APR 29 1983

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

FROM: Robert B. Minogue, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER NO. 134, "MULTIDIMENSIONAL PHENOMENA DURING THE REFILL PHASE OF A BWR LOCA"

This memorandum transmits the results of completed research investigating multidimensional phenomena that may occur during the refill phase of a boiling water reactor (BWR) loss-of-coolant accident (LOCA). This research is applicable to both large- and small-break LOCAs and other BWR transients where the automatic depressurization system (ADS) is activated. The BWR Blowdown Heat Transfer Research Review Group reviewed the material in this Research Information Letter (RIL) on October 15, 1982, and their comments are included in this summary.

RILs 126 and 127 summarized research in the Two-Loop Test Apparatus (TLTA) investigating heat transfer and system hydraulics during large- and small-break BWR LOCAs. These RILs identified a large degree of potential conservatism in the LOCA calculations performed for licensing of BWRs. These results were qualified, however, by indicating that the TLTA was essentially a one-dimensional facility and that final conclusions should be withheld until results from other research were available.

The 30° Steam Sector Test Facility (SSTF) was a full scale model of a 30° sector of a BWR which used steam injection to simulate core heat. The SSTF was used to investigate potential phenomena that might only occur at large scale or with many channels in a facility that, while large, did not have the heated channels and high pressue capability that would be prohibitively expensive in a facility of this size. These tests indicate that the results from one-dimensional, integral tests, such as the TLTA, must be modified to include multidimensional effects prior to extrapolating them to a BWR. The SSTF findings do not negate the TLTA results, but rather indicate that multidimensional effects provide additional conservatism over that already identified under the TLTA program. Some of the key findings from the SSTF tests are:

1. Data on the distribution of core spray in a steam environment are available to provide a limited evaluation of the methods used in licensing to calculate core spray distribution.

2. Fluid injected in the upper plenum easily penetrated the bypass area between the fuel channels (this would promote early bundle refill by leakage of fluid from the bypass to the bottom of the fuel channels).

3. Significant multichannel behavior was observed. Peripheral bundles operated in a downflow manner allowing upper plenum fluid to penetrate to the lower plenum and central bundles operated in an upflow manner, venting lower plenum steam.

4. Liquid accumulating in the upper plenum was rapidly subcooled near the spray headers by the injection of subcooled ECC. This caused breakdown of the countercurrent flow limit (CCFL) at the tops of peripheral bundles near the spray header and allowed upper plenum fluid to penetrate the core.

5. BWR/4 low pressure coolant injection in the jet pumps was shown to be an effective method of refilling the vessel with little ECC fluid lost out the break.

These data, when used in conjunction with previous TLTA data, should provide a better understanding of the actual behavior expected during a BWR LOCA or other transient during which the ADS is activated. The primary method of integrating the SSTF and TLTA results will be the BWR TRAC code, which is being assessed using data from these and other facilities. These data, both directly and through use of BWR TRAC results, should provide sufficient information to evaluate improved BWR licensing models currently under evaluation by the Office of Nuclear Regulatory Research. A more complete summary of these research results, which also includes a list of references, is enclosed.

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Enclosure: Summary of SSTF Research

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SUMMARY OF
30° STEAM SECTOR TEST FACILITY (SSTF)
RESEARCH RESULTS

William D. Beckner

Research in the Two-Loop Test Apparatus (TLTA)[1,2] investigated heat transfer and system hydraulics during large- and small-break boiling water reactor (BWR) loss-of-coolant accidents (LOCA). This research identified a large degree of potential conservatism in the LOCA calculations performed for licensing of BWRs. These results had to be qualified, however, since the TLTA was essentially a one-dimensional facility and final conclusions had to be withheld until results from other research were available. This research has now been completed and an assessment of the influence of multidimensional effects on the conclusions obtained from the TLTA can be made.

The BWR Refill/Reflood Program[3] was jointly sponsored by the U.S. Nuclear Regulatory Commission, the Electric Power Research Institute, and the General Electric Company to investigate potential multidimensional effects which might not be observed in one-dimensional facilities such as the TLTA. This program contained a number of different tasks investigating the refill and reflood phases of a BWR LOCA both experimentally and through analytical modeling. While this program was primarily oriented toward the large-break LOCA, the results are applicable to small- and intermediate-break LOCAs and other BWR transients where activation of the automatic depressurization system would lead to rapid system depressurization.

Because of the prohibitively high cost of a large-scale, heated integral test, the effects of large scale or the effects of many channels had to be investigated in a simpler, separate effects facility. The 30° Steam Sector Test Facility (SSTF)[4,5] was a full scale model of a 30° sector of a BWR which used steam injection to simulate core heat. Regions at the top and bottom of the core, the upper plenum and the emergency core cooling (ECC) spray headers were simulated exactly using actual reactor hardware. Other regions were simulated using the correct volumes (1/12 the volume of a BWR). The SSTF was used to investigate potential phenomena that might only occur at large scale or with many channels in a facility that, while large, did not have the heated channels and high pressure capability that would be prohibitively expensive in a facility of this size.

Two general types of tests were performed in the SSTF: (1) separate effects tests to obtain data involving specific phenomena and (2) system transients.

The separate effects tests included steady-state tests of core spray distribution, countercurrent flow limit (CCFL) tests at various locations, and mixing of emergency core coolant (ECC) fluid with steam and water in various regions. The system transients were experimental simulations of the latter phases of the LOCA blowdown (from 150 psia), refill and reflood (without heated rods, core heat was simulated by steam injection). These tests have shown significant multidimensional and multichannel effects. These effects are, in general, beneficial and result in more effective refill and reflood than that observed in one-dimensional tests.

CORE SPRAY DISTRIBUTION

Tests were conducted to evaluate the distribution of ECC system core spray over the top of the core and the effect of the steam environment on the spray distribution.[6,7] These tests do not provide an indication of the amount of liquid that would penetrate down a fuel channel during a LOCA, but rather only the amount of liquid that would reach the top of each fuel channel. This information is important since the heat transfer coefficients specified in Appendix K were obtained assuming that a minimum flow of liquid would reach the top of each fuel channel. Data were obtained from the SSTF in geometries representative of a BWR/6 with both high- and low-pressure core spray headers and with one of two spray headers in a BWR/4 or BWR/5 system. These data were used to qualify the method used to calculate the effect of steam on the spray distribution.[8]

The SSTF data generally show that the method is adequate to predict the spray distribution as shown in Figure 1.[8] Because of the fact that the SSTF is only a 30° sector, however, the data cannot be used to qualify the method for the center of the core (or the apex of the sector). This is due to the fact that the effect of spray overlapping in the center of the core cannot be simulated in a sector. We have no spray distribution data for a full circle in a steam environment and, therefore, one cannot qualify the spray calculated to reach the tops of the central fuel channels.

One interesting phenomenon relevant to spray distribution was noted during later separate effects tests and systems transient tests. A residual amount of liquid always remained in the upper plenum whenever the spray flow exceeded CCFL limited drainage through the core. This residual liquid remained even after CCFL breakdown and drainage of the bulk of the upper plenum liquid.

Liquid could, therefore, flow to the tops of the fuel channels regardless of the distribution of the spray over the tops of the channels. Thus, while spray distribution may be very important to current evaluation model calculations, the spray distribution may not be important to the actual system response. This phenomenon should be considered during any reevaluation of spray distribution for licensing calculations and should be included in any best estimate analyses.

CCFL AT THE TOP OF THE BYPASS REGION

Both calculations and tests in the TLTA have shown that steam flowing up between the individual fuel channels (bypass region) might result in CCFL at the top of the bypass and prevent upper plenum liquid from draining down between the fuel channels. Penetration of liquid between the fuel channels is desirable since liquid in the bypass area would provide cooling for the channel boxes and also provide a means to refill the fuel channels through leakage paths between the channels and bypass region. Both TLTA tests and SSTF system transient tests have shown that leakage of liquid from the bypass is an important means of refilling the fuel channels and, therefore, makes liquid penetration from the upper plenum into the bypass an important phenomenon to understand.

Tests were conducted in the SSTF to measure CCFL at the top of the bypass. Steam was injected in the bypass in an attempt to limit the flow of liquid from the upper plenum down between the fuel channels. During these tests, it was not possible to limit the penetration of upper plenum liquid between the fuel channels.[9] This penetration occurred even though several times the amount of steam required, based on a one-dimensional CCFL correlation, was injected. Multidimensional effects occurred during this test which enhanced the ability of the liquid to penetrate over that calculated using a standard one-dimensional correlation (e.g., liquid penetrated one part of the bypass while steam vented up another area). This finding is significant in view of the importance of leakage from the bypass in providing an additional mechanism to refill the fuel channels.

UPPER PLENUM MIXING TESTS

Upper plenum mixing tests were performed to investigate the mixing of the subcooled ECC spray with a two-phase mixture in the upper plenum and the process by which liquid penetrates down through the fuel channels. These tests differed from the spray distribution tests in that sufficient steam was flowing up through the fuel channels to limit flow of liquid down the channels. Thus, significant liquid could accumulate in the upper plenum. These tests were also conducted with the bypass full of liquid since, as indicated previously, liquid easily penetrates the bypass and it is impossible to accumulate significant liquid in the upper plenum until the bypass is filled. The objective of these tests was to investigate how long it takes the core spray to subcool the upper plenum mixture sufficiently to cause subcooled CCFL breakdown above the fuel channels and allow the accumulating upper plenum liquid to drain into the core and lower plenum.

Typical results from these tests are reported in Reference 9. It was determined that, when the spray header was covered by a liquid pool or two-phase mixture, the ECC spray rapidly subcooled the pool in a localized area near the spray header. This is illustrated in Figure 2 which shows that temperatures below the upper tieplates of peripheral bundles (near the spray header) were subcooled immediately after initiation of ECC spray. Other bundles away from the spray header showed no evidence of subcooling. This localized subcooling above the peripheral bundles caused subcooled breakdown of CCFL at the tops of these bundles and allowed upper plenum liquid to rapidly drain down the peripheral bundles. Once the upper plenum drained so that the spray header was uncovered, the spray was exposed to steam which rapidly heated the ECC liquid and eliminated the local subcooling. Thus, CCFL was once again established. The result was an oscillation of the liquid level at the vicinity of the header, as shown in Figure 2, with localized subcooling and subcooled CCFL breakdown being periodically established as the header was covered and uncovered. This scenario of maintaining a level in the vicinity of the spray header would provide an optimal situation where all ECC spray penetrates to the core and lower plenum to promote bottom reflood, but a residual mass remains in the upper plenum to provide liquid to the tops of all bundles to provide cooling from above.

MULTICHANNEL BEHAVIOR

Multichannel behavior was observed during both the separate effects tests and the system transients. Reference 10 provides a detailed discussion of the phenomena observed. This behavior is illustrated schematically in Figure 3. At the initiation of the transients, the entire core was operating in a CCFL mode similar to the "average" bundle in Figure 3. Steam flowing up from the lower plenum caused CCFL at the inlet orifice located at the bottom of the bundles and limited the drainage of the two-phase mixture in the bundles. The bundles were filling through leakage from the bypass and draining from the upper plenum (limited drainage due to CCFL at the upper tieplate). This mode of operation is similar to that observed in single-channel TLTA tests. As time progressed, however, multichannel behavior was established. The mass accumulating in the average bundles controlled the elevation head or differential pressure across the core. The other bundles had to behave in a manner to match the increasing elevation head in the average bundles in order to maintain the same differential pressure across each bundle. The central bundles, with their higher void fraction, soon filled to the top of the bundle with a two-phase mixture and could not accumulate additional mass to match the increasing elevation head of the average bundles. In order to maintain the equal differential pressure required across parallel channels, the central bundles had to switch to a high upflow mode to provide a flow friction pressure drop to match the elevation head of the average bundles. This upflow mode consisted of a two-phase mixture of steam from the lower plenum and liquid entering the bundle at the bottom from the bypass leakage paths. The peripheral bundles started to fill with liquid due to a smaller inlet orifice limiting the drainage rate. Subcooled CCFL breakdown above the peripheral bundles also increase the filling rate. These peripheral bundles, therefore, developed an elevation head faster than the average bundles and switched to a downflow mode to provide the flow friction pressure drop necessary to match the average bundles. Thus, the core entered a mode as shown in Figure 3. The bulk of the bundles operated in a CCFL mode similar to single-channel TLTA tests. However, the peripheral bundles operated in a downflow mode, draining upper plenum liquid to the lower plenum, and the central bundles operated in an upflow mode, venting lower plenum steam.

The above scenario resulted in global behavior slightly different from that observed in single-channel tests. While the bulk of the core maintained a flow regime similar to that observed in TLTA tests, the behavior of the peripheral and central bundles differed. The downflow in the peripheral bundles resulted in easier penetration of upper plenum liquid to the lower plenum. The upflow mode of the central bundles allowed a vent path for lower plenum steam. This resulted in less liquid entrained out the jet pumps and allowed the lower plenum to fill above the jet pump exit.

The multichannel behavior described above is what is expected to occur in a BWR with many channels. It should be realized, however, that, while the SSTF had multiple channels, it did not have a heated core and used steam injection to simulate core heat. The Two Bundle Loop (TBL)[11] represents a bridge between the single channel, heated TLTA tests, and the multichannel, unheated SSTF tests. The TBL contains two electrically heated channels. While two channels cannot duplicate the three modes of simultaneous operation observed in the SSTF, the TBL did exhibit some of the behavior observed in the SSTF and gives confidence that the SSTF results are typical of that which would occur with many heated channels.

SYSTEM TRANSIENTS

The separate effects tests were designed to look at phenomena separately, while the system transients were designed to combine all the phenomena in a test simulating the late LOCA blowdown and refill. These tests were conducted by initializing the mass distribution to that expected at this point in the transient (approximately 50 seconds) and blowing the system down from 150 psia. The net result of the multichannel and multidimensional phenomena described above was a more rapid and effective refill than that observed in one-dimensional TLTA tests. The results of these transient tests are reported in Reference 12.

The results of a BWR/4 simulated large-break LOCA are shown in Figure 4. The system was completely filled within 100 seconds of the start of the test (approximately 150 seconds into a LOCA). Figure 5 shows, however, that the bundles were completely filled with a two-phase mixture within 50 seconds (approximately

100 seconds into the LOCA). This test also illustrated the effectiveness of the BWR/4 low-pressure injection into the jet pump. The lower plenum was rapidly filled and very little liquid was lost to the break.

CONCLUSIONS

These tests have shown that multidimensional and multichannel effects have the potential to improve the system response over that observed in single-channel tests. These results cannot be applied directly to a BWR, however, since these are not true integral tests simulating the entire transient. In addition, the SSTF did not have heated rods. Thus, some mechanism is required to bridge the gap between the TLTA, TBL, and SSTF results and then extrapolate the results to a BWR. The mechanism for this is the BWR TRAC[13] code. TRAC is being assessed with data from these and other facilities to increase our confidence that we can adequately predict BWR response.[14] Research Information Letter No. 132 provides a summary of BWR TRAC research completed to date.[15] TRAC will be the primary method to provide a best estimate evaluation of BWR response and to evaluate the models used in the licensing of BWRs.

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2. Letter from Minogue to Denton, "Research Information Letter No. 127, 'Heat Transfer and Hydraulics During A BWR Large-Break LOCA'," December 4, 1981.

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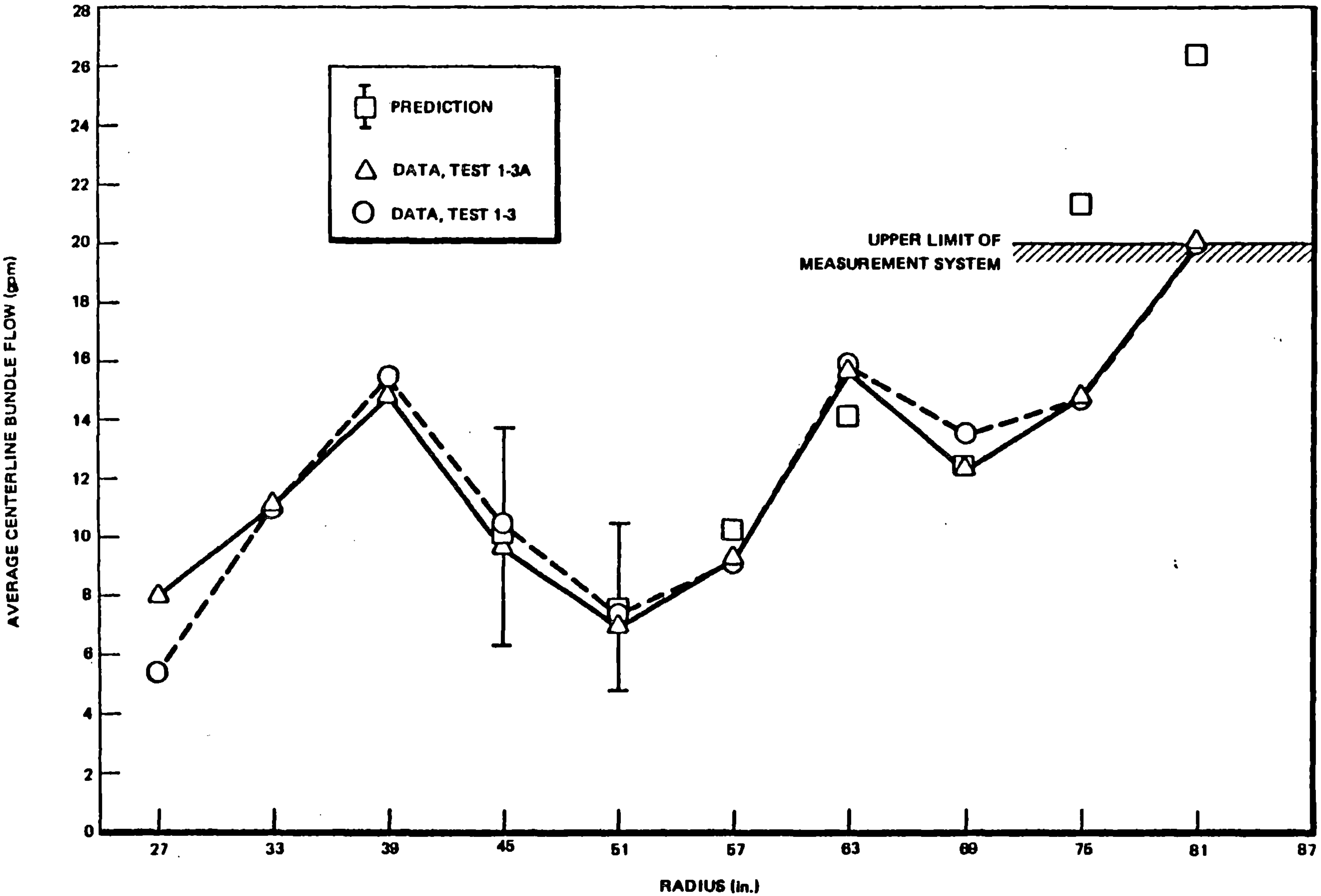

Figure 1 Comparison of SSTF Data to Pre-Test Prediction for LPCS and HPCS Operation

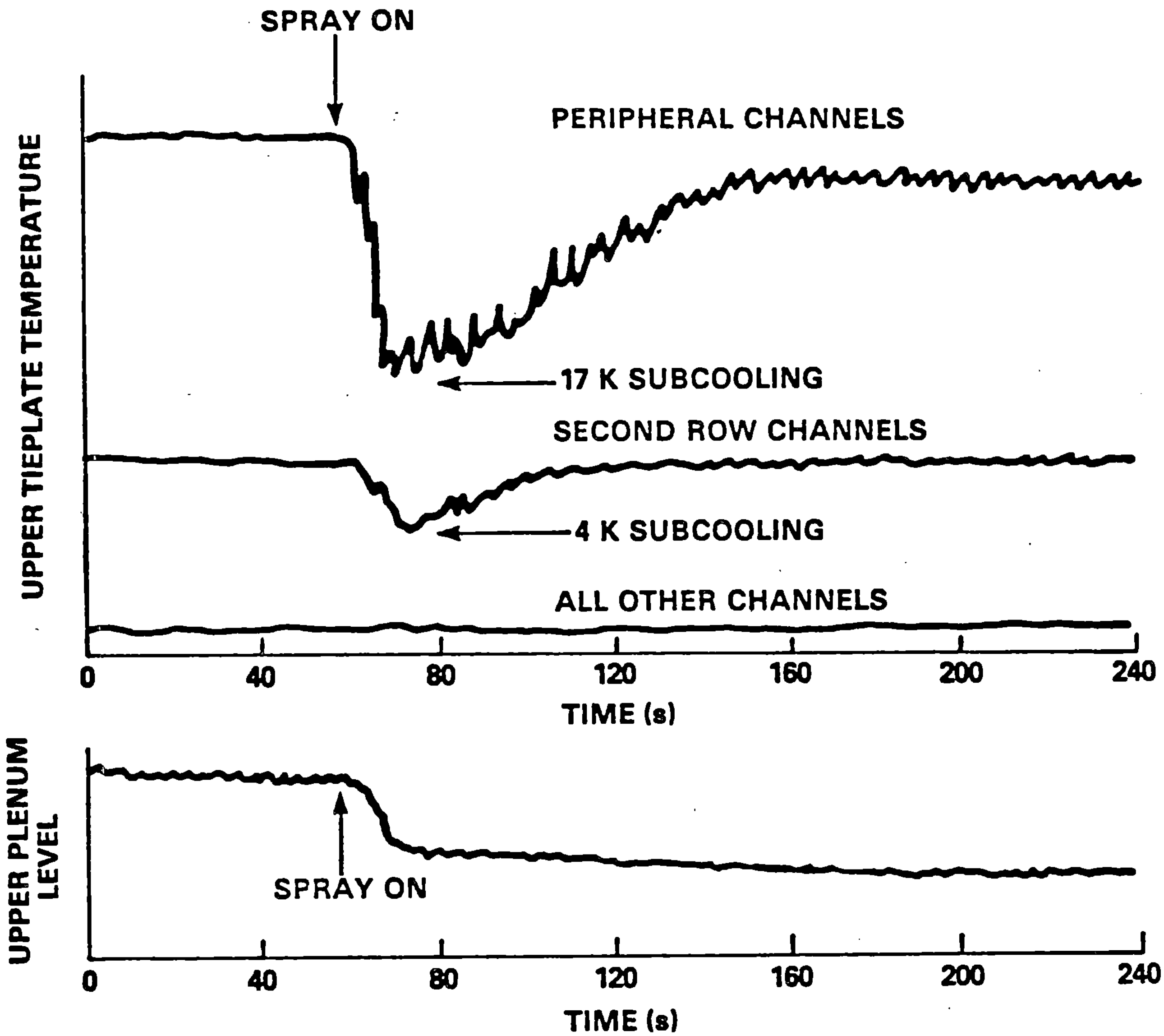

Figure 2. Upper Plenum Mixing Test Results from the 30° SSTF Showing the Rapid Subcooled CCFL Breakdown in Peripheral Bundles Caused by the Subcooled Core Spray.

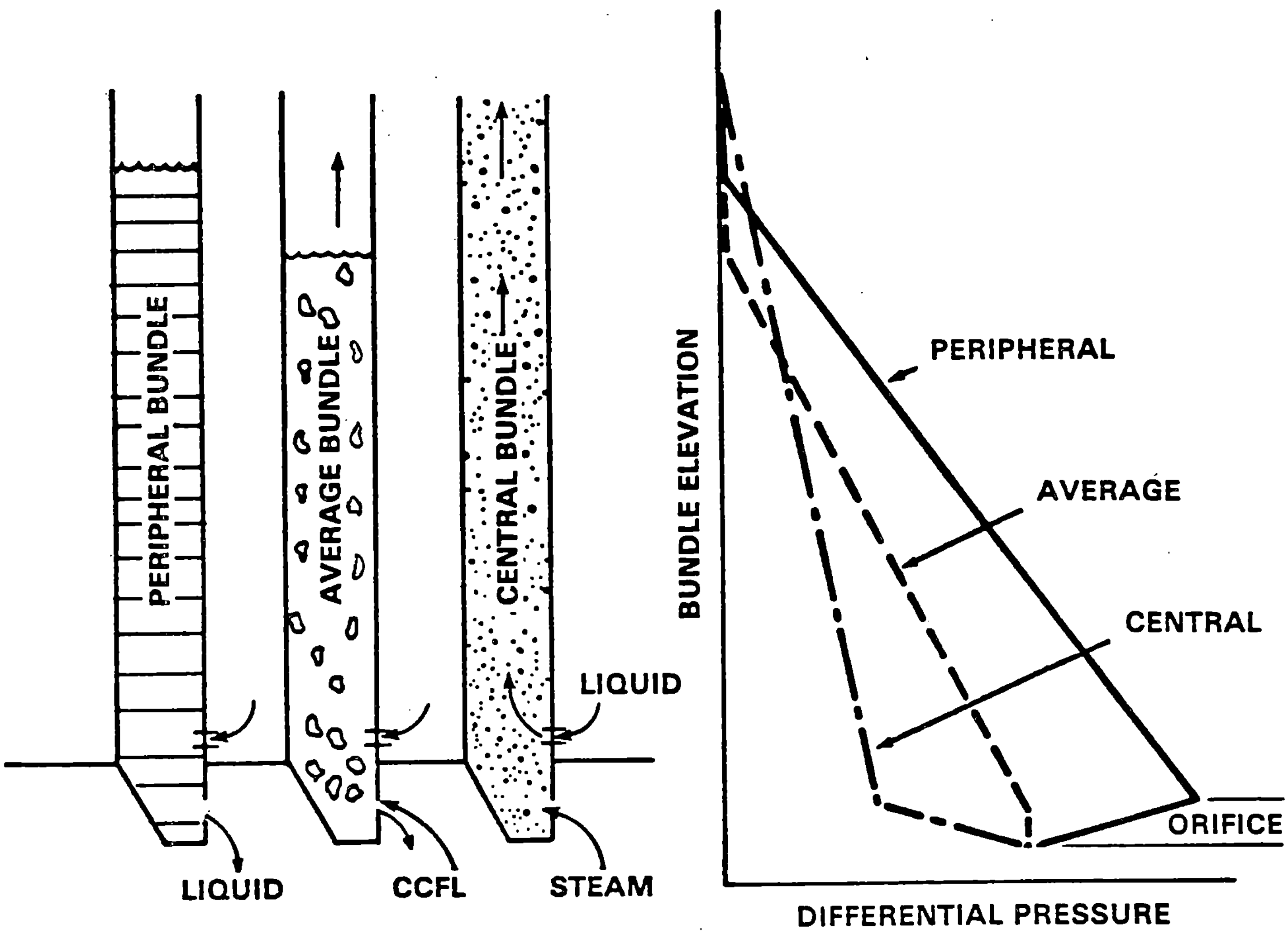

Figure 3. Schematic of Multichannel Behavior Observed in 30° SSTF.

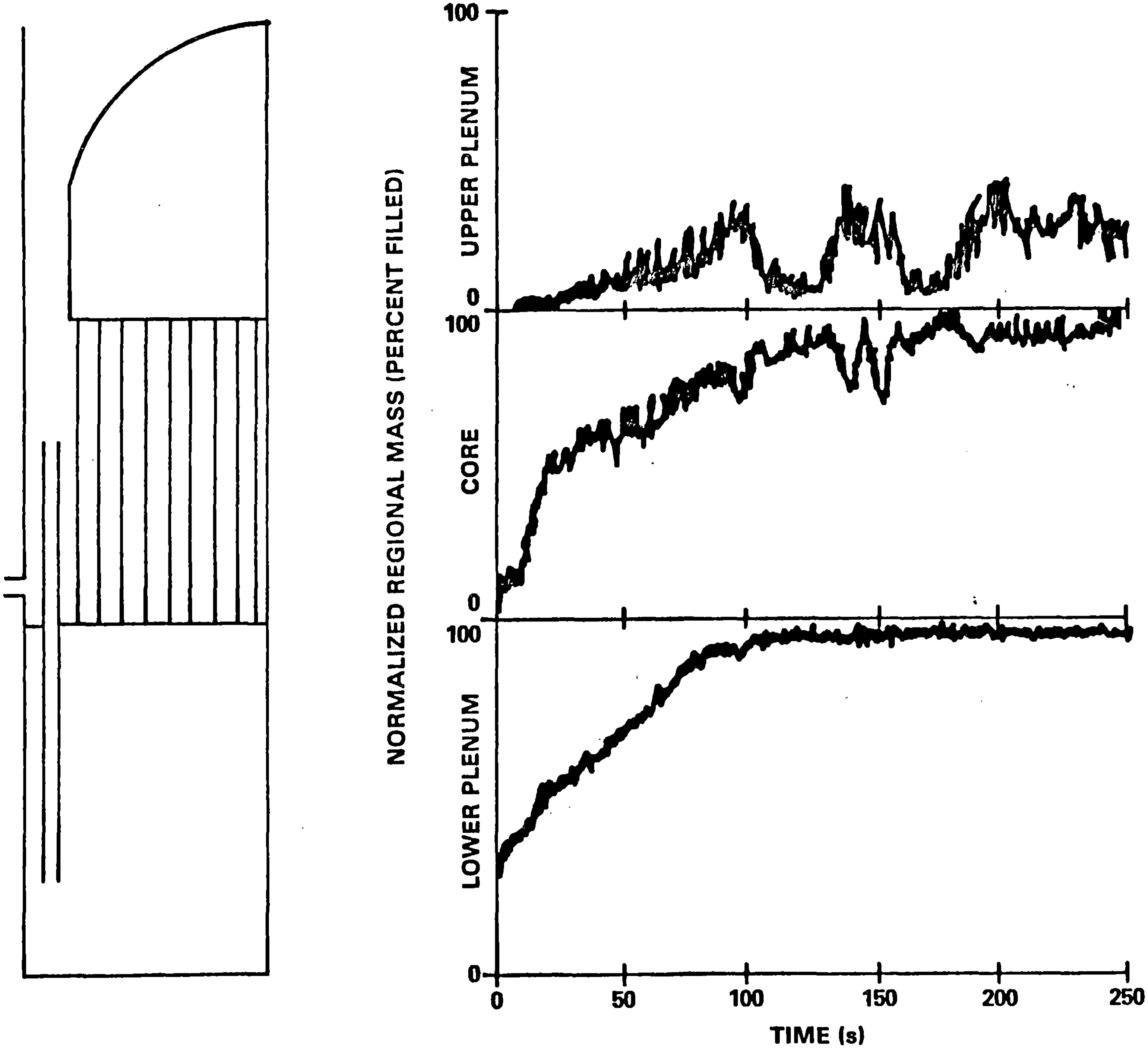

Figure 4. Regional Mass During 30° SSTF BWR/4 Large-Break LOCA Refill Test.

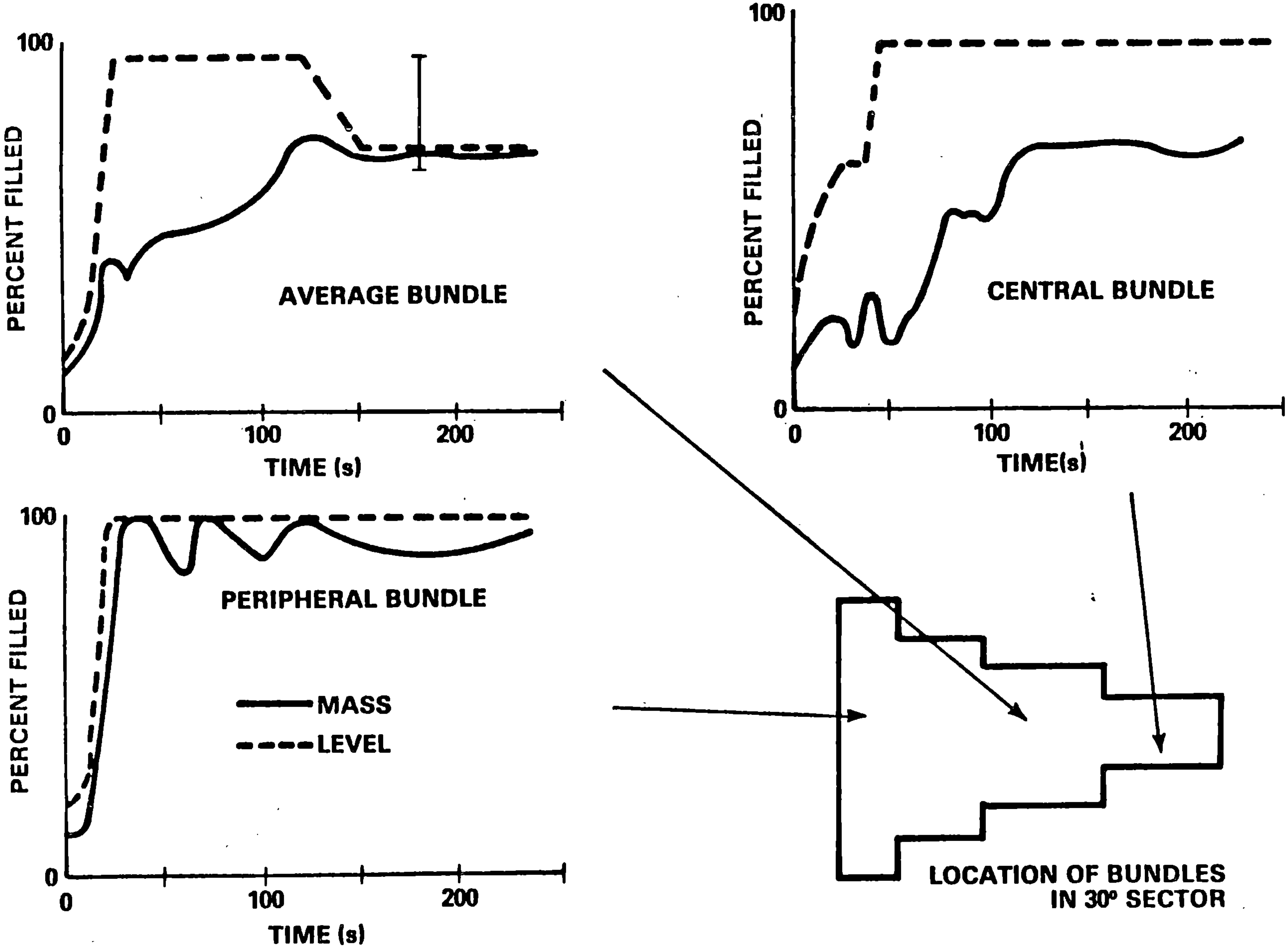

Figure 5. Individual Bundle Mass and Level During 30° SSTF BWR/4 Large-Break LOCA Refill Test.

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Enclosure: Summary of SSTF Research

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APR 20 1983

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