. For this class of small-break LOCAs, the HPSI pumps and steam generators play important roles: The HPSI pumps provide makeup water to replenish the reactor coolant inventory and steam generators remove heat from the RCS. Either the steam dump system (preferred) or the steam generator power operated relief valves can be used as the mechanism to extend secondary side cooling of the RCS. Where steam generator cooling is not possible, feed and bleed cooling is evaluated.

The third class of small-break LOCAs are those which may repressurize either by loss of the steam generators as a heat sink, by isolation of the break or by HPSI flow exceeding the inventory loss through the break[4]. For the reference PWR plant, these smaller-size small- breaks have an area of less than $5.07x10^{-4}$ m^2 (one inch diameter break). Decay heat in this class of LOCAs is removed almost entirely by the steam generators.

If the break area is large enough, there will be a transition to reflux boiling. Depending on the break size, the coolant level in the RCS may continue to decrease during the period of reflux boiling. Eventually, the RCS pressure will decrease sufficiently that the rate of water injected by ECCS will exceed the rate of flow out of the break and the primary system may be gradually refilled.

The results of RELAP5 and TRAC Break Spectrum analysis reported in Reference 5 indicate that the smaller break size tends to enhance the differences in event timing. It should be noted that these calculations are limited to simulation of early cooldown phase. For the purpose of more realistic assessment of the boron dilution and relevant mixing processes the thermal-hydraulic conditions during the refill phase of small-break LOCAs and the effects of secondary side depressurization on primary inventory recovery and reestablishment of natural circulation should be further evaluated.

2.2 Natural Circulation Phenomena

Natural circulation is an essential decay heat removal mechanism during small-break LOCAs. There are three distinct modes of natural circulation within the RCS: single phase, two phase (liquid continuous) and reflux condensation. An important conclusion reached from the model tests for PWRs is that the occurrence of a given natural circulation mode is principally a function of primary system coolant mass inventory.[7]

Single-phase natural circulation provide heat redistribution from the core to the steam generators after the RCPs coast down. By integrating the loop momentum equation and expressing the density variation in terms of the volumetric thermal expansion coefficient, the steady state single phase natural circulation flow can be expressed as:[8]

$$W_{1\phi} = \left[\frac{2\beta g \rho_l^2 Q_o \Delta L}{C_p R_f}\right]^{\frac{1}{3}} \tag{1}$$

Where Q_o is the core decay heat rate and ΔL is the elevation difference between the thermal centers of the core (the heat source) and the steam generator (the heat sink). The flow resistance parameter R_f is taken as that for forced flow in the system.[8] A comparison of the theoretical predictions using Equation 1 with the test results for Zion Unit 1[6] (Westinghouse four loops design, 3250 MWt) is shown in Figure 3.

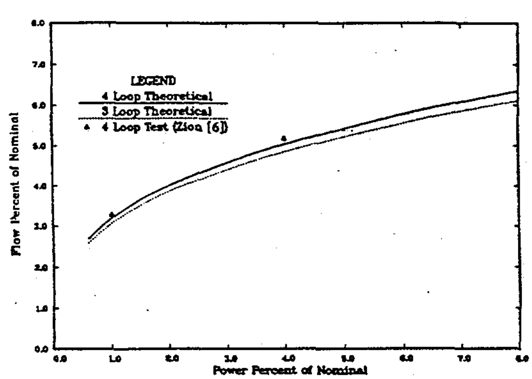

Figure 3 Comparison of single phase natural circulation calculations with test data for Zion.

The single-phase natural circulation occurs from 100% primary coolant inventory down to the onset of voiding in the upper plenum above the hot leg elevation.[7] Further depletion of coolant causes the upper plenum voiding to reach the elevation of hot leg. Initially steam produced by flashing in the reactor vessel will be condensed soon after it enters the inlet to the steam generator tubes, and natural circulation flow will be maintained and even increases because of the overall coolant density in the core, hot leg and upflow side of steam generators decreases.

Continued loss of reactor coolant inventory through the break causes the vessel upper plenum, hot leg and the steam generator primary side become predominantly vapor filled. With this condition the primary mode of natural circulation cooling is reflux condensation. Steam generated in the core rises through the hot legs to the steam generator tubes. The portion of steam that condenses on the upflow side of the U tubes may flow back to the vessel through the hot leg or is carried over to the downflow side. The carryover, with the remaining condensation in the downflow side drops into the pump suction piping (pump seal). The results of Semiscale natural circulation tests[9] shows that the reflux flow rate is almost 50% of the core vapor generation (see Figure 2.6). As it is pointed out in Reference 7, this ratio remained relatively constant, independent of core power, secondary side inventory and primary system inventory. The accumulating condensate mass flow into the loop seals under steady-state phase separating natural circulation, q_a, can be expressed by:

$$q_a = \frac{0.5 Q_o}{(h_{fg} + \Delta h)} \tag{2}$$

Where h_{fg} and Δh are the latent heat and inlet subcooling respectively.

Utilizing the quasi-steady hypothesis and by solving analytically the loop momentum balance together with conservation of mass and energy, Duffey and Sursock[10] obtained expressions for the core flow rate as a function of inventory. Their model predictions has been shown to be in good agreement with the experimental data from the Semiscale[10] and FLECHT-SEASET[11] facilities. For a detail discussion of their simplifying assumptions and model formulation refer to Reference 10. Here we used the Duffey and Sursock model and developed a map of natural circulation flow rate (fraction of nominal) versus normalized mass inventory for 2% decay power level for different RCS pressure conditions as shown in Figure 4. This map can be used for estimating the natural circulation flow under increasing inventory (refill phase).

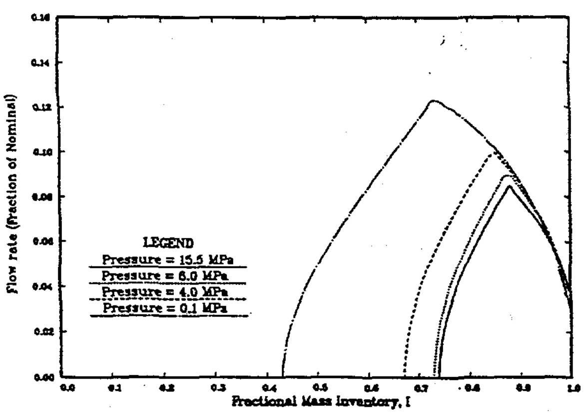

Figure 4 Calculated natural circulation flow rate as a function of fractional mass inventory and pressure (2% decay power).

2.3 Loop Seal Clearing

A typical pressurized water reactor has U-shaped crossover pipes which connect the steam generator outlet plenum to the reactor coolant pump (see Figure 2). During small-break LOCAs, steam passing through the steam generators may blow the water in the crossover legs out to either the break or vessel (loop seal clearing).

Experimental studies on loop seal clearing 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.[12-13] This seemingly simple phenomena should be clearly recognized for analysis of boron mixing prior to loop seal clearing.

3 MIXING PROCESSES AND PHENOMENA

In Section 2, the potential for accumulation of diluted water in the loop seals due to the reflux condensation mode of operation during certain small-break LOCAs was discussed. However, the buoyancy and turbulent mixing along the way from the loop seals to the core may sufficiently increase the boron concentration of the diluted stream to prevent a power excursion leading to fuel failure.

In this section, the quantitative aspects of different mixing mechanisms are first presented and a methodology for their integration into an overall prediction of dilution boundary is discussed. Bounding calculations for the concentration of boron in the coolant entering the core during the refill phase of a small break LOCA and the re-establishment of natural circulation flow in a Westinghouse 4-loop plant will be presented in Section 4.

3.1 Mixing in the Loop Seals

During reflux condensation the loop mean flow rate is virtually null. The safety injection of cold, highly borated water into a stagnant loop of a PWR leads to stratification accompanied by counter-current flows and recirculation. The ensuing flow regime was first established analytically by Theofanous and Nourbakhsh[14,15] as part of the work in support of NRC Pressurized Thermal Shock (PTS) study to predict the overcooling transients due to high pressure safety injection into a stagnant loop of a PWR. The physical situation may be described with the help of Figure 5. A "cold stream" originates with the safety injection buoyant jet at the point of injection, continues toward both ends of the cold leg, and decays away as the resulting buoyant jets fall into the downcomer and pump/loop-seal regions. A "hot stream" flows counter to this "cold stream" supplying the flow necessary for mixing (entrainment) at each location. This mixing is most intensive in certain locations identified as mixing regions (MRs).

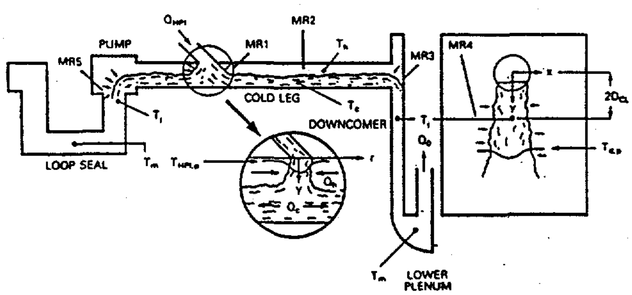

Figure 5 Conceptual definition of flow regime and regional mixing model.

MR1 indicates the mixing associated with the buoyant, nearly axisymmetric safety injection jet. MR3 and MR5 are regions where mixing occurs because of transions (jumps) from horizontal layers into falling jets. MR4 is the region where the downcomer (planar) buoyant jet finally decays. The cold streams have special significance because they induce 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 quantitative aspects of this physical behavior may be found in the regional mixing model.[15,16] 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. The regional mixing model and the associated computer program REMIX[17] has been successfully employed to the interpretation of all available thermal mixing experimental data obtained from the system simulation tests performed in support of the PTS study.[18]

A similar thermal stratification and mixing behavior may even exist in the presence of low loop mean flow. The criterion for the existence of thermal stratification in the presence of loop flow will be discussed in Section 3.2. 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:

$$\rho V \frac{dC_m}{dt} = q_{SI}(C_{SI} - C_m) + q_L(C_L - C_m) \quad (3)$$

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 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 3 can be integrated analytically to:

$$C_m = \frac{C_{SI} + RC_L}{1+R} + \left[C_o - \frac{C_{SI} + RC_L}{1+R}\right] e^{\frac{(1+R)t}{\tau}} \quad (4)$$

where

$$\tau = \frac{\rho V}{q_{SI}} \quad (5)$$

and

$$R = \frac{q_L}{q_{SI}} \quad (6)$$

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 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 6. Neglecting the variation of condensate level in the vertical downflow leg, the flow of condensate entering the bottom horizontal leg, q_L, can be estimated from Equation 2. 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 ≈ 1. With a flow ratio of R = 1, the boron concentration would be more than 1100 PPM.

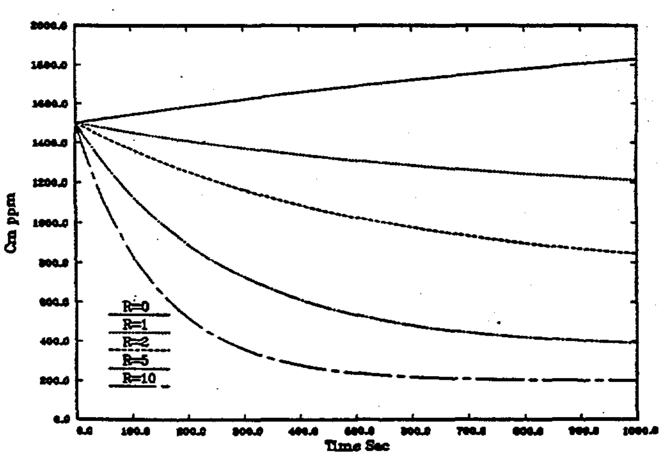

Figure 6 Dilution transient under stratified and recirculating flow regime.

3.2 Mixing at the Safety Injection Point

For a well mixed condition (see Figure 7) 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[19] 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:

$$Fr_{SI,CL} = \left(1 + \frac{Q_L}{Q_{SI}}\right)^{-7/5} \quad (7)$$

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:

$$Fr_{SI,CL} = \frac{Q_{SI}}{A_{CL}}\left\{gD_{CL}\frac{(\rho_{SI} - \rho_L)}{\rho_{SI}}\right\}^{-1/2} \quad (8)$$

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

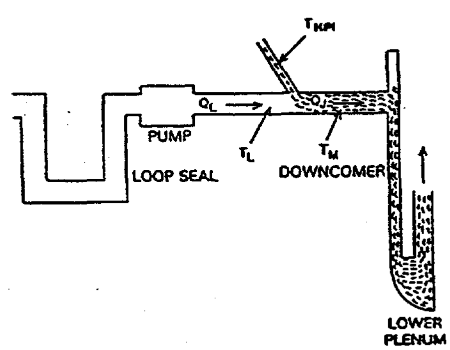

Figure 7 Conceptual representation of the well-mixed condition[19]

This stratification criterion should be considered as providing a high estimate of 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.

$$C_{pm} = \frac{C_{SI} + RC_L}{1+R} \tag{9}$$

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.

3.3 Mixing in the Downcomer

A highly complicated three dimensional mixing pattern occurs at the cold leg-downcomer junction.[15] 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 condition, the diluted stream entering the downcomer would be colder than the downcomer coolant due to mixing with the safety injection. The resulting positively buoyant planar jet 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 constitute a negatively buoyant jet (Inverted Fountain). A schematic of both positive and negative buoyant jets is illustrated in Figure 8.

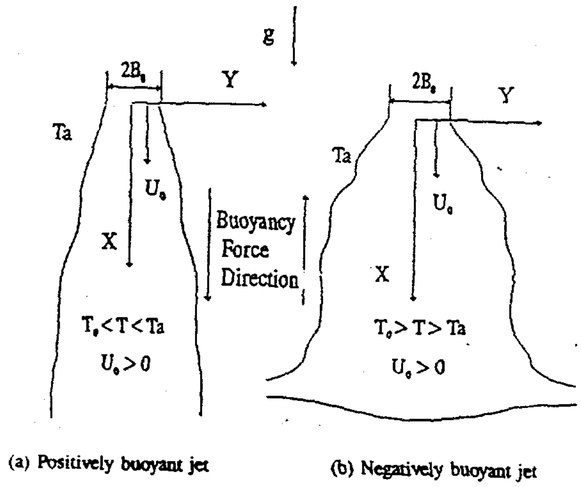

Figure 8 Schematic of a positively and a negatively buoyant jet.

Except for limited data on maximum penetration distance[20], 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 negative buoyant jets was performed as a part of the present work.[21] The jet model of Chen and Rodi[22] was adopted for this purpose. The model utilizes the standard equations for natural convection boundary layer type flows with a vertically oriented buoyance force and a K-ϵ-$\overline{T}^2$ differential turbulence model to evaluate the transport terms in the equations. With the choice of appropriate scales, these equations may be put in dimensionless form such that only one main parameter, the Froude number, appears.

The integration was carried out using the Patankar-Spalding method.[23] 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 Froude number of interest here (Fr = 1.5) are presented in Figures 9 and 10. 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:

$$X^* = \frac{x}{2B_o} \tag{10}$$

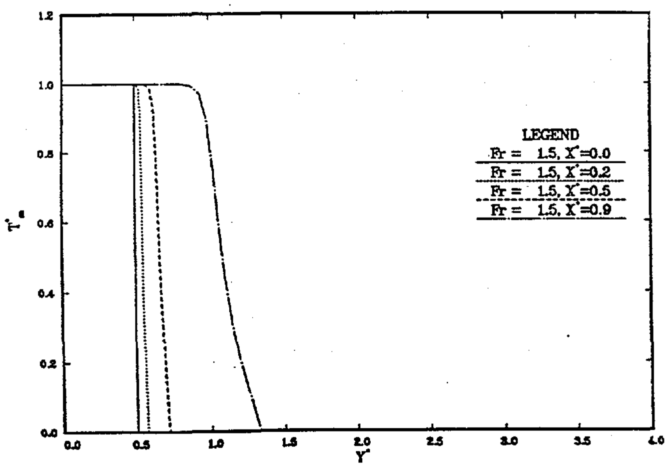

Figure 9 Calculated results of temperature (or concentration) profiles for a negatively buoyant planar jet (Fr = 1.5)

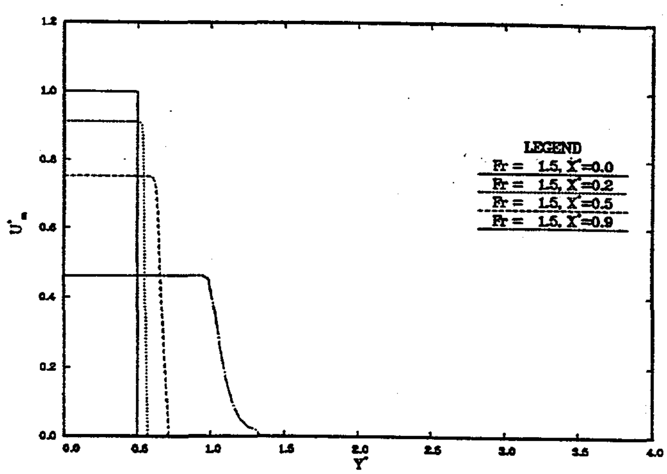

Figure 10 Calculated results of velocity profiles for a negatively buoyant planar jet (Fr = 1.5)

$$Y* = \frac{Y}{2B_o} \tag{11}$$

$$T* = \frac{T-T_a}{T_o-T_a} = \frac{C-C_a}{C_o-C_a} \tag{12}$$

$$U* = \frac{U}{U_o} \tag{13}$$

$$Fr = \frac{U_o}{\sqrt{2B_o g(\rho_a-\rho_o)/\rho_o}} \tag{14}$$

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 decelerates 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 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, being sufficiently reduced, approaches zero and significant lateral spreading of the jet occurs.

The general adequacy of the turbulent jet model utilized here has been demonstrated by Chen, Rodi and co-workers[22,24,25] for positively buoyant jets. To ensure the applicability of turbulence model for negatively buoyant jets the model was used to predict the maximum height of negatively buoyant round (axisymmetric) jets.[21] The maximum height was defined as the point where the centerline velocity decays to 1% of the discharging velocity. The result was found to be in excellent agreement with Turner's correlation,[26] deduced from his experimental data of the penetration height of salt water injected upward into fresh water.

The turbulent jet model was also utilized to predict the maximum penetration distance for negatively buoyant planar jets.[27] 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,[26] the maximum penetration distance of a negatively buoyant planar jet, H_{max}, can be defined by the dimensional consistency requirement as:

$$H_{max} = \text{constant} \times \left(\frac{M_o}{\rho_o}\right)\left(\frac{F_o}{\rho_o}\right)^{-2/3} \quad (15)$$

where

$$M_o = 2B_o \rho_o U_o^2 \quad (16)$$

$$F_o = 2B_o\, \rho_o\, U_o\, g\, (\rho_a - \rho_o)\, / \rho_a \quad (17)$$

Combined with the definition of densimetric Froude number, (Eq. 14), the maximum penetration distance (Eq. 15) can be expressed by:

$$\frac{H_{max}}{2B_o} = \text{constant} \times F_r^{4/3} \quad (18)$$

The proportionality constant evaluated by the turbulent jet model predictions is 2.42 as shown in Figure 11. 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, $H_{max}/2Bo$, should be a constant. This is also supported by the experimental data reported by Goldman and Jaluria[19] which indicate a finite value of penetration distance as Froude number decreases to a very low value. Thus, the maximum penetration distance for $Fr > 2$ can be correlated by:

$$\frac{H_{max}}{2Bo} = 2.42\ Fr^{\frac{4}{3}} \ for\ Fr > 2 \quad (19)$$

A comparison of the present correlation with the data reported by Goldman and Jaluria is also presented in Figure 11.

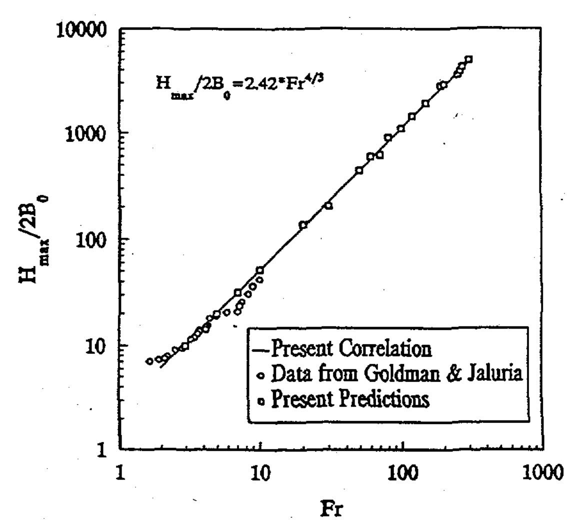

Figure 11 Comparison of predicted maximum penetration distance of negatively buoyant vertical planar jets with experimental data.

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:

$$\rho V_a \frac{dC_a}{dt} = q_{ent}(C_{mj} - C_a) \qquad (20)$$

$$C_{mj} = \frac{C_o + \frac{q_{ent}}{q_o} C_a}{1 + \frac{q_{ent}}{q_o}} \qquad (21)$$

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 the lateral direction and thus would occupy the whole downcomer circumference before reaching to the lower plenum. In this case, the volume of ambient would be reduced accordingly (see Section 4).

Equations 20 and 21 can be integrated analytically to:

$$\frac{C_a - C_o}{C_a^o - C_o} = e^{-\frac{\alpha}{1+\alpha}\frac{q_o}{\rho V_a}t} \qquad (22)$$

$$\frac{C_{mj} - C_o}{C_a^o - C_o} = \frac{\alpha}{1+\alpha} e^{-\frac{\alpha}{1+\alpha}\frac{q_o}{\rho V_a}t} \qquad (23)$$

where

$$\alpha = \frac{q_{ent}}{q_o} \qquad (24)$$

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

3.4 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[18] (under stagnated flow condition) indicate no thermal stratification in the lower plenum (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 higher boron concentration of flow entering the core compared with that entering the lower plenum. The detailed quantification of mixing in lower plenum is beyond the scope of the present study. Some bounding calculations to show the impact of lower plenum mixing are presented in Section 4.

4 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 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 of 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.

The boron dilution necessary to cause fuel damage depends on many factors including the initial shutdown margin, the doppler feedback, the delayed neutron fraction, the neutron lifetime and the speed at which the slug of diluted water moves through the core. The consequence analysis to predict the effect of dilution on fuel integrity is beyond the scope of the present study. However, it should be noted that the results of neutronics calculations,[28] based on an approximate synthesis method, obtained within the context of externally caused rapid boron dilution (with an insurge slug velocity corresponding to 13% of rated flow) indicate that a slug with a concentration of 750 ppm entering the core region with an initial 1500 ppm concentration, could result in an excursion that breaches reactivity insertion accident (RIA) criteria.

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 (RESAR-3S) are presented.

4.1 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.[3] 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 (see Section 2.3). 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 3 (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 a condensation rate (Eq. 2) and the TRAC results of loop seal level change for a 3 in. break reported in Reference 5, is estimated to be $\approx$ 11.9 Kg/s. 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 (4) (see also Figure 6). 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 time duration of level reduction before loop seal clearing reported in Reference 5) is more than 1200 ppm.

4.2 Boron Dilution Due to Reestablishment of Natural Circulation Flow

The re-establishment of natural circulation flow may occur during the refill phase of small break LOCAs (SBLOCAs) as long as the secondary heat sink is available. The magnitude and timing of the natural circulation flow depend 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 re-establishment of natural circulation proceed at low pressure (a characteristic of relatively large SBLOCAs) high flow of cold, highly borated water injected into the cold leg, 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, estimated by conservatively assuming 2% core decay power is about 4% of the nominal flow or 175 Kg/s per loop. 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 (9) 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 a RCS pressure of 4.8 MPa ($\approx$ 700 Psia), decay power of 2% and with the assumption that three steam generators stay active, the estimated two phase natural circulation flow under increasing inventory (based on Figure 4, assuming 36 Kg/sec net refill rate) is 112 Kg/sec. The boron concentration of flow after mixing with the HPI injection of 12 Kg/sec (perfect mixing condition) is 213 PPM. The resulting flow of 124 Kg/sec into downcomer was assumed to form a planar jet with an initial Froude number of $\approx$ 1.5. Using the mixing models presented in Section 3 with $V_a = 0.3m^3$ and $\alpha = 0.08$, the resulting transient boron concentration entering the core was calculated for total condensate volume of $4m^3$ and $10m^3$. Calculations were performed under two limiting conditions of mixing in lower plenum as shown in Figures 12 and 13. Sensitivity calculations were also performed with a bounding estimate of single phase natural circulation flow of 225 Kg/sec per loop as shown in Figure 14.

5 SUMMARY AND CONCLUSIONS

A scoping study of boron dilution and mixing phenomena during small break LOCAs in pressurized water reactors was performed. The mixing processes associated with a slow moving stream of diluted water through the loop seals to the core were examined. The quantitative aspects of different mixing mechanisms and a simplified, yet physically based, methodology for their integration into an overall prediction of dilution boundary were presented. Bounding case analyses for boron concentration of coolant entering the core due to loop seal clearing or re-establishment of natural circulation flow in a typical Westinghouse-designed, 4-loop plant were also presented.

During reflux condensation, the loop mean flow rate is virtually null. Based on the results of thermal mixing studies related to pressurized thermal shock issue, the safety injection of cold and highly borated water into a stagnant loop leads

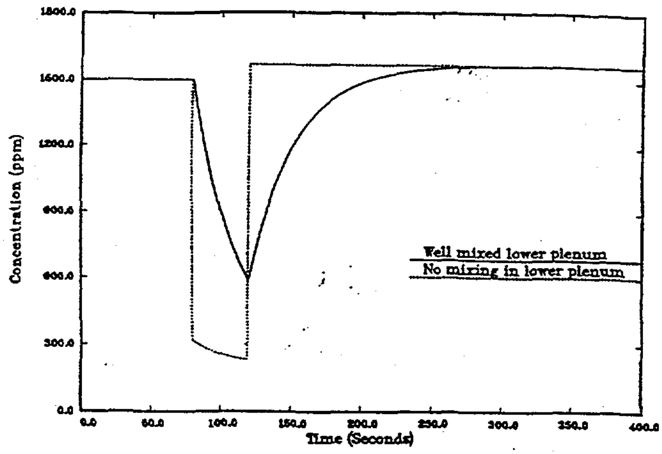

Figure 12 Transient boron concentration entering the core (condensate volume = $4m^3$, natural circulation flow = 112 Kg/sec)

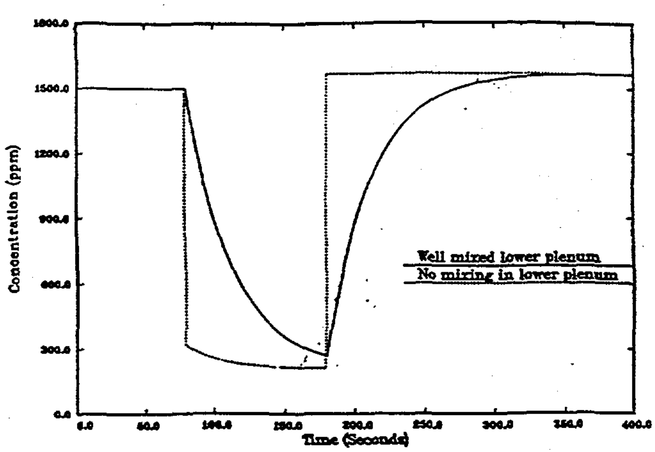

Figure 13 Transient boron concentration entering the core (condensate volume $10m^3$, natural circulation flow 112 Kg/sec)

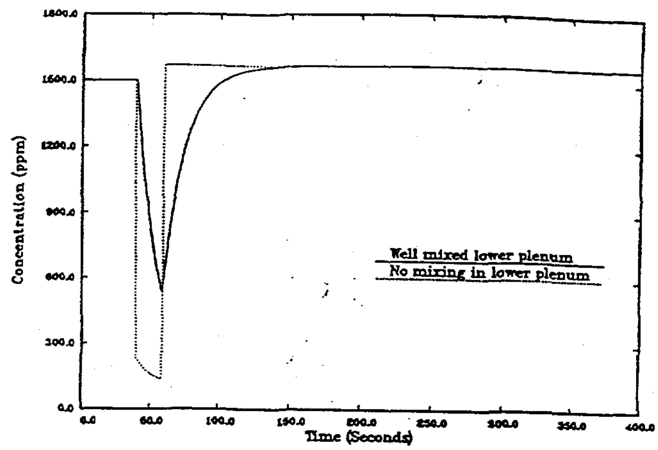

Figure 14 Transient boron concentration entering the core (condensate volume = $4m^3$, natural circulation flow = 225 Kg/sec)

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. Assuming that a similar thermal stratification and mixing behavior may even exist in the presence of low loop mean flow, the boron concentration of flow entering the core was obtained analytically by integrating the global boron mass conservation equation.

Under low loop flow conditions, the diluted stream entering the downcomer would be colder than the downcomer coolant due to mixing with safety injection. The resulting positively buoyant planar jet decays 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 mixing with the safety injection flow, would be higher than the downcomer temperature and thus the inlet flow into the downcomer constitutes a negatively buoyant planar jet (inverted fountain). 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 planar jets was performed as a part of the present work. The differential turbulence model of Chen and Rodi was adopted for this purpose. Using dimensional analysis and the results of the turbulent jet model, a correlation for the maximum penetration distance of a negatively buoyant planar jet, as a function of densimetric Froude number, was also obtained as a part of this study.

Experimental studies on loop seal clearing 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 safety injection of cold and highly borated water into the cold leg leads to stratification accompanied by counter-current flow and recirculation. An illustrative prediction for a typical Westinghouse-designed, 4-loop plant indicates that the boron concentration of flow entering the core does not fall below 1200 PPM when the initial boron concentration in the vessel is 1500 PPM.

If the RCS refill and re-establishment of natural circulation flow proceeds at low pressure (a characteristic of relatively large SBLOCAs), the loop flow of unborated water mixes with the highly borated water injected into the cold leg via accumulators and the low pressure safety injection system. This leads to a significant increase in boron concentration of the resulting flow before it enters the core region.

For the present scoping analyses, it was also assumed that the re-establishment of natural circulation flow occurs at a RCS pressure higher than the accumulator injection setpoint (a characteristic of relatively smaller SBLOCAs). For the bounding cases considered, the boron concentration of the loop flow after mixing with the high-pressure injection (HPI) is 213 PPM. The resulting low Froude number negatively buoyant jets entering the downcomer (assuming symmetric flow of diluted water from different loops) grow rapidly in the lateral direction (without significant- mixing) and will occupy the entire downcomer circumference before reaching the lower plenum. Sensitivity calculations indicate the importance of quantification of mixing in the lower plenum for a more realistic prediction of boron concentration entering the core region.

A more realistic assessment of the boron dilution and relevant mixing processes requires further evaluation of the thermal-hydraulic conditions during the refill phase of small break LOCAs, and the effects of secondary side depressurization on primary inventory recovery and reestablishment of natural circulation flow. Detailed quantification of mixing in the lower plenum is also desirable.

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NOMENCLATURE

Latin Letters

A	area
B	initial half width of a planar jet
C	concentration
D	diameter
F_o	buoyancy flux at the jet source
Fr	Froude number
g	gravitational acceleration
H	height
M_o	momentum flux at the jet source
Q	volumetric flow rate

q	mass flow rate
R	flow ratio (see Eq. 4)
T	temperature
t	time
U	velocity
V	volume
X	coordinate in axial direction
Y	coordinate in transverse direction

Greek Letters

α	nondimensional entrainment flow (see Eq. 22)
ρ	density
τ	mixing time constant under no loop flow condition (see Eq. 3)

Subscripts

o	initial
α	ambient
CL	cold leg
ent	entrainment
L	loop
m	mixed mean
max	maximum
SI	safety injection

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