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DCP/NRC1059
NSD-NRC-97-5353
Docket No.: 52-003

October 1, 1997

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555

ATTENTION: T. R. QUAY

SUBJECT: RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION ON MIXING IN DOWNCOMER AND LOWER PLENUM (RAI 440.724)

Dear Mr. Quay:

Attached is the response to a request for additional information on mixing in the downcomer and lower plenum during post-RCP trip natural circulation for small break LOCAs. This response closes, from a Westinghouse perspective, RAI 440.724 (OITS-5657). The Westinghouse status column in the OITS will be changed to "Action N" for the above item. The NRC should inform Westinghouse of the status to be designated in the "NRC Status" column of the OITS.

Please contact Ms. Susan V. Fanto (412)374-4028, if you have any questions concerning this material.

Brian A. McIntyre

Brian A. McIntyre, Manager
Advanced Plant Safety and Licensing

jml

Attachment

E004

cc: W. C. Huffman, NRC (w/Attachment)
N. J. Liparulo, Westinghouse (w/o Attachment)

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Attachment to Westinghouse Letter
DCP/NRC1059
October 1, 1997

RAI 440.724:

In the Westinghouse response to RAI 440.120 dated May 14, 1997, Westinghouse stated that "the relatively low flow rate of fluid from the downcomer into the core during post-RCP trip natural circulation phase of AP600 small break LOCA events enables mixing to occur in the core and lower plenum. No unmixed slugs of highly dilute liquid from the PRHR are present in the downcomer to enter the core during the LOCA design basis scenarios." Please provide quantitative technical justification to support engineering judgement regarding mixing in the downcomer and the lower plenum of the core. The justification should include break size (worst case scenario), as well as condensate flow rate and final boron concentration(s). The boron concentration and concentration uniformity in the downcomer should also be addressed.

Response:

The spectrum of AP600 LOCA breaks was reviewed to identify the worst case scenario(s) for mixing of PRHR condensate in the reactor vessel downcomer and lower plenum. Two scenarios were identified for quantitative assessment. The first is the potential boron dilution during the two-phase natural circulation period, in which a liquid/vapor mixture enters the PRHR heat exchanger and the PRHR exit flow circulates into a full reactor vessel; the maximum PRHR condensate flow rate occurs for the limiting case break size in this scenario. The second scenario occurs during the DEDVI break after the completion of the two-phase natural circulation period when the reactor coolant system has drained to the break elevation, and the PRHR heat exchanger acts as a steam condenser that generates boron-free condensate which flows into the downcomer. This scenario results in the maximum condensate velocity in the downcomer and the minimum calculated boron concentration in the liquid within the downcomer and lower plenum.

A. Boron Dilution during Two-phase Natural Circulation of AP600 LOCA Events

The downcomer mixing behavior during the two-phase natural circulation period of AP600 small break LOCA events has been assessed quantitatively for the 2-inch break in the cold leg equipped with cold leg balance lines. In terms of PRHR performance during natural circulation, the quantity of condensate delivered to the downcomer and the rate at which it is produced are greater for this case than for the 0.5-inch break, as indicated in the RAI 440.120 response. A review of the PRHR condensate generation during two-phase natural circulation for a 4-inch diameter break also indicates that the two-inch break in the balance line loop is limiting. As regards break location, a two-inch break in the cold leg of the PRHR loop would be less limiting due to the loss of PRHR condensate out the break before reaching the downcomer. Also, were the break to occur in a hot leg, some of the steam generated in the core would vent directly out the break and be unavailable to condense in the PRHR. Based on these considerations, the two-inch break in the cold leg balance line loop represents the limiting case for downcomer mixing of PRHR condensate during two-phase natural circulation among the AP600 small break LOCA analysis cases.

During natural circulation, condensate produced in the PRHR flows continuously into the downcomer via the two cold legs in the PRHR loop. As calculated by NOTRUMP, the PRHR exit flow rate is 90 lbm/sec during the limiting two-inch cold leg break natural circulation period (approximately 500-620 seconds transient time); it flows into a full reactor vessel downcomer together with other liquid circulating in the cold leg. For conservatism, the PRHR effluent is assumed to contain zero boron, and no mixing with the other liquid is credited in the cold legs. The behavior of the PRHR condensate stream once it enters the downcomer is calculated based on its behavior as a free turbulent jet, following the method of Reference 440.724-1, pages 69-70. The PRHR condensate jet enters the downcomer with horizontal momentum until it impinges on the core barrel, at which time it begins to move down the downcomer. In the Reference 440.724-1 terminology, the virtual origin where the constant velocity flow ends is the AP600 vessel downcomer gap width, a length of 0.8 ft. The velocity of the PRHR condensate stream, which is 0.45 ft/sec entering the downcomer, diminishes as the plume proceeds down the downcomer. Before the dilute PRHR condensate plume reaches the bottom of the core barrel, where it can physically turn in the lower plenum from its downward direction and proceed upward toward the core, its velocity has decreased to 0.02 ft/sec. Thus, the dilute fluid stream will mix with the surrounding, high boron downcomer liquid because its movement has effectively stalled out. The concentration of boron in this dilute region of the downcomer/ lower plenum liquid is bounded by the DEDVI break dilution scenario presented next.

B. DEDVI Break Condensate Mixing in the AP600 Downcomer

A second scenario, in which PRHR condensate flow rates of approximately 60-70 lbm/sec are produced, occurs during the DEDVI break after the end of the two-phase natural circulation period. Steam generated in the core condenses in the PRHR and flows through the voided cold legs in the PRHR loop into the downcomer. Until the downcomer level has fallen to the elevation of the DVI nozzles at 170 seconds of the AP600 SSAR DEDVI break transient, the PRHR condensate is part of the break flow as the reactor coolant system inventory drains out the break. However, once the level in the downcomer has fallen such that the break is uncovered and no longer discharges liquid, the PRHR condensate can collect in the downcomer and form an injection plume that moves downward into the lower plenum.

The PRHR condensate stream leaving the cold legs strikes the core barrel and then falls by gravity to the downcomer liquid surface. Based on the fall height of 2.5 ft, the velocity of the dilute plume emanating downward from the DVI nozzle elevation is 12.7 ft/sec. It flows through a downcomer annulus which has been filled with water at a boron concentration of 1860 ppm during the DEDVI break transient. During the 80-140 second time interval of the transient, 35000 lbm of liquid flows from the core into the downcomer, toward the break location. The boron concentration of this fluid, which fills the downcomer annulus, is increased from the initial 1600 ppm level due to boiling in the core region. The boron content of the PRHR condensate plume of zero boron water will increase due to mass transfer from the 1860 ppm boron surrounding fluid as the plume proceeds down the downcomer.

The mixing which occurs between the dilute plume and the downcomer liquid has been calculated using the method of Reference 440.724-2, applying the analogy between heat and mass transfer. Based on the conditions predicted to exist in the downcomer in the SSAR DEDVI break NOTRUMP analysis, a Froude number is computed for the plume. The degree to which the boron content of the plume approaches the 1860 ppm surrounding concentration is then calculated in the same way that the density profile is calculated in Reference 440.724-2. The average boron concentration within the plume is calculated to be 1290 ppm at the bottom of core barrel elevation. Since the plume will undergo internal mixing and mix further with the surrounding liquid after it contacts the reactor vessel bottom surface in the lower plenum and is redirected to flow upward to the core inlet, the use of the plume average boron concentration is a reasonable approximation of the minimum boron content of the liquid entering the core.

Reference 440.724-3 states that a boron concentration of 1200 ppm is adequate to prevent a return to critical in the fluid temperature range which prevails during the 170-240 second time interval of the DEDVI break transient. The DEDVI case during this time interval represents the limiting case scenario for potential boron dilution associated with the AP600 small break LOCA analysis. After 240 seconds of the DEDVI break transient have elapsed, the intact accumulator injects a large flow of highly borated (2600 ppm) safety injection water into the downcomer, increasing the ambient boron concentration above the 1820 ppm value. Also, the PRHR condensation rate diminishes as shown in Figure 440.724-1. Therefore, the potential for boron dilution diminishes as the DEDVI transient proceeds beyond the time period analyzed above, during which the minimum boron concentration is adequate. Also, the boron dilution calculated for Case A above is more favorable (at >1300 ppm boron concentration in the dilute plume region) than is true for the DEDVI break scenario.

Summary

Limiting case scenarios for AP600 small break LOCA boron dilution events have been assessed for two-phase natural circulation condensation in the PRHR, and for the steam condensation which occurs during the DEDVI break. The results obtained demonstrate that recriticality due to boron dilution is not of concern for these worst case scenarios.

References:

440.724-1 Davies, J. T., "Turbulence Phenomena," Academic Press, 1972.

440.724-2 Swanson, L. W. and Catton, I., "PWR Annulus Thermal Hydraulics Important to Analysis of Pressurized Thermal Shock," Nuclear Engineering and Design, 102 (1987) pages 105-114.

440.724-3 Macian, R., et. al., "Analysis of Boron Dilution Transients in the AP600," Pennsylvania State University, June, 1995, page 5-34.

SSAR Revision: NONE

FIGURE 440.724-1