ABB

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Docket No. 52-002

Attn: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Subject: System 80+™ Small Break LOCA

Dear Sirs:

This letter transmits a revision to the Combustion Engineering Standard Safety Analysis Report - Design Certification (CESSAR-DC) which documents resolution of the NRC concern on Small Break LOCA with Boron Dilution.

If you have any questions, please call me or Mr. Stan Ritterbusch at (203) 285-5206.

Very truly yours,

COMBUSTION ENGINEERING, INC.

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APPENDIX 6C

System 80+ Standard Design

Boron Dilution During A Small Break LOCA ...

Assuming RCP Restart

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APPENDIX 6C

1.0 SUMMARY OF RESULTS

It has been shown in Appendix 6B that even if it is assumed that unborated water enters the System 80+ core at natural circulation flow rates, the core remains adequately cooled. However, there is a concern that the operator could restart a RCP which in turn introduces unborated water into the core at an unacceptable rate.

In order to evaluate this event, this study shows:

1) The possibility of unborated water in the RCS is limited to a very small range of break sizes (1 to 3 inch diameter),

2) The amount of unborated water produced is very limited because the boiling-condensing time is very short (<1.5 hours for the most limiting break),

3) Unborated water entering the core at RCP flow rates would only be significant for the first third of core life, and

4) The minimum concentration of borated water entering the core is well above that required for criticality.

Finally, in order to reduce the probability of this event to a level that is considered an engineering impossibility, the EOGs have been modified to further ensure that the operator cannot erroneously restart a RCP.

2.0 Small Break LOCA Scenarios

2.1 Break Sizes of Concern

In order for unborated condensate to accumulate in the cold side of the RCS after a Small Break (SB) LOCA, the liquid circulation loop across the tops of the steam generators must be broken and the SG secondary side temperature must be less that that of the primary. This forces the core to boil steam in order to reject heat. The steam is condensed back to liquid in the steam generators and a portion flows into the cold side.

The break sizes of concern are in the range from $0.05ft^2$(3"dia.) to $0.0055ft^2$(1"dia.).

For break sizes smaller than $0.0055ft^2$ the liquid loop in the RCS is generally intact, the RCS refills very quickly and very little condensate is formed.

For break sizes larger than $0.05ft^2$ the RCS may not refill and condensation is minimized by removing much more energy through the break. This will minimize the condensate available to be delivered to the core should an RCP be restarted.

2.2 Equipment Operating (RCPs and HPSIs)

If power is not available for restart of an RCP, this mode of introducing boric acid to the core is ruled out.

If it is assumed that offsite power is available then the possibility of RCP restart does exist. However, the same offsite power is also available to power all four of the High Pressure Safety Injection (HPSI) pumps. On a best estimate basis all four of the HPSI pumps are available to deliver highly borated liquid to the reactor vessel. Thus, the analysis described below considers the availablity of offsite power and four operating HPSI pumps.

2.3 Condensate Produced and Refill Times

Analyses have been performed with the CELDA code (described in Reference 1 and approved by the NRC) in order to estimate the amount of low boration condensate produced on the cold side of the RCS for the long term after a SBLOCA. Break sizes of $0.05ft^2$ and $0.0055ft^2$ were analyzed. The calculations were based on operator cooldown of the SG secondary side starting at one half hour after the SBLOCA occurred. In addition, the maximum cooldown rate permitted by the EOGs was assumed. The time dependent decay heat function employed is based on the licensing model described in Reference 1.

The results are given in Table 2.3-1 on a per cold leg basis.

2.4 Reactor Vessel Boric Acid Concentrations at Refill

During the long term following the SBLOCA for a cold side break the boric acid concentration in the inner vessel (core support barrel) continues to rise. This is a result of the input of highly borated HPSI liquid from the vessel annulus and the boiloff of low boration steam in the core (only half of which refluxes back from the hot side of the steam generators). The highly borated liquid in the cold discharge legs, the vessel annulus and inside the CSB is available to mix with the assumed unborated condensate arriving from the RCPs, loop seals and steam generators.

Values for the concentration of the condensate inside the CSB at the RCS refill time are given in Table 2.3-1. These values were obtained with the NRC approved BORON code (Reference 1).

Table 2.3-1

System 80+ Unborated Condensate During a Small Break LOCA*

Break size (cold side) (ft^2)	0.05	0.0055
Operating HPSI pumps	4	4
SG cooldown starts after LOCA (hr)	0.5	0.5
RCS fill time (hr.)	1.4	1.1
Condensate volume available per cold leg (ft^3)	375	290
Boric acid concentration inside CSB at RCS refill time		
(wt/0)**	14.6	12.3
(ppm)	25,500.	21,500.

* Above results based on licensing decay heat model which maximizes core boiloff and unborated condensate formation.

**These results are based on those presented in Figure 6.3.3.4-3 of CESSAR-DC.

3.0 Critical Boron Concentrations

The effect of the critical boric acid concentration and transient xenon effects on a hypothetical return to power after a SBLOCA have been investigated. The following conclusions are applicable.

3.1 Cycle Time Effects (Burnup)

At BOC the maximum boric acid concentration is approximately 1500 ppm at hot full power. The minimum boric acid concentration at EOC is essentially zero.

The variation of boric acid concentration with burnup is fairly linear. The fraction of the cycle time with any risk of post LOCA return to power is about one third.

For post LOCA conditions about 550 ppm of boric acid will maintain the core subcritical at BOC and 300F. Zero ppm will maintain the core subcritical after the first third of the fuel cycle.

3.2 Xenon Effects

Xenon peaks occur after shutdown from hot full power in all commercial PWRs. The magnitude of peak xenon is worth about 250 ppm in terms of soluble boric acid.

The presence of xenon is worth about 200 ppm in terms of soluble boric acid from about 5 to 15 hours after trip.

If xenon effects are accounted for then the fraction of cycle life with any risk of post LOCA return to power, while near peak xenon (Xe worth > 200 ppm equivalent) is about 0.20.

3.3 Critical Concentrations vs. Temperature

The critical concentrations of boron are a function of temperature. Values of the critical boron concentration, at BOC, are given in Table 3.3-1 where no credit has been taken for the negative reactivity effects of xenon.

Table 3.3-1

Critical Boron Concentration at BOC*
(no boron required after the the first third of the fuel cycle)

Temperature	Concentration**
500 F	200 ppm
300 F	550 ppm

* These values do credit the negative reactivity effect of xenon.

** Prompt critical values are about 70 ppm lower.

4.0 Boron Mixing Analysis

Starting from a conservative estimate of the volume of an unborated slug of water which is assumed to collect in the suction legs of the primary coolant pumps, a computational fluid dynamic (CFD) analysis demonstrates substantial mixing in the lower annulus and lower head of the reactor vessel with the start-up of one reactor coolant pump (RCP). This mixing is sufficient to ensure the core remains adequately borated to remain subcritical.

4.1 FLUENT Code Description

FLUENT (2) is a general purpose CFD computer program for the modeling of fluid flow, heat transfer, and chemical reaction. The following list of capabilities make it a very suitable candidate for the boron mixing analysis in the reactor vessel:

2-D/3-D geometries in cartesian, cylindrical, or generalized curvilinear coordinates.

Steady state or transient flow.

Incompressible or compressible flow.

Laminar or turbulent flow.

Chemical species mixing or reaction.

Coupled conduction/convection heat transfer.

Flow through porous media.

The coupled conservation equations for mass, momentum, energy and chemical species are solved using a control volume based finite difference method. The conservation equations are discretized using the power law scheme, and the pressure-velocity coupling is made using the SIMPLE algorithm. The resulting set of discrete algebraic equations are solved using line-iterative procedures.

This solution technique has been the basis for incompressible CFD programs, including the two tools sponsored by the NRC and DOE: TEMPEST (3) and COMMIX (4). It is also the basis for other contemporary CFD programs such as PHOENICS and FLOW3-D.

There are three turbulence models available including the standard κ-ϵ model. The others are a renormalization-group (RGN) based κ-ϵ* model and the higher-order Reynolds Stress Model (RSM).

A porous media approach is applied to model pressure loss characteristics for which component detail is finer than the grid size. For the purposes of this application, the approach includes an inertial resistance term for such pressure losses.

4.2 FLUENT Code Validation

Validation of FLUENT, or any other CFD tool, has not specifically been conducted for this problem. However, the basic features of FLUENT applicable to this problem are validated (5). Validation of other CFD tools are conducted in the same manner (6,7). Since these tools are, in general, based on the same solution methodologies, the qualification of one program to represent a particular flow physics is sufficient to support that the others are also capable. In addition, the process of validating a program on specific elemental examples is the same type of procedure used to validate finite element analysis structural evaluation programs. Finally, FLUENT is being applied by approximately 800 licensees, and the combined user-base for this type of methodology is approximately 3000 licensees.

The basic features of interest to this problem are the basic numerical solution procedure, turbulent boundary layer flows, unsteady flows, and species transport. The validation manual (5) contains 14 sample problems which address these concerns and the concerns of other applications.

The laminar flow examples are proof that the numerical procedures are correct. These are the basic stepping-stones giving confidence that the program can model flow physics. One such problem, laminar flow in a tube with a constriction, tests the inlet and outlet boundary conditions and the power law discretization scheme. The results show the flow separation and reattachment on the tube wall downstream of the constriction. The size of the separated zone is demonstrated to increase with Reynolds number, and the agreement with experimental measurements is good.

An example of laminar flow around a circular cylinder demonstrates the ability of the program to model steady and unsteady flow around a bluff body and the flow separation and vortex shedding downstream of the body. The size of the recirculation regions and the frequency of the vortex shedding are shown to agree fairly well with experimental data.

The prediction of the turbulent flow over a backward-facing step illustrates the capability of the κ-ϵ turbulence model and boundary layer development. Although the reattachment length is under predicted by about 25%, the overall velocity profile is well predicted at the point of attachment. Here, the near wall velocities are over predicted because the κ-ϵ model suggests the boundary layer has already begun to redevelop.

A final example considers reacting flow in a conical combustor. This example tests the κ-ϵ turbulence model in axisymmetric flow and the mass transport capability. Without accurate representation of turbulent mass diffusion the combustion could not be correctly predicted. The mole fraction profiles of a reactant and product of combustion are quite well predicted considering the complexity of the processes and the approximations taken.

The preceding represent a sampling of problems which exercise the basic modeling capabilities needed to model this reactor problem. They yield sufficient confidence in FLUENT's ability to model mixing of boron in a reactor vessel.

4.3 Description of 2-D Model

A two-dimensional axisymmetric model (radial plane) of the reactor vessel from the top of the fuel alignment plate to the bottom of lower head is applied to model the turbulent chemical species mixing. This model begins at an elevation just below the inlet nozzles. The radial grid of the downcomer annulus is selected to be fine enough to allow the direct simulation of the annulus downflow pressure drop and radial mixing. In the lower head region, the grid structure is also fine enough for the prediction of turning losses and associated shear generated turbulence and mixing. Through the flow skirt, lower core support structure, and active core the inertial resistance factors of the porous media model are applied to represent flow resistances.

A uniform downward velocity is specified on the core barrel side of the annulus to represent the lower portion of the planar jet caused by the inlet nozzle. This inlet velocity is time dependent to reflect the pump flow rate acceleration. Based on a conservative maximum pump speed acceleration and ignoring reactor coolant inertia effects, the maximum pump flow rate is achieved in 15 seconds.

Reactor coolant system hydraulic analyses for System 80+ indicate the maximum RCP flow rate with one-pump operation is 150% of nominal. In the reactor vessel annulus, this flow rate splits such that 98% passes through the core and reverse flows exist in the three, non operating cold legs. Although 98% of the pump flow rate passes downward through the annulus, the mixing analysis is conducted with an inlet velocity boundary condition for both 98 and 150 percent pump flow rate.

Before the unborated slug from the RCP inlet pipe may enter the reactor vessel, it must first pass through the RCP and the RCP discharge pipe. These volumes are considered as a delay of the injection, and the delay is accounted for in the time dependence of the model inlet velocity.

The volume of the slug of unborated water immediately injected into the reactor vessel by the start-up of one RCP is chosen to be the volume below the centerline of the entire cold leg from the reactor vessel nozzle to the steam generator outlet plenum. This volume is 262 ft^3. Since there are two RCP's connected to one steam generator, there may be a second unborated slug which could be drawn into the RCP. However, this second slug must first pass through the steam generator outlet plenum. The boron dilution analysis is conducted for two volumes of the unborated slug: 262 and 524 ft^3. The latter volume exceeds the maximum amount of condensate that can occur (Section 2.3).

The initial condition of the reactor coolant is assumed stagnant with a uniform 4000-ppm boron concentration and 300°F temperature. The actual boron concentration is much higher, as discussed in Section 2.4, and the temperature would likely be higher than 300°F when incorrect RCP starting is assumed. Since buoyancy forces generated by variations in the boron concentration and temperature are expected to be small relative to the inertia forces, the flow is assumed to be constant density without heat transfer.

4.4 Justification of 2-D Model

This axisymmetric approach is a simplified model of very complex 3-dimensional mixing hydraulics. However, the approach is representative of the flow physics, and there are number of reasons to judge this simplified analysis of mixing in the downcomer annulus and lower head to lead to a conservative approximation to the prediction of a minimum boron concentration in the active core.

1. No mixing is included in the RCP and pump discharge pipe. The total volume associated with these components is 251 ft^3. This volume, however, is included as a delay time to represent the velocity of the slug at the inlet to the model as the pump flow rate accelerates.

2. No mixing is included in the annulus at and above the elevation of the inlet nozzle. The associated volume is 439 ft^3. Deductions from the flow patterns known to exist from 4-pump operation (Figure 4.4-1) and 1-pump operation (Figure 4.4-2) suggest a planar mixing jet will form opposite the inlet nozzle, and much of this volume will participate in the mixing.

3. The entrainment of the volume of highly borated water in the downcomer annulus is significantly underestimated. This volume totals 719 ft^3. In the axisymmetric model, the bulk of the mixing occurs at the slug front. In planar jets, substantial entrainment occurs along the lateral edges. At a distance of 10 jet-diameters from the inlet nozzle, roughly the height of the downcomer annulus, the entrainment rate may be 3-times the jet volumetric flow rate (8). This entrainment represents a substantial amount of mixing.

4. Flow mixing through the flow skirt is underestimated. Although the porous media approach correctly models the pressure loss of the flow skirt, it does not model the intense turbulence producing shear layers created by the jets through the skirt. Representation of this turbulence generation would greatly increase mixing downstream of the flow skirt.

5. Flow mixing in the lower head and lower support structure is underestimated. The lower head contains many instrument lines in crossflow and a horizontal plate which create turbulence and additional mixing. The lower support structure is modeled using the porous media approach which, again, does not represent the additional turbulence production caused by the bluff bodies and orifices in the flow stream. The volume associated with items 4 and 5 totals 679 ft^3.

6. The larger assumption for the unborated slug volume does not consider mixing of the second slug as it passes through the steam generator outlet plenum. This volume likely contains highly borated water which will mix with the second slug as it travels toward the core. The volume of the steam generator outlet plenum is 423 ft^3. In addition, a substantial flow rate (120% of the pump flow rate) of highly borated water is injected into this volume by flow from the steam generator tubes.

7. In Reference 9, a boron dilution analysis conducted with another CFD tool for start of the RCP's in a different PWR yields similar results to the current analysis.

4.5 Minimum Boron Concentrations

The minimum boron concentration in the active core is found to be a function of time and position. As the pump starts and accelerates, approximately 5 seconds elapse before the unborated slug reaches the reactor vessel. Another 2 to 3 seconds elapse before the slug, which has been mixing with the borated water in the annulus, starts to enter the core. This small deviation in annulus transport time is due to the different assumptions for the flow rate. After entering the core, the larger, initially unborated slug delays attainment of the minimum boron concentration about 2.5 seconds.

As the mixing slug enters the core, boron concentration first decreases at the base and outer radius of the core, and the minimum boron concentration during the transient occurs at this location. Afterward, the minimum concentration sweeps radially inward and then upward through the core as the highly borated water which follows flushes the mixing slug out of the core.

Time traces of the spacial minimum core boron concentration are shown in Figure 4.5-1. At a slug volume of 262 ft^3, there is a slight reduction of minimum boron concentration at the lower annulus downflow rate. Since specie diffusion is both a function of turbulent diffusion and time, the increased turbulence due to the higher annulus Reynolds number increased the mixing at the higher flow rate.

The minimum core boron is dominated by the initial slug volume. For either annulus flow rate, doubling the initial slug volume reduced the minimum boron concentration by approximately 35 percent (Table 4.5-1).

Case 5 is a special case with reduced time step size and grid size to tighten convergence of the solution. This case represents the minimum concentration predicted by this analysis and a conservative approximation of the minimum boron concentration, 1350 ppm, in the core due to an initial unborated slug volume of 524 ft^3.

Table 4.5-1

Minimum Boron Concentration In Core For 1-Pump Start

CASE	BORON CONCENTRATION, ppm
1. 1.5X-PUMP ANNULUS FLOW RATE 262-FT3 UNBORATED VOLUME	2900
2. 1.5X-PUMP ANNULUS FLOW RATE 524-FT3 UNBORATED VOLUME	1870
3. 0.98-PUMP ANNULUS FLOW RATE 262-FT3 UNBORATED VOLUME	2820
4. 0.98-PUMP ANNULUS FLOW RATE 524-FT3 UNBORATED VOLUME	1850
5. 0.98-PUMP ANNULUS FLOW RATE 524-FT3 UNBORATED VOLUME	1350

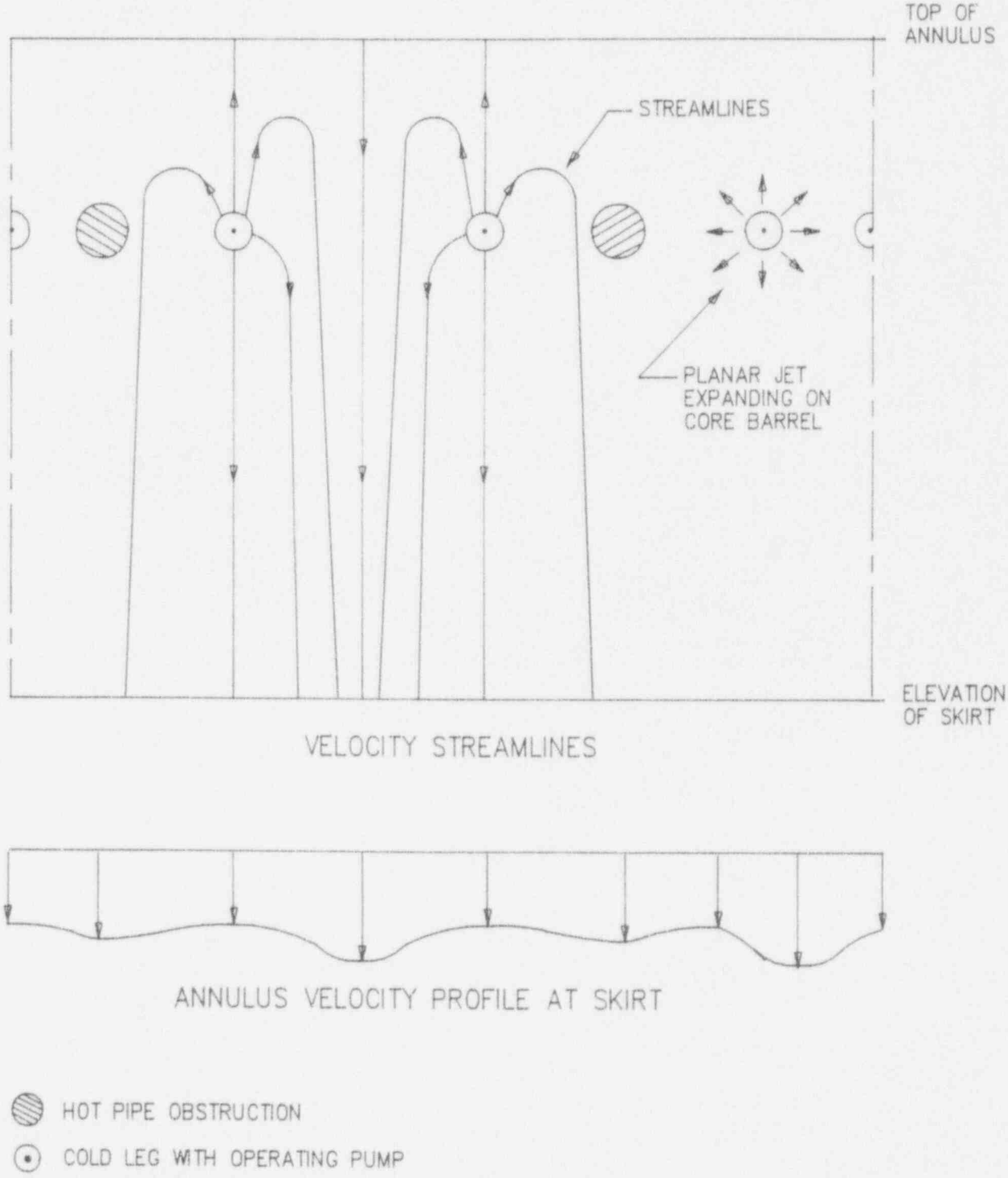

Figure 4.4-1, Unwrapped Annulus - 4-Pump Operation

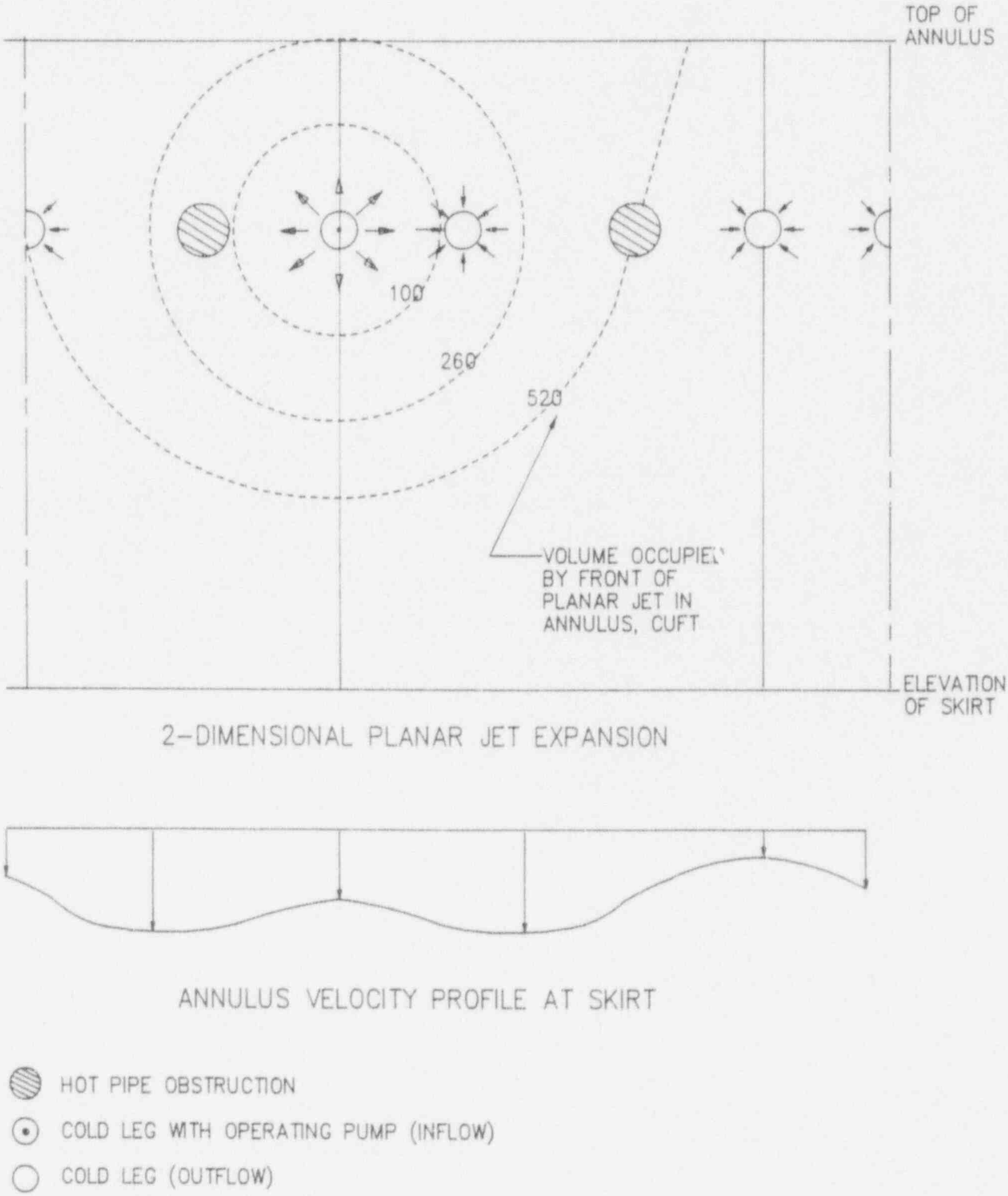

Figure 4.4-2, Unwrapped Annulus – 1-Pump Operation

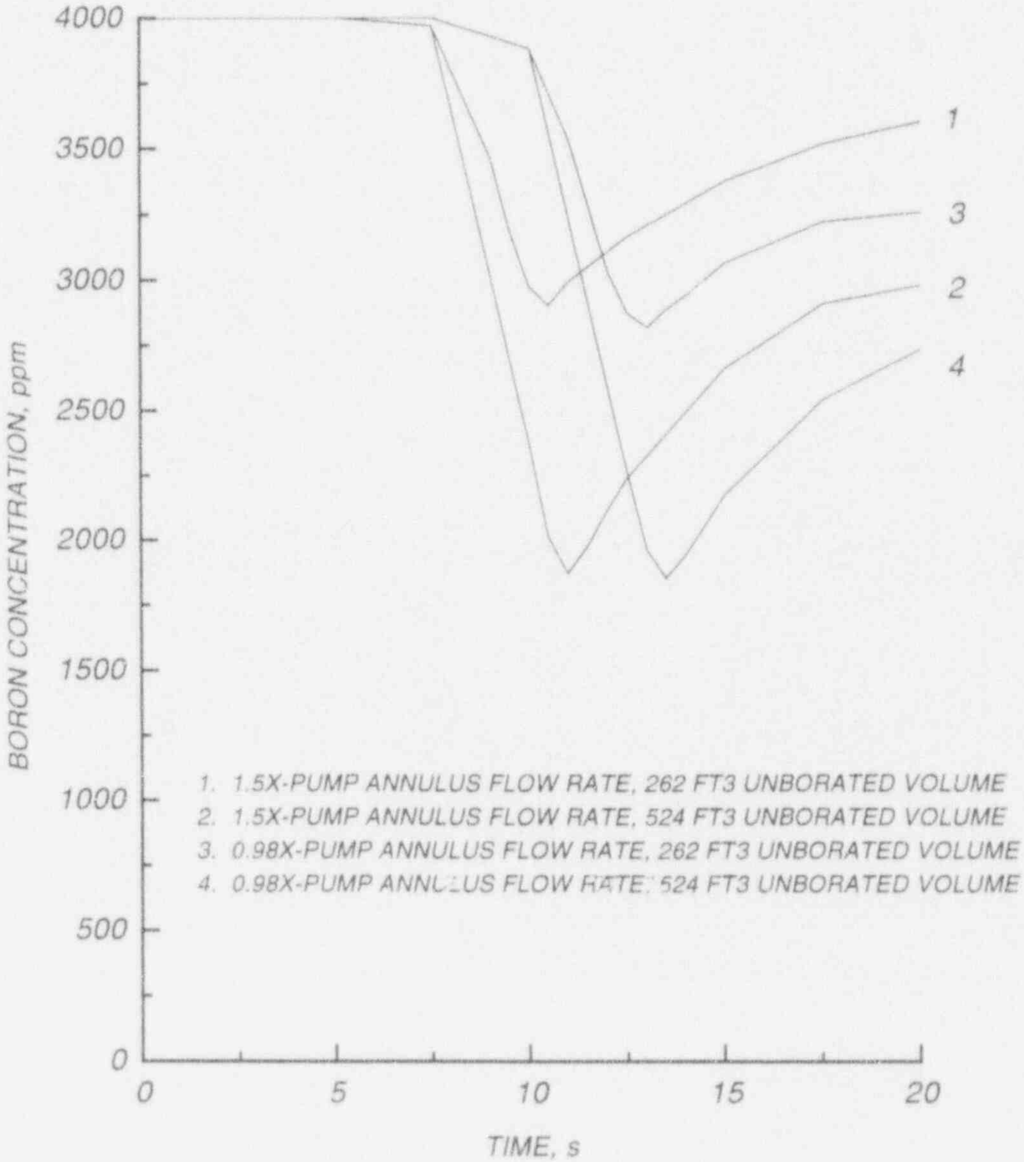

Figure 4.5-1, Minimum Boron Concentration With 1-Pump Start

5.0 EOG Modifications

5.1 Objective

The Emergency Operations Guidelines (EOGs) were modified to reduce the likelihood of an erroneous restart of an RCP following a LOCA which results in significant reflux boiling.

5.2 Modifications

A. Originally, the RCP restart steps of the EOG were presented in the following order:

1. Determine if RCP restart is needed and desired.
2. Verify that all RCP restart criteria are met.
3. Restart RCP.
4. If RCP not running, verify adequate single-phase natural circulation.
5. If single-phase natural circulation cannot be established, verify adequate two-phase natural circulation.

It was determined through consultation with human factors experts and operations personnel, that this may mislead the operator into believing that it is more important to restart an RCP than it is to verify natural circulation. While it is obvious that this is not the case, the EOG bases clearly state (Introduction section) that the EOG procedure steps are presented in the order which is most commonly expected during the event for which the EOG Optimal Recovery Guideline is designed. Therefore, the EOG was modified (along with its bases) to re-order the steps as follows:

1. Verify adequate single-phase natural circulation.
2. If single-phase natural circulation cannot be established, verify adequate two-phase natural circulation.
3. Determine if RCP restart is needed and desired.
4. Verify that all RCP restart criteria are met.
5. Restart RCP.

B. Add Supplementary Information item:

The EOGs contain a "Supplementary Information" section located after each guideline and prior to the bases section. This Supplementary Information section contains data that is helpful to the operator, but is not a procedure step (i.e., not an action statement). The EOG intends this information to become a site specific procedure "Caution" or "Note", and/or become information which is placed in the site operator training program.

Since it is important for the operator to consider whether or not condensate could have built up in the suction leg of the RCP prior to RCP restart, Supplementary Information was added to the LOCA guideline that cautions the operator about this possibility prior to RCP restart. In addition, the Supplementary Information item specifies that this should become a caution in the plant specific procedures. It is intended for this caution to be placed prior to the RCP Restart Desirability Determination step (step #3 above) in the plant specific procedure.

B. Modifications to step #3 above (RCP Restart Desirability):

1) The EOGs were originally written with the assumption that if the performance of a step was optional (e.g., restarting RCPs after a LOCA), the operator would check with the Technical Support Center (TSC) to obtain concurrence on its performance before implementing it. It was felt by many that because the consequences of restarting an RCP post-LOCA were potentially unacceptable, rather than assume the operator would follow this process, it would be best to <u>require</u> the operator to obtain a recommendation from the TSC as to whether or not RCP restart was desirable. Therefore, a step requiring a TSC evaluation was added to the RCP restart desirability determination step (#3 above).

3) Since this event is concerned with the buildup of condensate in the suction leg of an RCP following prolonged two-phase natural circulation (post-LOCA), a criterion was added to this step to require the operator and the TSC to consider the length of time the plant had been in two-phase natural circulation.

4) Studies have demonstrated that if single-phase natural circulation has been established for at least 20 minutes prior to RCP restart (following prolonged two-phase natural circulation), the consequences of RCP restart are acceptable. Therefore, this step was modified to require the operator and the TSC to consider the length of time the plant has been in continuous single-phase natural circulation (after it exited two-phase natural circulation) when evaluating the desirability of RCP restart.

C. Modifications to step #4 above (RCP Restart Criteria):

1) As was the case with step #3 above, the EOGs were originally written with the assumption that if the performance of a step was optional, the operator would check with the TSC prior to implementing it. Therefore, this step originally did not require TSC permission prior to RCP restart. However, for the same

reason as was stated above in explanation B.1), rather than assume the operator would follow this process, this step was modified to require the operator to obtain permission from the TSC prior to starting an RCP.

2) Originally, the criterion to verify that at least 20 minutes of continuous single-phase natural circulation has been established prior to restarting an RCP, had been listed last. However, it was felt by many that even though all RCP restart criteria receive equal weight, if this was listed immediately following the criterion to obtain TSC permission to restart an RCP and the criterion could not be met, there would be no need for the operator and the TSC to observe the rest of the criteria. Since this would be more efficient, the step was modified accordingly.

D. Modifications to the Bases:

Since the steps were modified, it was necessary to modify the bases. All bases match the new step order, and the new steps all have bases explanations.

E. Summary of Procedure Implementation

The operator will reach these steps after attempting to isolate the leak. First, the step to verify adequate single-phase natural circulation will be reached. If adequate single-phase natural circulation exists, the operator will skip the next step (verification of two-phase natural circulation) and proceed to the step to determine the desirability of restarting an RCP.

If the operator cannot verify adequate single-phase natural circulation, he/she will proceed to the next step which verifies adequate two-phase natural circulation.

Once the "RCP restart" steps are reached, the caution will be read alerting the operator to the possibility of condensate buildup in the RCP suction leg.

Next, the operator will request that the TSC determine the desirability and need to restart an RCP. The operator will make a concurrent determination. Since the caution was just read by the operator, its information will be factored into the evaluation. Both the operator and the TSC will base their decisions on at least the following criteria:

- Adequacy of core heat removal using natural circulation
- The need for main pressurizer spray capability
- Existing RCS pressure and temperature
- The duration of CCW interruption to the RCPs
- RCP seal staging pressures and temperatures
- Time the plant was in two-phase natural circulation
- Time the plant has been in single-phase natural circ.

If any of the above criteria do not indicate that an RCP restart is desirable, the operator will skip the remaining RCP steps. Otherwise, he/she will proceed to the next step.

The operator next determines if an RCP restart can be performed based on at least the following criteria:

- The TSC has recommended RCP restart
- Single-phase natural circulation has been established for at least 20 minutes
- Power available to the RCP bus
- RCP auxiliaries are operating
- At least one SG is available
- Pressurizer level > 33%
- RCS is subcooled
- Other criteria satisfied per RCP operating instructions

If any of the above criteria do not indicate that an RCP restart is desirable, the operator will skip the remaining RCP steps. Otherwise, he/she will proceed to the next step.

Once it has been determined that RCP restart is desirable, and the restart criteria are met, the operator will proceed to the next step and restart an RCP.

5.3 Human Reliability Analysis

A Human Reliability Analysis (HRA) was performed to determine the probability of erroneously restarting an RCP prior to the establishment of at least 20 minutes of continuous single-phase natural circulation. The analysis is described below.

A. Model Assumptions

The analysis provides a reasonable and conservative estimate of the frequency of erroneous RCP restart, given the existence of the physical plant conditions necessary for the event to occur. The following conservative assumptions are part of the model:

- Operating experience suggests that it is unlikely that the operating crew would have reason to restart an RCP after prolonged post-LOCA two-phase natural circulation. However, having such a reason is not necessarily an error, and HRA is thus not an appropriate method for estimating its probability. Therefore, the model conservatively assumes that the control room staff will always want to restart an RCP.

- Other than the lack of 20 minutes of Single-Phase Natural Circulation (SPNC), it is assumed that no plant conditions exist to preclude RCP restart (even though at least 12 conditions must be considered).

- No credit is taken for improved plant or procedure ergonomics.

- Activities required for pump restart are assumed to require no execution time (a potential mitigating factor), and to be 100% successful.

Three other reasonable assumptions have been made to limit the model complexity:

- No single (i.e., random) error will cause an RCP restart.

- If the TSC is asked to consider the RCP restart, it will proactively communicate to the Main Control Room (MCR) if any of the RCP restart criteria are not met.

- The Main Control Room will follow the TSC directions if they are given.

B. Model Structure

Two HRA event trees were constructed to determine the probability of erroneously restarting an RCP (figures 5.3-1 and 5.3-2). The event tree of figure 5.3-1 determines the lower bound of probability and the event tree of figure 5.3-2 determines the upper bound.

There are several decisions/evaluations/actions the operator and the TSC could take. Therefore, the model structure for both trees incorporates the following actions:

- In Node A, the MCR staff requests the TSC staff to evaluate the need and acceptability of restarting an RCP.

- In Nodes B and F, the MCR staff notes that the criterion for ensuring the establishment of 20 minutes of Single-Phase Natural Circulation (SPNC) prior to starting an RCP, is not met.

- In Nodes D and E, the TSC staff notes that the criterion for ensuring the establishment of 20 minutes of SPNC prior to starting an RCP, is not met.

- In Node C, the MCR staff verifies that the TSC will permit the restarting of an RCP.

Any time movement is made along the tree down and to the left, the correct actions are being taken. If movement is made down and to the right, errors are being made.

C. Model Quantification

THERP models are highly sensitive to the adjustment of their individual event weights (i.e., performance shaping factors). In addition, decision research has shown that model structure, rather than weighting, is the more frequent strength of "experts" (Dawes, 1979). Thus, two quantifications of the same model were used to provide reasonable limits for discussion and assessment.

The lower limit was obtained by using unweighted nominal HEP values (i.e., 3.0 E-3) for each event in the tree (figure 5.3-1). The unweighted quantification is presented as a best estimate result for this model. This produced a total HEP of 2.7 E-6 for the event tree.

The upper limit was obtained by "overweighting" the model with a set of hyperconservative values (figure 5.3-2). Relatively poor procedure ergonomics were assumed. Therefore, a larger-than-nominal value (1.0 E-2) was used as the basic Human Error Probability (HEP). The effects of stress and dependency were then incorporated at unfavorably high levels. This produced a total HEP of 5.54 E-2 for the event tree.

Finally, the geometric mean of the two values was taken to account for uncertainty as follows:

- Geometric mean is the N^{th} root of the product of N terms.

  For this case:

  - N=2
  - A = Lower Bound = 2.75 E-6 (unweighted estimate)
  - B = Upper Bound = 5.54 E-2 (overweighted estimate)

  Therefore:

  The geometric mean $= (A \times B)^{1/2}$

  $= (2.75\text{ E-6} \times 5.54\text{ E-2})^{1/2}$

  $= 3.91$ E-4

This value of 3.91 E-4 is presented as a conservative estimate of the total HEP for this event.

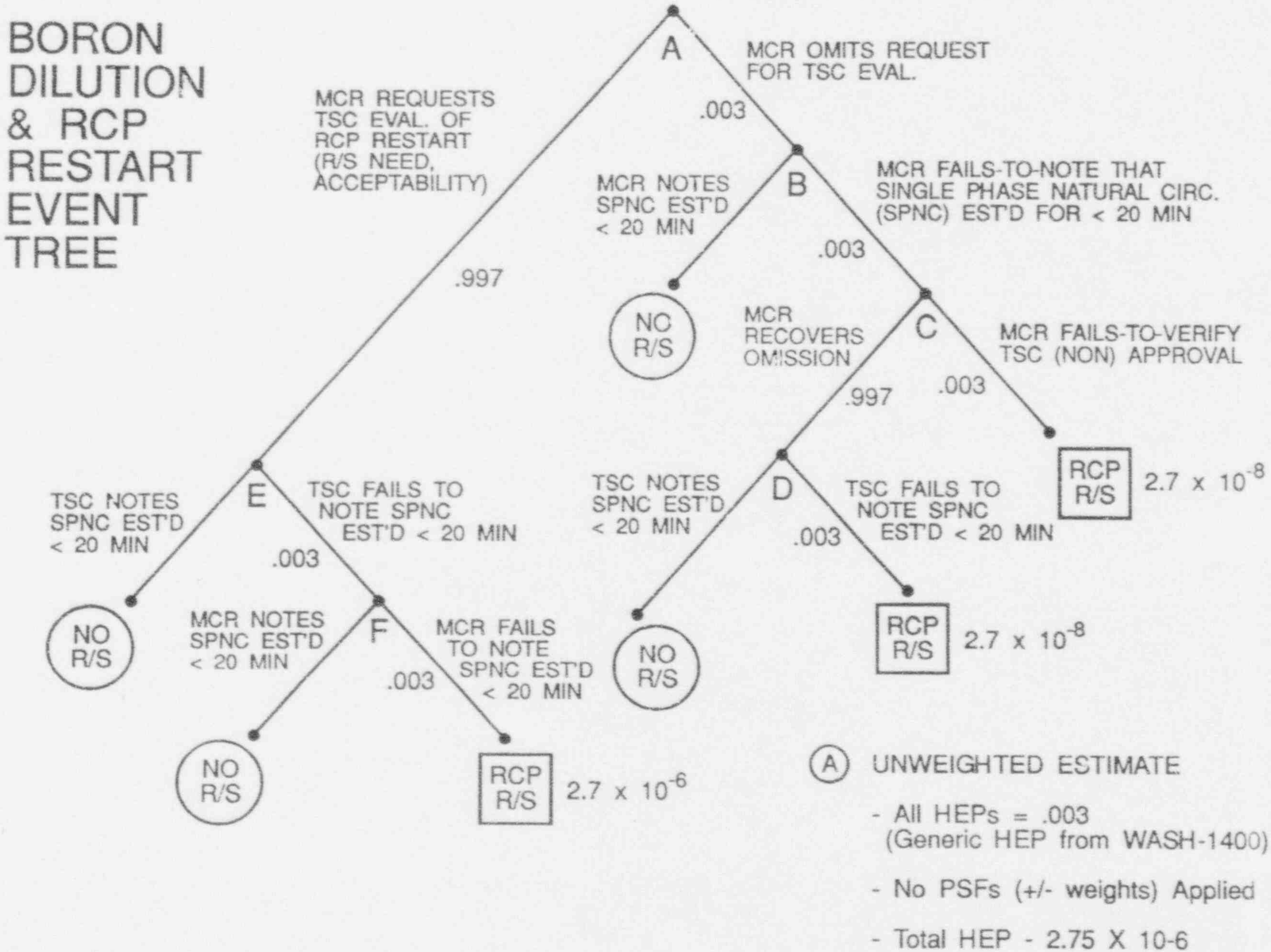
BORON DILUTION & RCP RESTART EVENT TREE
A
MCR REQUESTS TSC EVAL. OF RCP RESTART (R/S NEED, ACCEPTABILITY)
.997
MCR OMITS REQUEST FOR TSC EVAL.
.003
B
MCR NOTES SPNC EST'D < 20 MIN
MCR FAILS-TO-NOTE THAT SINGLE PHASE NATURAL CIRC. (SPNC) EST'D FOR < 20 MIN
.003
NC R/S
C
MCR RECOVERS OMISSION
.997
MCR FAILS-TO-VERIFY TSC (NON) APPROVAL
.003
RCP R/S
2.7 x 10-8
D
TSC NOTES SPNC EST'D < 20 MIN
TSC FAILS TO NOTE SPNC EST'D < 20 MIN
.003
NO R/S
RCP R/S
2.7 x 10-8
E
TSC NOTES SPNC EST'D < 20 MIN
TSC FAILS TO NOTE SPNC EST'D < 20 MIN
.003
NO R/S
F
MCR NOTES SPNC EST'D < 20 MIN
MCR FAILS TO NOTE SPNC EST'D < 20 MIN
.003
NO R/S
RCP R/S
2.7 x 10-6
A UNWEIGHTED ESTIMATE
- All HEPs = .003 (Generic HEP from WASH-1400)
- No PSFs (+/- weights) Applied
- Total HEP - 2.75 X 10-6

Figure 5.3-1

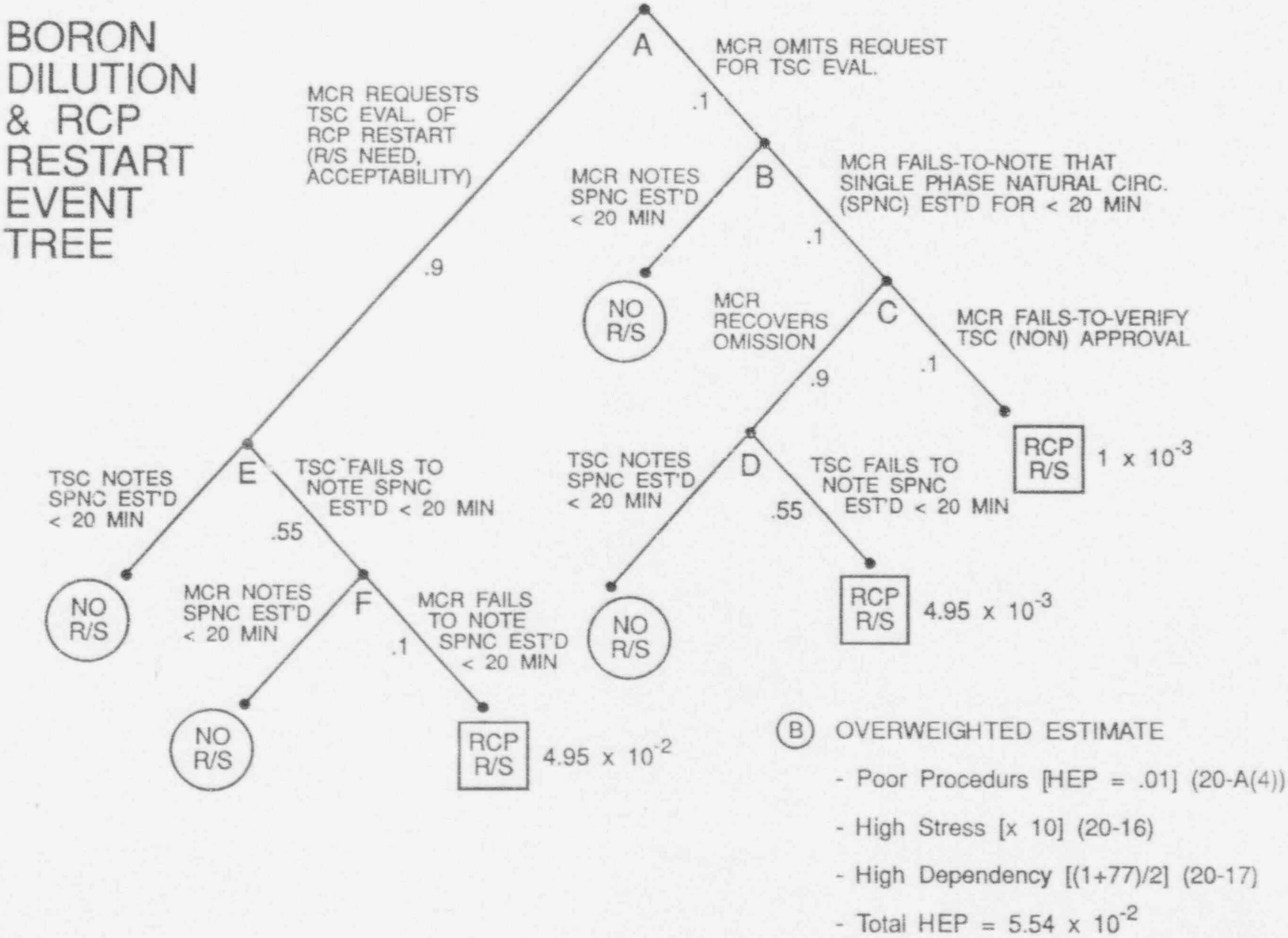
BORON DILUTION & RCP RESTART EVENT TREE
A
MCR OMITS REQUEST FOR TSC EVAL.
.1
MCR REQUESTS TSC EVAL. OF RCP RESTART (R/S NEED, ACCEPTABILITY)
.9
B
MCR NOTES SPNC EST'D < 20 MIN
NO R/S
MCR FAILS-TO-NOTE THAT SINGLE PHASE NATURAL CIRC. (SPNC) EST'D FOR < 20 MIN
.1
C
MCR RECOVERS OMISSION
.9
MCR FAILS-TO-VERIFY TSC (NON) APPROVAL
.1
RCP R/S
1 x 10-3
D
TSC NOTES SPNC EST'D < 20 MIN
NO R/S
TSC FAILS TO NOTE SPNC EST'D < 20 MIN
.55
RCP R/S
4.95 x 10-3
E
TSC NOTES SPNC EST'D < 20 MIN
NO R/S
TSC FAILS TO NOTE SPNC EST'D < 20 MIN
.55
F
MCR NOTES SPNC EST'D < 20 MIN
NO R/S
MCR FAILS TO NOTE SPNC EST'D < 20 MIN
.1
RCP R/S
4.95 x 10-2
B OVERWEIGHTED ESTIMATE
- Poor Procedurs [HEP = .01] (20-A(4))
- High Stress [x 10] (20-16)
- High Dependency [(1+77)/2] (20-17)
- Total HEP = 5.54 x 10-2

Figure 5.3-2

6.0 OVERALL RISK ASSESSMENT

The overall risk associated with boron dilution during a small LOCA is assessed in this section of the report. The assessment involves the description of two potential scenarios of concern and the quantification of the scenario probabilities. The impact of the scenario probabilities on the Probabilistic Risk Assessment results presented in Section 19.9 of CESSAR-DC is also assessed in this section.

6.1 Scenario Probabilities

Two small LOCA scenarios were assessed:

1. A small LOCA during which all safety injection pumps operate, and the operator initiates an incorrect restart of a Reactor Coolant Pump (RCP) during the first third of the fuel cycle.

2. A small LOCA during which only two of the four safety injection pumps operate, and the operator initiates an incorrect restart of a RCP during the first third of the fuel cycle.

The probability of scenario 1 can be expressed as follows:

$$F_{s1} = SLOCA * HEP_{RCP} * X_{cycle}$$

where,

F_{s1}	=	Scenario probability of small LOCA and incorrect restart of a RCP during the first third of fuel cycle
SLOCA	=	Small LOCA initiator (3.0E-03 per year)
HEP_{RCP}	=	Human error probability for un- desired restart of a RCP (3.9E-04)
X_{cycle}	=	Probability multiplier of a small LOCA occurring during the first third of cycle (0.33)

The above frequency of a small break LOCA is used in the System 80+ PRA and is obtained from Table 19.3.3-2. The human error probability (HEP) for incorrect restart of a RCP is based on the procedures for mitigating a small LOCA and is estimated as shown in Section 5.3 of this Appendix. The cycle time reflects the fact that boron is required during the first third of the fuel cycle and the small LOCA must also occur during this time in order for the scenario to be of safety significance. By substituting the values in the above expression, the probability for scenario 1 becomes:

$$F_{s1} = 3.0E\text{-}03 * 3.9E\text{-}04 * 0.33$$

$$= 3.9E\text{-}07 \text{ per year.}$$

The probability of scenario 2 can be expressed as follows:

$$F_{s2} = SLOCA * SI_2 * HEP_{RCP} * X_{cycle}$$

where,

F_{s2}	=	Scenario probability of small LOCA, failure of two of four safety injection pumps to operate, and incorrect restart of a RCP during the first third of the fuel cycle
SLOCA	=	Small LOCA initiator (3.0E-03 per year)
SI_2	=	Failure probability of 2 of 4 safety injection pumps to operate (2.2E-04)
HEP_{RCP}	=	Human error probability for un- desired restart of a RCP (3.9E-04)
X_{cycle}	=	Probability multiplier of a small LOCA occurring during the first third of cycle (0.33)

The frequency of a small LOCA, the HEP for incorrect restart of a RCP, and the probability multiplier for the cycle time are the same as describe for scenario 1. The dominant contributors to the probability of 2 of 4 safety injection pumps failing to operate include common cause failure of the pump breakers to close, common cause of the pumps to start, and common cause failure of the pumps to operate. Simultaneous independent failures of the pumps are not significant contributors to the overall failure probability of the pumps. The failure probability of 2 of 4 safety injection pumps to operate is 2.2E-04 per demand. This probability is based on failure rates used in the System 80+ PRA. By substituting the values in the above expression for scenario 2, the probability becomes:

$$F_{s2} = 3.0E\text{-}03 * 2.2E\text{-}04 * 3.9E\text{-}04 * 0.33$$

$$= 8.5E\text{-}11 \text{ per year.}$$

6.2 Impact on PRA Results

The PRA results presented in Table 19.9.1-4 show that the core damage frequency of internal events is 1.67E-06 per year. If scenario 1 described in Section 6.1 is assumed to cause core damage, the overall core damage frequency for internal events would increase. The core damage frequency for internal events would increase from 1.67E-06 to 2.06E-06 per year. Scenario 2 would have no impact on the core damage frequency for internal events. Therefore, from a deterministic standpoint this scenario is not considered.

If the worst case conditions are assumed and boron mixing is ignored, the outcome of the limiting small LOCA boron dilution event is a damaged but otherwise coolable core. Core recovery is considered likely because of (1) the availability of safety injection, (2) the short duration of the induced core power spike, (3) the RCS pressure relief through the existing hole in the RCS, and (4) the pressure absorption capability in the partially voided upper portions of the RCS when the reactivity insertion event takes place. Severe accident analyses, as well as experience with TMI-2, indicate that adequate core cooling can be established even in the presence of severely damaged core, provided an adequate internal water supply is available. As long as the RCS pressure does not produce material stresses that exceed the ASME Service Level C limits, emergency core cooling system integrity is expected. As a consequence of items 2, 3, and 4 above, pressurization of the RCS to levels that exceed Service Level C stresses is highly unlikely.

In the event that an unrecoverable core damage event occurs, containment spray and cavity flooding systems would be capable of arresting the event within the intact containment. Since the systems required to mitigate the post-vessel breach corium progression are not influenced by the small LOCA boron dilution event, and both AC power and component cooling water are available, at least one train of the containment spray system will be available and containment integrity will not be compromised.

Based on the guidelines and requirements of the Advanced Light Water Reactor (ALWR) Utility Requirements Document, the industry has established a mean core damage frequency goal of 1.0E-05 per year. Even if scenario 1 causes core damage, the increased core damage frequency is well within this goal. Since in-vessel recovery of the scenario will occur if the RCS pressure remains below the Level C stress limits, and since essential containment safeguard systems are available even if the RCS pressure exceeds the Level C stress limits the increase in overall plant radiation releases will be negligible. The PRA conclusions are preserved even when the worst case boron dilution scenario is considered.

7.0 CONCLUSION

Although there is a potential to produce some unborated condensate during some small break LOCAs, this condensate will be mixed with highly borated water in the RCS upon the onset of single-phase natural circulation. Appendix 6B provides a very conservative core coolability assessment of the natural circulation case assuming no mixing of the condensate.

This appendix provides Emergency Operating Guideline (EOG) modifications which significantly reduce the probability of RCP restarting prior to achieving adequate mixing by natural circulation. It also provides a demonstration that, even if RCP restart is assumed to occur at the worst time, sufficient mixing occurs to ensure the core remains subcritical and adequately cooled.

8.0 References for Appendix 6C

1. CENPD-254-P-A, Post-LOCA Long Term Cooling Evaluation Model, June 1980.

2. FLUENT User's Guide Version 4.0, Fluent, Inc., December 1991.

3. D.S. Trent and L.L. Eyler, TEMPEST: A Three-Dimensional Time-Dependent Computer Program for Hydrothermal Analysis: Vol. I Numerical Methods and Input Instructions, PNL=4348, Pacific Northwest Laboratory, 1989.

4. H.M. Domanus, et al., COMMIX-1C: a Three-Dimensional Transient Single-Phase Computer Program for Thermal-Hydraulic Analysis of Single-Component and Multicomponent Engineering Systems. NUREG/CR-5649, November 1990.

5. FLUENT V4.2 Validation Problems, TM-127, Fluent, Inc., July 1993.

6. D.S. Trent and L.L. Eyler, TEMPEST: A Three-Dimensional Time-Dependent Computer Program for Hydrothermal Analysis: Vol. II Assessment and Verification Results, PNL=4573, Pacific Northwest Laboratory, 1983.

7. H.M. Domanus, et al., COMMIX-1A: A Three-Dimensional Transient Single-Phase Computer Program for Thermal Hydraulic Analysis of Single and Multicomponent Systems: Vol. II Assessment and Verification, NUREG/CR-2896, December 1983.

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9. J.G. Sun and W.T.Sha, Analysis of Thermal Mixing and Boron Dilution in a PWR, NUREG/CR-5822, February 1993.