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Multiloop Integral System Test (MIST): Final Report

MIST Phase IV Tests

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Prepared for
U.S. Nuclear Regulatory Commission
and
Electric Power Research Institute
and
Babcock & Wilcox Owners Group

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ABSTRACT

The Multiloop Integral System Test (MIST) is part of a multiphase program started in 1983 to address small-break loss-of-coolant accidents (SBLOCAs) specific to Babcock & Wilcox designed plants. MIST is sponsored by the U. S. Nuclear Regulatory Commission, the Babcock & Wilcox Owners Group, the Electric Power Research Institute, and Babcock & Wilcox. The unique features of the Babcock & Wilcox design, specifically the hot leg U-bends and steam generators, prevented the use of existing integral system data or existing integral facilities to address the thermal-hydraulic SBLOCA questions. MIST and two other supporting facilities were specifically designed and constructed for this program, and an existing facility--the Once-Through Integral System (OTIS)--was also used. Data from MIST and the other facilities will be used to benchmark the adequacy of system codes, such as RELAP5 and TRAC, for predicting abnormal plant transients.

The MIST Program is reported in 11 volumes. The program is summarized in Volume 1; Volumes 2 through 8 describes groups of tests by test type, Volume 9 presents inter-group comparisons; Volume 10 provides comparisons between the calculations of RELAP5/MOD 2 and MIST observations, and Volume 11 presents the later Phase 4 tests. This Volume 11 addendum pertains to MIST natural circulation tests.

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1. INTRODUCTION

In Phase IV an attempt was made to simulate a plant transient on MIST. The purpose of such a test was to provide a link between MIST and a plant such that the differences could be attributed to the composite effect of MIST atypicalities due to scaling compromises. Such a link would provide the code analyst and the plant operator more confidence in MIST test results and minimize the number of calculations necessary to relate MIST data to the plant. Many plant transients were reviewed for the completeness of a data base and two were selected for simulation.

The CR-3 "Loss of Offsite Power" transient of June 16, 1981 was simulated on MIST. The test could not be used as a scaling transient because the attempt to account for the plant initial power at 100% was not successful.

Next the Rancho Seco "Loss of ICS" event of December 26, 1985 was simulated. However, the MIST secondary steam flow capacity was too small to keep up with the simulation and this test likewise was not successful.

The PMG considered then that the TMI Natural Circulation tests of October 7, 1985 would be a good candidate for the scaling test. After exhaustive review of available data and a discussion with TMI operations personnel B&W recommended that several short tests be performed to replicate phenomena observed at TMI instead of a scaling test. The PMG agreed.

The review of the TMI-1 plant data and the reports that were written revealed that there were two time periods of particular interest. During these times it is believed that the plant was experiencing flow interruption phenomena similar to that observed during many of the MIST Phase III Mapping Tests and the MIST Phase IV Tests. The observed occurrences were termed "cold leg temperature anomalies" (see Figure 1.1 for an example) in a draft report written by GPU where it was postulated that they were caused by RCP seal leakage that impacted the cold leg RTD (stratified counter-current flow).

It was decided that the MIST test would attempt to replicate this cold leg temperature anomaly experienced during the period of natural circulation testing at TMI-1.

With the extensive instrumentation system on MIST it was expected that the transient of interest could be dissected to provide a clear unambiguous understanding of the cause of the cold leg temperature anomaly and the sensitivity of the event to selected parameter changes on the MIST facility.

The PMG approved four additional tests which were designed to simulate phenomena observed at the plants under single phase natural circulation at low decay heat power condition.

1. Test 4NCSM1 - A simulation of one phase of the TMI-1 natural circulation test where the "cold leg temperature anomaly" was observed. The objective of this test was to determine if the phenomena observed at the TMI-1 plant could be simulated on the MIST facility.

2. Test 4NCVV1 - A repeat of Test 4NCSM1; however, the reactor vessel vent valves would be manually closed. The objective of this test was to determine the effect of the reactor vessel vent valves on the flow interruption phenomena.

3. Test 4NCHL1 - A repeat of Test 4NCSM1 with heat losses imposed in selected reactor coolant pumps. The objective of this test was to determine the effect of this local heat loss on the occurrence of back flow in the cold legs.

4. Test 4NCLM1 - A repeat of Test 4NCSM1, with letdown and makeup flow active. The objective of this test was to investigate the effect of letdown and makeup flow on the observed phenomena.

Subsequent to the establishment of the trend of the MIST facility response various potential operator actions were performed to determine the effect on the MIST system response. These actions included high point vent actuations, reactor coolant pump starts, PORV actuations and core power increases.

This report provides the test specifications, the test conduct, the observations obtained from each test, an explanation of the phenomena that cause the "cold leg temperature anomaly," and a summary of the natural circulation test program.

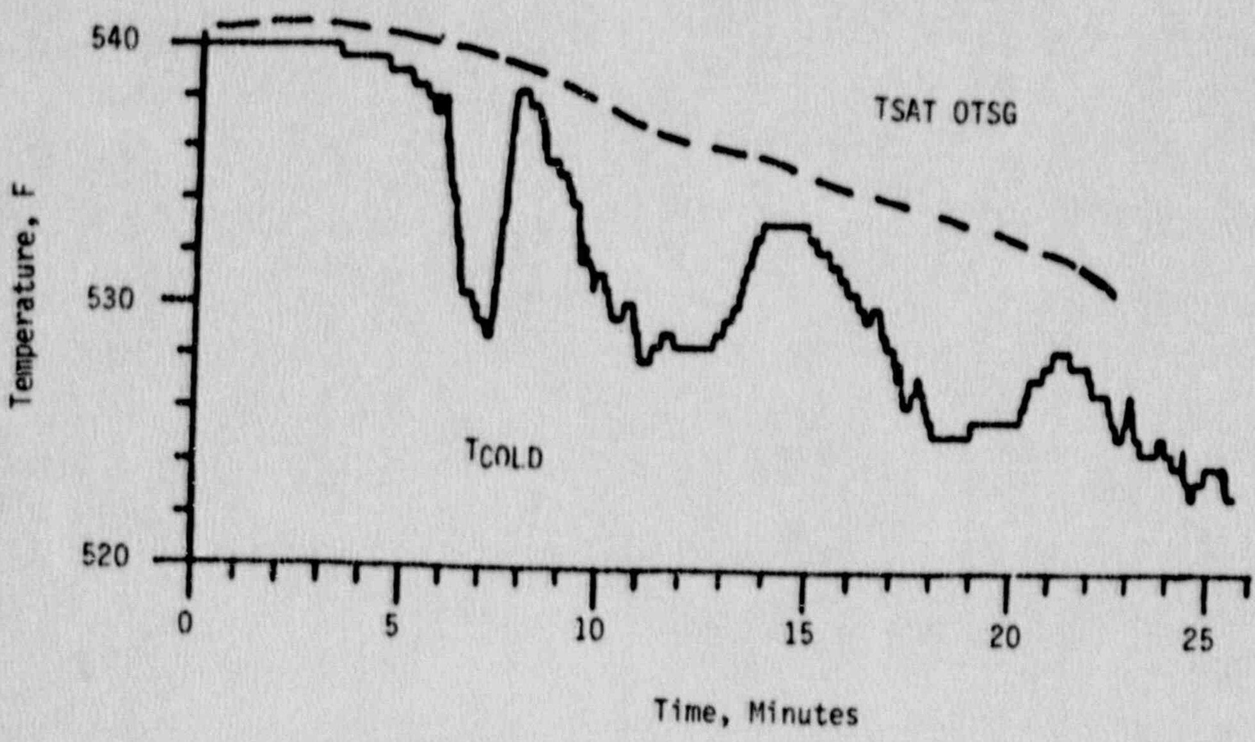

Figure 1.1 TMI-1 Natural Circulation Data Cold Leg Temperature Decrease at 1405 October 7, 1985

2. TEST SPECIFICATIONS

The specifications for the MIST Natural Circulation Tests have been extracted from the MIST Natural Circulation Test Specifications BAW-2090 Rev.1 August 1989 (Reference 1).

2.1. Test 4NCSM1 - Natural Circulation Simulation Test

Test 4NCSM1 is a natural circulation transient that investigates the MIST facility response to a controlled decrease in core power while attempting to maintain all other boundary conditions constant. The reduction in core power will be similar to the core power ramp used during the conduct of the TMI-1 natural circulation test on October 7, 1985.

2.1.1. Test Objectives

The objective of this test is to provide data and insight to the MIST facility response for a controlled core power reduction during natural circulation conditions. It is anticipated that flow interruption will occur and that the phenomena observed in the cold legs and the hot legs in an actual plant will also be observed in the MIST facility. Dependent upon the primary system response variations in loop recovery procedures will be attempted.

2.1.2. Steady-State Pretest Conditions

The loop is to be in the natural circulation testing configuration, i.e., with the venturi flowmeters installed and the turbine meters removed. The system is to be held in steady-state conditions for at least ten or more minutes prior to test initiation. The initial conditions for this steady-state period are listed in Table 2.1. The initial conditions attempt to simulate the conditions during one phase of the natural circulation tests conducted on October 7, 1985 at the TMI-1 plant.

The primary system is to be in subcooled natural circulation, forward flow in all four cold legs, at a core power level that results in hot leg temperatures comparable to that experienced at the TMI-1 plant, approximately 577^{o}F. Core power augmentation is not used. The guard heaters are to be active and controlling in the automatic mode. The steam generator secondary pressures are to be 965 psia. This pressure corresponds to a saturation temperature of 540^{o}F. The fluid temperature in all four cold legs, measured at the RCP inlet RTD, should be approximately 540^{o}F.

The steam generator secondary levels are maintained at 20.7ft, 50% on the operate range, using heated main feedwater. The use of heated main feedwater for the MIST tests rather than auxiliary feedwater (as used during the TMI-1 natural circulation tests) was necessitated as a result of the screening tests performed on the MIST facility prior to the conduct of the MIST Natural Circulation Test Program. The screening tests revealed that for the test conditions investigated the cold leg temperature anomaly could not be produced on the MIST facility when using auxiliary feedwater. The use of heated main feedwater, however, resulted in the observance of the cold leg temperature anomaly.

The pressurizer is controlled to obtain approximately 2175 psia with a level that is sufficient to accommodate the expected primary system volume contraction while still providing pressurizer heater control necessary to maintain primary system pressure. The pressurizer spray control valve is manually closed. The PORV is in the automatic overpressure control mode as described in Appendix E of reference 2. The presently installed PORV orifice, 0.040 in diameter, (simulates a plant diameter of approximately 1 5/32 in) may be used. The RVVV's are in the automatic independent control mode (open/close setpoints of 0.125/0.04 psi). The primary boundary systems are inactive. The core flood tanks are isolated. The HPI/MU and LPI systems are off. The letdown (LD) line is closed. The pressurizer surge line fluid temperature is to be within 5^{o}F of the hot leg fluid temperature. As an indication of steady-state all fluid and metal temperatures are to be varying less than 5°F/hr and 15°F/hr, respectively. The entire primary system, exception being the pressurizer, must be subcooled.

2.1.3. Test Initiation

The test is started after recording at least ten minutes of steady-state data. The test is initiated by actuating the simulated TMI-1 core power ramp. The core power ramp should start from the initial core power level determined in Section 2.1.2 followed by 1) a step change down to 1.5% power 2) a linear ramp down to 0.65% power in approximately five minutes and 3) then maintain the core power constant at a value of 0.65% until the loop recovery attempts are performed. No other actions are required.

2.1.4. Control During Testing and Test Termination

The primary system pressure is to be controlled by the pressurizer using the pressurizer heaters. The pressurizer should attempt to maintain a constant primary system pressure of approximately 2175 psia.

> Note: When the primary loop flow interrupts, a core heat up will occur that may cause an increase in primary system pressure. Therefore the pressurizer heater power must decrease proportionately in an attempt to maintain a constant primary system pressure. If the core heat up is of sufficient magnitude to repressurize the primary system to a value greater than 2175 psia, verify that the pressurizer heaters turn off.

The steam generator secondary level control is to maintain the levels of both steam generators at 20.7ft throughout the entire transient. The steam generator pressure control setpoint is to remain at 965 psia for both steam generators throughout the entire transient. A decrease in the steam generator secondary pressure can be expected when primary-to-secondary heat transfer ceases.
It is anticipated that the primary system will remain subcooled throughout the entire transient. The pressurizer is the only primary system component that can contain steam. The pressurizer must also contain a sufficient amount of liquid inventory such that primary system pressure control is maintained throughout the entire transient.

The test consists of three separate phases:

Phase 1 - Test Initiation Through Flow Interruption

Phase 2 - Four Hour Hold Period

Phase 3 - Loop Recovery Attempts Through Test Termination

Specific control which applies during these phases of the test is described in the following sections.

2.1.4.1. Phase 1 - Test Initiation Through Flow Interruption

This phase of the test should consist of only the core power ramp. As the core power decreases the primary system temperatures will decrease thus resulting in a contraction of the primary system liquid volume. It is anticipated that a sufficient amount of liquid inventory will be available from the initial pressurizer liquid inventory to accommodate the primary system contraction. However, in the event that a sufficient amount of liquid inventory cannot be maintained within the pressurizer to provide pressure control (due to the contraction of the primary system fluid) inventory (makeup, MU) may be added to the primary system through the MU nozzle (A2 cold leg HPI nozzle is to be used for the MU nozzle). Add MU fluid to the primary system gradually in an attempt to minimize primary loop perturbations. The maximum MU flow rate should be equivalent to a plant flow rate of 20 gpm. Terminate the MU flow when the pressurizer level increases sufficiently to provide adequate margin for primary system pressure control.

Phase 1 of the test is to continue until primary loop flow interruption or intermittent primary loop flow is observed.

2.1.4.2. Phase 2 - Four Hour Hold Period

Subsequent to primary loop flow interruption the test shall continue for at least 4 hours such that the response of the test facility can be observed. During this time no operator actions should be performed. Exceptions for taking operator actions are as follows:

1. If facility design limits are approached the loop operators may perform whatever actions are deemed necessary to prevent damage to the test facility.

2. If additional primary system inventory is required to maintain pressurizer pressure control during this time, MU flow may be actuated. The MU flow rate restrictions previously discussed should be adhered to. Primary loop pressure control should be maintained by means of the pressurizer. Therefore, if the potential exists to uncover the pressurizer heaters makeup flow rate may be increased above the previously defined maximum (plant equivalent flow of 20 gpm) to maintain or gradually increase the pressurizer level. The makeup flow rate under these conditions should be increased gradually until the pressurizer level is maintained at a level which provides satisfactory pressure control, however do not exceed a plant equivalent maximum makeup flow rate of 190 gpm. Revert back to the previously defined maximum plant equivalent makeup flow of 20 gpm when the pressurizer level can be maintained.

It should be noted that primary loop flow interruption is expected to occur. It is expected that intermittent primary loop flow will also occur. If, during this phase of the test, the core heat up is sufficient to cause an increase in the primary system pressure allow automatic PORV actuation.

2.1.4.3. Phase 3 - Loop Recovery Attempts Through Test Termination

When the transient has reached 4 hours after flow interruption the primary system pressure trend and primary loop flow status shall be assessed. The loop operator must first determine if primary loop flow (up the hot leg) exists in loop A and /or loop B. The loop operator must also determine if the primary system pressure trend indicates that it is constant, has stabilized in a quasi-steady-state condition, or is increasing. Depending upon the outcome of this assessment various operator actions will be performed depending on the primary loop status at this time. The primary loop status and the associated loop operator actions are as follows:

1. Loop Status - Primary pressure trend is essentially constant and primary loop flow (up the hot legs) exists in both loops such that stable natural circulation conditions are present in both loops.

   - Operator Actions - None. Record 30 minutes of steady-state data. If both loops remain in the steady-state natural circulation condition the test may be terminated. If either loop exhibits interrupted flow or intermittent flow during this 30 min period increase the core power in an attempt to re-establish primary loop natural circulation. The manner in which the core power is increased, i.e., steps or linear ramps, and the final power level attained may be specified by the test engineer. Primary pressure control should be maintained by means of the pressurizer heaters, and if necessary letdown and makeup flow. Then record an additional 30 minutes of data to determine if primary loop steady-state natural circulation is attained. Then terminate the test.

2. Loop Status - Primary pressure trend is either constant or has stabilized in a quasi steady-state condition and primary loop flow (up the hot legs) is interrupted or exhibits intermittent flow in either loop.

- Operator Actions - Attempt to establish primary loop flow (up the hot legs) by means of opening the hot leg U-bend high point vent(s) (HPV). This is to be performed as follows:

  a. Verify that sufficient pressurizer inventory exists such that pressure control is maintained.

  b. Determine primary loop flow status in both loops.

  c. Open the HPV of the loop that indicates flow interruption (if both loops indicate flow interruption open both HPVs). Limit the time the HPV(s) are open to approximately 15 minutes. Maintain a sufficient amount of pressurizer inventory such that pressurizer pressure control is maintained. If the pressurizer level decreases sufficiently to impede pressure control close the HPV(s), gradually add makeup to the primary system (limiting MU flow to a maximum of 20 gpm plant equivalent), allow the primary system to stabilize after the addition of makeup and attempt to establish primary loop flow via HPV actuation as discussed previously.

  d. Close the HPVs when primary loop flow starts in an initially interrupted loop. If stable natural circulation conditions are attained in either loop after HPV actuation record data for 30 minutes or until the pressurizer level becomes low. If flow in both loops is interrupted or intermittent, attempt (for a second time) to establish primary loop flow by opening the HPV(s) as discussed above.

  e. Subsequent to step (d) if primary loop flow remains interrupted or intermittent in either loop increase core power in an attempt to re-establish primary loop natural circulation as discussed in Loop Status 1.

3. Loop Status - Primary system pressure trend is increasing.

- Operator Actions - Allow the primary system pressure to increase to the PORV setpoint and allow automatic PORV actuation. Subsequent to the PORV actuation, or if one hour has elapsed with the primary system pressure trending towards the PORV setpoint but the setpoint has not been attained, open both hot leg U-bend HPVs and attempt to reduce primary system pressure to the control pressure setpoint. If the primary pressure does not decrease to the control pressure setpoint with only the HPVs open, also initiate letdown flow (minimum flow 45 gpm maximum flow 140 gpm plant equivalent). Note makeup flow (maximum flow rate of 190 gpm plant equivalent) may be actuated to maintain pressurizer inventory whenever deemed necessary. Subsequent to performing the operator actions under Loop Status 3 reassess the loop status and perform the following actions:

3a. Loop Status - Primary pressure decreases to and is maintaining approximately the control pressure setpoint.

- Operator Actions - Close the HPVs and maintain the pressurizer inventory approximately constant by adjusting makeup and letdown flow as necessary. Allow the primary system to stabilize for approximately 30 minutes. Then record data for an additional 30 minutes. Subsequent to this perform the core power increase as discussed in Loop Status 1.

3b. Loop Status - Primary pressure cannot be reduced to the control pressure setpoint.

- Operator Actions - Terminate letdown flow and attempt to adjust makeup flow (may exceed 190 gpm plant equivalent flow if necessary) to maintain an approximately constant pressurizer inventory. If the primary loop pressure increases to the PORV setpoint initiate full HPI flow, record data for 30 minutes then terminate the test. If the primary loop pressure remains stable or decreases record 30 minutes of data. At this time close the HPVs and increase the core power as discussed in Loop Status 1.

2.1.5. Acceptance Criteria

1. At least ten minutes of steady-state data is recorded at the specified initial conditions.

2. Test initiation is performed as specified.

3. The specified boundary system control settings are maintained throughout the test.

4. The primary system remains subcooled through 4 hours after flow interruption.

5. Test termination is performed as specified.

6. All critical instrument data as specified in Appendix F reference 2 is recorded at intervals of ten seconds or less throughout the test.

Table 2.1. Test 4NCSM1 Initial Conditions

	Quantity	Specification	Tolerance (+/-)	Derived[1]
1.	Primary Pressure	2175 psia	25	
2.	RC Pump Inlet Temperature			540F
3.	Hot Leg Inlet Temperature			577F
4.	Core Exit Subcooling[2]			71F
5.	Core Power			(3)
6.	Pressurizer Level			(4)
7.	Surge Line Temperature	Hot Leg Temp., F	5	
8.	RVVVs	Automatic Independent (0.125 psi Open/0.04 psi Close)		
9.	Secondary Pressure	965 psia	10	
10.	Secondary Level[5]	20.7 ft	1	
11.	Main Feedwater Temperature[6]			420F
12.	Fluid Temperature Gradients	0F/hr	5	
13.	Metal Temperature Gradients	0F/hr	15	

[1]Derived quantities are for information only and should not be interpreted as control specification.

[2]The primary system with the exception of the pressurizer is to be subcooled. The value in the table corresponds to the subcooling attained with a hot leg inlet temperature of 577F.

[3]The core power is to be adjusted to obtain a hot leg inlet temperature of approximately 577F. DO NOT augment core power.

[4]The pressurizer level is to be sufficiently high to accommodate the primary system contraction without adding inventory to the system if at all possible. The pressurizer heaters are to be active throughout the entire test and should be set to control at 2175 psia.

[5]All levels are relative to the secondary face of the lower SG tube sheet.

[6]The main feedwater temperature is effected by heat losses in the MIST secondary system. This is the expected main feedwater temperature for the low power levels and secondary flow rates at which this test will be performed.

2.2. Test 4NCVV1 - Natural Circulation Simulation Without Operable Vent Valves

Test 4NCVV1 is a natural circulation transient that investigates the MIST facility response to a controlled decrease in core power with the reactor vessel vent valves closed while attempting to maintain all other boundary conditions constant. The reduction in core power will attempt to simulate the core power ramp used during the conduct of the TMI-1 natural circulation test on October 7, 1985.

2.2.1. Test Objective

The objective of this test is to provide data and insight to the MIST facility response for a controlled core power reduction during natural circulation conditions when the reactor vessel vent valves are closed. This test in conjunction with test 4NCSM1 should highlight the secondary flow path that is established when the reactor vessel vent valves are open and result in a different facility response. It is anticipated that the phenomena observed in the cold legs of the MIST facility will be different from that observed in an actual plant and also that observed in the first test (4NCSM1).

The effect of a reactor coolant pump start on the facility response will also be investigated.

2.2.2. Steady-State Pretest Conditions

The steady-state pretest conditions are to be identical to those specified for Test 4NCSM1 with the exception of the reactor vessel vent valve control. For Test 4NCVV1 the reactor vessel vent valves are to be manually closed through the entire test. The initial conditions are listed in Table 2.2.

2.2.3. Test Initiation

Test initiation is identical to Test 4NCSM1 as specified in Section 2.1.3.

2.2.4. Control During Testing and Test Termination

This test will also consist of three separate phases:

Phase 1 - Test Initiation Through Flow Interruption

Phase 2 - Hold Period

Phase 3 - Loop Recovery Attempts Through Test Termination

Control during the test is to be as specified for Test 4NCSM1 through Phase 2. Phase 2, however, may be terminated earlier than four hours after flow interruption at the discretion of the test engineer when the trend in the test facility response has been established. For this test the Phase 3 (Loop Recovery Attempts Through Test Termination) will differ from those used in Test 4NCSM1.

[illegible] Phase 3 - Loop Recovery Attempts Through Test Termination

Upon completion of the hold period (Phase 2) perform an assessment of the anticipated primary and secondary system response to an RCP start. If it is determined that facility design limits will not be exceeded start one RCP. It should be noted that reactor coolant pump starts can result in a contraction of the primary system fluid and a reduction in the pressurizer inventory should be expected. Therefore prior to initiating an RCP start verify that a sufficient amount of pressurizer inventory exists (add inventory by means of makeup flow if necessary) such that pressurizer pressure control is maintained subsequent to the RCP start. After 15 minutes of operation start another RCP (this RCP should be chosen to be in the opposite cold leg of the other loop). Obtain 15 minutes of data with two RCPs operating then terminate the test.

2.2.5. Acceptance Criteria

1. At least ten minutes of steady-state data is recorded at the specified initial conditions.
2. Test initiation is performed as specified.
3. The specified boundary system control settings are maintained throughout the test.
4. The primary system remains subcooled through Phase 2.
5. Test termination is performed as specified.

6. All critical instrument data as specified in Appendix F reference 2 is recorded at intervals of ten seconds or less throughout the test.

Table 2.2. Test 4NCVV1 Initial Conditions

	Quantity	Specification	Tolerance (+/-)	Derived[1]
1.	Primary Pressure	2175 psia	25	
2.	RC Pump Inlet Temperature			540F
3.	Hot Leg Inlet Temperature			577F
4.	Core Exit Subcooling[2]			71F
5.	Core Power			(3)
6.	Pressurizer Level			(4)
7.	Surge Line Temperature	Hot Leg Temp., F	5	
8.	RVVVs	Manual Closed		
9.	Secondary Pressure	965 psia	10	
10.	Secondary Levels[5]	20.7 ft	1	
11.	Main Feedwater Temperature[6]			420F
12.	Fluid Temperature Gradients	0F/hr	5	
13.	Metal Temperature Gradients	0F/hr	15	

[1]Derived quantities are for information only and should not be interpreted as control specification.

[2]The primary system with the exception of the pressurizer is to be subcooled. The value in the table corresponds to the subcooling attained with a hot leg inlet temperature of 577F.

[3]The core power is to be adjusted to obtain a hot leg inlet temperature of approximately 577F. DO NOT augment core power.

[4]The pressurizer level is to be sufficiently high to accommodate the primary system contraction without adding inventory to the system if at all possible. The pressurizer heaters are to be active throughout the entire test and should be set to control at 2175 psia.

[5]All levels are relative to the secondary face of the lower SG tube sheet.

[6]The main feedwater temperature is affected by heat losses in the MIST secondary system. This is the expected main feedwater temperature for the low power levels and secondary flow rates at which this test will be performed.

2.3. Test 4NCHL1 - Natural Circulation Simulation With Heat Losses Imposed

Test 4NCHL1 is a natural circulation transient that investigates the MIST facility response to a controlled decrease in core power with intentionally imposed local heat losses in the cold legs while attempting to maintain all other boundary conditions constant. The reduction in core power will attempt to simulate the core power ramp used during the conduct of the TMI-1 natural circulation test on October 7, 1985.

2.3.1. Test Objective

The objective of this test is to provide data and insight to the MIST facility for a controlled power reduction during natural circulation conditions with intentionally imposed local heat losses in the cold legs. Previous MIST test results, eg 3004CC, have indicated that heat losses exist between the upper most instrumented location in the cold leg suction pipes (approximately two feet below the reactor coolant pump suction) and the upper most instrumented location in the cold leg discharge pipes (at the reactor coolant pump discharge), i.e., heat loss caused by the reactor coolant pumps. These heat losses appear to contribute to the flow interruption phenomena and the subsequent flow direction in the cold legs. This test will impose additional heat loss near the reactor coolant pump in one cold leg of each loop. The cold legs that will have the additional heat loss imposed will be chosen based upon the observed results from Test 4NCSM1. Present plans for increasing the heat losses are to increase the cooling water flow to selected RCPs and/or shutting off the guard heaters in the upper region of selected cold leg suction pipes. It is anticipated that Test 4NCHL1 will highlight the cold leg temperature anomalies observed during low power natural circulation conditions in actual plant transients.

The effect of actuating the high point vents and makeup flow during loop recovery will be investigated. At the conclusion of the above the effect of a reactor coolant pump start will also be investigated, if feasible.

2.3.2. Steady-State Pretest Conditions

The steady-state pretest conditions are to be identical to those specified for Test 4NCSM1. The increased heat losses in two of the cold legs may result in cold leg temperatures at the reactor coolant pump inlet that are not within the test specification tolerances. Therefore, for this test the cold leg fluid temperature specification will be applied at a lower elevation in the cold leg suction pipe. The initial conditions are listed in Table 2.3.

2.3.3. Test Initiation

Test initiation is identical to Test 4NCSM1.

2.3.4. Control During Testing and Test Termination

This test will also consist of three separate phases:

Phase 1 - Test Initiation through Flow Interruption

Phase 2 - Hold Period

Phase 3 - Loop Recovery Attempts Through Test Termination

Control during the test is to be as specified for Test 4NCSM1 through Phase 2. Phase 2, however, may be terminated earlier than four hours after flow interruption at the discretion of the test engineer when the trend in the test facility response has been established. For this test the Phase 3 (Loop Recovery Attempts Through Test Termination) will differ those used in Test 4NCSM1.

2.3.4.1. Phase 3 - Loop Recovery Attempts Through Test Termination

Upon completion of the hold period (Phase 2) open both hotleg U-bend high point vents (HPVs) and maintain the pressurizer inventory constant by means of makeup flow (maximum 190 gpm plant equivalent). Observe the facility response for approximately one hour or until the pressurizer inventory becomes low. Then close the HPVs, terminate makeup flow and observe the facility response for approximately 30 minutes. Note that the duration of the observation periods can be altered based upon the discretion of the test engineer.

When the above is completed consideration should be given to performing another reactor coolant pump start similar to that specified for Phase 3 of Test 4NCVV1. This recovery procedure is contingent upon the results obtained during Test 4NCVV1 and should be performed at higher core and hot leg fluid temperatures. If the reactor coolant pump start is to be performed, a core power increase (and a loop stabilization period) may be required to attain the higher fluid temperatures. The reactor coolant pump start should not result in challenging any facility design limits.

2.3.5. Acceptance Criteria

1. At least ten minutes of steady-state data is recorded at the specified initial conditions.
2. Test initiation is performed as specified.
3. The specified boundary system control settings are maintained throughout the test.
4. The primary system remains subcooled through Phase 2.
5. Test termination is performed as specified.
6. All critical instrument data as specified in Appendix F reference 2 is recorded at intervals of ten seconds or less throughout the test.

Table 2.3. Test 4NCHL1 Initial Conditions

Quantity	Specification	Tolerance (+/-)	Derived[1]
1. Primary Pressure	2175 psia	25	
2. RC Pump Inlet Temperature[2]			540F
3. Hot Leg Inlet Temperature			577F
4. Core Exit Subcooling[3]			71F
5. Core Power			(3)
6. Pressurizer Level			(4)
7. Surge Line Temperature	Hot Leg Temp., F	5	
8. RVVVs	Auto. Indepen. (0.125 psi Open/0.04 psi Close)		
9. Secondary Pressure	965 psia	10	
10. Secondary Levels[6]	20.7 ft	1	
11. Main Feedwater Temperature[7]			420F
12. Fluid Temperature Gradients	0F/hr	5	
13. Metal Temperature Gradients	0F/hr	15	

[1]Derived quantities are for information only and should not be interpreted as control specification.

[2]Dependent upon the method used for increasing the heat loss either the RCP inlet temperature (RTD) or a fluid temperature (TC) in the lower region of the cold leg suction pipe of the cold legs that have heat losses imposed will be used for establishing the initial conditions.

[3]The primary system with the exception of the pressurizer is to be subcooled. The value in the table corresponds to the subcooling attained with a hot leg inlet temperature of 577F.

[4]The core power is to be adjusted to obtain a hot leg inlet temperature of approximately 577F. DO NOT augment core power.

[5]The pressurizer level is to be sufficiently high to accommodate the primary system contraction without adding inventory to the system if at all possible. The pressurizer heaters are to be active throughout the entire test and should be set to control at 2175 psia.

[6]All levels are relative to the secondary face of the lower SG tube sheet.

[7]The main feedwater temperature is affected by heat losses in the MIST secondary system. This is the expected main feedwater temperature for the low power levels and secondary flow rates at which this test will be performed.

2.4. Test 4NCLM1 - Natural Circulation Simulation Effects of Letdown and Makeup Flow

Test 4NCLM1 is a natural circulation transient that investigates the MIST facility response to a controlled decrease in core power with letdown and makeup flow active while attempting to maintain all other boundary conditions constant. The reduction in core power will attempt to simulate the core power ramp used during the conduct of the TMI-1 natural circulation test on October 7, 1985. This test also simulates plant operator actions taken frequently during natural circulation conditions.

2.4.1. Test Objective

The objective of this test is to provide data and insight to the MIST facility response for a controlled core power reduction during natural circulation conditions when letdown and makeup flow are active. This test in conjunction with Test 4NCSM1 should provide insight on the effect of letdown and makeup flow on flow interruption and flow direction subsequent to flow interruption.

The effect of actuating the highpoint vents with letdown and makeup flow active during loop recovery will be investigated. At the conclusion of the above the effect of a reactor coolant pump start with letdown and makeup flow active will also be investigated, if feasible.

2.4.2. Steady-State Pretest Conditions

The steady-state pretest conditions are to be identical to those specified for Test 4NCSM1 with the exception of letdown and makeup flow. For Test 4NCLM1 the letdown flow is to be active at a plant equivalent flow rate of approximately 45 gpm at test initiation. Similarly makeup flow is to be active and is to be adjusted to a value that will maintain the pressurizer level approximately constant. The initial conditions are listed in Table 2.4.

2.4.3. Test Initiation

The test is started after recording at least ten minutes of steady-state data.

The test is initiated by actuating the core power ramp (as specified for Test 4NCSM1) and subsequently increasing the makeup flow. The makeup flow is to be manually increased (the maximum allowable makeup flow is 190 gpm plant equivalent) in an attempt to maintain a constant pressurizer inventory (the pressurizer inventory should decrease as a result of the primary loop fluid contraction caused by the core power reduction). For operator guidance the test results from Test 4NCSM1 should be used to estimate the makeup flow required to account for fluid contraction during the early initiating events.

2.4.4. Control During Testing and Test Termination

The primary system pressure is to be controlled by the pressurizer using the pressurizer heaters. The pressurizer should attempt to maintain a constant primary system pressure of approximately 2175 psia.

The steam generator secondary level control is to maintain the levels of both steam generators at 20.7 ft throughout the entire transient. The steam generator pressure control setpoint is to remain at 965 psia for both steam generators throughout the entire transient.

This test will also consist of three separate phases:

Phase 1 - Test Initiation Through Flow Interruption

Phase 2 - Hold Period

Phase 3 - Loop Recovery Attempts Through Test Termination

2.4.4.1. Phase 1 - Test Initiation Through Flow Interruption

Subsequent to attaining an approximately constant pressurizer inventory, i.e., the makeup flow is approximately balancing the letdown flow (plant equivalent flow of 45 gpm) and primary system contraction, begin increasing the letdown flow and simultaneously increase the makeup flow such that the pressurizer inventory remains essentially constant. Letdown flow is to be maintained within plant equivalent limits of 45 gpm and 140 gpm. Makeup flow is also to be maintained within the plant equivalent maximum of 190 gpm.

Since the makeup flow must account for both fluid contraction and the primary system inventory loss as a result of the letdown flow, the loop operator is to attempt to obtain as high a letdown flow as possible, i.e., the resultant letdown flow may be less than the maximum allowed letdown flow, while attempting to maintain a constant pressurizer inventory by the addition of makeup flow.

As the transient progresses the effect of the fluid contraction (caused by the core power ramp) should diminish. Therefore, in an attempt to minimize operator actions and loop perturbations, the loop operator should attempt to attain the highest letdown flow as possible and maintain pressurizer inventory essentially constant as quickly as possible after test initiation. The control valve positions for letdown flow should then remain fixed and adjustments should only be made to the makeup flow for maintaining an approximately constant pressurizer inventory. The results of Test 4NCSM1 should be used to estimate the expected primary system contraction and aid in establishing the letdown flow rate for test 4NCLM1.

This method for inventory control should continue through primary loop flow interruption or when intermittent primary loop flow is observed.

2.4.4.2. Phase 2 - Hold Period

Subsequent to flow interruption the loop operator should continue to attempt to maintain an essentially constant letdown flow and maintain an essentially constant pressurizer inventory by means of makeup flow. The Phase 2 Hold Period may be terminated at the discretion of the test engineer when the trend in the test facility response has been established.

2.4.4.3. Phase 3 - Loop Recovery Attempts Through Test Termination

Upon completion of the hold period (Phase 2) an assessment of the capability of makeup to maintain a constant pressurizer level with the present letdown flow and two hot leg U-bend high point vents (HPV) open is to be performed. Adjust the letdown flow as necessary such that when two HPVs are open the summation of the letdown flow and the flow through the HPVs is less than the maximum makeup flow capacity (190 gpm plant equivalent). If an adjustment in the letdown flow is required, attempt to maintain a constant pressurizer inventory by simultaneously adjusting the makeup flow. When the desired letdown flow is attained no further letdown flow adjustments are to be performed until all the HPV actuations, as described below, are completed.

It should be noted that the above may not be attainable. Preliminary estimates indicate that the maximum makeup flow may be sufficient to maintain a constant pressurizer inventory with one HPV open and minimum letdown flow. Therefore, when performing Phase 3 of this test the maximum makeup flow limitation is rescinded. The makeup flow may be increased sufficiently to maintain a constant pressurizer inventory with two HPVs open and a relatively high letdown flow (greater than 70 gpm plant equivalent). The makeup flow should be injected into the A2 cold leg, however, if flow limitations occur in the injection line a second injection line into the A1 cold leg may be opened. Although this procedure exceeds the maximum makeup flow, it does attempt to simulate the start of a second HPI pump in an actual plant.

Phase 3 of this test is to be initiated when the desired letdown flow is attained and when the pressurizer inventory is being maintained approximately constant by means of the makeup flow. At this time open the hot leg U-bend HPV in loop B and adjust the makeup flow to maintain an approximately constant pressurizer inventory. Observe the primary system response for approximately 30 minutes. Then open the hot leg U-bend HPV in loop A (both HPVs are now open) and adjust the makeup flow to maintain an approximately constant pressurizer inventory. Observe the system response for approximately 30 minutes. Then close the hot leg U-bend HPV in loop B and adjust the makeup flow to maintain an approximately constant pressurizer inventory. Again observe the system response for approximately 30 minutes.

Upon completion of the above close the hot leg U-bend HPV in loop A, maximize the letdown flow (140 gpm plant equivalent flow) and adjust the makeup flow to maintain an approximately constant pressurizer inventory. Subsequent to the above consideration should be given to performing another reactor coolant pump start similar to that performed for Test 4NCNV1, however, letdown and makeup flow are to remain active.

2.4.5. Acceptance Criteria

1. At least ten minutes of steady-state data is recorded at the specified initial conditions.

2. Test initiation is performed as specified.

3. The specified boundary system control settings are maintained throughout the test.

4. The primary system remains subcooled through Phase 2.

5. Test termination is performed as specified.

6. All critical instrument data as specified in Appendix F reference 2 is recorded at intervals of ten seconds or less throughout the test.

Table 2.4. Test 4NCLM1 Initial Conditions

Quantity	Specification	Tolerance (+/-)	Derived[1]
1. Primary Pressure	2175 psia	25	
2. RC Pump Inlet Temperature			540F
3. Hot Leg Inlet Temperature			577F
4. Core Exit Subcooling[2]			71F
5. Core Power			(3)
6. Pressurizer Level			(4)
7. Surge Line Temperature	Hot Leg Temp., F	5	
8. Letdown Flow	45 gpm Plant Equivalent	--	
9. Makeup Flow			(5)
10. RVVVs	Auto./Indepen. (0.125 psi Open/0.04 psi Close)		
11. Secondary Pressure	965 psia	10	
12. Secondary Levels[6]	20.7 ft	1	
13. Main Feedwater Temperature[7]			420F
14. Fluid Temperature Gradients	0F/hr	5	
15. Metal Temperature Gradients	0F/hr	15	

[1]Derived quantities are for information only and should not be interpreted as control specification.

[2]The primary system with the exception of the pressurizer is to be subcooled. The value in the table corresponds to the subcooling attained with a hot leg inlet temperature of 577F.

[3]The core power is to be adjusted to obtain a hot leg inlet temperature of approximately 577F. DO NOT augment core power.

[4]The pressurizer level is to be sufficiently high to provide primary system inventory control when makeup and letdown are active. The pressurizer level is to be maintained at approximately this level throughout the entire test. The pressurizer heaters are to be active throughout the entire test and should be set to control at 2175 psia.

[5]The makeup flow is to be adjusted to maintain the pressurizer level approximately constant.

[6]All levels are relative to the secondary face of the lower steam generator tube sheet.

[7]The main feedwater temperature is effected by heat losses in the MIST secondary system. This is the expected main feedwater temperature for the low power levels and secondary flow rates at which this test will be performed.

3. PERFORMANCE

The acceptability of each of Test 4NCSM1, 4NCVV1, 4NCHL1, and 4NCLM1 was determined by examining both the conduct of the test and the performance of the measurement systems. The acceptance criteria for each test was defined in the corresponding test procedure which was based on MIST Natural Circulation Test specifications. Any condition, action, or measurement that did not meet the acceptance criteria was evaluated for its impact on test acceptability. The tests reported herein are only those that were determined to be acceptable. Any specific deviations of these tests from the acceptance criteria are described in this section.

The review of test conduct included the following checks for each test:

- System conditions and stability just prior to test initiation
- Test initiation actions
- Test termination criteria

The impact of out-of-specification conditions or actions was assessed. The deviations of those tests that were determined to acceptable are described in Section 3.1.

The following pre-test and post-test data qualification checks were performed for each test:

- The acquisition of the critical measurements
- The operation of the measurement systems within their calibrated range of operation
- Self-consistent measurements, considering both comparable measurements and derived quantities

The appropriate measurement uncertainties were used to assess the individual measurements. The impact of the individual out-of-specification conditions was assessed. The deviations of the critical measurements of those tests that were determined to acceptable are noted in Section 3.2.

3.1. Conduct

All the tests specified were acceptable as performed. All initial conditions were acceptable except as specified in section 3.1.1. Test initiations and terminations were acceptable. Operation of the control systems and manual interactions during the test transients were acceptable for all the tests except as noted below and discussed in Section 3.1.3.

In Test 4NCSM1, a sticky control valve in the A steam generator steam line caused the A-SG pressure and main feedwater to oscillate. Consequently, the primary flow in the A-loop was oscillating by $\pm$ 110 lbm/hr (14% of current flow rate), and the A-loop primary fluid temperatures were oscillating by $\pm$ 0.4 deg F during the pre-test steady state period.

In all tests, the core power was acceptably controlled and remained within the intended power decay curve, except for the first few scans after test initiation. It is believed the observed deviations did not influence the course of the natural circulation events.

Ten critical instruments were unavailable, during all tests, without sufficient backup instrumentation as defined in the test procedure. These instruments included eight guard heater control differential temperatures, the B-steam generator downcomer differential pressure (DP) transmitter (only during Test 4NCSM1), and one fluid thermocouple in the A-SG. Approval to continue testing without the differential temperatures was obtained through PMG transmittal 566, 606, and 716. The absence of the B-SG downcomer differential pressure transmitter and the A-SG fluid thermocouple do not warrant a test repeat.

In Test 4NCHL1, the C4 cold leg venturi reverse flow differential pressure transmitter (C4DP06) showed significant shift in its zero after the completion of the test. However, this zero bias was known since the transmitter zero was recorded for about 35 minutes during the test performance. The readings of transmitter C4DP06 were corrected using the recorded zero bias. The overall uncertainty in the mass flow rate measurement based on C4DP06 was increased to reflect the shift in the transmitter zero at pre- and post-test conditions.

In Test 4NCLM1, the differential pressure transmitters, which are listed in Table 3.2.3, were brought into service about 12 minutes after the RCP were turned off. The absence of these instruments during this 12 minutes period does not warrant a test repeat.

Significant deviation in the secondary mass closure was observed in Tests 4NCVV1, 4NCHL1, and 4NCLM1 due to relatively long periods of steam generator inactivity. During these periods, an offset in the B-SG feedwater measurement (within the measurement uncertainty) at zero flow was integrated into total feedwater flow, offsetting the overall mass closure.

3.1.1. Initial Conditions

Initial conditions for the natural circulation tests were defined by the governing test procedures, ARC-TP-893, -894, -895, and -896. These initial conditions are repeated in Table 3.1.1 along with the actual values from each test. All initial conditions were met as expected. However, in Test 4NCSM1, a sticky control valve in the A steam generator steam line caused the A-SG pressure and main feedwater to oscillate. Consequently, the primary flow in the A-loop was oscillating by ± 110 lbm/hr (14% of current flow rate) and the A-loop primary fluid temperatures were oscillating by ± 0.4 deg F during the pre-test steady-state period.

3.1.2. Test Initiation

The initiation actions in all the tests were acceptable as performed. All four tests were initiated by triggering the core decay ramp.

3.1.3. Control During Testing

The performance of the automatic control systems and manual interactions during the test transients are described in this section. The controls for the core power, steam generator secondary level and pressure, pressurizer heaters, pressurizer fluid level, PORV, primary system subcooling, makeup flow, letdown flow, high pressure injection, reactor coolant pumps, reactor vessel vent valves, and vent system performed acceptably for all the tests in this group except as noted in the following text.

Core Power

In all tests, the core power was acceptably controlled and remained within the intended power decay curve, except for the first few scans after test initiation. In Tests 4NCSM1 and 4NCHL1, the actual core power was higher then the desired power by 1.5-2.5 kW for the first 5 data scans (1 scan = 5 seconds). In Test 4NCVV1, the core power deviation was between 2.5 and 5 kW for the first 7 scans. In Test 4NCLM1, the core power remained above the intended curve by 2.5 kW for the first scan and 2.5 kW for the next 6 scans. This core power anomaly was due to lack of proper tuning of the core power controller. It is believed that the observed deviations did not influence the course of the natural circulation events.

Steam Generator Secondary Level Control

The A and B steam generator secondary fluid levels were maintained at the desired level, 20.7 ± 1 ft, during the entire duration of Tests 4NCSM1, 4NCVV1, 4NCHL1, and 4NCLM1. However, few isolated deviations were observed in Tests 4NCSM1 and 4NCLM1. The largest of these deviations occurred in Test 4NCSM1 when the B steam generator level dropped below the lower limit by 0.3 ft for 14 minutes towards the end of the test.

Steam Pressure Control

Performance of steam pressure control was examined using the steam generator secondary pressures, S1GP01 and S2GP01. The steam pressure in both generators was to remain constant at 965 ± 10 psia during the entire transient in all tests. The steam pressure control performance was effected by the primary loop response, especially during flow reversal in the cold legs and by heat losses in the steam generators.

In Test 4NCVV1, the A and B steam generator secondary pressures were maintained within the control limits during the entire test, except during the test recovery period following the activation of the RCPs. In this test, the primary loop flow remained intact during the entire test supporting the primary-to-secondary heat transfer in the steam generators.

In Tests 4NCHL1, the A and B steam generator secondary pressures continuously drifted below the allowable control limit (955 psia) between 86 and 360 minutes. In this period, the A and B secondary pressure dropped as low as 830 and 790 psia, respectively. During the test recovery period, the A and B secondary pressures were restored to 965 ± 10 psia after the natural circulation was re-established in the A and B loop.

In Test 4NCLM1, the A and B steam generator secondary pressures dropped below 955 psia shortly after test initiation, and kept dropping until they reached ~537 psia at 239 minutes. This pressure drop was due to ambient heat losses from the secondary exceeding the primary-to-secondary heat transfer rate.

In Test 4NCSM1, the B steam generator secondary pressure was maintained within the expected control limits for the entire test. However, the A generator pressure dropped below 955 psia during the first 50 minutes of the test and between 270 and 324 minutes. In these periods, the reduction in the A-Loop primary flow reduced the primary-to-secondary heat transfer in the A generator leading to the secondary pressure decrease.

It should be noted that none of the above deviations in the steam generator secondary pressure was due to a malfunction in the steam generator pressure controls.

Pressurizer Main Heaters

In all tests, the control of the pressurizer main heaters performed acceptably as the primary pressure exceeded the setpoint of 2175 psia. Occasionally, the main heater power was manually controlled to prevent the differential pressure between the steam generator primary and secondary from exceeding 1500 psia. In Tests 4NCSM1 and 4NCHL1, the pressurizer main heaters were tripped off on low pressurizer level (19.4 ft) at about 271 minutes for Test 4NCSM1 and 250 minutes for Test 4NCHL1.

Pressurizer Fluid Level

The pressurizer fluid level was maintained approximately constant (between 24 and 25.6 ft) during Test 4NCLM1 by balancing makeup and letdown flows, as intended. No control actions were required for the other tests.

Pilot-Operated Relief Valve (PORV)

In Tests 4NCSM1, 4NCVV1, and 4NCHL1 primary pressure remained below the 2350 psia actuation pressure and the PORV remained closed, as required. During Test 4NCLM1 the primary pressure remained below 2350 psia, but the PORV was manually actuated to prevent the differential pressure between the steam generator primary and secondary from exceeding the generator design pressure limit, 1500 psid.

Primary System Subcooling

In all tests, the primary system remained subcooled during the test duration, as expected.

Makeup Flow Control

In all tests, except 4NCLM1, the makeup flow was not to exceed 12 lb/hr during the pressurizer fill. But if the pressurizer level had dropped below 19.4 ft and more flow was needed to quickly restore the pressurizer inventory, the allowable makeup flow was to be 116 lb/hr. As for Test 4NCLM1, the makeup flow was not to exceed 116 lb/hr, and HPI flow into the A1 & A2 cold legs was to be used to supplement makeup flow during the HPVs opening.

In Test 4NCSM1, makeup flow was initiated at about 267 minutes at a flow rate which exceeded 12 lb/hr in an attempt to restore the pressurizer inventory which had dropped below 19.4 ft, as expected.

In Test 4NCHL1, makeup flow was initiated at about 250 and 300 minutes at a rate of approximately 95 lb/hr. As the flow was initiated, the makeup flow exceeded the maximum allowable limit (116 lb/hr) for several data scans.

In Test 4NCLM1, makeup flow was used to balance the letdown flow. When the hot leg high point vent were activated the makeup flow was increased to its maximum allowable limit (116 lb/hr), and then the A2 cold leg HPI flow was used to help maintain the pressurizer inventory constant. The HPI flow was metered by the same Micro Motion flowmeters as the letdown flow, HPMM03 and HPMM05. HPMM03 was overanged between 126 and 230 minutes, but HPMM05 was available for backup.

Makeup flow was not used in Test 4NCVV1.

Letdown Flow Control

In all tests, the letdown flow was maintained at or below 85 lb/hr as intended, except for Test 4NCLM1. In this test, the letdown flow exceeded the 85 lb/hr maximum allowable flow by about 3 lb/hr between 256 and 272 minutes. During this period the letdown flow was intentionally maintained at 85 lb/hr.

High Pressure Injection (HPI) Flow

The high pressure injection system was only used in Test 4NCLM1 during 126 and 230 minutes. In this period, HPI flow was injected in the A2 cold leg to supplement the makeup flow system in order to maintain a stable pressurizer fluid inventory. The HPI flow used was below that of head/flow characteristic curve.

Reactor Coolant Pump Operation

The C1 and C4 reactor coolant pumps were used in all tests, except 4NCSM1, to help restore natural circulation in the primary loop, as intended.

Reactor Vessel Vent Valve Control

The reactor vessel vent valves (RVVVs) were set to automatic "independent" control mode for all tests except 4NCVV1. In this test, the RVVVs were manually closed, as intended, for the entire test.

In Test 4NCSM1, the RVVVs remained open (automatic control) throughout the entire test. In Test 4NCLM1, all RVVVs remained opened from test initiation until the RCP pump bump, at which time the RVVVs were manually closed until test termination.

In Test 4NCHL1, all RVVVs remained opened until test recovery. At about 337 minutes, the A1 RVVV automatically closed as the differential pressure between the reactor vessel and the RV downcomer dropped below 0.045 psid. The A2, B1, and B2 RVVVs were manually closed at about 345 minutes, as expected, in preperation for the RCP pump bump.

Leak and Vent System Control

For all tests in this group, all leaks and vents were actuated in accordance to the test procedure. None of the leaks or vents were actuated in Test 4NCVV1 because the natural circulation up the hot legs was maintained throughout the entire test.

The orifice sizes of the vents that were utilized in the natural circulation tests are:

HPVs: 0.0155 inches, throat I.D.

PORV: 0.0400 inches, throat I.D.

The instrument fluctuation at zero flow for the HPVs and PORV flow meters were less than ± 0.75 and ± 1.0 lb/hr, respectively.

Mass Closure

Primary mass closure (Pc) is defined as the difference between the calculated mass (using levels) and the indicated mass (using weigh tank measurements for the letdown,vents, and time integration of makeup or HPI flow) divided by the accumulated total mass of makeup or HPI added (HPMM25). Only in Test 4NCLM1 a significant amount of fluid was transferred across the primary loop boundary. The (Pc) in Test 4NCLM1 was 6.0%.

Secondary mass closure (Sc) is defined as the difference between the calculated mass (using levels) and the indicated mass (using the time integration of feed and steam flow rates) divided by the accumulated total mass of feedwater added. The secondary mass closure for the natural circulation tests are:

Test	Sc
4NCSM1	0%
4NCVV1	-14%
4NCHL1	-32%
4NCLM1	-32%

The deviation in the secondary mass closure was larger than usual due to relatively long periods of steam generator inactivity. During these periods, an offset in the B-SG feedwater measurement (within the measurement uncertainty) at zero flow was integrated into total feedwater flow, increasing the value of SLML21.

All primary and secondary mass balance calculations were performed at the end of data acquisition. For reference, the governing relations are as follows:

$$Pc = \frac{PLML20 - PLML22}{HPMM25} \times 100$$

$$Sc = \frac{SLML20 - SLML21}{SFOR30 + SFOR31} \times 100$$

where

PLML20 = Total primary mass using levels

PLML22 = Total primary mass using boundary flows

HPMM25 = Integrated total HPI flow

SLML20 = Total secondary mass using levels

SLML21 = Total secondary mass using boundary flows

SFOR30 = Integrated A-SG total feedwater flow

SFOR31 = Integrated B-SG total feedwater flow

3.1.4. Termination

Test termination activities for all the tests in this group were specified to be based on recording 30 minutes of steady-state data after re-establishing natural circulation flow in both loops.

All tests in this group were terminated as specified in the technical procedure.

3.2. Instruments

Each of the four natural circulation tests used a common set of instrumentation. The critical instruments in this set are defined in Table 3.2.1. The measurements obtained from the instrumentation were checked to assure acceptable operation during the tests. Checks on instrument measurements were performed by computer-automated data qualification activities and manual examination of the analysis plots. Data qualification activities for each natural circulation test were performed at steady-state pre-test initial conditions, during the test transient, and after test termination as summarized below:

		Time of Performance		
Check	Purpose	Before Test	During Test	After Test
NOREAD	Definition of instruments not acquiring data	x	x	x
ANDCHK	Calibration check of the Analogic data acquisition system	x		x
ZEROS	Zero check of instrument transmitters	x		x
RANGE	Validity of instrument measurement as compared to expected range	x	x	x
CONSIS	Instrument and derived quantity consistency check	x	x	

As a result of these manual and automatic data qualification checks applied to the measurements and derived quantities in the test data base, the critical instruments identified in Tables 3.2.2 and 3.2.3 were determined to be invalid during all or part of Tests 4NCSM1, 4NCVV1, 4NCHL1, and 4NCLM1. In most instances, there was sufficient redundancy in the group of critical instruments so that the individual failure did not violate the requirements of the Critical Instrument List. In the other cases, the existence of the failed critical instrument did not warrant test repeat.

The critical instruments that were not available during all of the natural circulation tests are listed in Table 3.2.2. Ten critical instruments were unavailable without sufficient backup instrumentation as defined in the test procedure. These instruments included eight guard heater control differential temperatures, the B-steam generator downcomer differential pressure transmitter (only during Test 4NCSM1), and one fluid thermocouple in the A-SG.

Approval to continue testing without the differential temperatures was obtained through PMG transmittal 566, 606, and 716. The absence of the B-SG downcomer differential pressure transmitter and the A-SG fluid thermocouple do not warrant a test repeat.

In Test 4NCSM1, the control differential temperature for guard heater zone 3 was not available for the last 78 minutes of the test. In this period, the guard heater power was automatically turned off. This anomaly did not impact the test performance, especially since it occured during the test recovery period.

Also in Test 4NCSM1, about 50 spikes were observed in the readings of PZTC02 (pressurizer surge line horizontal temperature). These spikes were faulty temperature measurements. Other than these spikes, PZTC02 readings were as expected in comparison to other thermocouple readings in the pressurizer. Besides, PZTC02 did not show any abnormalities in Tests 4NCVV1, 4NCHL1, and 4NCLM1 which were performed later. These spikes do not warrant a test repeat.

Table 3.2.3 lists the differential pressure transmitters in the primary loop which were valved out of service during the RCP forced circulation in Tests

4NCVV1, 4NCHL1, and 4NCLM1 to avoid overanging and damaging them. The periods during which these instruments were not available are:

Test	Period - Minutes From	To
4NCVV1	100.0	132.7
4NCHL1	344.9	380.3
4NCLM1	238.2	282.7

It should be noted that in Test 4NCLM1 the differential pressure transmitters, which are listed in Table 3.2.3, were brought into service about 12 minutes after the RCP were turned off. No significant events took place during this 12 minutes period.

Prior to and after completion of the test, a "zero" reading was obtained for all differential pressure and pressure transmitters, mass flowmeters, weigh tank load cells, and reactor core voltage and current measurements. The critical instruments that failed the zero check are listed in Table 3.2.4. The magnitude of the failure was small enough such that measurement performance was not degraded to a condition that warranted test repeat. However, one instrument (C4DP06, C4 cold leg reverse flow venturi DP) showed significant shift in its zero after the completion of Test 4NCHL1. The magnitude of the zero bias was known since the transmitter zero was recorded prior to test initiation, during the test performance and after the test was terminated. The C4DP06 transmitter zero was recorded for a period of 35 minutes during the test when the reactor coolant pumps were running. During the reactor pump bumps almost all primary differential transmitters were zeroed to avoid over-ranging them. In computing the reverse flow in the C4 cold leg, the readings of transmitter C4DP06 were corrected using the zero bias that was recorded during the test. The overall uncertainty in the mass flow rate measurement based on C4DP06 should be increased by about 120 lb/hr to reflect the shift in the transmitter zero at pre- and post-test conditions.

The instrumentation performance during these tests was fully acceptable based upon this check.

Table 3.1.1. Test Initial Conditions

System	Parameter	VTAB	Units	Desired	Tolerance	Actual Values 4NCSM1	4NCVV1	4NCHL1	4NCLM1
Primary	Primary pressure	RVGP01	psia	2175.	± 25	2173.9	2175.0	2178.6	2175.6
	Core power	RVWM20	kW	*		58.95	74.5	59.0	62.3
	Pressurizer level	PZLV20	ft	27.,** (25. for 4NCLM1)	± 5	26.8 and steady	26.8 and steady	26.9 and steady	25[illegible]2 and steady
	Pressurizer surge line fluid temperature	PZTC01	deg F	H1TC11	± 5	- 2.6	4.8	4.7	- 2.7
	Fluid/Metal temperatures	***	deg F	Varying less than 5 F/hr (Fluid), than 10 F/hr (Metal) over a 30 minute interval		acceptable	acceptable	acceptable	acceptable
	Hot Leg Inlet Temperature	H1RT01 H2RT01	deg F	577	****	577.8 578.5	578.2 578.8	576.9 577.6	576.1 576.6
	RCPs Inlet Temperature	C1RT01 C2RT01 C3RT01 C4RT01	deg F	540	****	540.2 540.7 540.3 540.7	541.0 541.3 541.2 541.2	539.6 540.7 540.6 539.7	540.5 540.9 540.7 540.9
	Subcooling	RVRF20-H1TC11	deg F	71	****	69.3	68.5	70.1	71.0
	Letdown Flow	V2M[illegible]2	lb/hr	28. (only Test 4NCLM1)	± 2	NA	NA	NA	27.3

Table 3.1.1. Test Initial Conditions (Cont'd)

System	Parameter	VTAB	Units	Desired	Tolerance	Actual Values 4NCSMI	4NCVVI	4NCHLI	4NCLMI
Secondary	Pressure	S1GP01	psia	965	± 10	966.38	965.9	964.8	965.0
		S2GP01				965.34	965.8	965.3	966.9
	Level	S1LV20	ft	20.7	± 1.0	20.3	20.1	20.3	19.9
		S2LV20				20.0	19.9	20.1	20.3
	Feedwater temperature	SFRT03	deg F	420	± 10	425.4	424.7	417.9	413.0
		SFRT04				421.9	423.5	413.0	410.1

*The core power must be adjusted so the hot leg inlet temperature (H1RT01 and H2RT01) are about 577 ± 10 deg F.

**Pressurizer level must be varying less then ± 0.6 feet per hour over the same time interval used for primary fluid temperatures.

***The following fluid and metal temperature measurements were used to define steady state (minimum time interval of 30 minutes without test operator manual control adjustments):

Fluid: H1RT01, H2RT01, P1RT02, P2RT02.
Metal: P1MT01, P2MT01, C1MT04, C2MT04, C3MT04, C4MT04, RVMT24, RVMT25.

****These quantities were for information only and were not be used as control specifications.

Table 3.2.1. Critical Instruments for the NC Test Series

Component	Instrument Type	Critical Instruments
Reactor Vessel	Ammeter	RVAM01
	DP Transmitter	RVDP01-09
	Diff. Temperature	RVDT01-04,23
	Pres. Transmitter	RVGP01
	Limit Switch	RVLS01-04,09
	Metal Thermocouple	RVMT01-04,23
		RVMT05-22 (12 of 18)
		RVMT24,25
	Fluid Thermocouple	RVTC01,02,RVTC16-20
		RVTC03-15 (9 of 13)
		RVTC21-23 (2 of 3)
	Voltmeter	RVVM01
Hot Legs	DP Transmitter	H1DP01-15
		H2DP01-16
	Diff. Temperature	H1DT01-04
		H2DT01-04
	Limit Switch	H1LS01,H2LS01
	Metal Thermocouple	H1MT01-04,H2MT01-04
	RTD	H1RT01 (or H1TC01)
		H2RT01 (or H2TC01)
	Fluid Thermocouple	H1TC02-09 (5 of 8)
		H2TC02-09 (5 of 8)
		H1TC10-12 (1 of 3)
		H2TC10-12 (1 of 3)
		H1TC13-19 (5 of 7)
		H2TC13-19 (5 of 7)
SG-A	DP Transmitter	P1DP04,S1DP01,03
	Diff. Temperature	S1DT01-05
	Pres. Transmitter	P1GP01,S1GP01
	Limit Switches	S1LS02,S1LS03
	Metal Thermocouple	S1MT01-05, P1MT01
	RTD	P1RT01,02
	Fluid Thermocouple	P1TC01-03,13-16,23-26,33-36 (10 of 15)
		P1TC18,27,28,37,38 (3 of 5)
		P1TC09-12,19-22,29-32 (8 of 12)
		S1TC01,02,26 (2 of 3)
		S1TC03-12 (7 of 10)
		S1TC13-23,25 (8 of 12)
		S1TC24

Table 3.2.1. Critical Instruments for the NC Test Series (Cont'd)

Component	Instrument Type	Critical Instruments
SG-B	DP Transmitter	P2DP06,S2DP01,S2DP12
		S2DP02-11 (5 of 10)
	Diff. Temperature	S2DT01-05
	Pres. Transmitter	P2GP01,S2GP01
	Limit Switches	S2LS02, S2LS05
	Metal Thermocouple	S2MT01-05, P2MTO
	RTD	P2RT01,02
	Fluid Thermocouple	P2TC01-13 (9 of 13)
		P2TC14-28 (10 of 15)
		P2TC29-43 (10 of 15)
		P2TC44-53 (7 of 10)
		S2TC01-08,55 (6 of 9)
		S2TC09-19 (7 of 11)
		S2TC20-33,54 (10 of 15)
		S2TC34-53 (13 of 20)
Cold Legs	DP Transmitter	C1DP01,C2DP01
		CnDP02-04,06-08 (n=1,2,3,4)
		C2DP09
	Diff. Temperature	CnDT01-03
	Limit Switches	CnLS03,04,06
	Metal Thermocouples	CnMT01-03
	RTD	CnRT01,02
	Fluid Thermocouple	CnTC02
		CnTC03-06 (3 of 4)
		CnTC07-10 (3 of 4)
		CnTC11-14 (3 of 4)
RV Downcomer	DP Transmitter	DCDP01,02,04-08
	Diff. Temperature	DCDT01-03
	Metal Thermocouple	DCMT01-04
	RTD	DCRT01
	Fluid Thermocouple	DCTC01-04,
		DCTC05-12 (5 of 8)
		DCTC13-40 (19 of 28)
		DCTC41-46 (4 of 6)
Pressurizer	DP Transmitter	PZDP01,02
	Diff. Temperature	PZDT01,03
	Pres. Transmitter	PZGP01
	Metal Thermocouple	PZMT01-03
	RTD	PZRT01 (or PZTC09)
	Fluid Thermocouple	PZTC01,02,09
		PZTC04-08 (4 of 5)
	Wattmeter	PZWM04

Table 3.2.1. Critical Instruments for the NC Test Series (Cont'd)

Component	Instrument Type	Critical Instruments
HPI	DP Transmitter	HPDP01
	Flowmeter	HPMM01-05
	Fluid Thermocouple	HPTC01
Makeup	Flowmeter	HPMM03
Single-Phase Leak System	Load Cell	V1LC01,02*
	Limit Switch	V1LS01,02,07
	Fluid Thermocouple	V1TC02
	Flowmeter	V1MM01
Two-Phase Vent System	Load Cell	V2LC01-04*
	Limit Switch	V2LS03-06
	Flowmeter	V2MM01 &03
	Fluid Thermocouple	V2TC01-04
Letdown System	Flowmeter	V2MM02
Gas Addition System	Fluid Thermocouple	GATC02-04 (1 of 3)
Feedwater Circuit	DP Transmitter	SFDP01-06
	RTD	SFRT03,04
Steam Circuit	DP Transmitter	SSDP01-06
	RTD	SSRT01,02
	Fluid Temperature	SSTC01,03 (1 of 2) SSTC02,04 (1 of 2)
Miscel.	RTD Shunt	MSRF01
	Reference Oven Tamp	MSTC01-07

*These instruments were not used in the natural circulation tests.

Table 3.2.2. Critical Instruments Not Available for the Natural Circulation Test Series

Instrument	Description	4NCSM1	4NCVV1	4NCHL1	4NCLM1	Backup Available
C1DT01	Guard heater zone 1 control-loop A1 2.60	X	X	X	X	*
C1DT02	Guard heater zone 2 control-loop A1 17.3	X	X	X	X	*
C1DT03	Guard heater zone 3 control-loop A1 23.46	X	X	X	X	*
C2DT03	Guard heater zone 3 control-loop B1 23.46	**				
C3DT03	Guard heater zone 3 Control-loop A2 23.48	X	X	X	X	*
C4DT01	Guard heater zone 1 control-loop B2 2.59	X	X	X	X	*
C4DT03	Guard heater zone 3 control-loop B2 23.47	X	X	X	X	*
H1DT01	Guard heater zone 1 control-loop A1 29.63	X	X	X	X	*
P1TC09	Generator A primary fluid temperature at 51.06 ft	X	X	X	X	***
P1TC10	Generator A primary fluid temperature at 50.56 ft	X	X	X	X	***
P1TC11	Generator A primary fluid temperature at 50.06 ft	X	X	X	X	***
P1TC12	Generator A primary fluid temperature at 49.06 ft	X	X	X	X	***
P1TC14	Generator A primary fluid temperature at 43.06 ft	X	X	X	X	YES
P1TC15	Generator A primary fluid temperature at 39.06 ft	X	X	X	X	YES
P1TC16	Generator A primary fluid temperature at 35.06 ft	X	X	X	X	YES
P1TC18	Generator A primary fluid temperature at 23.06 ft	X	X	X	X	YES
P1TC30	Generator A primary fluid temperature at 50.58 ft	X	X	X	X	***
P1TC35	Generator A primary fluid temperature at 39.08 ft	X	X	X	X	YES
P2TC01	Generator B primary fluid temperature at 50.50 ft	X	X	X	X	YES
P2TC12	Generator B primary fluid temperature at 49.50 ft	X	X	X	X	YES
P2TC29	Generator B primary fluid temperature at 29.25 ft	X	X	X	X	YES
P2TC30	Generator B primary fluid temperature at 29.25 ft	X	X	X	X	YES

Table 3.2.2. Critical Instruments Not Available for the Natural Circulation Test Series (Cont'd)

Instrument	Description	4NCSM1	4NCVV1	4NCHL1	4NCLM1	Backup Available
P2TC32	Generator B primary fluid temperature at 26.25 ft	X	X	X	X	YES
P2TC38	Generator B primary fluid temperature at 14.25 ft	X	X	X	X	YES
P2TC40	Generator B primary fluid temperature at 14.25 ft	X	X	X	X	YES
RVDT01	Core inlet guard heater control DT 1.88	X	X	X	X	*
RVTC07	Core fluid temperature (mid bundle) at 13.15 ft	X	X	X	X	YES
S1DP03	A-SG downcomer level DP 0.45 to 32.16 ft	X				NO

XInstrument was not available during a test.

*Project Management Group approval for a modified guard heater control scheme that did not use these instruments was obtained through PMG Transmittal Nos. 566, 606, and 716.

**This instrument failed during the last 78 minutes of Test 4NCSM1.

***These TCs are part of P1TC09-12, 19-22, 29-32, where 8 TCs out of 12 are required. Therefore, one TC has no backup.

Table 3.2.3. Critical Instruments Not Available During the Pump Bumps

These instruments were not available for part of the test. The Differential pressure transmitters would have been overranged and possibly damaged by the high differential pressures during the the RCP forced circulation, so they were valved out of service to prevent damage.

Instrument	Description
C1DP03	Venturi low-range forward flow DP -0.52 to 0.58
C1DP04	Venturi Mid-range forward flow DP -0.52 to 0.58
C1DP06	Venturi Hi-range forward flow DP 0.58 to 1.69
C1DP07	Across RCP-Loop A1 23.8 to 24.30
C1DP08	RCP to DC nozzle 24.30 to 20.94
C2DP03	Venturi low-range forward flow DP -0.51 to 0.60
C2DP04	Venturi Mid-range forward flow DP -0.51 to 0.60
C2DP06	Venturi Hi-range forward flow DP 0.60 to 1.70
C2DP07	Across RCP-Loop A1 23.82 to 24.30
C2DP08	RCP to DC nozzle 24.30 to 20.94
C2DP09	Cold leg nozzle DP 24.30 to 15.53
C3DP03	Venturi low-range forward flow DP -0.51 to 0.59
C3DP04	Venturi Mid-range forward flow DP -0.51 to 0.59
C3DP06	Venturi Hi-range forward flow DP 0.59 to 1.70
C3DP07	Across RCP-Loop A1 23.8 to 24.21
C3DP08	RCP to DC nozzle 24.21 to 20.94
C4DP03	Venturi low-range forward flow DP -0.53 to 0.59
C4DP04	Venturi Mid-range forward flow DP -0.53 to 0.59
C4DP06	Venturi Hi-range forward flow DP 0.59 to 1.70
C4DP07	Across RCP-Loop A1 23.8 to 24.32
C4DP08	RCP to DC nozzle 24.32 to 20.94
DCDP03	Downcomer circumferential DP & CL 20.94
DCDP04	Venturi DP-HI flow range 5.41 to 6.79
DCDP05	Venturi DP-MID flow range 5.41 to 6.79
DCDP06	Venturi DP-low flow range 5.41 to 6.79
DCDP07	Venturi DP-reverse direction 4.04 to 5.41
DCDP08	Lower Downcomer lower-plenum DP 1.54 to -1.03

Table 3.2.3. Critical Instruments Not Available During the Pump Bumps (Cont'd)

Instrument	Description
H1DP01	Hot leg nozzle to U-bend DP 20.94 to 66.65
H1DP02	Hot leg narrow range DP 20.94 to 23.51
H1DP03	Hot leg narrow range DP 23.51 to 27.92
H1DP04	Hot leg narrow range DP 27.92 to 30.20
H1DP05	Hot leg narrow range DP 35.20 to 37.47
H1DP06	Hot leg narrow range DP 42.48 to 44.73
H1DP07	Hot leg narrow range DP 49.76 to 52.01
H1DP08	Hot leg narrow range DP 57.70 to 62.59
H1DP09	Hot leg narrow range DP 62.59 to 64.83
H1DP10	Hot leg narrow range DP 64.83 to 66.65
H1DP11	Hot leg narrow range DP 64.83 to 66.65
H1DP12	Hot leg narrow range DP 62.57 to 64.83
H1DP13	Hot leg narrow range DP 53.10 to 62.57
H1DP14	OTSG-A inlet to U-bend DP 53.10 to 66.65
H2DP01	Hot leg nozzle to U-bend DP 20.92 to 66.61
H2DP02	Hot leg narrow range DP 20.92 to 23.50
H2DP03	Hot leg narrow range DP 23.50 to 27.89
H2DP04	Hot leg narrow range DP 27.89 to 30.14
H2DP05	Hot leg narrow range DP 35.17 to 37.43
H2DP06	Hot leg narrow range DP 42.44 to 44.69
H2DP07	Hot leg narrow range DP 49.72 to 51.98
H2DP08	Hot leg narrow range DP 57.68 to 62.56
H2DP09	Hot leg narrow range DP 62.56 to 64.81
H2DP10	Hot leg narrow range DP 64.81 to 66.61
H2DP11	Hot leg narrow range DP 64.81 to 66.61
H2DP12	Hot leg narrow range DP 62.56 to 64.81
H2DP13	Hot leg narrow range DP 53.09 to 62.56
H2DP14	OTSG-B inlet to U-bend DP 53.09 to 66.61
H2DP16	Hot leg nozzle DP 16.77 to 23.50
RVDP01	Overall vessel fluid DP -1.03 to 29.00
RVDP02	Upper core fluid DP14.49 to 16.77
RVDP03	Core top to hot leg nozzle DP 16.77 to 21.25
RVDP04	Hot leg to RVVV line fluid DP 21.25 to 24.15
RVDP06	DP control for RVVV 1
RVDP07	DP control for RVVV 2
RVDP08	DP control for RVVV 3
RVDP09	DP control for RVVV 4

Table 3.2.4. Instrument Zero Offset

Test	VTAB	Allowable Uncertainty in Zero Reading (+/- mVolts)	Deviation Beyond Allowable Uncertainty (Volts)	Deviation Beyond Allowable Uncertainty (Engineering Units)
Pre-Test				
4NCSM1	C1DP06	48.1	0.9	0.0001 psid
	C4DP03	50.3	23.9	0.0029 psid
	C4DP06	42.3	-6.4	-0.0010 psid
4NCVV1	C4DP03	50.3	-23.9	-0.0029 psid
4NCHL1	C1DP06	47.7	0.4	0.0001 psid
	C4DP03	50.3	43.4	0.0054 psid
	C4DP06	42.1	33.5	0.0050 psid
4NCLM1	C4DP03	51.5	9.87	0.0012 psid
Post-Test				
4NCSM1	C4DP03	50.5	23.7	0.0029 psid
	HPMM02	26.40	7.4	*
	HPMM05	2.20	-14.8	-1.6 lb/hr**
4NCVV1	C4DP03	53.44	22.3	0.0028 psid
	HPMM01	15.0	17.6	*
	HPMM03	15.5	-15.4	*
	V2MM01	7.8	3.0	*
	V2MM02	5.4	-41.4	*
	V2MM03	8.6	-7.6	*
4NCHL1	C4DP03	52.6	23.4	0.0029 psid
	C4DP06	42.3	89.7	0.0135 psid
	SFDP06	37.5	-2.2	0.0458 psid
	HPMM03	15.5	-32.2	-0.54 lb/hr
	HPMM05	2.2	-0.8	-0.08 lb/hr
	V2MM02	5.4	-16.0	-0.20 lb/hr
	V2MM03	8.6	-24.8	-0.62 lb/hr
4NCLM1	C4DP03	47.4	28.6	0.0036 psid
	C4DP06	40.4	141.3	0.0213 psid
	HPMM03	15.5	-28.5	-0.475 lb/hr
	V2MM02	5.4	-18.2	-0.23 lb/hr
	V2MM03	8.6	-12.5	-0.31 lb/hr

Table 3.2.4. Instrument Zero Offset (Cont'd)

Test	VTAB	Allowable Uncertainty in Zero Reading (+/- mVolts)	Deviation Beyond Allowable Uncertainty (Volts)	Deviation Beyond Allowable Uncertainty (Engineering Units)
Post-Calibration After All Tests				
	V2LC01	0.85 mv offset		0.02 lbm

*These instruments were not used in the test indicated.

**These instruments had backup available.

4. OBSERVATIONS

The intent of the MIST Natural Circulation Tests was to determine if the MIST facility exhibits phenomena similar to those observed during actual plant natural circulation events and to determine the effect of selected parameter changes on natural circulation in MIST. The MIST tests were expected to provide insight into the better understanding of natural circulation and interruption at low decay heat levels in an operating plant.

The phenomena observed during various plant natural circulation events was a reduction of the fluid temperature in one cold leg of a loop to a value that is less than the saturation temperature of the steam generator secondary in that loop while the other cold leg fluid temperature appeared to remain at or near the steam generator secondary saturation temperature. This phenomena did occur both in one loop and both loops (see Appendixes A, B, and C).

The phenomena in MIST apparently occurs when an insufficient amount of natural circulation driving head exists to maintain primary loop natural circulation (up the hot legs) and a flow path via the reactor vessel vent valves is established. This flow path causes back flow i.e., the flow direction in one cold leg is backwards while the flow direction in the other cold leg of the same loop is forward. The decrease in the cold leg fluid temperature occurs in the cold leg that experiences back flow and appears to be caused by the heat losses in the upper regions of the cold leg suction pipe and the reactor coolant pump.

The MIST natural circulation tests were initialized at essentially identical primary and secondary system conditions. Differences in the boundary conditions were utilized for the four tests as discussed in the following sections. The tests were initiated in the same manner, i.e., a power ramp was used which was similar to that in the TMI-1 test. The conversion factors used for these tests were:

MIST Core Power	1% Scaled Full Power	= 33 KW
MIST Primary Flow	1% Scaled Full Flow	= 1660 lbm/hr
MIST Secondary Flow	1% Scaled Full Flow	= 138 lbm/hr

The observations from each test are presented in the following sections. Section 4.5 provides a detailed discussion of the "cold leg temperature anomaly" and its cause as observed in the MIST facility.

4.1. Observations of Test 4NCSM1

During the initialization period heat losses across the reactor coolant pumps were apparent. This was exhibited by a positive temperature difference of approximately 8F between the reactor coolant pump suction and discharge (Figure 4.1 through 4.4, See 1). Also during the initialization period the reactor vessel vent valves were open. This can be observed by comparing the summation of the four cold leg flow rates and the downcomer flow rate (Figure 4.5, See 1) or by observing that the fluid in the cold legs is heated prior to entering the core region, i.e., fluid from the core exit mixes with the fluid entering the downcomer from the cold legs (Figure 4.6, See 1).

The test was initiated by actuating the core power ramp (Figure 4.7, See 1) while all other boundary conditions remained constant. The effect of decreasing the core power was a decrease in the core exit and hot leg fluid temperatures (Figure 4.8, See 1) and resulted in an increase in the core region and hot leg fluid density. The increase in the fluid density resulted in a decrease in the primary loop (up the hot leg) natural circulation driving head, therefore a decrease in the cold leg flow rates occurred (Figures 4.9 and 4.10, See 1). The reduction in primary loop (up the hot leg) flow can be observed by summing the flow rate in both cold legs of a given loop (Figures 4.11 and 4.12, See 1). Also, by comparing the summation of the four cold leg flow rates with the downcomer flow rate, it can be observed that flow from the reactor vessel through the reactor vessel vent valves exists during the entire test time shown (Figure 4.5). Thus the reactor vessel vent valves are open.

The reduction in the primary loop flow rate in conjunction with the heat loss in the reactor coolant pumps resulted in an increased positive temperature difference between the reactor coolant pump suction and discharge fluid temperatures (Figures 4.1 through 4.4, See 2). These figures also show that during this time the reactor coolant pump suction temperature remains approximately equal to the steam generator saturation temperature while the discharge temperature decreases. This is indicative of a decreasing cold leg flow rate with flow in the forward direction and heat losses present between the two temperature measurement locations.

The existence of a secondary flow path (via the reactor vessel vent valves) in conjunction with the decrease in the primary loop (up the hot leg) natural circulation driving head and the physically induced natural circulation driving head in the cold legs (reactor coolant pump heat loss) resulted in back flow in the A2 cold leg (Figure 4.9, See 2). The forward flow in the A1 cold leg similarly increased (Figure 4.9, See 3) as the back flow from the A2 cold leg entered the A1 cold leg suction pipe. The primary loop (up the hot leg) flow rate in each loop can be inferred by summing the flow rate through the cold legs of each loop. The summation of the flow rates through the B cold legs indicates that primary loop flow exists in the B loop (Figure 4.12, See 2). However, the summation of the flow rates through the A cold legs indicates that primary loop flow interrupted in the A loop (Figure 4.11, See 2). The interruption of the primary loop flow in the A loop can also be inferred from the decrease in the steam generator A secondary pressure (Figure 4.13, See 1).

4.1.1. Facility Hold Period

Subsequent to the flow interruption the test procedure required that no operator actions be performed for four hours (through approximately 250 minutes) such that the response of the MIST facility could be observed. The transient response is provided on Figures 4.14 through 4.25.

As can be observed from these figures, the primary system established new steady-state natural circulation conditions with forward flow of approximately 800 lb/hr in each B cold leg (Figure 4.17). The A1 cold leg flow stabilized at approximately 1050 lb/hr (forward flow) while the A2 cold leg stabilized in reverse flow at approximately 435 lb/hr (Figure 4.16). The fluid contraction (caused by the reduction in the primary loop fluid temperatures as a result of the core power decrease) was essentially completed at the end of the four hour period. The stabilization of the primary loop fluid temperatures (Figures 4.18 through 4.24) and relatively constant pressurizer level (Figure 4.25) confirms that the fluid contraction was essentially complete.

4.1.2. Operator Actions and Loop Recovery Period

Subsequent to the four hour hold period the loop operator opened the A loop high point vent (Figure 4.26, See 1) in an attempt to re-establish forward low in the A2 cold leg. When the A loop high point vent was opened hotter fluid from the pressurizer was discharged through the pressurizer surge line into the A hot leg and an increase in the A hot leg temperature was observed (Figure 4.27, See 1). The response of the B hot leg temperature was not effected by the pressurizer discharge (Figure 4.28, See 1) since the pressurizer surge line is connected to the A hot leg. When the A loop high point vent was opened the primary loop flow rate in the A loop initially increased (Figure 4.29, See 1) and the primary loop flow rate in the B loop initially decreased (Figure 4.30, See 1). Although the primary loop flow rate in the A loop increased at this time forward flow was not established in the A2 cold leg (Figure 4.31, See 1). Thus the increase in the A loop primary flow rate occurred via the A1 cold leg (Figure 4.31, See 2). The reduction in the B loop primary flow rate appears to be distributed equally between both B cold legs (Figure 4.32, See 1). Approximately four minutes after the A loop high point vent was opened the primary loop flow rate decreased in loop A (Figure 4.29, See 2) and increased in loop B (Figure 4.30, See 2).

The A loop high point vent remained open for approximately 13 minutes. During this time the primary system pressure decreased (Figure 4.33, See 1). The pressurizer inventory also decreased (Figure 4.34, See 1) and the pressurizer heaters turned off when the pressurizer heater low level trip setpoint was attained, thus causing the loss of pressurizer heater control.

The loop operators immediately established makeup flow (Figure 4.35, See 1) in an attempt to regain pressurizer level. The makeup flow was injected into the A2 cold leg discharge pipe downstream of the reactor coolant pump discharge RTD. When the makeup flow was actuated the fluid temperature at the reactor coolant pump discharge decreased (Figure 4.36, See 1). The fluid temperature at the reactor coolant pump suction also decreased (Figure 4.36, See 2). The observed response of these cold leg fluid temperatures indicate that they responded to changes in the makeup flow rate, i.e., back flow continued in the A2 cold leg. Primary loop flow, however, eventually stopped in the A loop (Figure 4.29, See 3) while the makeup flow was active. Makeup flow was terminated (Figure 4.35, See 2) when a sufficient amount of inventory existed in the pressurizer. When the makeup flow was terminated primary loop flow in the A loop was re-established (Figure 4.29, See 4) but the flow direction in the A2 cold leg continued in the reverse direction (Figure 4.31, See 3).

The loop recovery procedure for Test 4NCSM1 was to increase the core power to approximately the initial value (Figure 4.37, See 1). The core power increase resulted in an immediate increase in the primary loop natural circulation driving head. The primary loop flow rate in both loops increased (Figure 4.29, See 5 and Figure 4.30, See 3) and forward flow was re-established in the A2 cold leg (Figure 4.31, See 4).

Subsequent to the core power increase primary system temperatures increased and caused a primary system liquid inventory expansion. The primary system pressure then began to increase (Figure 4.33, See 2). The loop operators initiated letdown flow (Figure 4.38, See 1) to maintain the primary system pressure at approximately 2175 psia. The letdown line was located in the B1 cold leg suction pipe. The actuation of letdown flow did not have any apparent effect on the primary system response. Test 4NCSM1 was terminated approximately 350 minutes after test initiation.

Figures for Test 4NCSM1

Natural Circulation Test

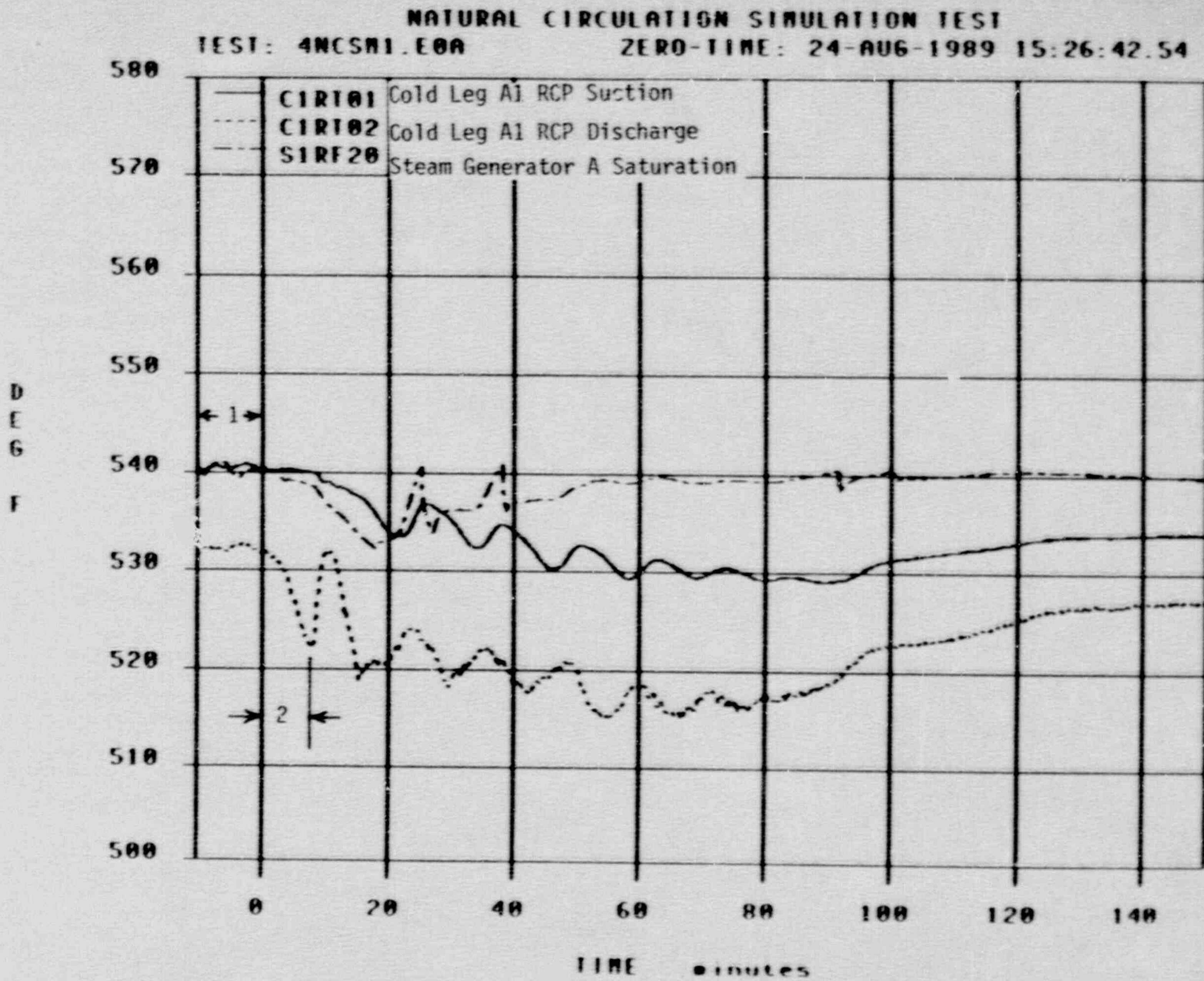

Figure 4.1 Steam Generator A Saturation Temperature and Cold Leg A1 Reactor Coolant Pump Suction and Discharge Temperature

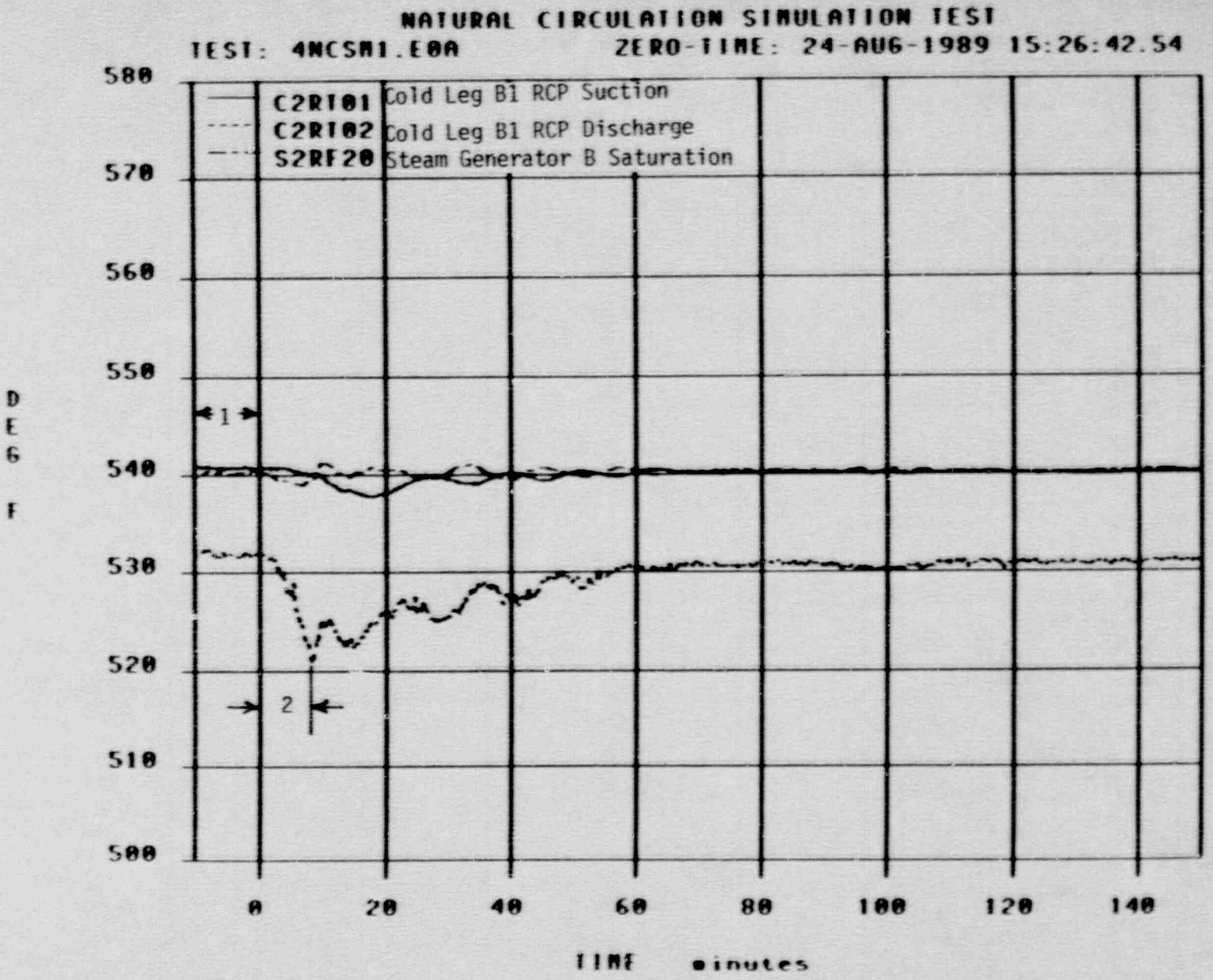

Figure 4.2 Steam Generator B Saturation Temperature And Cold Leg B1 Reactor Coolant Pump Suction And Discharge Temperature

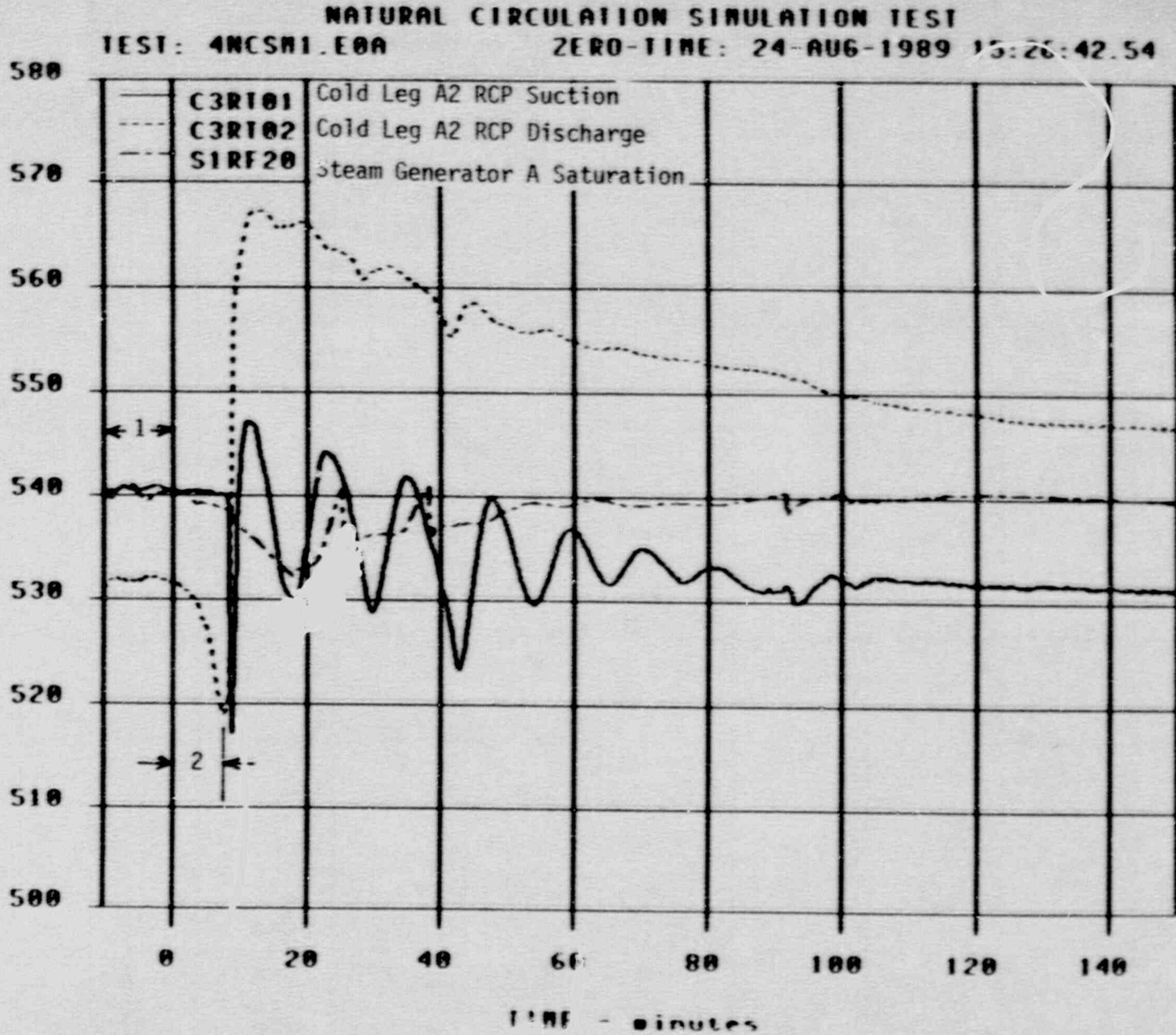

Figure 4.3 Steam Generator A Saturation Temperature And Cold Leg A2 Reactor Coolant Pump Suction And Discharge Temperature

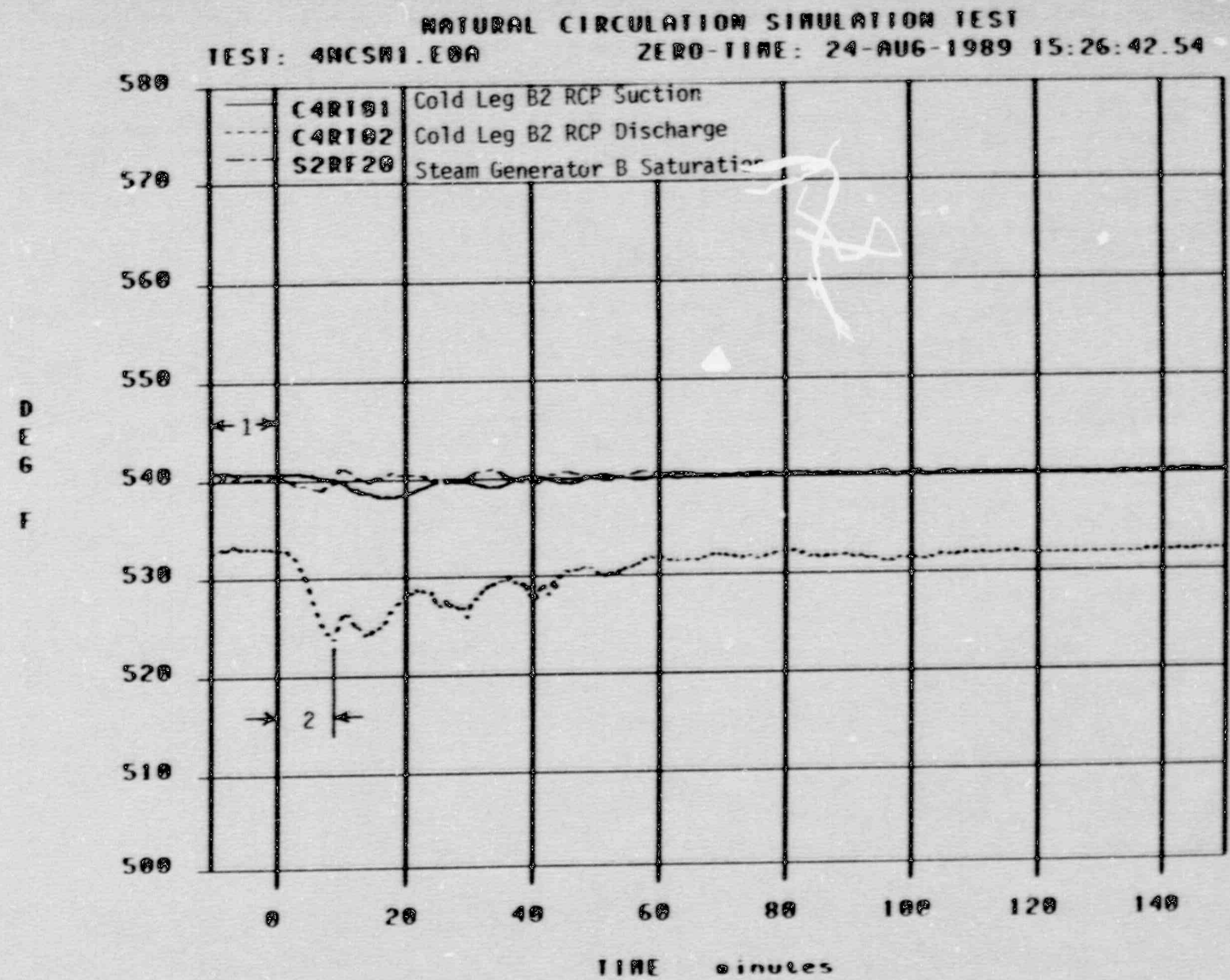

Figure 4.4 Steam Generator B Saturation Temperature and Cold Leg B2 Reactor Coolant Pump Suction and Discharge Temperature

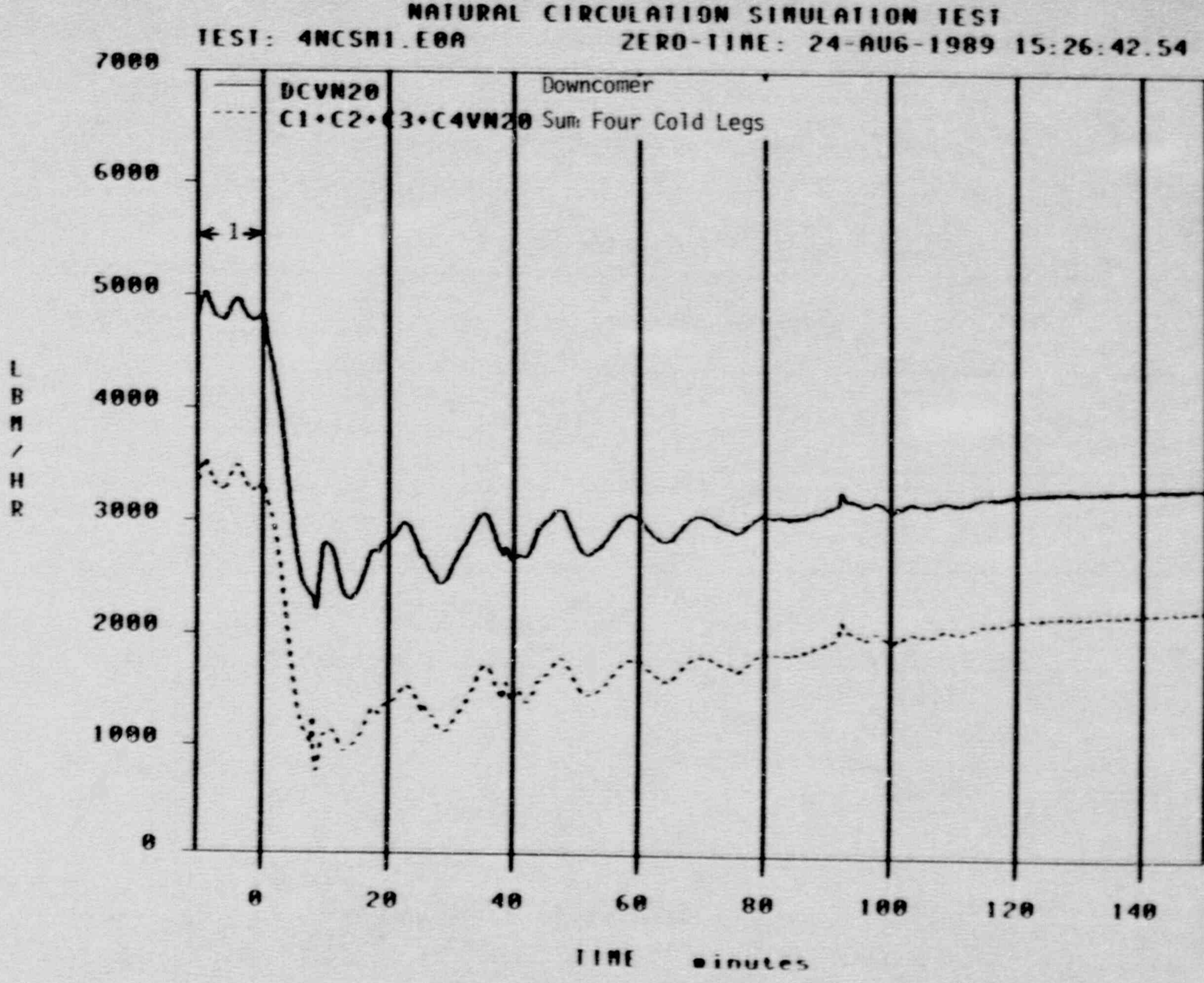

Figure 4.5 Downcomer Flow Rate And The Summation Of The Flow Rate In All Four Cold Legs

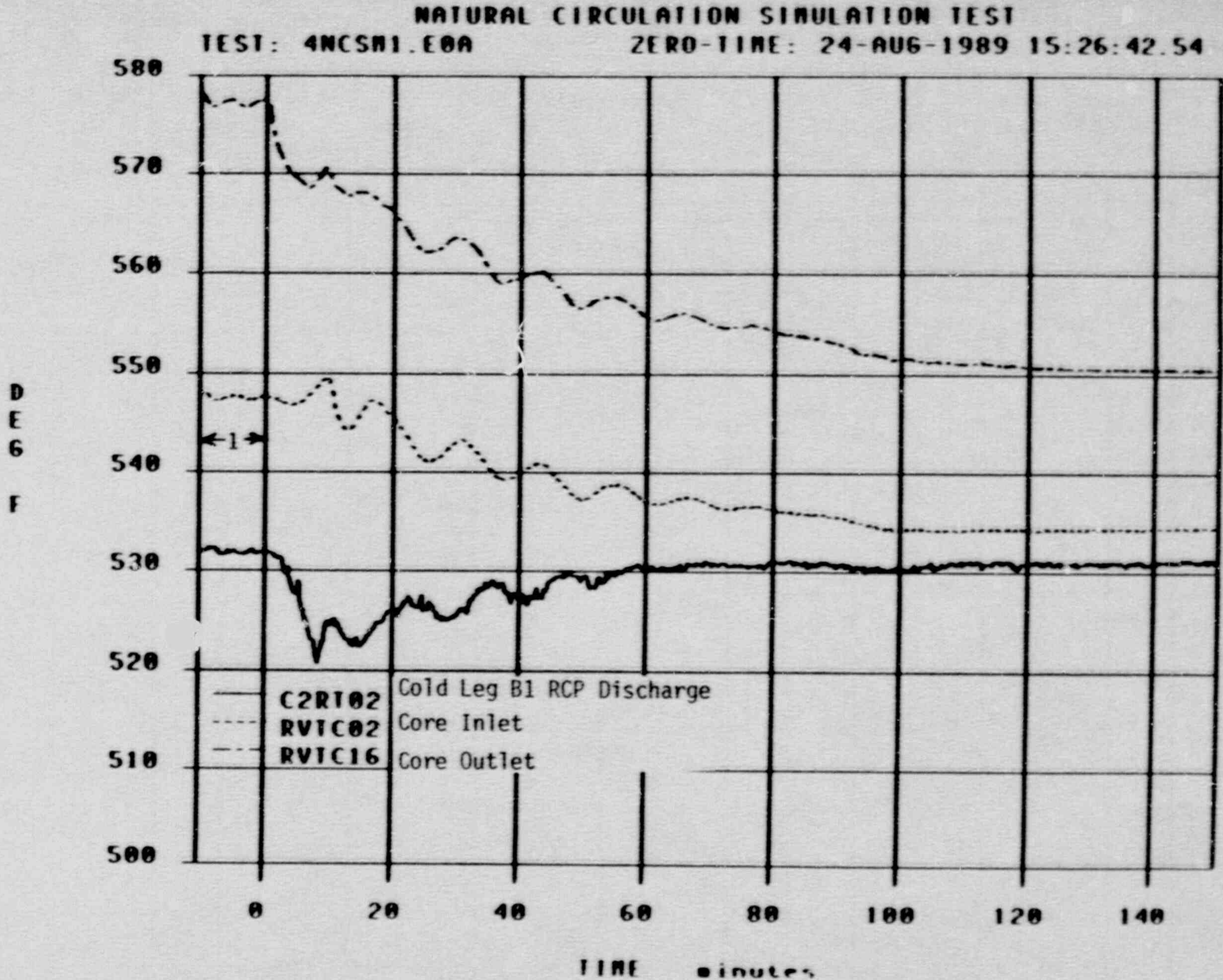

Figure 4.6 Cold Leg B1 Reactor Coolant Pump Discharge Temperature And Core Inlet And Outlet Temperature

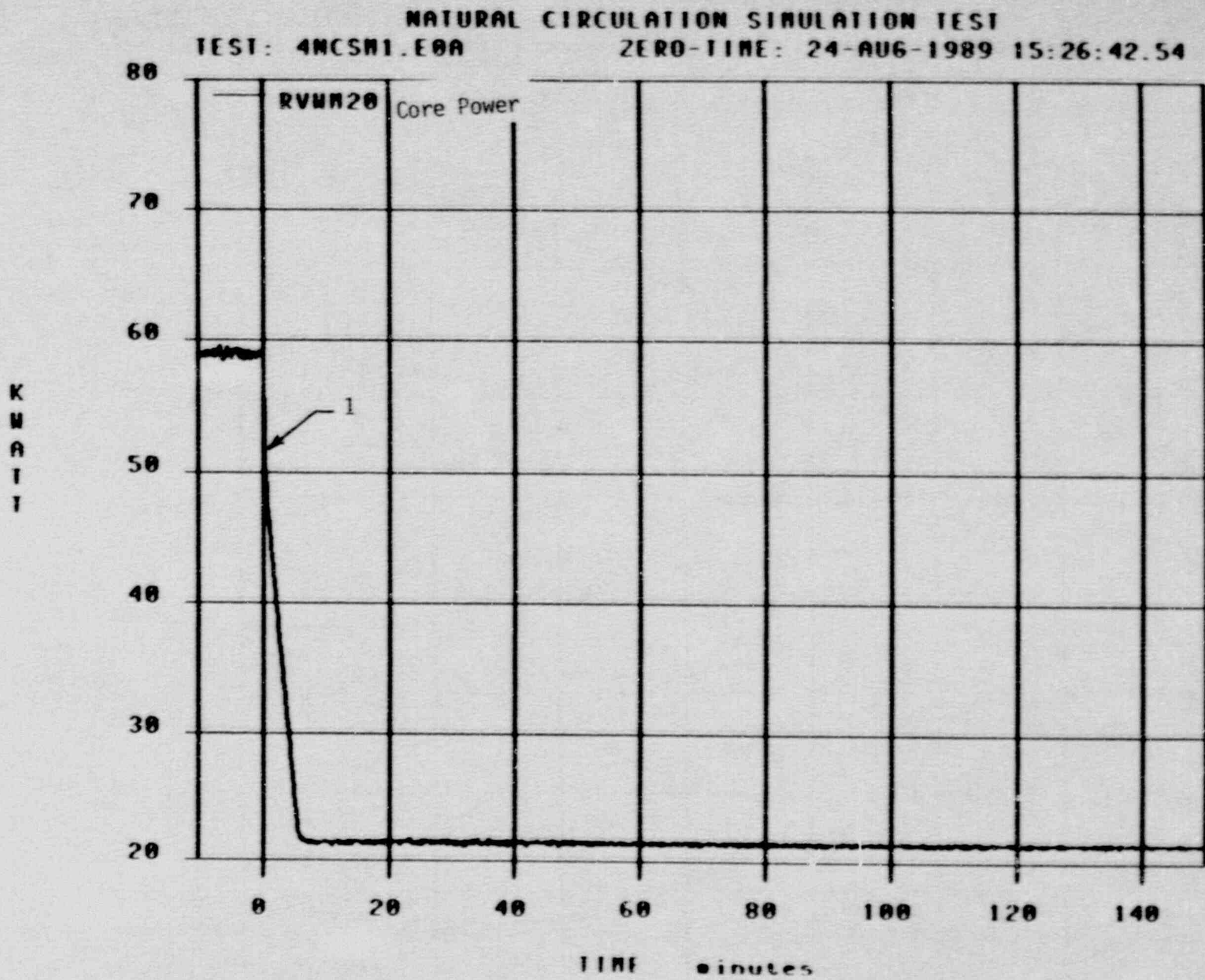

Figure 4.7 Core Power

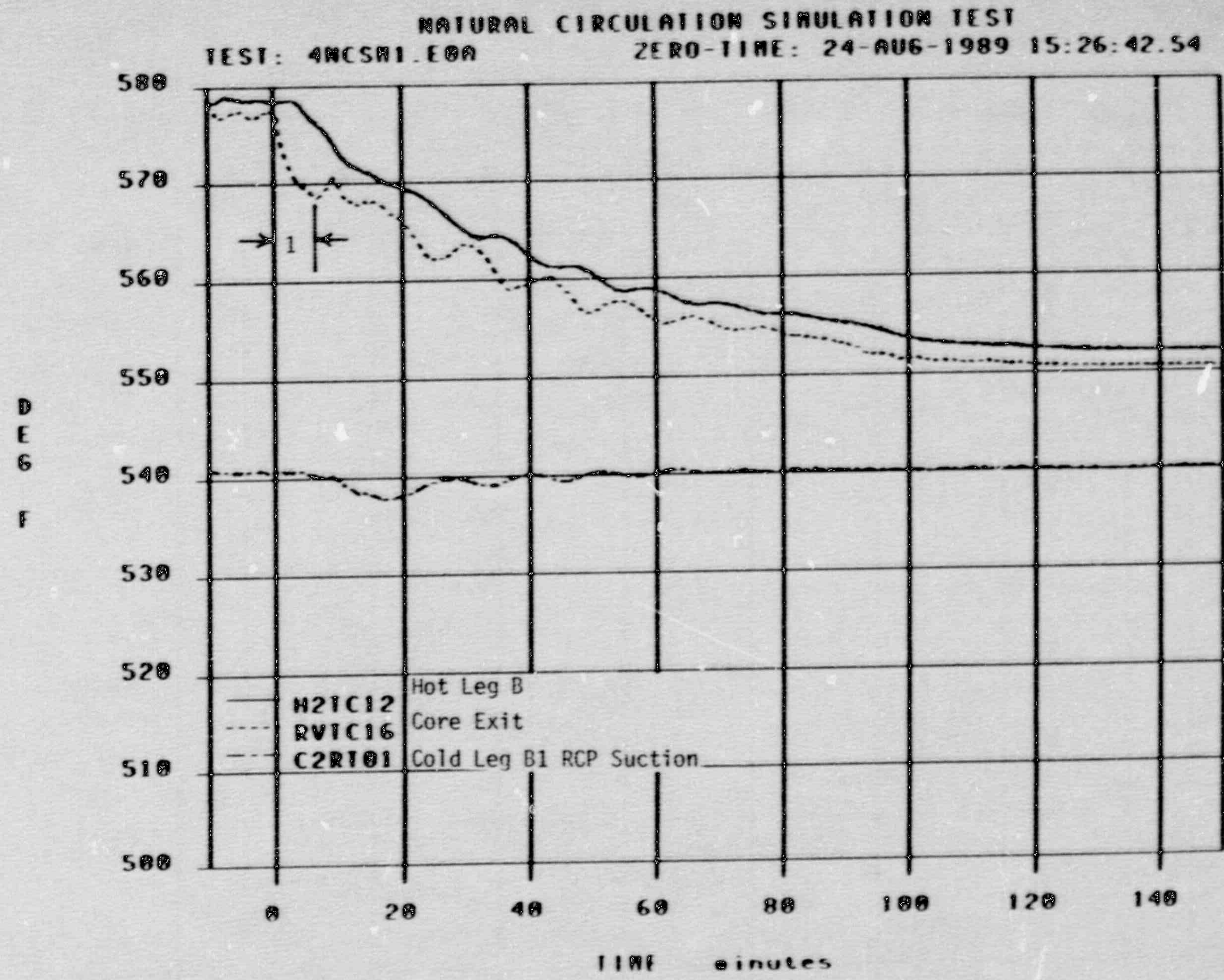

Figure 4.8 Core Exit, Hot Leg B And Cold Leg B1 Reactor Coolant Pump Suction Temperatures

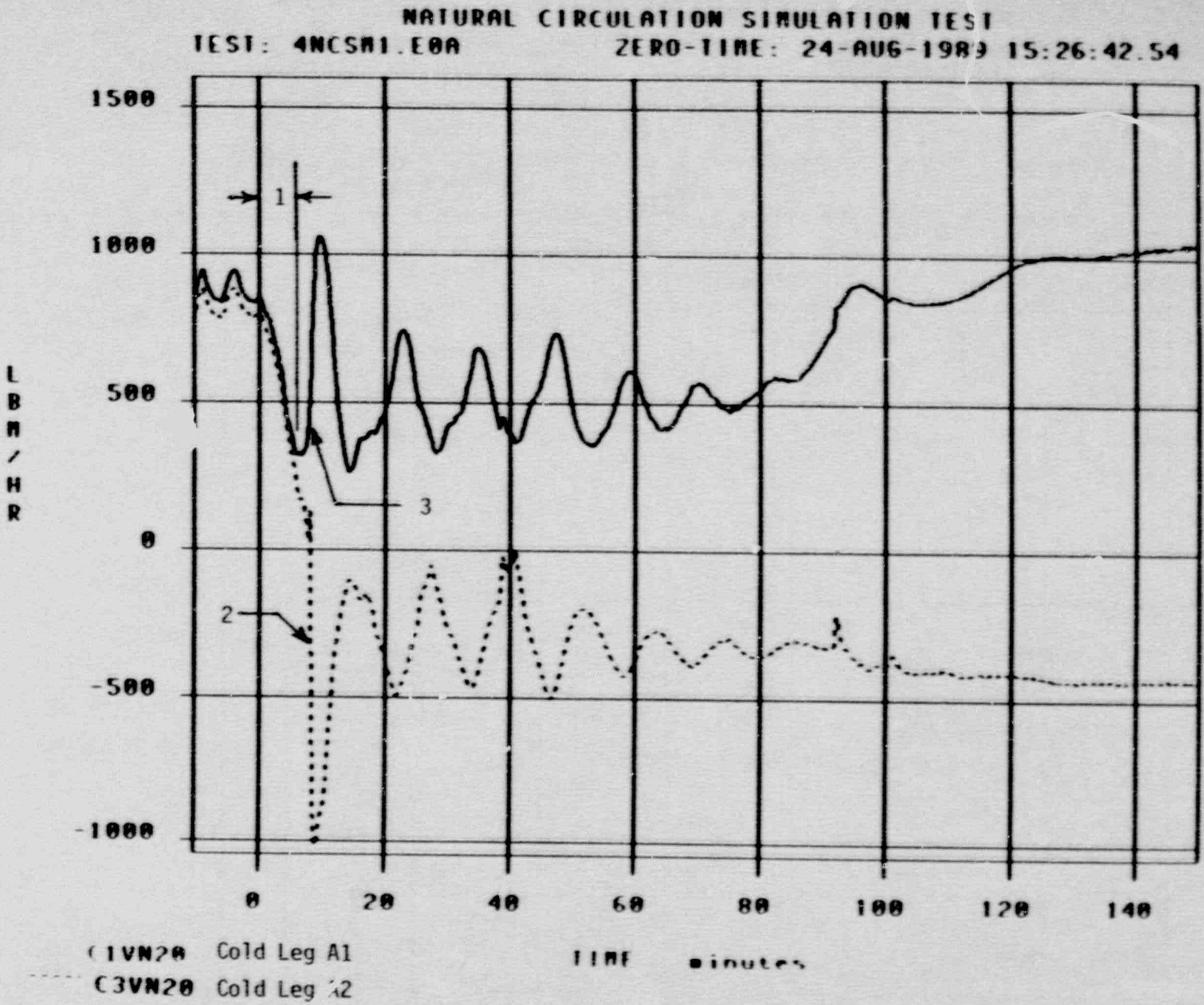

Figure 4.9 Cold Leg A1 And A2 Flow Rate

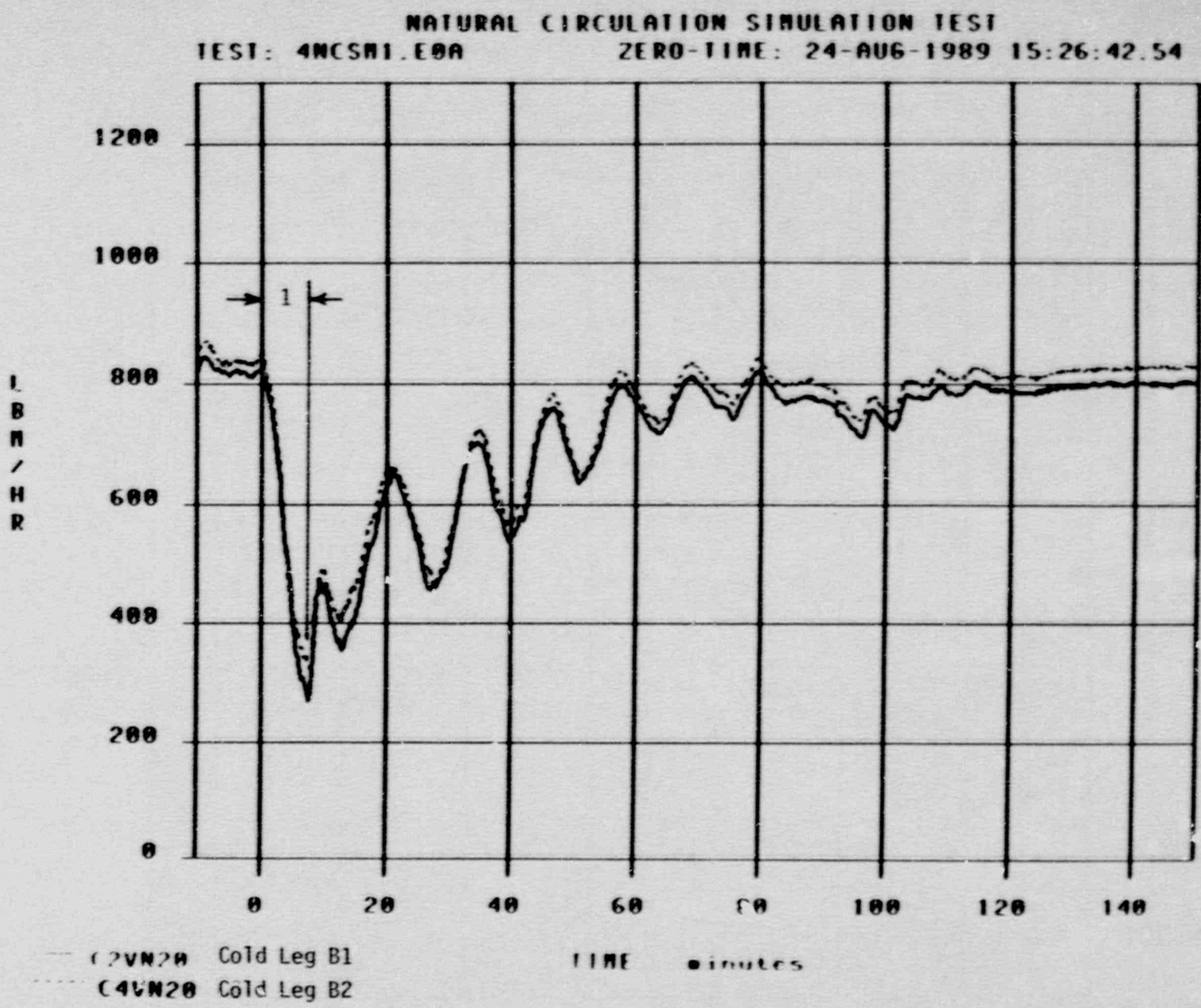

Figure 4.10 Cold Leg B1 And B2 Flow Rate

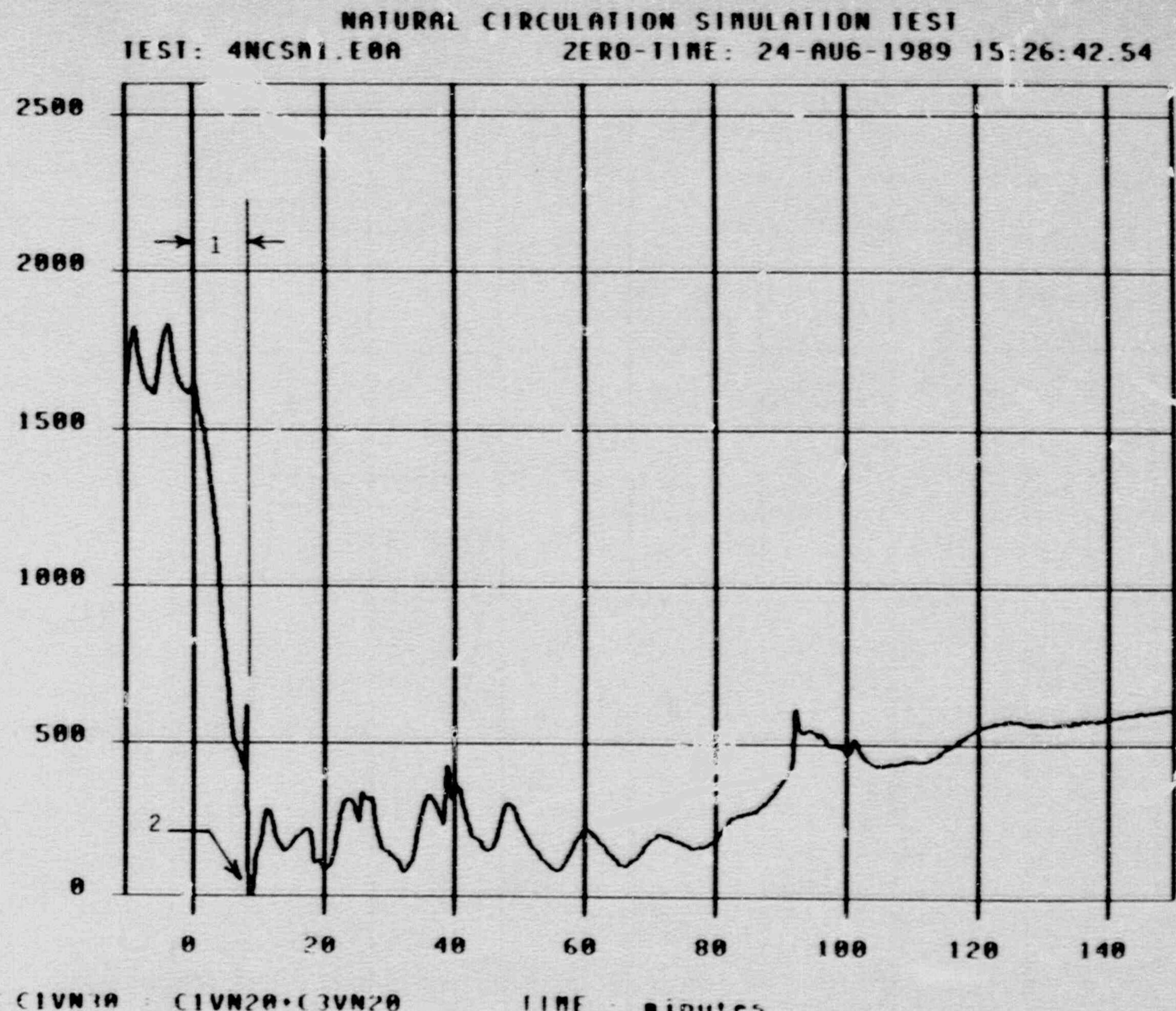

Figure 4.11 Summation Of The A1 And A2 Cold Ley Flow Rates

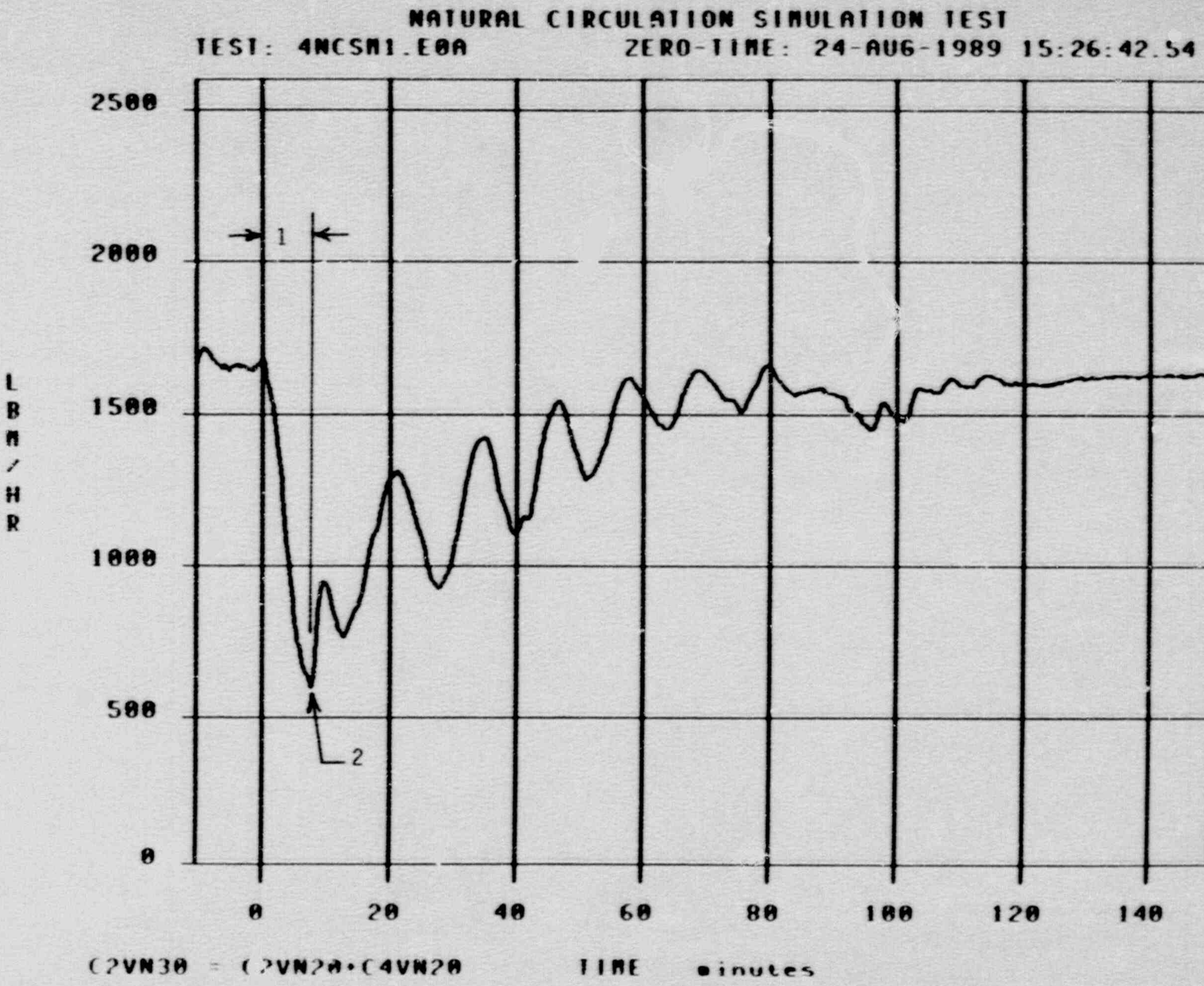

Figure 4.12 Summation Of The B1 And B2 Cold Leg Flow Rates

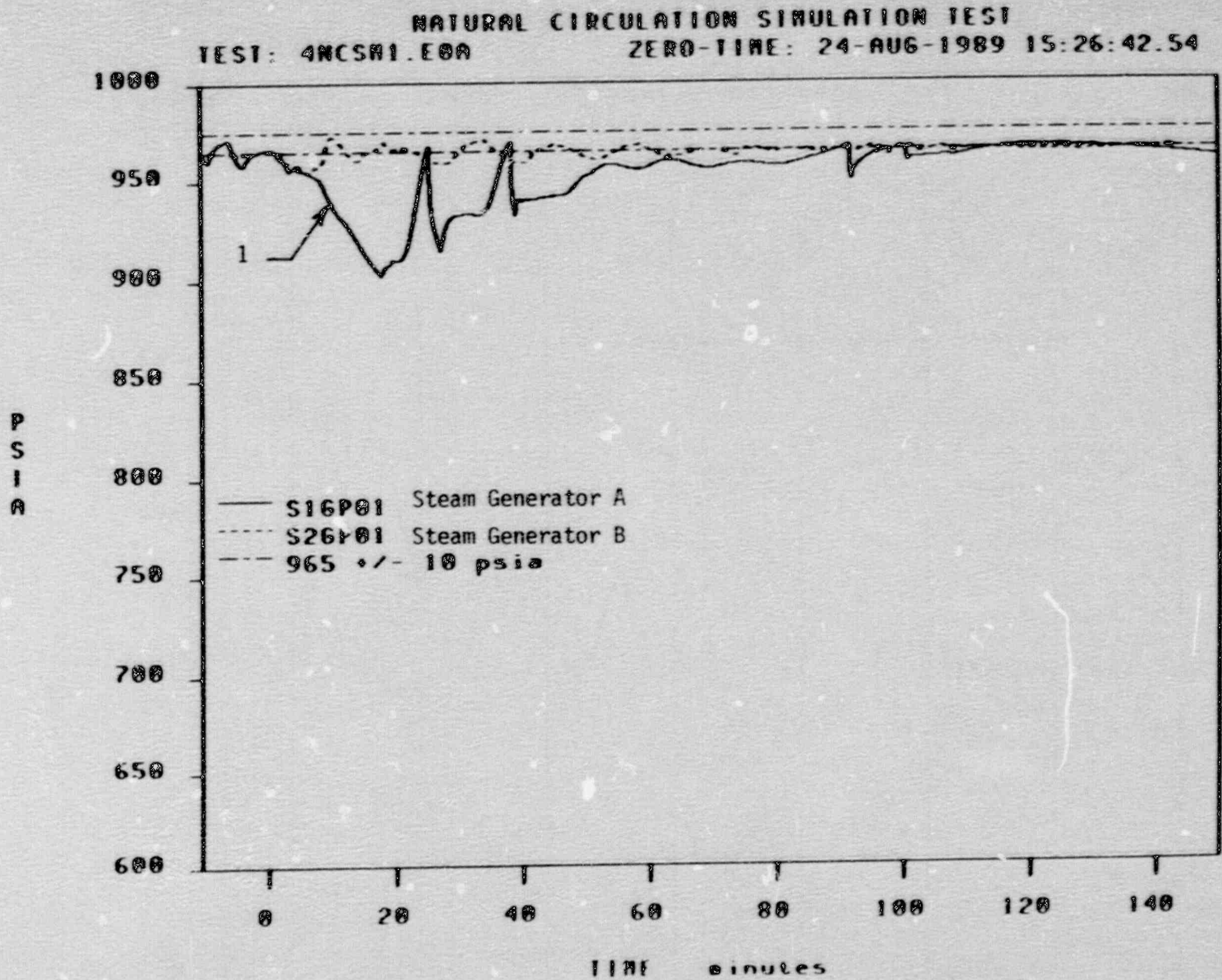

Figure 4.13 Steam Generator Pressure

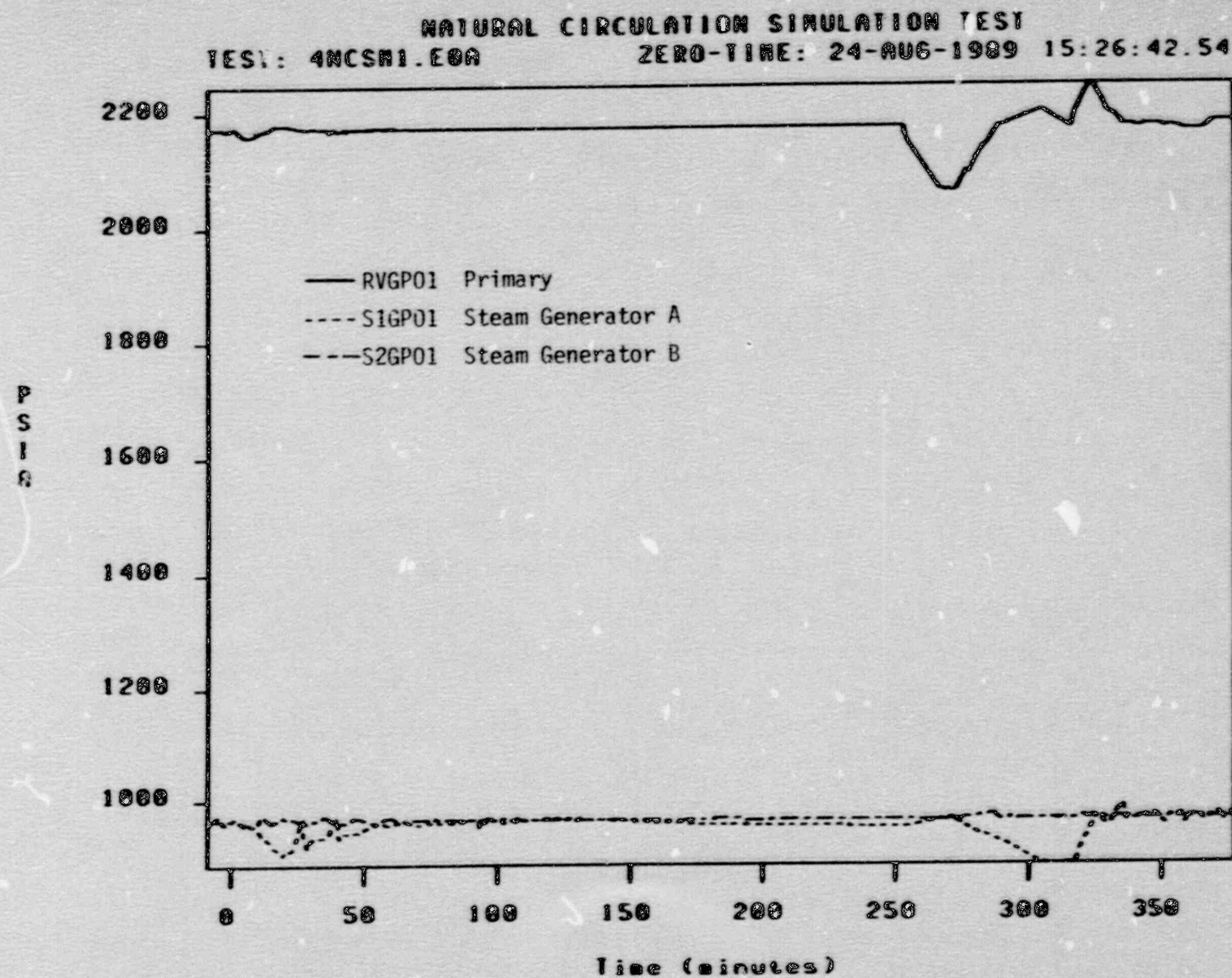

Figure 4.14 Primary And Secondary Pressures

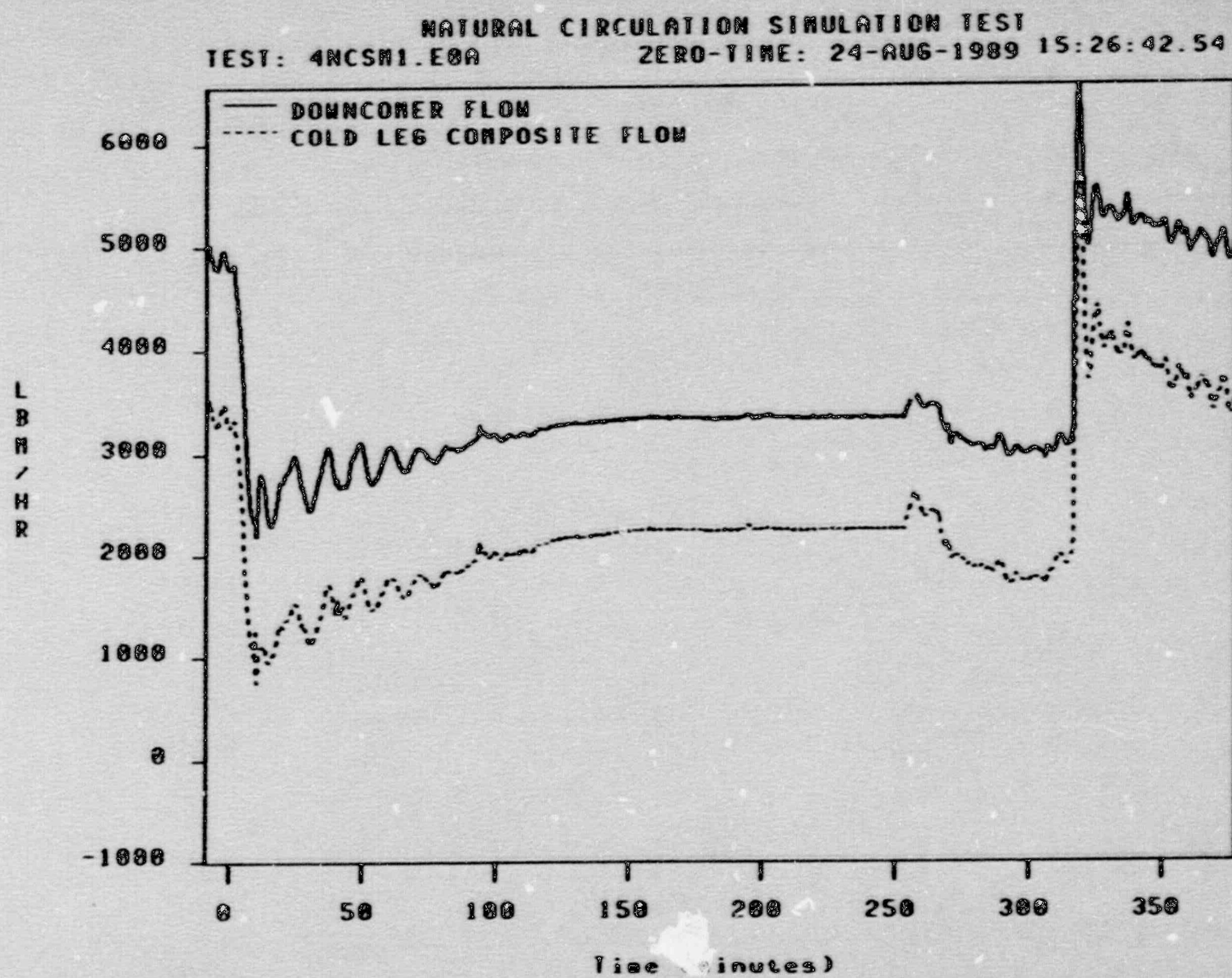

Figure 4.15 Downcomer Flow Rate And The Summation Of The Flow Rate In All Four Cold Legs

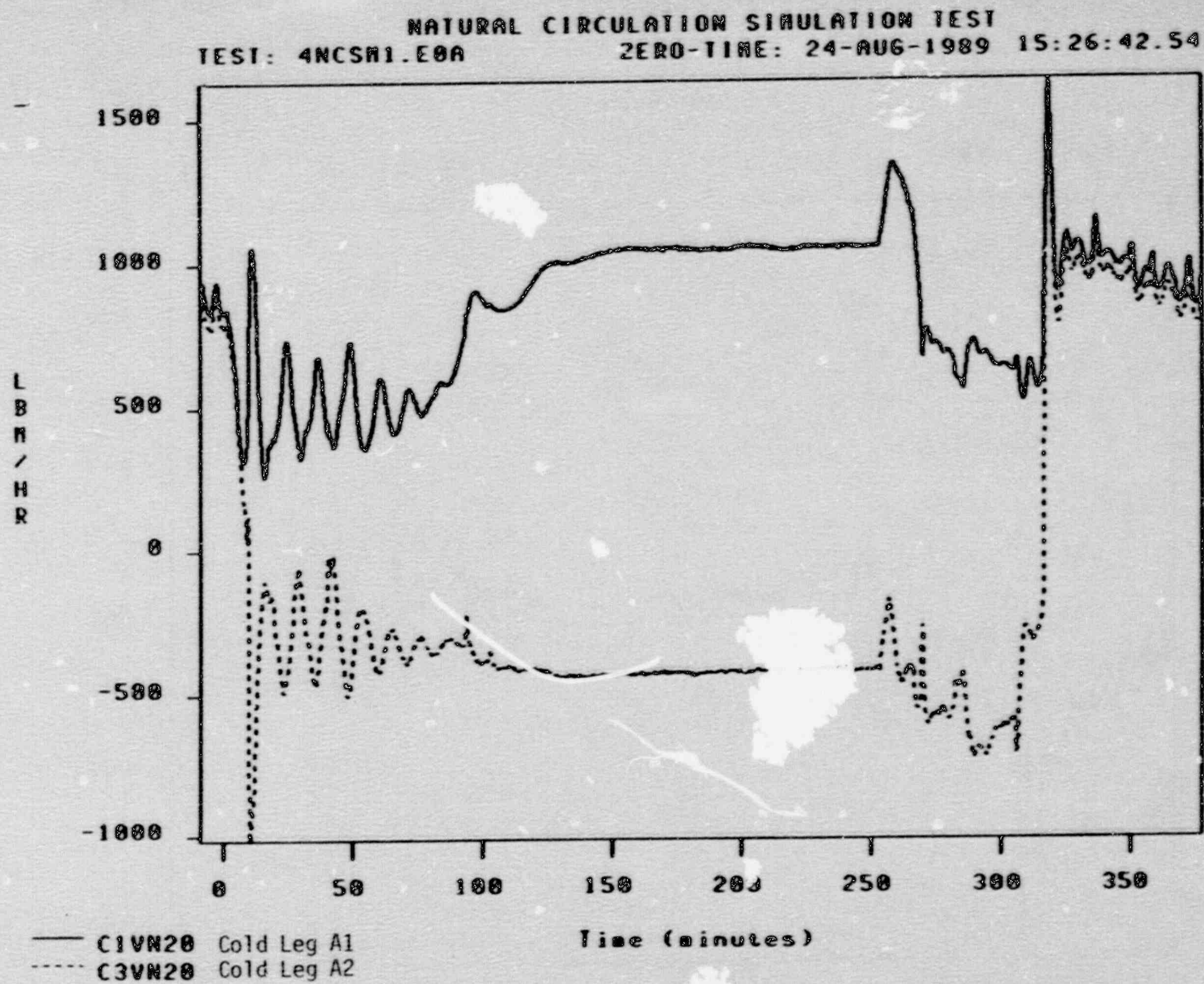

Figure 4.16 Cold Leg A1 And A2 Flow Rate

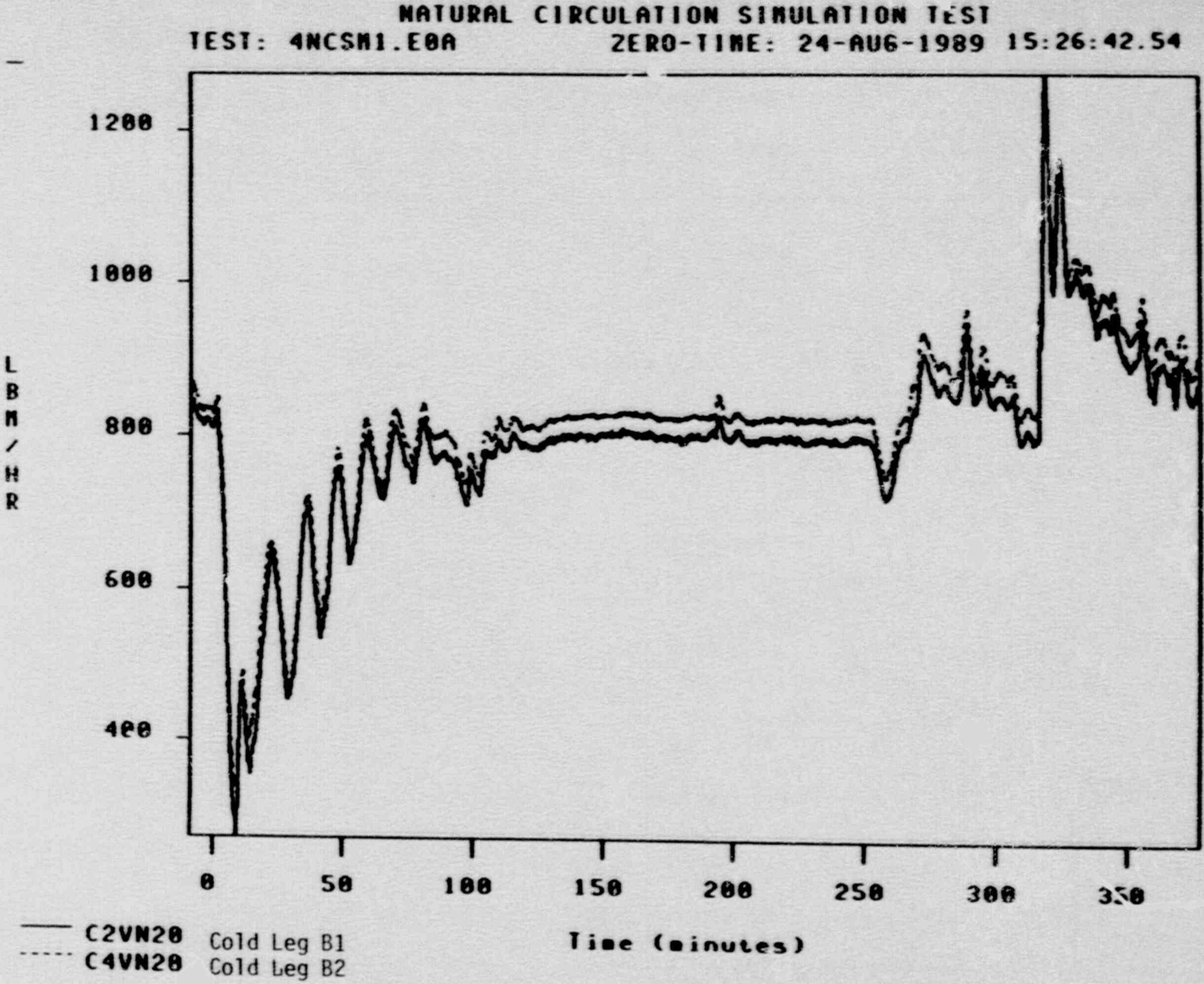

Figure 4.17 Cold Leg B1 And B2 Flow Rate

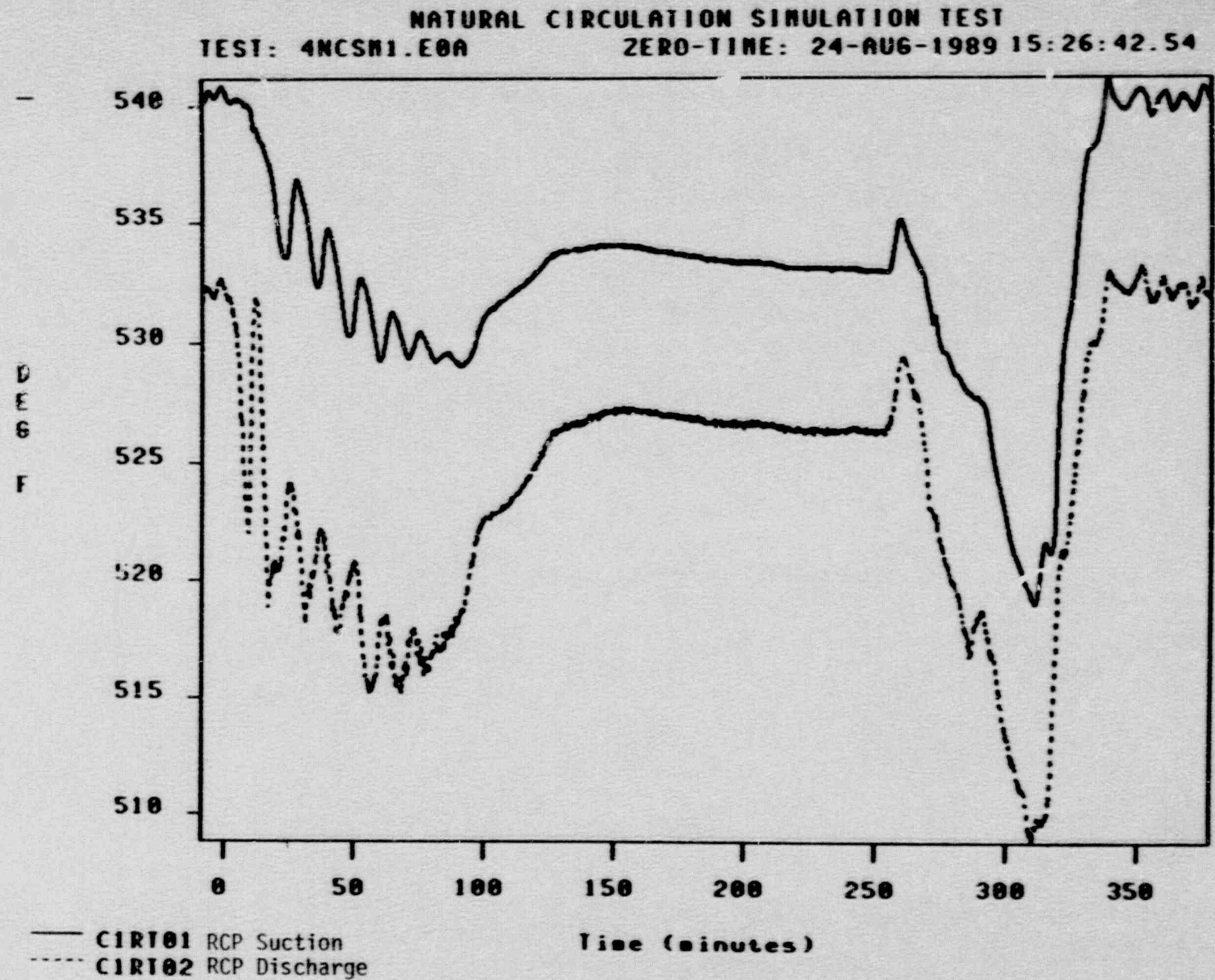

Figure 4.18 Cold Leg A1 Reactor Coolant Pump Suction And Discharge Temperature

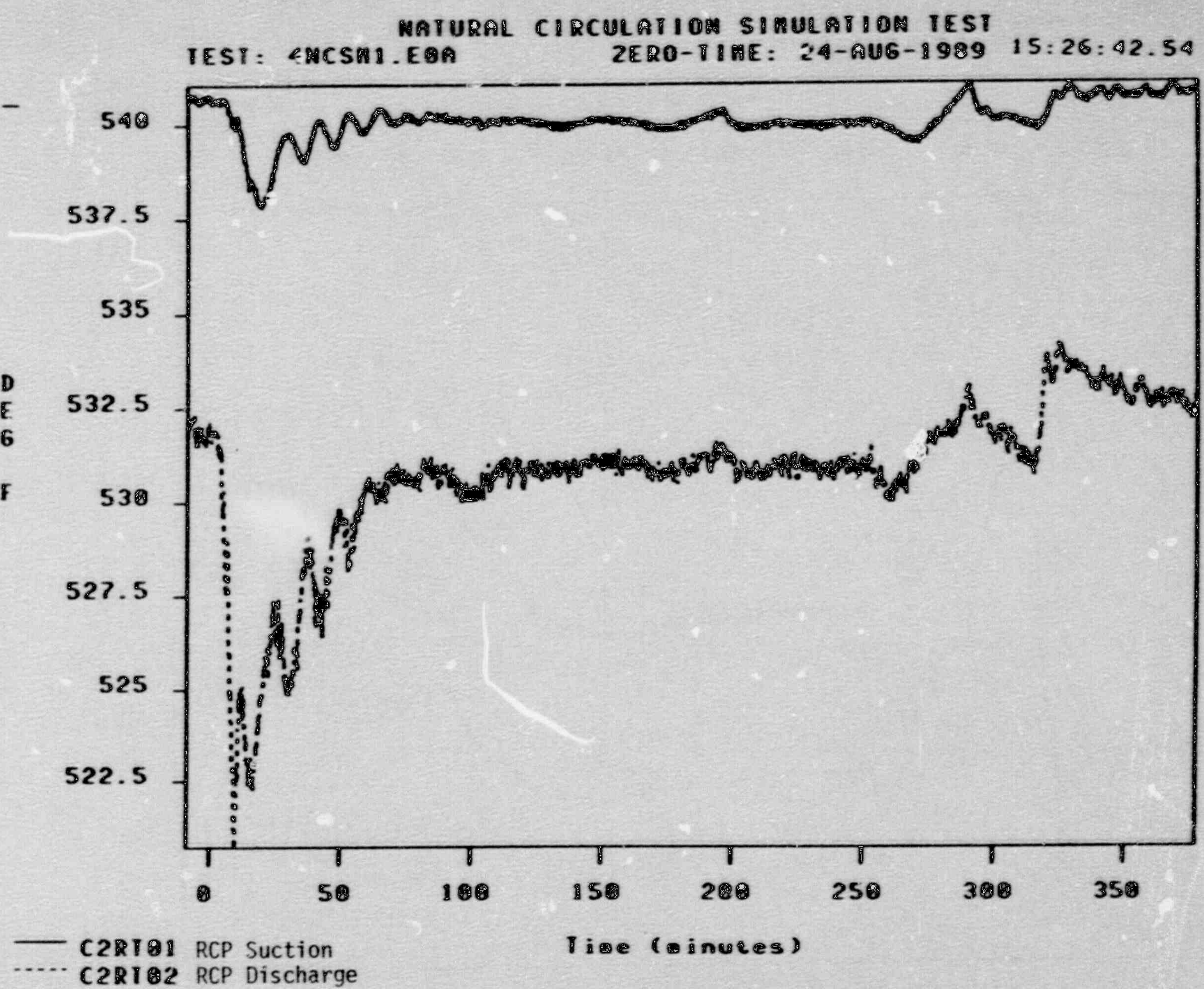

Figure 4.19 Cold Leg B1 Reactor Coolant Pump Suction And Discharge Temperature

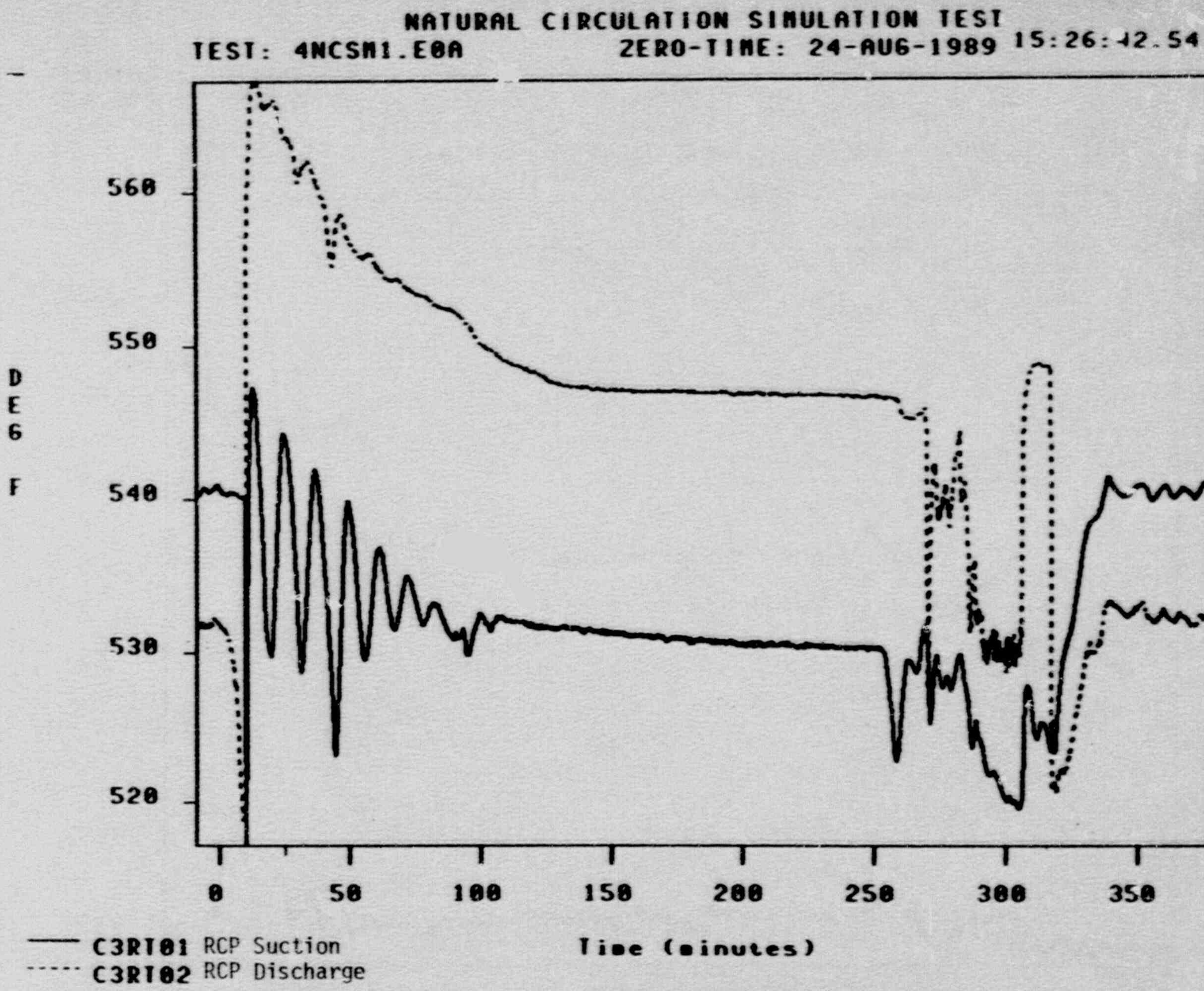

Figure 4.20 Cold Leg A2 Reactor Coolant Pump Suction And Discharge Temperature

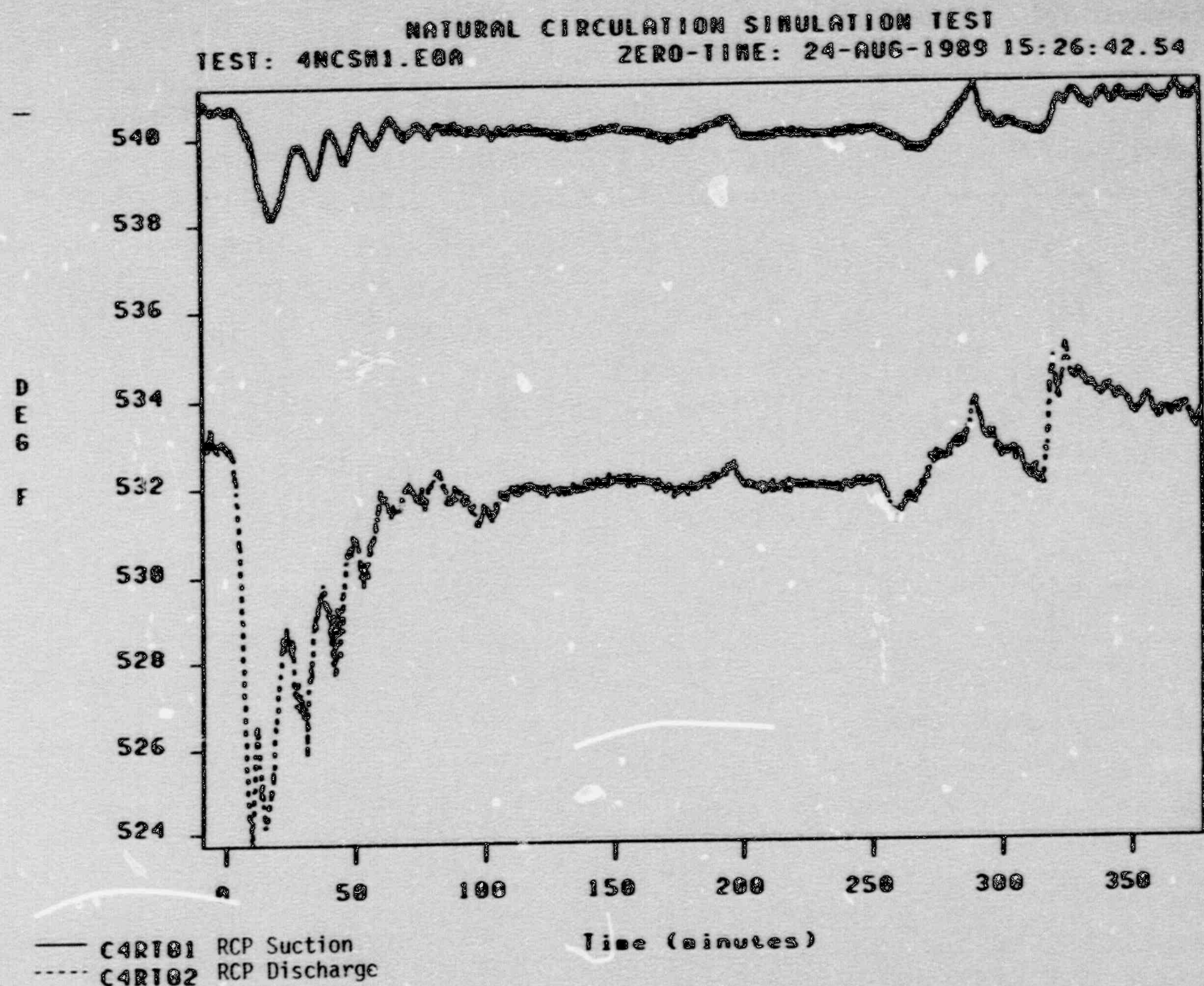

Figure 4.21 Cold Leg B2 Reactor Coolant Pump Suction And Discharge Temperature

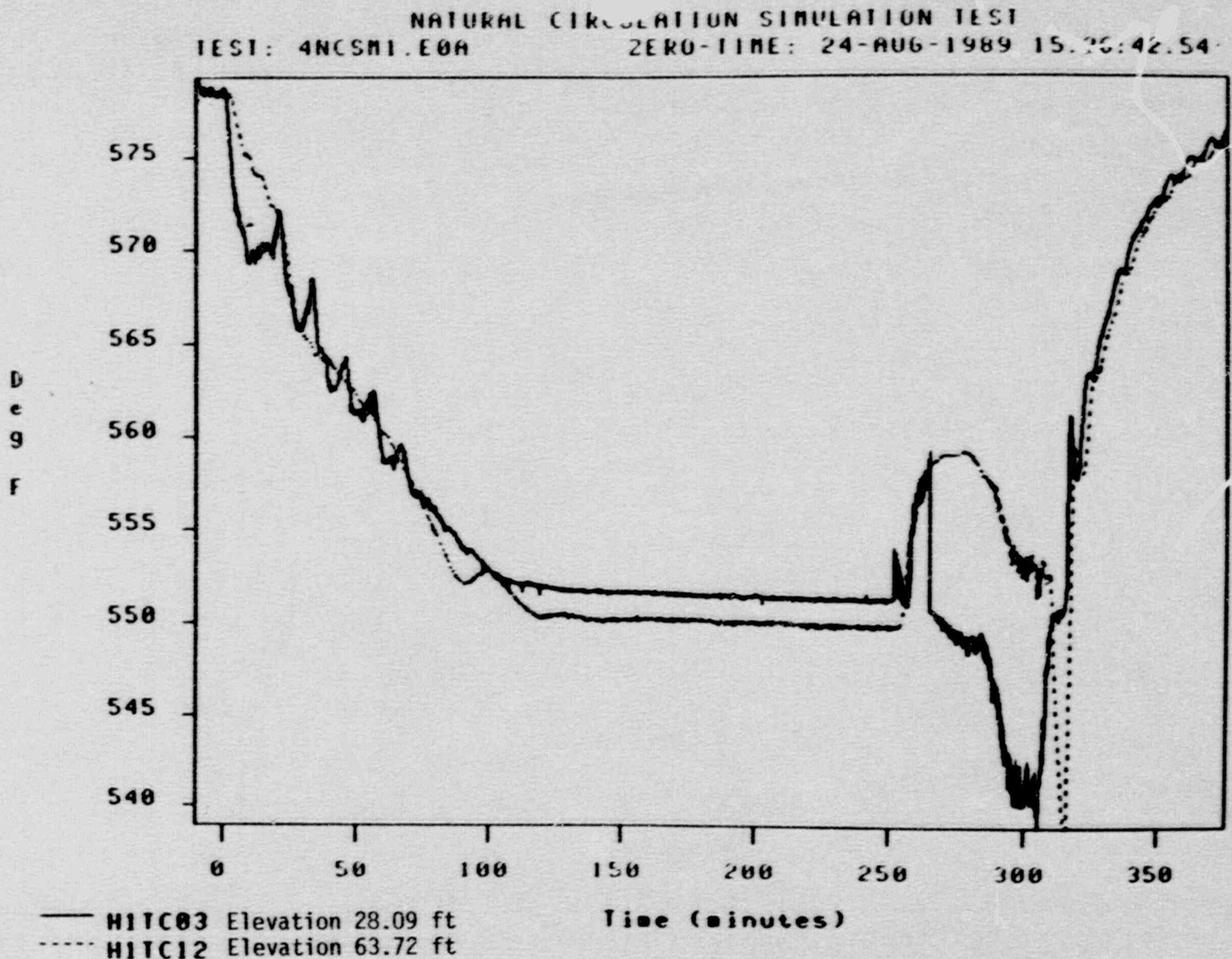

Figure 4.22 Hot Leg A Fluid Temperatures

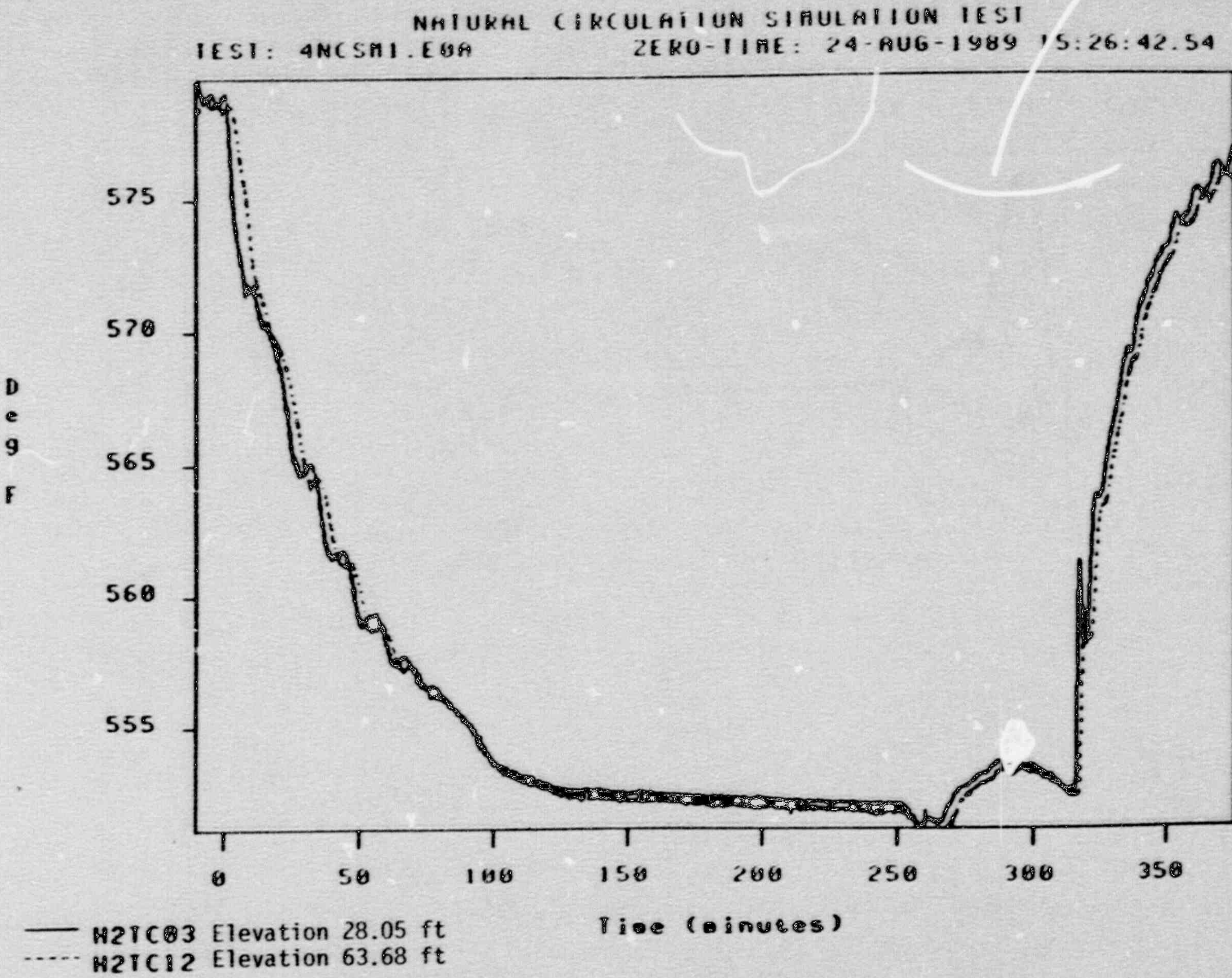

Figure 4.23 Hot Leg B Fluid Temperatures

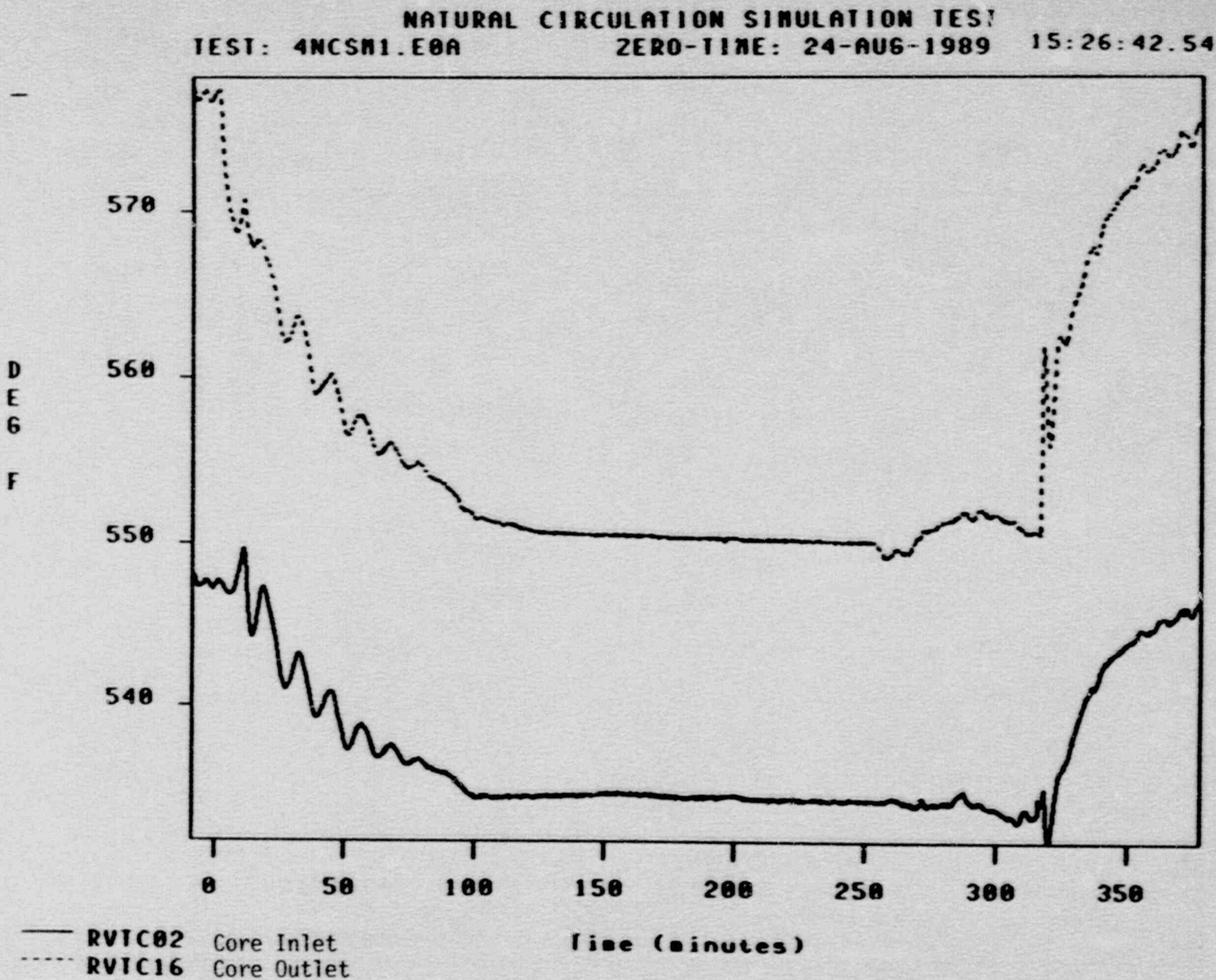

Figure 4.24 Core Inlet And Core Outlet Fluid Temperature

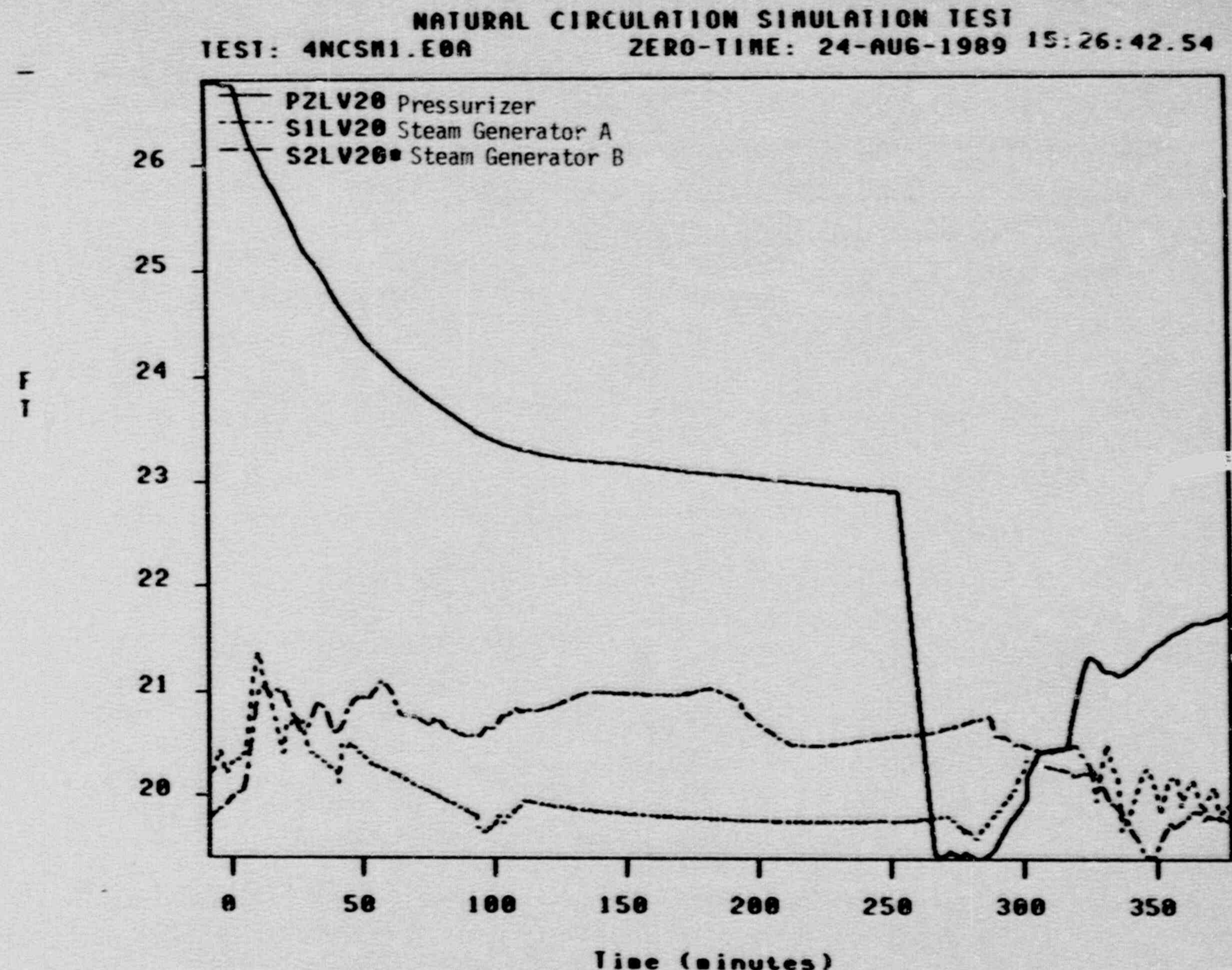

Figure 4.25 Pressurizer Level And Steam Generator Levels

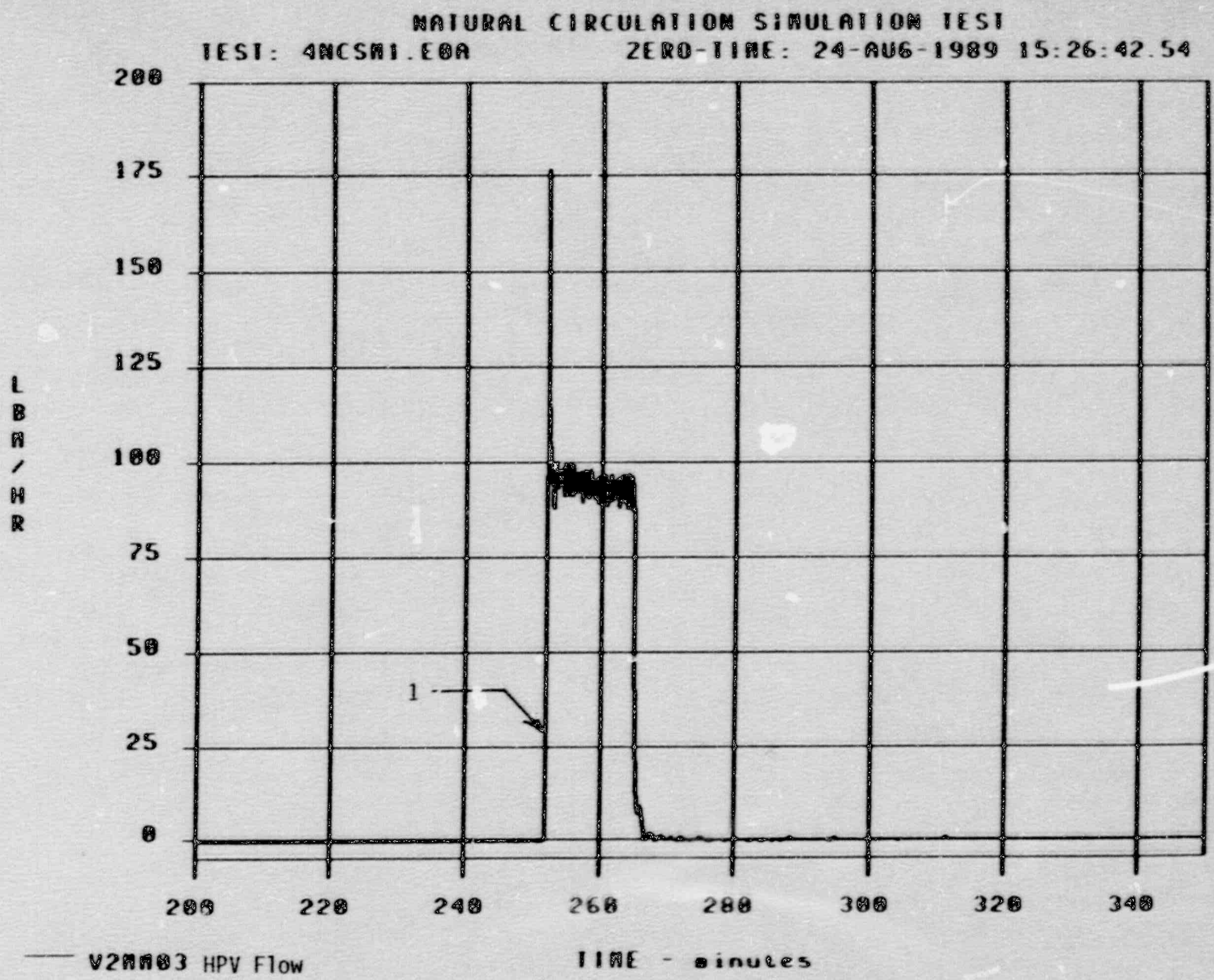

Figure 4.26 High Point Vent Flow Rate, Loop A

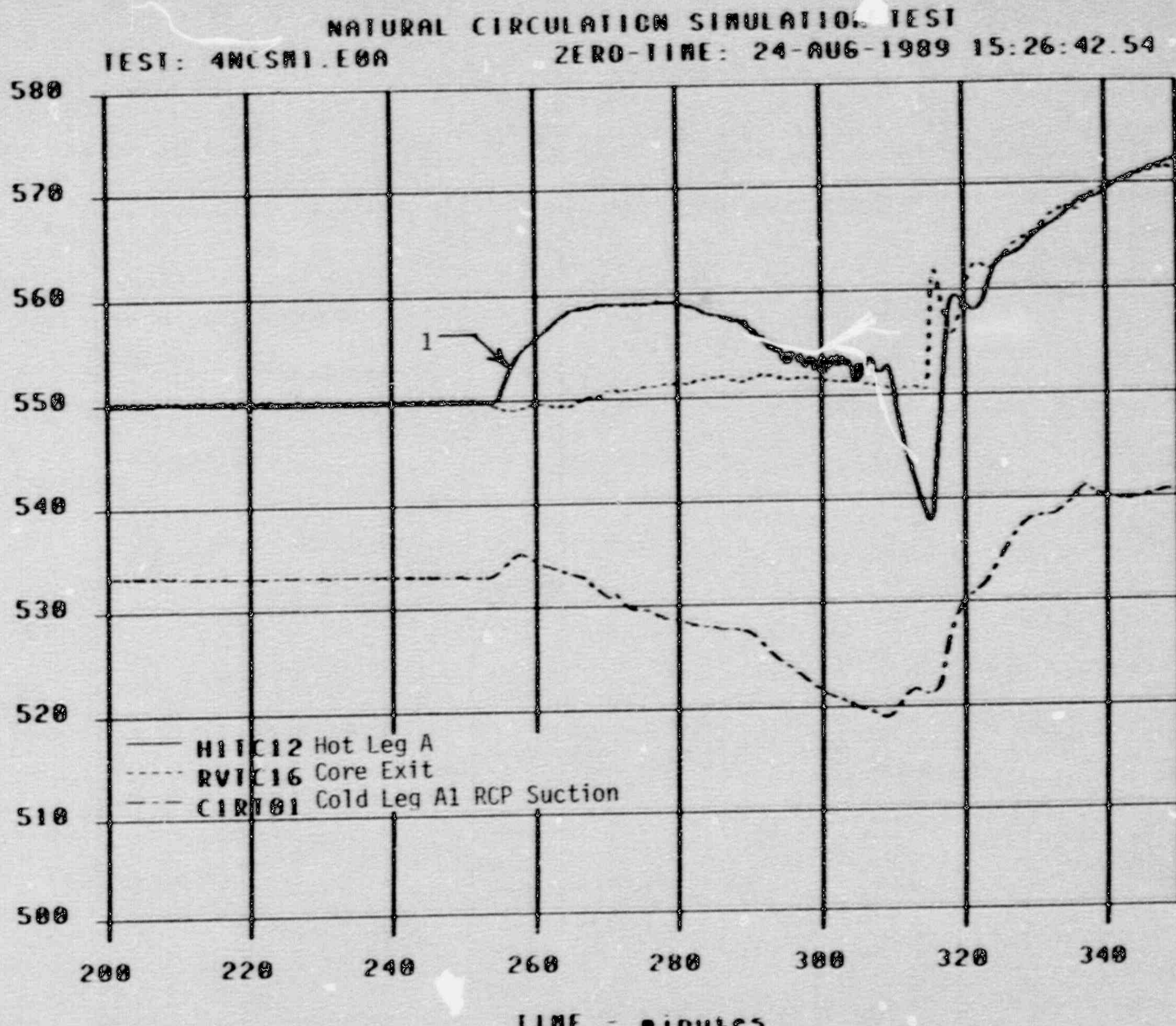

Figure 4.27 Cold Leg A1 Reactor Coolant Pump Suction, Core Outlet And Hot Leg A Fluid Temperatures

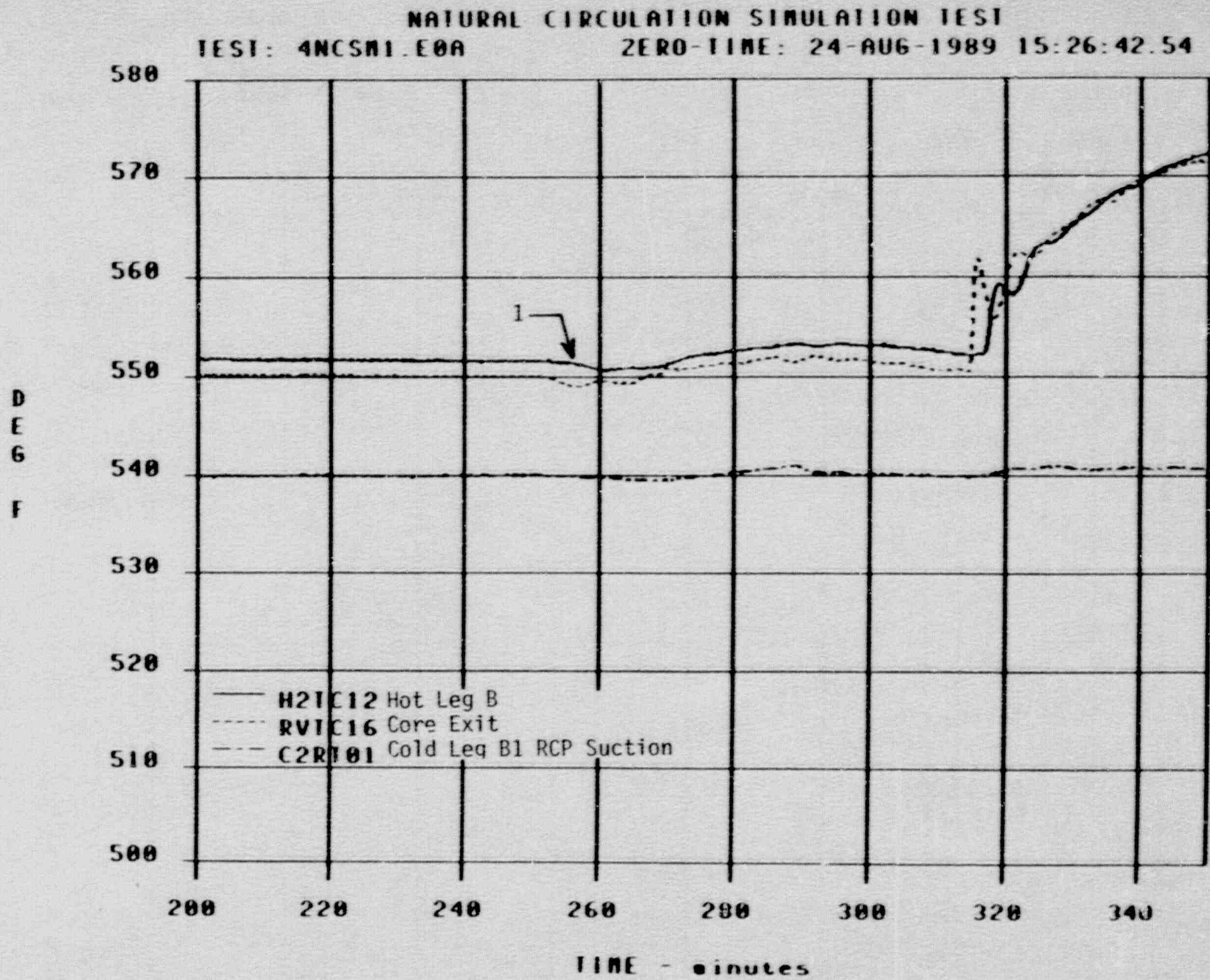

Figure 4.28 Cold Leg B1 Reactor Coolant Pump Suction, Core Exit And Hot Leg B Fluid Temperatures

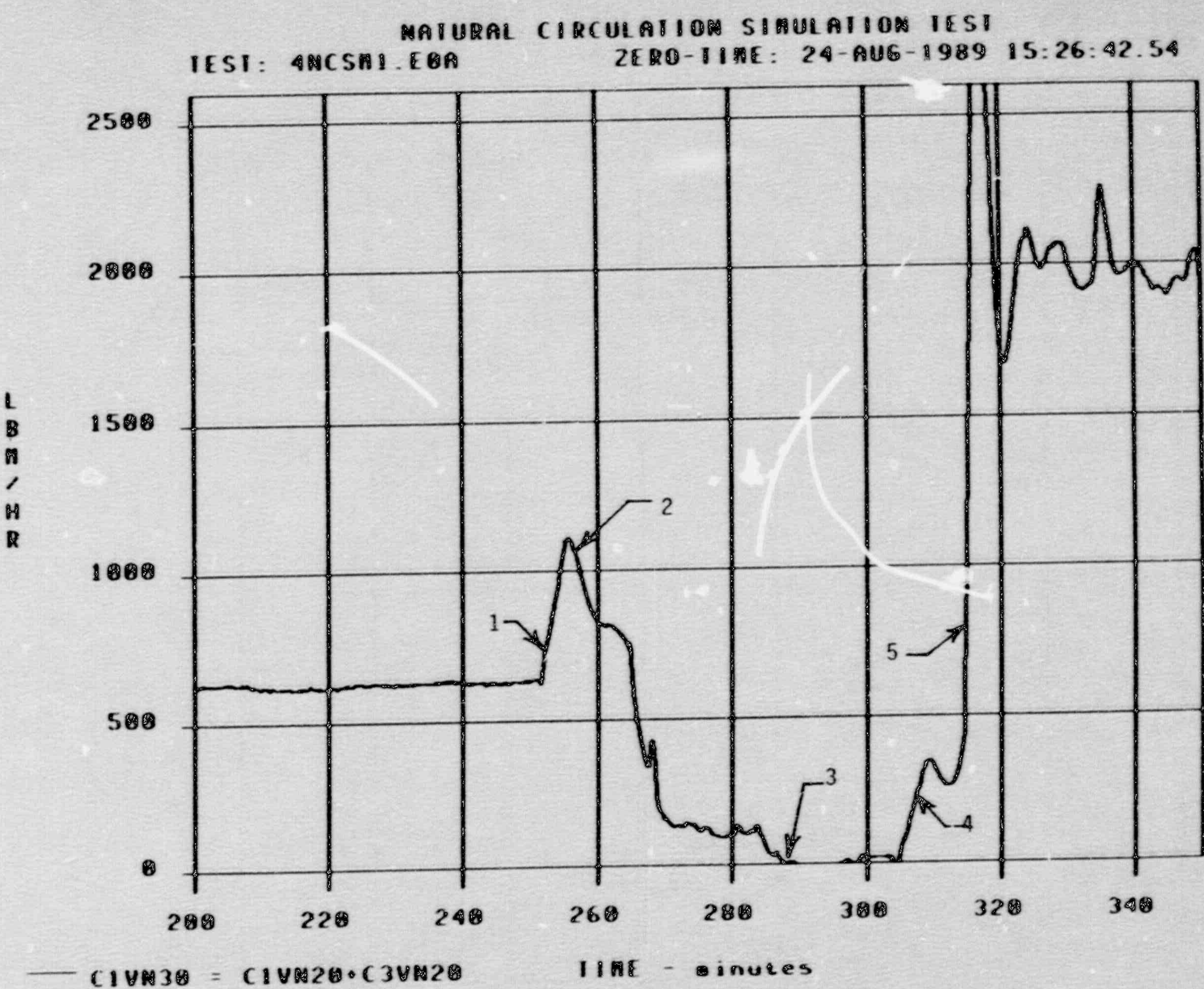

Figure 4.29 Summation Of The A1 And A2 Cold Leg Flow Rates

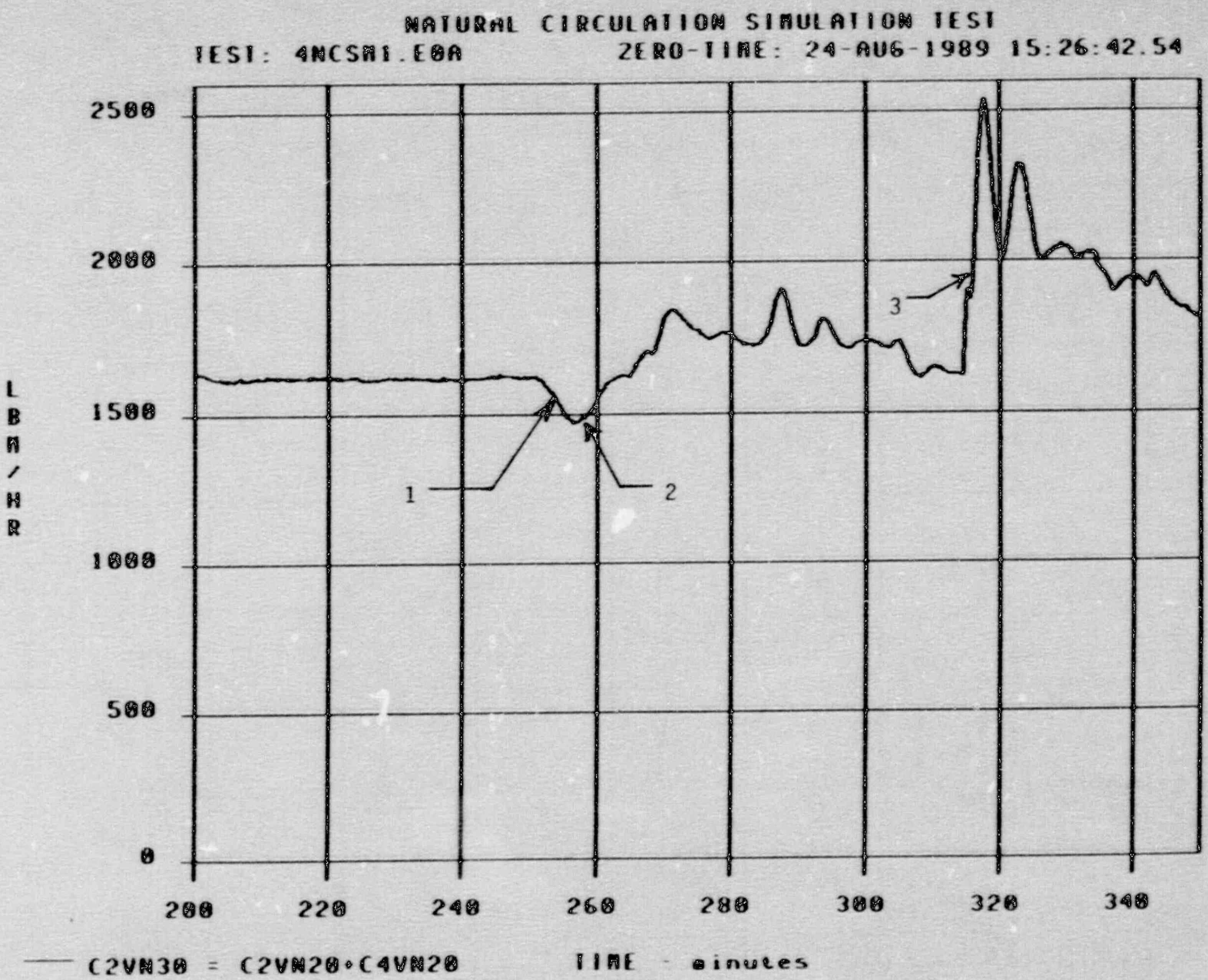

Figure 4.30 Summation Of The B1 And B2 Cold Leg Flow Rates

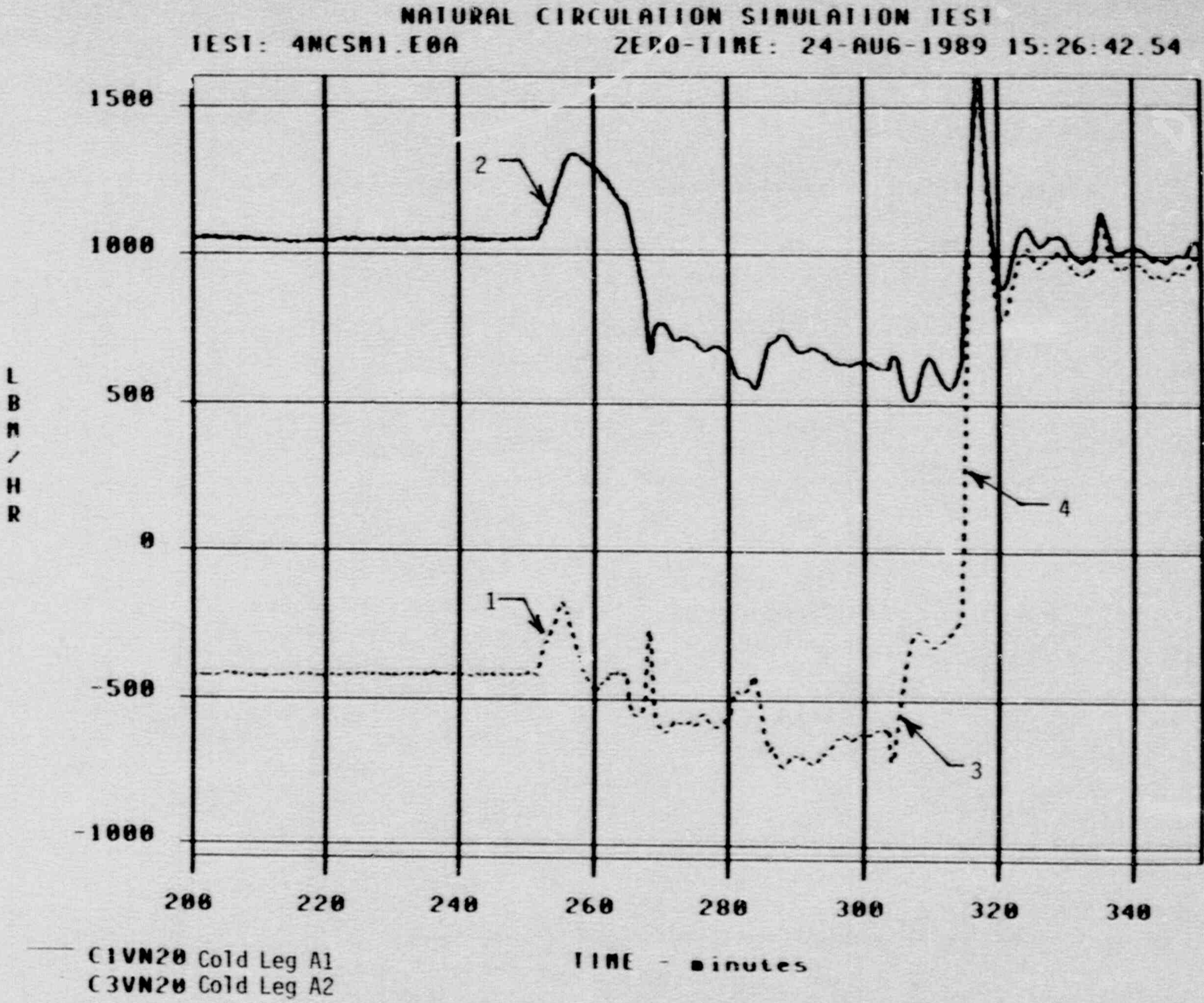

Figure 4.31 Cold Leg A1 And A2 Flow Rate

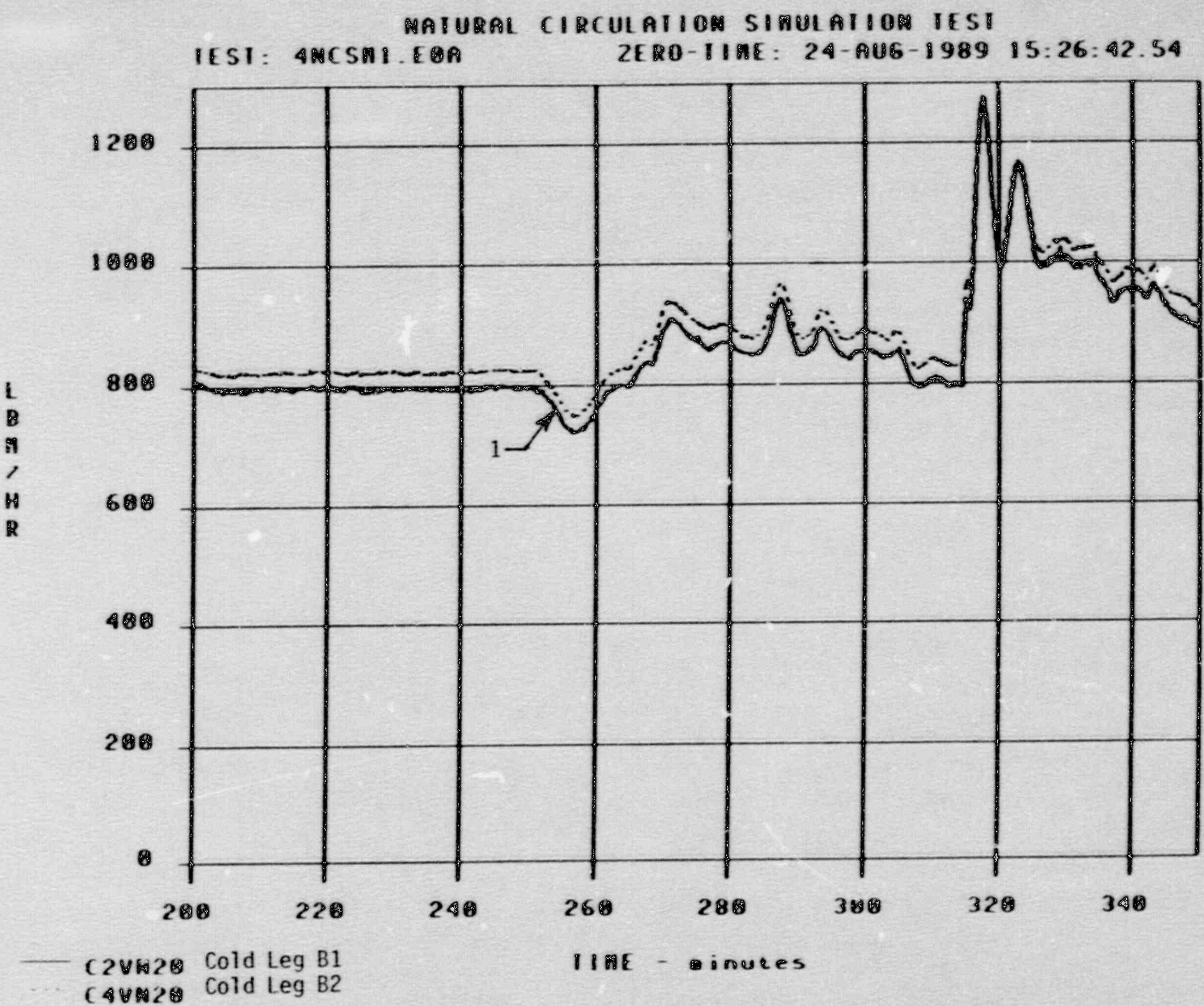

Figure 4.32 Cold Leg B1 And B2 Flow Rate

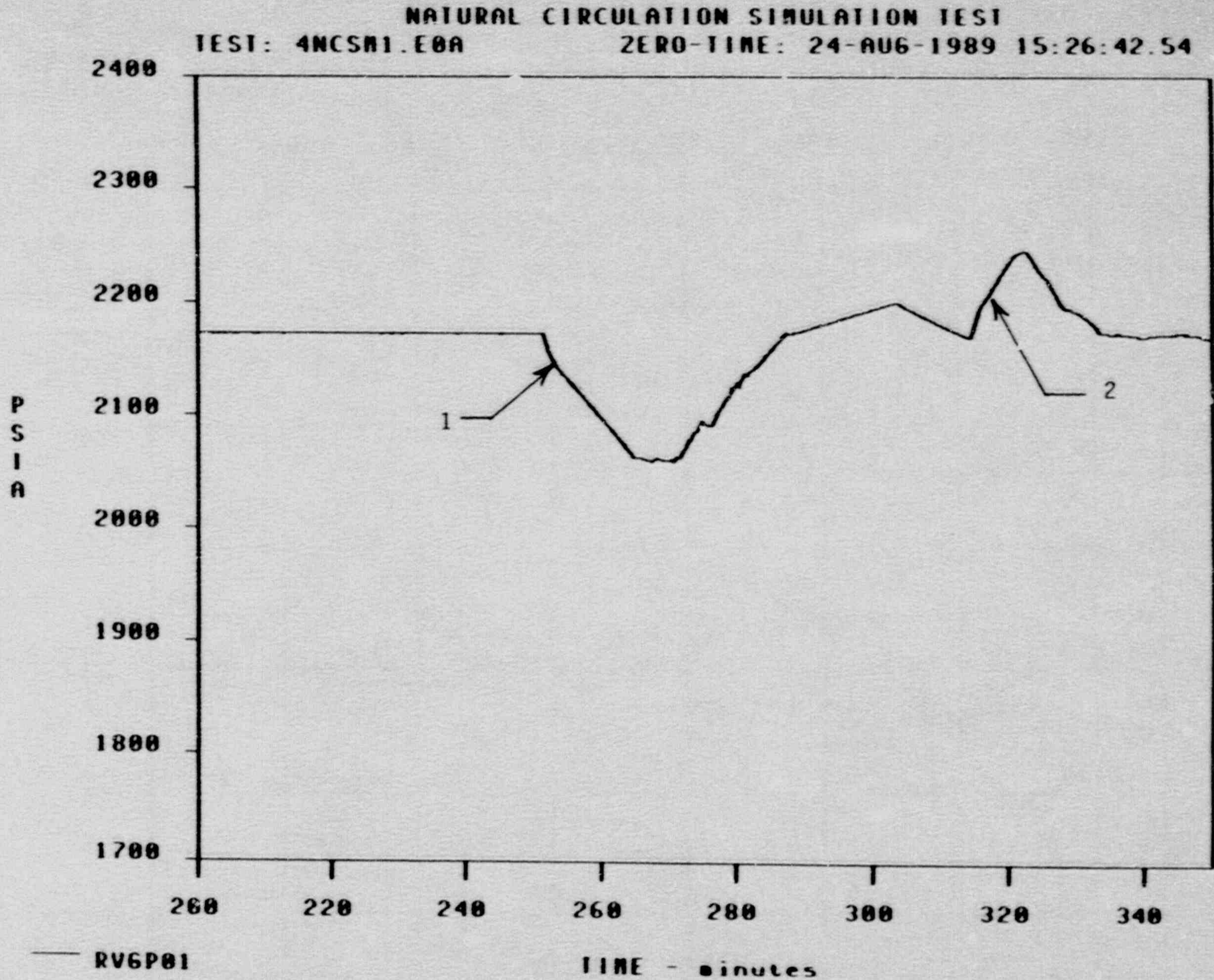

Figure 4.33 Primary System Pressure

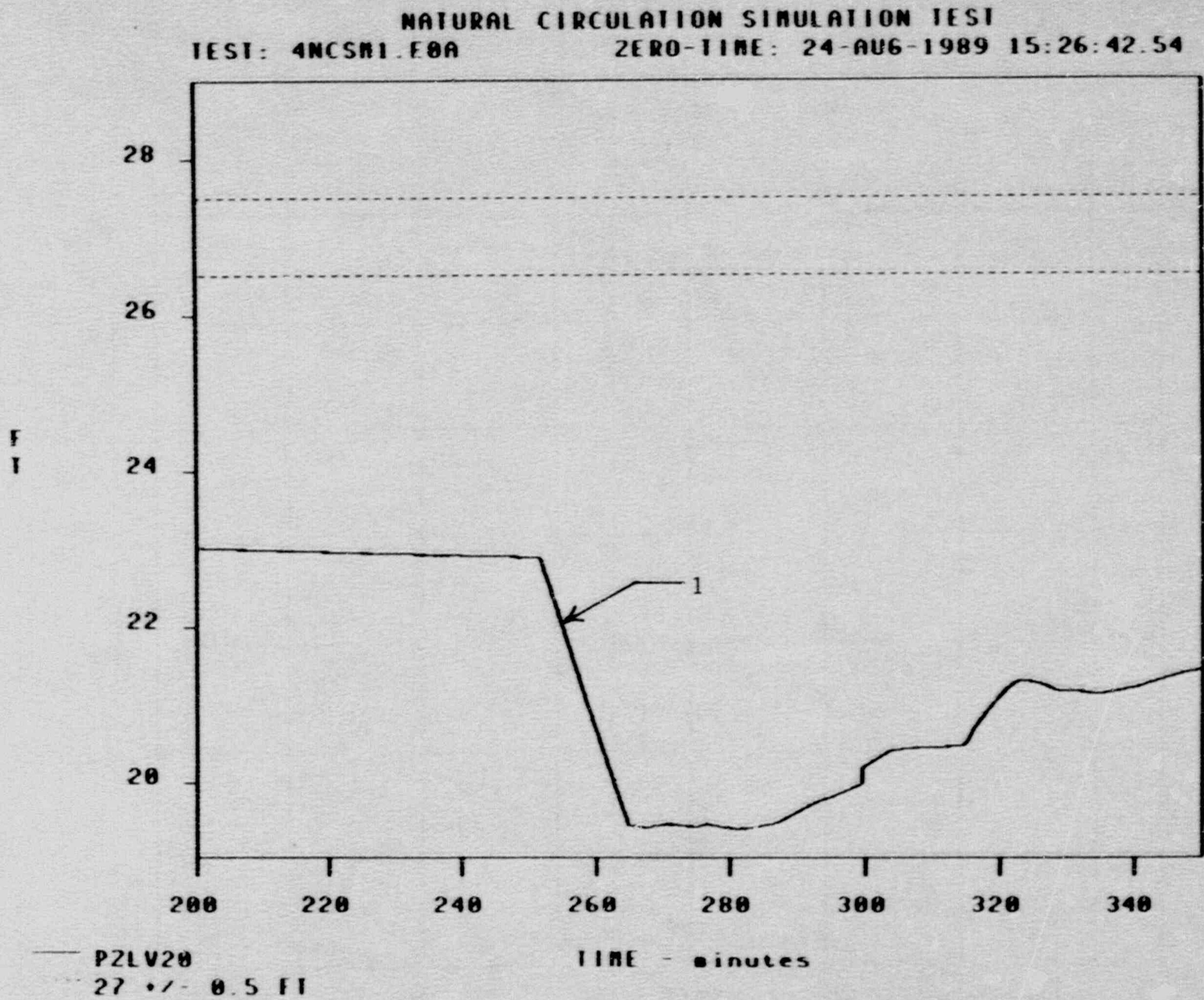

Figure 4.34 Pressurizer Level

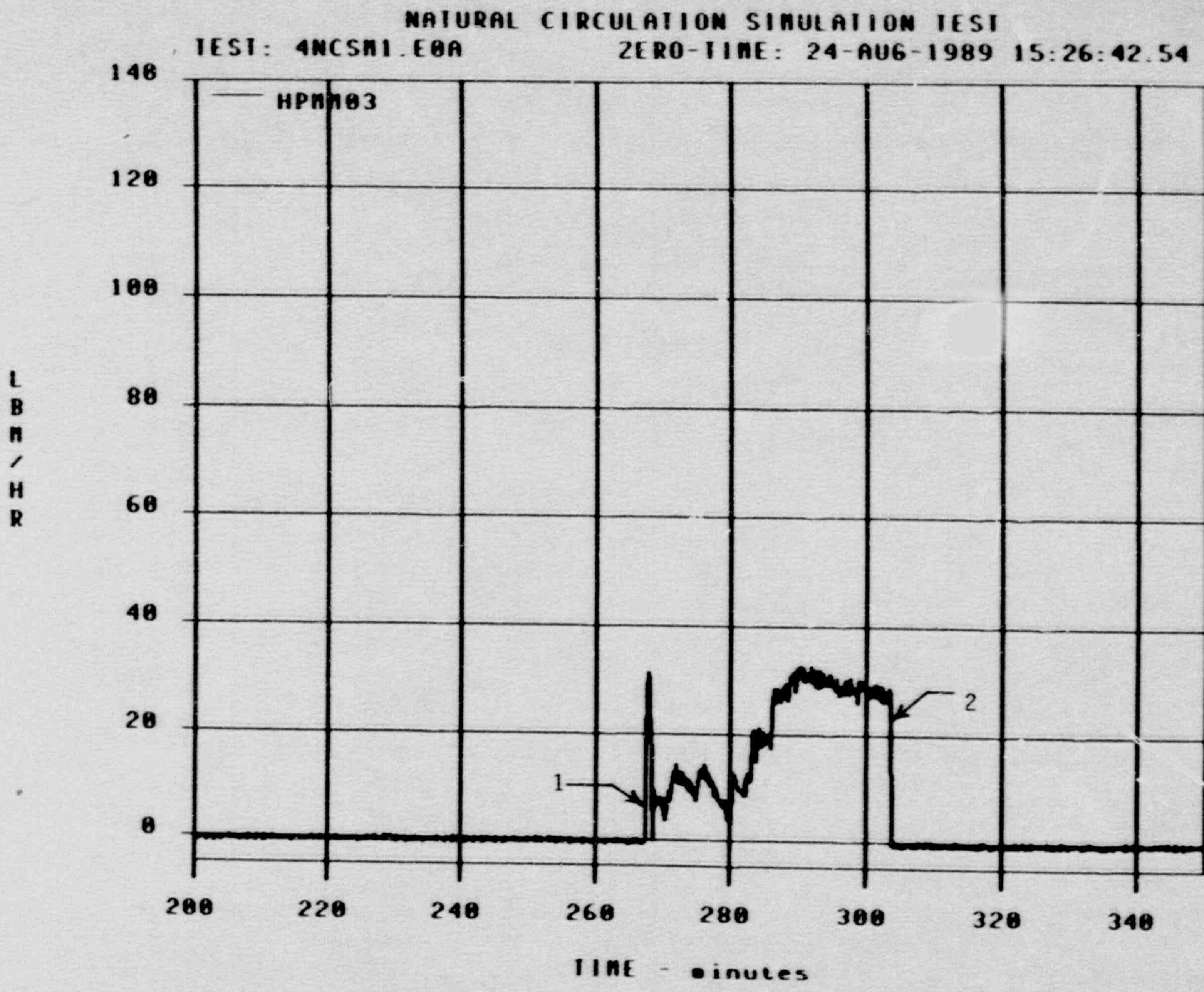

Figure 4.35 Makeup Flow Rate

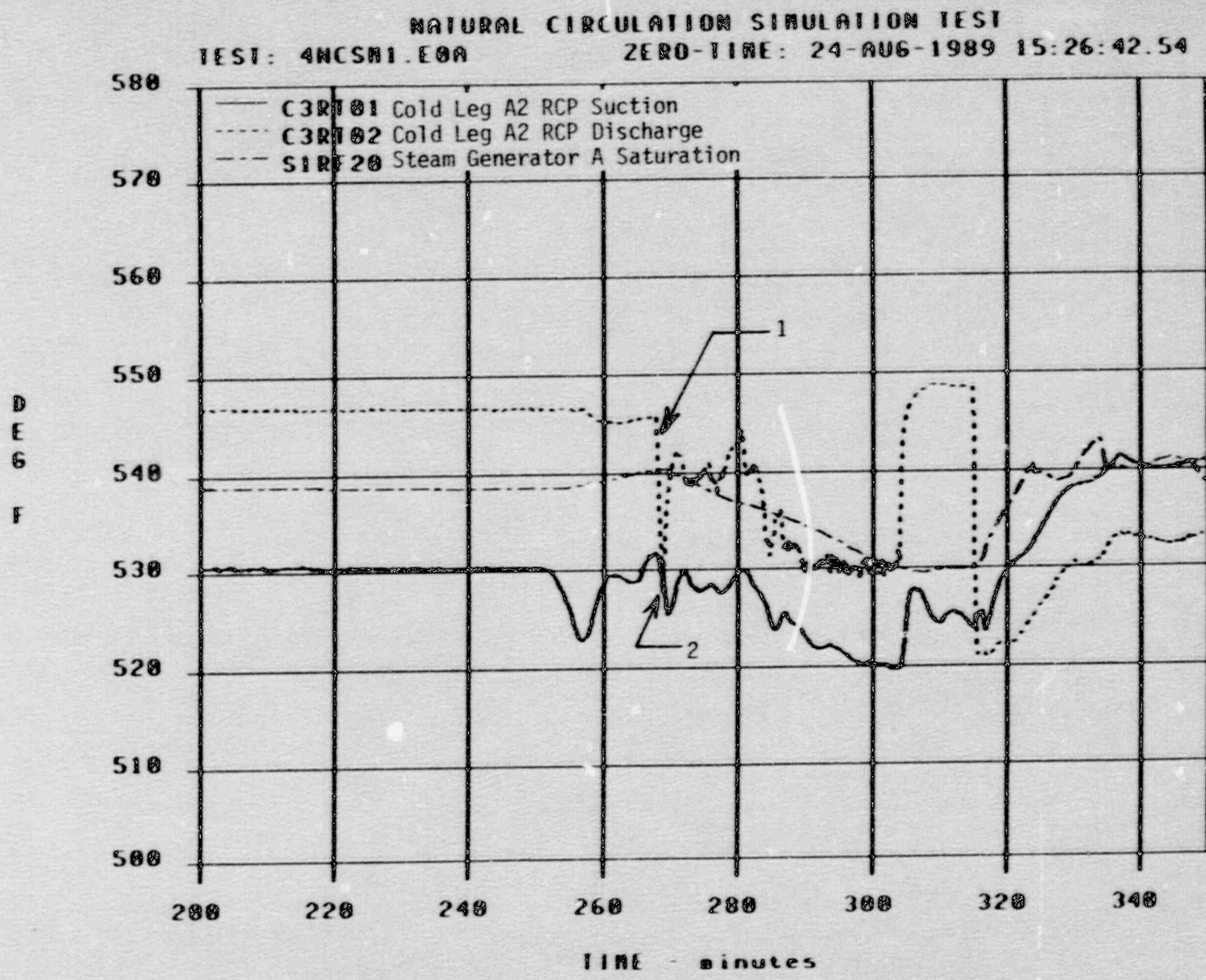

Figure 4.36 Steam Generator B Saturation Temperature And Cold Leg A2 Reactor Coolant Pump Suction And Discharge Temperature

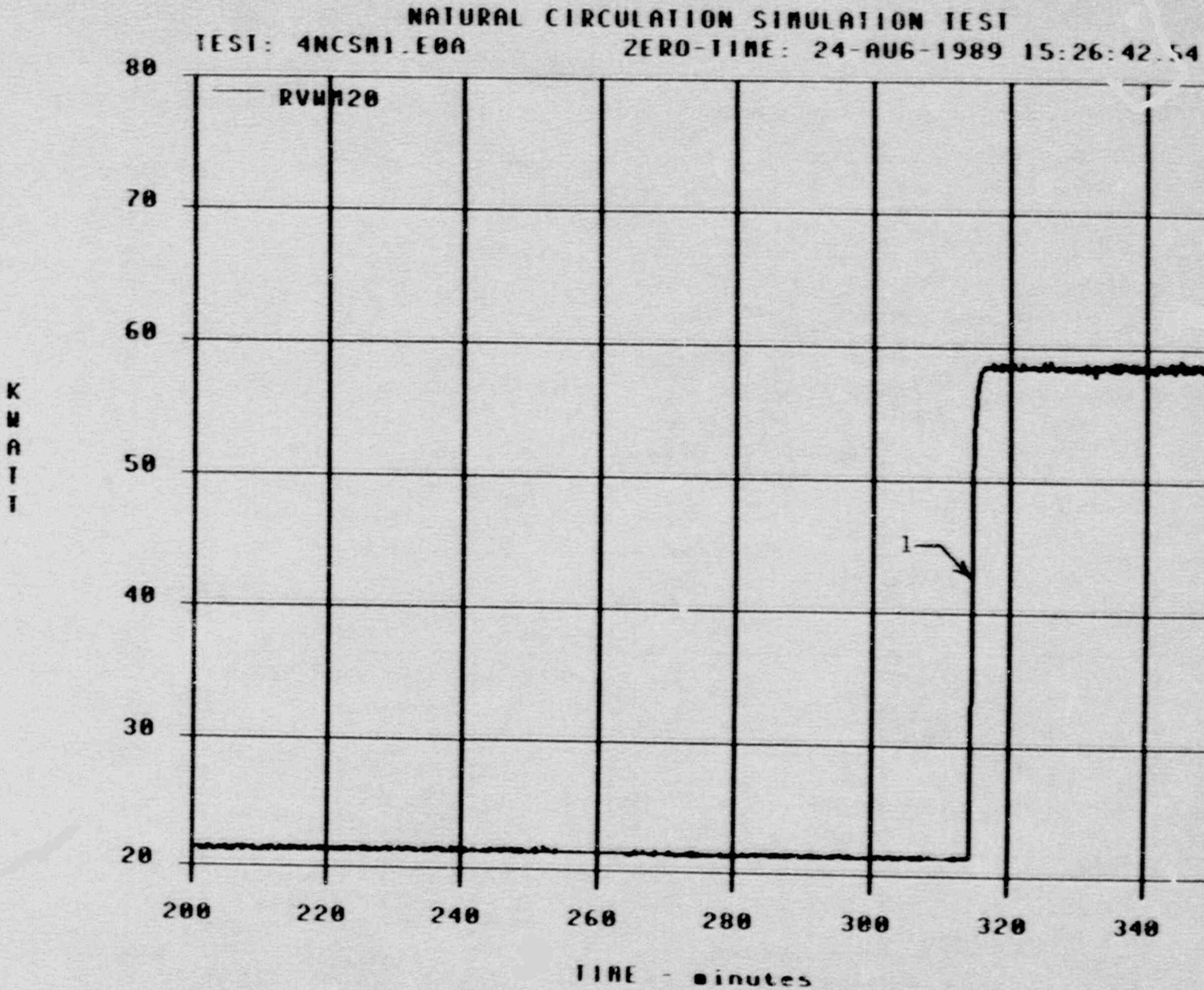

Figure 4.37 Core Power

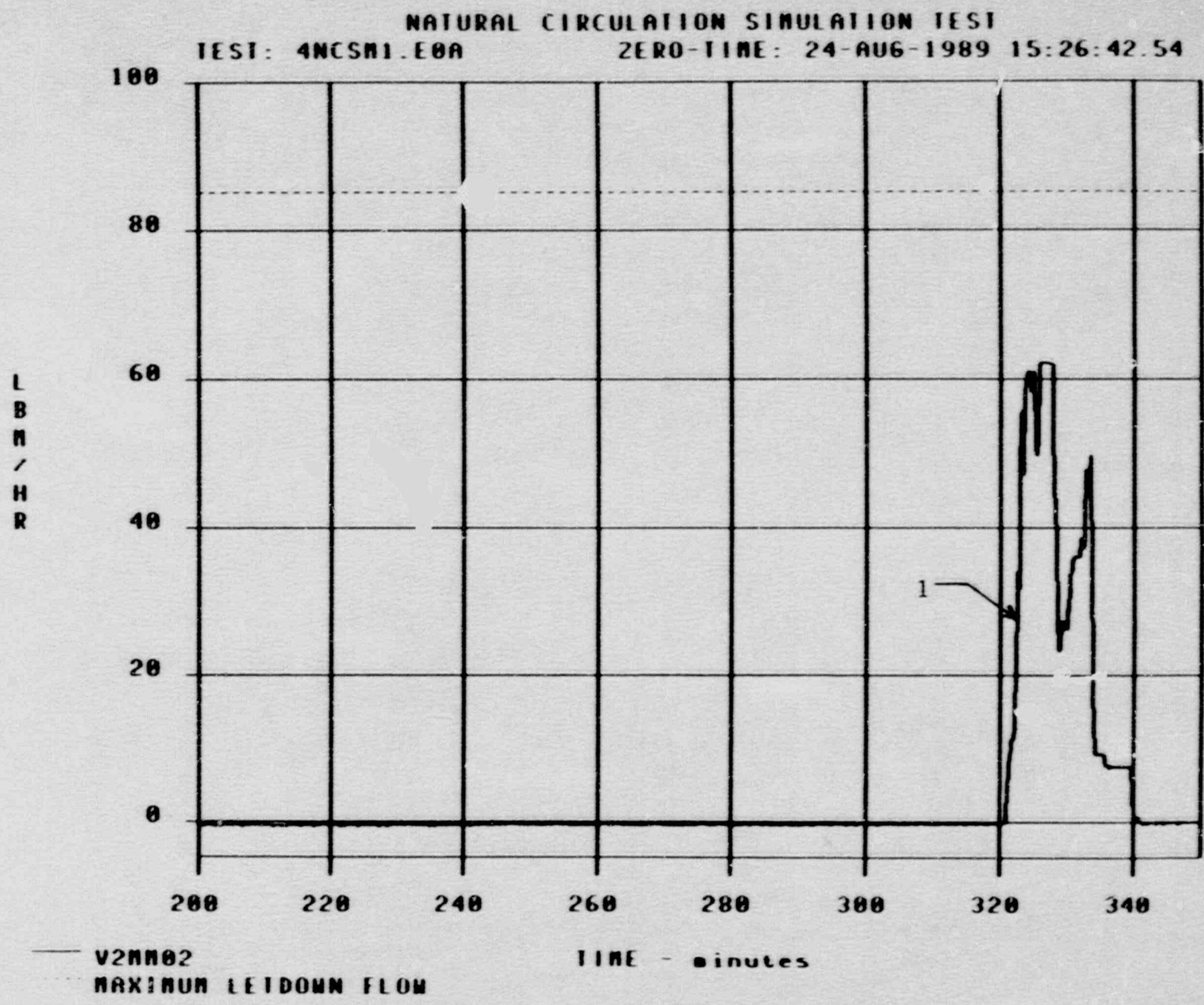

Figure 4.38 Letdown Flow Rate

4.2. Observations of Test 4NCVV1

During the initialization period heat losses across the reactor coolant pumps was also apparent (Figure 4.39 through 4.42, See 1). Since the cold leg flow rates for this test were greater than those for Test 4NCSM1, the temperature difference between the reactor coolant pump suction and discharge are less for Test 4NCVV1 (approximately 5F) than for Test 4NCSM1 (approximately 8F).

For Test 4NCVV1 the reactor vessel vent valves were manually closed for the entire test. The effect of the closed reactor vessel vent valves can be observed on the initial conditions: the downcomer flow rate was approximately equal to the summation of the four cold leg flow rates (Figure 4.43, See 1), the fluid in the cold legs was not heated prior to entering the core region (Figure 4.44, See 1) and a higher core power (compared to the other natural circulation tests where the reactor vessel vent valves were open) was required to achieve the specified core outlet fluid temperature (Figure 4.45, See 1).

The test was initiated by actuating the core power ramp (Figure 4.45, See 2). The core power decrease resulted in a decrease in the core exit and hot leg fluid temperatures (Figure 4.46, See 1) thus an increase in the core region and hot leg fluid density occurred. The increase in the fluid density resulted in a decrease in the primary loop (up the hot leg) natural circulation driving head and a decrease in the cold leg flow rates occurred (Figures 4.47 and 4.48, See 1). The reduction in the primary loop flow (up the hot leg) can again be observed by summing the flow rate in both cold legs of a given loop (Figures 4.49 and 4.50, See 1).

The reduction in the primary loop flow rate in conjunction with the heat loss in the reactor coolant pumps resulted in an increased positive temperature difference between the reactor coolant pump suction and discharge fluid temperature (Figure 4.39 through 4.42, See 2). The response of Test 4NCVV1 through the initial portion of the test was similar to that of Test 4NCSM1.

Although reactor coolant pump heat losses existed and a decrease in the primary loop natural circulation driving head occurred, the secondary flow path (via the reactor vessel vent valves) did not exist for Test 4NCVV1. The cold leg flow rates decreased to a minimum of approximately 400 lb/hr in A1 and A2 cold legs (Figure 4.47, See 2) and approximately 500 lb/hr in the B1 and B2 cold legs (Figure 4.48, See 2). subsequently the flow rate in each of the cold legs increased (Figure 4.47 and 4.48, See 3).

The flow in each of the four cold legs was in the forward direction throughout this entire period. Therefore without the potential for a secondary flow path, i.e., via the reactor vessel vent valves, primary loop flow interruption and flow reversal in the cold leg did not occur.

4.2.1. Facility Hold Period

The response of the MIST facility was then observed until new steady state natural circulation conditions were attained (through approximately 100 minutes). During this time no operator actions were performed. The transient response is provided in Figure 4.51 through 4.63. As can be observed from these plots, the primary system established new steady-state natural circulation conditions with forward flow of approximately 830 lb/hr in each cold leg (Figures 4.54 and 4.55). The fluid contraction was nearly complete at approximately 100 minutes and can be observed by the stabilization of the primary loop fluid temperatures (Figures 4.56 through 4.62) and the relatively constant pressurizer level (Figure 4.63).

4.2.2. Operator Actions and Loop Recovery Period

At approximately 100 minutes the loop operator started the A1 reactor coolant pump. The downcomer flow rate (Figure 4.64, See 1) increased to approximately 30000 lb/hr (note that the cold leg venturi meters are over ranged for pumps operating conditions). The reactor coolant pump start resulted in a rapid convergence of all primary loop fluid temperatures (Figure 4.65 through 4.68, See 1), a slight increase in the primary system pressure (Figure 4.51, See 1) and an increase of approximately 30 psi in the steam generator A pressure (Figure 4.52, See 1). During the time that the A1 reactor coolant pump was operating the hot leg B fluid temperature did not trend with the core outlet temperature (Figure 4.68, See 2). The hot leg B fluid temperature however does appear to trend with the steam generator B saturation temperature (Figure 4.40, See 3). Therefore backflow existed in the B loop while the A1 reactor coolant pump was operating.

Approximately 15 minutes after the A1 reactor coolant pump was started the loop operator started the B2 reactor coolant pump. the downcomer flow rate increased to approximately 68000 lb/hr (Figure 4.64, See 2). Again an increase in the primary system pressure was observed (Figure 4.51, See 2). The steam generator B pressure also increased (Figure 4.52, See 2). When the B2 reactor coolant pump was started the hot leg B fluid temperature increased and then trended with the core outlet temperature (Figure 4.68, See 2) thus indicating the existence of forward flow in loop B.

Both the A1 and the B2 reactor coolant pumps were turned off approximately 15 minutes later (Figure 4.64, See 3). Natural circulation conditions were re-established and the test was terminated approximately 170 minutes after test initiation.

Figures for Test 4NCVV1

Natural Circulation Test With The
Reactor Vessel Vent Valves Closed

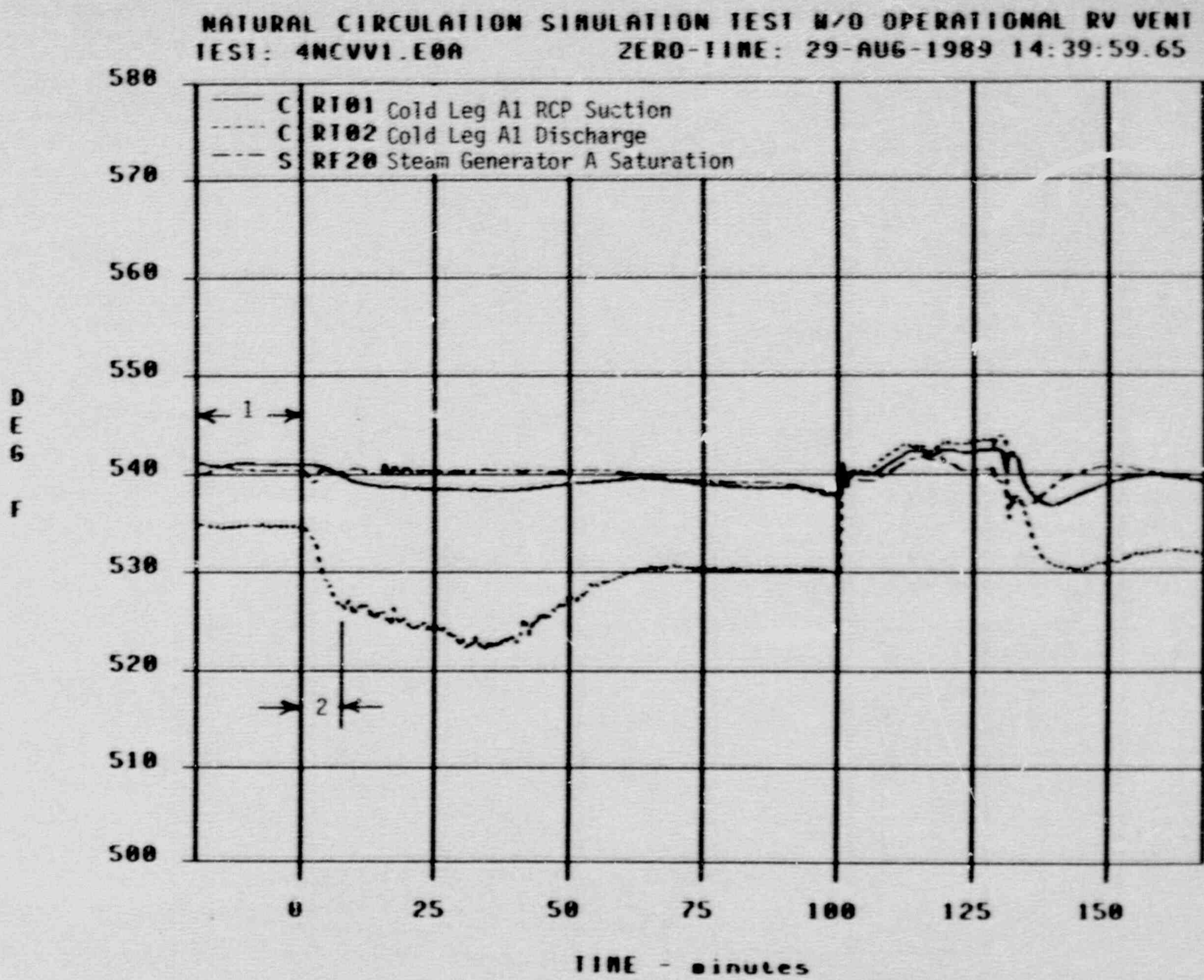

Figure 4.39 Steam Generator A Saturation Temperature And Cold Leg A1 Reactor Coolant Pump Suction And Discharge Temperature

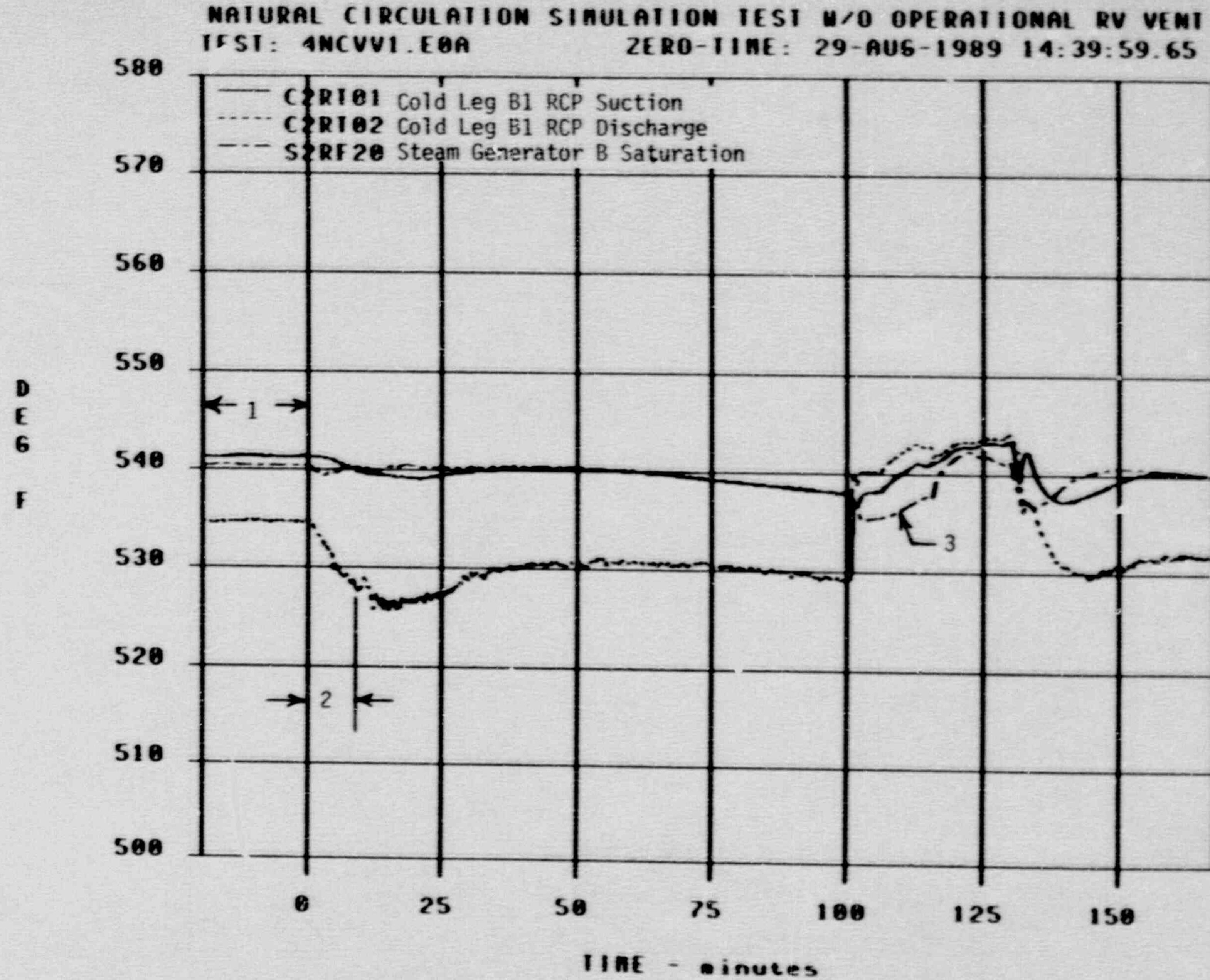

Figure 4.40 Steam Generator B Saturation Temperature And Cold Leg B1 Reactor Coolant Pump Suction And Discharge Temperature

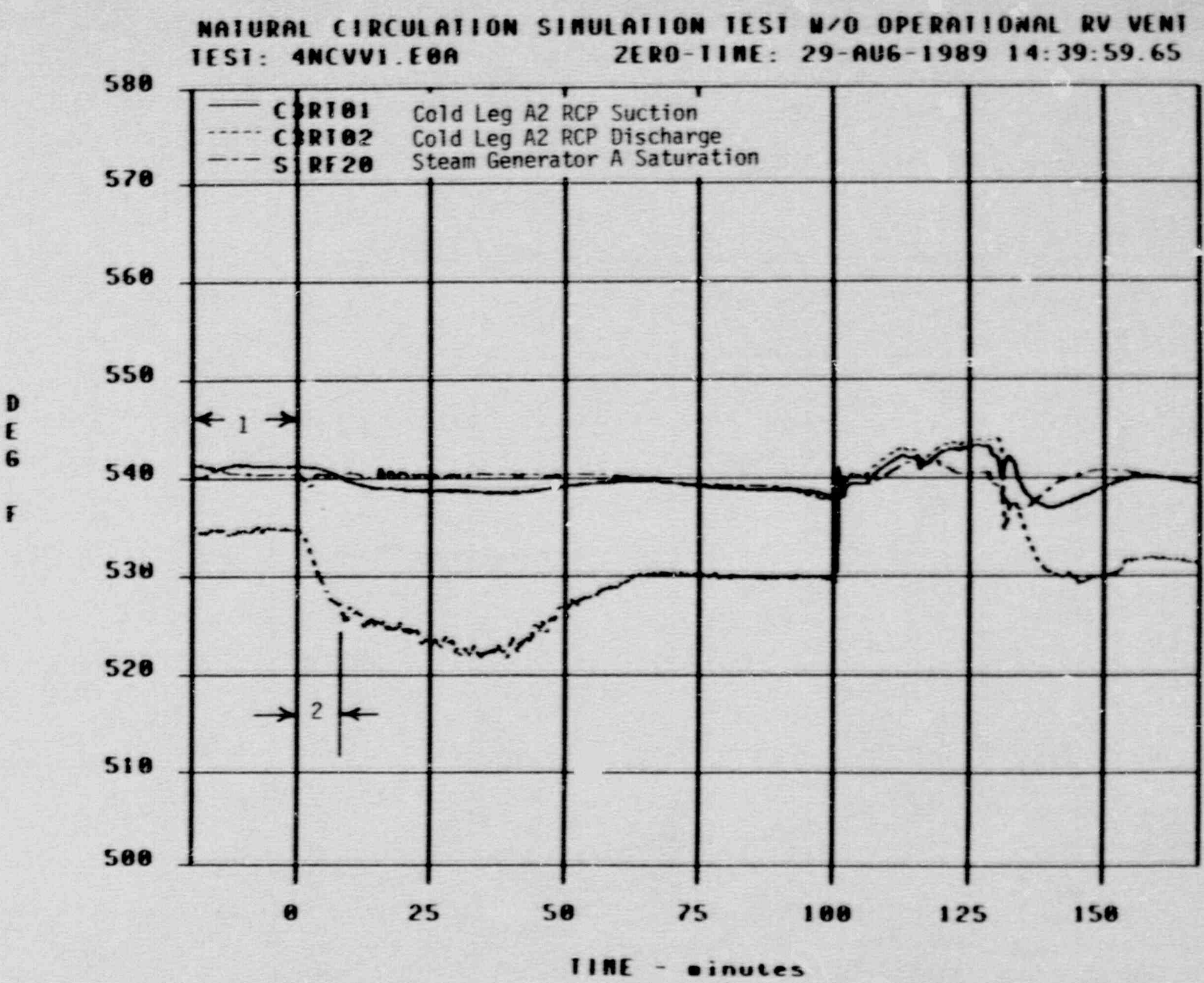

Figure 4.41 Steam Generator A Saturation Temperature And Cold Leg A2 Reactor Coolant Pump Suction And Discharge Temperature

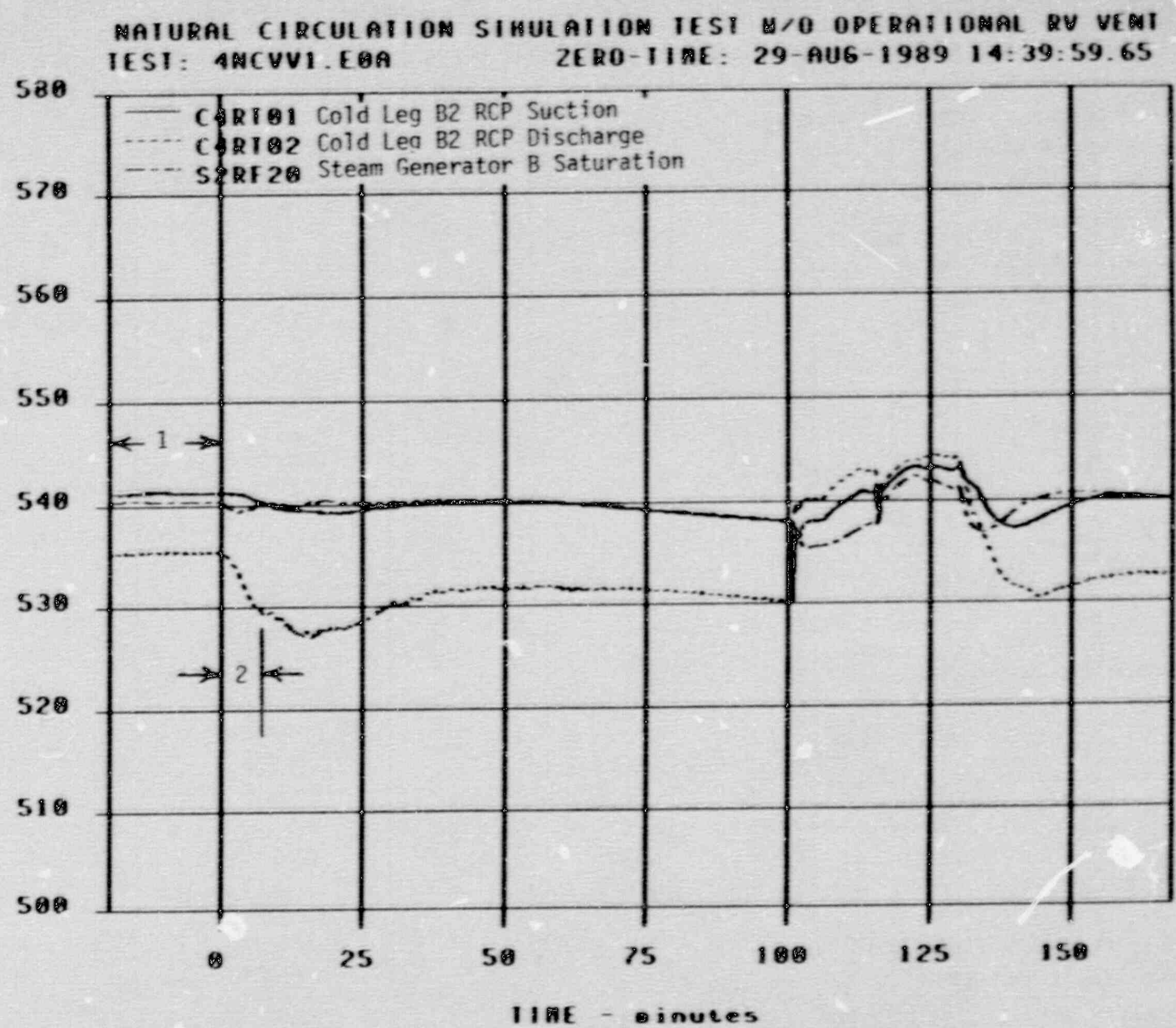

Figure 4.42 Steam Generator B Saturation Temperature And Cold Leg B2 Reactor Coolant Pump Suction And Discharge Temperature

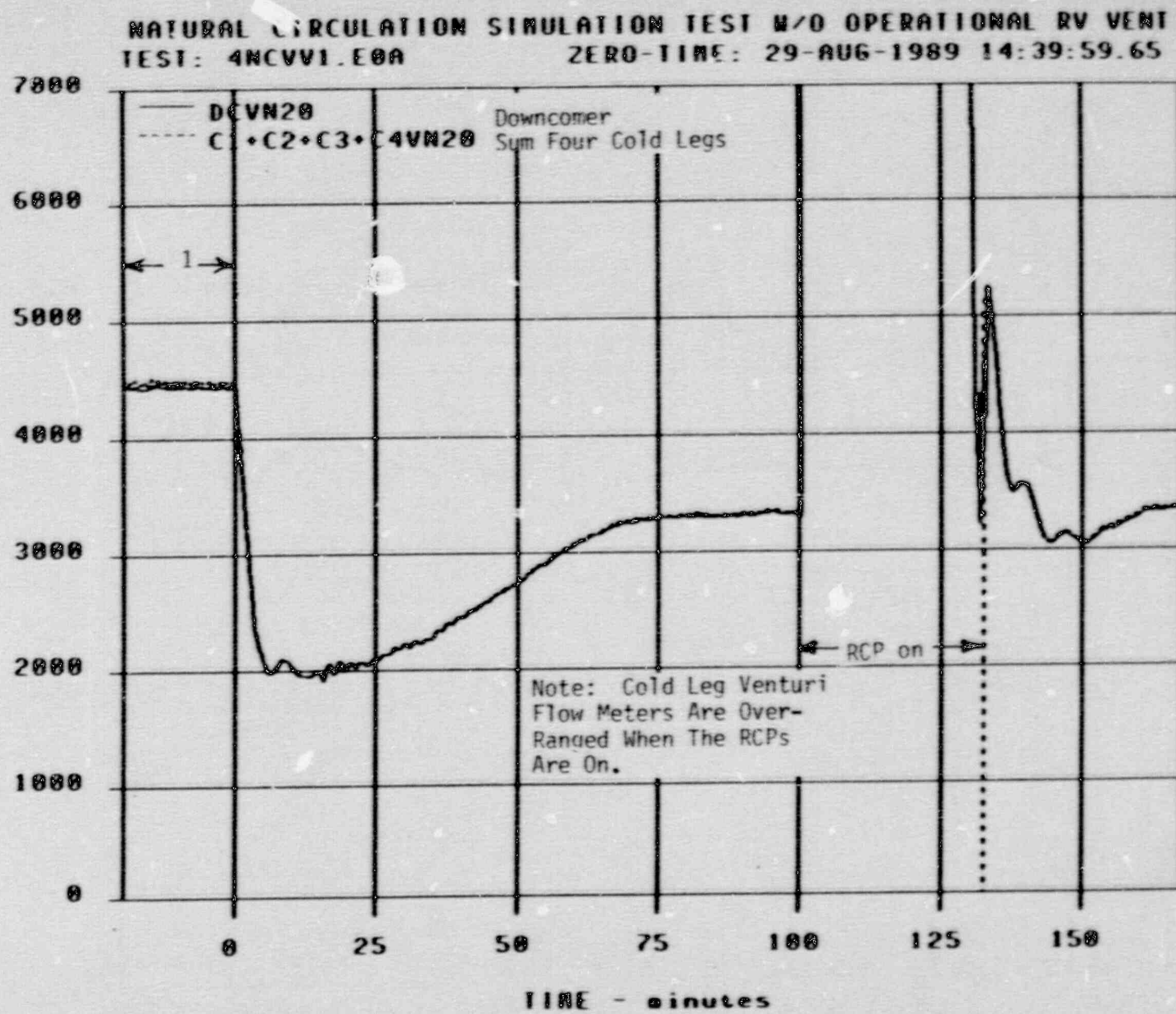

Figure 4.43 Downcomer Flow Rate And The Summation Of The Flow Rate In All Four Cold Legs

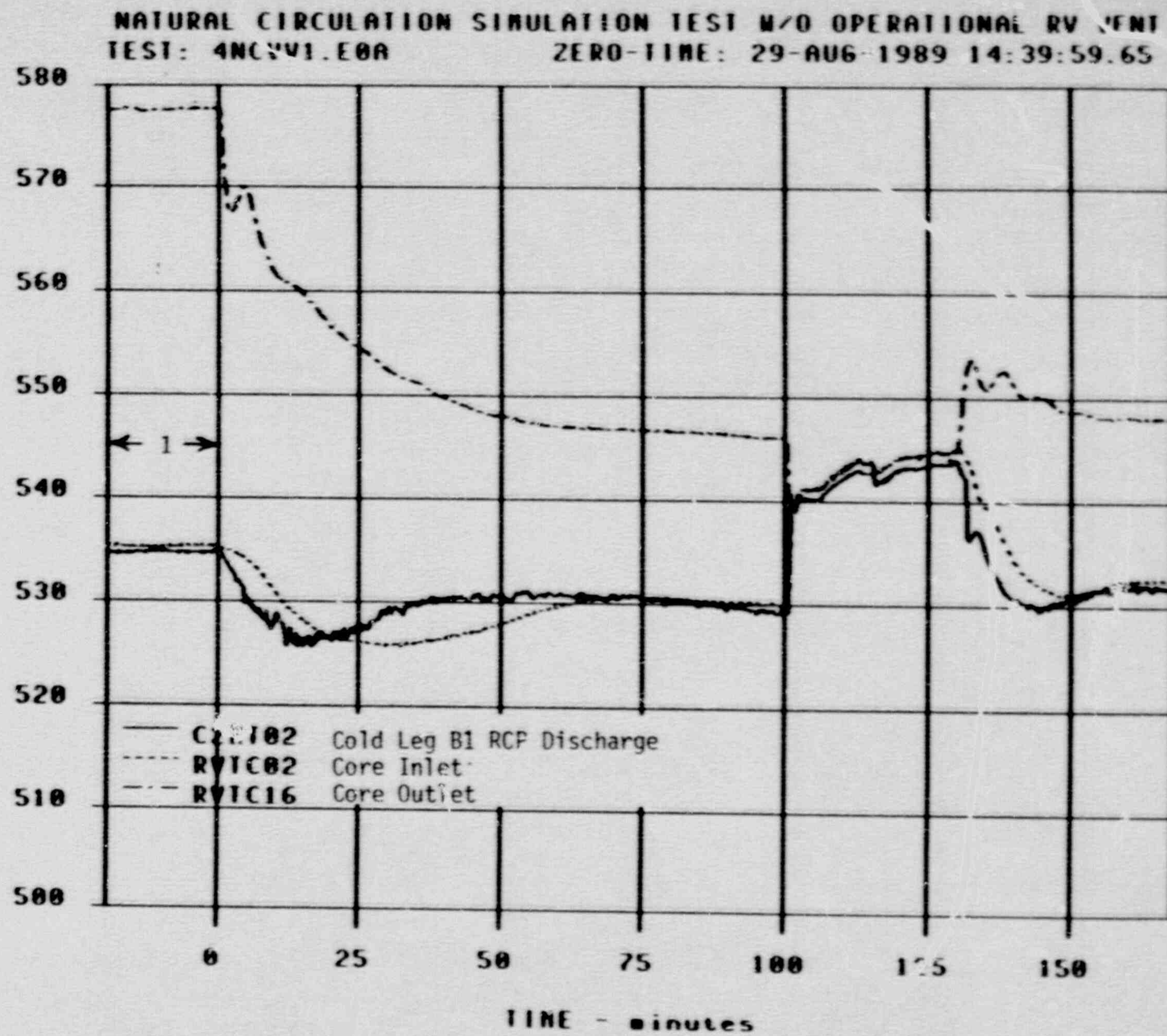

Figure 4.44 Cold Leg B1 Reactor Coolant Pump Discharge Temperature And Core Inlet And Outlet Temperature

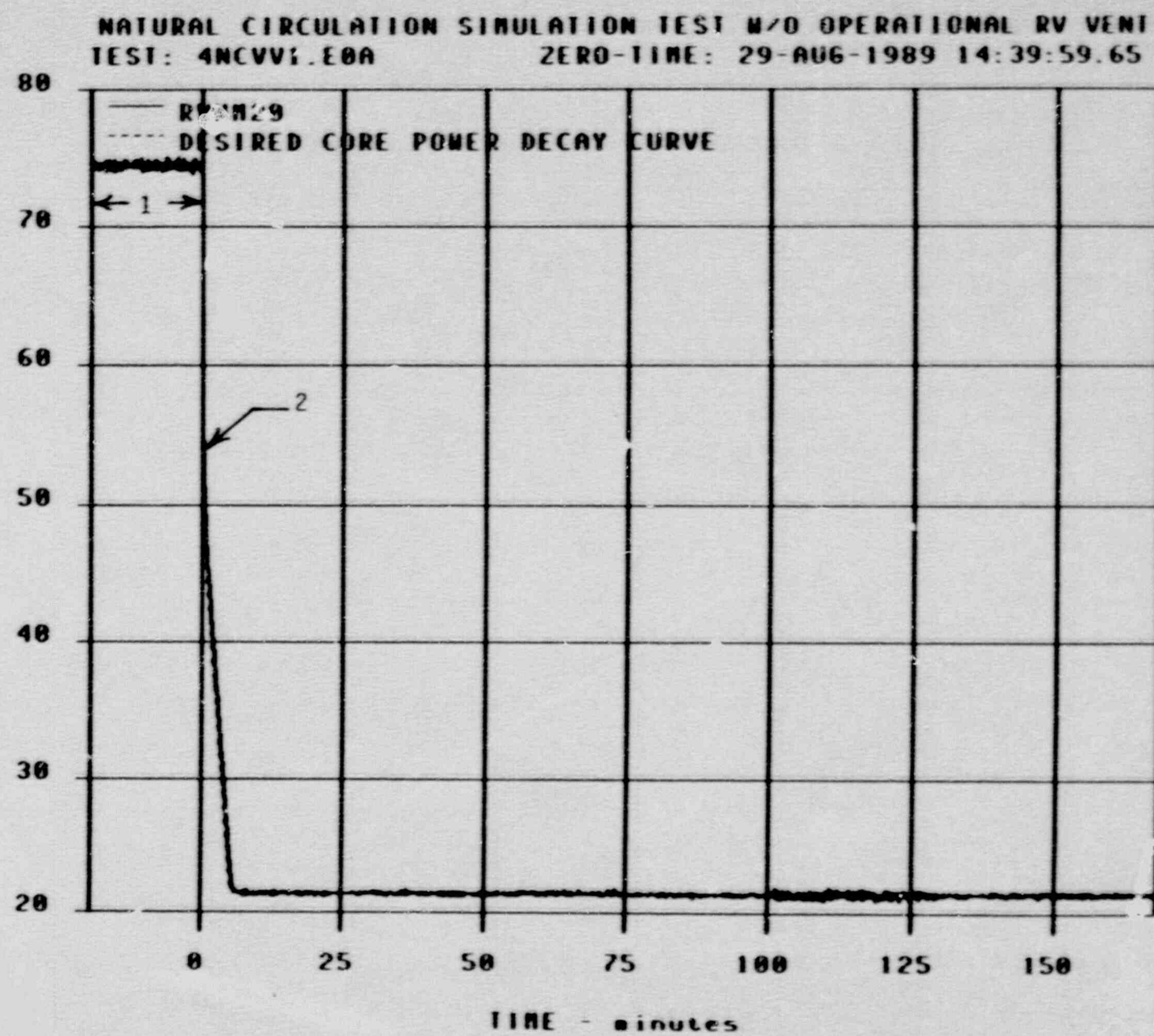

Figure 4.45 Core Power

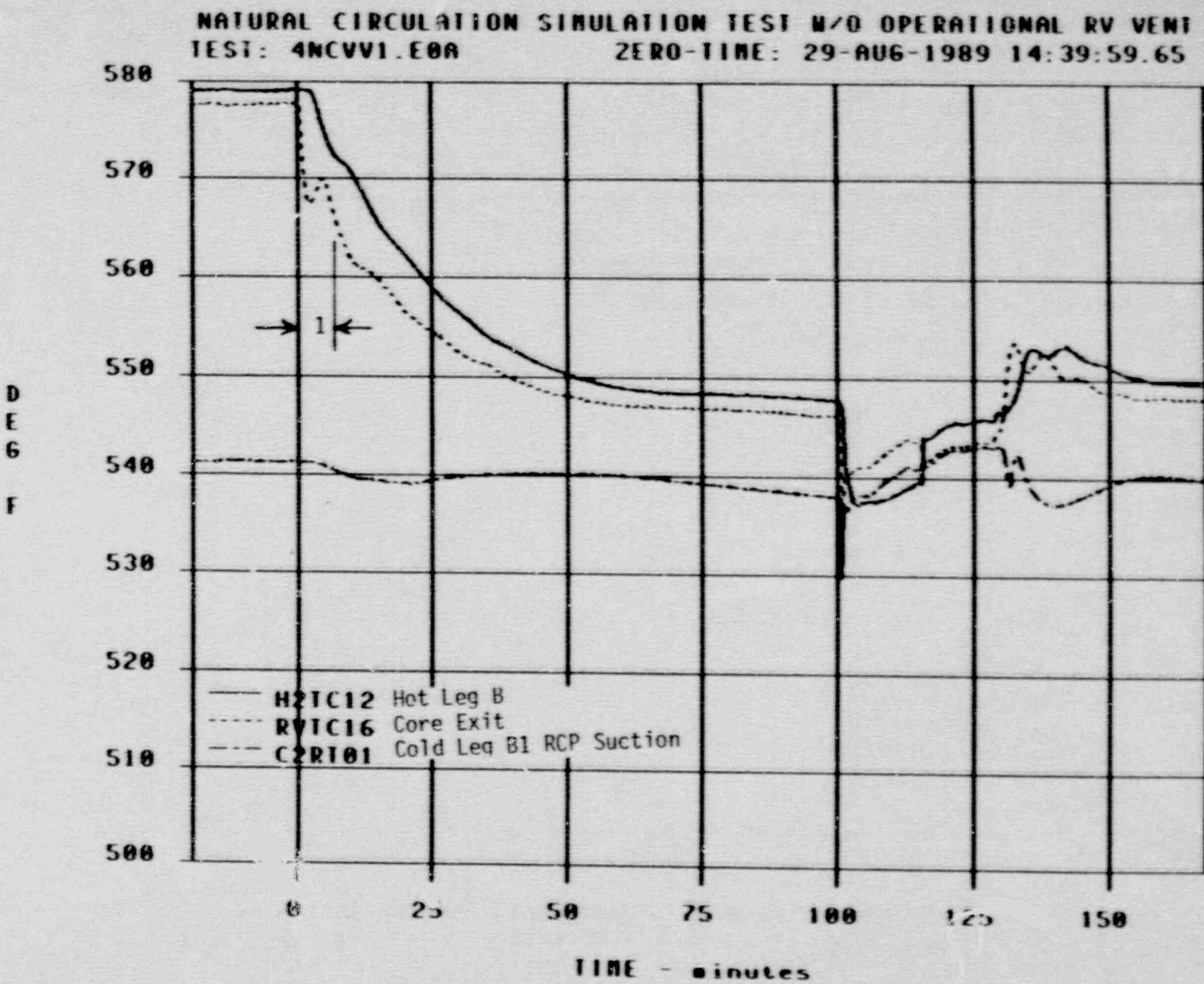

Figure 4.46 Core Exit, Hot Leg B And Cold Leg B1 Reactor Coolant Pump Suction Temperatures

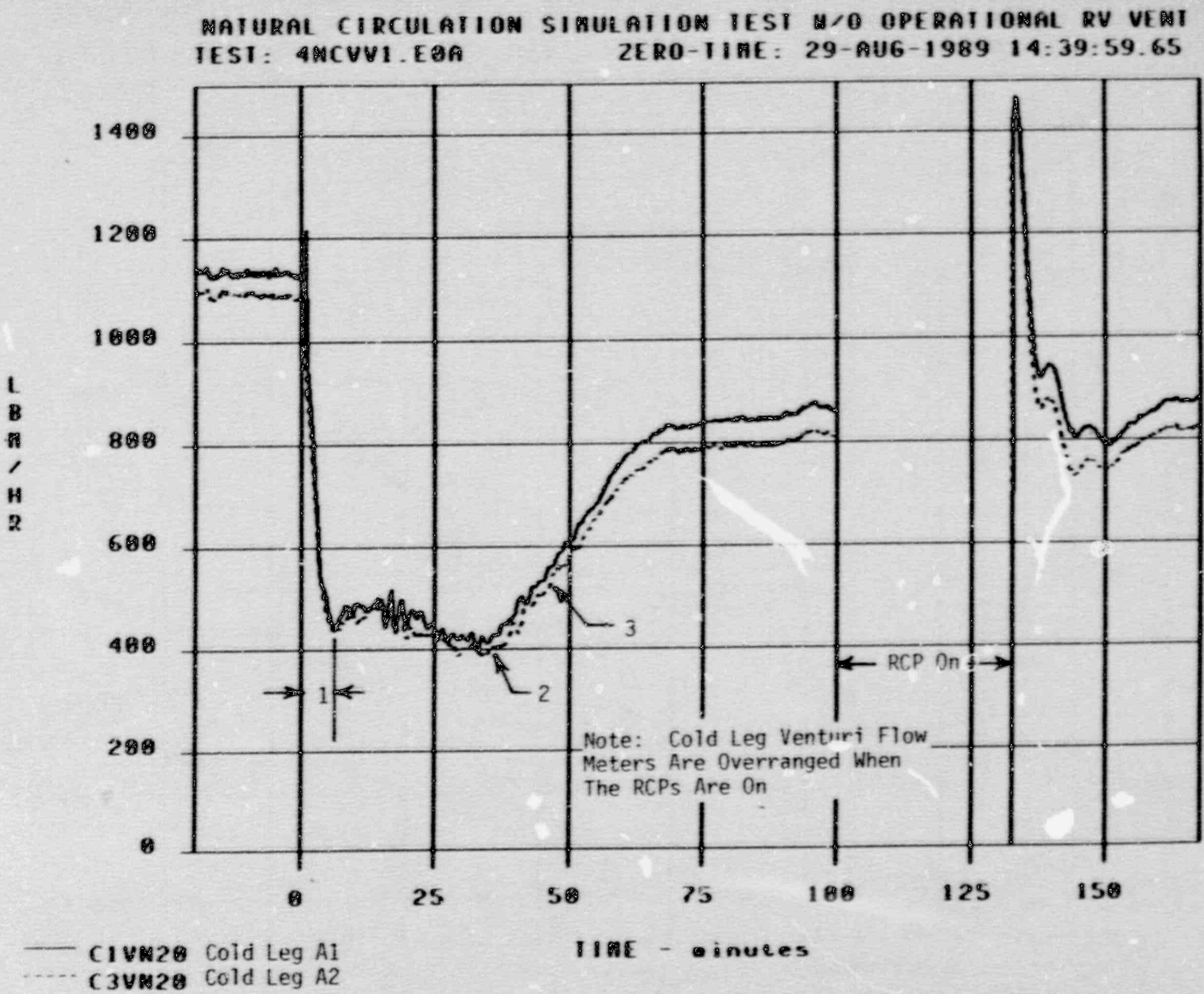

Figure 4.47 Cold Leg A1 And A2 Flow Rate

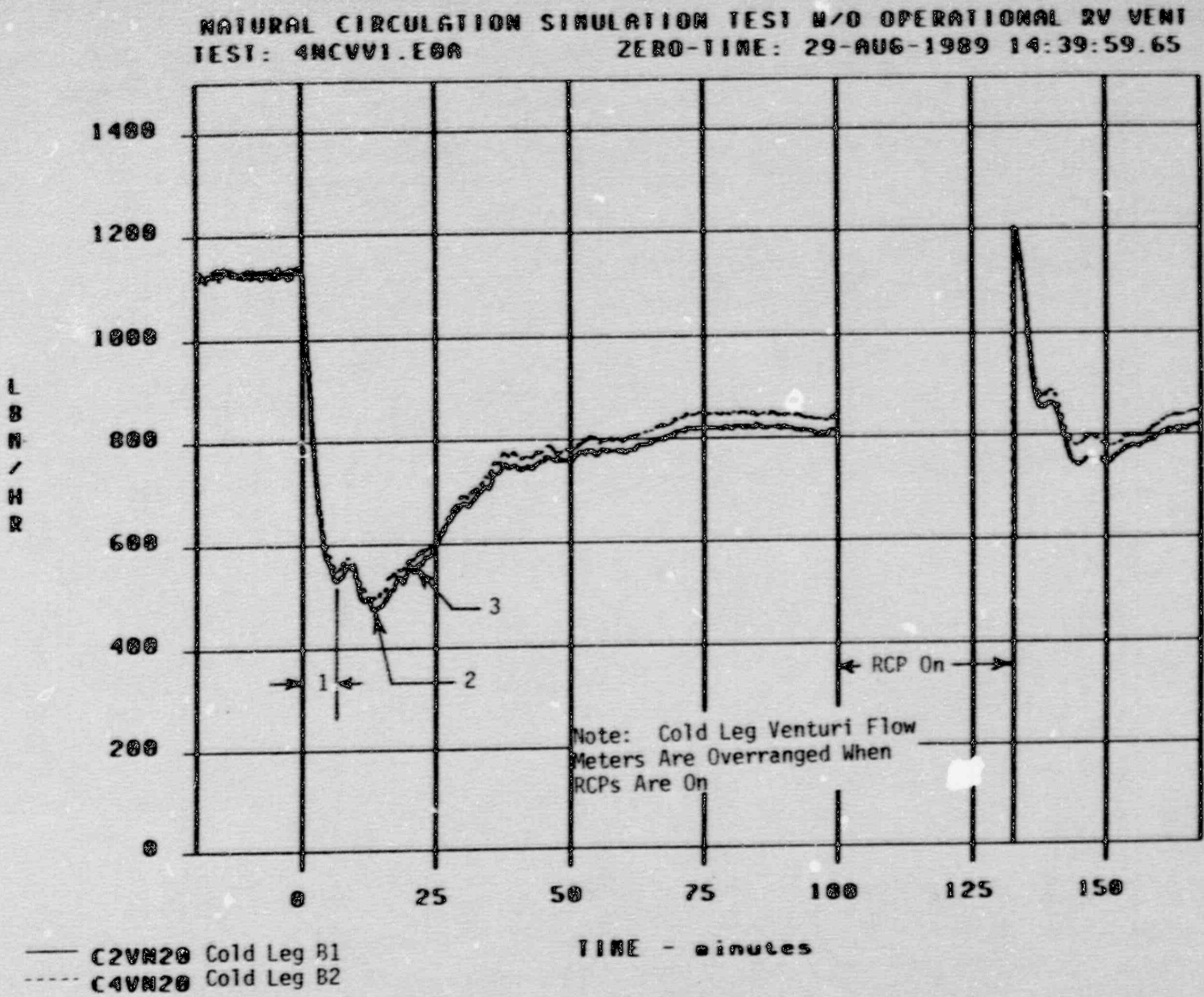

Figure 4.48 Cold Leg B1 And B2 Flow Rate

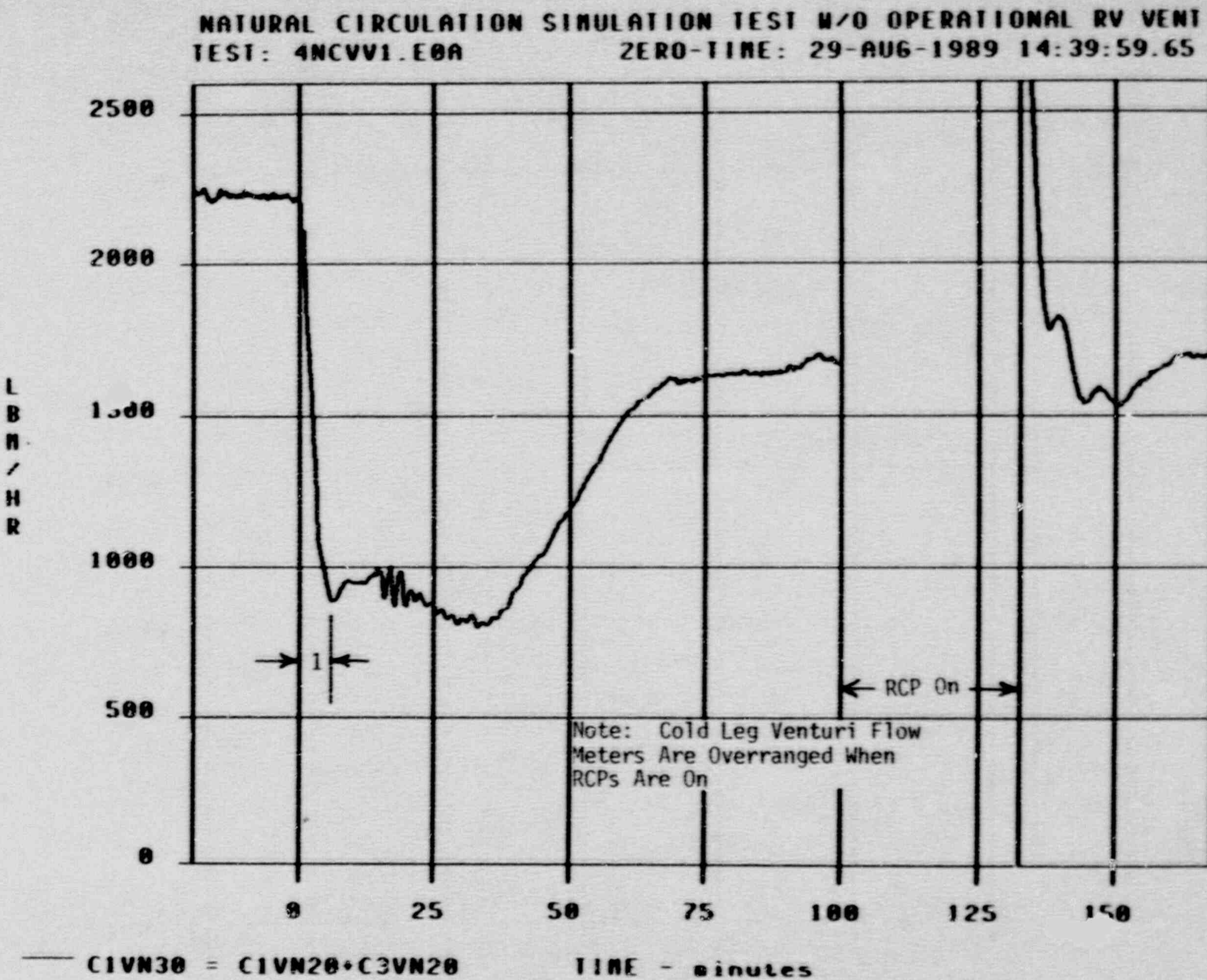

Figure 4.49 Summation Of The A1 And A2 Cold Leg Flow Rates

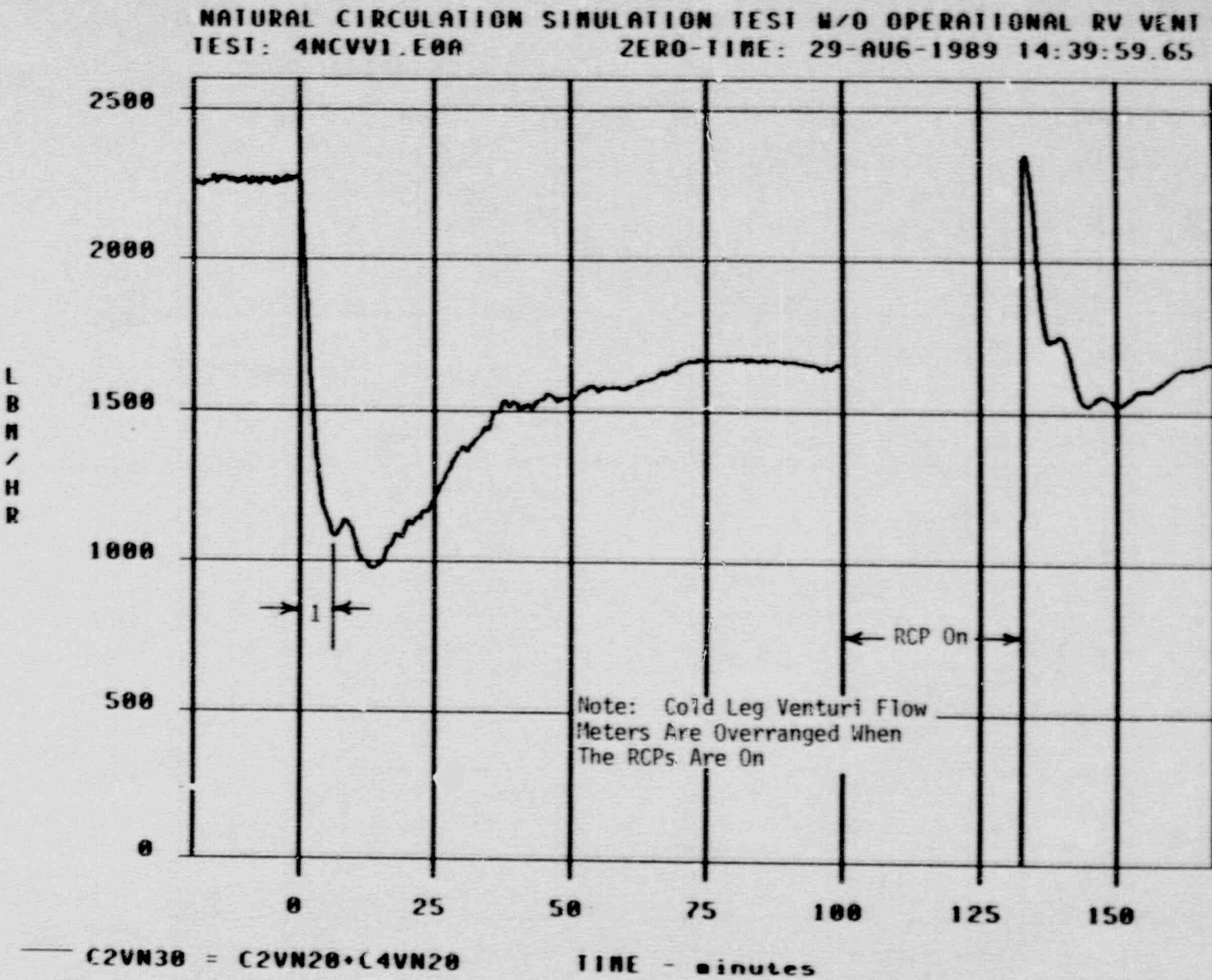

Figure 4.50 Summation Of The B1 And B2 Cold Leg Flow Rates

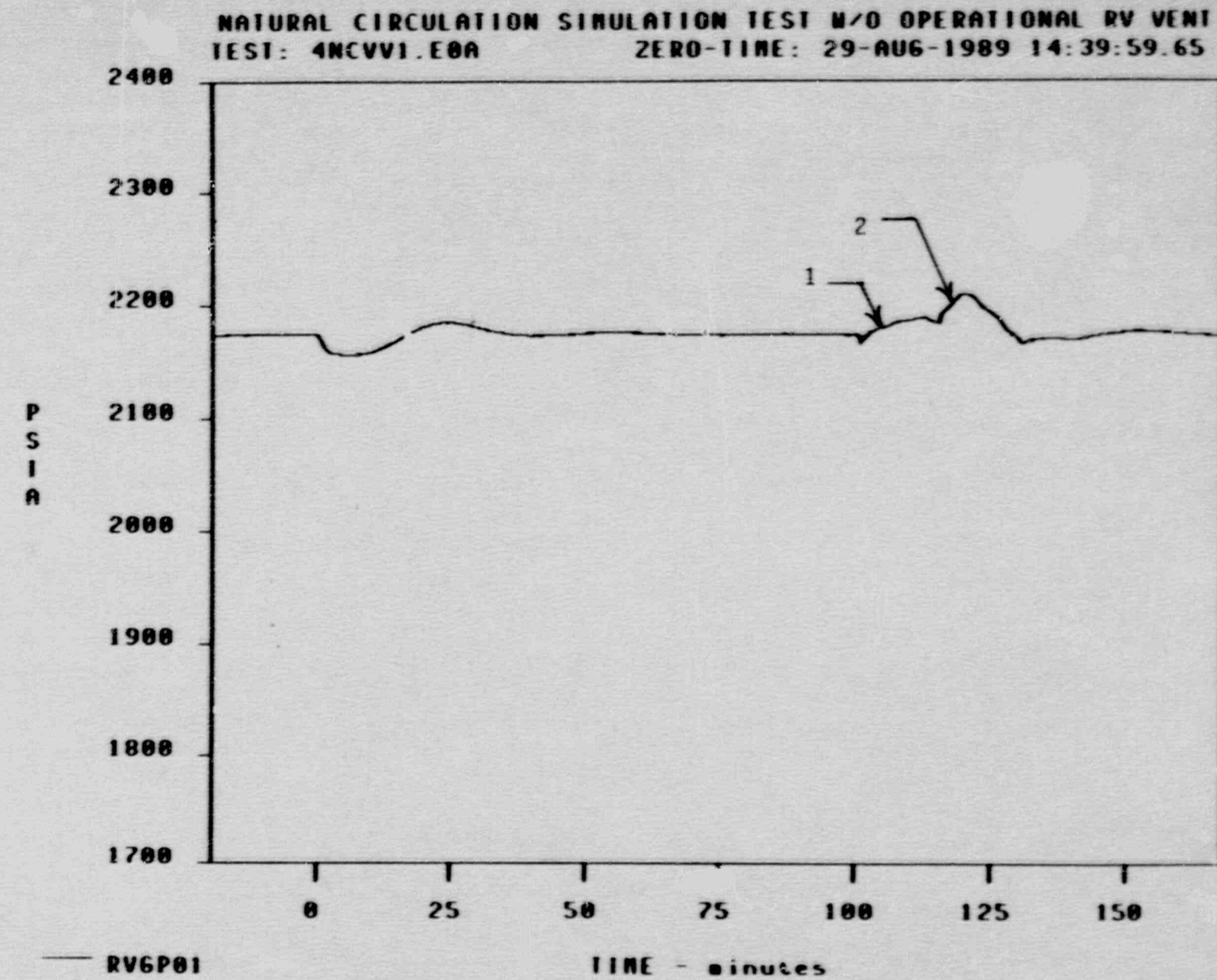

Figure 4.51 Primary System Pressure

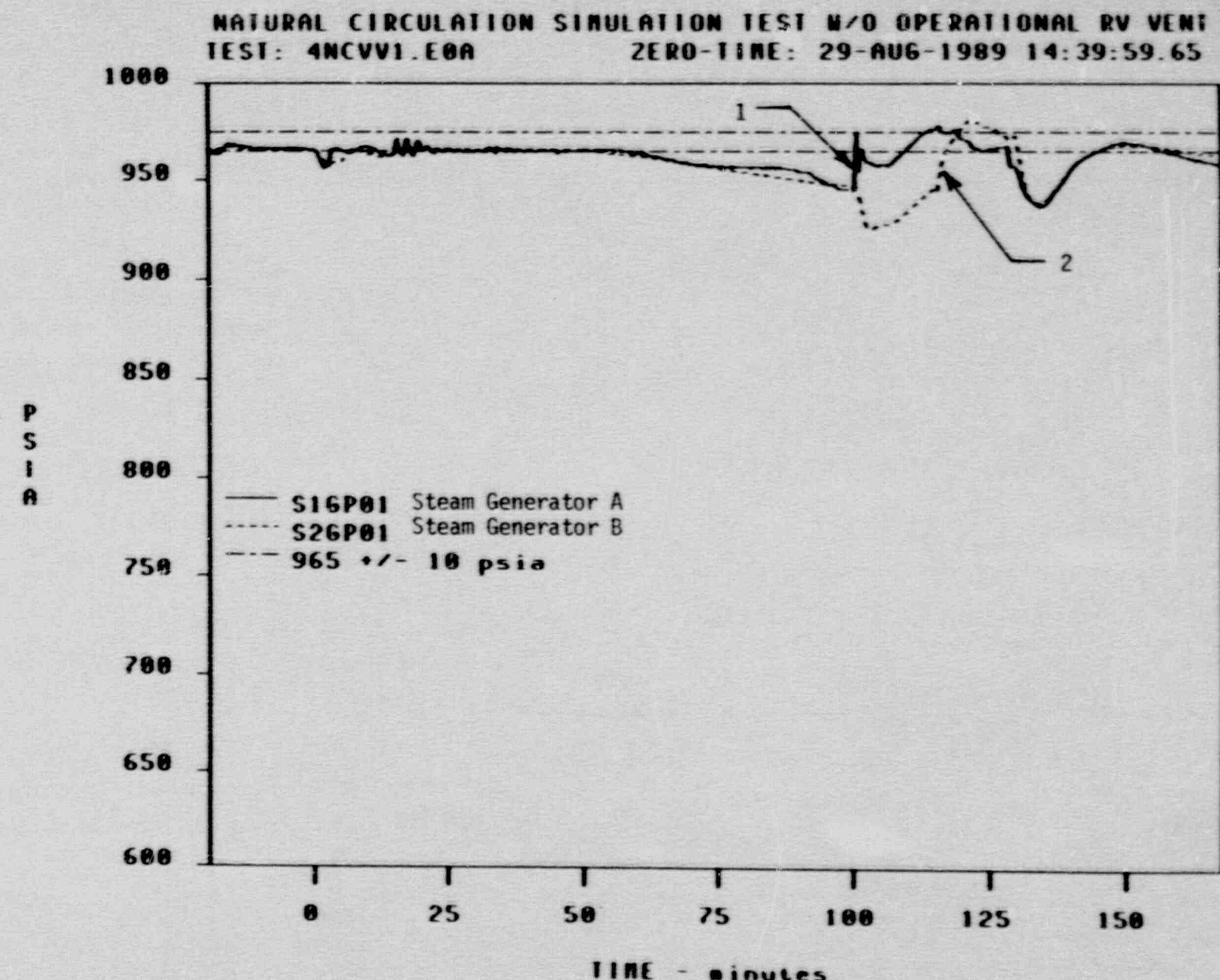

Figure 4.52 Secondary System Pressure

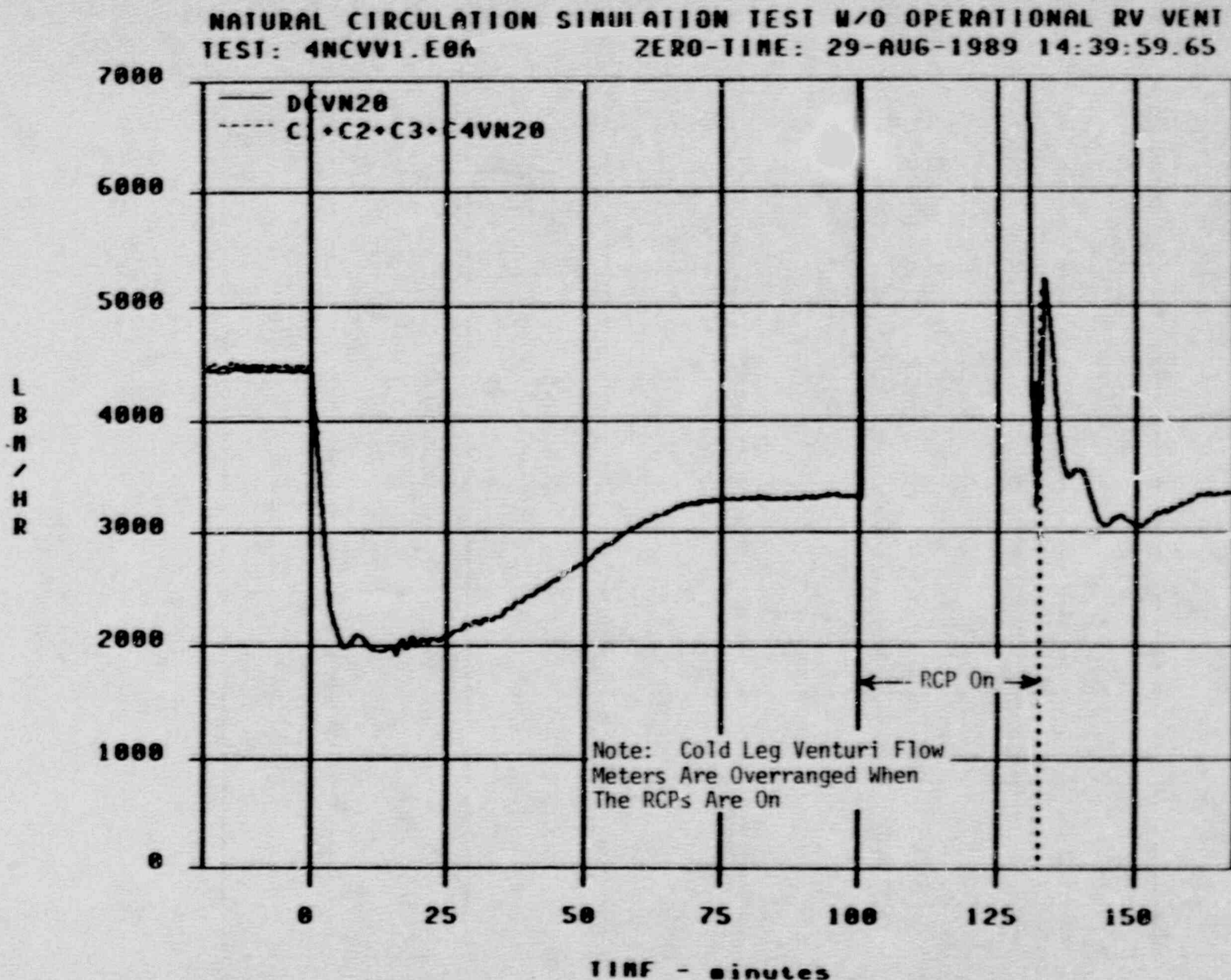

Figure 4.53 Downcomer Flow Rate And The Summation Of The Flow Rate In All Four Cold Legs

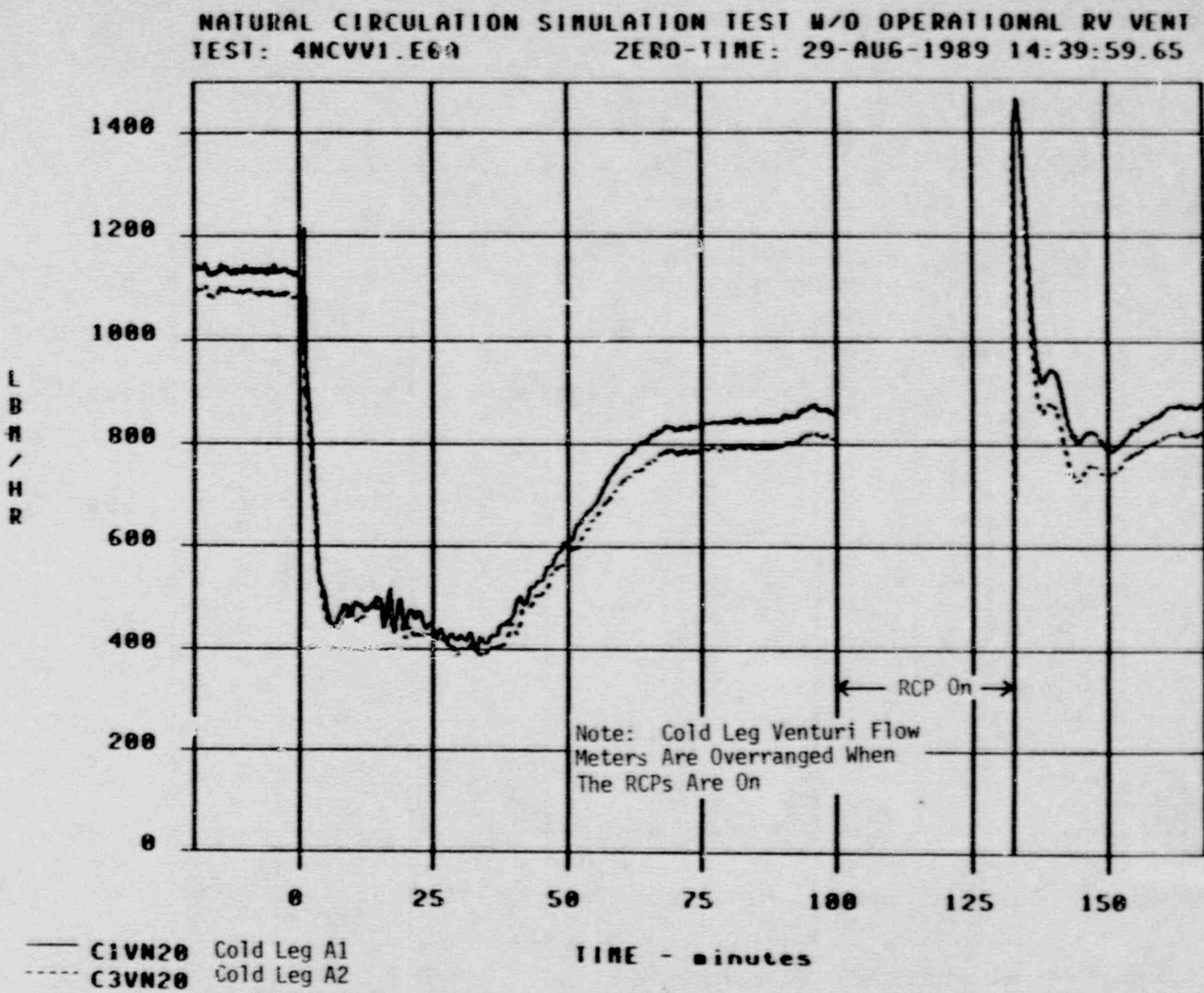

Figure 4.54 Cold Leg A1 And A2 Flow Rate

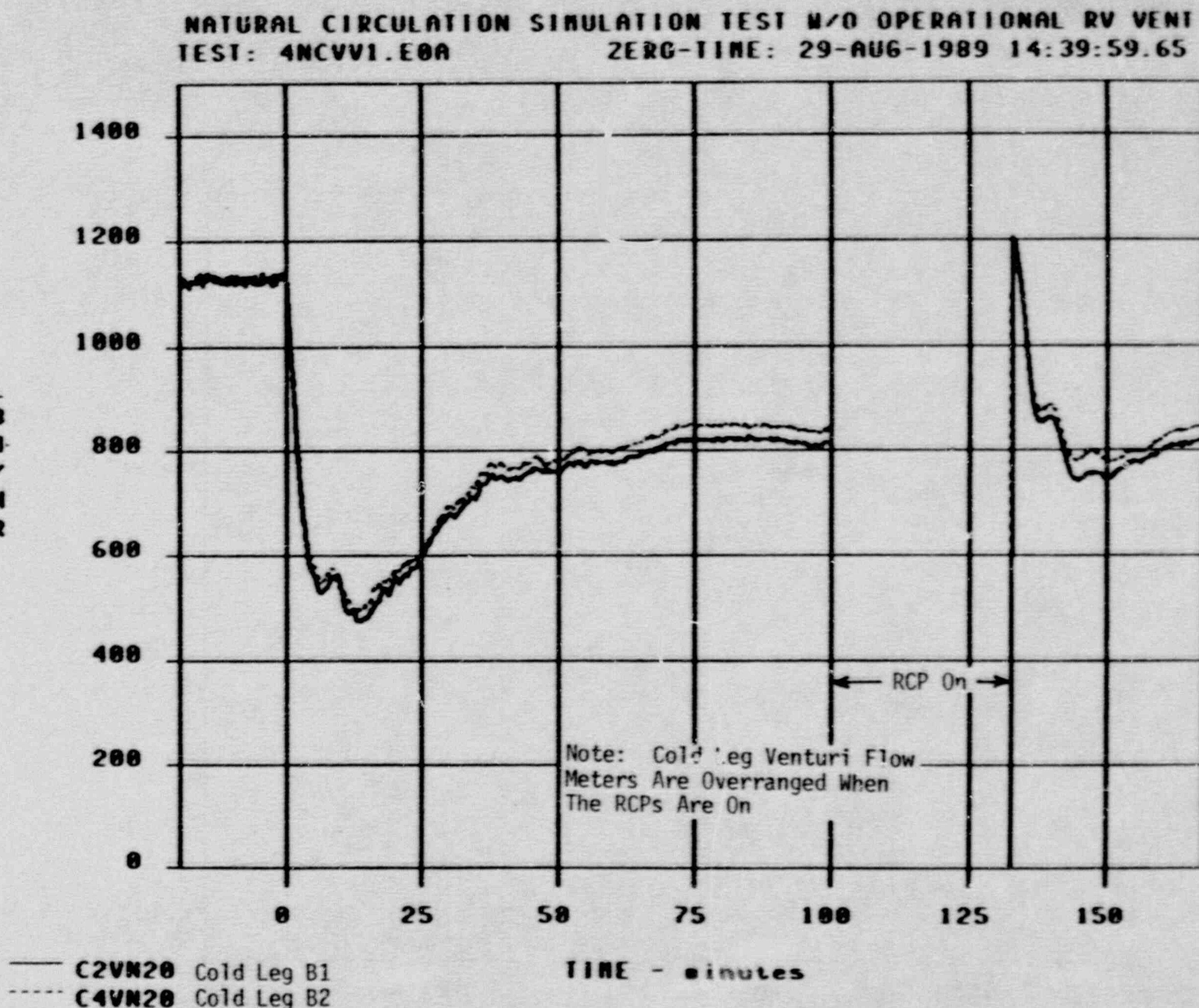

Figure 4.55 Cold Leg B1 And B2 Flow Rate

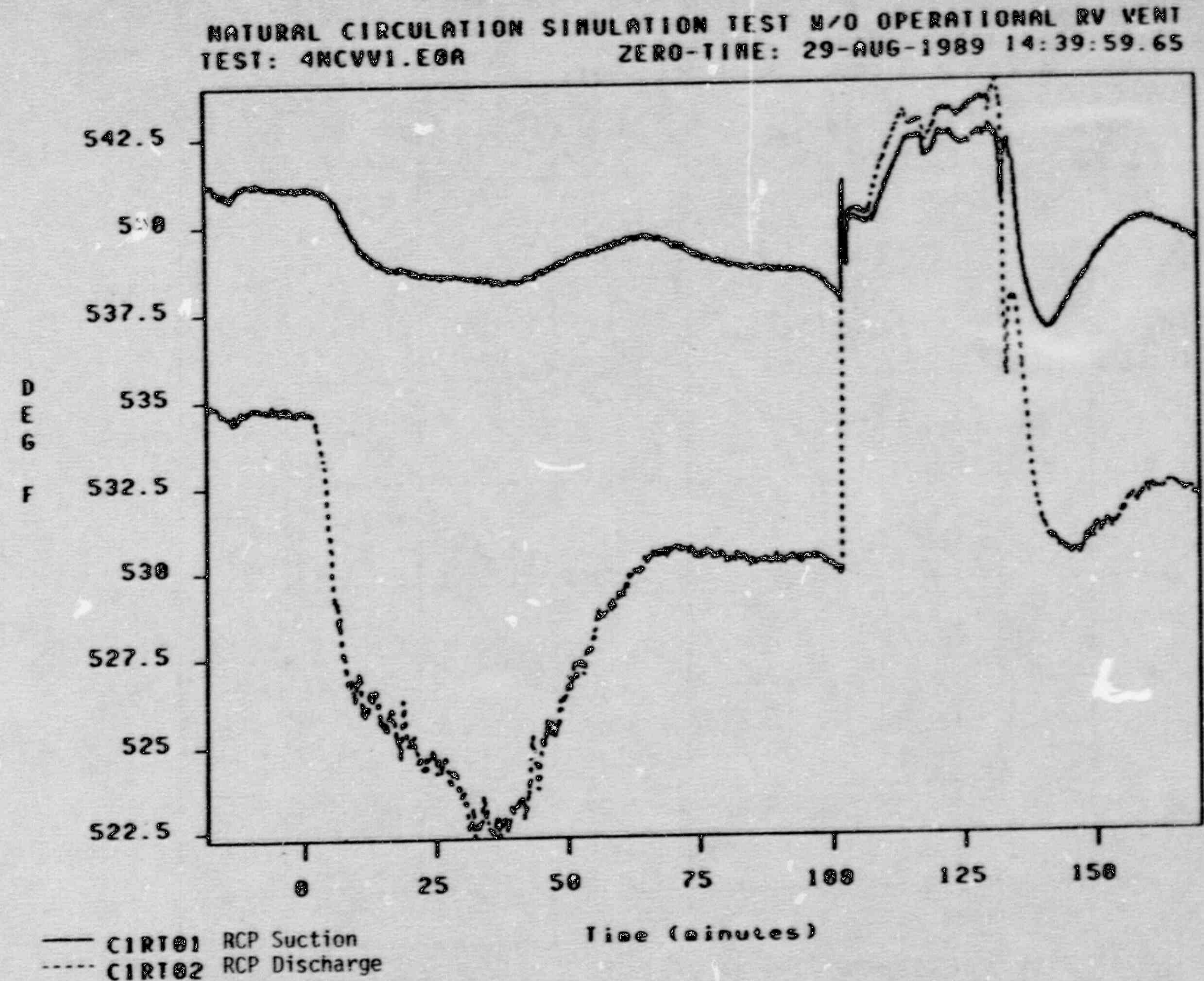

Figure 4.56 Cold Leg A1 Reactor Coolant Pump Suction And Discharge Temperature

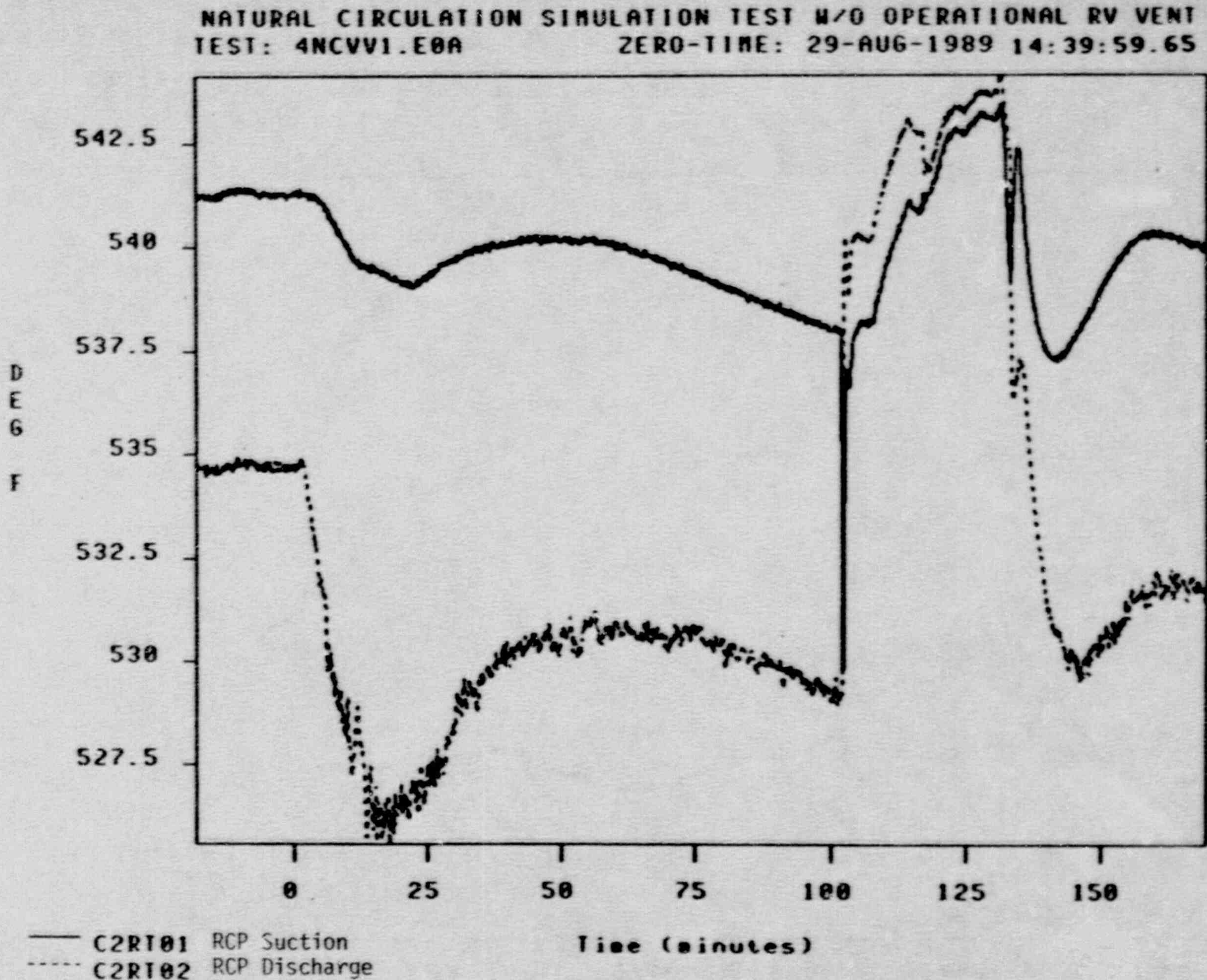

Figure 4.57 Cold Leg B1 Reactor Coolant Pump Suction And Discharge Temperature

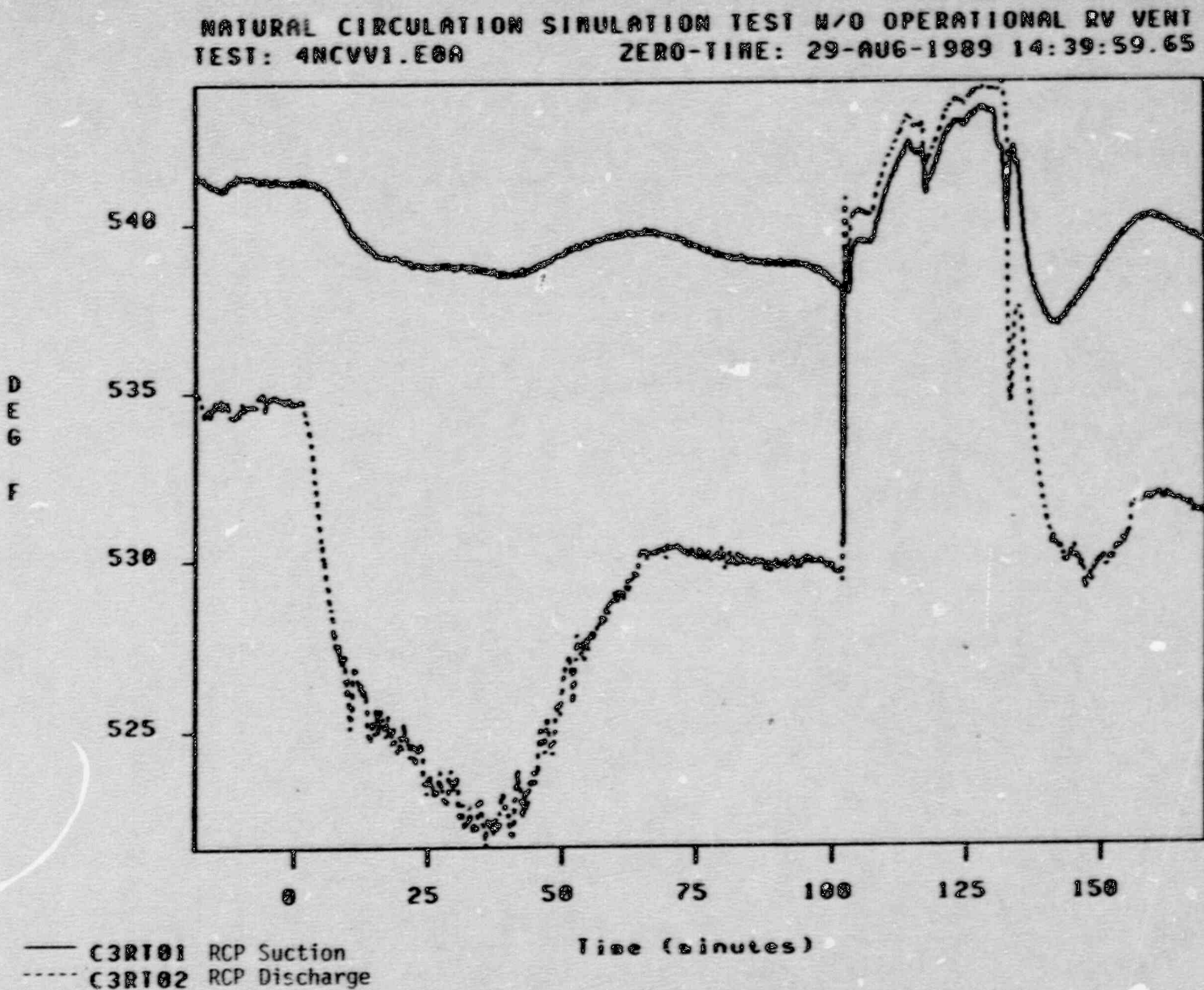

Figure 4.58 Cold Leg A2 Reactor Coolant Pump Suction And Discharge Temperature

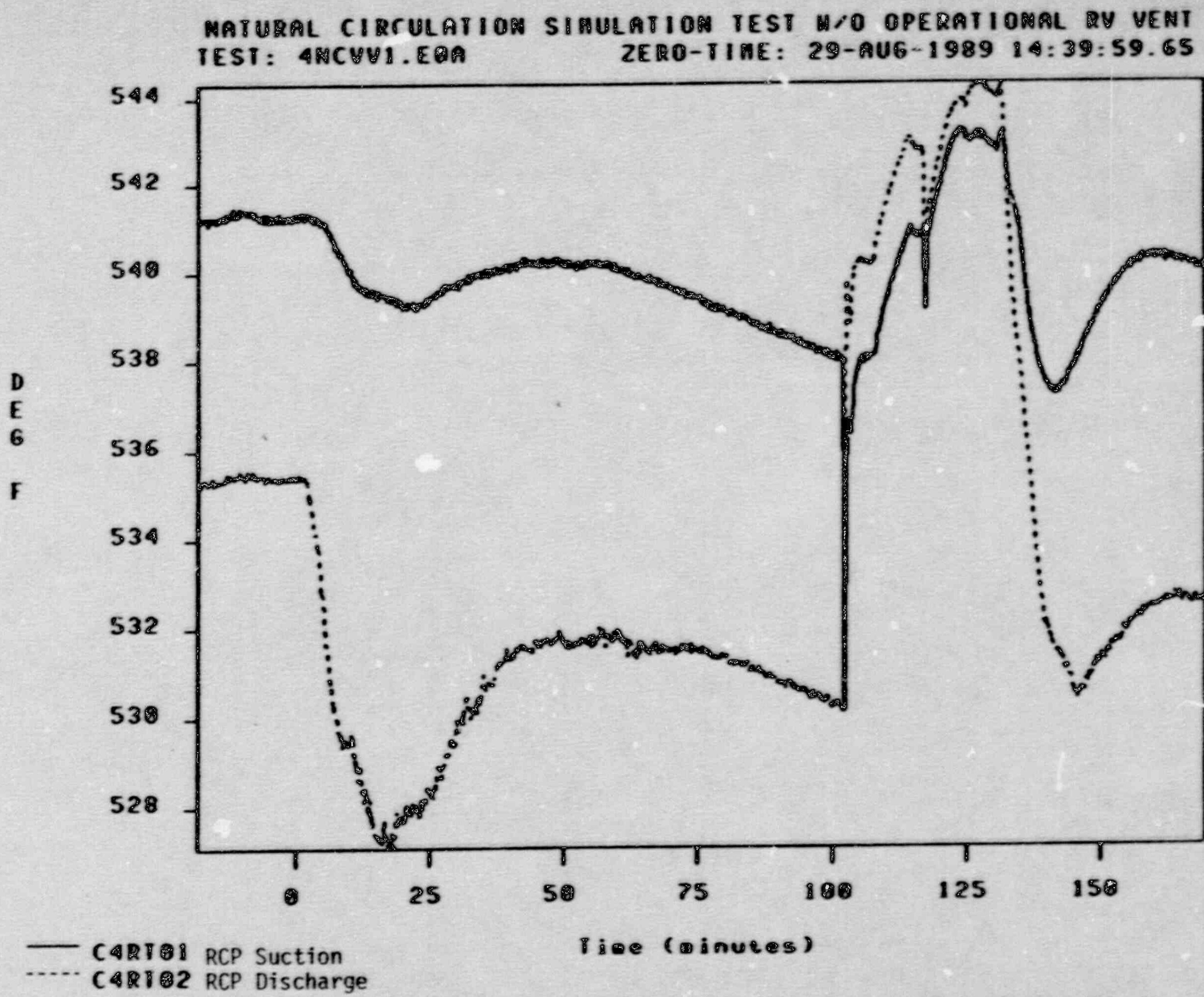

Figure 4.59 Cold Leg B2 Reactor Coolant Pump Suction And Discharge Temperature

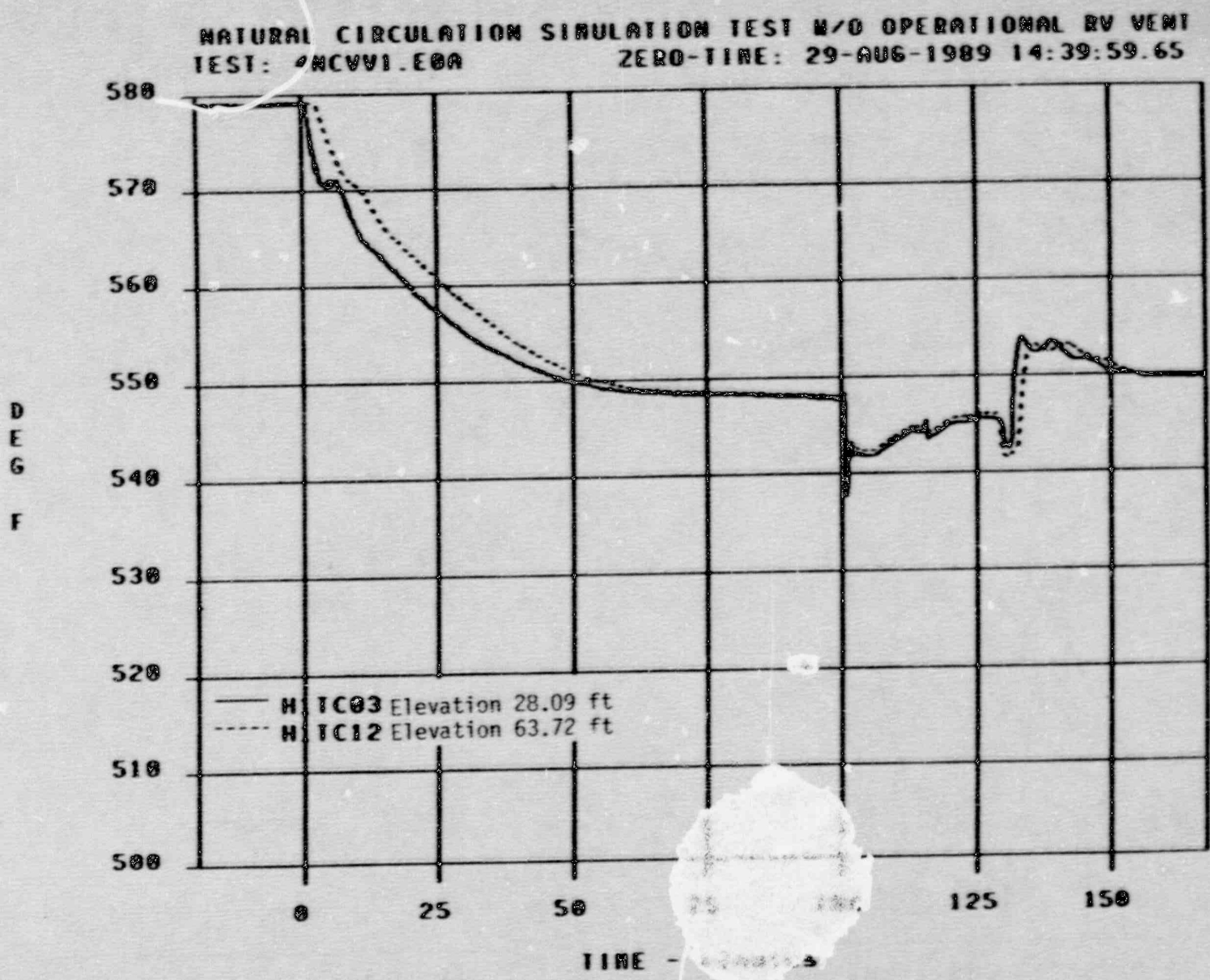

Figure 4.60 Hot Leg A Fluid Temperatures

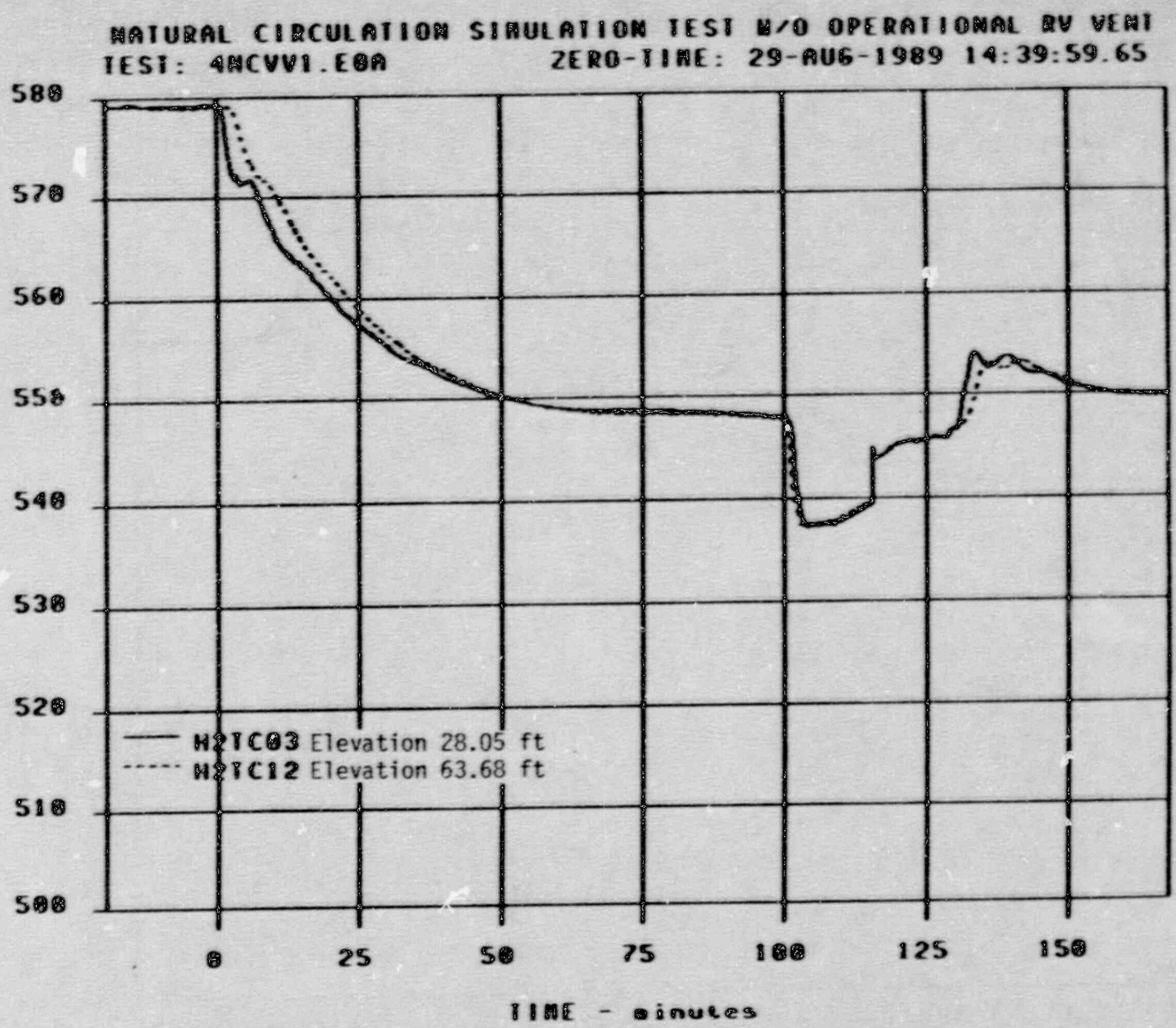

Figure 4.61 Hot Leg B Fluid Temperatures

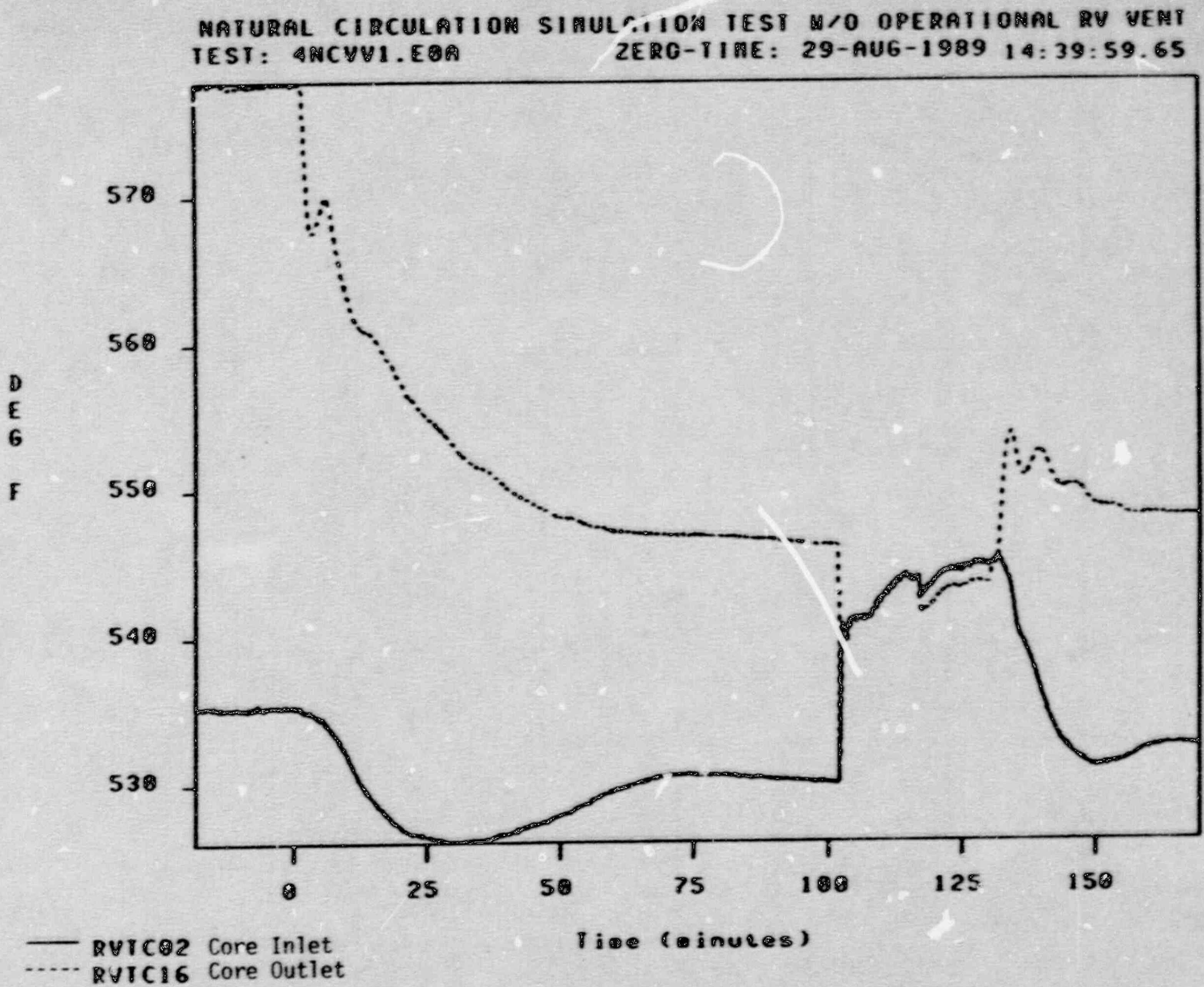

Figure 4.62 Core Inlet And Core Outlet Fluid Temperature

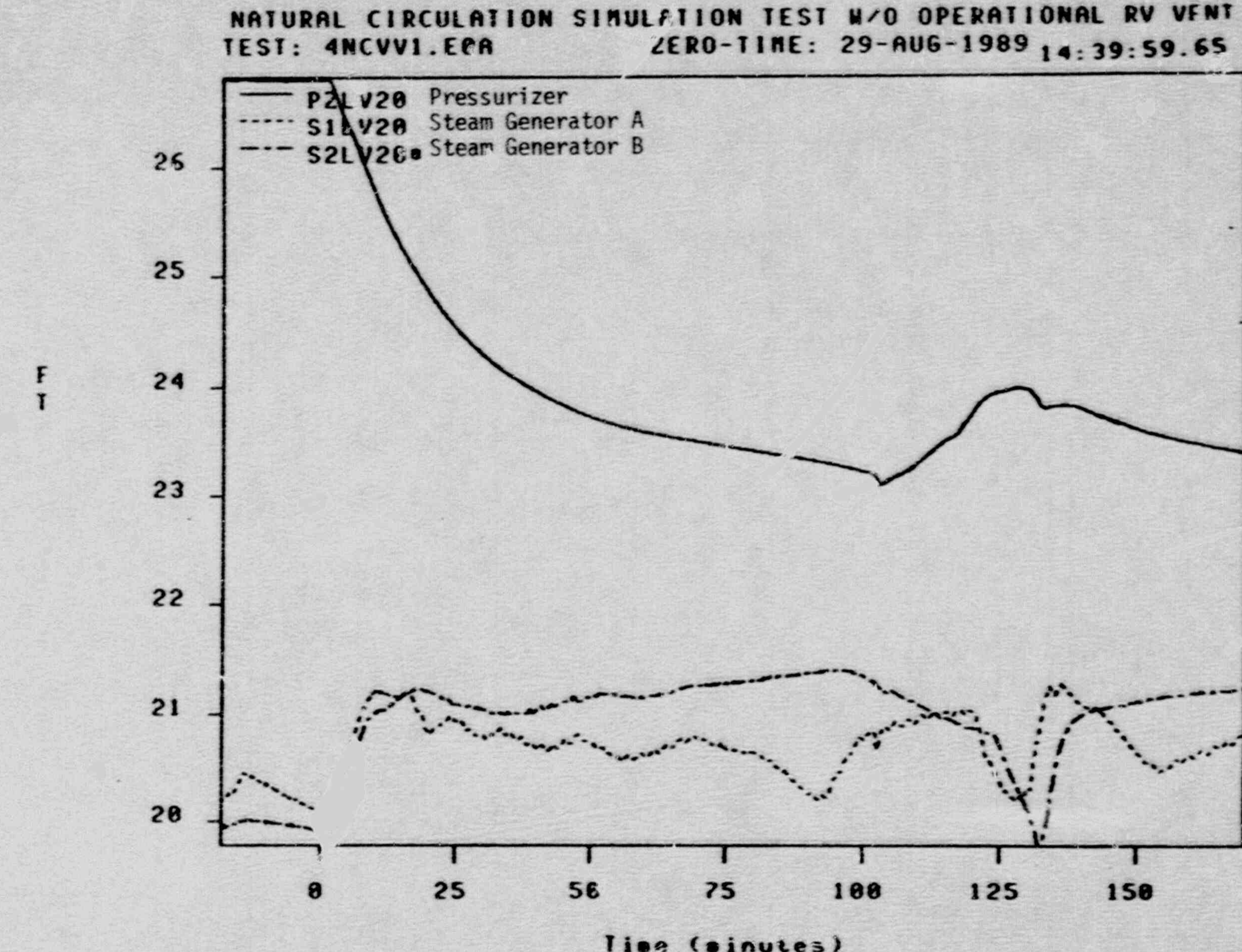

Figure 4.63 Pressurizer And Steam Generator Levels

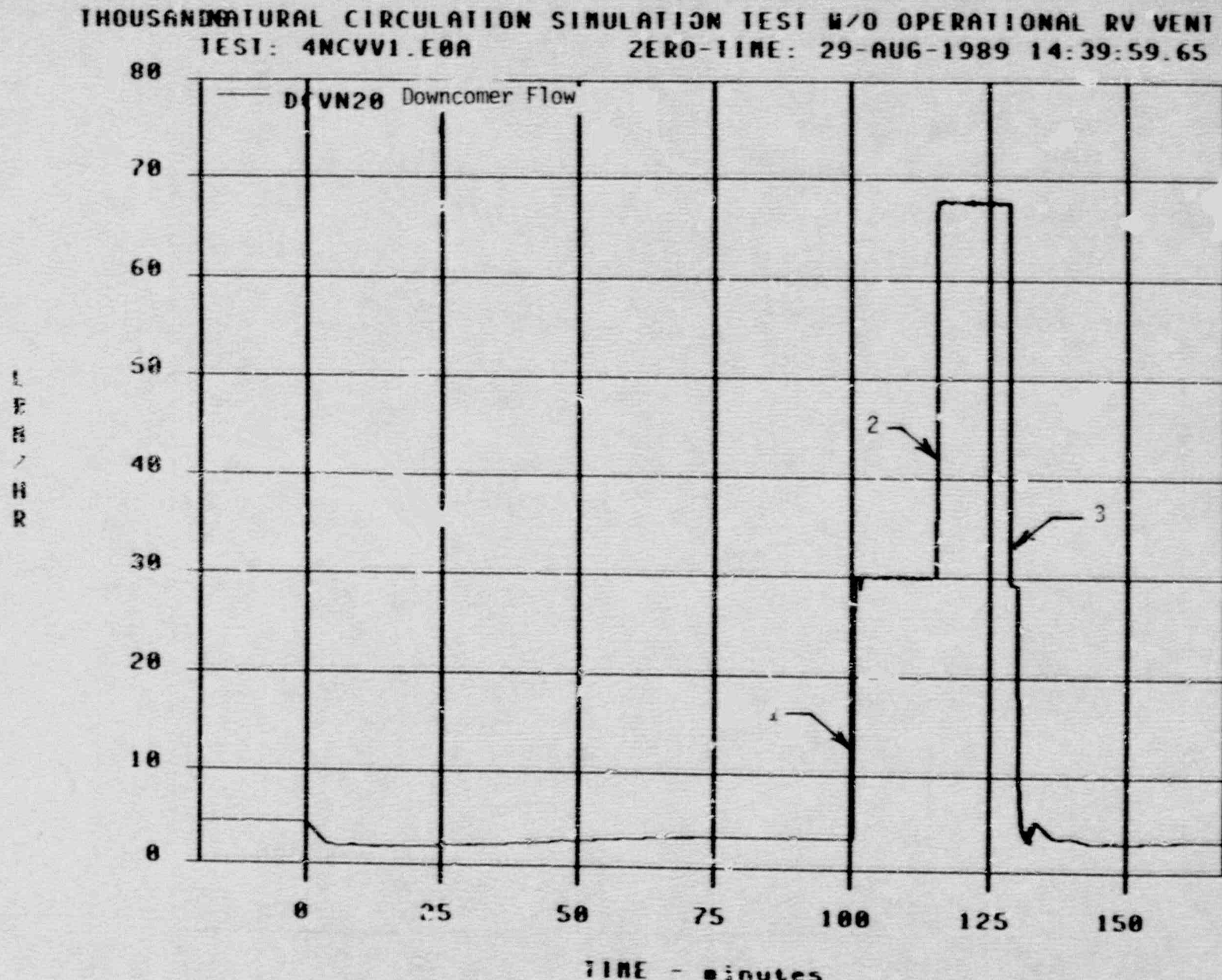

Figure 4.64 Downcomer Flow Rate

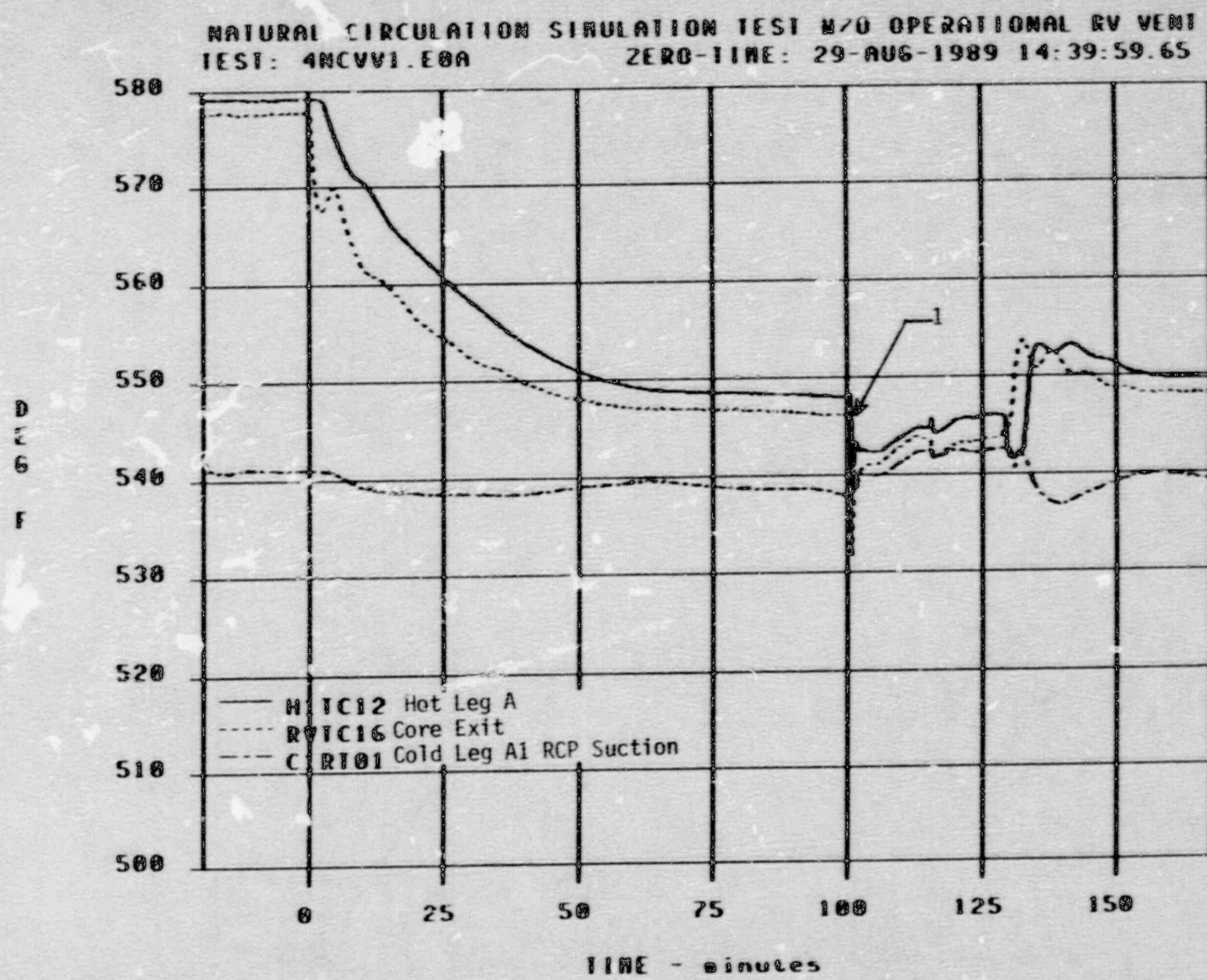

Figure 4.65 Core Exit Hot Leg A And Cold Leg A1 Reactor Coolant Pump Suction Temperatures

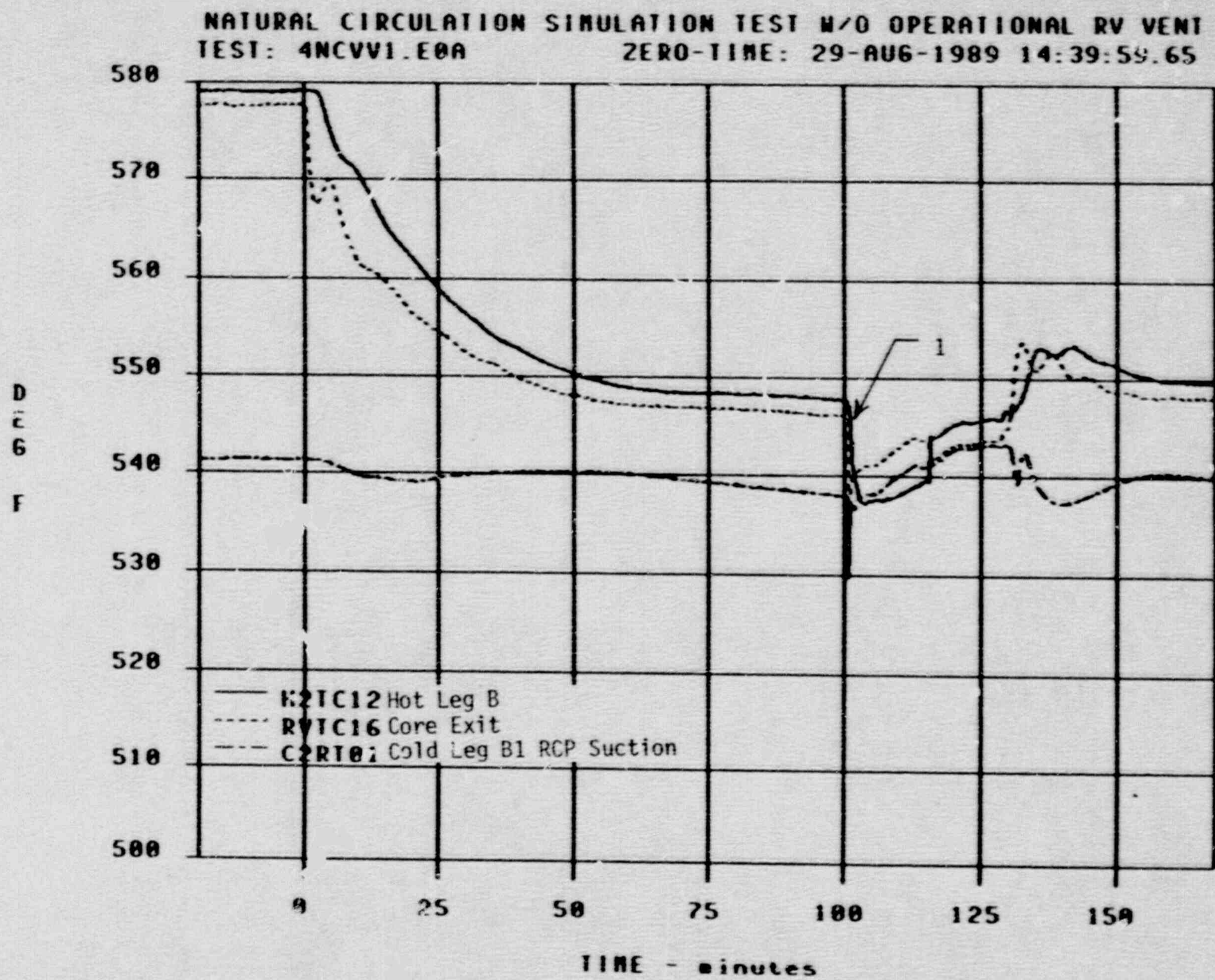

Figure 4.66 Hot Leg B, Core Exit And Cold Leg B1 Reactor Coolant Pump Suction Temperatures

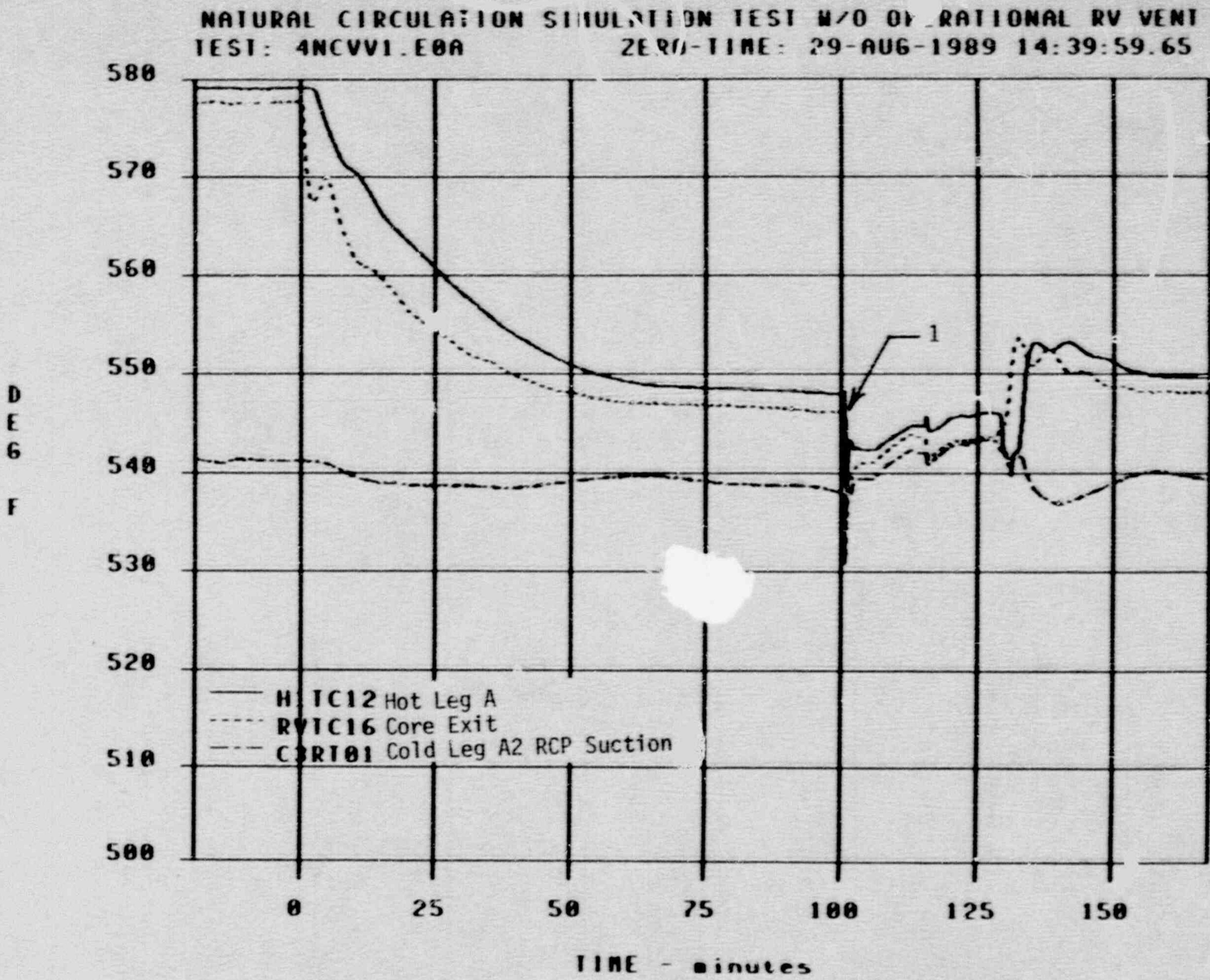

Figure 4.67 Hot Leg A, Core Exit And Cold Leg A2 Reactor Coolant Pump Suction Temperatures

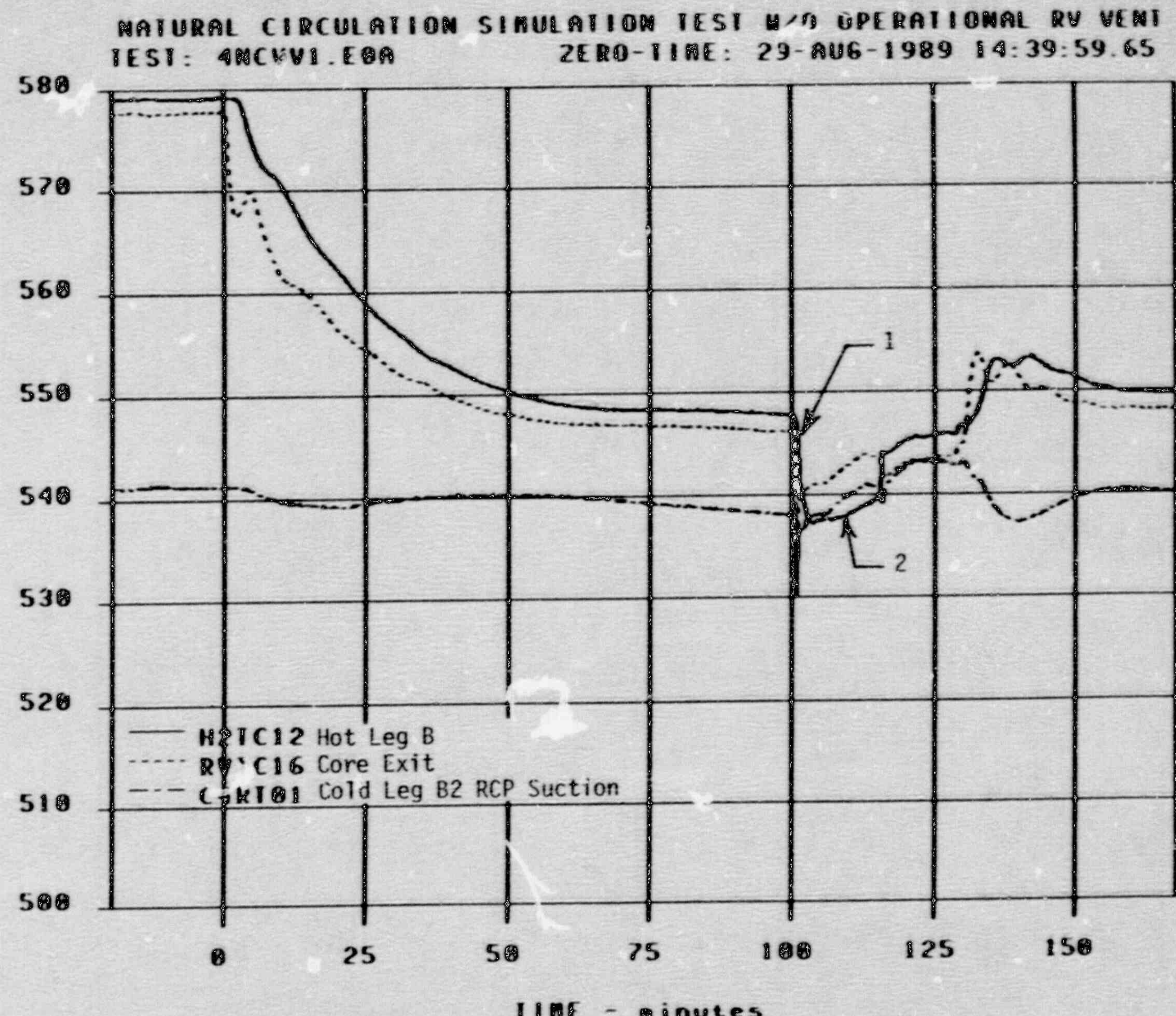

Figure 4.68 Hot Leg B, Core Exit And Cold Leg B2 Reactor Coolant Pump Suction Temperatures

4.3. Observations of Test 4NCHL1

In an attempt to highlight the effect of the heat losses in the reactor coolant pump region on the flow reversal in the cold legs, Test 4NCHL1 imposed additional heat loss in one selected cold leg in each loop. The additional heat loss was obtained by increasing the cooling water flow rate to the selected reactor coolant pumps and also turning off the guard heaters in the upper region of the selected cold leg suction pipes. The normal cooling water flow rate to each reactor coolant pump was approximately 5 gpm. For Test 4NCHL1 the cooling water flow rate in the reactor coolant pumps A2 and B1 was maintained at 5 gpm while the cooling water flow rate in reactor coolant pumps A1 and B2 was increased to 15 gpm. Thus a decrease in the A1 and B2 reactor coolant pump sink temperature was obtained. The MIST reactor coolant pumps are of a canned rotor design and therefore seal leakage does not occur. Similarly the guard heater in the upper regions of the A1 and B2 cold leg suction pipe were turned off.

The selection of the A1 and B2 cold leg was based on observations from numerous screening tests performed in preparation for the MIST Natural Circulation Testing Program wherein it was shown that these two cold legs did not exhibit flow reversals.

As in the previous tests during the initialization period heat losses were apparent across the reactor coolant pumps (Figure 4.69 through 4.72, See 1). Also, as shown for Test 4NCSM1, the reactor vessel vent valves were open (Figure 4.73 and 4.74, See 1). The test was initiated by actuating the core power ramp (Figure 4.75, See 1) again maintaining all other boundary conditions constant. The initial response for Test 4NCHL1 was similar to that observed for Test 4NCSM1, i.e., a decrease in the core exit and hot leg fluid temperatures (Figure 4.76, See 1) and a decrease in the primary loop (Figure 4.77 and 4.78, See 1) and cold leg flow rates (Figures 4.79 and 4.80, See 1) occurred.

As observed in the previous natural circulation tests the reduction in the primary loop flow rate in conjunction with the heat loss in the reactor coolant pumps resulted in an increased positive temperature difference between the reactor coolant pump suction (which remained approximately equal to the steam generator saturation temperature) and discharge fluid temperatures (Figure 4.69 through 4.72, See 2).

Again the combination of the existence of a secondary flow path via the reactor vessel vent valves, the reduction of the primary loop natural circulation driving head and the heat losses in the reactor coolant pumps region of the cold legs resulted in primary loop flow interruption and the establishment of backflow in the cold legs.

Test 4NCHL1 differed from Test 4NCSM1 in that both the A and B loops indicated flow interruption with the A loop interrupting first and the B loop interrupting approximately 5 minutes later (Figure 4.77 and 4.78, See 2). Backflow was established in the A1 cold leg (Figure 4.79, See 2) while the flow in the A2 cold leg was in the forward direction (Figure 4.79, See 3). Similarly backflow was established in the B2 cold leg (Figure 4.80, See 2) while the flow in the B1 cold leg was in the forward direction (Figure 4.80, See 3). Flow direction can also be inferred from the reactor coolant pump suction and discharge temperatures as discussed in Section 4.5.1. Therefore when the temperature difference between the reactor coolant pump suction and discharge becomes negative a flow reversal has occurred (Figure 4.72, See 3). A similar response can also be observed for the A1 cold leg (Figure 4.69, See 3).

Significantly the flow reversals occurred in the two cold legs that had increased heat losses imposed as a boundary conditions, i.e., cold legs A1 and B2.

4.3.1. Facility Hold Period

Subsequent to the flow interruption no operator actions were performed for approximately four hours and the response of the MIST facility was observed. The transient response can be observed on Figures 4.81 through 4.93. As can be observed from these figures the primary system exhibited a continuous cooling trend over this period (Figures 4.86 through 4.91). Primary loop flow appears to have been maintained throughout the period. The flow rate in the A2 cold leg stabilized at approximately 1060 lb/hr in the forward flow direction and the A1 cold leg flow rate stabilized at approximately 330 lb/hr in the reverse flow direction (Figure 4.84). The B1 cold leg flow rate also stabilized at approximately 1060 lb/hr in the forward flow direction and the B2 cold leg flow rate stabilized at approximately 360 lb/hr in the reverse flow direction (Figure 4.85).

4.3.2. Operator Actions and Loop Recovery Perio[illegible]

Subsequent to the hold period the loop operator opened both the A and the B loop high point vents (Figure 4.94, See 1) . The primary system pressure rapidly decreased (Figure 4.81, See 1) and the pressurizer inventory decreased rapidly (Figure 4.92, See 1). The discharge of hotter fluid from the pressurizer increased the hot leg A fluid temperature (Figure 4.90, See 1), primary flow in the A loop increased and forward flow was established in the A1 cold leg (Figure 4.84, See 1). The response of the B loop appears to be similar to that observed in Test 4NCSM1 in that when the A loop flow increased the B loop flow decreased (Figure 4.85, See 1).

The rapid reduction in the pressurizer level at this time necessitated the actuation of makeup flow (Figure 4.95 , See 1). The resultant effect of (1) the increase in the flow through the core, reduction in the core outlet temperature (Figure 4.91, See 1), (2) the injection of cold makeup fluid into the A2 cold leg, reduction in the core inlet temperature (Figure 4.91, See 2), and (3) the closure of the high point vents (Figure 4.94, See 2) was a decrease in the primary loop natural circulation driving head and reverse flow was re-established in the A1 cold leg (Figure 4.84, See 2).

The loop operator then began decreasing the makeup flow rate (Figure 4.95, See 2). The effect of the reduction and subsequent termination of makeup flow was a decrease in the A2 cold leg natural circulation driving head and a reduction in the A2 cold leg flow rate occurred (Figure 4.96, See 1). The primary loop [illegible] in the A loop then interrupted (Figure 4.97, See 1) and the core exit temperature began a heatup (Figure 4.98, See 1). The termination of makeup flow, [illegible] interruption of A loop primary flow and the mixing in the downcomer of hotter fluid from the core exit via the reactor vessel vent valves resulted in an increase in the core inlet temperature (Figure 4.98, See 2). The increase in the core region fluid temperatures resulted in an increase in the natural circulation driving head that eventually established forward flow in the A1 cold leg (Figure 4.96, See 2). Both the A1 and the A2 cold legs continued flowing in the forward direction through the remainder of the natural circulation phase of the test. However, at approximately 300 minutes the loop operator again actuated makeup flow (Figure 4.95, See 3) in an attempt to increase pressurizer level. The makeup flow again caused a reduction in the core region fluid temperatures (Figure 4.98, See 3), an increase in the A2 cold leg (makeup injection location) flow rate (Figure 4.96, See 3) and a reduction in the A1 cold leg flow (Figure 4.96, See 4). The A1 cold leg flow rate then began increasing (Figure 4.96, See 5) and trended with reductions in the makeup flow rate. When the makeup flow was terminated (Figure 4.95, See 4) the A2 cold leg flow rate decreased and both the A1 and A2 flow rates became equal (Figure 4.96, See 6).

At approximately 305 minutes the loop operator noticed the primary system pressure was increasing (Figure 4.99, See 1) and initiated letdown flow (Figure 4.100, See 1) in an attempt to maintain the specified primary system pressure of 2175 psia. The letdown line was located at the low point of the B1 cold leg suction pipe. While the letdown flow was active, through approximately 321 minutes, the cold leg B1 flow rate decreased continuously (Figure 4.101, See 1). The flow direction in the B2 cold leg, as deduced by the negative temperature difference across the reactor coolant pump (Figure 4.102) remained in the reverse flow direction and the reverse flow rate increased slightly (Figure 4.101, See 2).

At approximately 322 minutes the loop operator increased the core power approximately 5 Kw (Figure 4.103, See 1) and the flow rate in the A1, A2 and B1 cold legs increased (Figure 4.96, See 7 and Figure 4.101, See 3). The flow direction in the B2 cold leg remained in the reverse flow direction as indicated by the reactor coolant pump suction and discharge temperatures (Figure 4.102) and the venturi flow meter (Figure 4.101, See 4).

The loop operator increased the core power further (Figure 4.103, See 2) and, when the core power attained approximately 31 Kw, forward flow was established in the B2 cold leg (Figure 4.102, See 1 and Figure 4.101, See 5). As the core power was increased the pressure in both steam generators began increasing (Figure 4.104 See 1) and indicates an increase in primary-to-secondary heat transfer occurred.

The core power was then maintained constant and at approximately 345 minutes the A1 reactor coolant pump was started. The primary system temperature response was similar to that observed following the pump start in Test 4NCVV1, Section 4.2.2. The primary system pressure, however, increased approximately 40 psi (Figure 4.99, See 2). A second reactor coolant pump (B2) was started approximately 15 minutes later. the primary system pressure then increased at a greater rate (Figure 4.99, See 3). the primary system pressure attained a maximum value of approximately 2350 psia (this was the PORV setpoint, but the PORV did not lift) and then began decreasing (Figure 4.99, See 4).

Approximately 15 minutes later both reactor coolant pumps were tripped and the MIST facility established new steady state conditions with forward flow of approximately 900 lb/hr in each cold leg. The test was terminated at approximately 423 minutes after test initiation.

Figures for Test 4NCHL1

Natural Circulation Test with Imposed Heat Losses

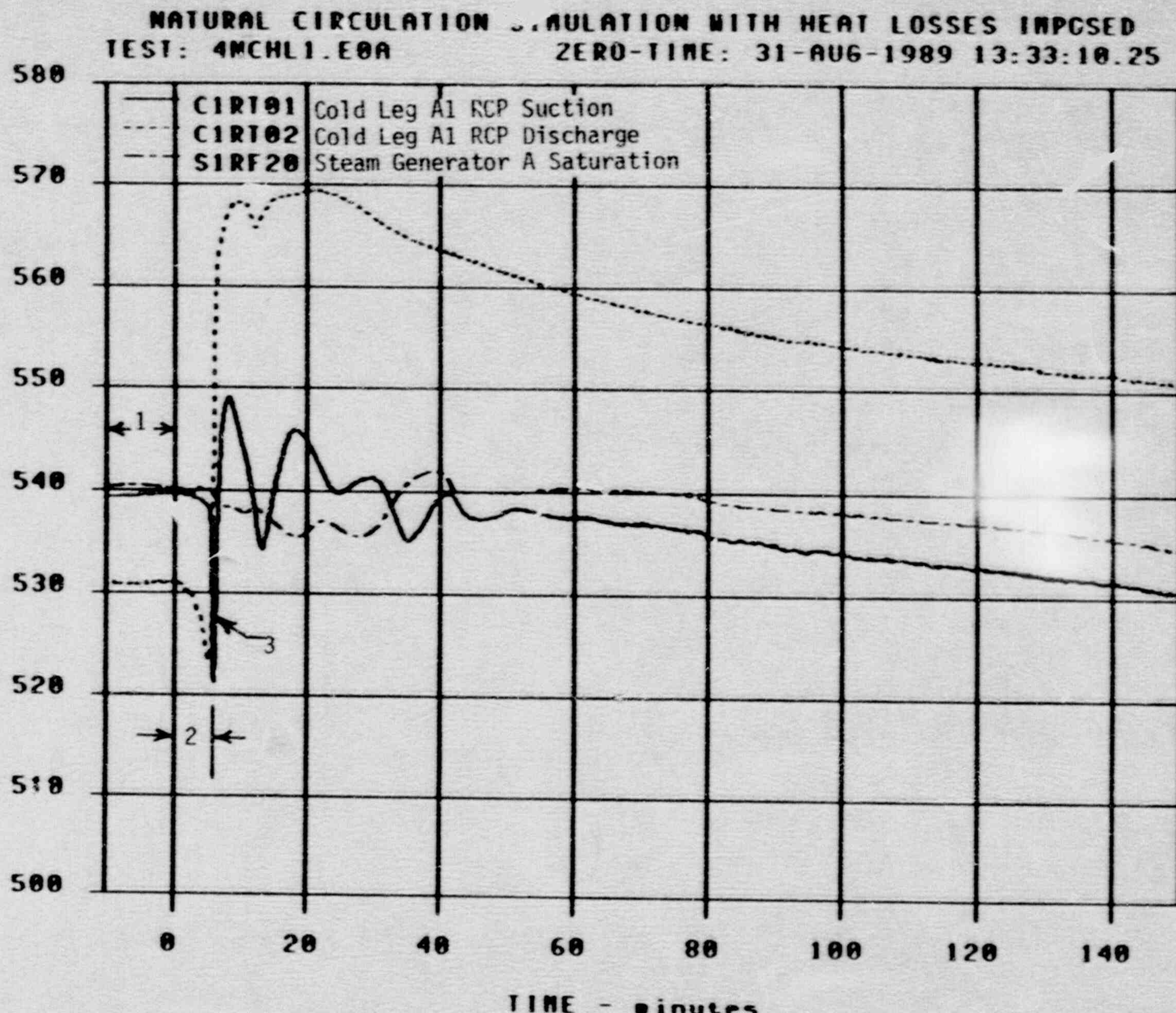

Figure 4.69 Steam Generator A Saturation Temperature And Cold Leg A1 Reactor Coolant Pump Suction And Discharge Temperature

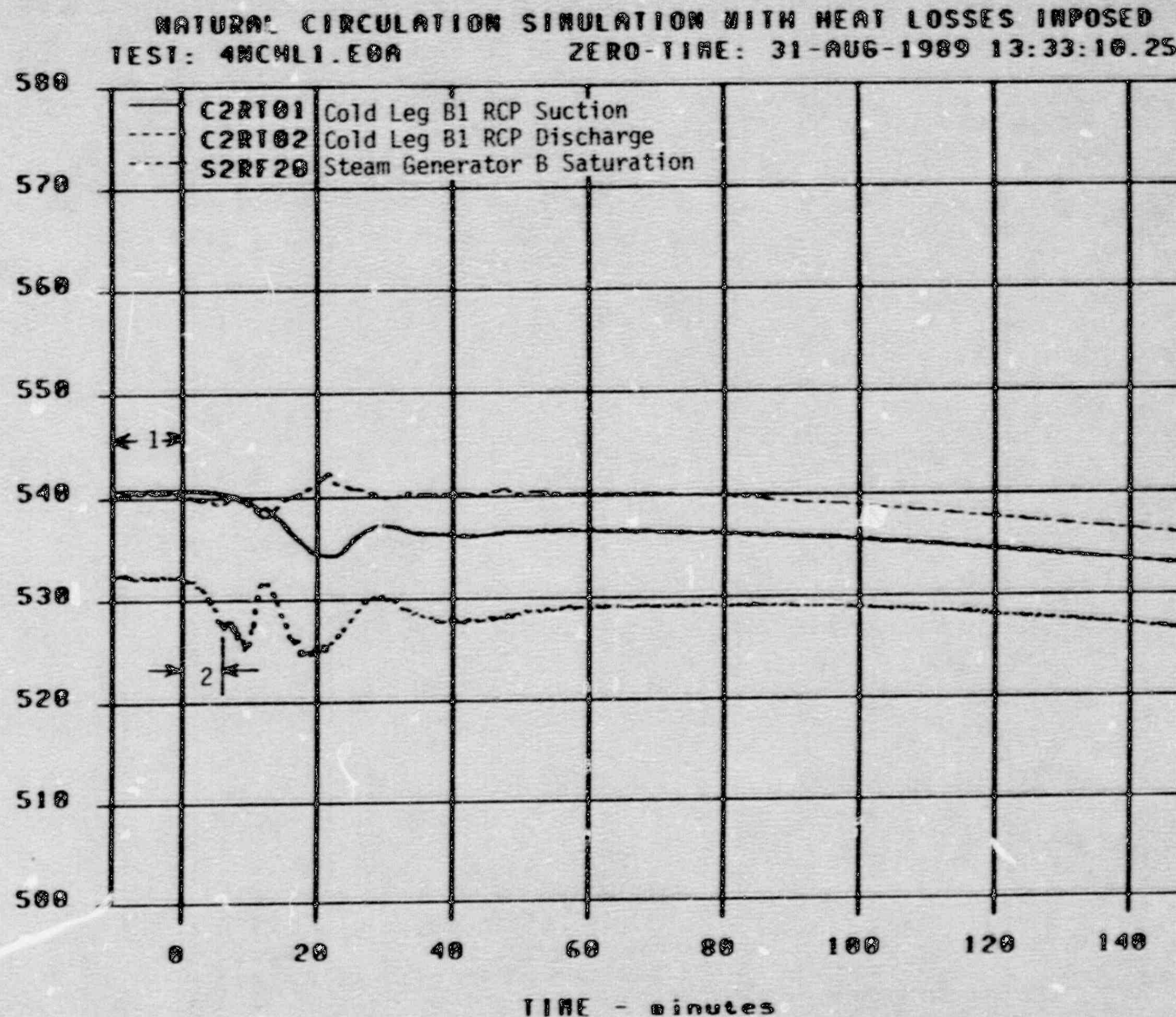

Figure 4.70 Steam Generator B Saturation Temperature And Cold Leg B1 Reactor Coolant Pump Suction And Discharge Temperature

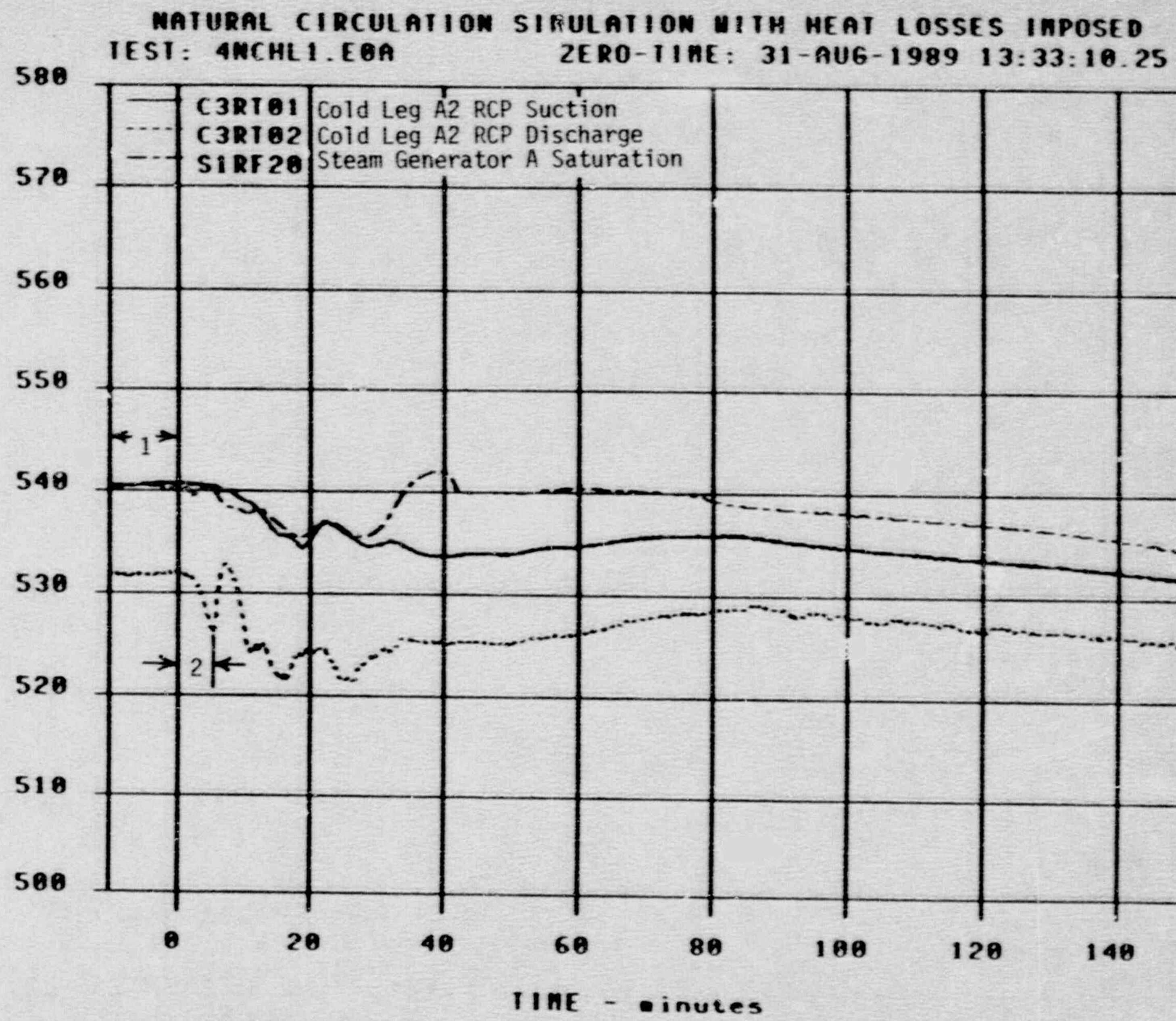

Figure 4.71 Steam Generator A Saturation Temperature And Cold Leg A2 Reactor Coolant Pump Suction And Discharge Tempe ature

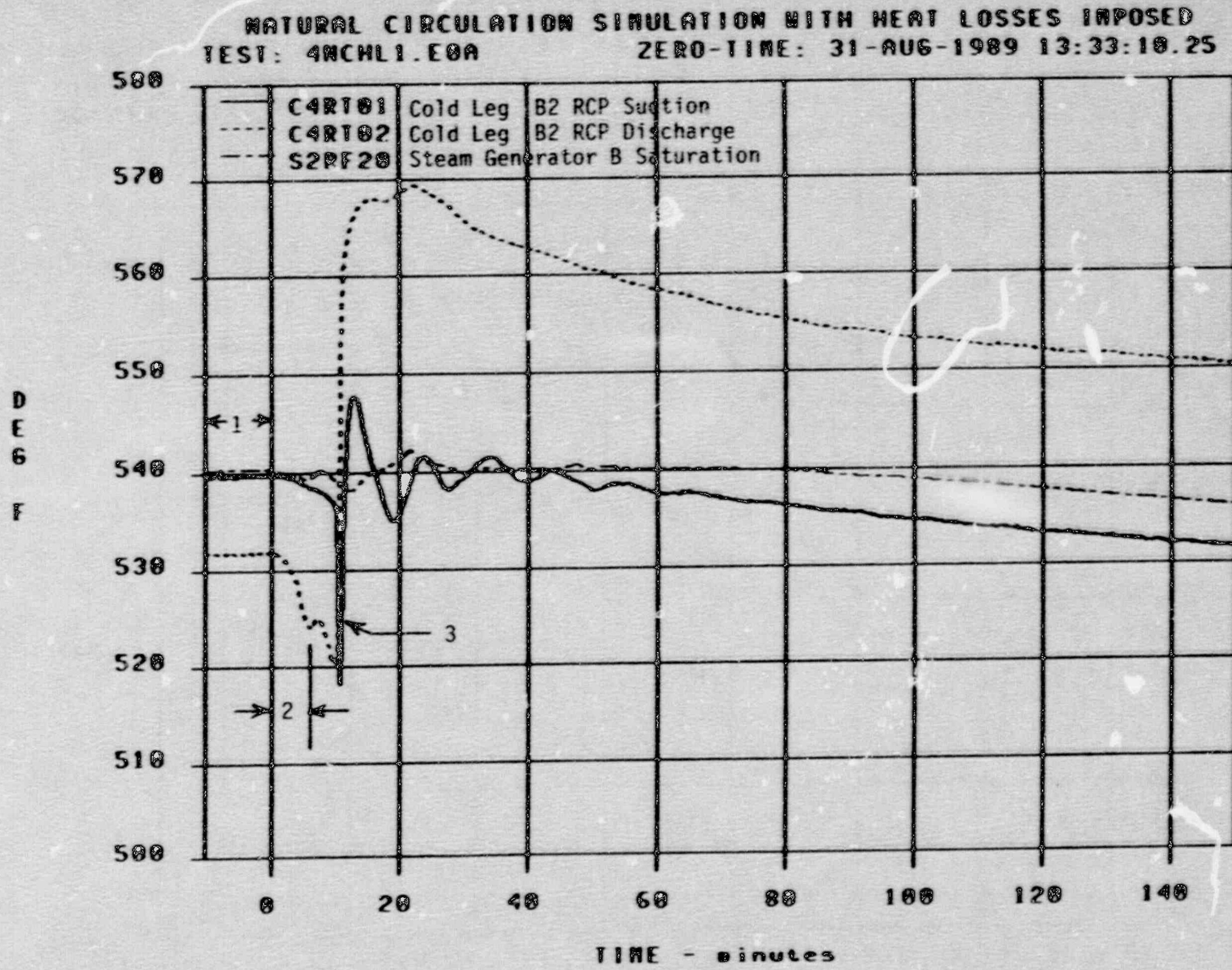

Figure 4.72 Steam Generator B Saturation Temperature And Cold Leg B2 Reactor Coolant Pump Suction And Discharge Temperature

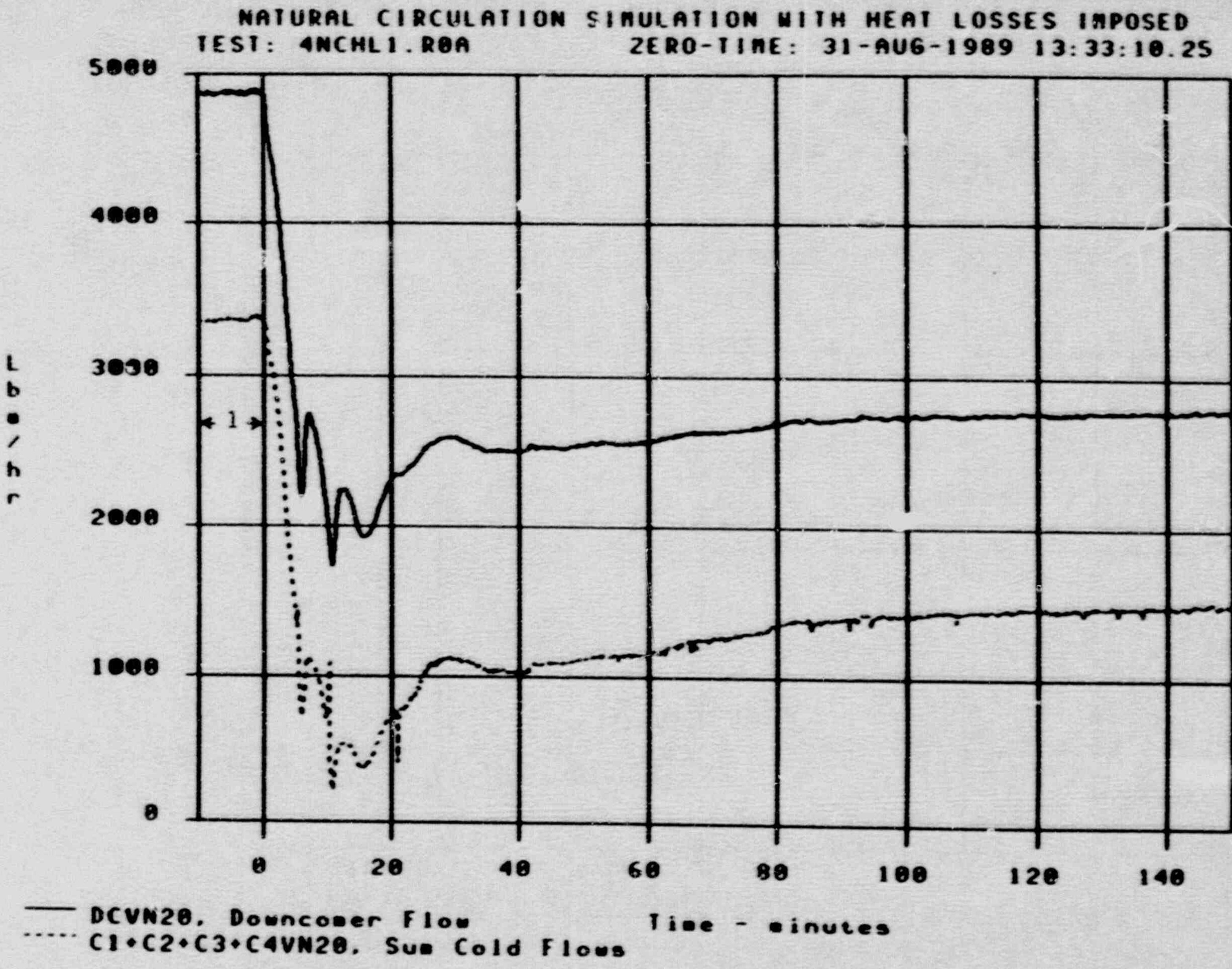

Figure 4.73 Downcomer Flow Rate and the Summation of the Flow Rate in All Four Cold Legs

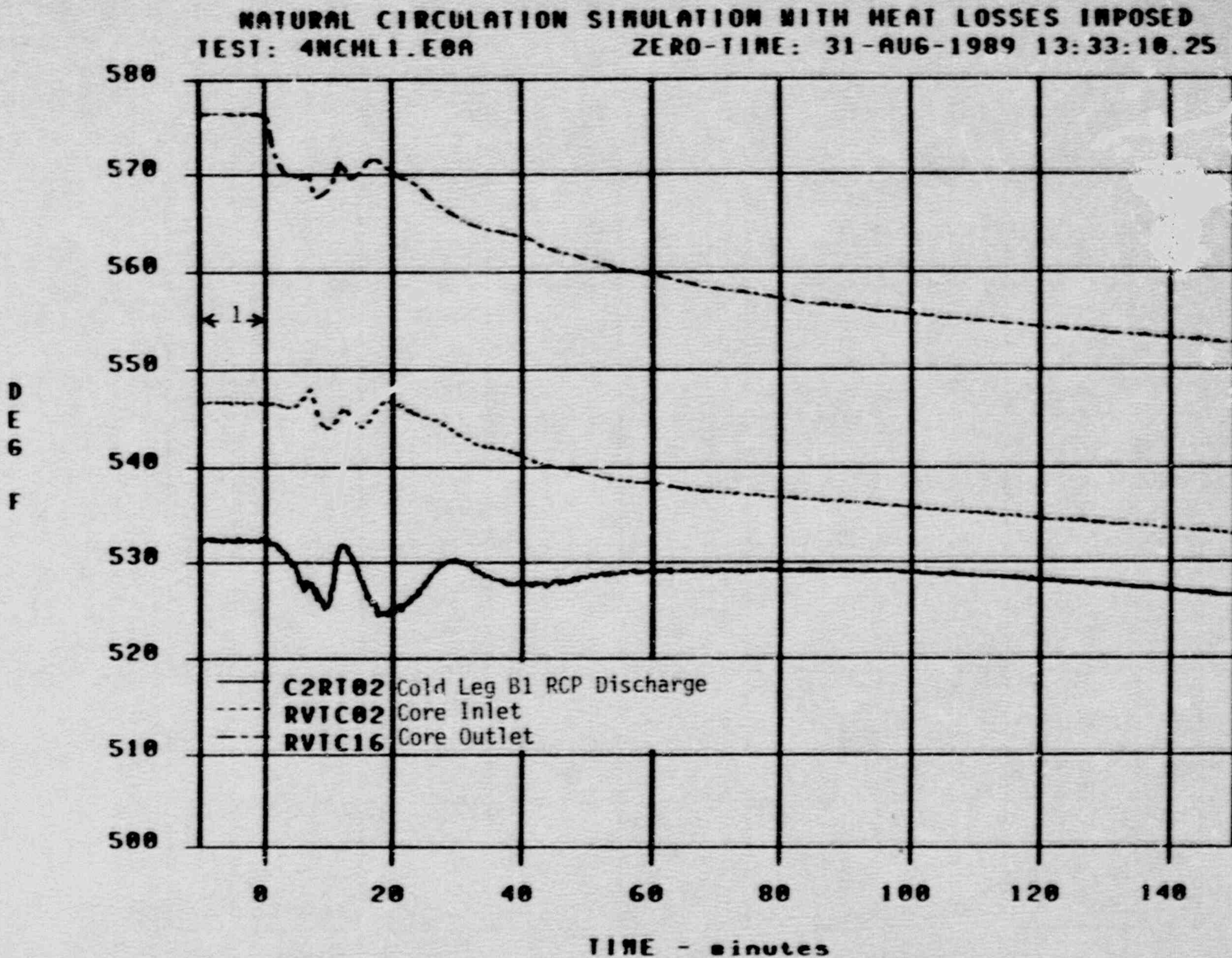

Figure 4.74 Cold Leg B1 Reactor Coolant Pump Discharge Temperature And Core Inlet And Outlet Temperaturc

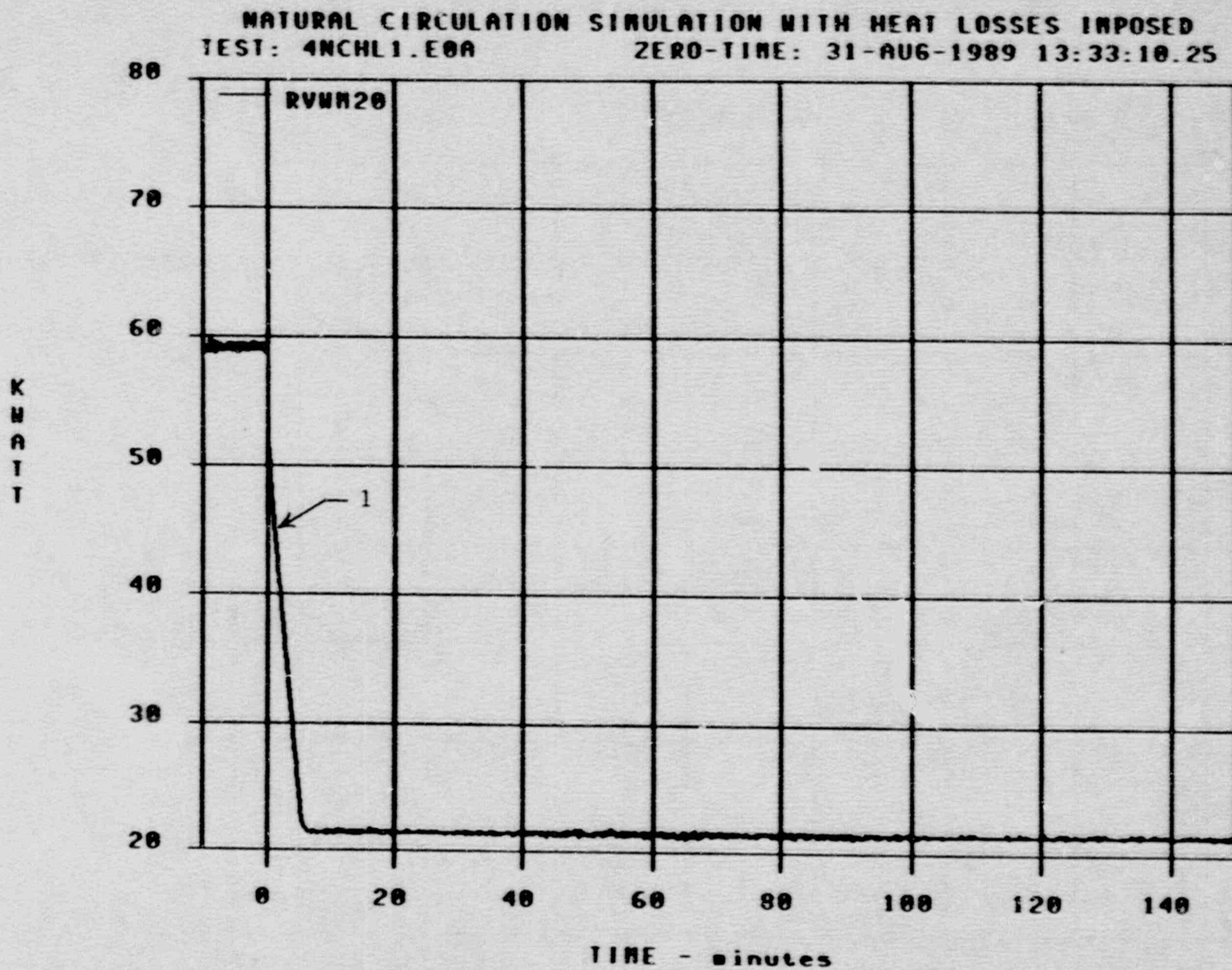

Figure 4.75 Core Power

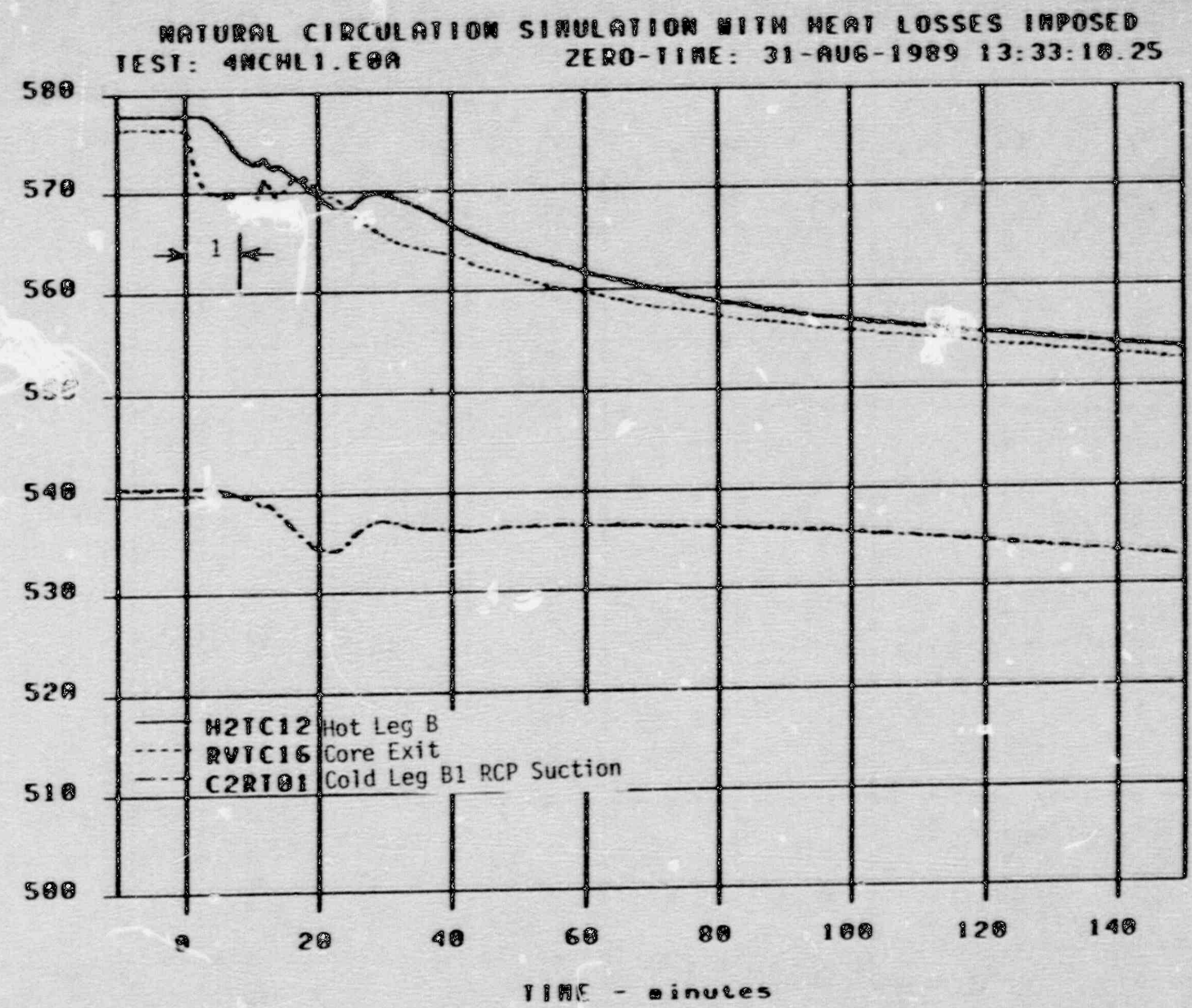

Figure 4.76 Core Exit, Hot Leg B And Cold Leg B1 Reactor Coolant Pump Suction Temperatures

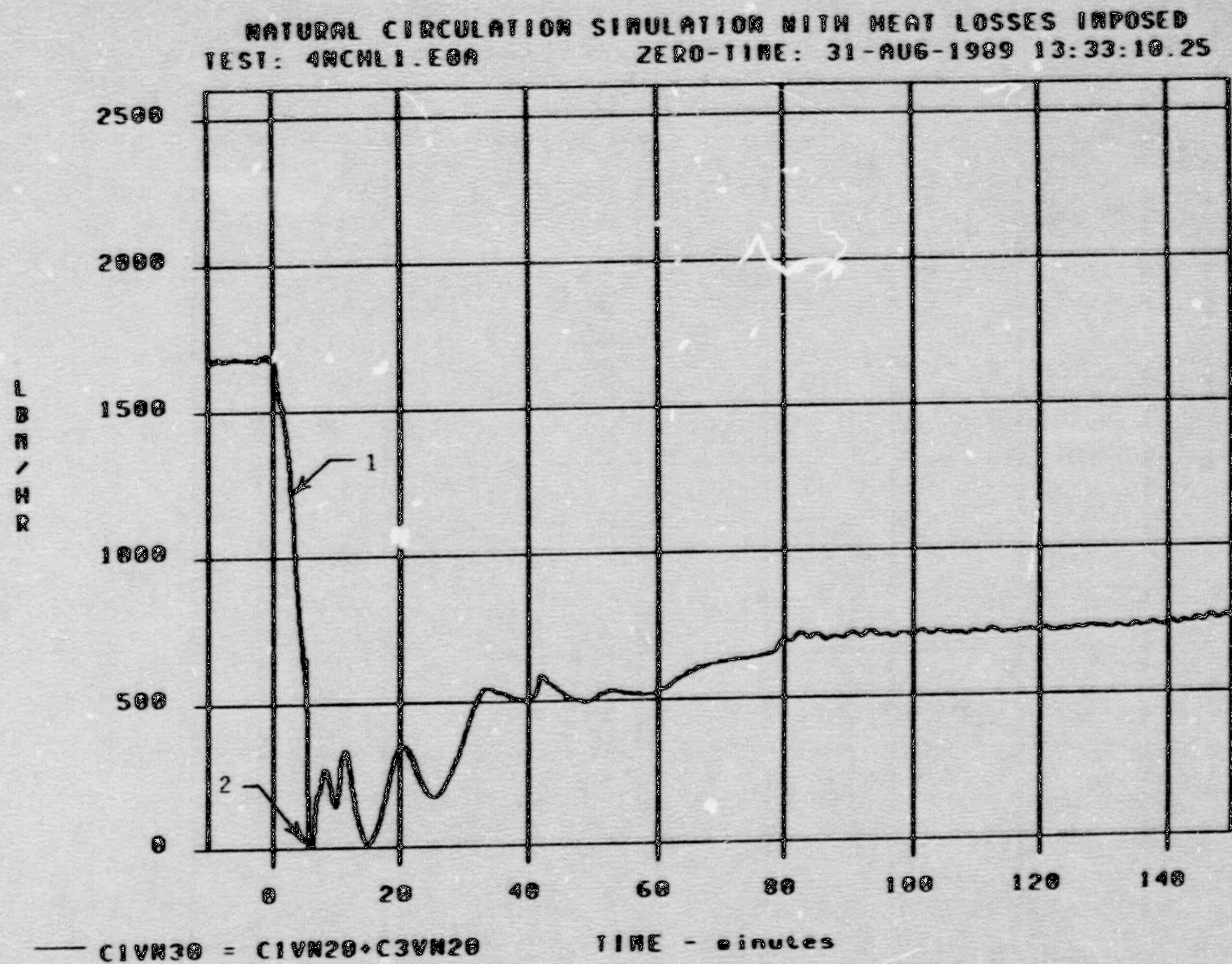

Figure 4.77 Summation Of The A1 And A2 Cold Leg Flow Rates

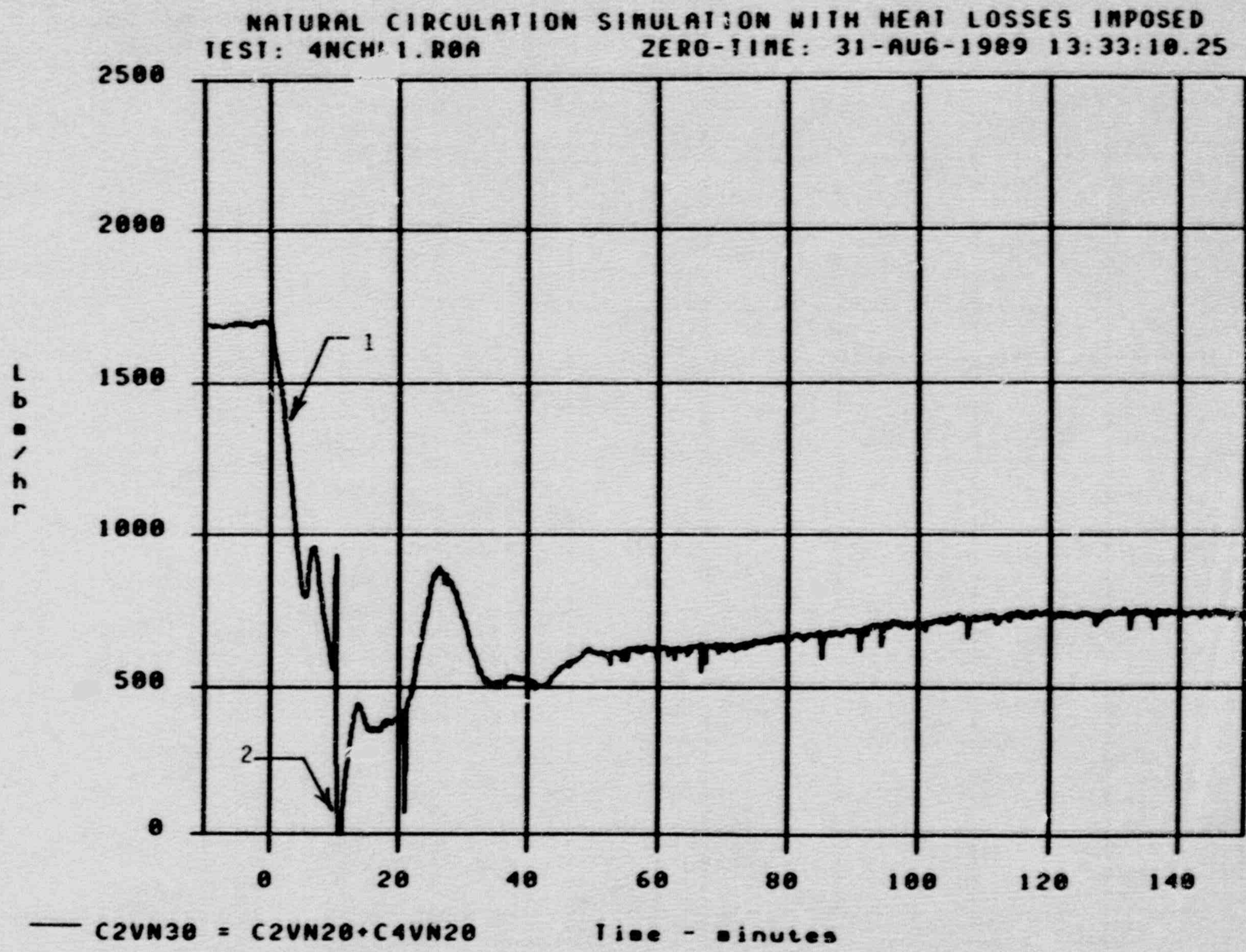

Figure 4.78 Summation of the B1 and B2 Cold Leg Flow Rates

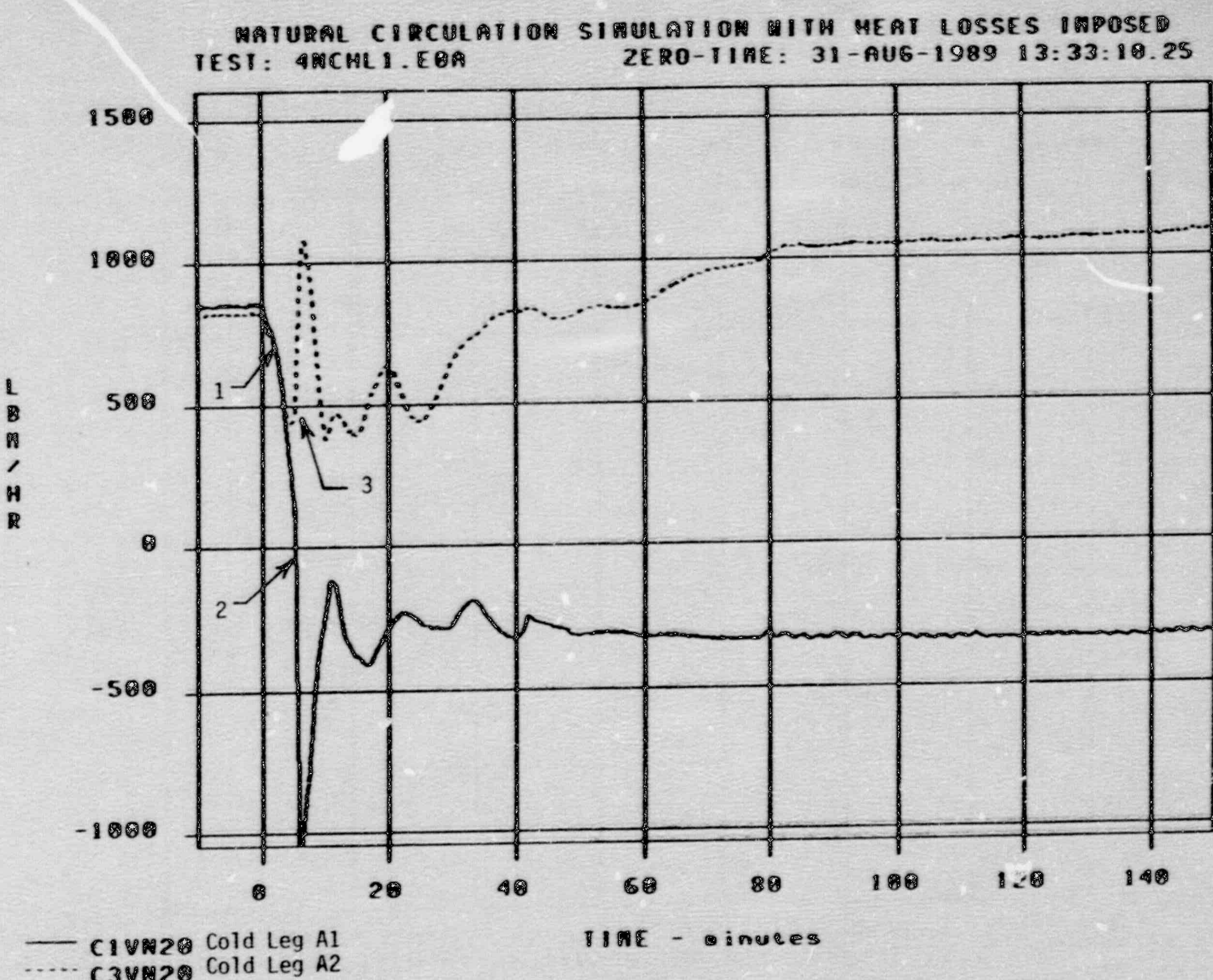

Figure 4.79 Cold Leg A1 And A2 Flow Rate

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IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6"

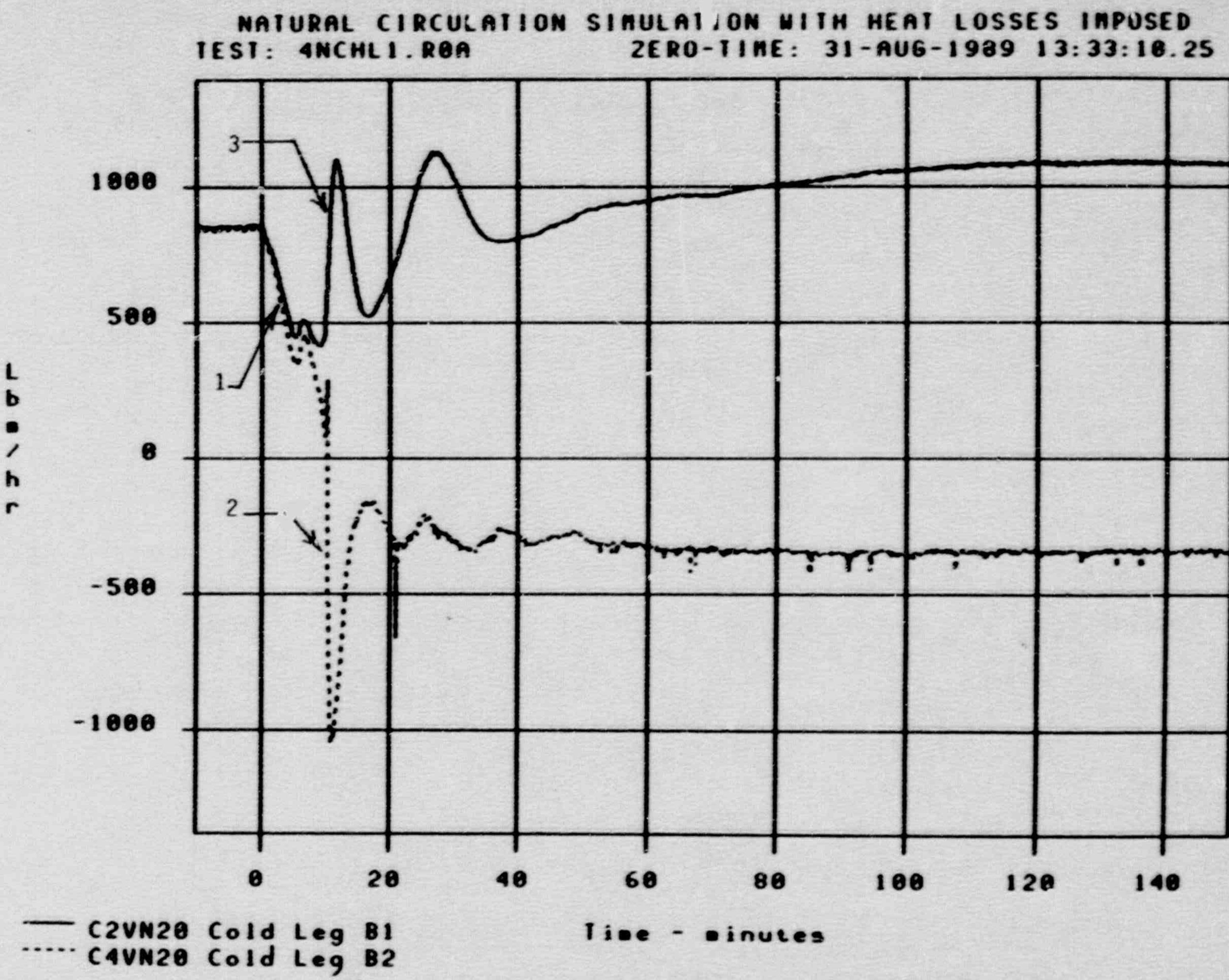


Figure 4.80 Cold Leg B1 and B2 Flow Rate

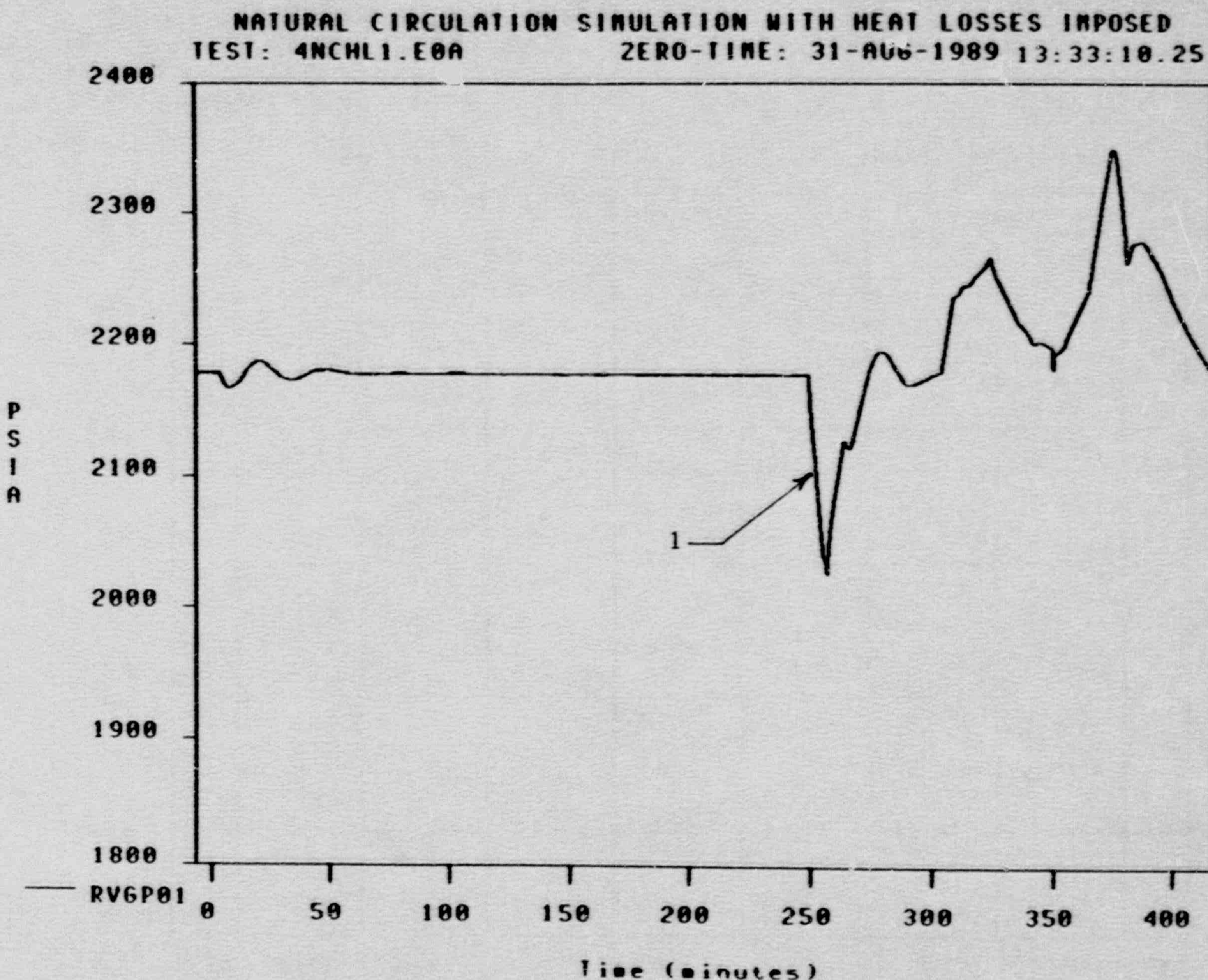


Figure 4.81 Primary System Pressure

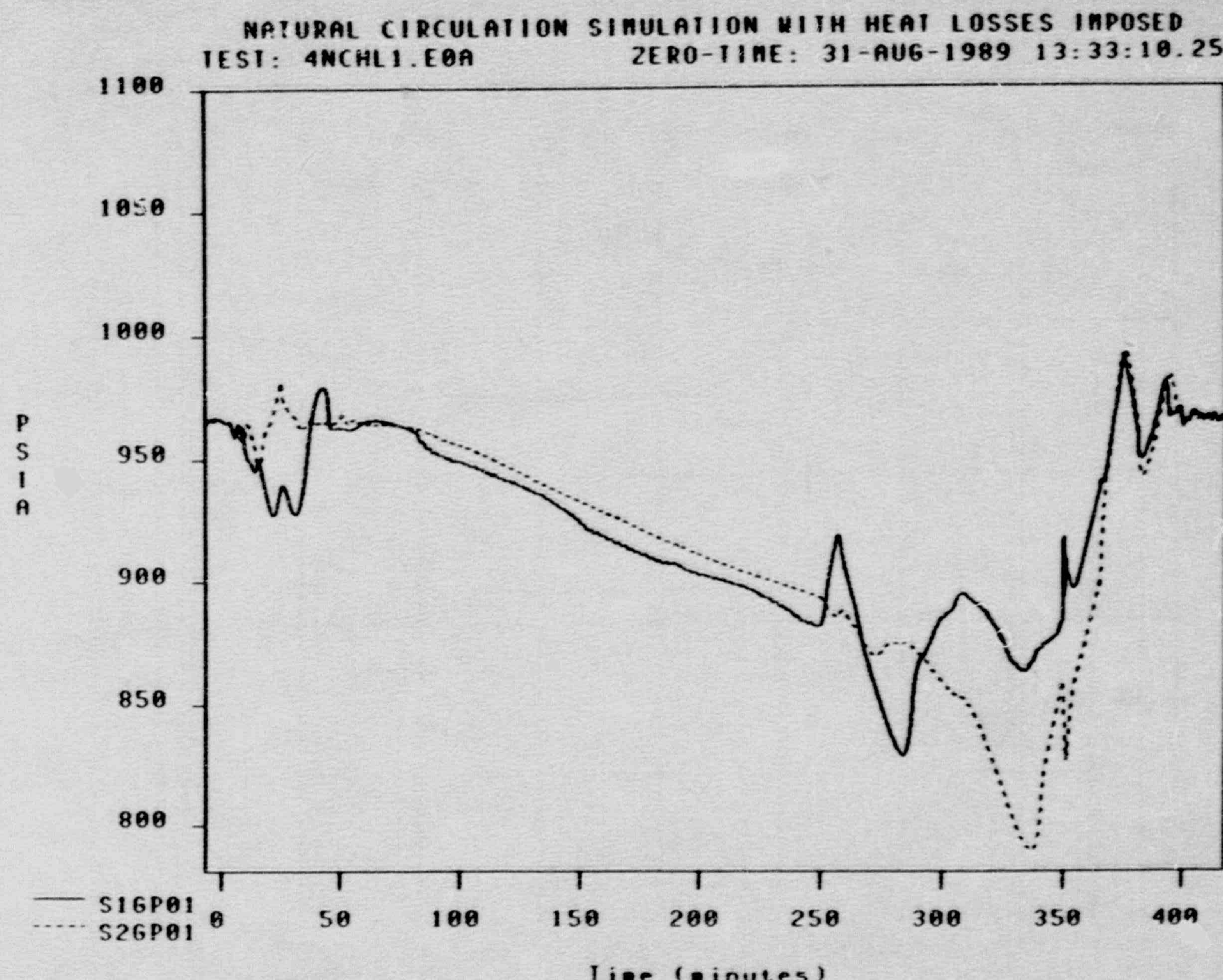


Figure 4.82 Secondary System Pressure

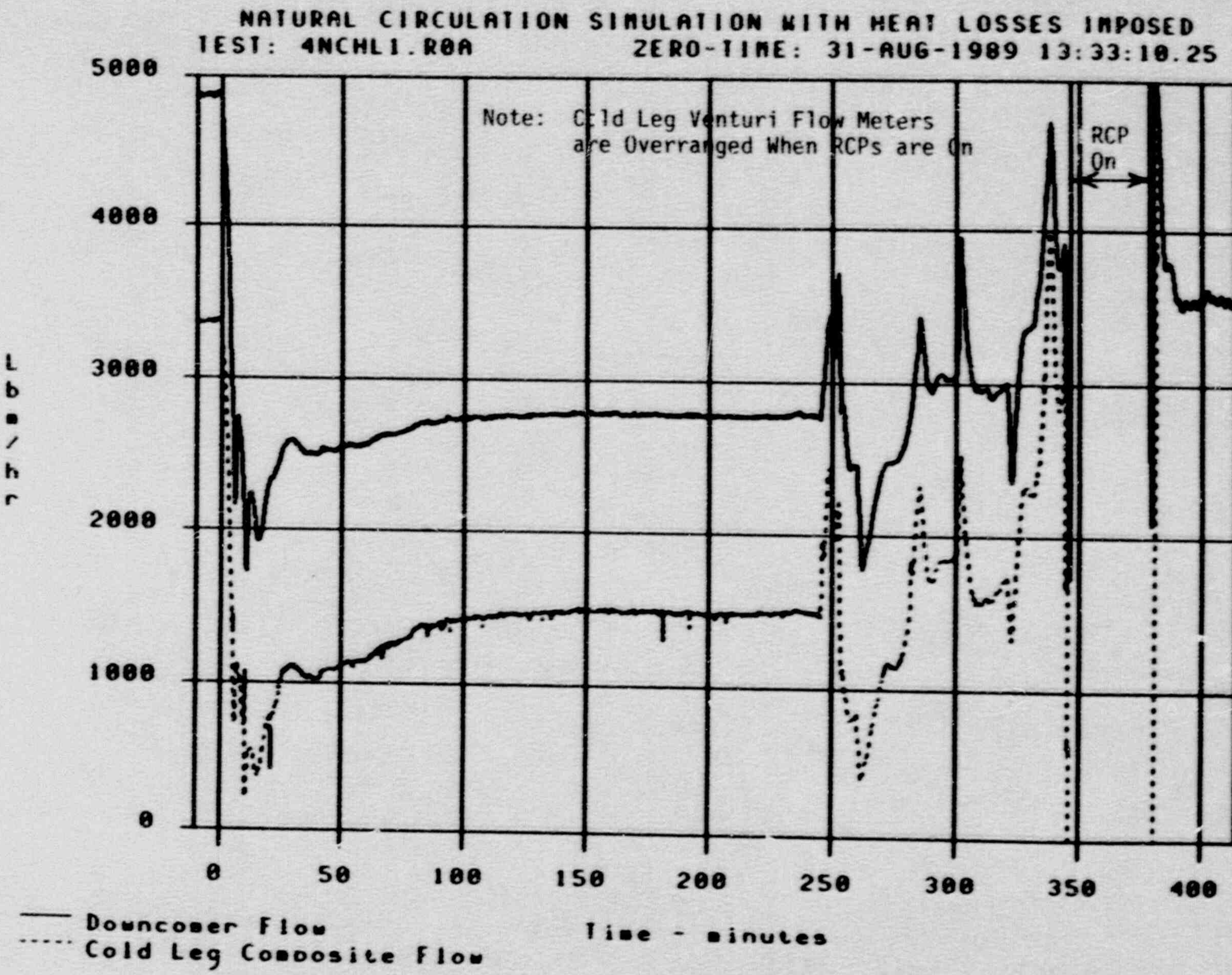


Figure 4.83 Downcomer Flow Rate and the Summation of the Flow Rate in All Four Cold Legs

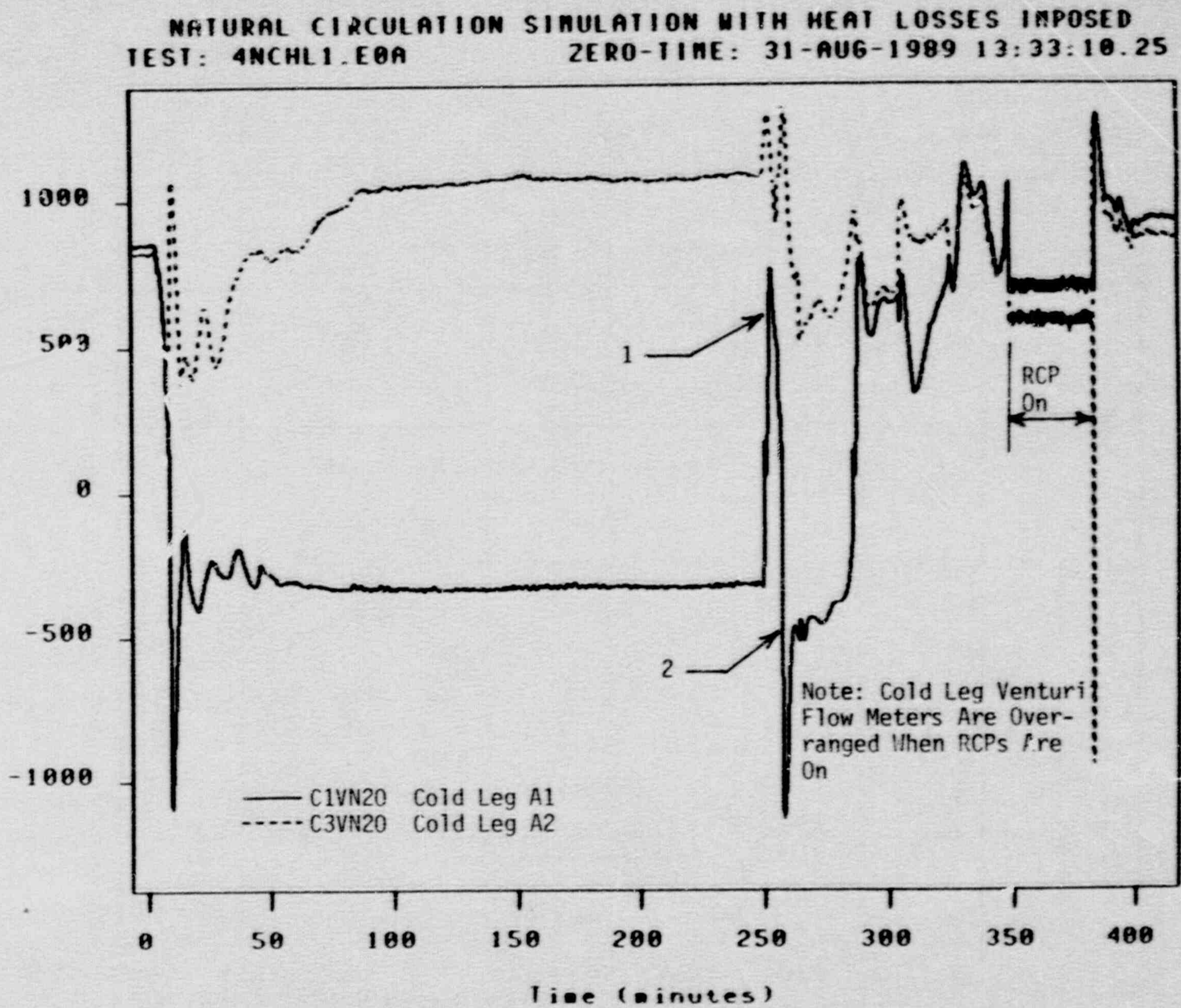


Figure 4.84 Cold Leg A1 and A2 Flow Rate

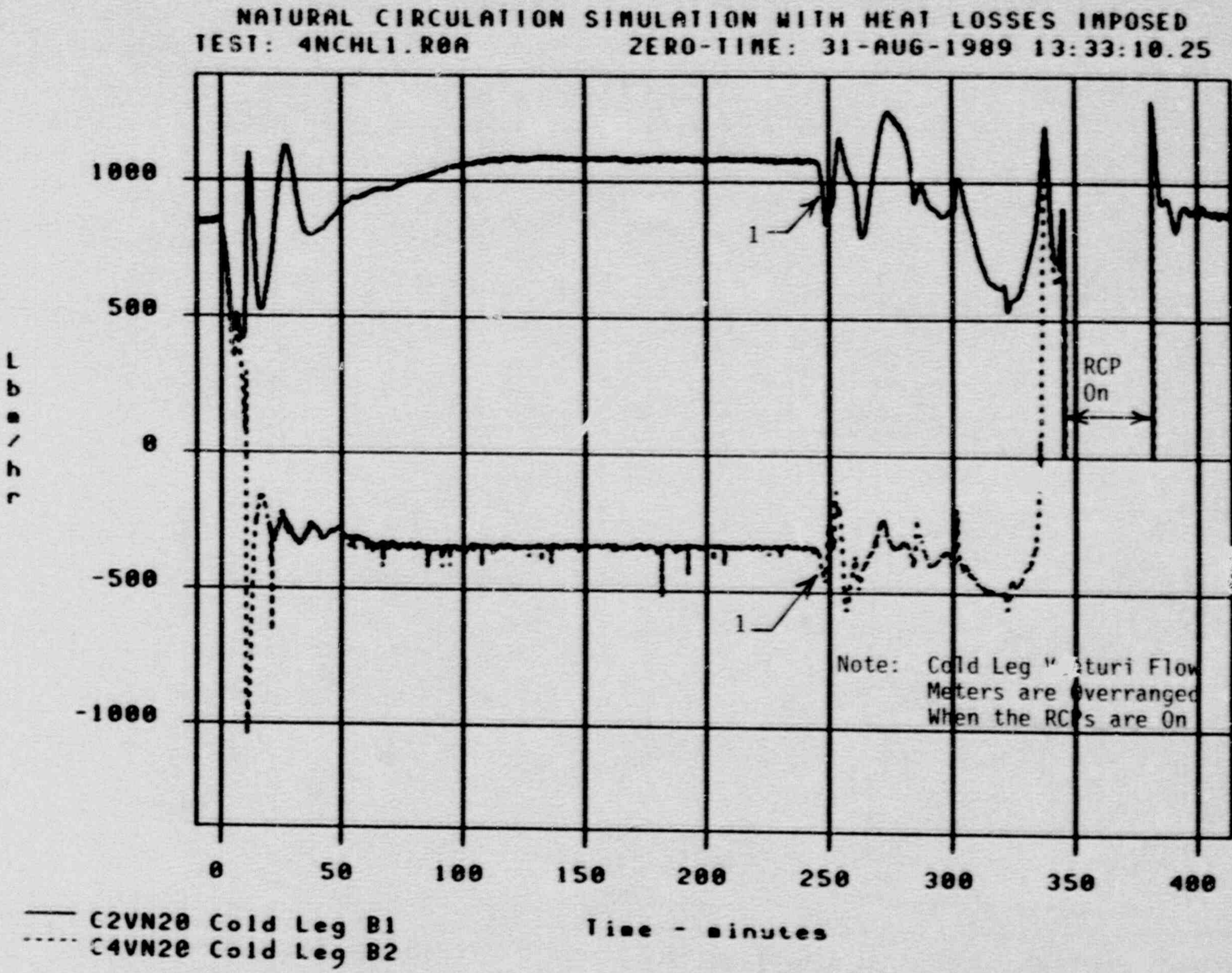


Figure 4.85 Cold Leg B1 and B2 Flow Rate

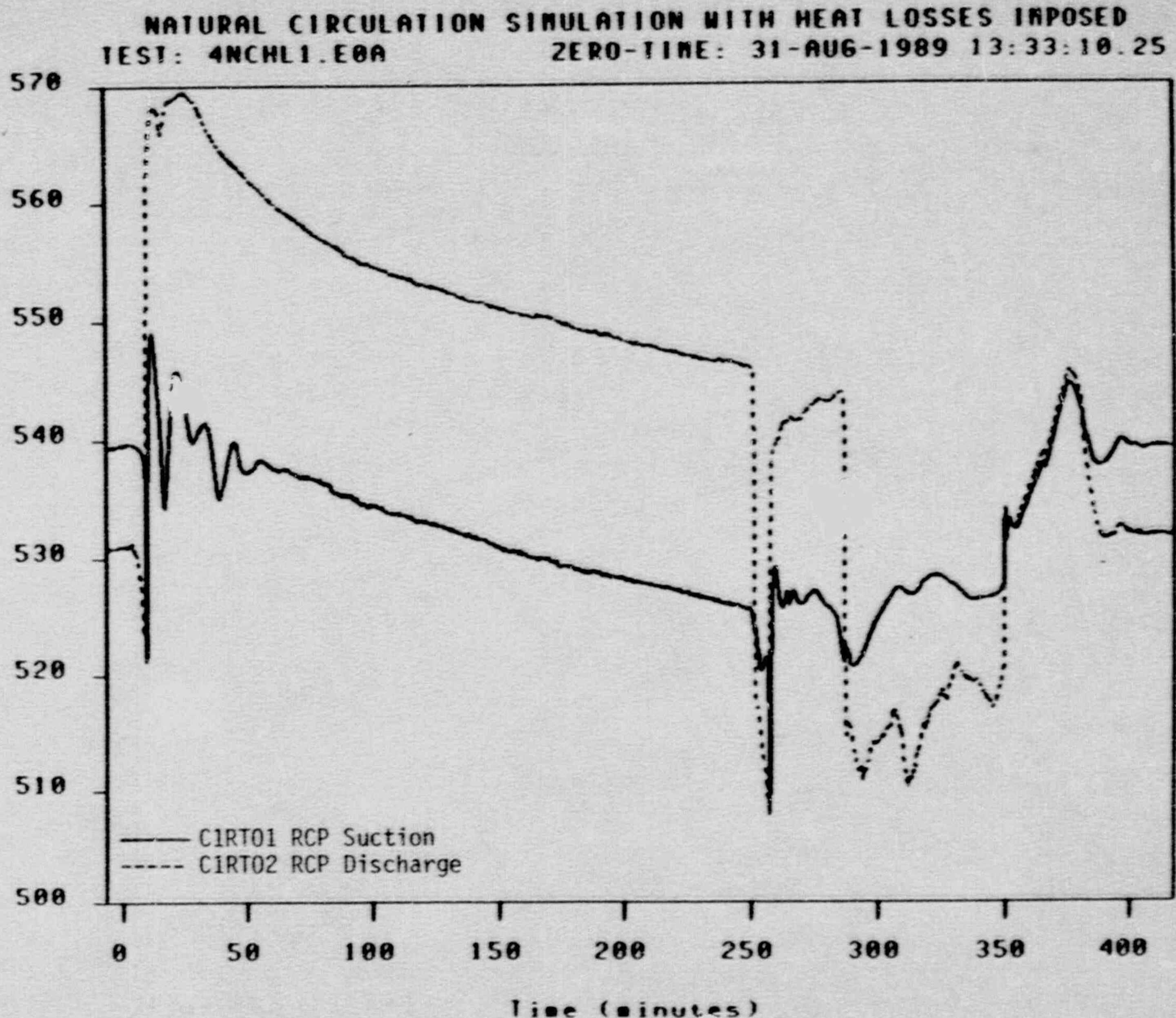


Figure 4.86 Cold Leg A1 Reactor Coolant Pump Suction And Discharge Temperature

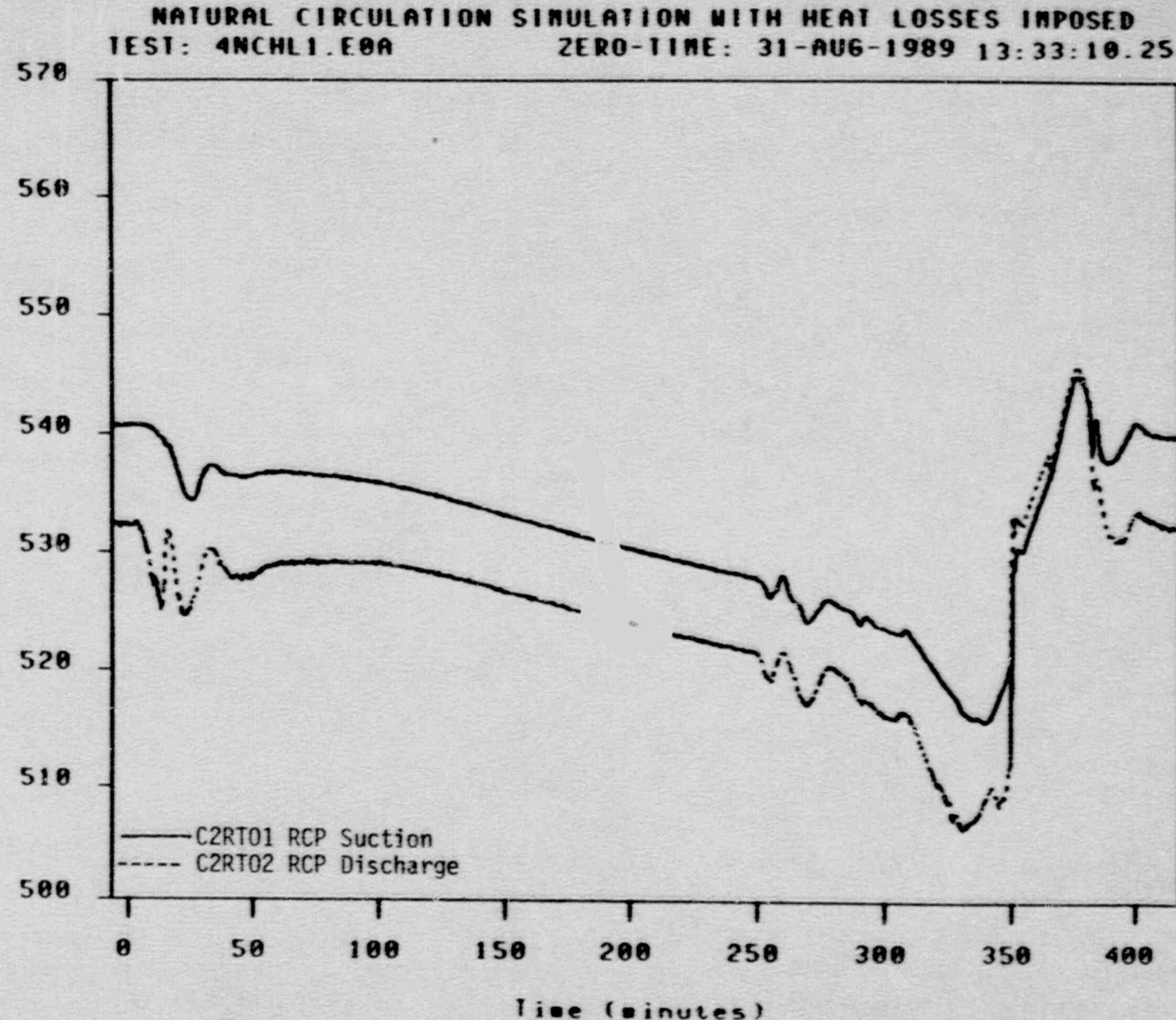


Figure 4.87 Cold L B1 Reactor Coolant Pump Suction And Discharge Temperature

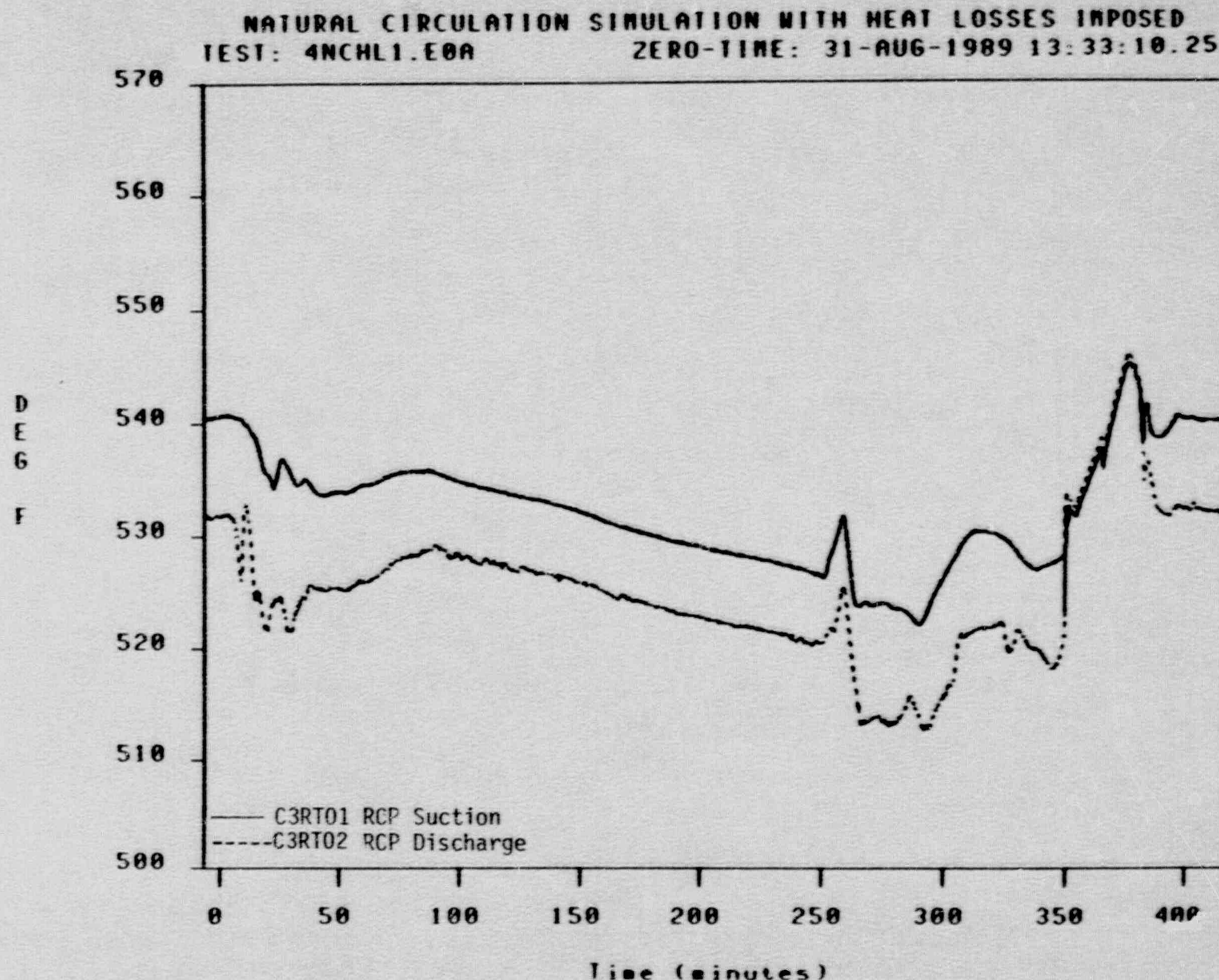


Figure 4.88 Cold Leg A2 Reactor Coolant Pump Suction And Discharge Temperature

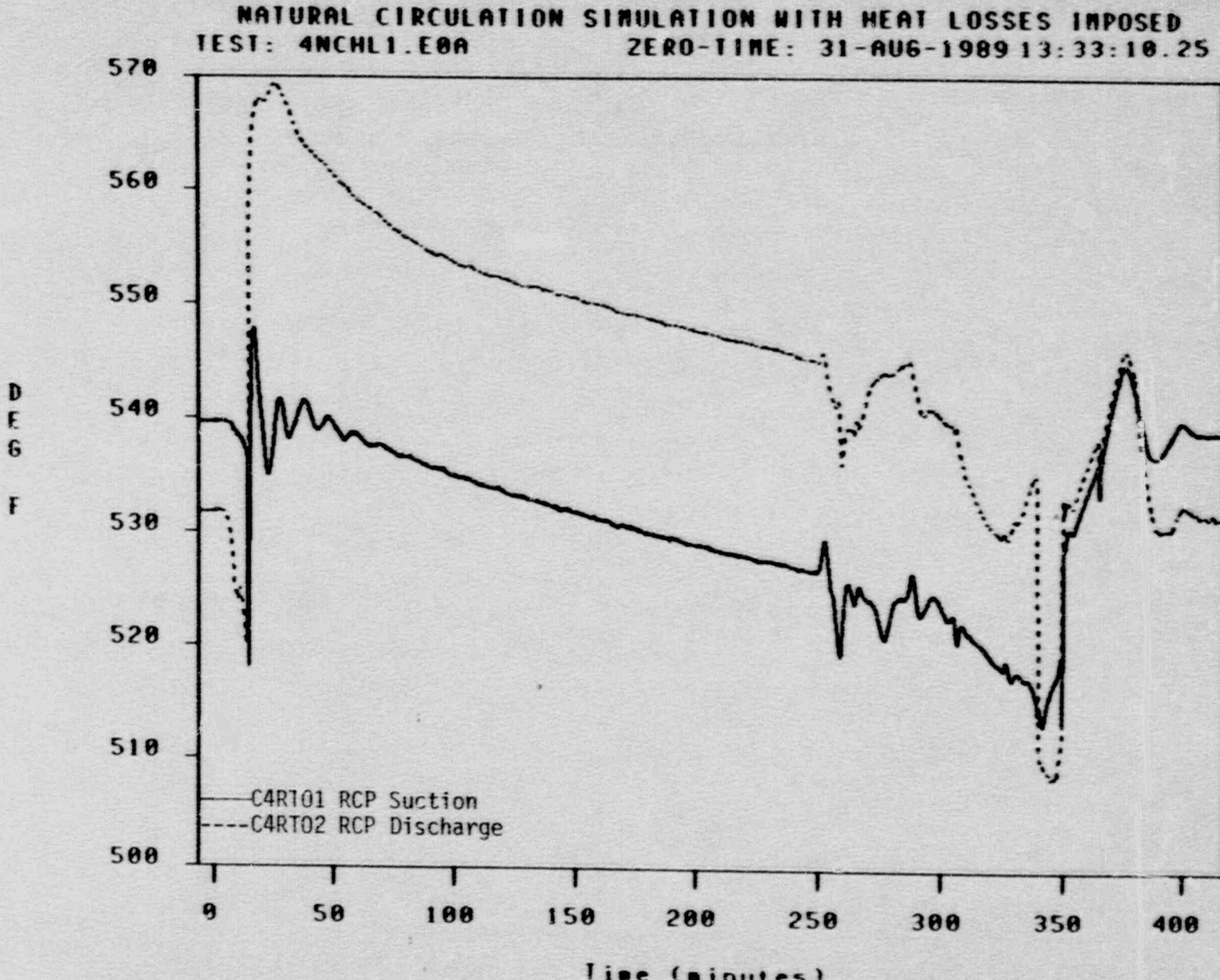


Figure 4.89 Cold Leg B2 Reactor Coolant Pump Suction And Discharge Temperature

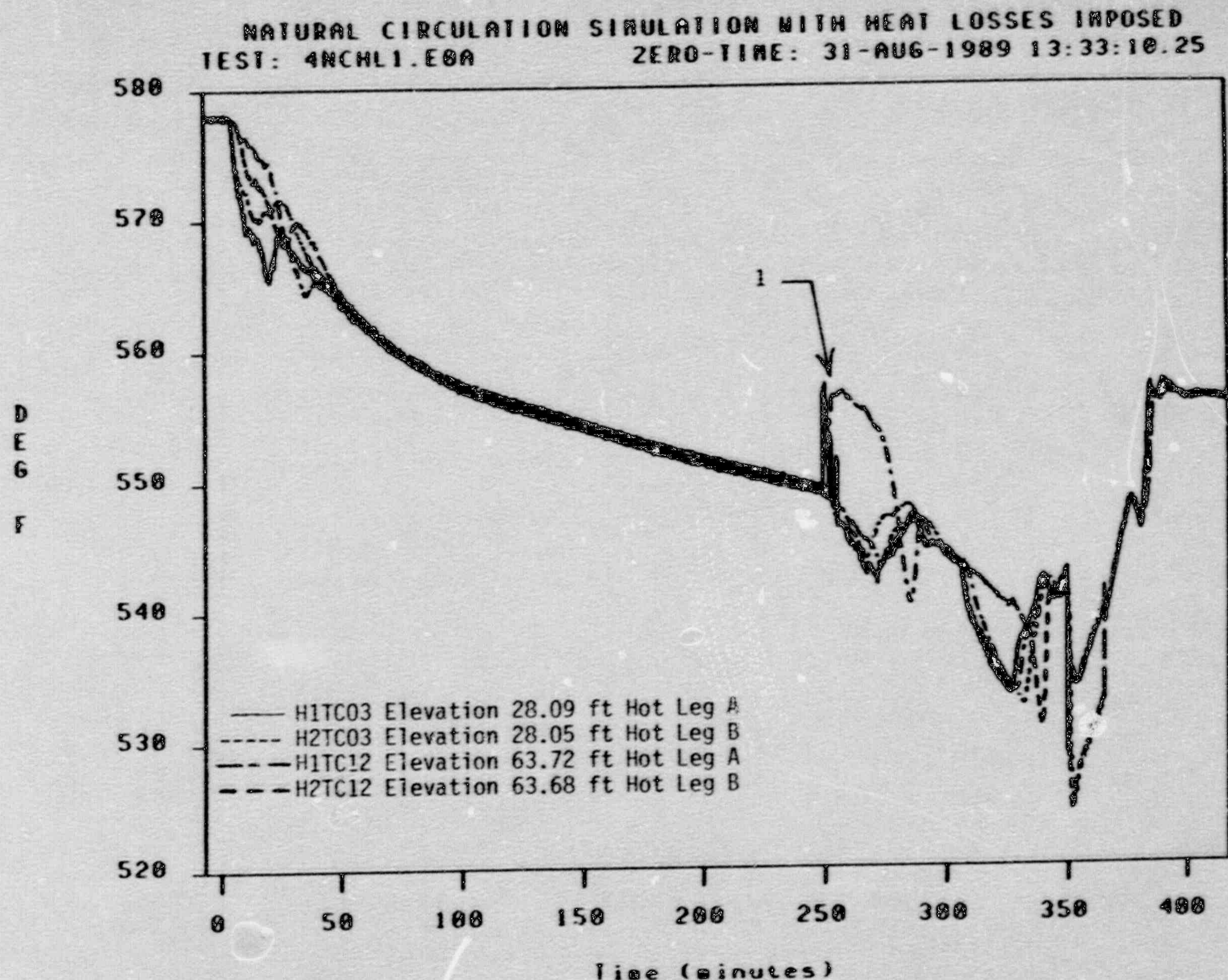


Figure 4.90 Hot Leg A And B Fluid Temperatures

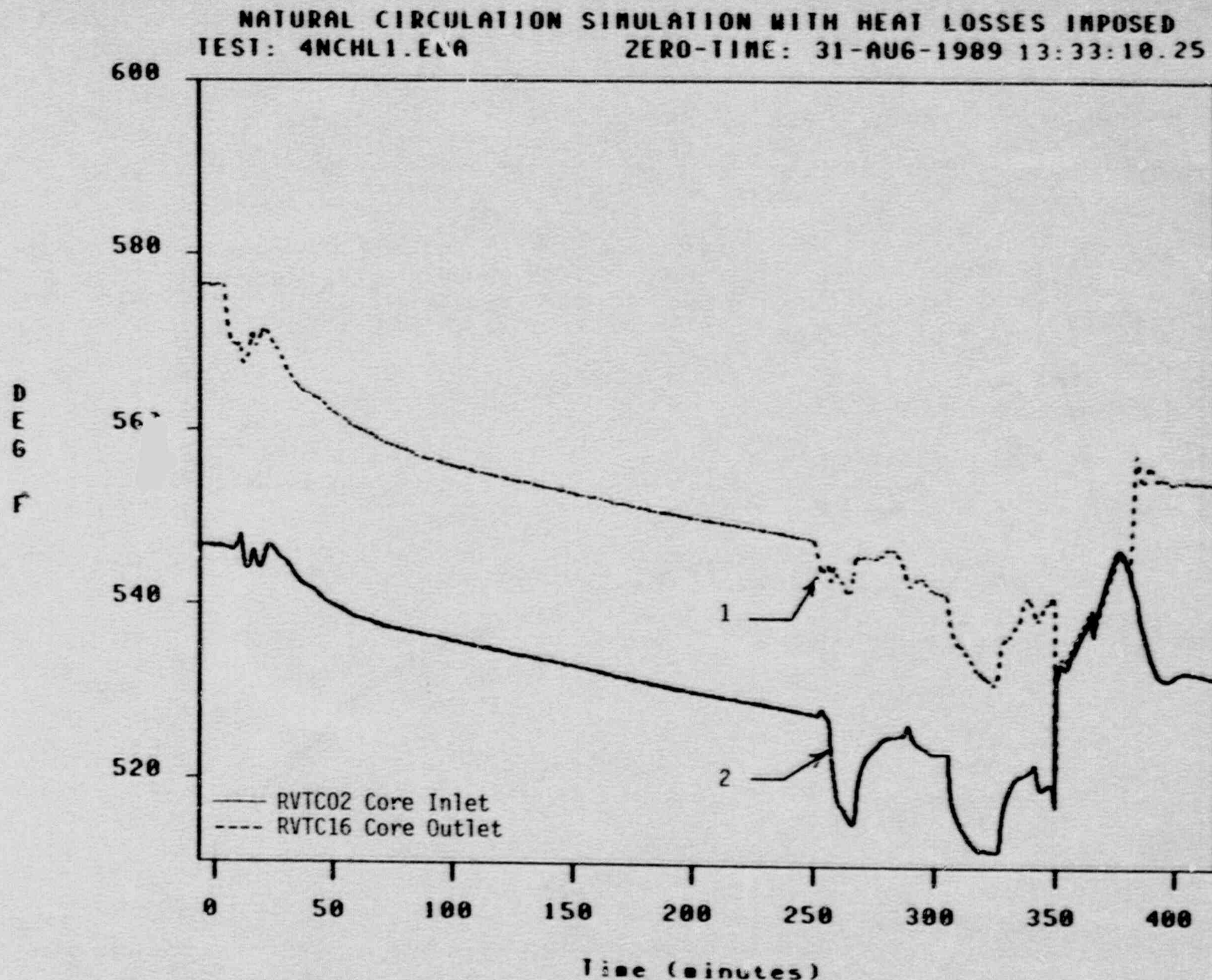


Figure 4.91 Core Inlet And Outlet Temperature

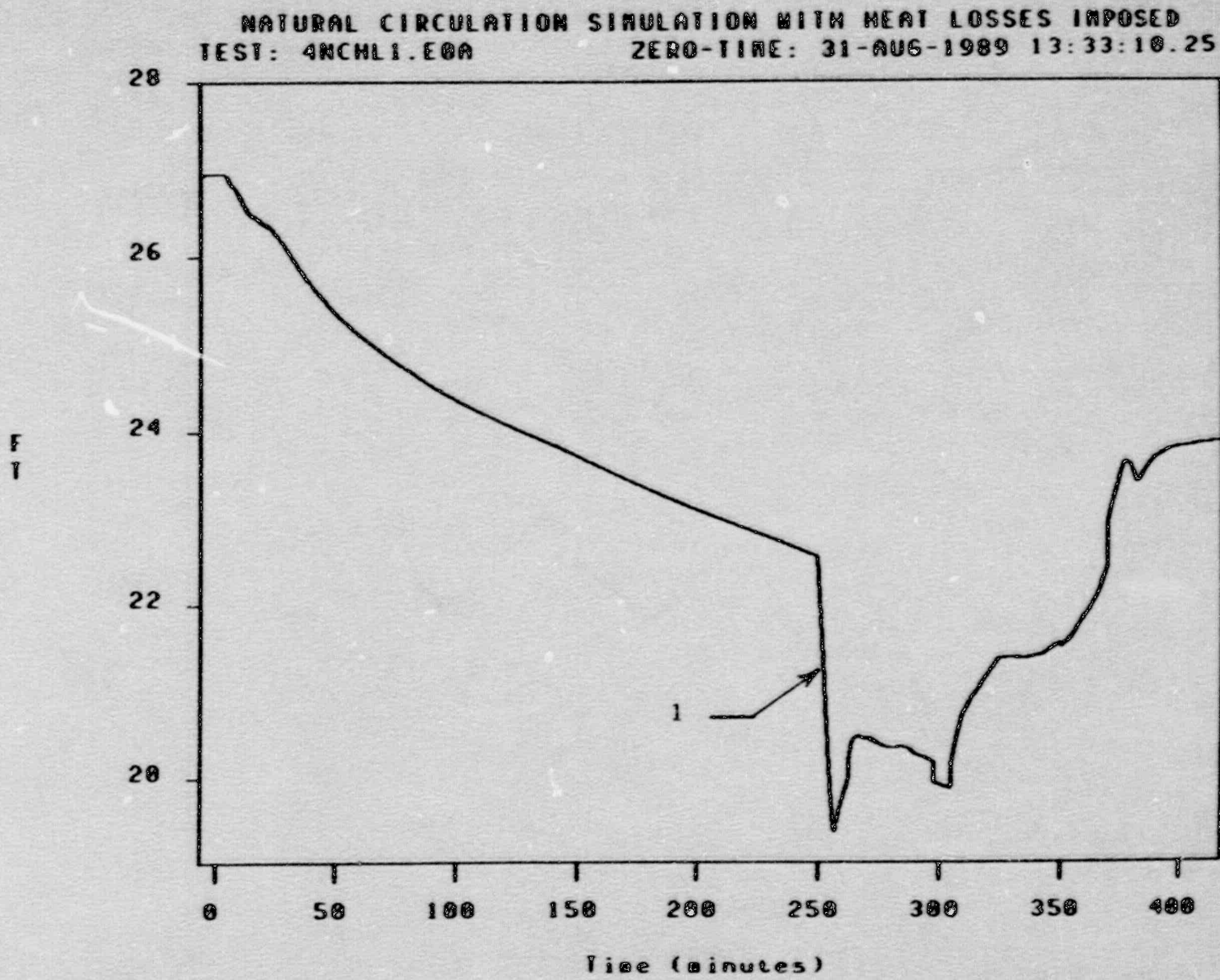


Figure 4.92 Pressurizer Level

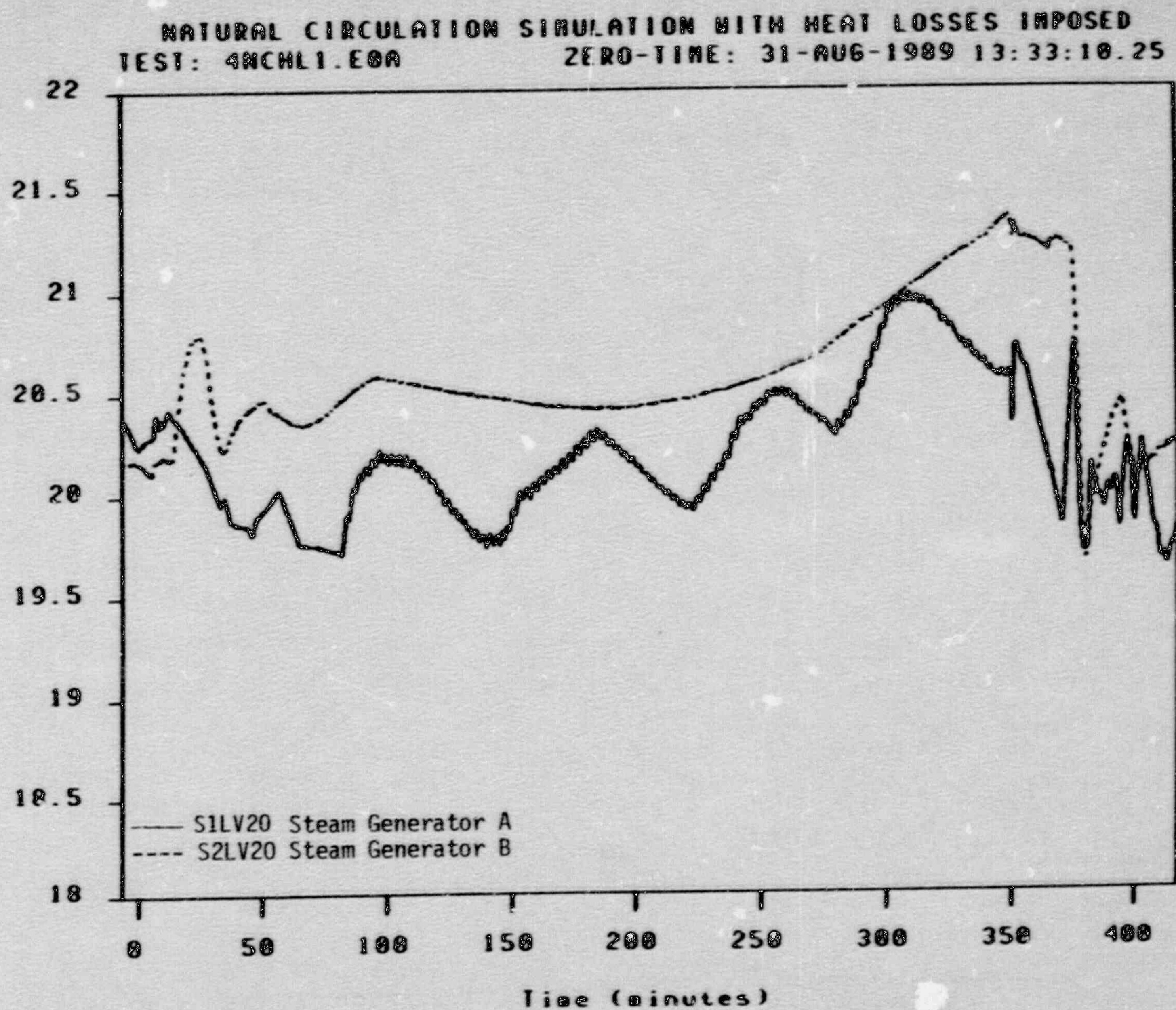


Figure 4.93 Steam Generator Level

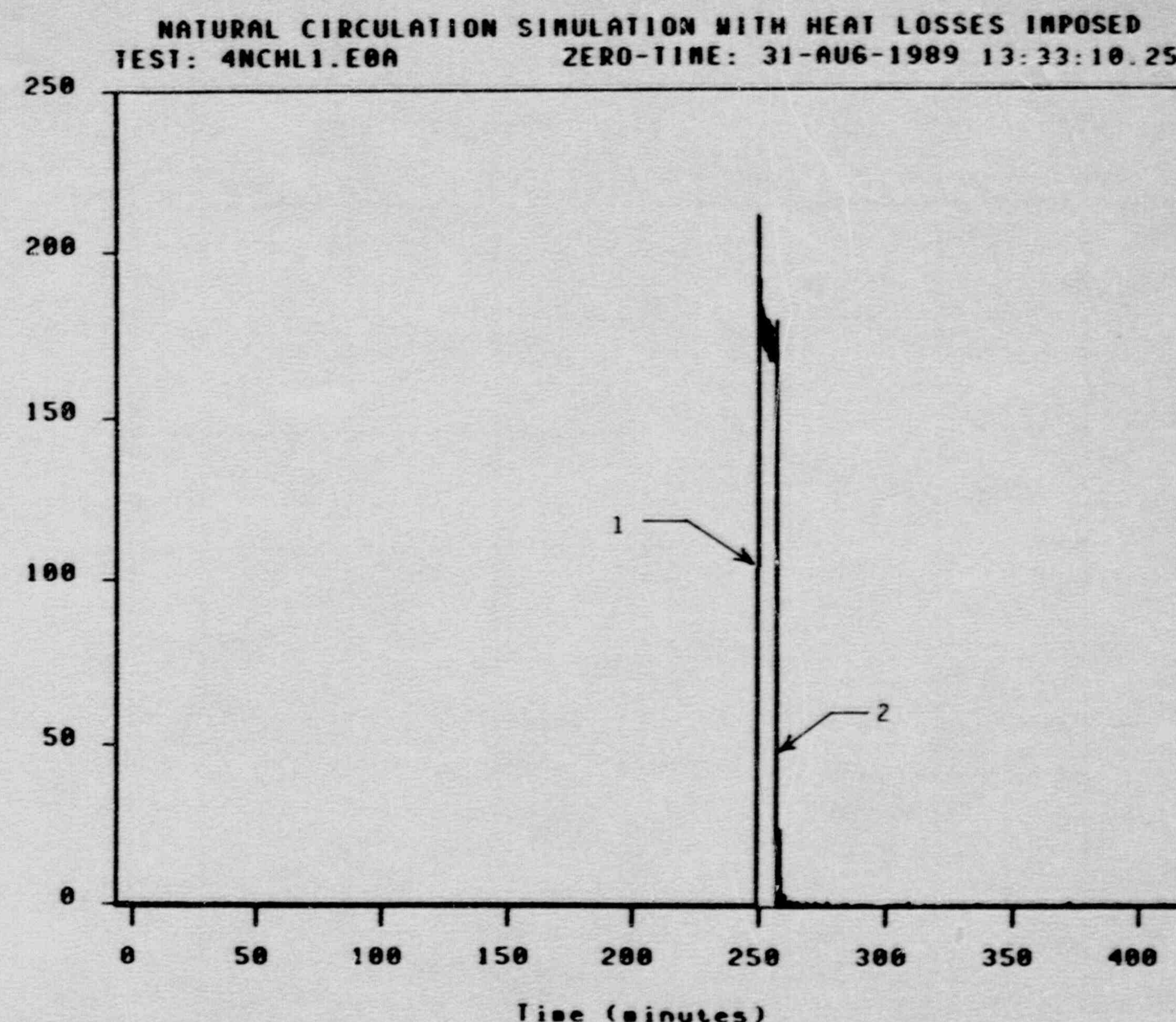


Figure 4.94 High Point Vent Flow Rate

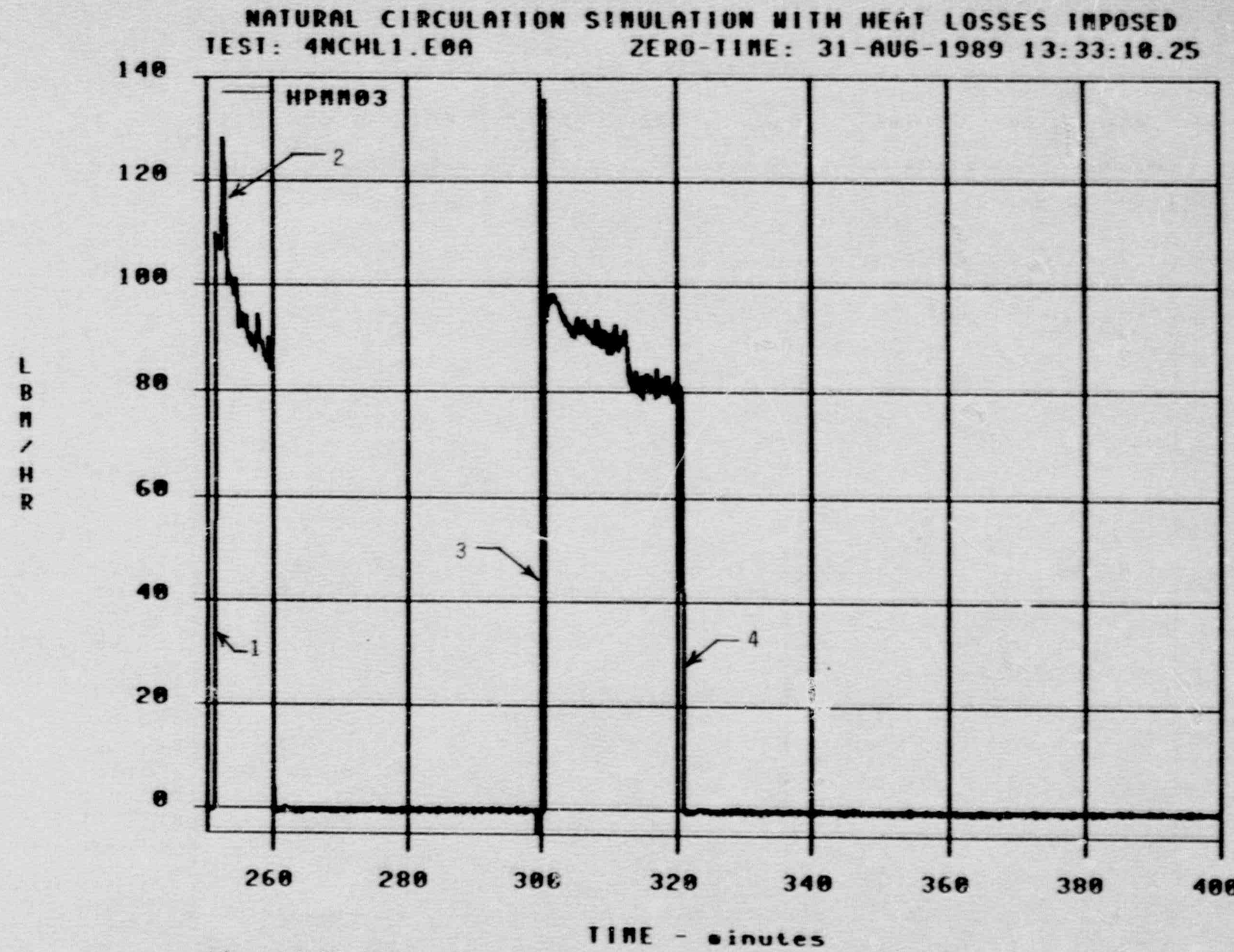


Figure 4.95 Makeup Flow Rate

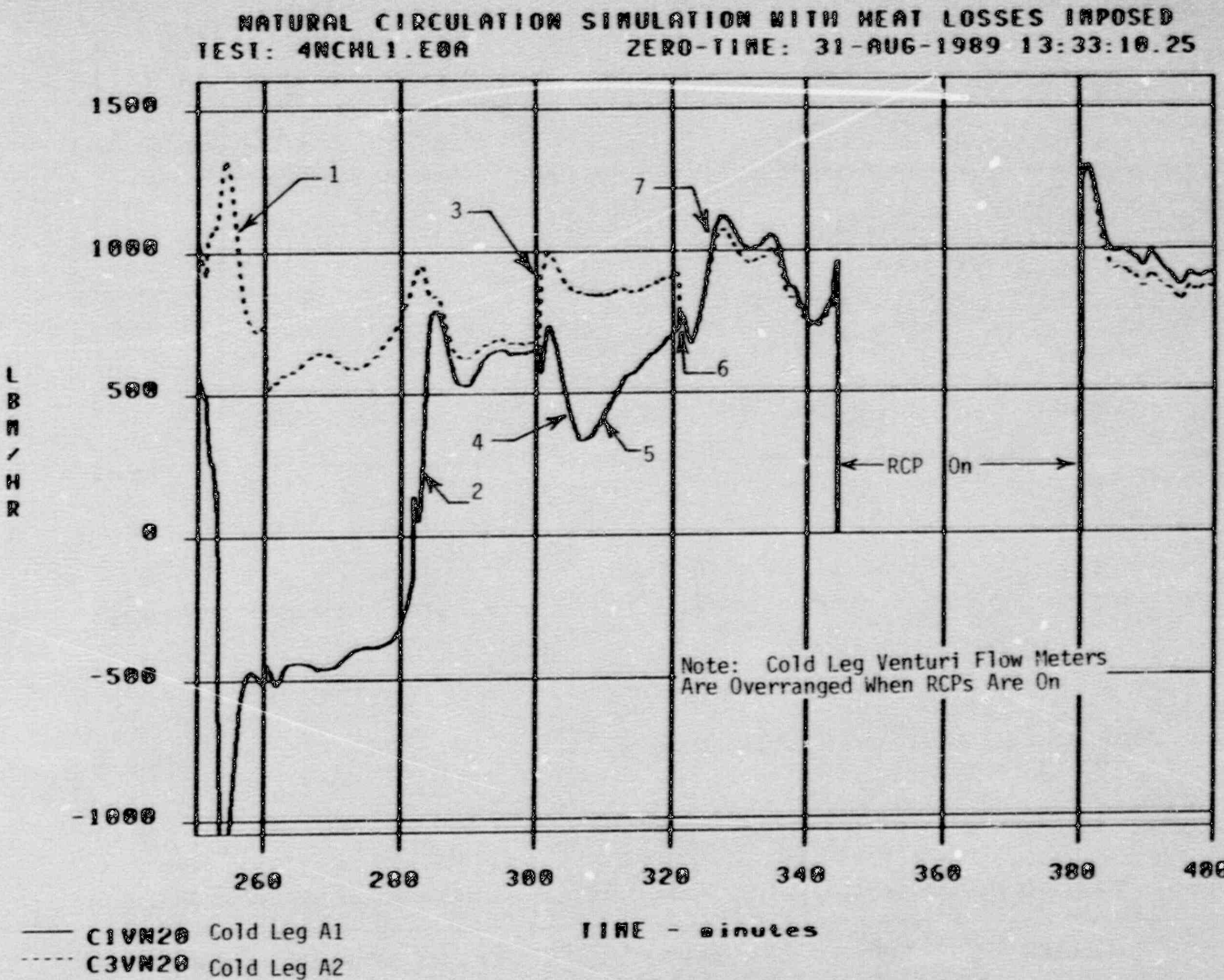


Figure 4.96 Cold Leg A1 And A2 Flow Rate

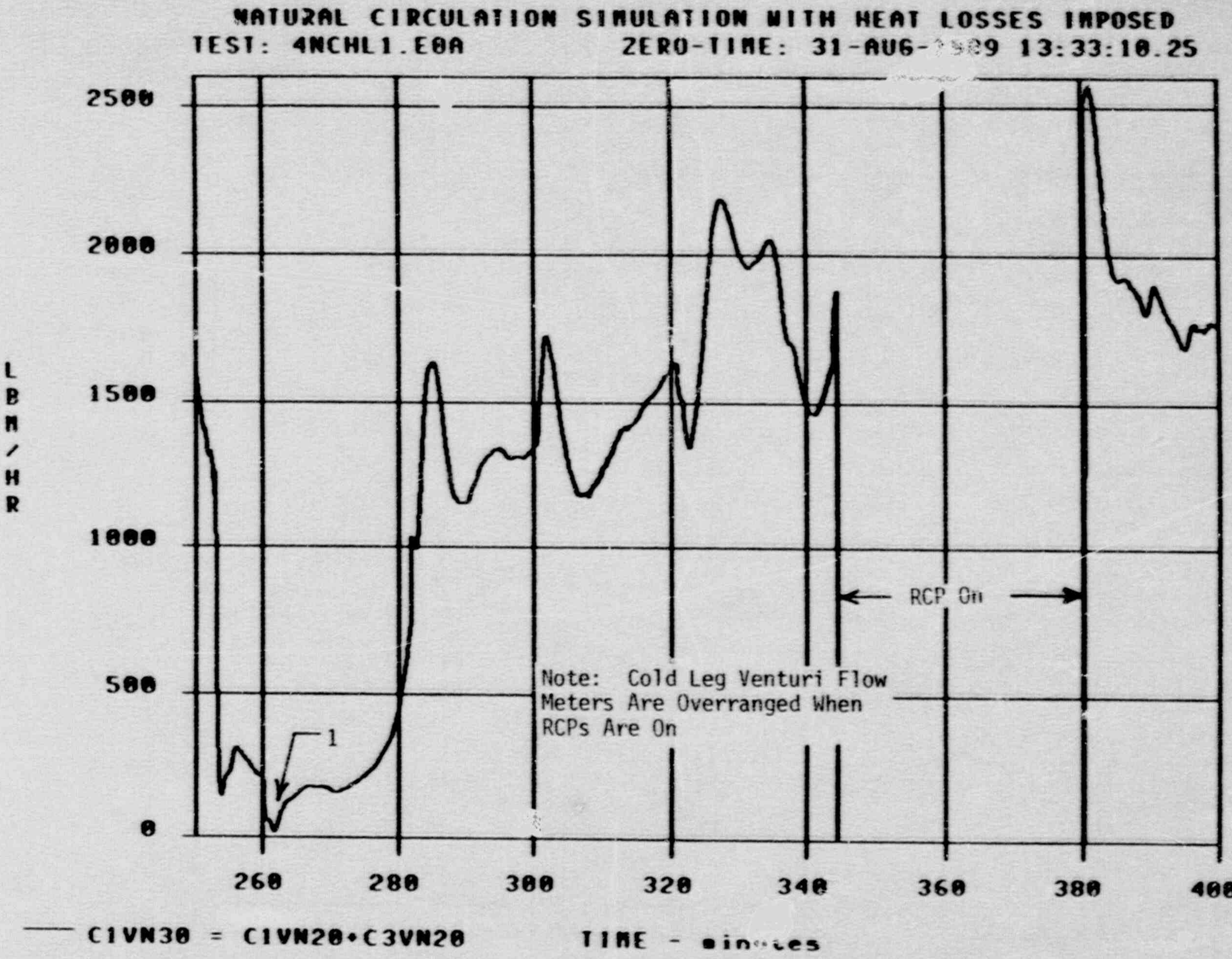
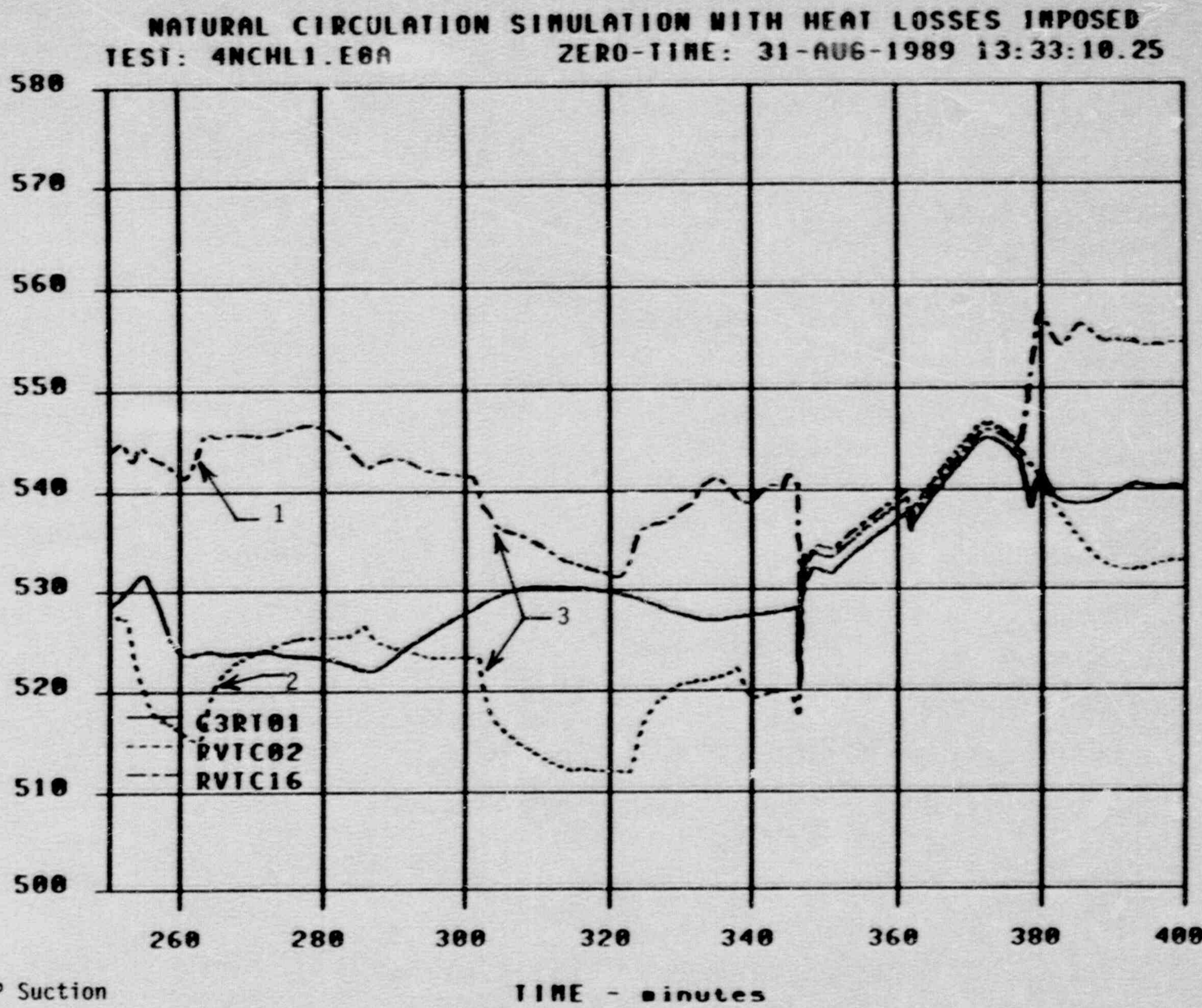


Figure 4.97 Summation of the A1 and A2 Cold Leg Flow Rate



——— Cold Leg A2 RCP Suction

------- Core Inlet

—-- — Core Outlet

Figure 4.98 Core Inlet And Outlet Temperature And Cold Leg A2 Reactor Coolant Pump Suction Temperature

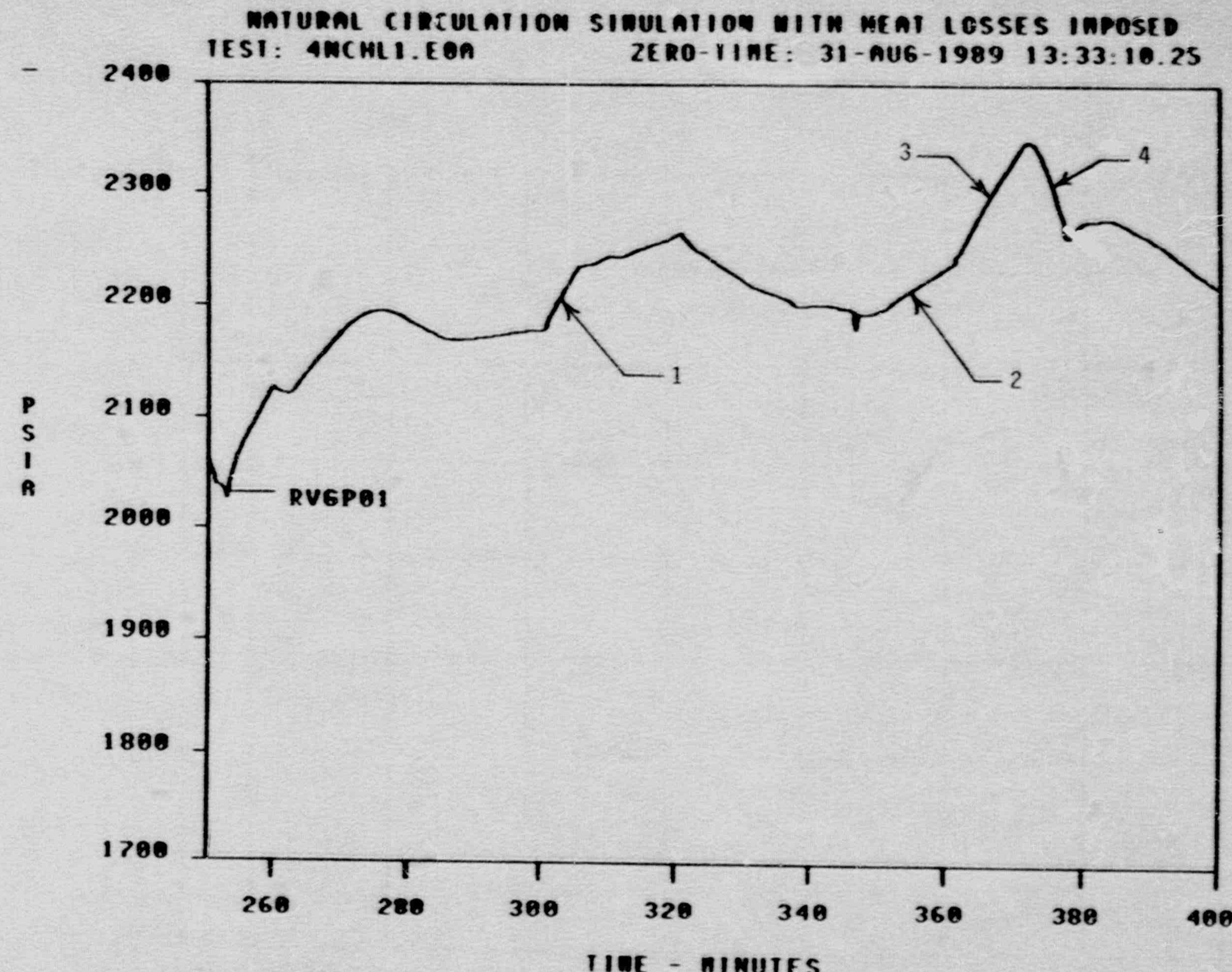


Figure 4.99 Primary System Pressure

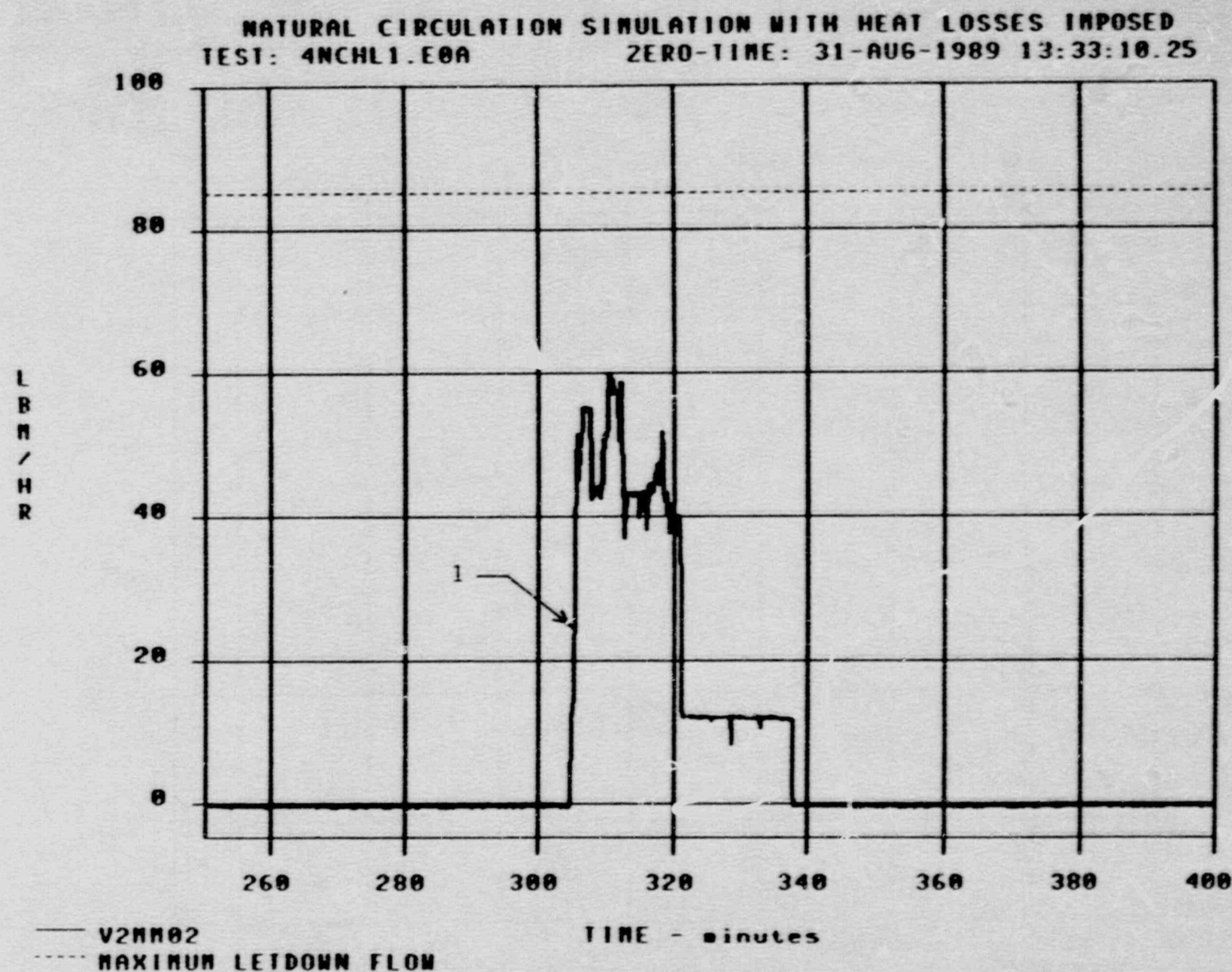


Figure 4.100 Letdown Flow Rate

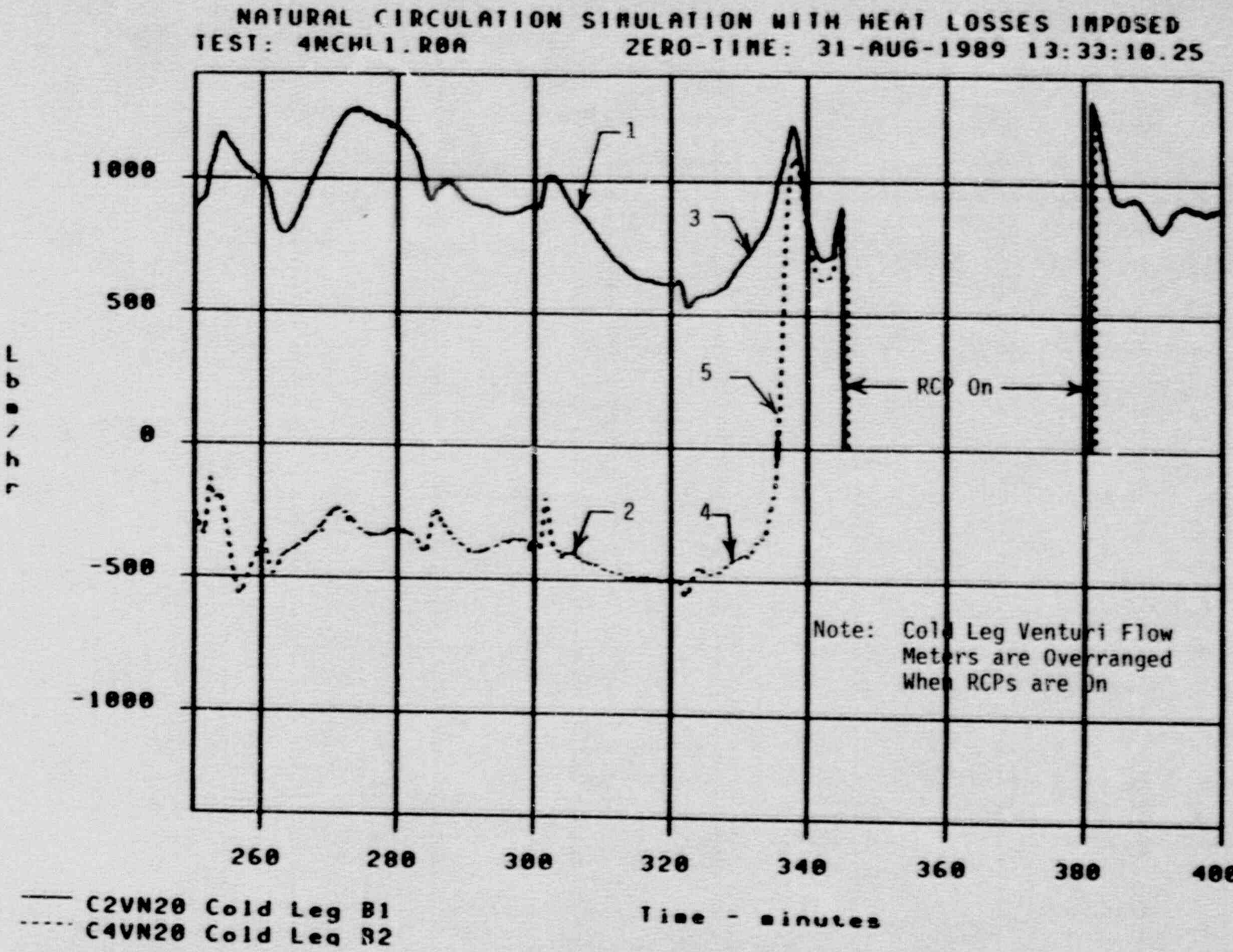


Figure 4.101 Cold Leg B1 and B2 Flow Rate

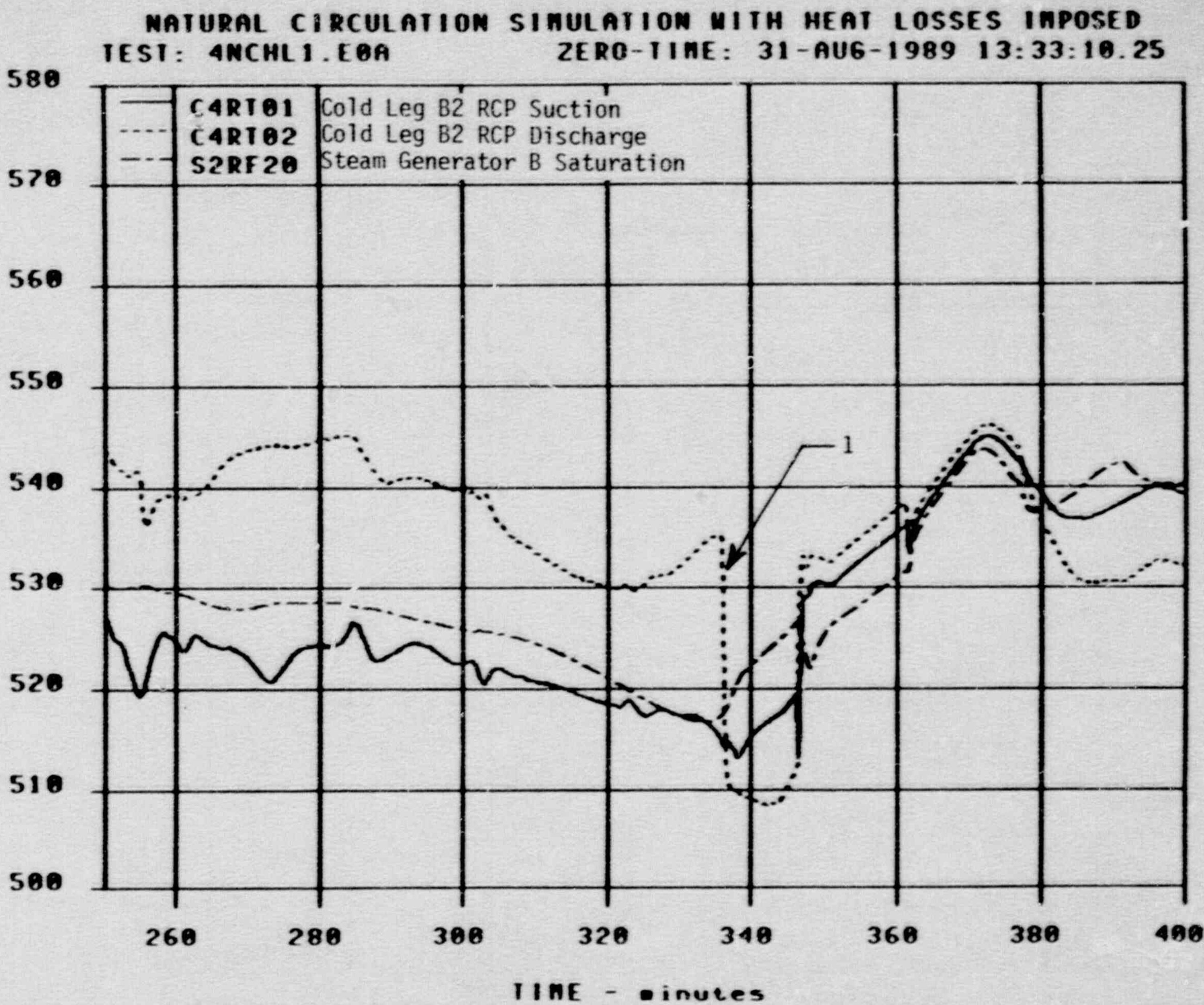


Figure 4.102 Steam Generator B Saturation Temperature And Cold Leg B2 Reactor Coolant Pump Suction And Discharge Temperature

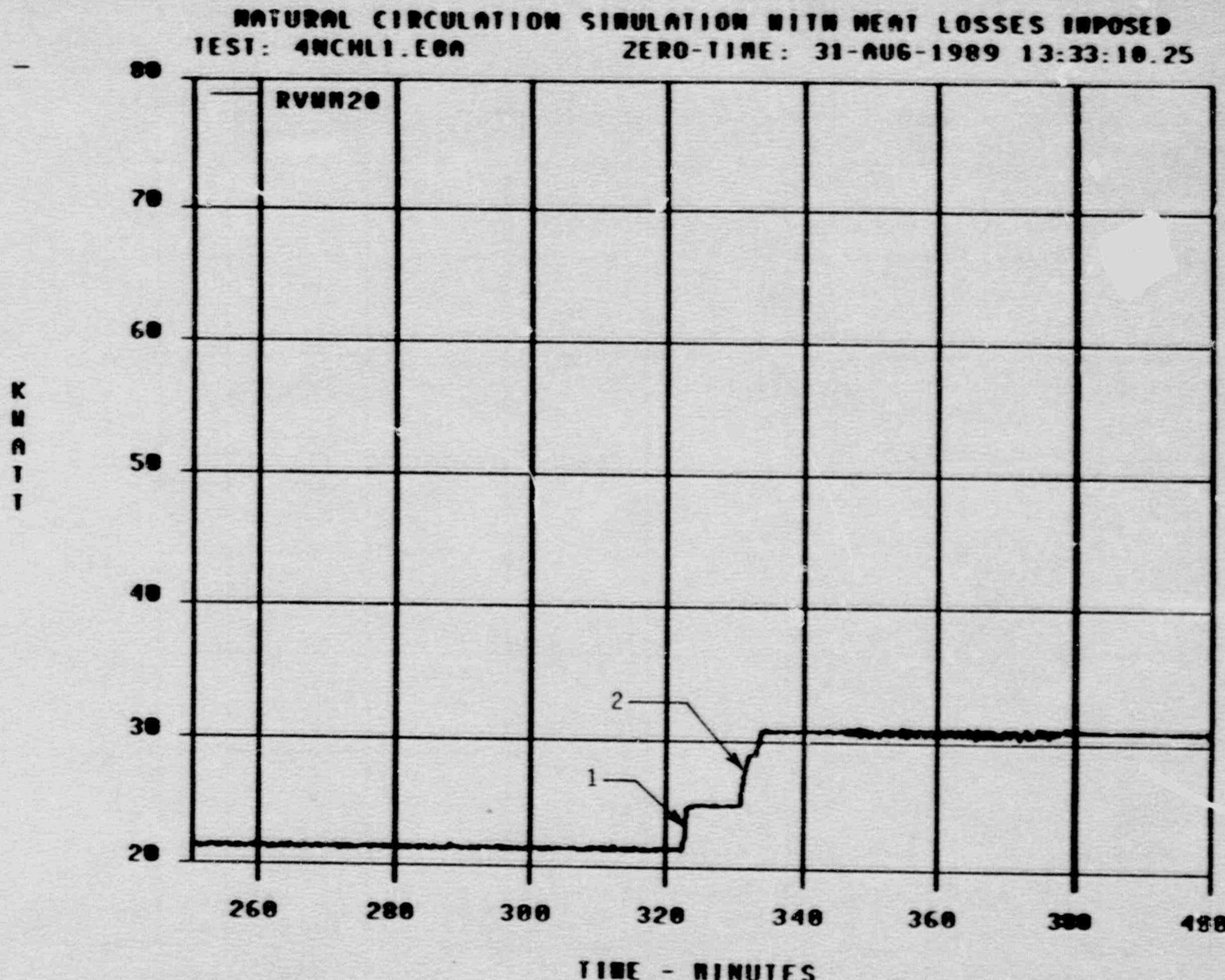


Figure 4.103 Core Power

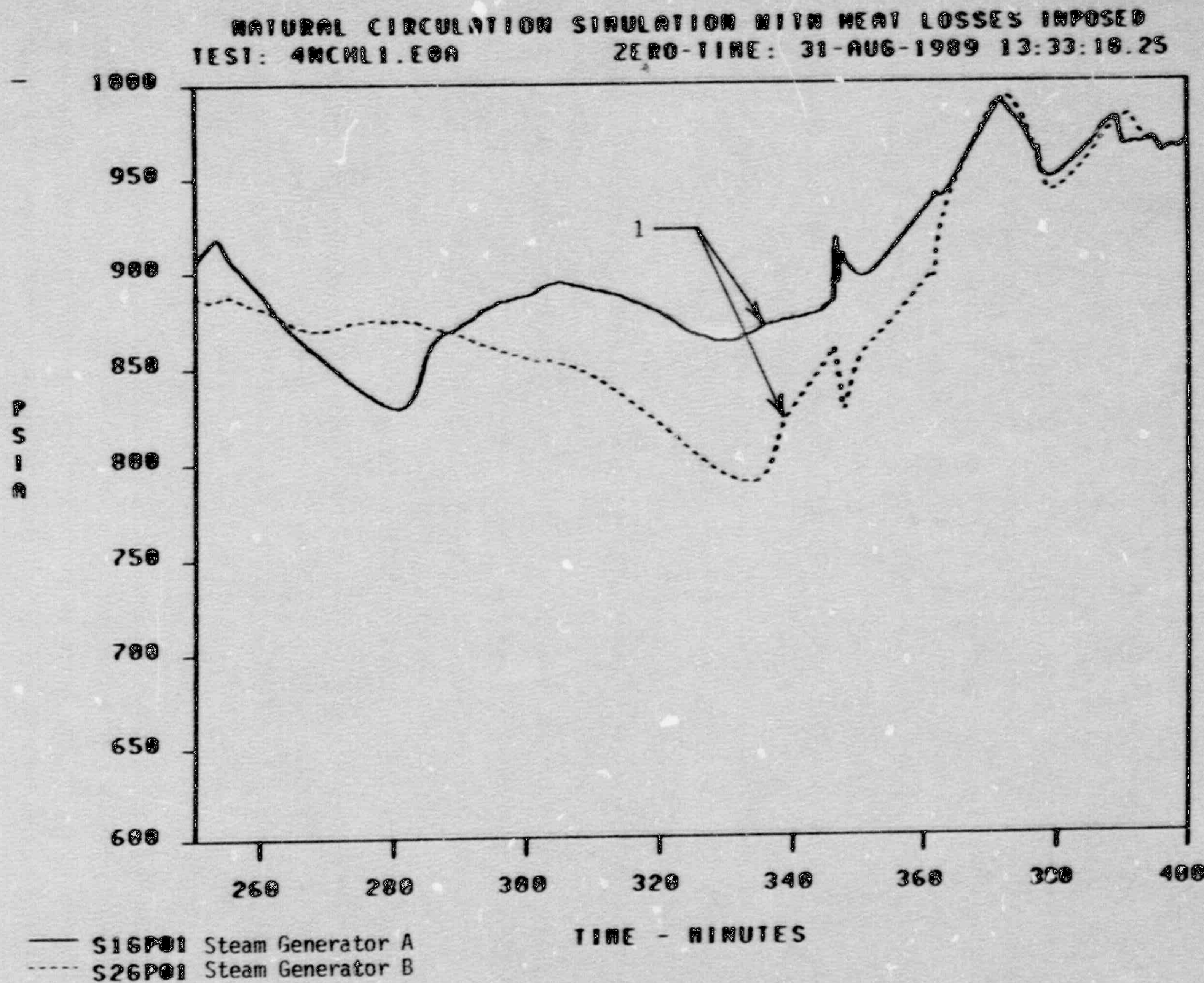


Figure 4.104 Secondary System Pressure

4.4. Observations of Test 4NCLM1

In an attempt to determine the potential effect of letdown and makeup flow on the flow reversal in the cold legs, Test 4NCLM1 was initialized with letdown and makeup flow active. Makeup flow was injected into the cold leg A2 discharge pipe and letdown flow was removed from the cold leg B1 suction pipe. At test initiation the makeup flow was increased and then maintained constant while the letdown flow was adjusted to maintain approximately a constant pressurizer level through the facility hold period of the test

As in the previous tests heat losses were apparent across the reactor coolant pumps during the initialization period (Figure 4.105 through 4.108, See 1). Also, as shown for the other tests where the reactor vessel vent valves were operable, the reactor vessel vent valves were open for Test 4NCLM1 (Figure 4.109 and 4.110, See 1).

During the initialization period the letdown flow rate was approximately 28 lb/hr (Figure 4.111, See 1), which is equivalent to an actual plant letdown flow of 45 gpm, and the makeup flow rate was approximately 30 lb/hr (Figure 4.112, See 1), which is equivalent to an actual plant makeup flow of 49 gpm.

The test was initiated by actuating the core power ramp (Figure 4.113, See 1) and by increasing the makeup flow (Figure 4.112, See 2). All other boundary conditions with the exception of letdown flow were maintained constant.

The initial response for Test 4NCLM1 was similar to that observed for Tests 4NCSM1 and 4NCHL1, i.e., a decrease in the core exit and hot leg fluid temperatures (Figure 4.114, See 1) and a decrease in the primary loop (Figures 4.115 and 4.116, See 1) and cold leg flow rates (Figures 4.117 and 4.118, See 1) occurred.

As observed in the previous natural circulation tests the reduction in the primary loop flow rate in conjunction with the heat loss in the reactor coolant pumps resulted in an increased positive temperature difference between the reactor coolant pump suction (which remained approximately equal to the steam generator saturation temperature) and discharge fluid temperatures (Figure 4.105 through 4.108, See 2).

Again the combination of the existence of a secondary flow path via the reactor vessel vent valves, the reduction of the primary loop natural circulation driving head and the heat losses in the reactor coolant pump region of the cold legs resulted in primary loop flow interruption and the establishment of backflow in the cold legs.

Test 4NCLM1 differed from Test 4NCSM1 in that both the A and B loops indicated flow interruption and differed from Test 4NCHL1 in that the flow reversal in the B loop occurred in the B1 cold leg (occurred in the B2 cold leg for Test 4NCHL1). The A loop again interrupted first and the B loop interrupted approximately 4 minutes later (Figures 4.115 and 4.116, See 2). Backflow was established in the A1 cold leg (Figure 4.117, See 2) while the flow in the A2 cold leg was in the forward direction (Figure 4.117, See 3). Similarly backflow was established in the B1 cold leg (Figure 4.118, See 2) while the flow in the B2 cold leg was in the forward direction (Figure 4.118, See 3). As discussed in Section 4.5.1, the flow direction can also be deduced from the reactor coolant pump suction and discharge temperature, (Figures 4.105 through 4.108).

The occurrence of backflow in the A1 and B1 cold legs appears to be related to the boundary conditions at test initiation, i.e., makeup and letdown flow were active. Past experiences, Test 4NCSM1 and numerous screening tests, revealed that the A2 cold leg consistently exhibited flow reversal. Test 4NCLM1 however injected makeup (cold water) into the A2 cold leg discharge pipe. The injection of the cold water at this location aids the positive natural circulation driving head in the A2 cold leg. Therefore, when the core power was reduced the primary loop natural circulation driving head decreased, the combination of heat loss in the reactor coolant pump region and reactor vessel vent valve flow would be more prone to establish backflow in the cold leg without makeup injection (A1).

For Test 4NCSM1 backflow was not observed in either the B1 or B2 cold leg. The existence of letdown flow, removed from the B1 cold leg, will reduce the flow rate through the B1 cold leg. The reduced flow rate and the heat loss in the reactor coolant pump region will therefore result in lower fluid temperatures in the B1 reactor coolant pump region. Therefore, when the core power was reduced the primary loop natural circulation driving head decreased, the colder fluid in the B1 reactor coolant pump region in conjunction with the flow through the reacto, vessel vent valves would be more prone to establish backflow in cold leg B1.

The makeup flow also effected the core inlet temperature during the conduct of this test. When compared to Test 4NCSM1 the core inlet temperature during test initialization was approximately 4F lower for Test 4NCLM1. When Test 4NCLM1 was initiated the makeup flow rate was increased (Figure 4.112, See 2) and a corresponding reduction in the core inlet temperature was observed (Figure 4.110, See 2). The reduction in the core inlet temperature can be observed to propagate to the core outlet temperature (Figure 4.110, See 3). The reduced core region fluid temperatures results in a reduction in the primary loop natural circulation driving head. Therefore, the makeup flow appears to have reduced the primary loop natural circulation driving head sufficiently to cause flow interruption in the B loop.

Approximately one minute after backflow occurred in the B1 cold leg, the loop operator increased the letdown flow rate to approximately 44 lb/hr, plant equivalent 70 gpm (Figure 4.111, See 2). The increased letdown flow did not result in any apparent effect on the primary system response.

4.4.1. Facility Hold Period

Subsequent to the flow interruption no operator actions, with the exception of changes in letdown flow to maintain an approximately constant pressurizer level, were performed for approximately 2 hours. The transient response can be observed on Figures 4.119 through 4.131. As can be observed from these figures the primary system exhibited a continuous cooling trend over this period (Figures 4.124 through 4.129). The cooling trend exhibited by Test 4NCLM1 exceeds that exhibited by Test 4NCHL1. The increased cooling rate appears to be directly related to the reduction in the core inlet temperature as a result of the injection of makeup flow.

Primary loop flow appears to have been maintained throughout the period. The flow rate in the A2 cold leg stabilized at approximately 1090 lb/hr in the forward flow direction and the A1 cold leg flow rate stabilized at approximately 370 lb/hr in the reverse flow direction (Figure 4.122). The B2 cold leg flow rate stabilized at approximately 1000 lb/hr in the forward flow direction and the B1 cold leg flow rate stabilized at approximately 350 lb/hr in the reverse flow direction (Figure 4.123).

4.4.2. Operator Actions and Loop Recovery Period

Subsequent to the hold period the loop operator decreased the letdown flow rate (Figure 4.111, See 3) to 44 lb/hr (a plant equivalent flow of 70 gpm which is the maximum flow rate through one letdown cooler), and opened the hot leg B high point vent (Figure 4.132, See 1). An anticipated decrease in the pressurizer level (Figure 4.133, See 1) necessitated an increase in the makeup flow rate (Figure 4.112, See 3). The increased makeup flow resulted in a decrease in the core inlet temperature (Figure 4.129, See 1). Although the hot leg B high point vent was open the hot leg A fluid temperature responded immediately to the decrease in the core exit temperature (Figure 4.134, See 1) while the hot leg B fluid temperature lagged and decreased at a lower rate (Figure 4.114, See 2). These hot leg fluid temperature responses indicate the predominant flow path was by way of the A loop. The reduction in the core region fluid temperatures resulted in a decrease in the primary loop flow rates (Figures 4.115 and 4.116, See 3) and a reduction in the primary-to-secondary heat transfer occurred as observed by the decreasing steam generator pressures (Figure 4.120, See 1).

At approximately 168 minutes the loop operator opened the hot leg A high point vent (Figure 4.135, See 1), both hot leg high point vents were open. Again an anticipated decrease in the pressurizer level (Figure 4.136, See 1) necessitated an increase in the makeup flow rate (Figure 4.137, See 1). The increased makeup flow resulted in a further decrease in both the core inlet (Figure 4.129, See

2) and the core exit temperature (Figure 4.129, See 3). The reduction in the core region fluid temperatures resulted in a further decrease in the primary loop flow rates (Figures 4.138 and 4.139, See 1). The reduction in the primary loop flow rate can also be observed in the response of both hot leg fluid temperatures, i.e., do not readily respond to the reduction in the core exit temperature (Figure 4.140 and 4.141, See 1).

At approximately 180 minutes the test facility design limit for primary-to-secondary pressure differential was approached and the loop operator cycled the PORV to decrease the primary system pressure (Figure 4.119, See 1). Numerous PORV actuations were required through the remainder of the test (Figure 4.119, See 2) as the test facility primary-to-secondary pressure differential design limit was approached. The PORV actuations did not effect the transient response other than reducing the primary system pressure.

The cold leg venturi flow meters indicated that the primary loop flow reversed during this period with the reversal occurring first in loop B (Figure 4.139, See 2) and then in loop A (Figure 4.138, See 2). The stabilization of the loop B hot leg temperature while the core exit temperature decreased (Figure 4.141, See 2) implies that fluid from the core exit did not traverse the hot leg. The B high point vent was open at this time and the steam generator B saturation temperature was greater than the core region fluid temperatures thus the steam generator became the heat source for the B loop at this time and therefore the potential for primary loop flow reversal exists. Similar conditions occurred at approximately 180 minutes in loop A. Further examination of all the primary loop fluid temperatures is warranted to confirm this observation.

At approximately 196 minutes the B high point vent was closed (Figure 4.135, See 2). To maintain an approximately constant pressurizer level the makeup flow was also reduced (Figure 4.137, See 2). The reduction in the makeup flow resulted in an increase and then a stabilization of both the core inlet and outlet temperature (Figure 4.129, See 4). At approximately 227 minutes the A high point vent was closed (Figure 4.135, See 3), the letdown flow rate was increased to its maximum value, plant equivalent flow of 140 gpm (Figure 4.142, See 1) and the makeup flow was reduced (Figure 4.137, See 3) to maintain an approximately constant pressurizer inventory. The reduction in the makeup flow again resulted in an increase in the core inlet and outlet temperature (Figure 4.129, See 5). The flow direction in the cold legs did not change (A2 and B2 forward flow, A1 and B1 reverse flow) and flow through the reactor vessel vent valves existed throughout this phase of the test Figures 4.143 through 4.145).

At approximately 238 minutes the A1 reactor coolant pump was started (Figure 4.146, See 1) and primary loop fluid temperatures rapidly converged (Figure 4.140, See 2 and Figure 4.141, See 3). As discussed in Section 4.2.2 reverse loop flow occurred in loop B. Approximately 15 minutes later a second reactor coolant pump (B2) was started (Figure 4.146, See 2) and forward loop flow as discussed in Section 4.2.2 was established in loop B. Both reactor coolant pumps were tripped at approximately 268 minutes (Figure 4.146, See 3). Subsequent to the coastdown of the reactor coolant pumps the primary system re-established steady-state natural circulation in both loops as observed by the primary loop fluid temperatures (Figure 4.140, See 3 and Figure 4.141, See 4) and the cold leg flow rates (Figures 4.143 and 4.144, See 1). The core power was not increased for this test (Figure 4.147) therefore the mixing of the primary fluids by the reactor coolant pump operation resulted in the establishment of sufficient loop natural circulation driving heads upon tripping of the reactor coolant pumps. At approximately 274 minutes the loop operator terminated makeup (Figure 4.137, See 4) and letdown (Figure 4.142, See 2). Natural circulation flow continued in both loops and the test was terminated at 300 minutes.

Figures for Test 4NCLM1

Natural Circulation Test With
Letdown and Makeup Flow Active

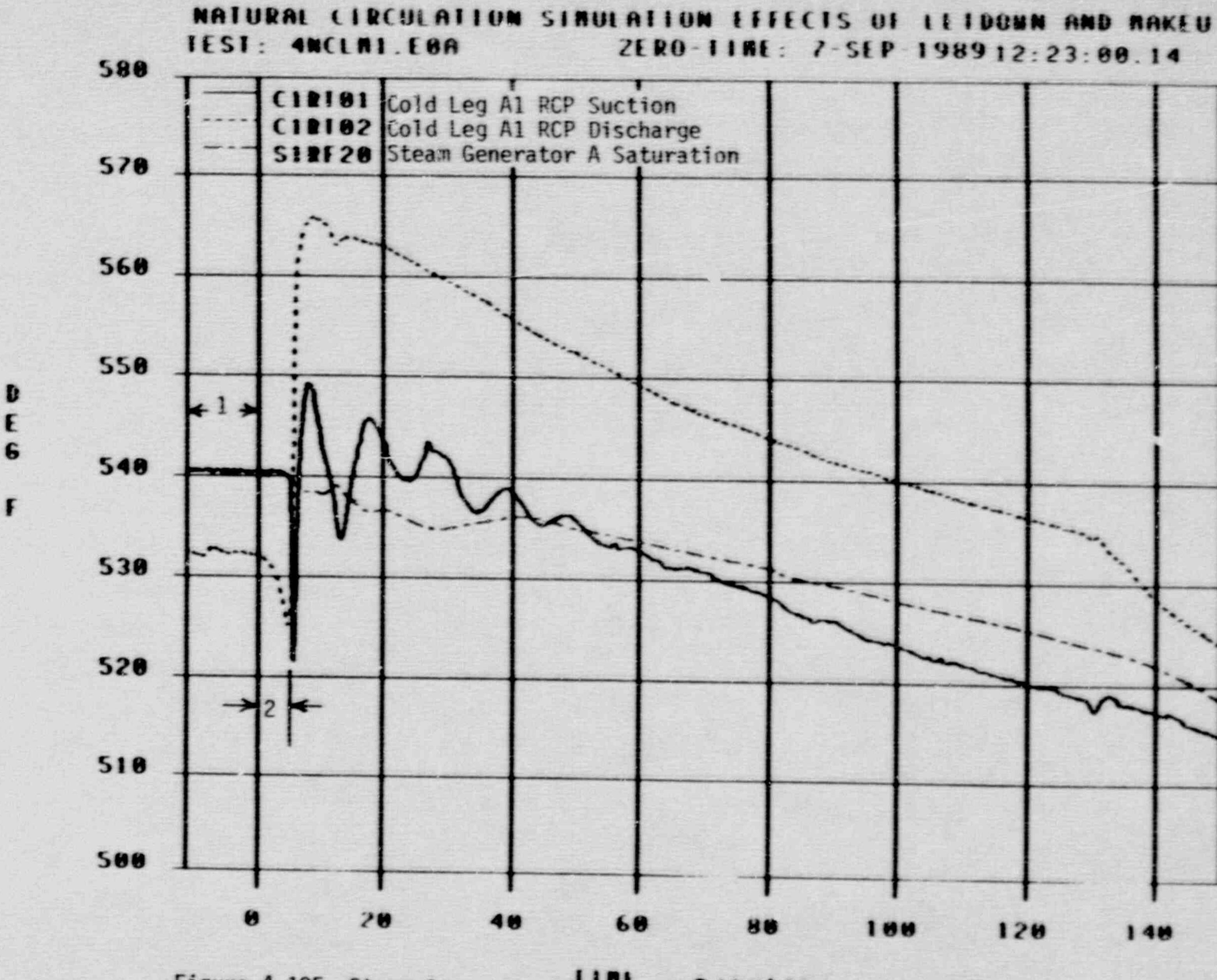


Figure 4.105 Steam Generator A Saturation Temperature And Cold Leg A1 Reactor Coolant Pump Suction And Discharge Temperature

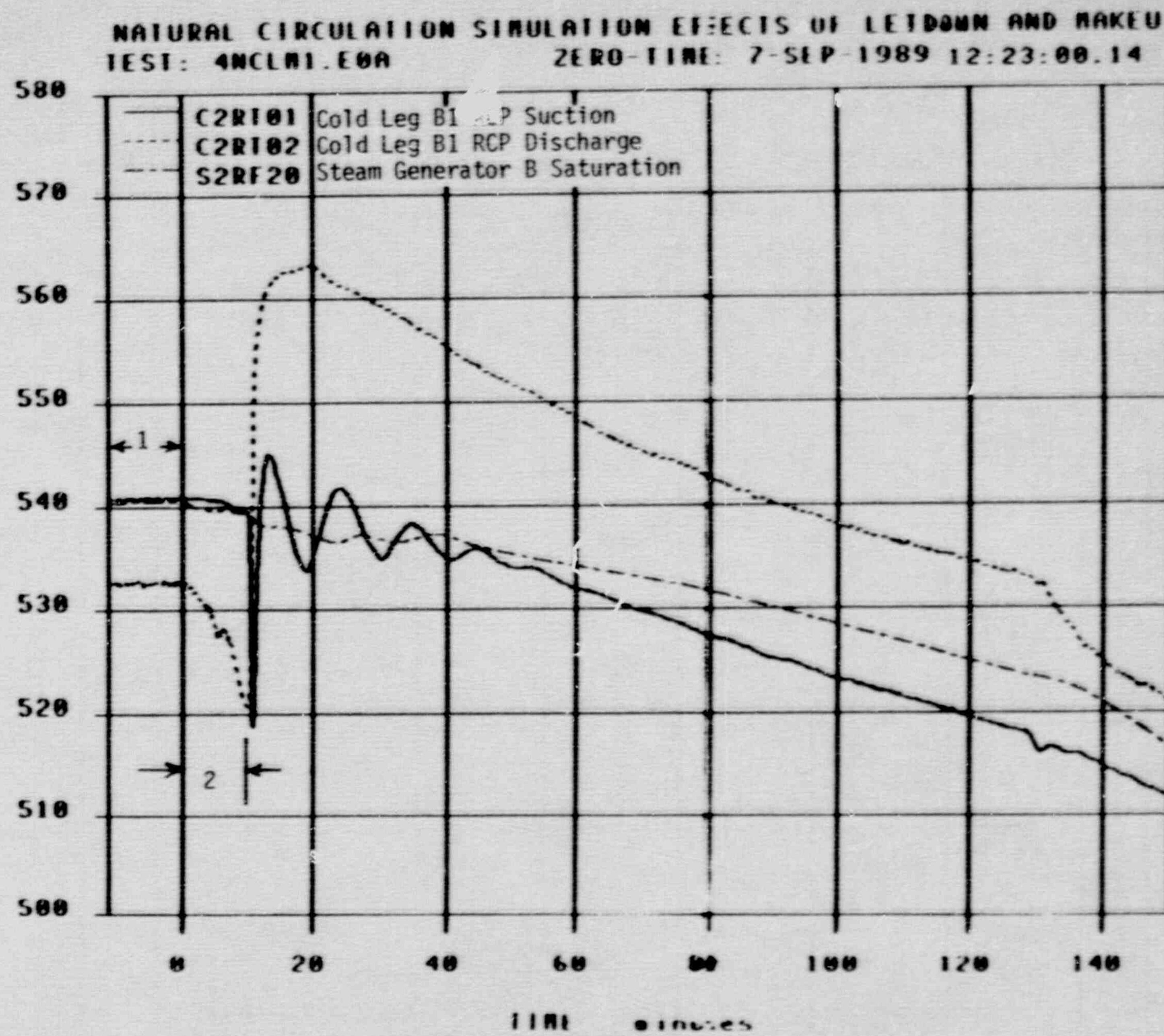


Figure 4.106 Steam Generator B Saturation Temperature And Cold Leg B1 Reactor Coolant Pump Suction And Discharge Temperature

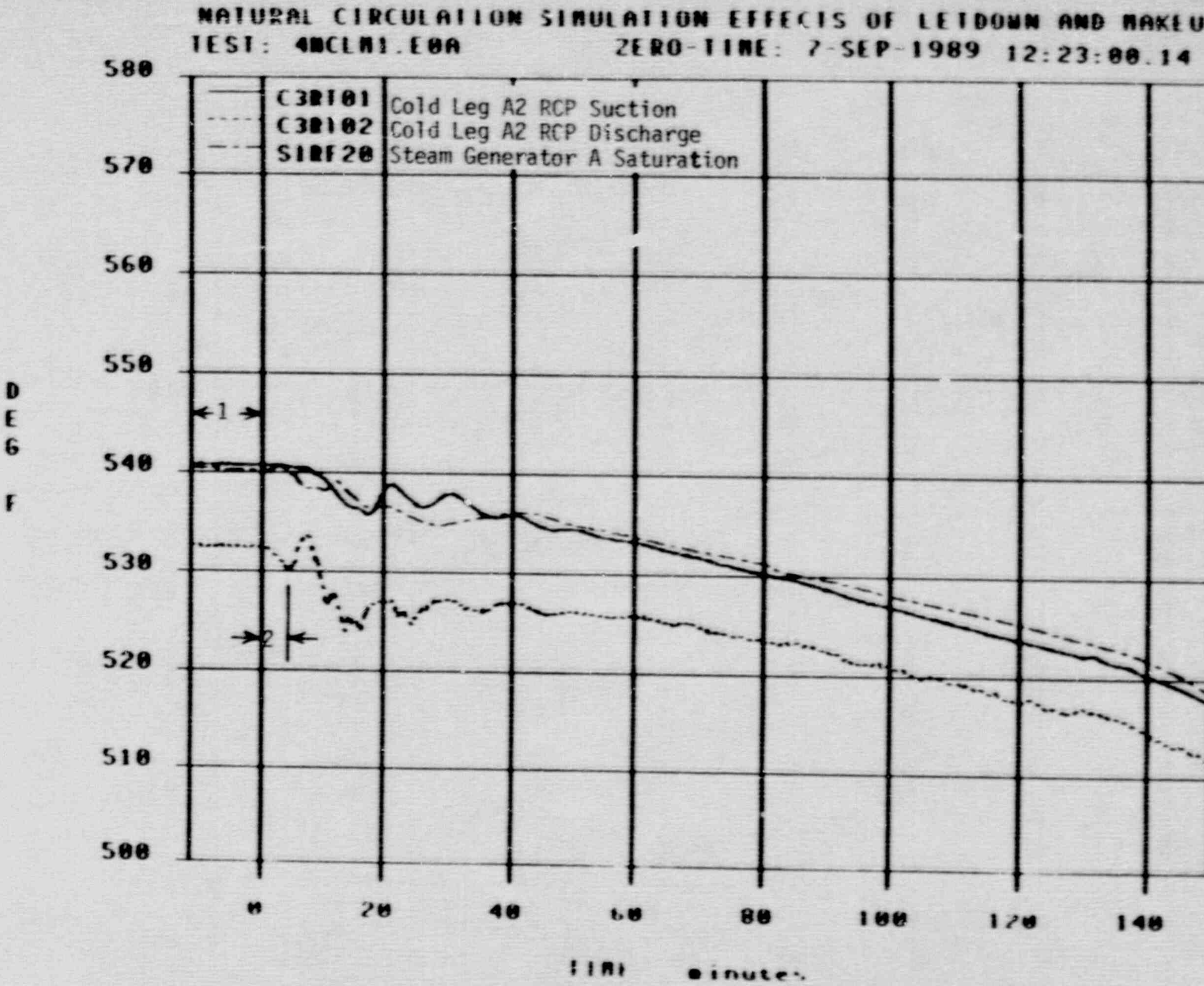


Figure 4.107 Steam Generator A Saturation Temperature And Cold Leg A2 Reactor Coolant Pump Suction And Discharge Temperature

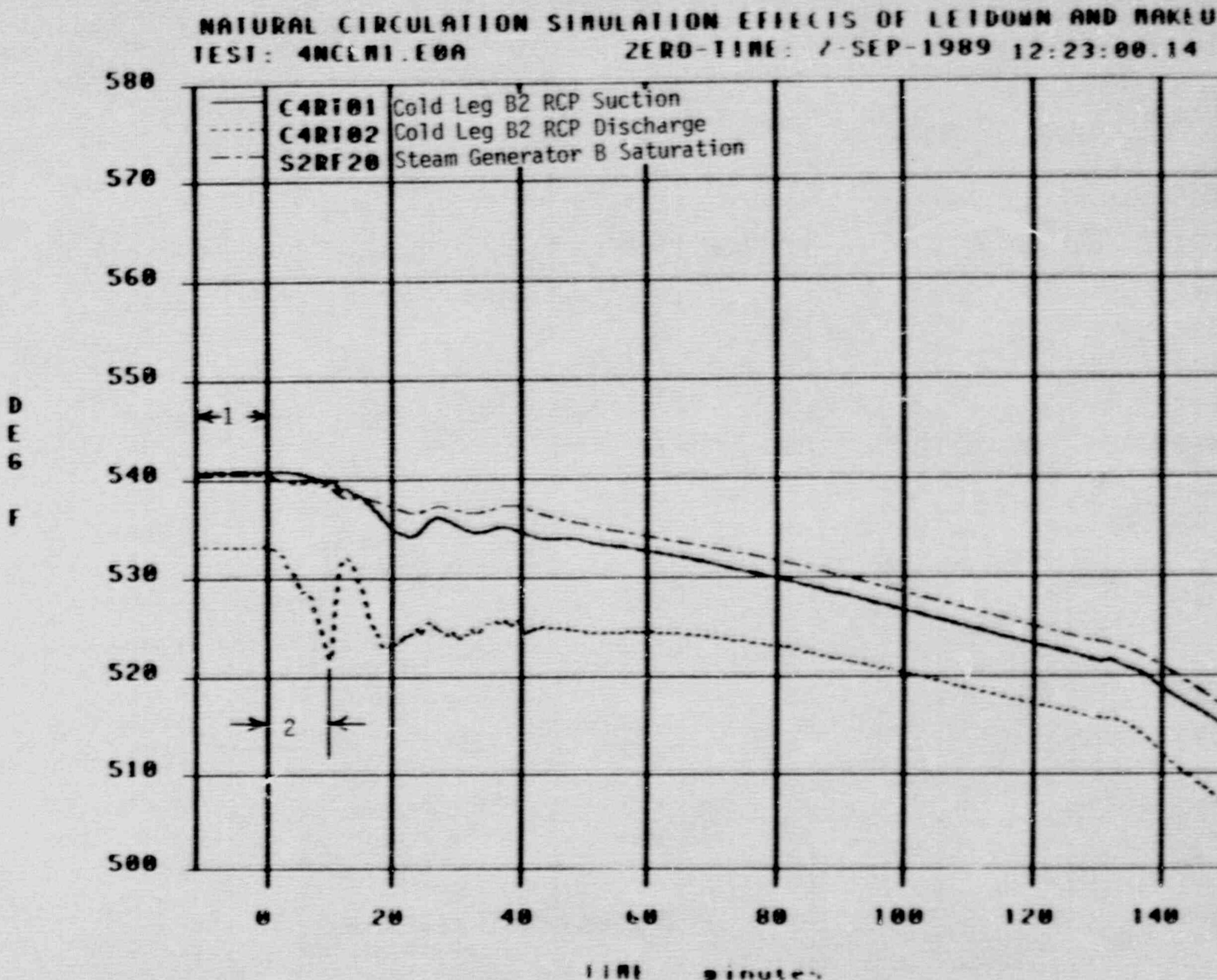


Figure 4.108 Steam Generator B Saturation Temperature And Cold Leg B2 Reactor Coolant Pump Suction And Discharge Temperature

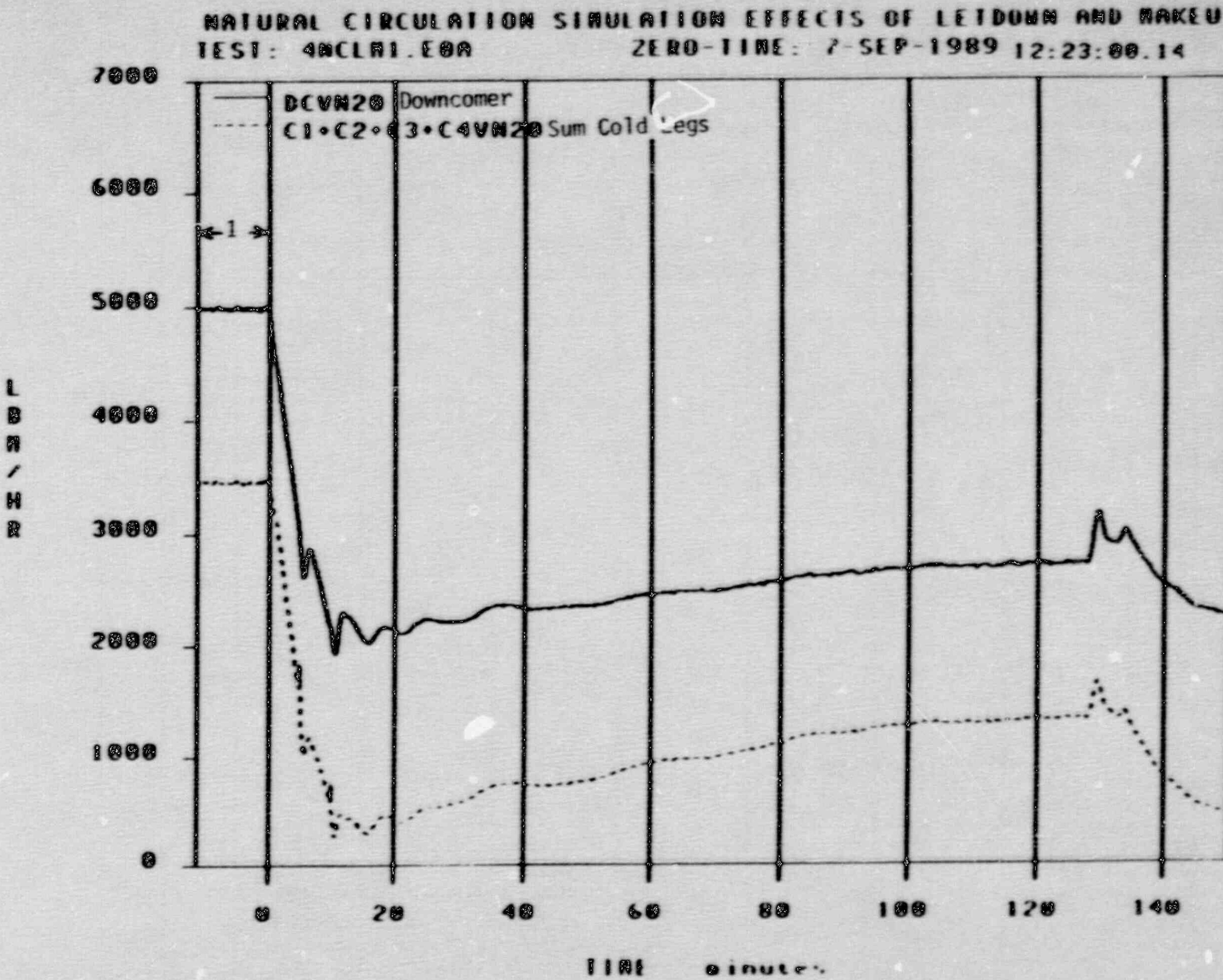


Figure 4.109 Downcomer Flow Rate And The Summation Of The Flow Rate In All Four Cold Legs

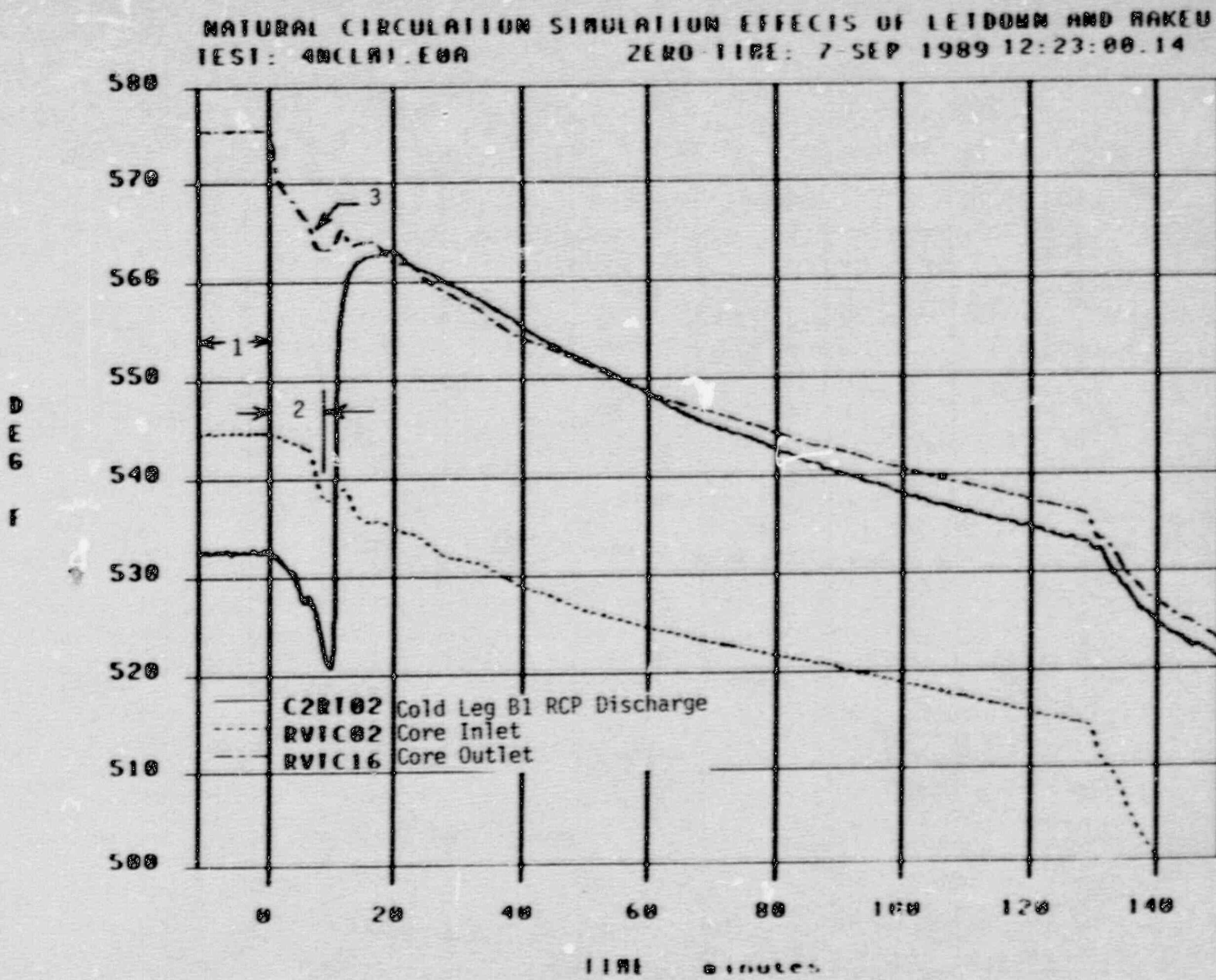


Figure 4.110 Cold Leg B1 Reactor Coolant Pump Discharge Temperature And Core Inlet And Outlet Temperature

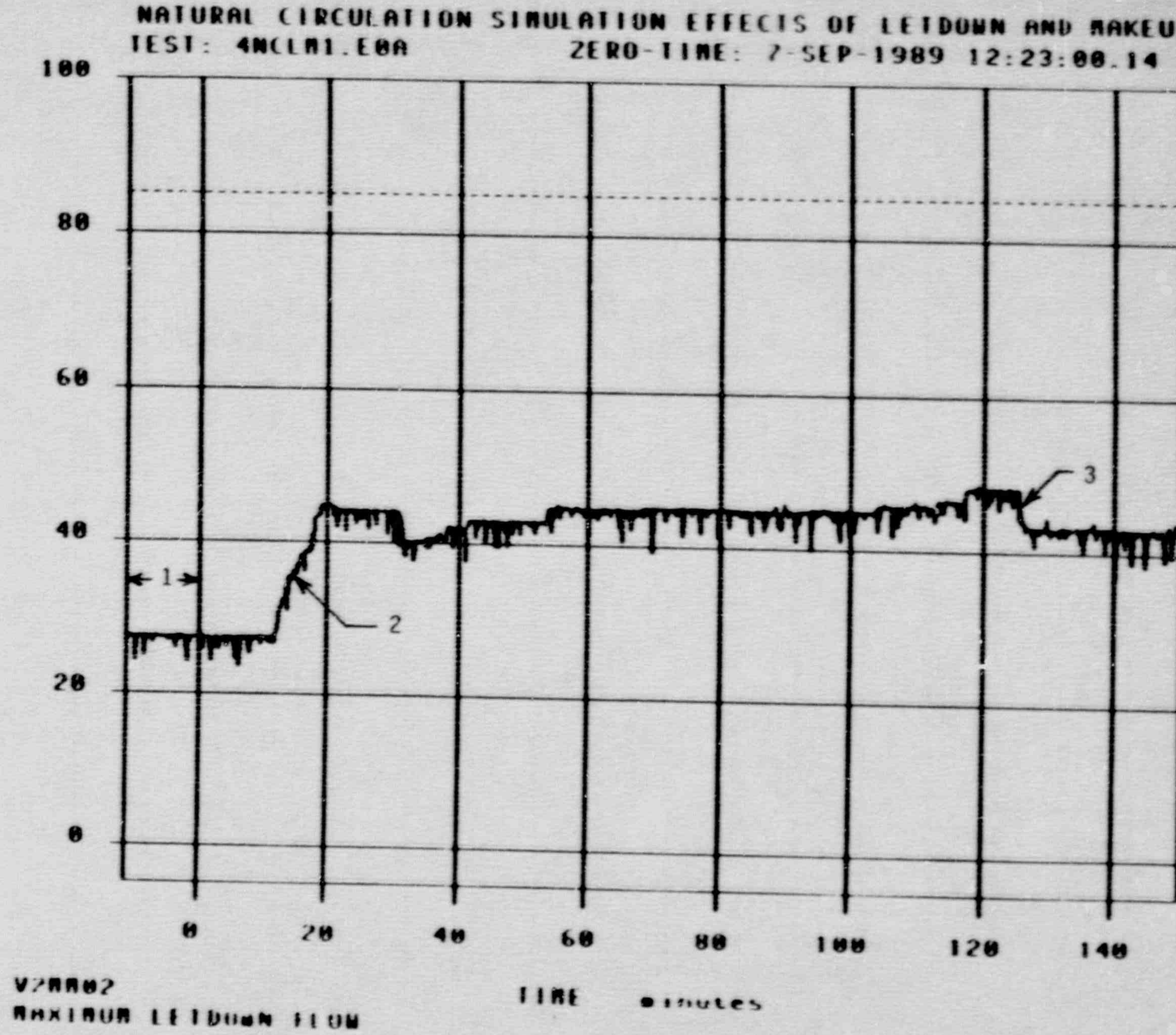


Figure 4.111 Letdown Flow Rate

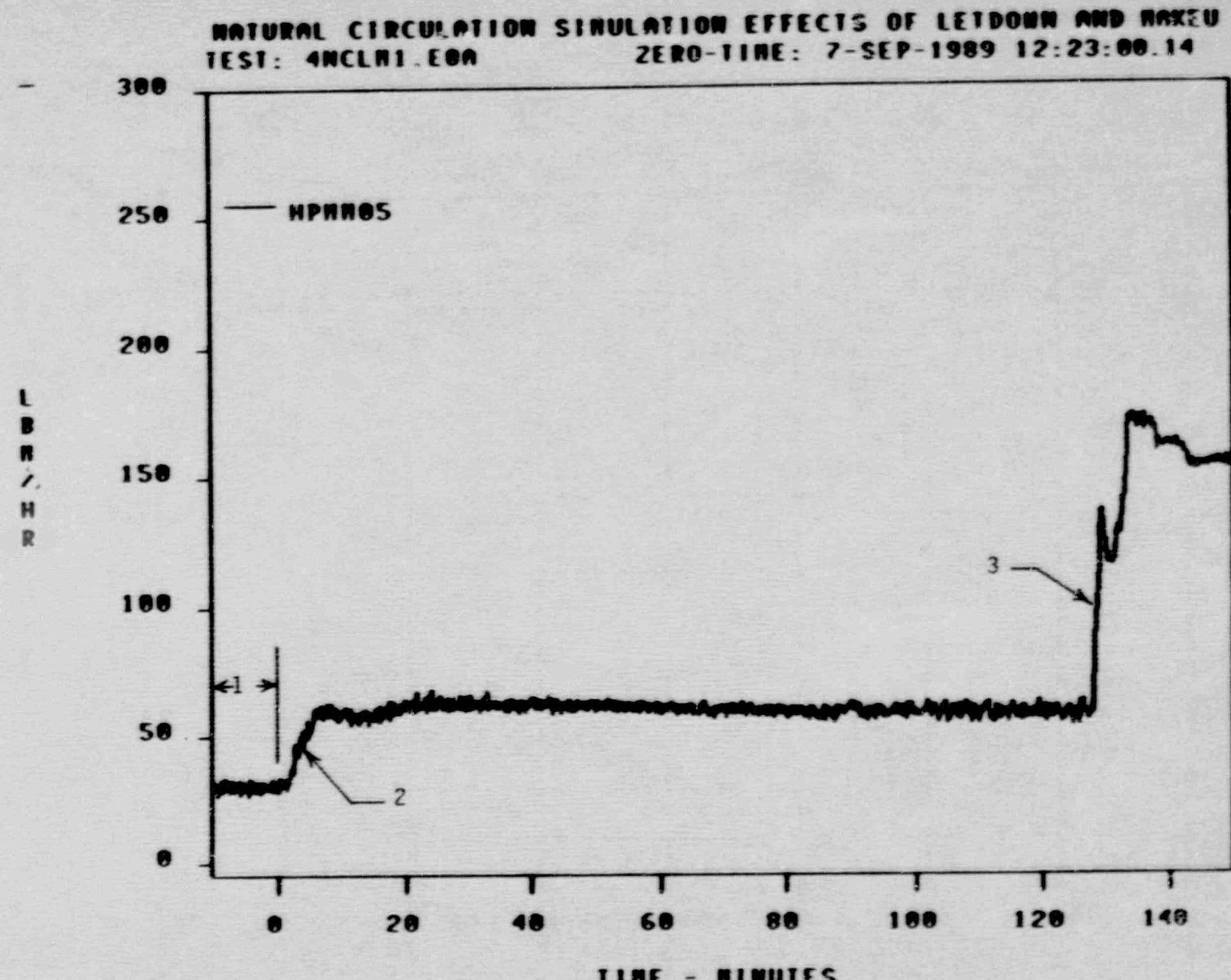


Figure 4.112 Makeup Flow Rate

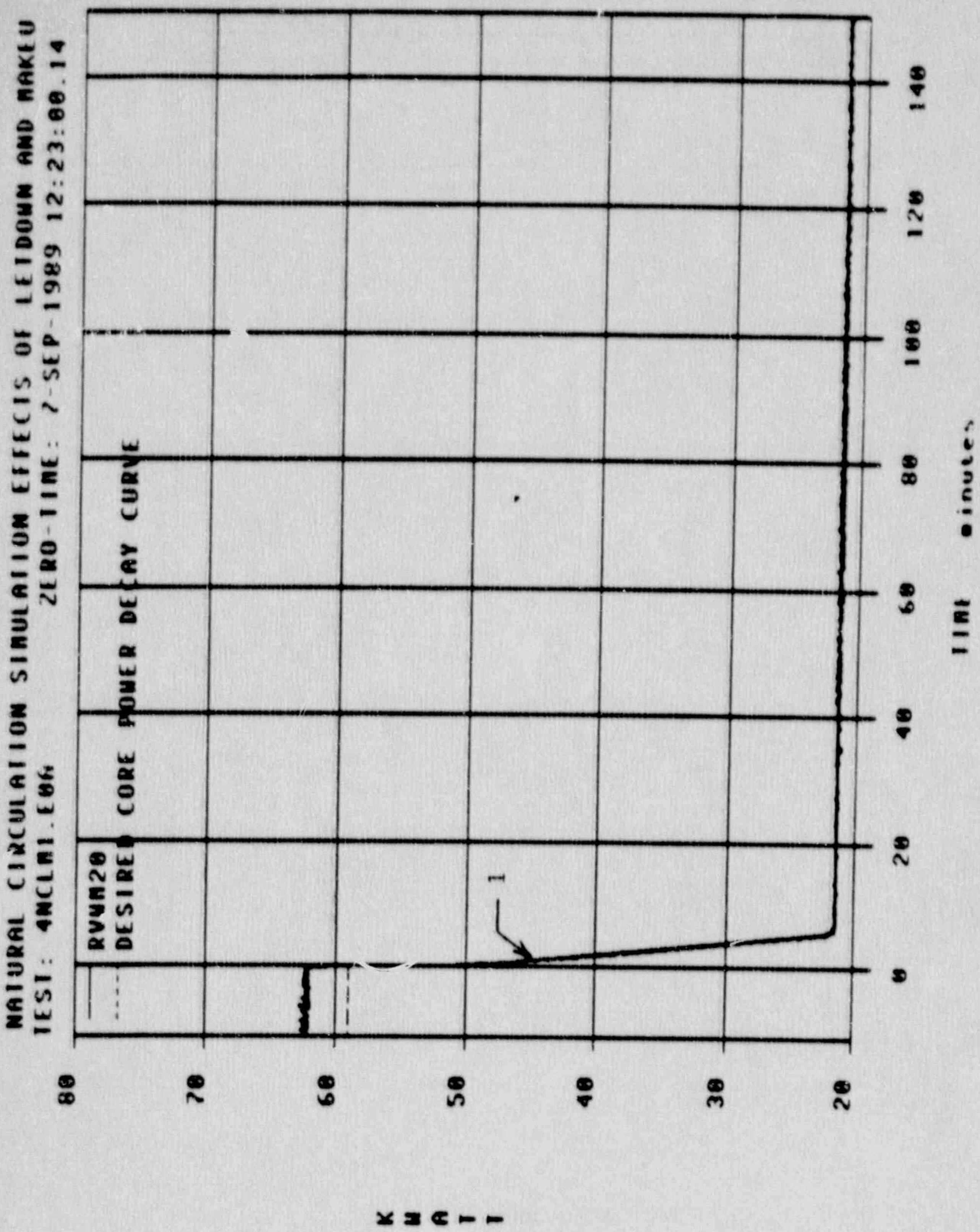


Figure 4.113 Core Power

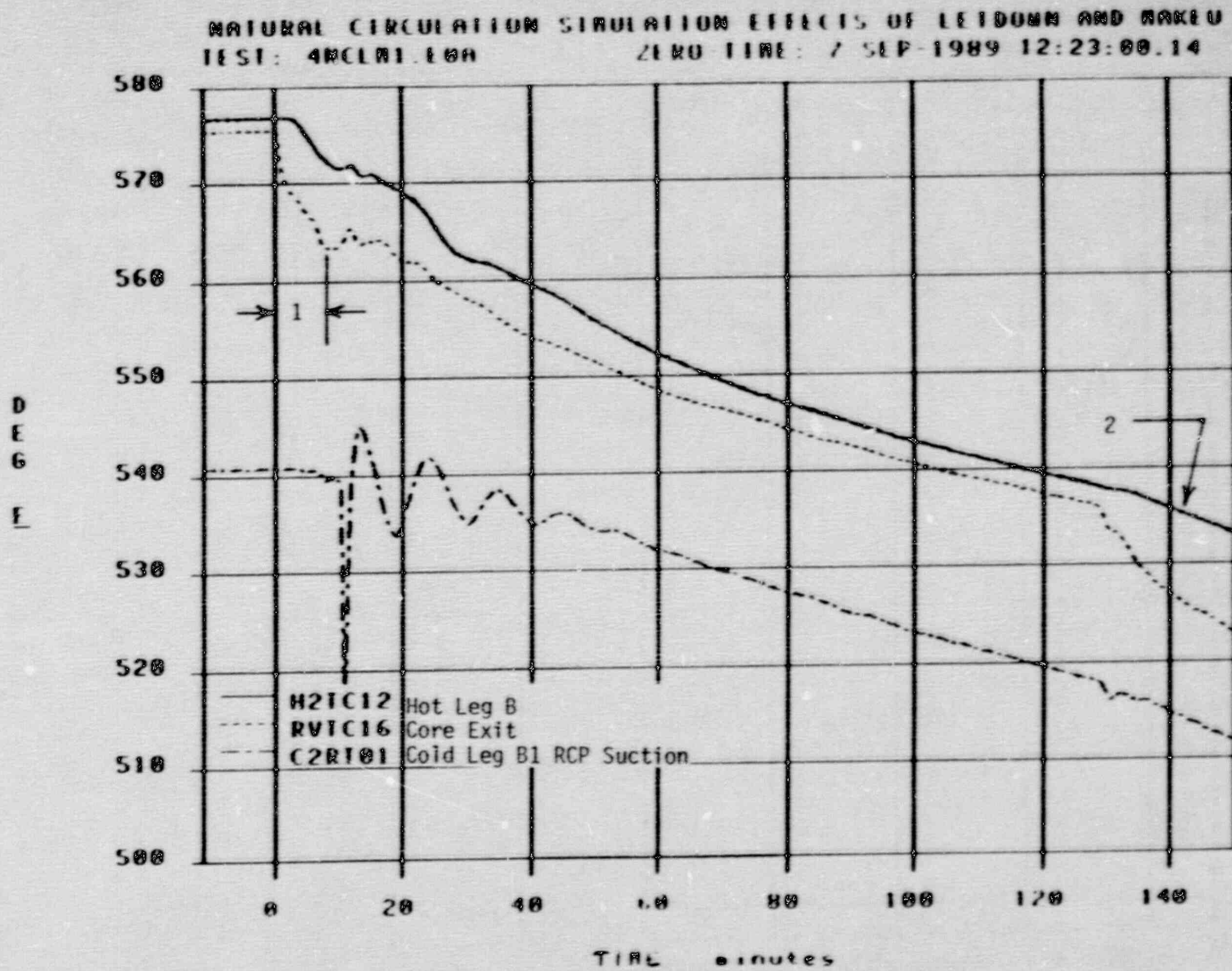


Figure 4.114 Core Exit, Hot Leg B And Cold Leg B1 Reactor Coolant Pump Suction Temperatures

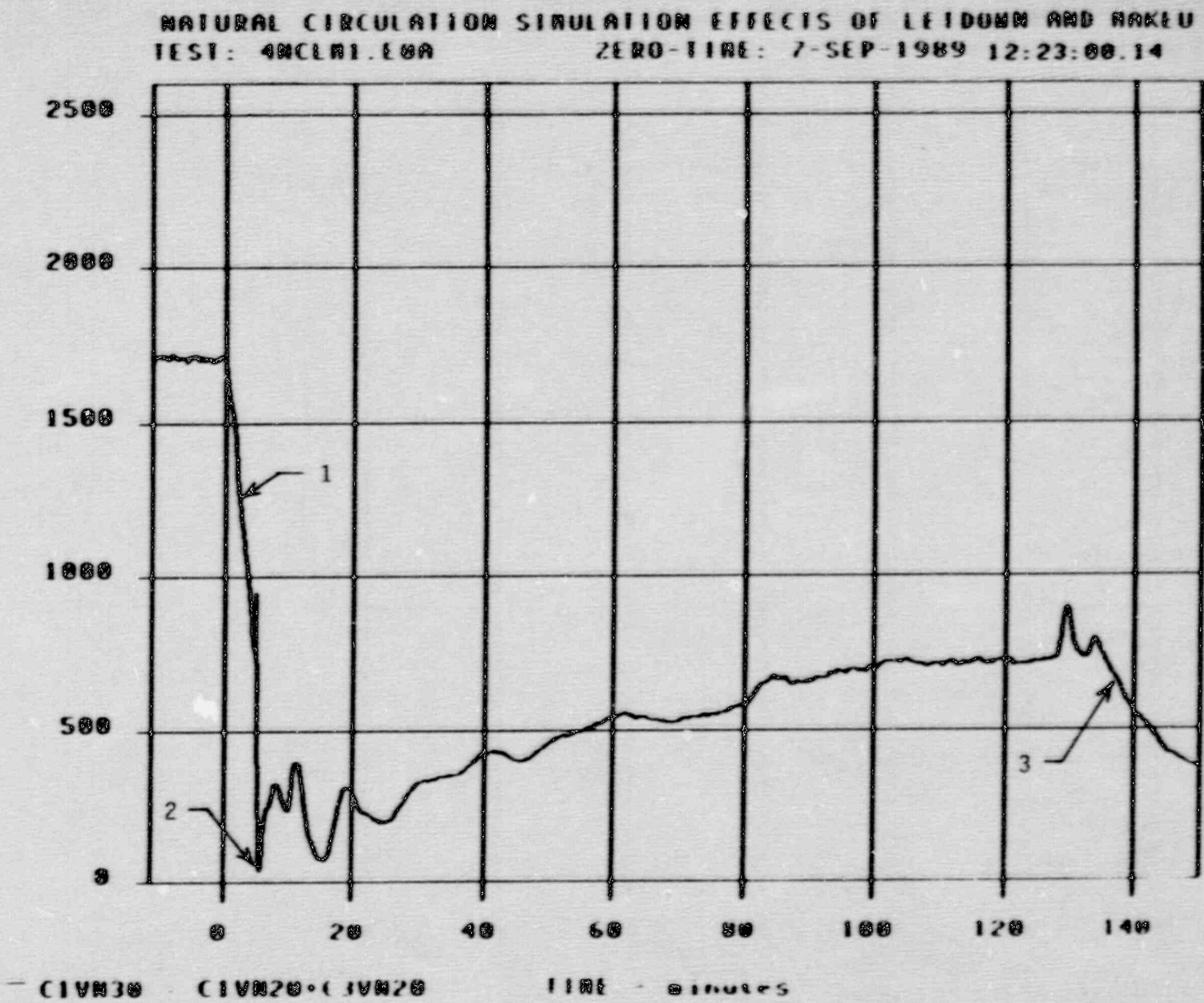


Figure 4.115 Summation of the A1 and A2 Cold Leg Flow Rates

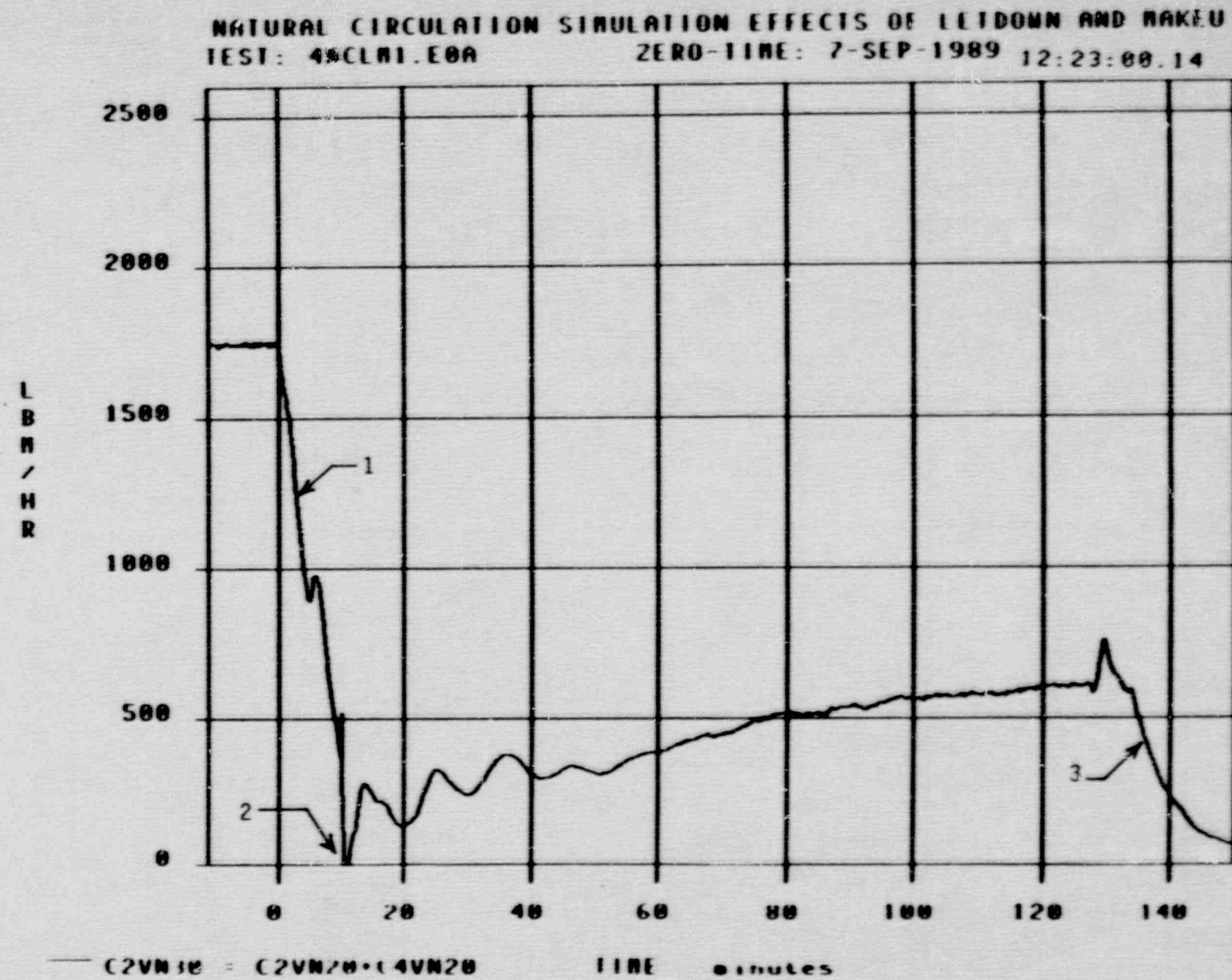


Figure 4.116 Summation Of The B1 And B2 Cold Leg Flow Rates

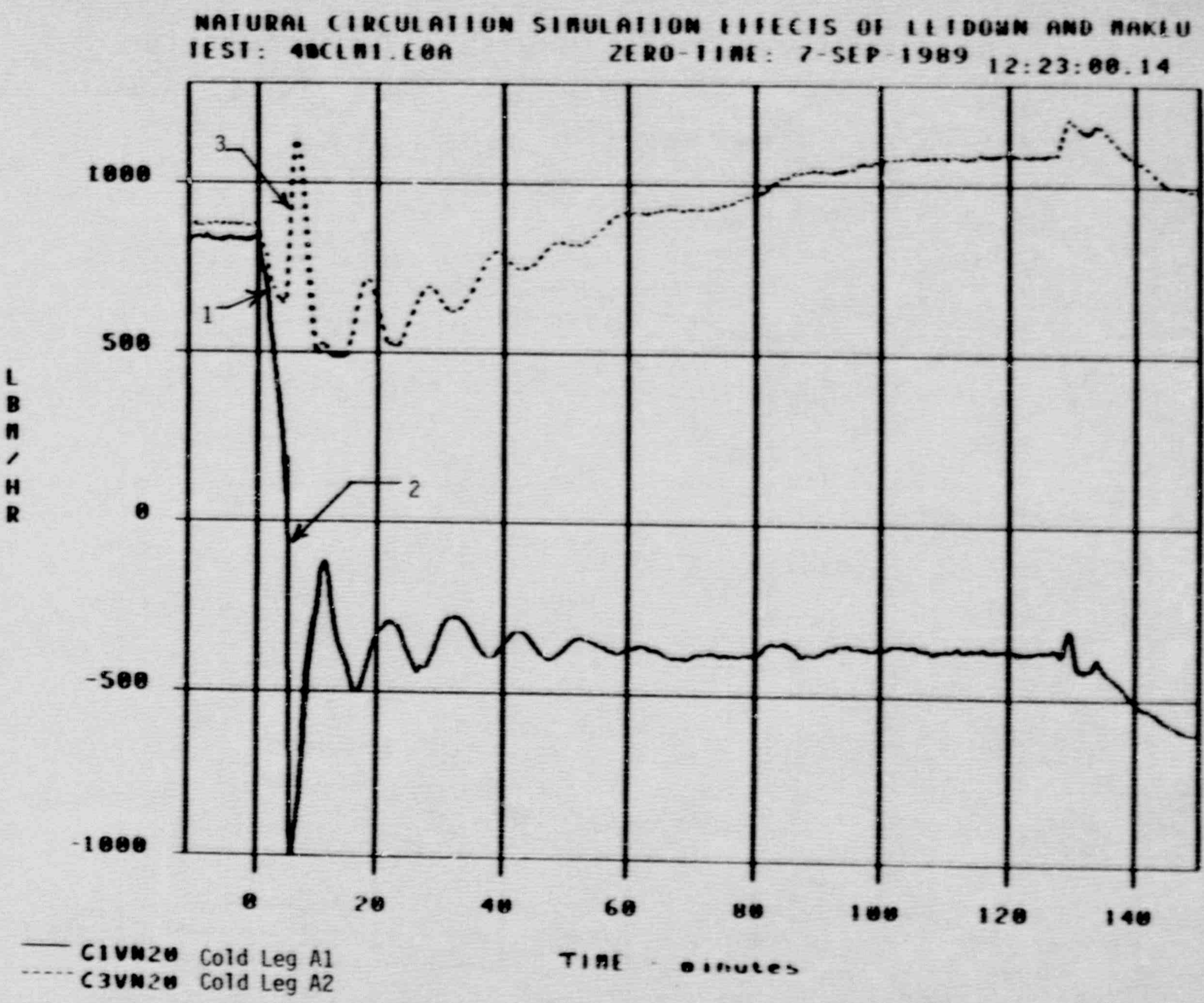


Figure 4.117 Cold Leg A1 And A2 Flow Rate

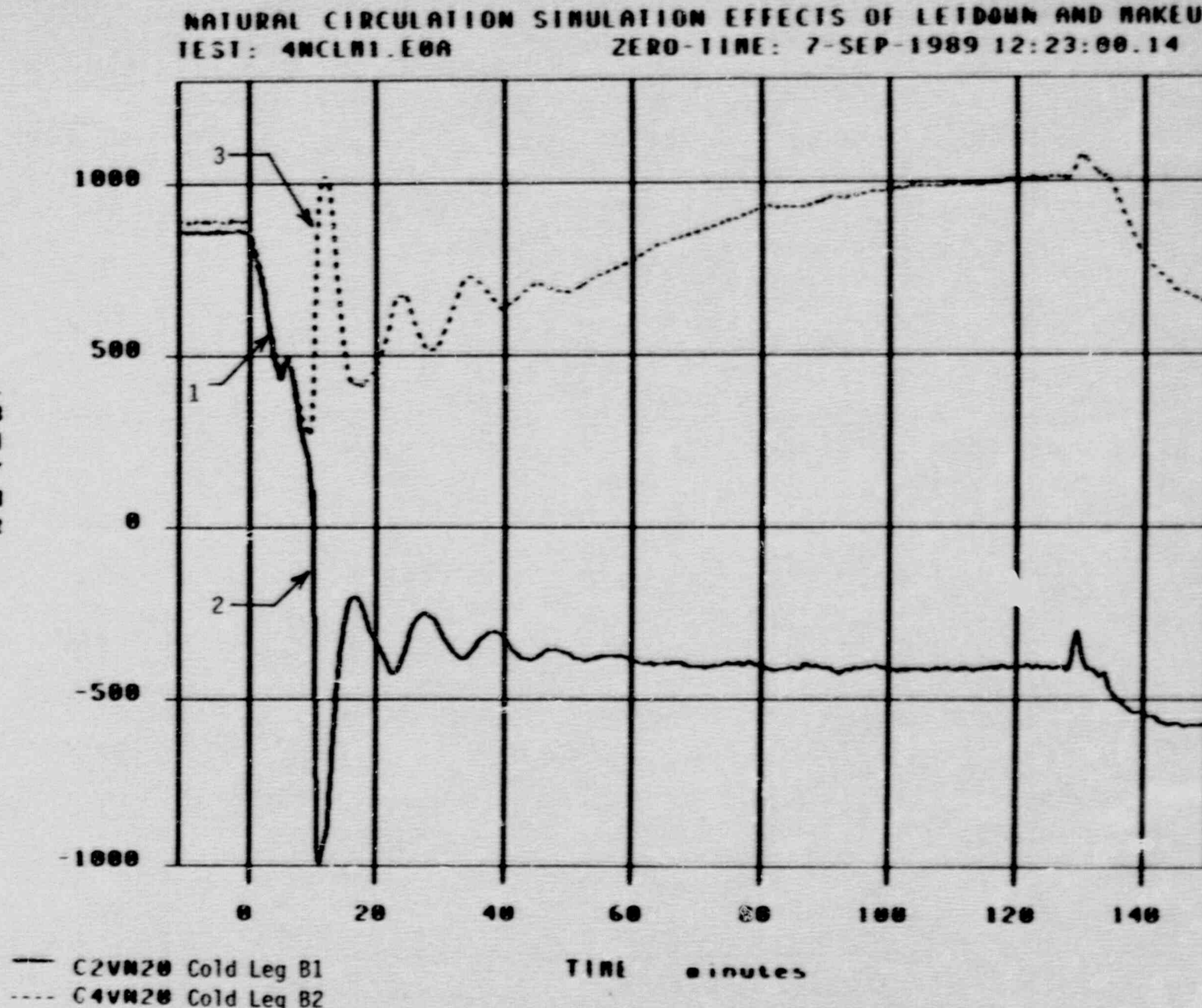


Figure 4.118 Cold Leg B1 And B2 Flow Rates

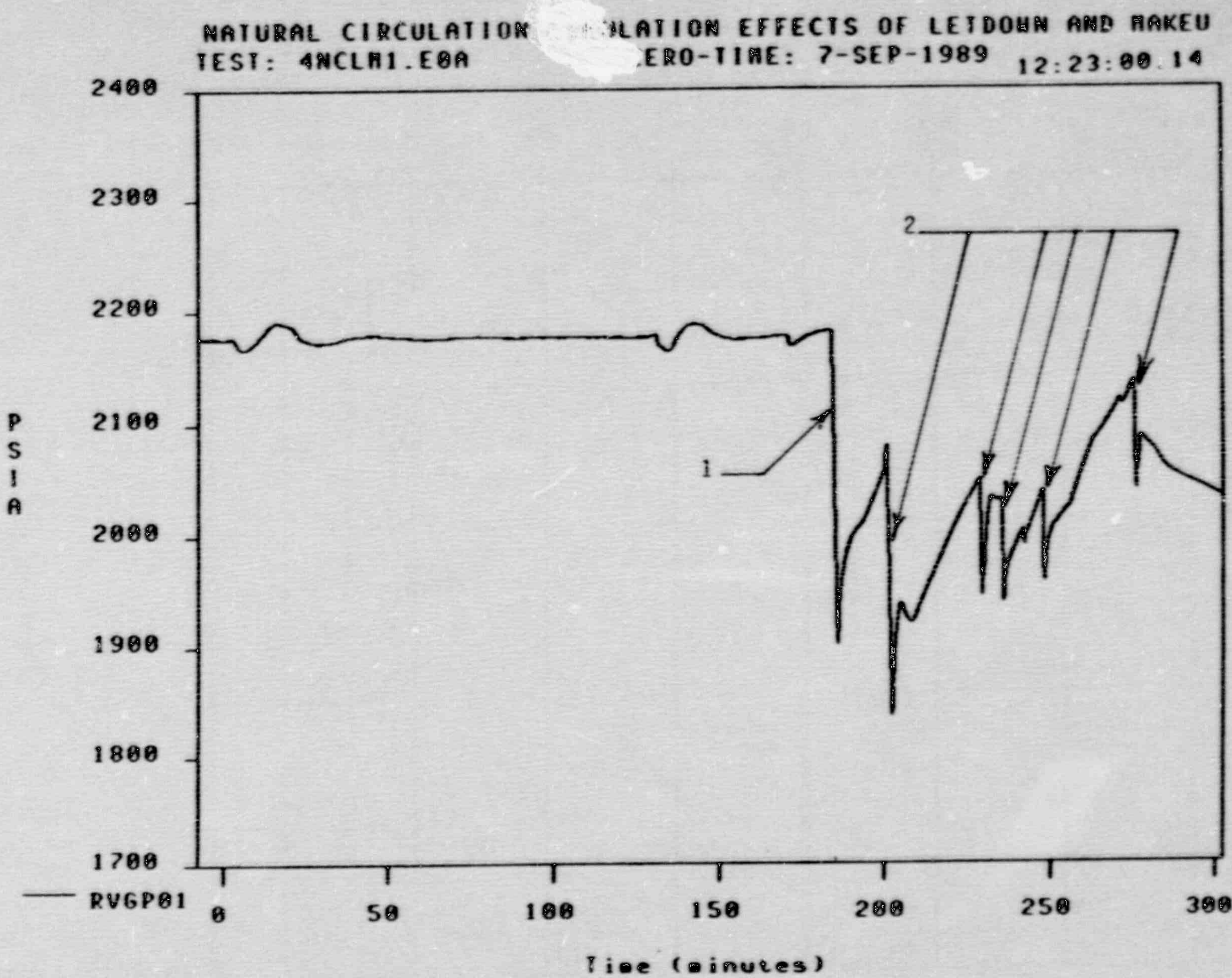


Figure 4.119 Primary System Pressure

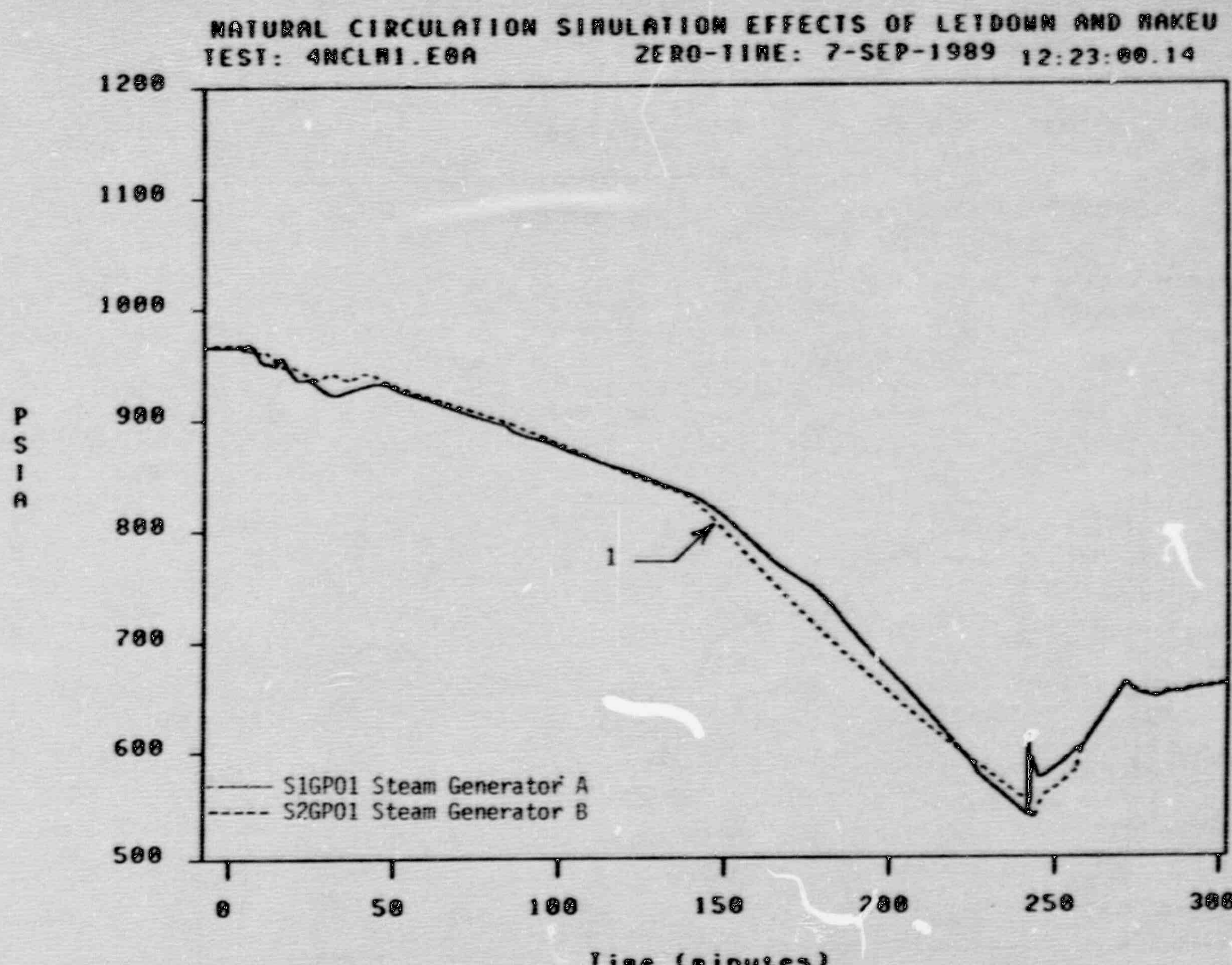


Figure 4.120 Secondary System Pressure

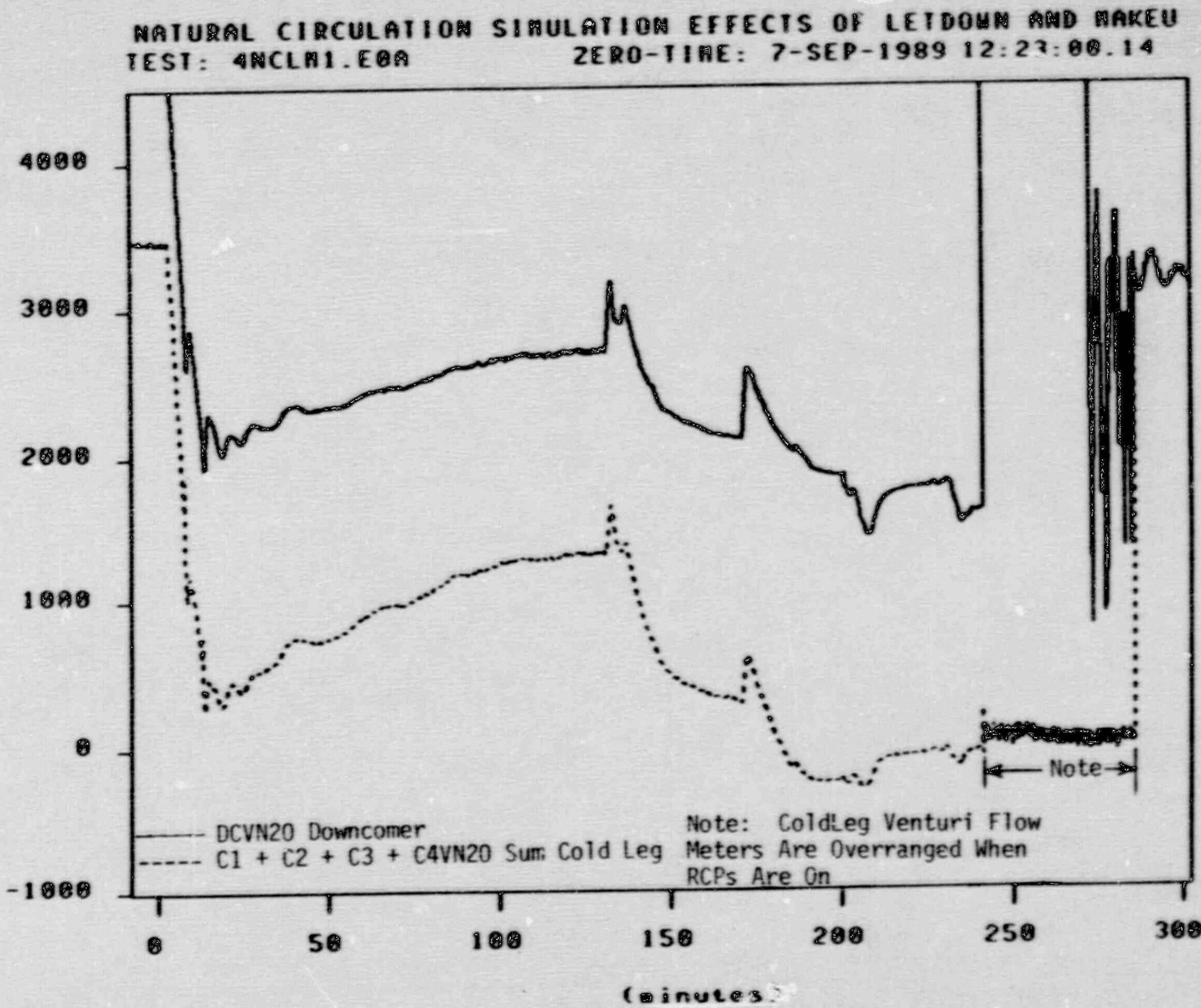


Figure 4.121 Downcomer Flow Rate And The Summation Of The Flow Rate In All Four Cold Legs

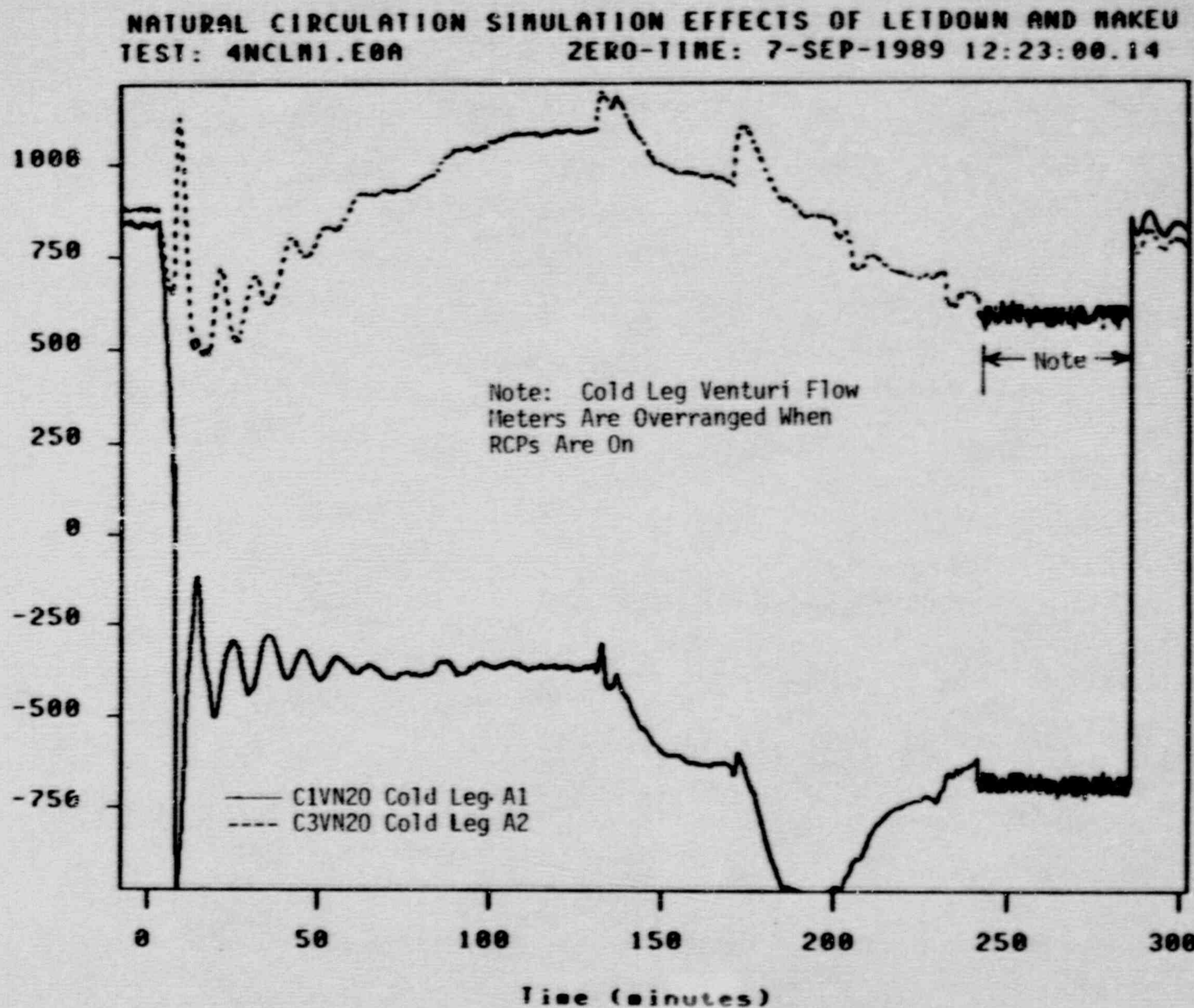


Figure 4.122 ColdLeg A1 And A2 Flow Rate

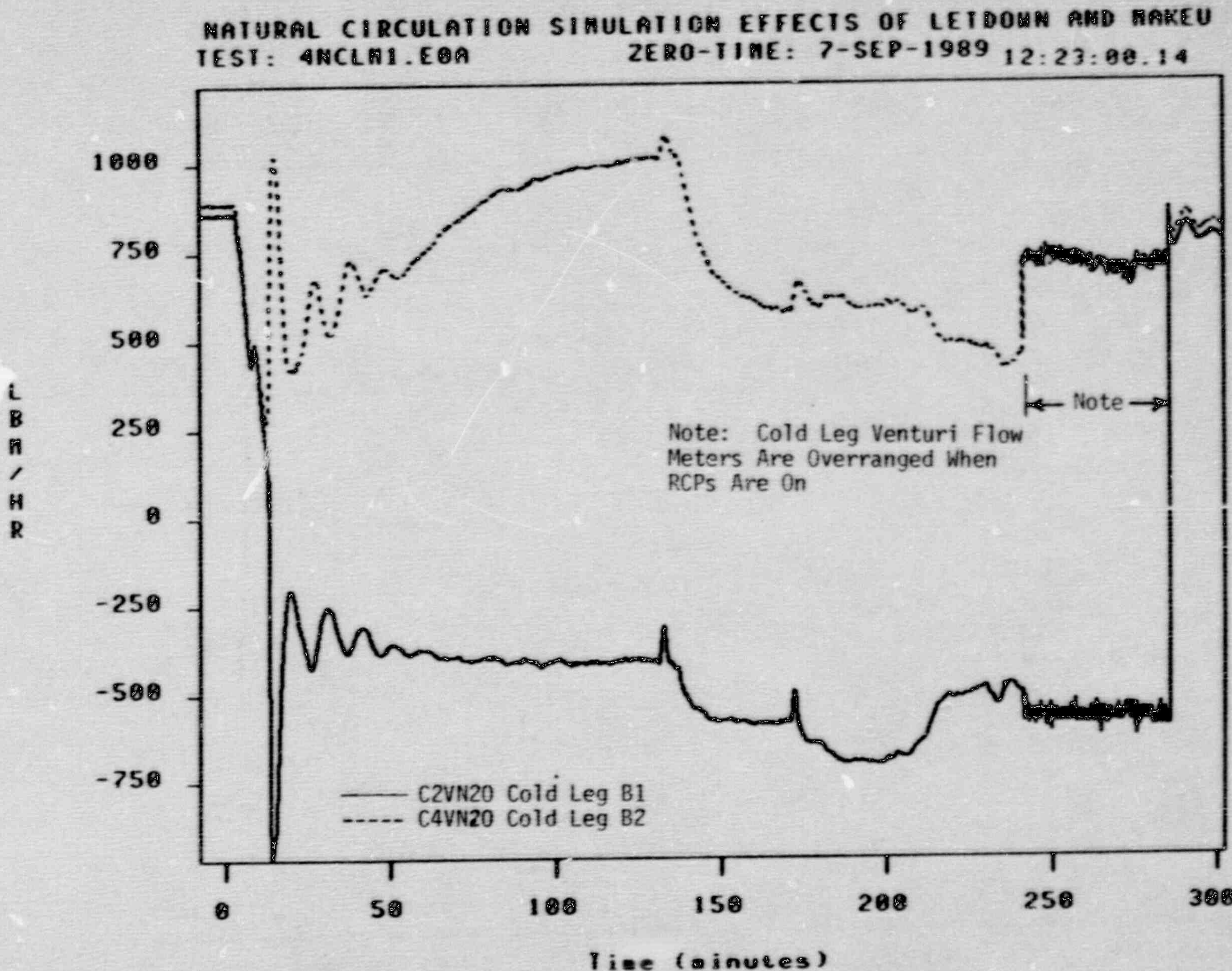


Figure 4.123 Cold Leg B1 And B2 Flow Rate

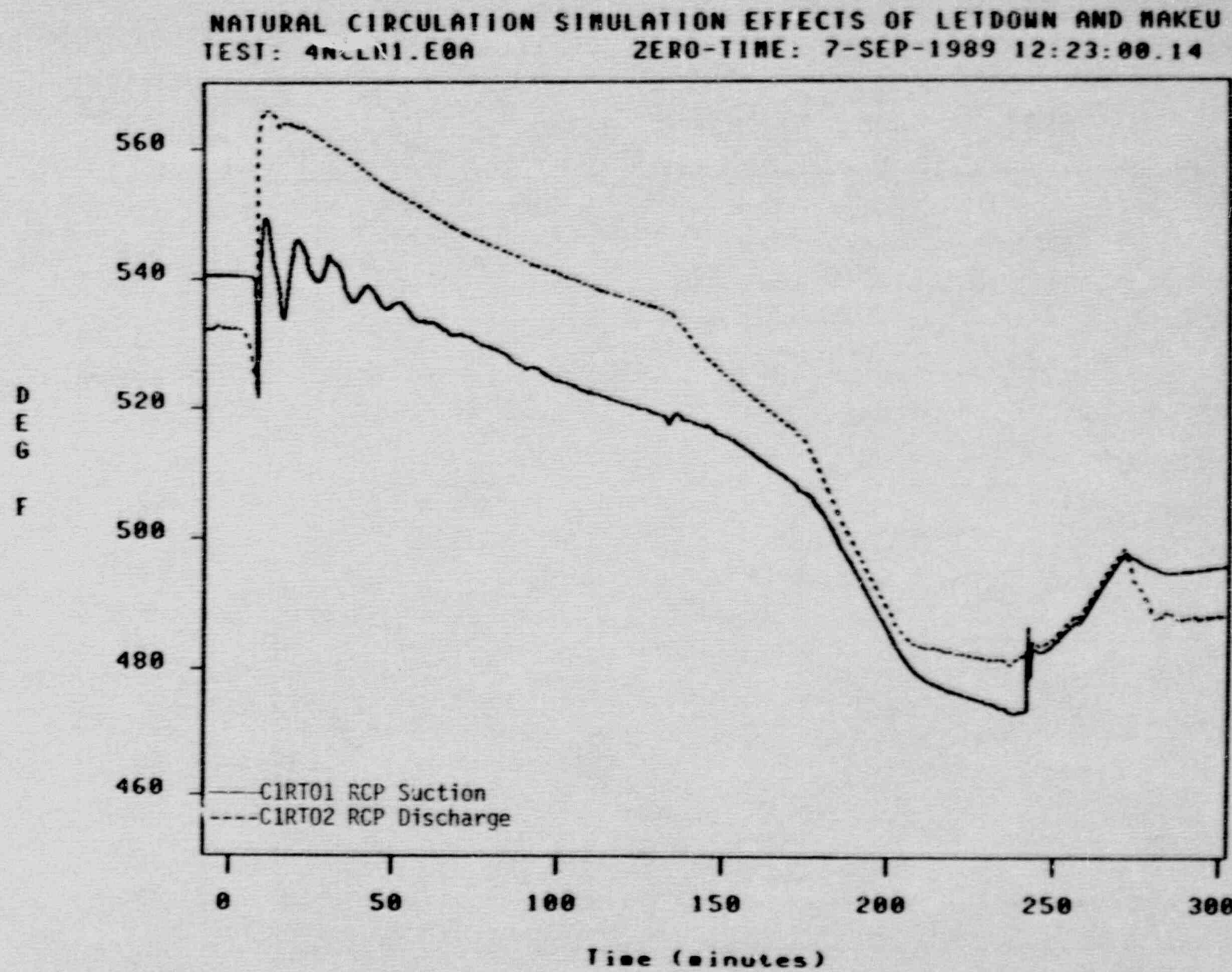


Figure 4.124 Cold Leg A1 Reactor Coolant Pump Suction And Discharge Temperature

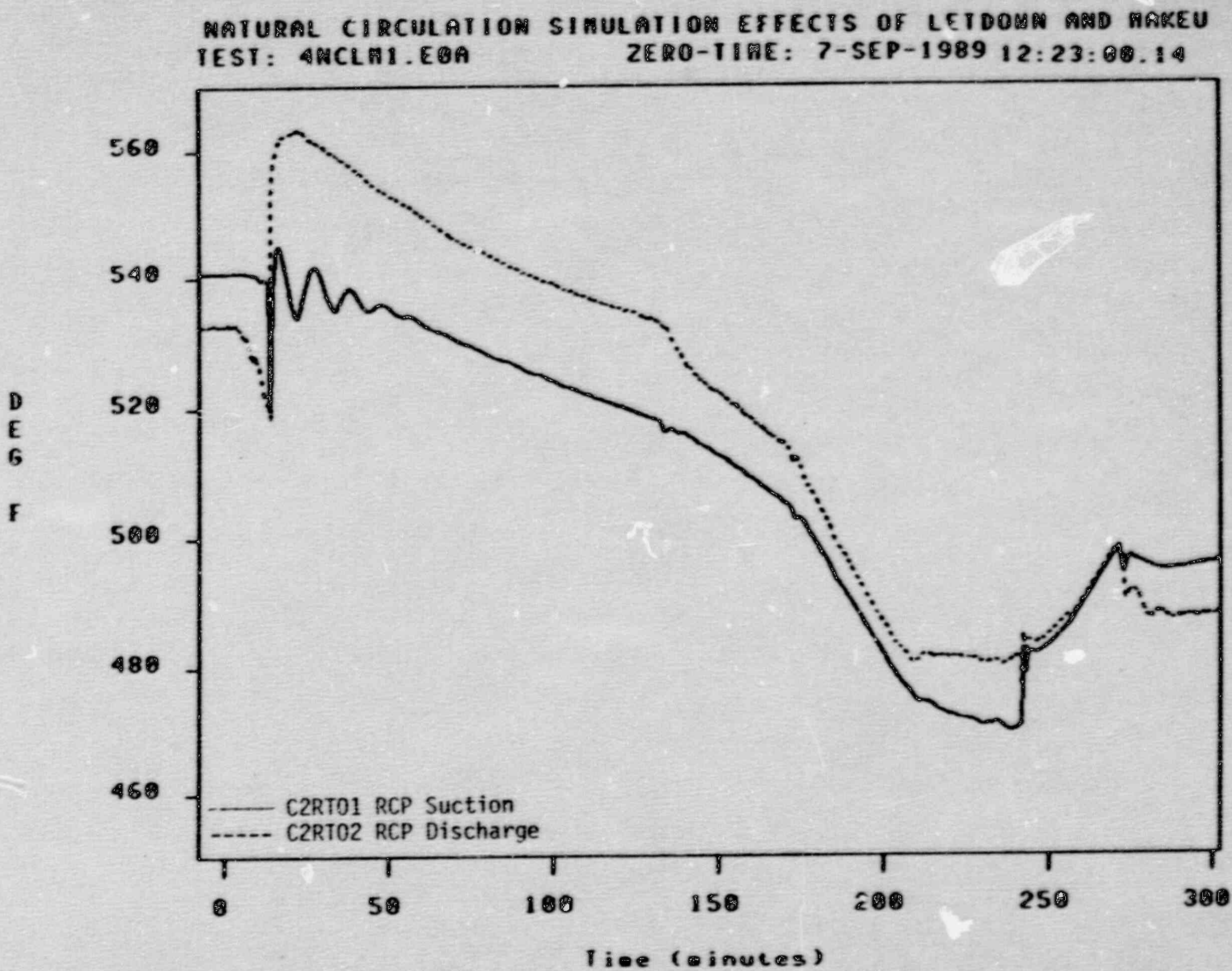


Figure 4.125 Cold Leg B1 Reactor Coolant Pump Suction And Discharge Temperature

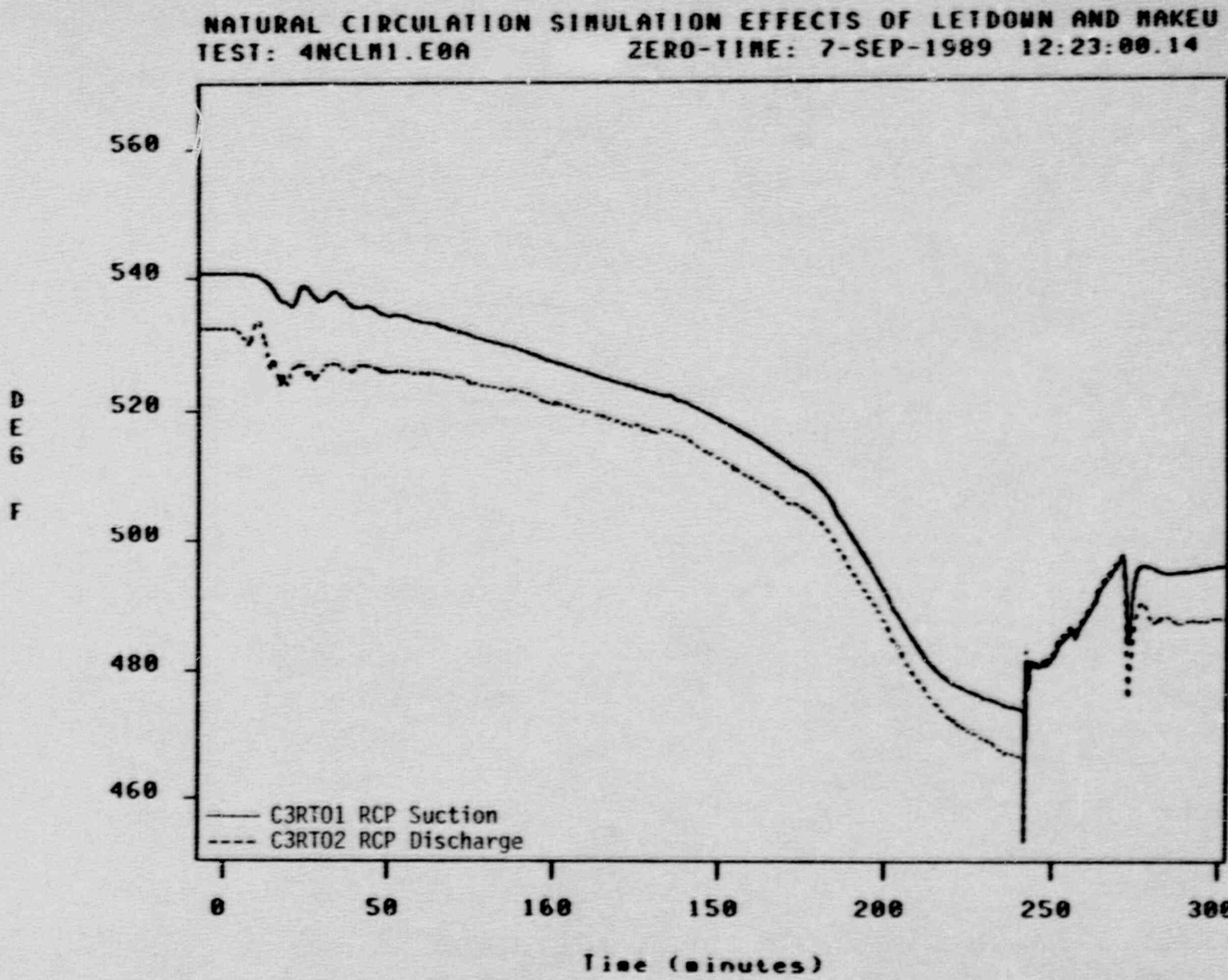


Figure 4.126 Cold Leg A2 Reactor Coolant Pump Suction And Discharge Temperature

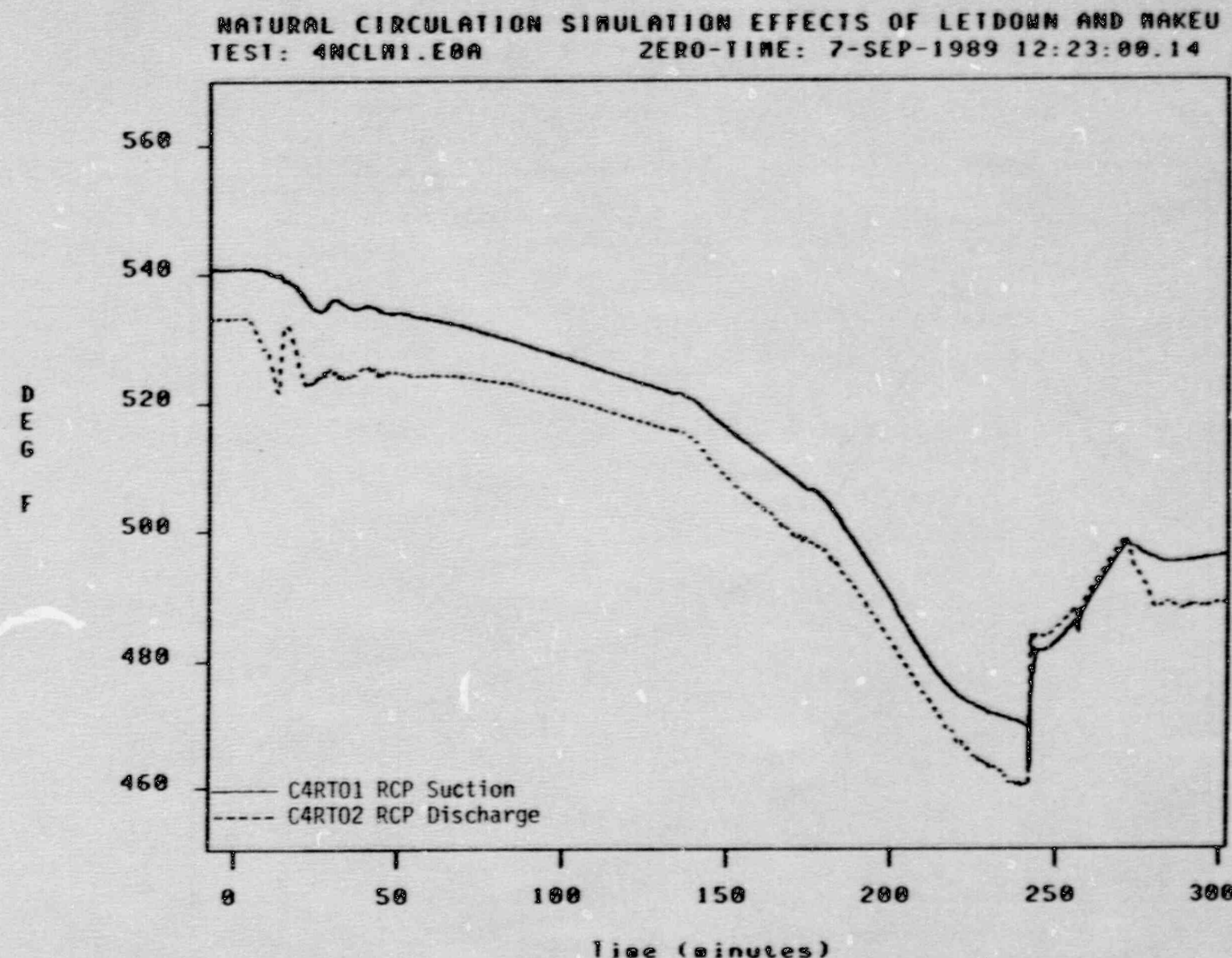


Figure 4.127 Cold Leg B2 Reactor Coolant Pump Suction And Discharge Temperature

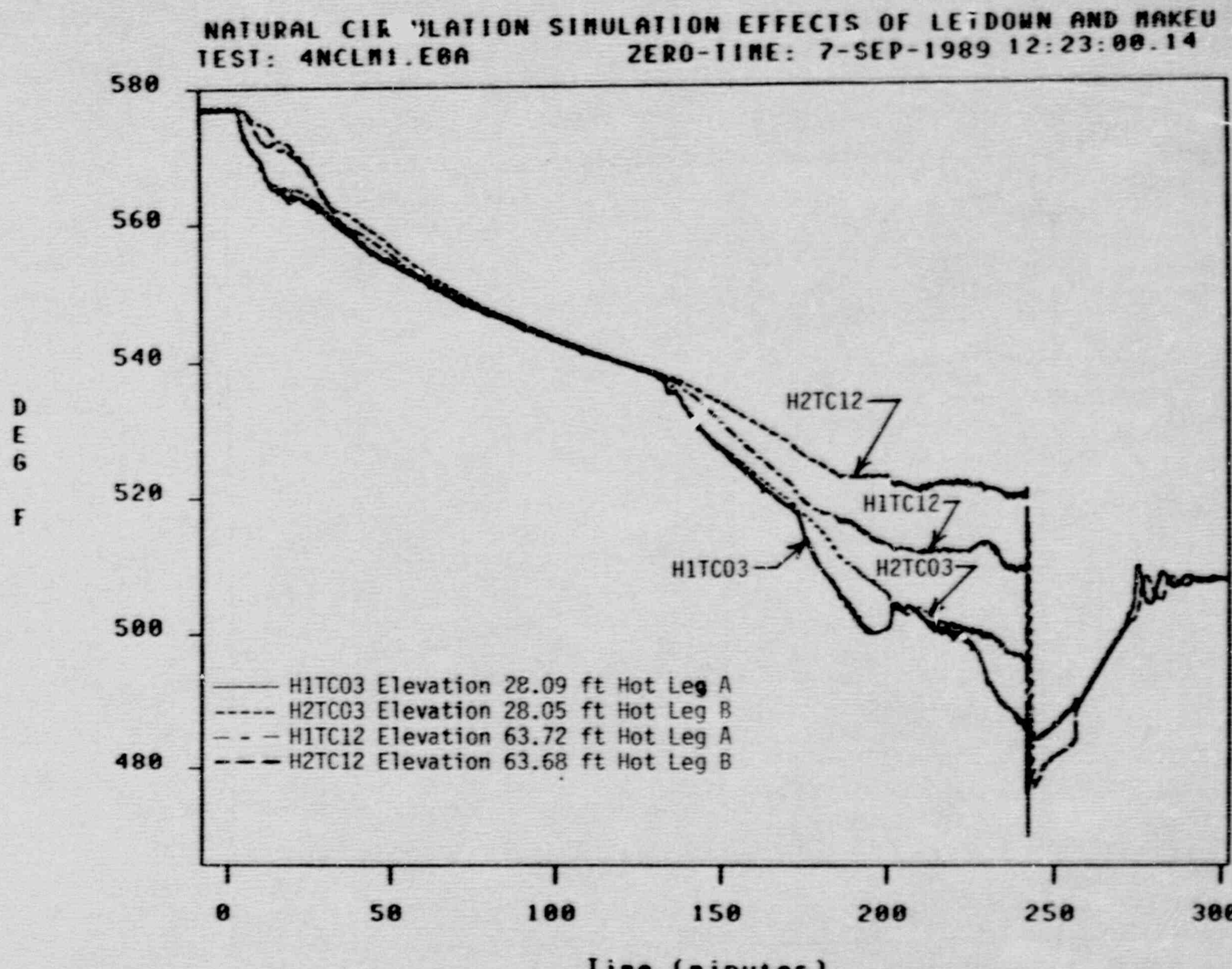


Figure 4.128 Hot Leg A And B Fluid Temperatures

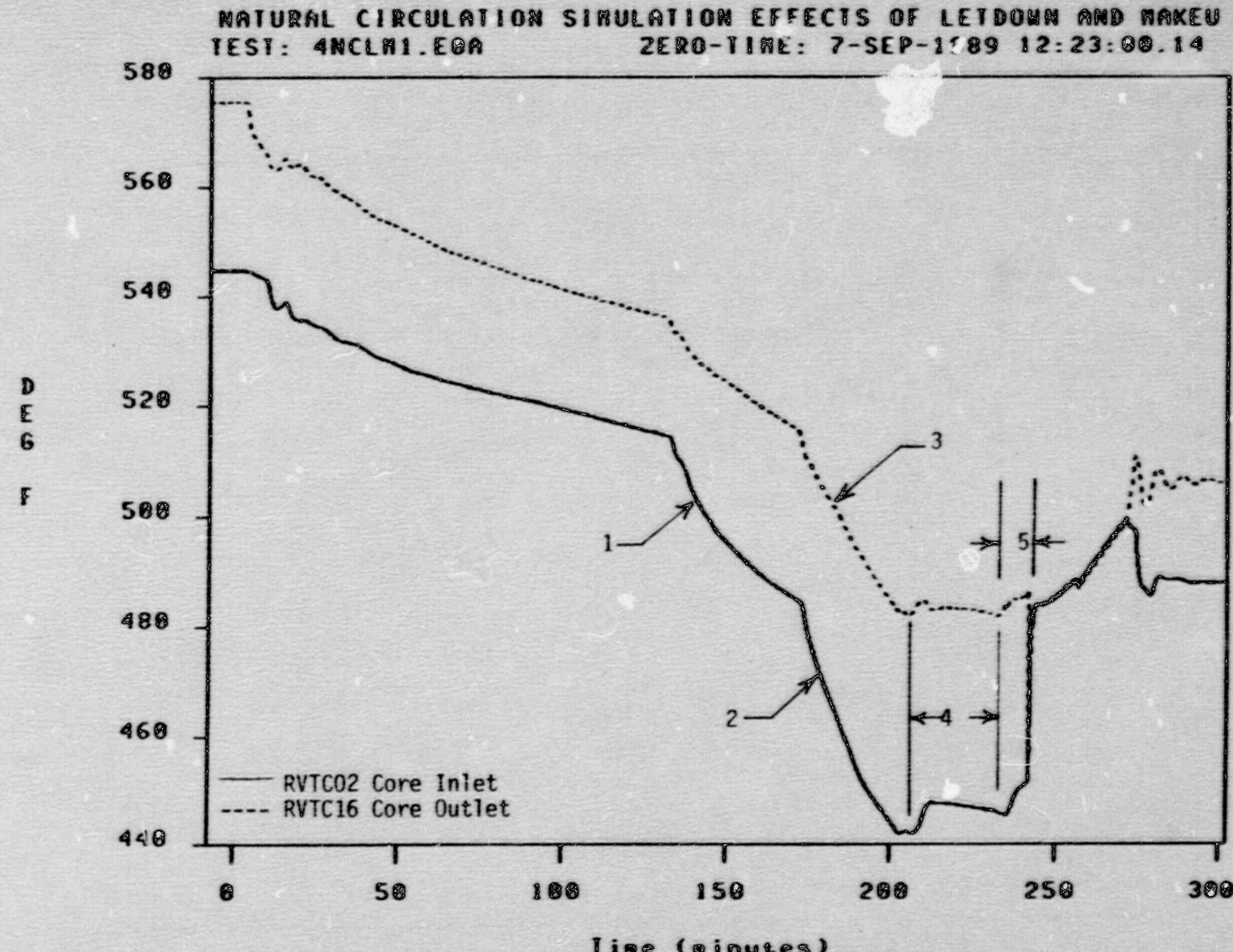


Figure 4.129 Core Inlet And Outlet Temperature

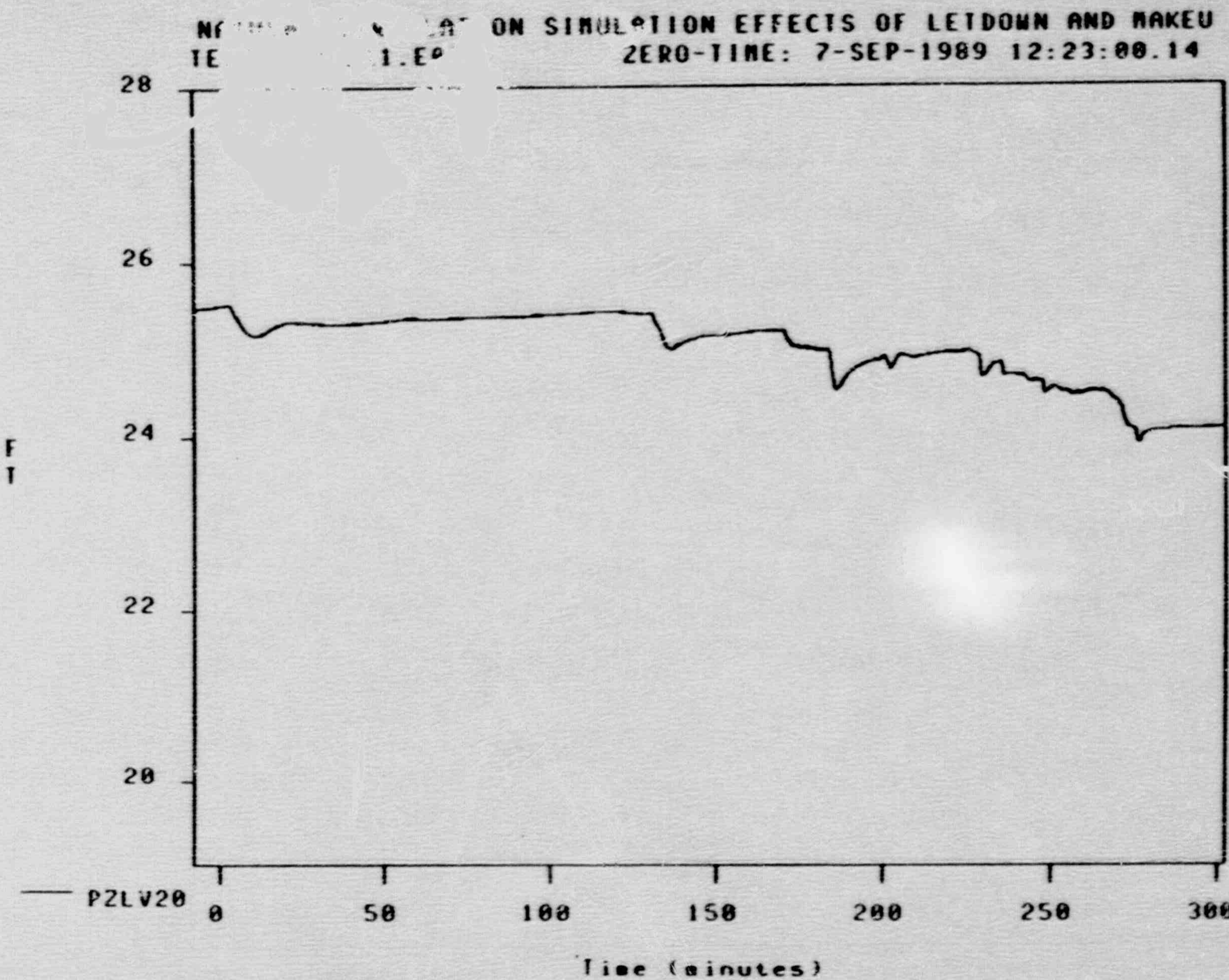


Figure 4.130 Pressurizer Level

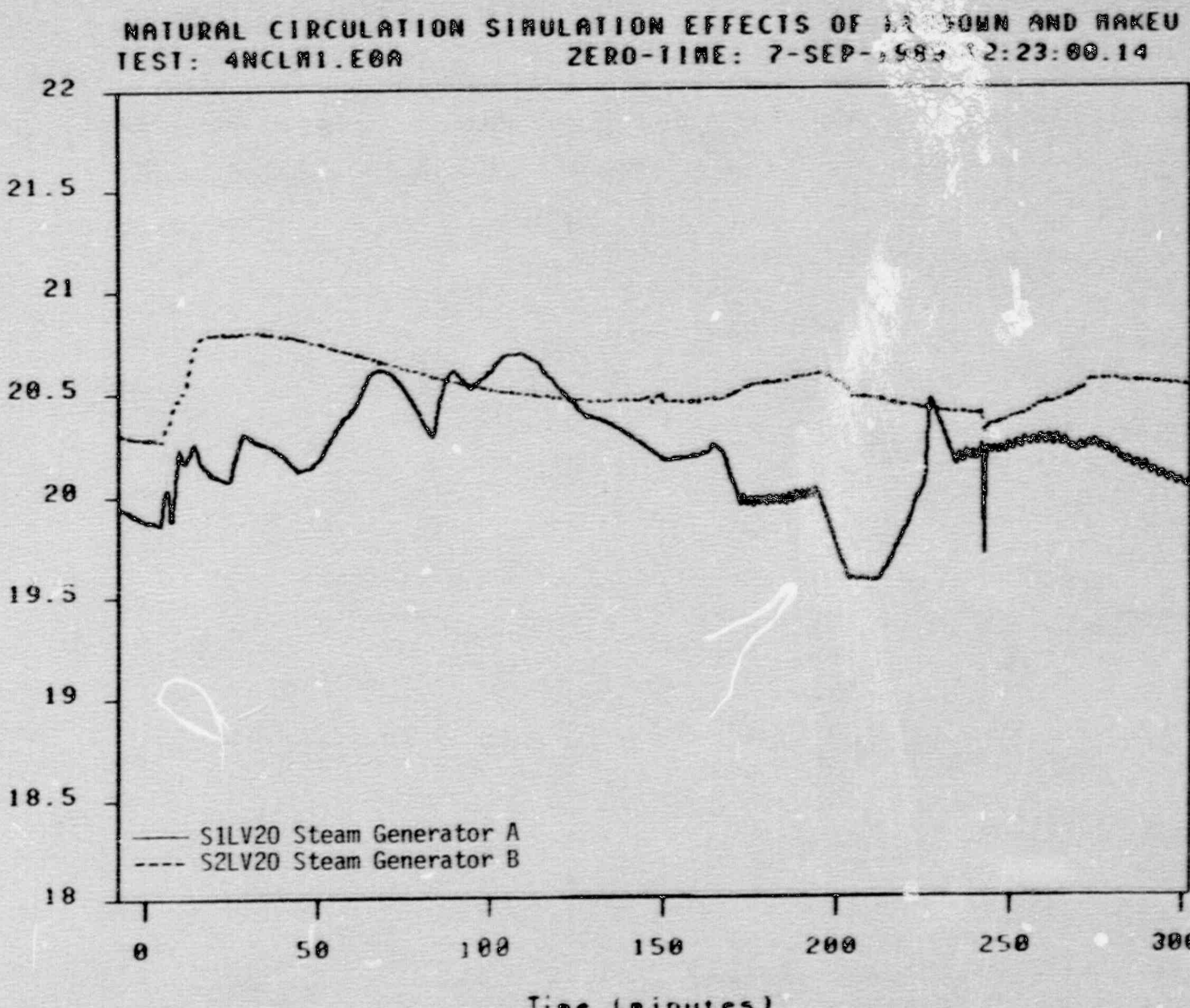


Figure 4.131 Steam Generator Level

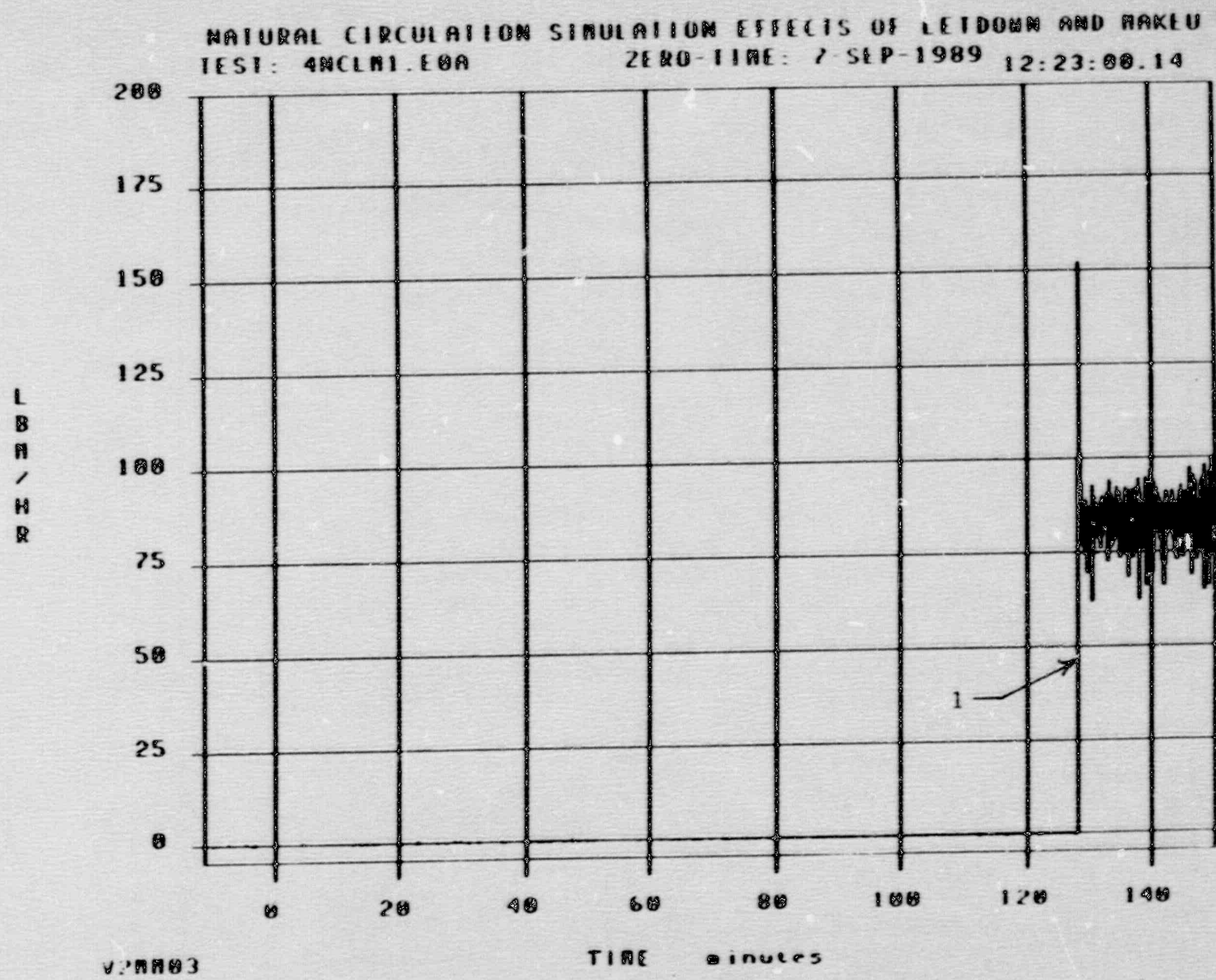


Figure 4.132 High Point Vent Flow Rate

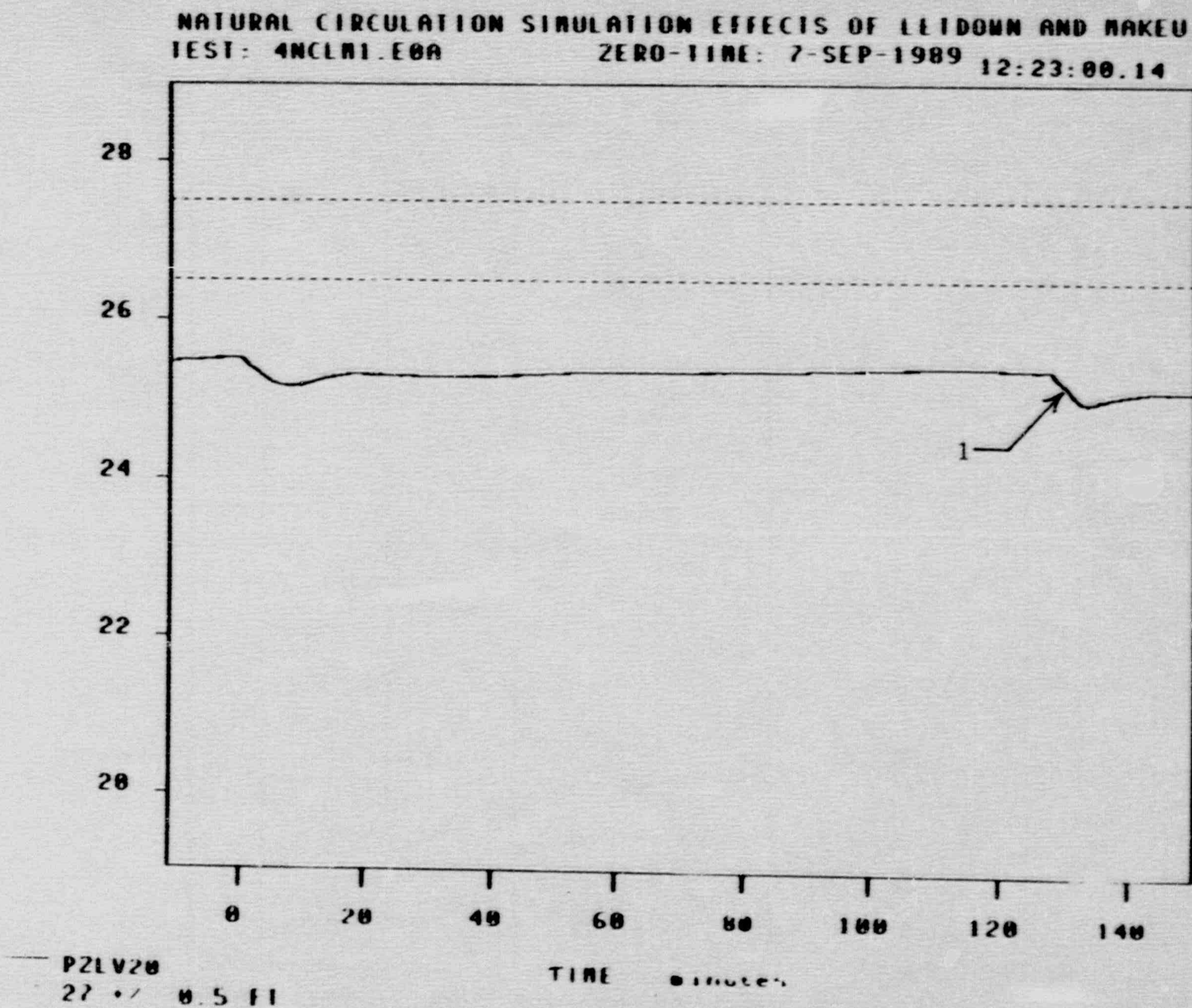


Figure 4.133 Pressurizer Level

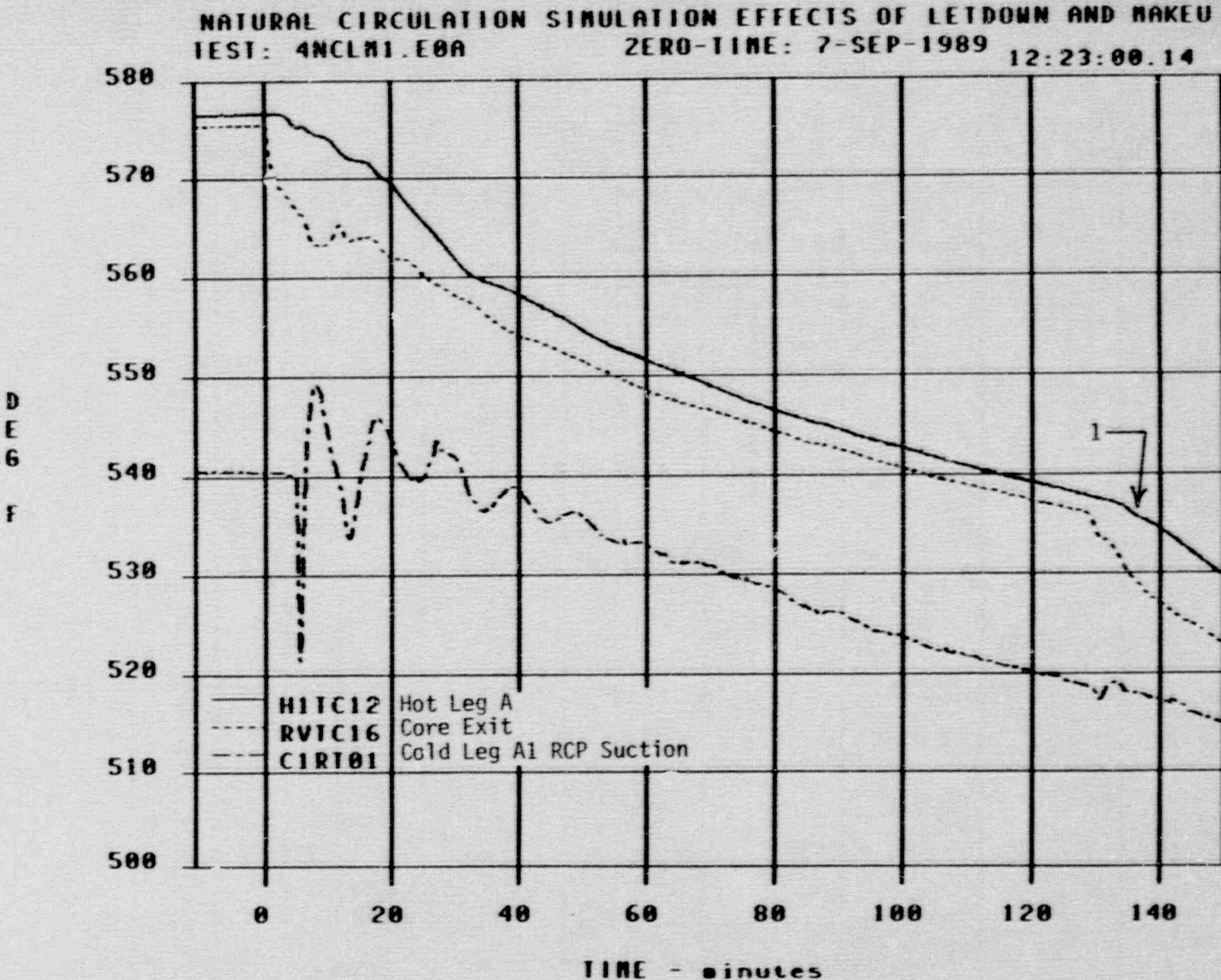


Figure 4.134 Core Exit, Hot Leg A And Cold Leg A1 Reactor Coolant Pump Suction Temperatures

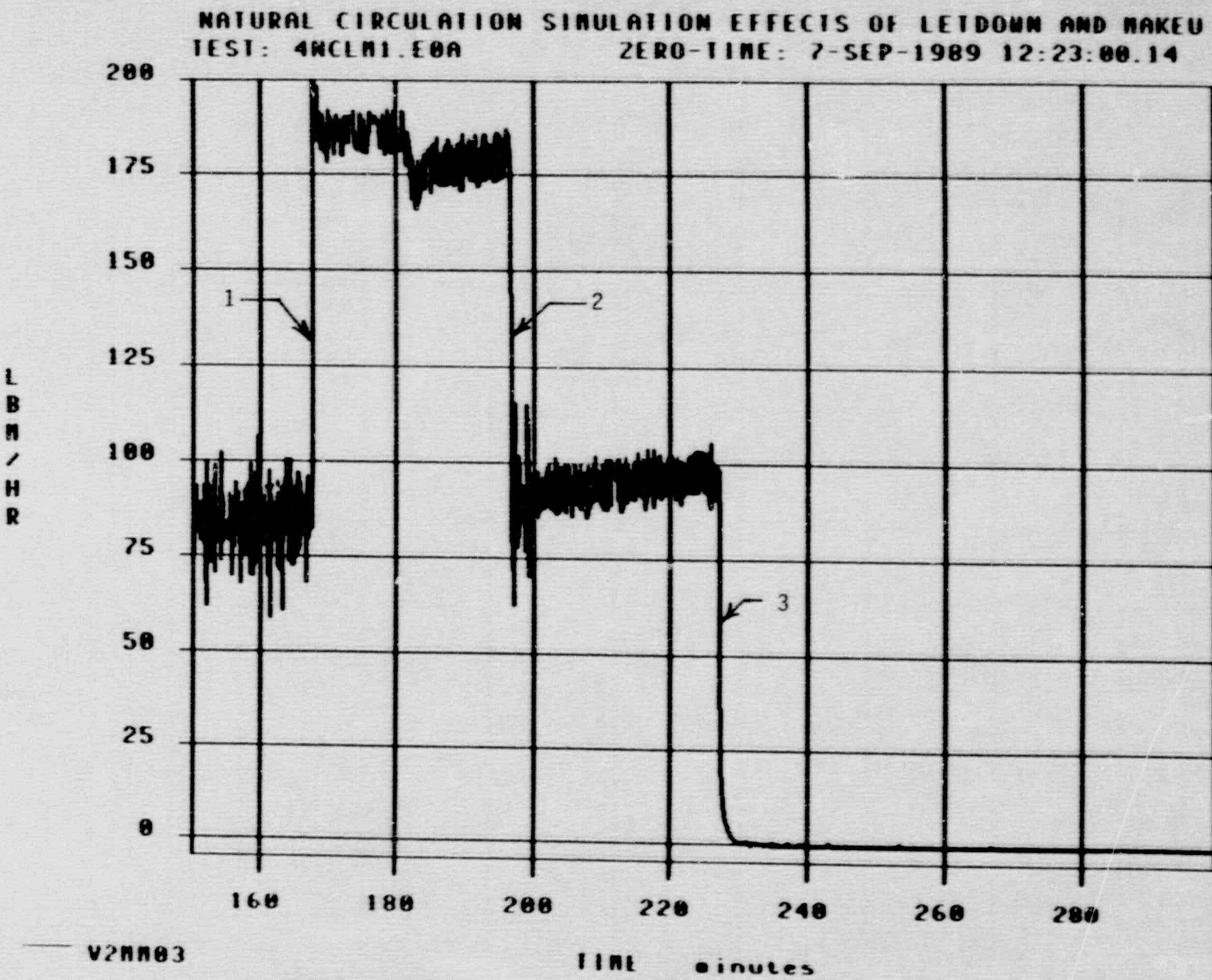


Figure 4.135 High Point Vent Flow Rate

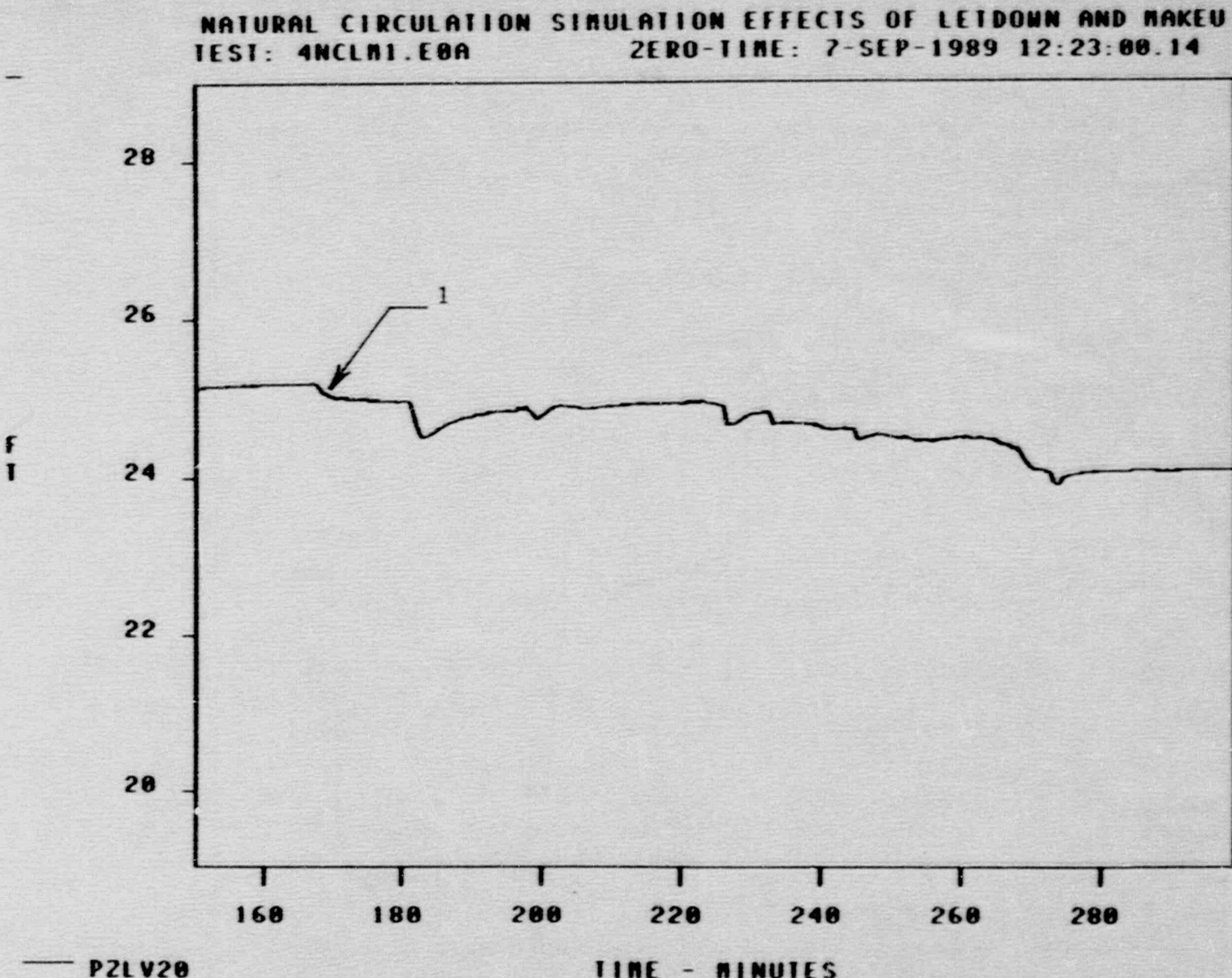


Figure 4.136 Pressurizer Level

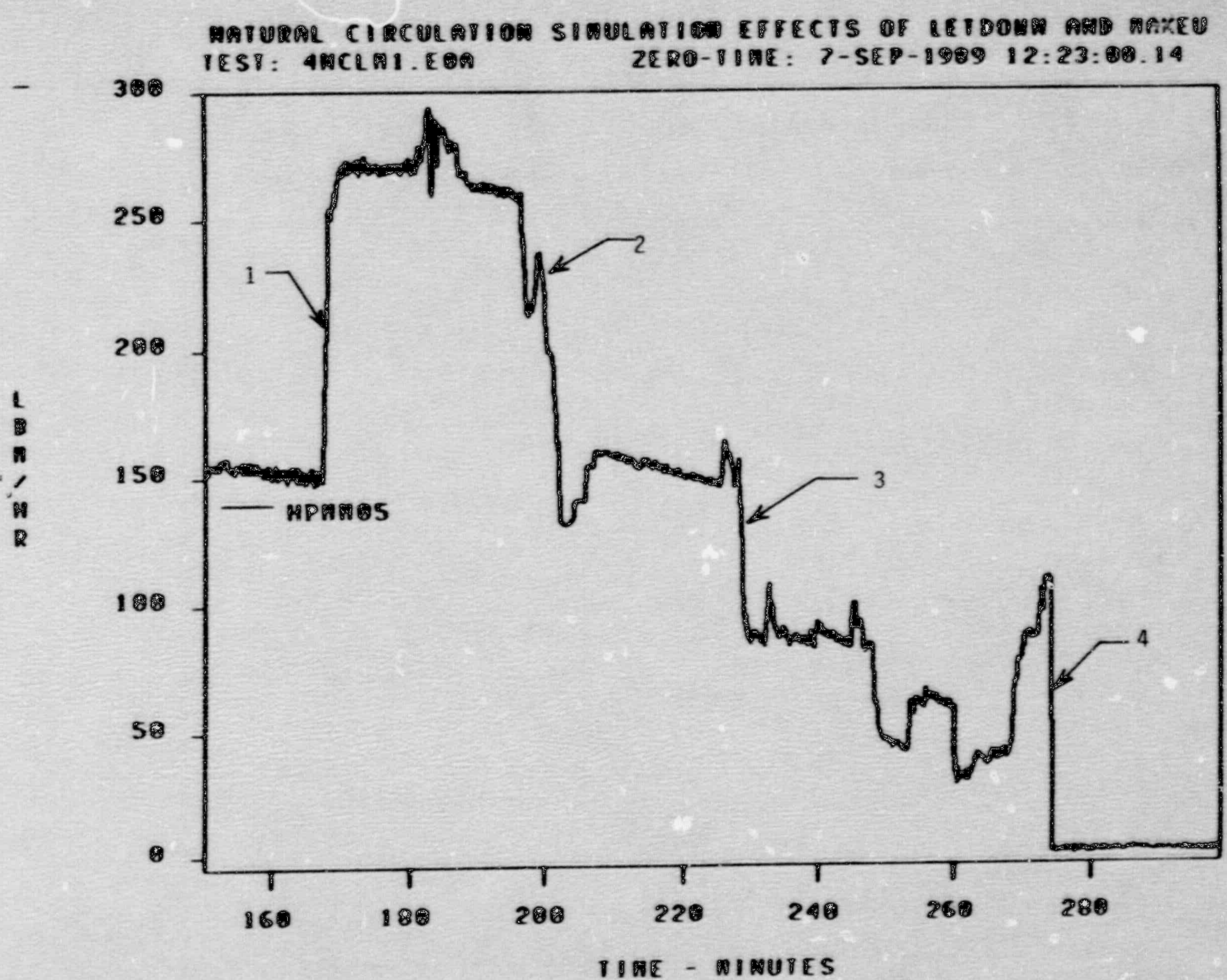


Figure 4.137 Makeup Flow Rate

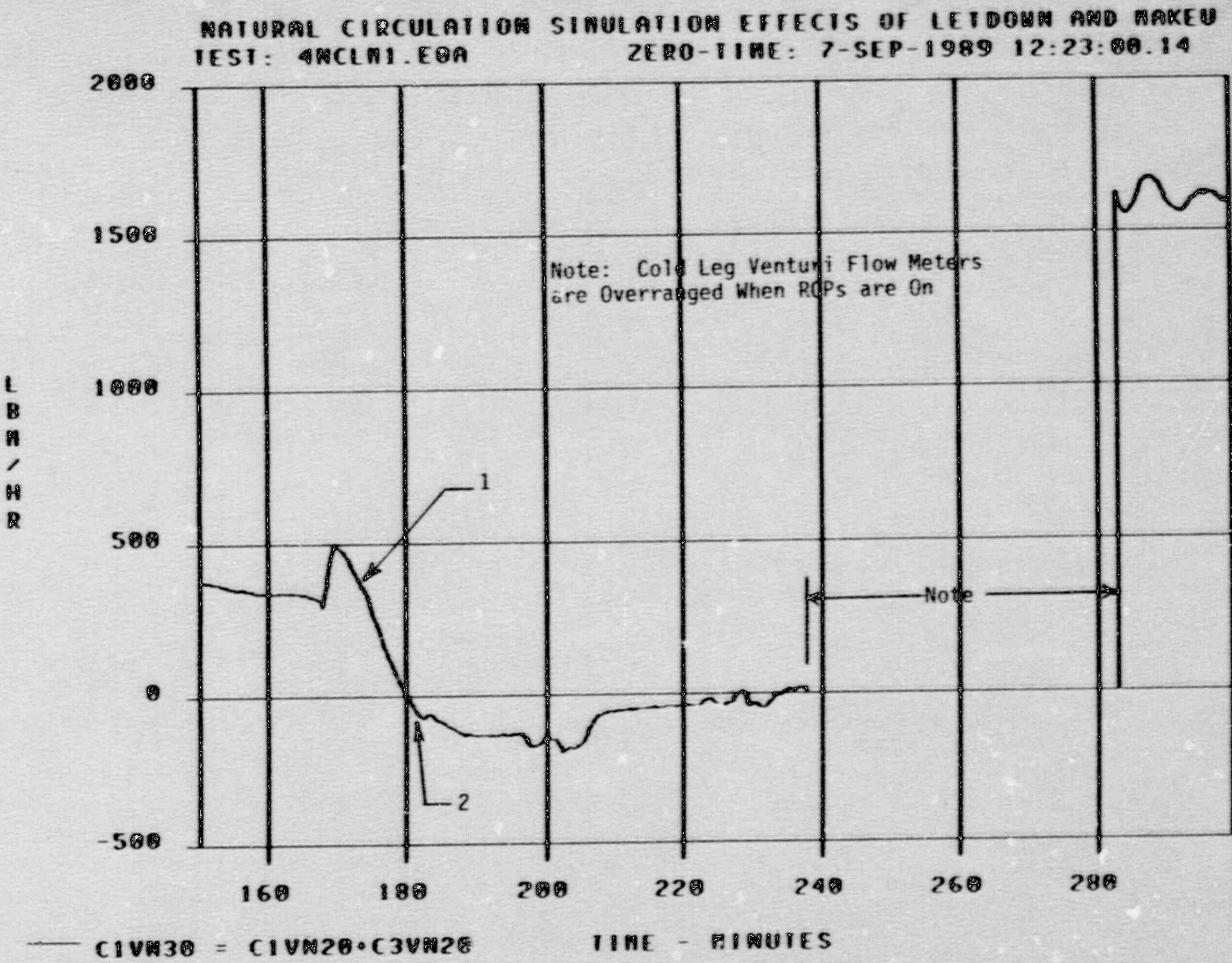


Figure 4.138 Summation Of The A1 And A2 Cold Leg Flow Rates

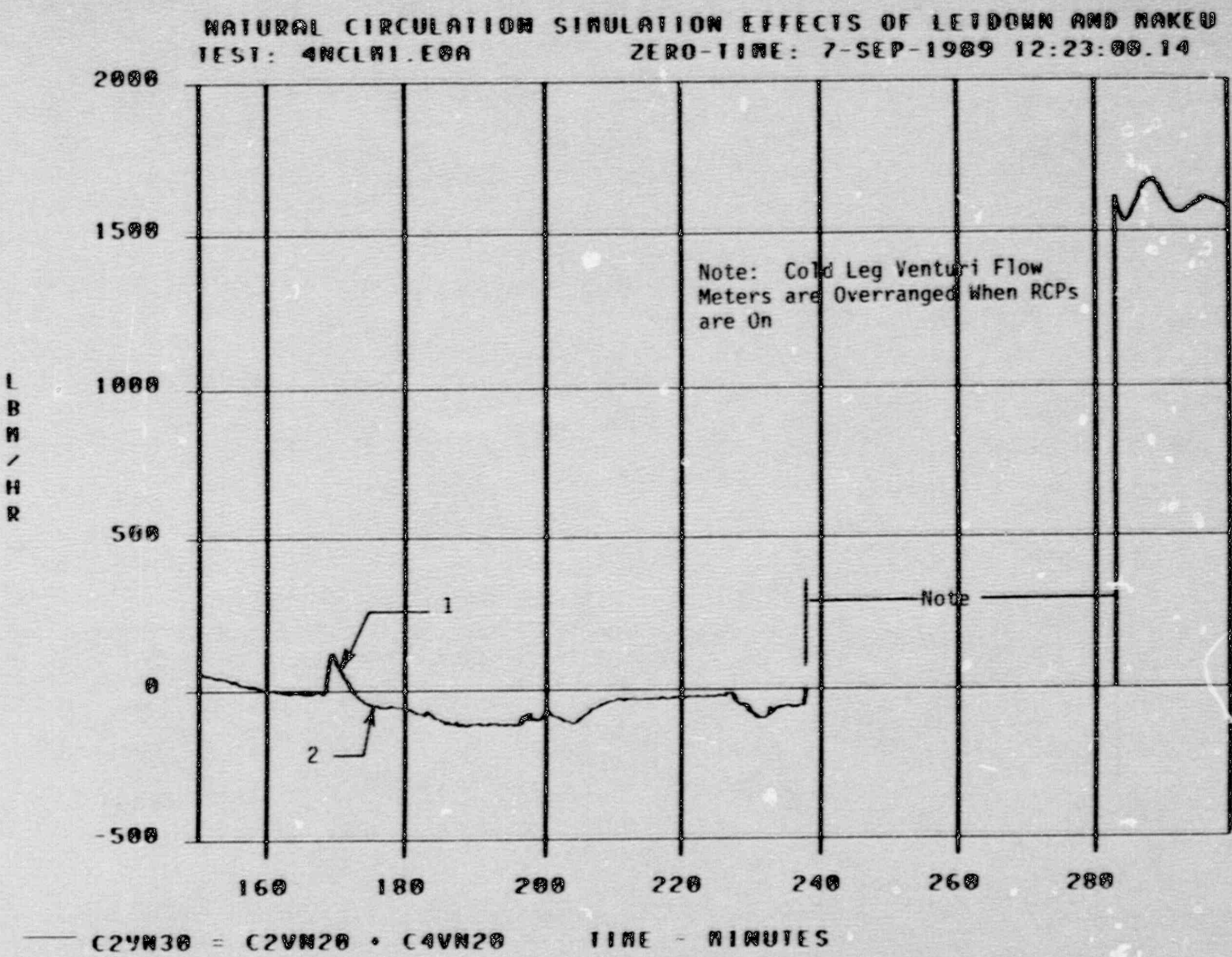


Figure 4.139 Summation Of The B1 And B2 Cold Leg Flow Rates

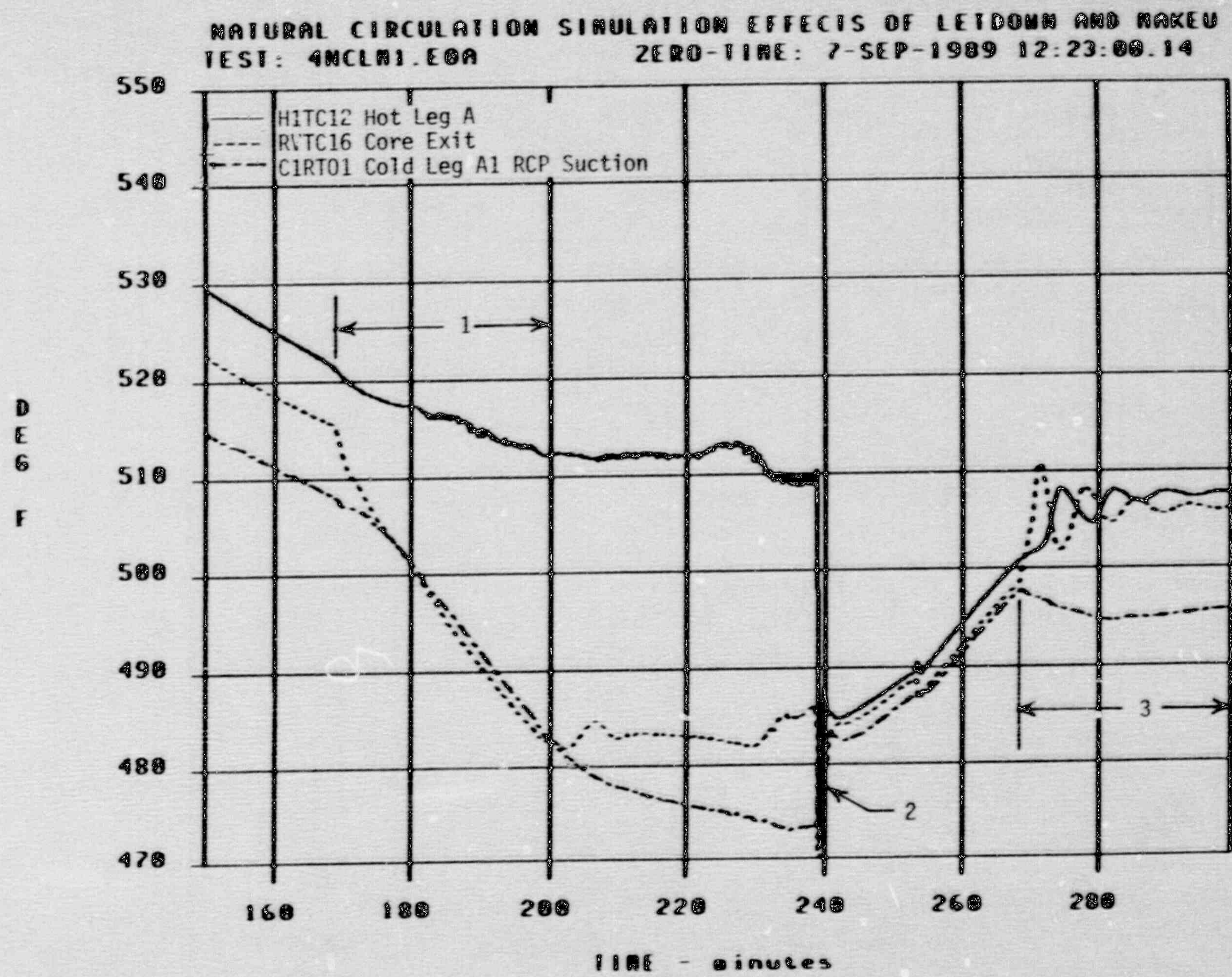


Figure 4.140 Core Exit, Hot Leg A And Cold Leg A1 Reactor Coolant Pump Suction Temperature

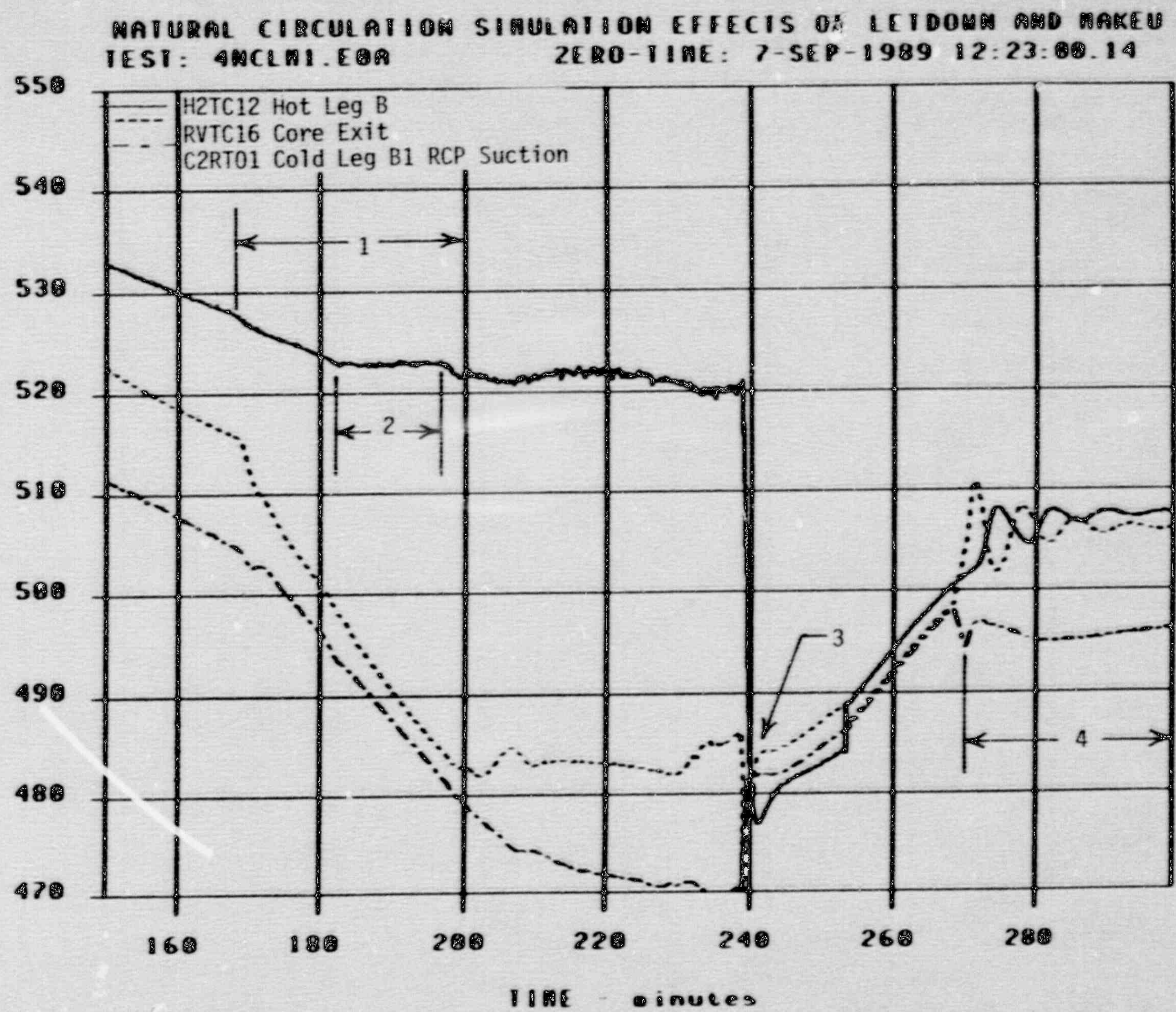


Figure 4.141 Core Exit, Hot Leg B And Cold Leg B1 Coolant Pump Suction Temperatures

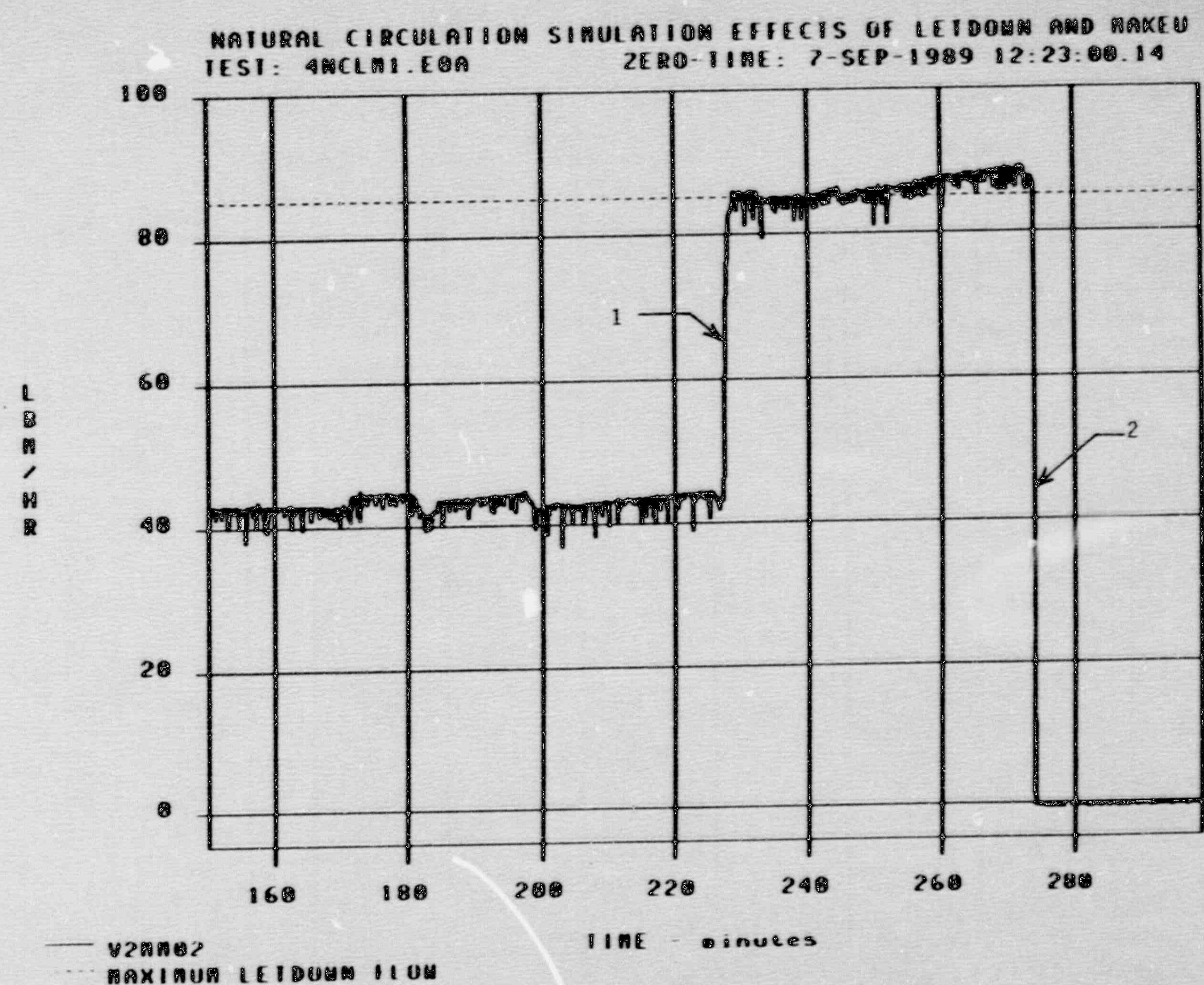


Figure 4.142 Letdown Flow Rate

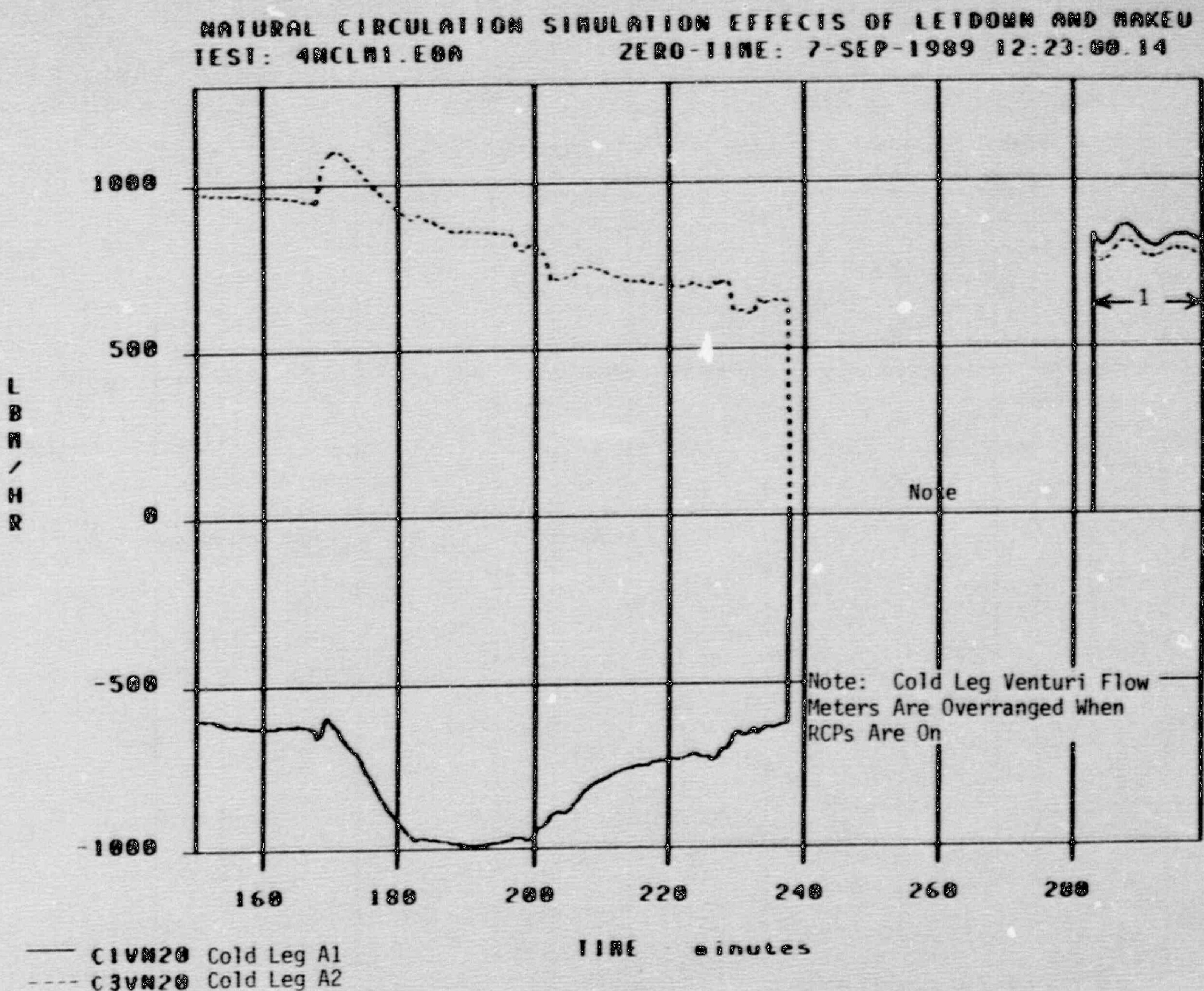


Figure 4.143 Cold Leg A1 And A2 Flow Rate

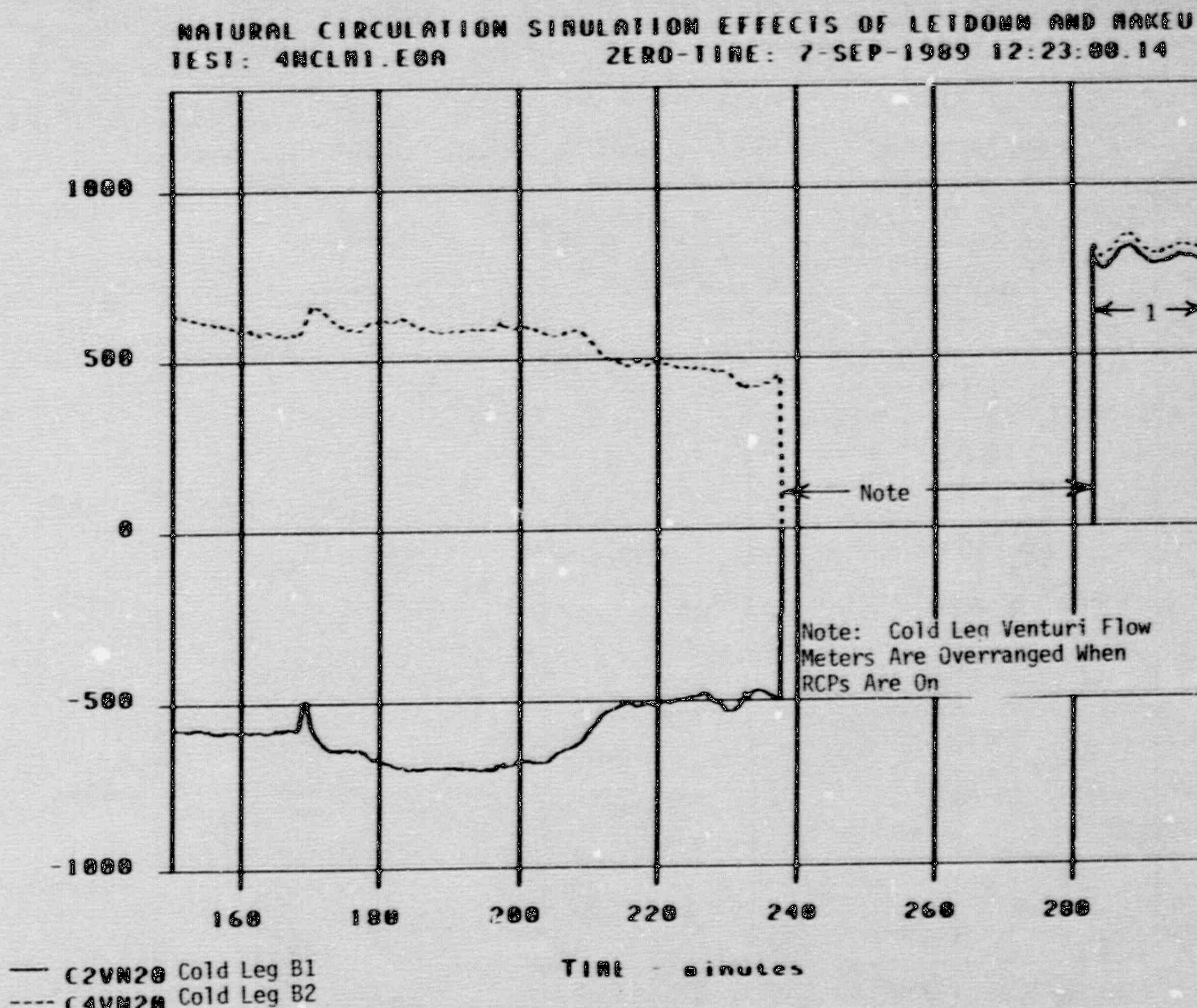


Figure 4.144 Cold Leg B1 And B2 Flow Rate

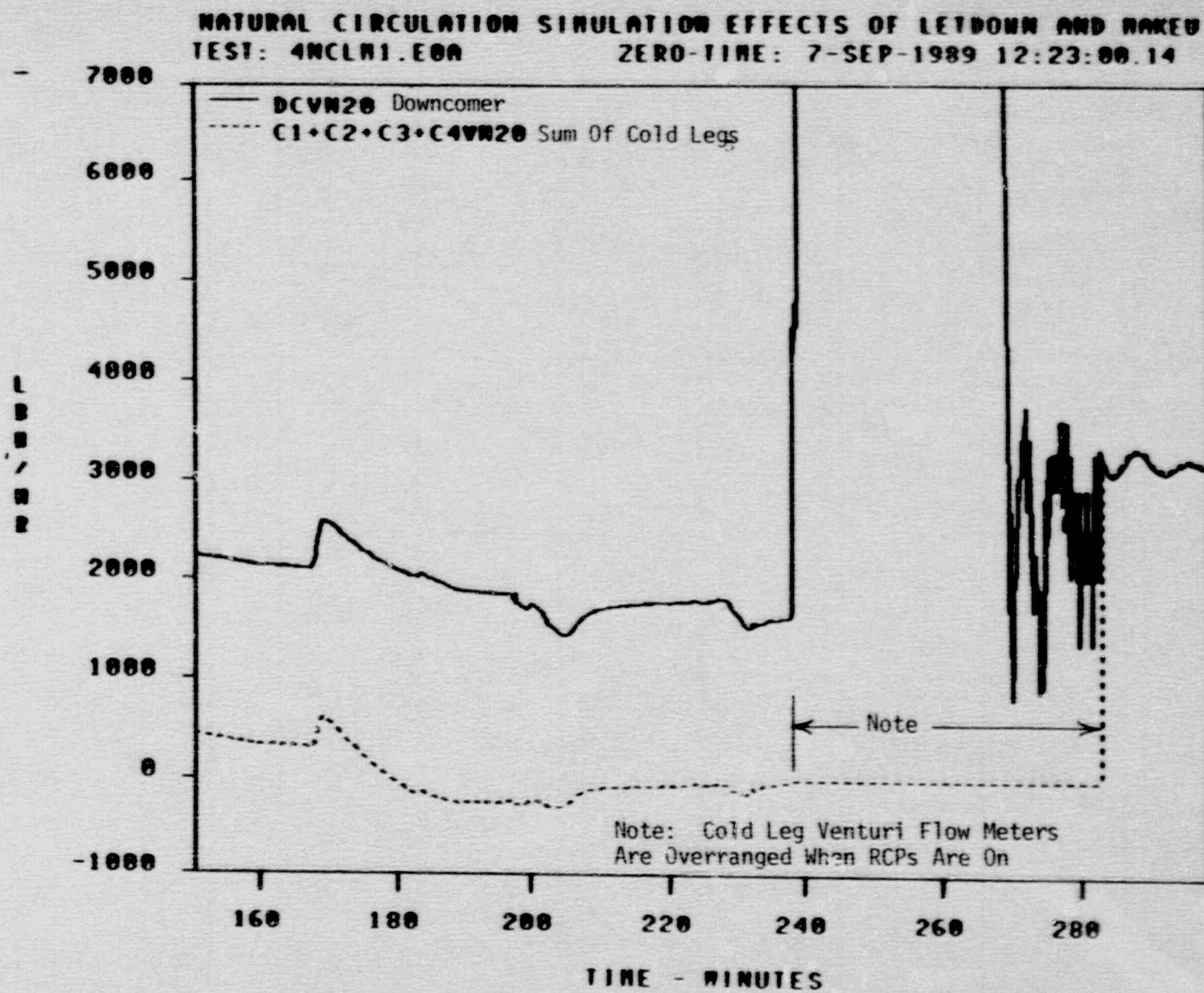


Figure 1.145 Downcomer Flow Rate And The Summation Of The Flow Rate In All Four Cold Legs

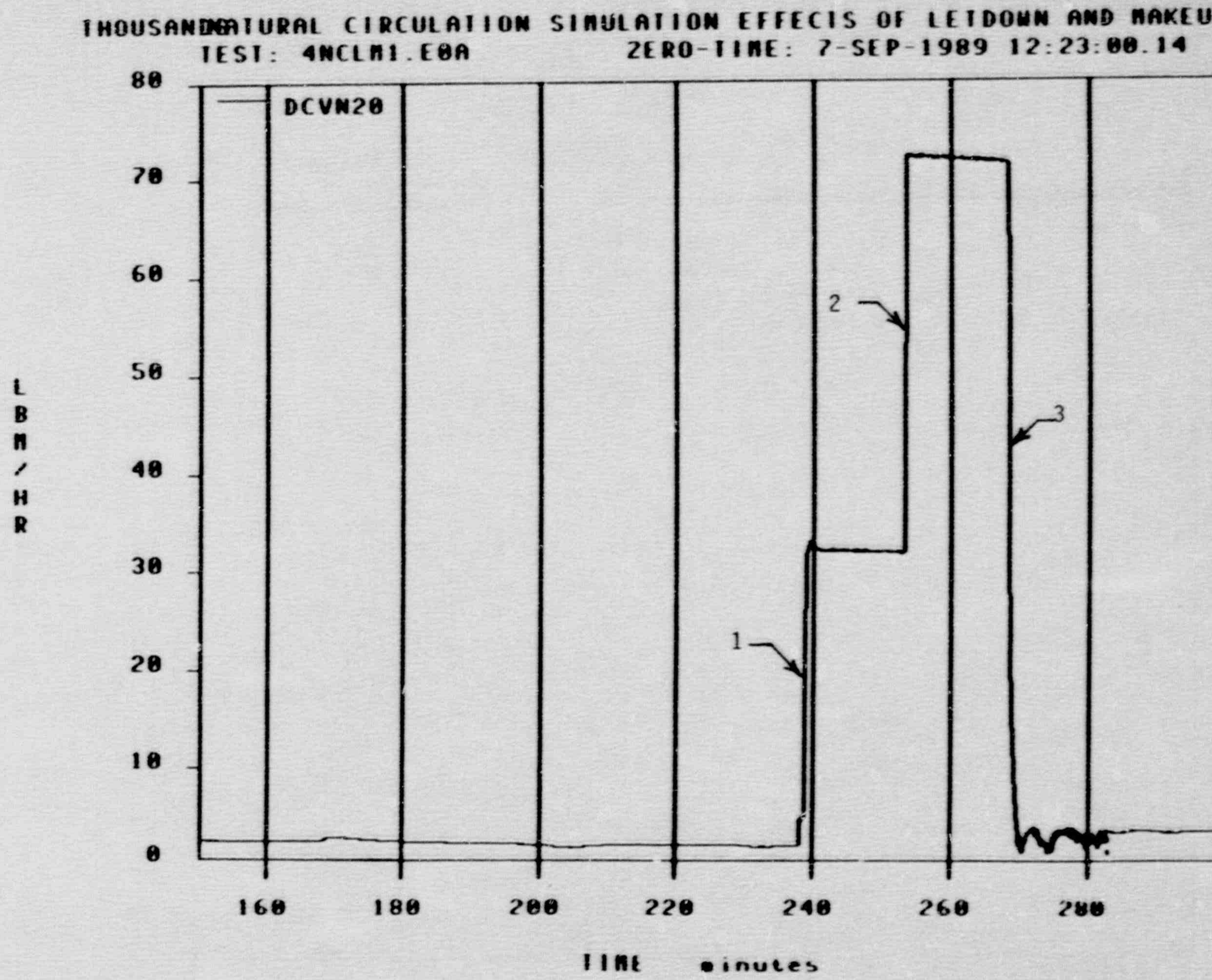


Figure 4.146 Downcomer Flow Rate

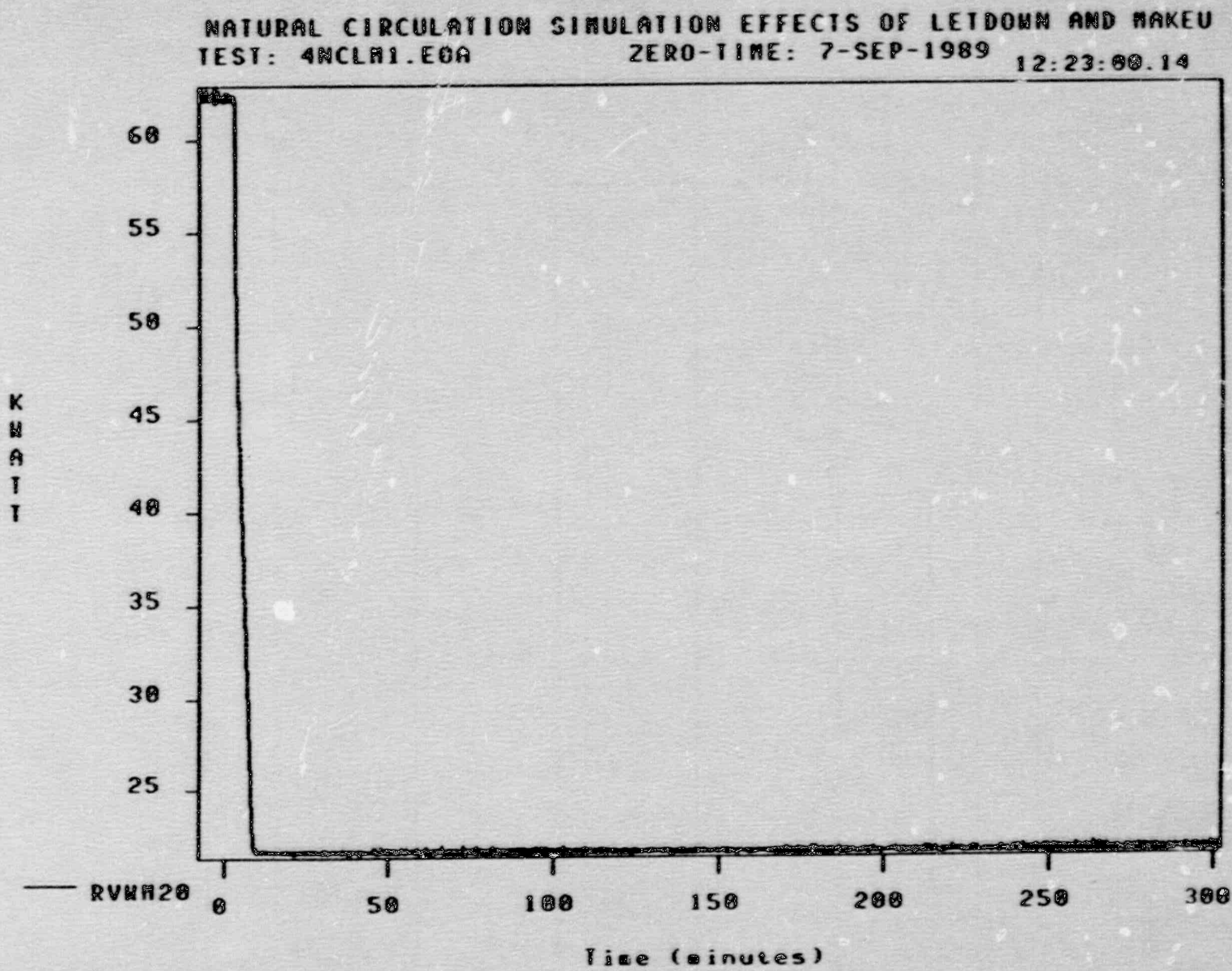


Figure 4.147 Core Power

4.5. Observation of the "Cold Leg Temperature Anomaly" During the Mist Natural Circulation Tests

A comparison of the cold leg temperature response of the MIST facility with that observed during the conduct of the TMI-1 Natural Circulation Tests on October 7, 1985, was performed. For reference purposes the response of the TMI-1 plant is provided in Appendix A. The intent of this comparison was to determine if the MIST facility exhibits the same phenomena as an actual plant, i.e., "cold leg temperature anomaly", and to determine the cause of the phenomena.

The "cold leg temperature anomaly" as observed at the TMI-1 plant was detected by cold leg RTDs. The cold leg RTDs are located in the cold leg suction pipe (upstream of the reactor coolant pump suction) in the TMI-1 plant. The plant instrumentation consists of RTDs in each cold leg (4), RTDs in each hot leg (2) and incore thermocouples (which provide indication of the core exit temperature). The MIST facility has thermocouples or RTDs located in similar locations. In addition to the above the steam generator saturation temperature is also available at both the actual plant and the MIST facility. The MIST plant similar instruments were used in the identification of the "cold leg temperature anomaly". Test 4NCSM1 was used to identify the existence of and the cause of the phenomena associated with the "cold leg temperature anomaly". Figures 4.148 through 4.150 provide temperature information for the B loop and Figures 4.151 through 4.153 provide temperature information for the A loop. An examination of the cold leg fluid temperature response reveals the following:

- Both B cold leg fluid temperatures respond in a similar manner and are approximately equal to the steam generator B saturation temperatures.
- The A1 and A2 cold leg fluid temperatures respond in a different manner from each other and from that observed in the B loop.
- The A loop cold leg fluid temperatures are not equal to the steam generator A saturation temperature.
- The cold leg A2 fluid temperature indicates a rapid reduction of approximately 23F (Figure 4.152, See 1) followed by a rapid increase of approximately 30F (Figure 4.152, See 2).

- Subsequently the response of both B cold leg fluid temperatures stabilizes at the steam generator B saturation temperature, whereas the response of both A cold leg fluid temperatures oscillate for a period of time and then stabilize at a value that is less than the steam generator A saturation temperature.

The fluid temperature response exhibited by the cold legs in the A loop, in particular the A2 cold leg, indicates that the "cold leg temperature anomaly" observed in actual operating plants also occurs in the MIST facility.

4.5.1. Phenomena That Cause the "Cold Leg Temperature Anomaly"

The cause of the observed "cold leg temperature anomaly" can be deduced by examining additional instrumentation available on the MIST facility but not available on operating plants. As discussed previously (Section 4.1) heat losses exist in the vicinity of the reactor coolant pumps. This heat loss can be observed by the decrease in the fluid temperature between the suction and discharge side of the pump during the steady-state initialization period of the test (Figures 4.154 through 4.157, See 1).

The reduction in the primary loop driving head (caused by the decrease in the core power) resulted in a decrease in the cold leg flow rates (Figure 4.158 and 4.159, See 1). The reduced cold leg flow rate in conjunction with the reactor coolant pump heat loss results in a reduction in the fluid temperature at the reactor coolant pump discharge (Figures 4.154 through 4.157, See 2).

When the primary loop flow interrupted in the A loop backflow developed in the A2 cold leg (Figure 4.158, See 2). When backflow occurred in the A2 cold leg the fluid that resided in the cold leg discharge, which was at a lower temperature (Figure 4.156, See 3) than the fluid in the cold leg suction side of the pump (Figure 4.156, See 4), was displaced backwards through the reactor coolant pump and into the cold leg suction pipe. The colder fluid is observed in the cold leg suction as a rapid decrease in the reactor coolant pump suction temperature (Figure 4.156, See 5), i.e., a "cold leg temperature anomaly" is observed. The fluid temperature at the reactor coolant pump discharge is observed to increase (Figure 4.156, See 6) and attains a value that is essentially equal to the core outlet temperature (Figure 4.160, See 1). This fluid temperature response is indicative of the flow of fluid from the core exit through the reactor vessel vent valves into the downcomer and backflowing into the A2 cold leg discharge pipe. As the warmer fluid from the core exit flows backward in the A2 cold leg it is observed to increase the reactor coolant pump suction temperature (Figure 4.156, See 7). The oscillatory response of the reactor coolant pump suction fluid temperature (Figure 4.156, See 8) is indicative of the effect of the reactor coolant pump heat losses to decreases and increases in the reverse flow rate.

The flow direction in each cold leg can also be inferred from the temperature difference across the reactor coolant pump when heat losses are present. A positive temperature difference between the reactor coolant pump suction and discharge is indicative of flow in the forward direction, whereas a negative temperature difference is indicative of flow in the reverse direction. Figures 4.154 through 4.157 show that the temperature difference across the reactor coolant pump is always positive (forward flow) in cold legs A1, B1 and B2, however, cold leg A2 (Figure 4.156) is initially positive (forward flow) and subsequently becomes negative (backflow). These flow directions can be confirmed by the venturi flow meters (Figure 4.158 and 4.159).

Although the previous discussion was associated with Test 4NCSM1, an examination of the figures provided for Sections 4.2 through 4.4 will reveal the following:

- The "cold leg temperature anomaly" was observed in cold legs A1 and B2 for Test 4NCHL1 (occurred in the two cold legs which had imposed excessive heat loss in the reactor coolant pump region).
- The "cold leg temperature anomaly" was observed in cold legs A1 and B1 for Test 4NCLM1 (occurred in the cold leg that did not have makeup flow injection, A1, and occurred in the cold leg that had letdown flow, B1).
- The "cold leg temperature anomaly" did not occur in the test that had the reactor vessel vent valves manually closed, 4NCVV1.

Appendix B and C provide temperature responses for natural circulation transients that occurred at the Oconee 1 and the Crystal River 3 plants respectively. The "cold leg temperature anomaly" was also apparent during these events.

Figures for the Observation of the
"Cold Leg Temperature Anomaly"

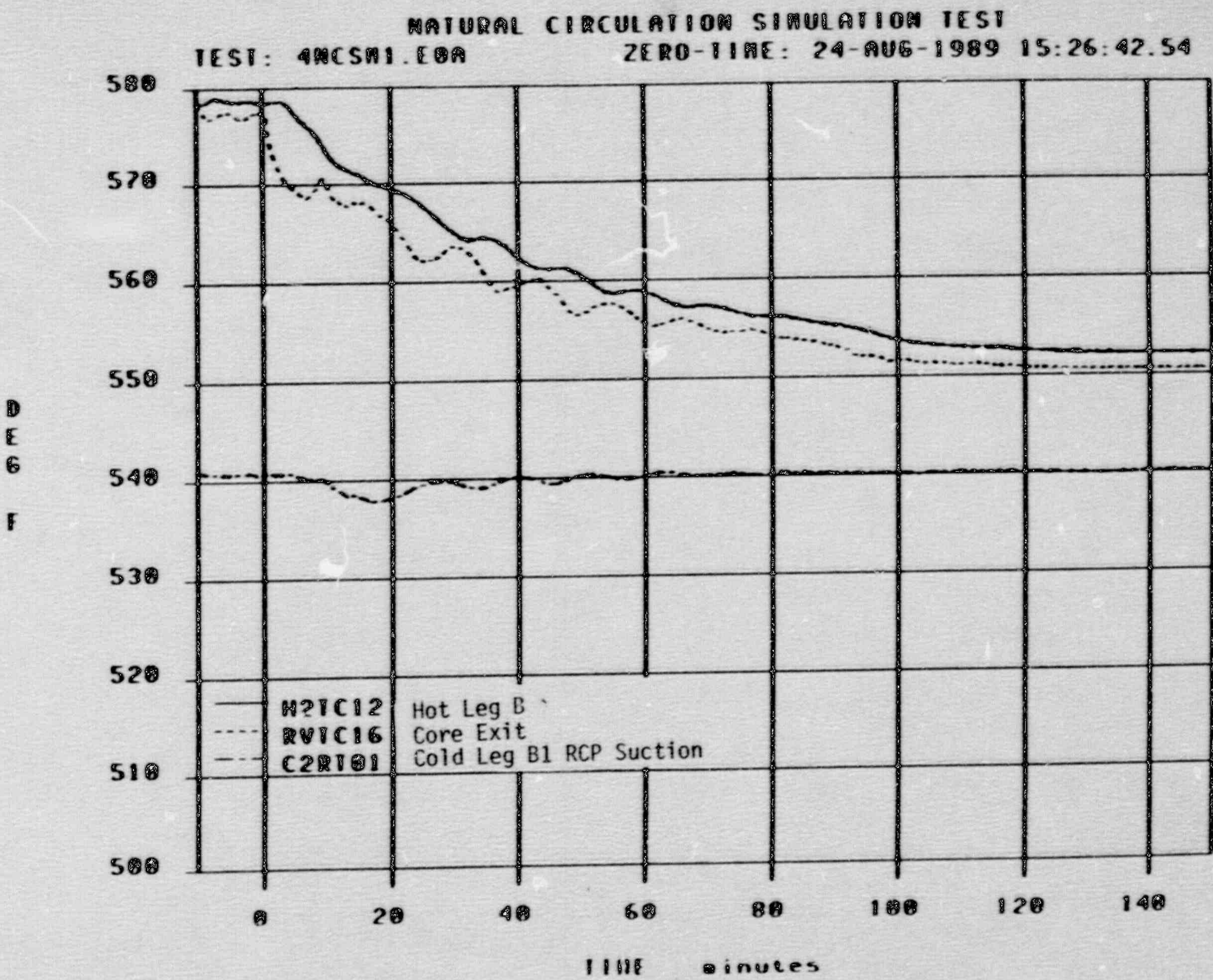


Figure 4.148 MIST Plant Similar Temperature Indications - Loop B

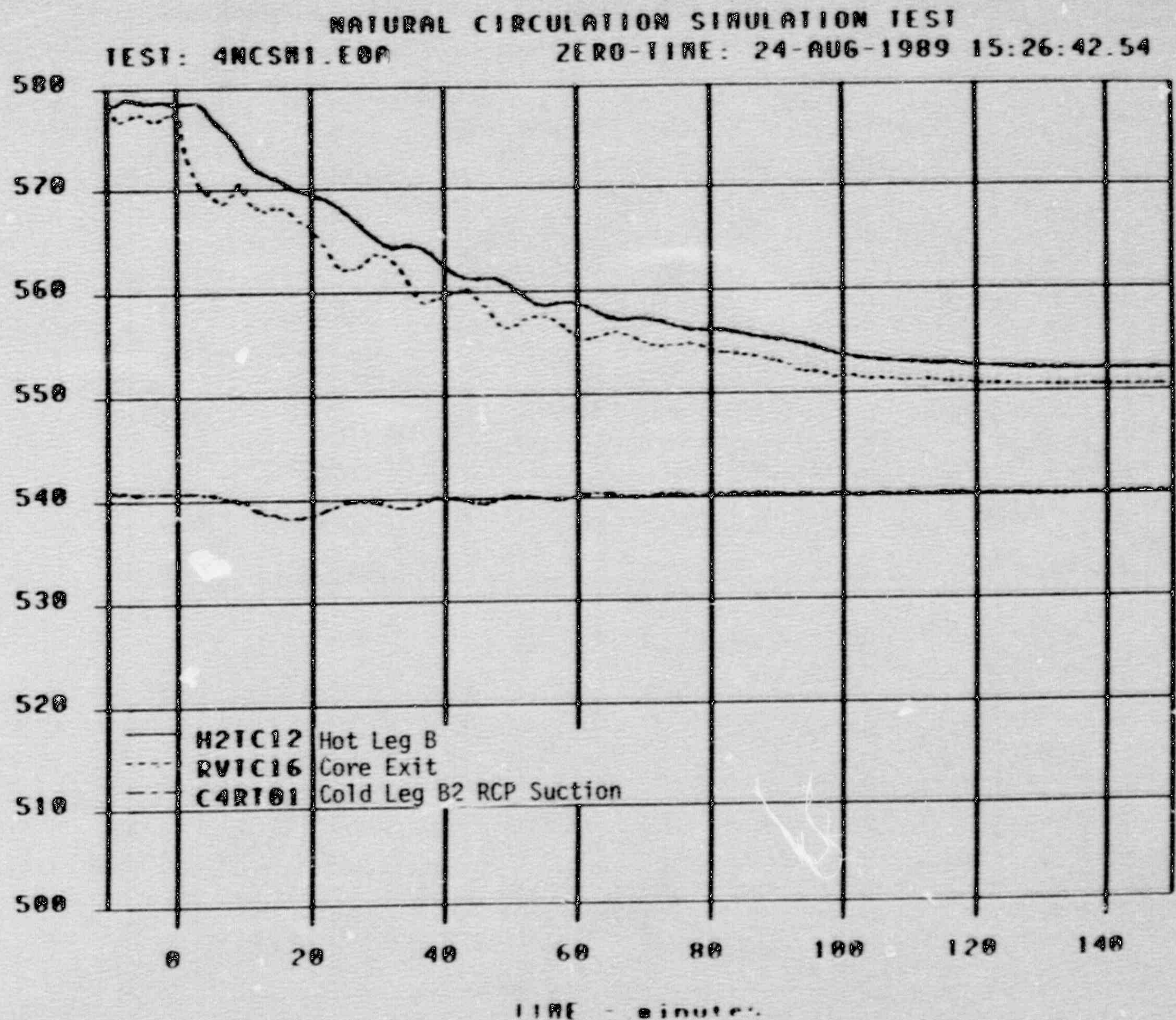


Figure 4.149 MIST Plant Similar Temperature Indications - Loop B

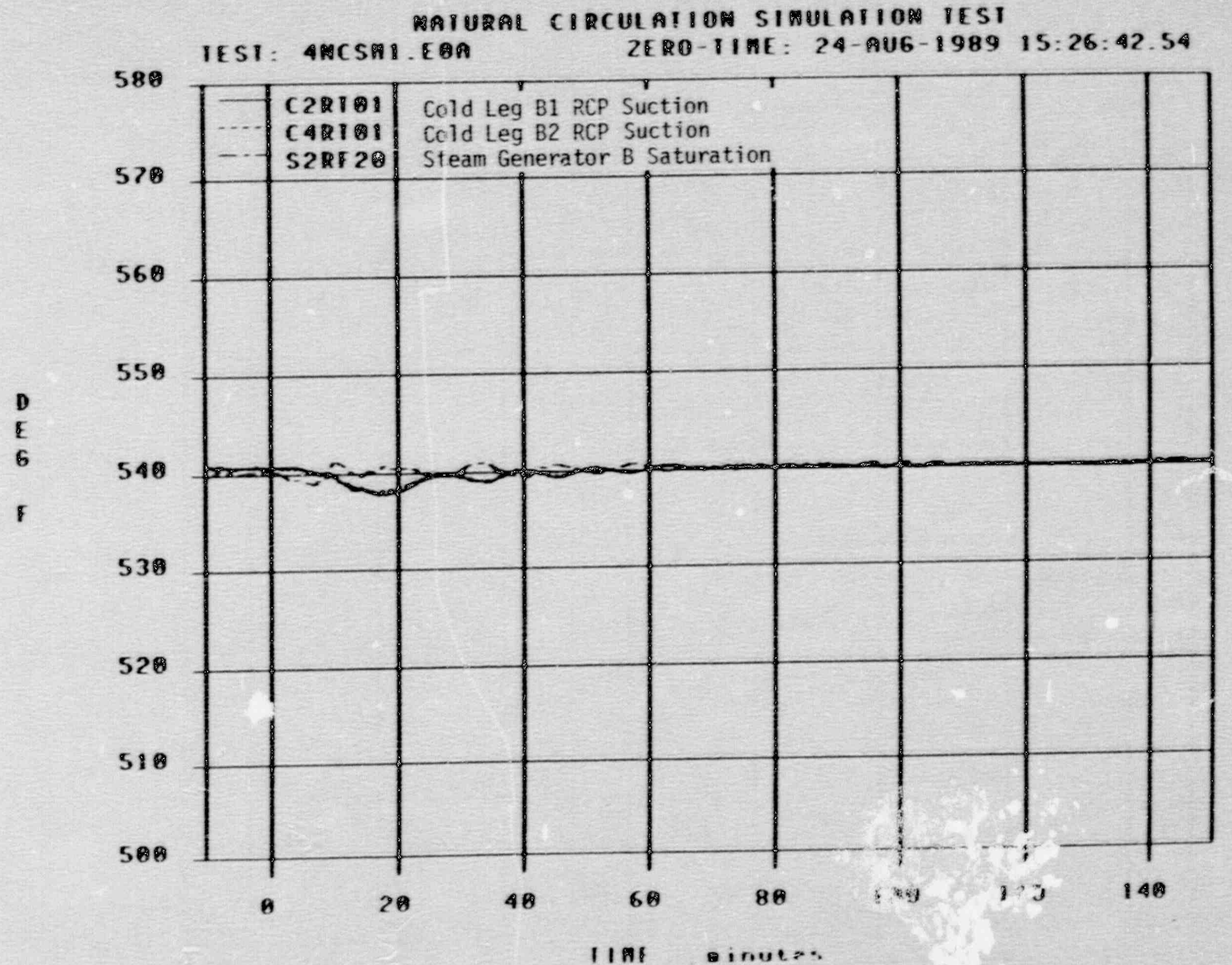


Figure 4.150 MIST Plant Similar Temperature Indications - Loop B

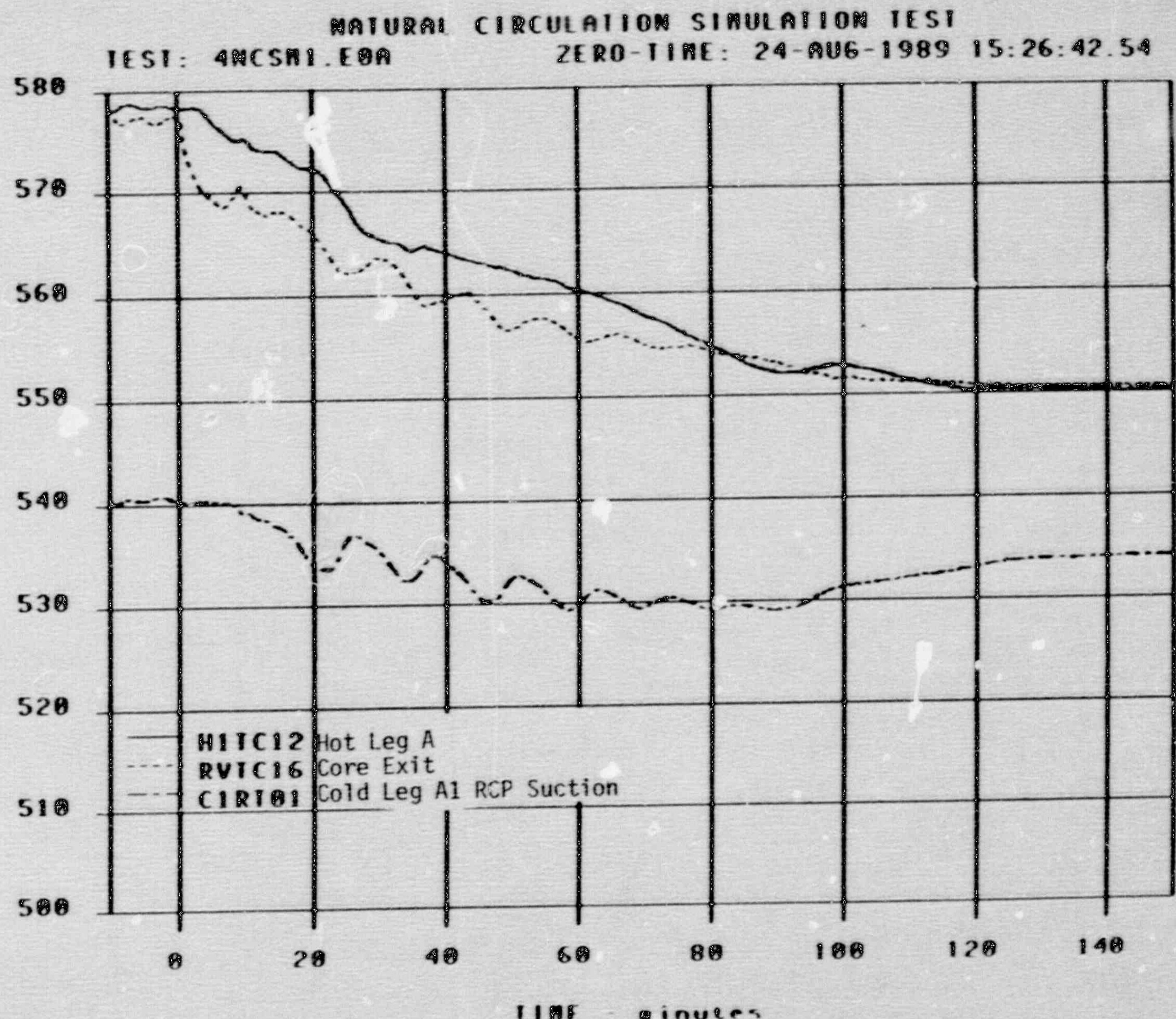


Figure 4.151 MIST Plant Similar Temperature Indications - Loop A

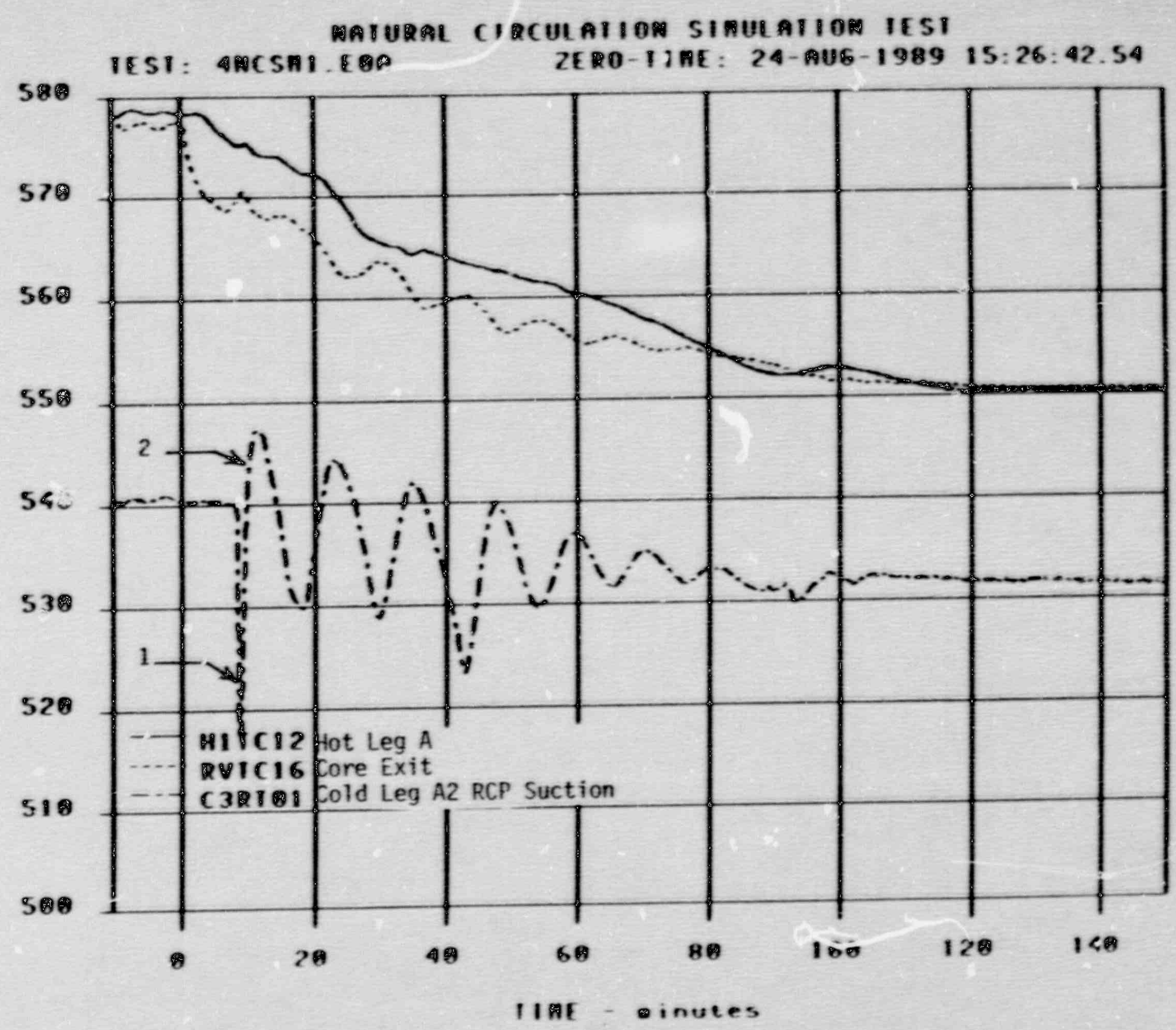


Figure 4.152 MIST Plant Similar Temperature Indicatons - Loop A

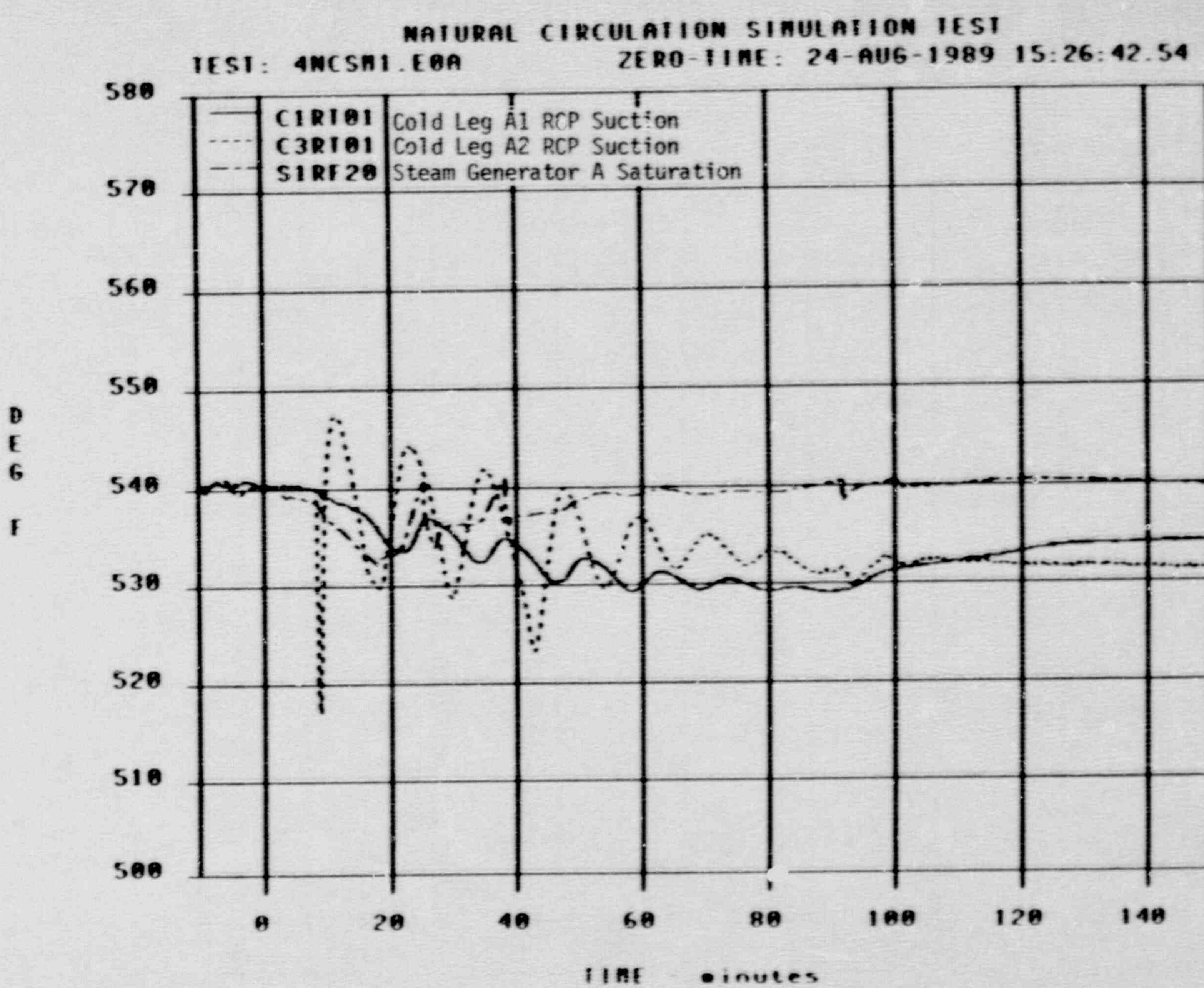


Figure 4.153 MIST Plant Similar Temperature Indications - Loop A

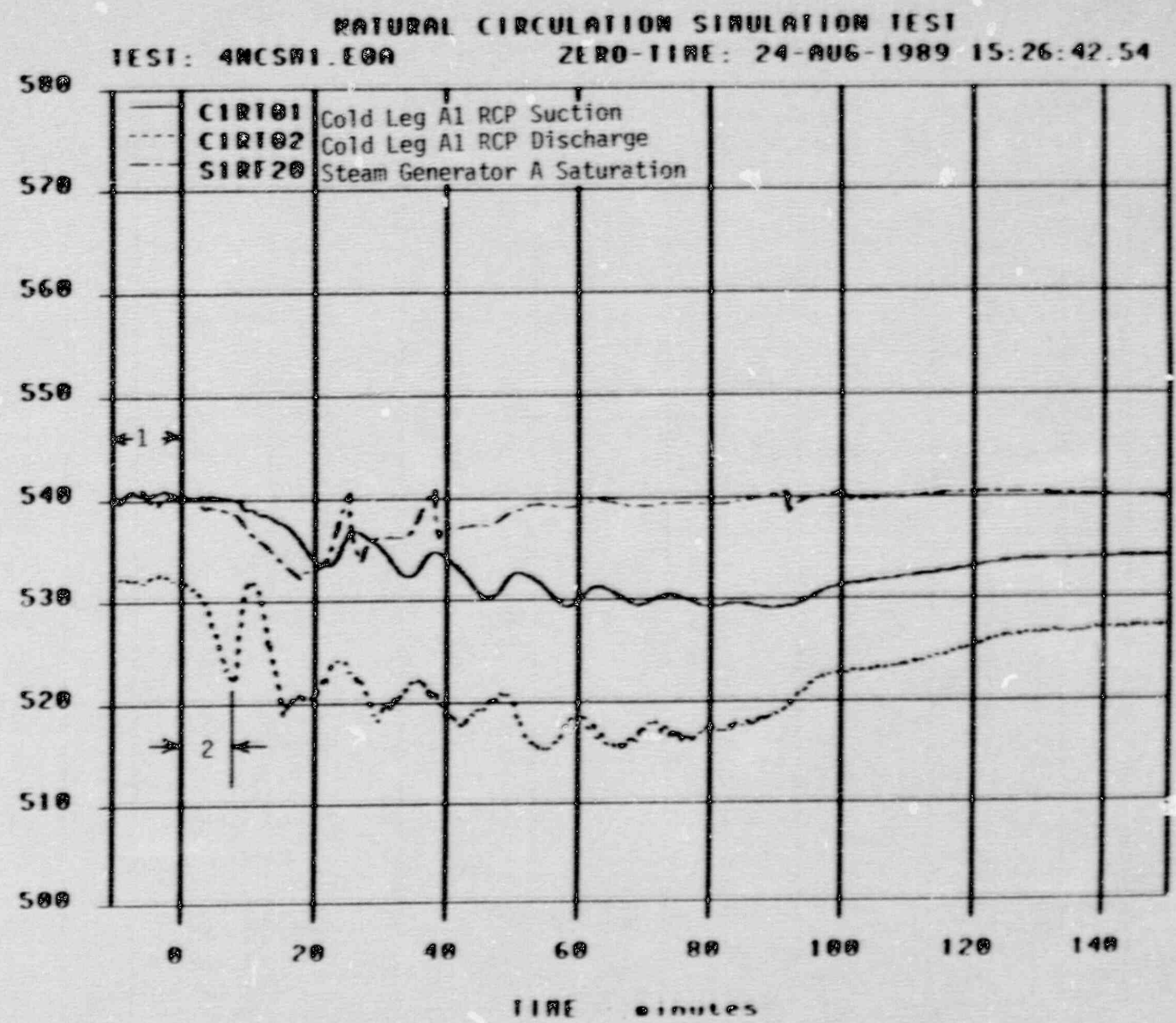


Figure 4.154 Steam Generator A Saturation Temperature And Cold Leg A1 Reactor Coolant Pump Suction And Discharge Temperature

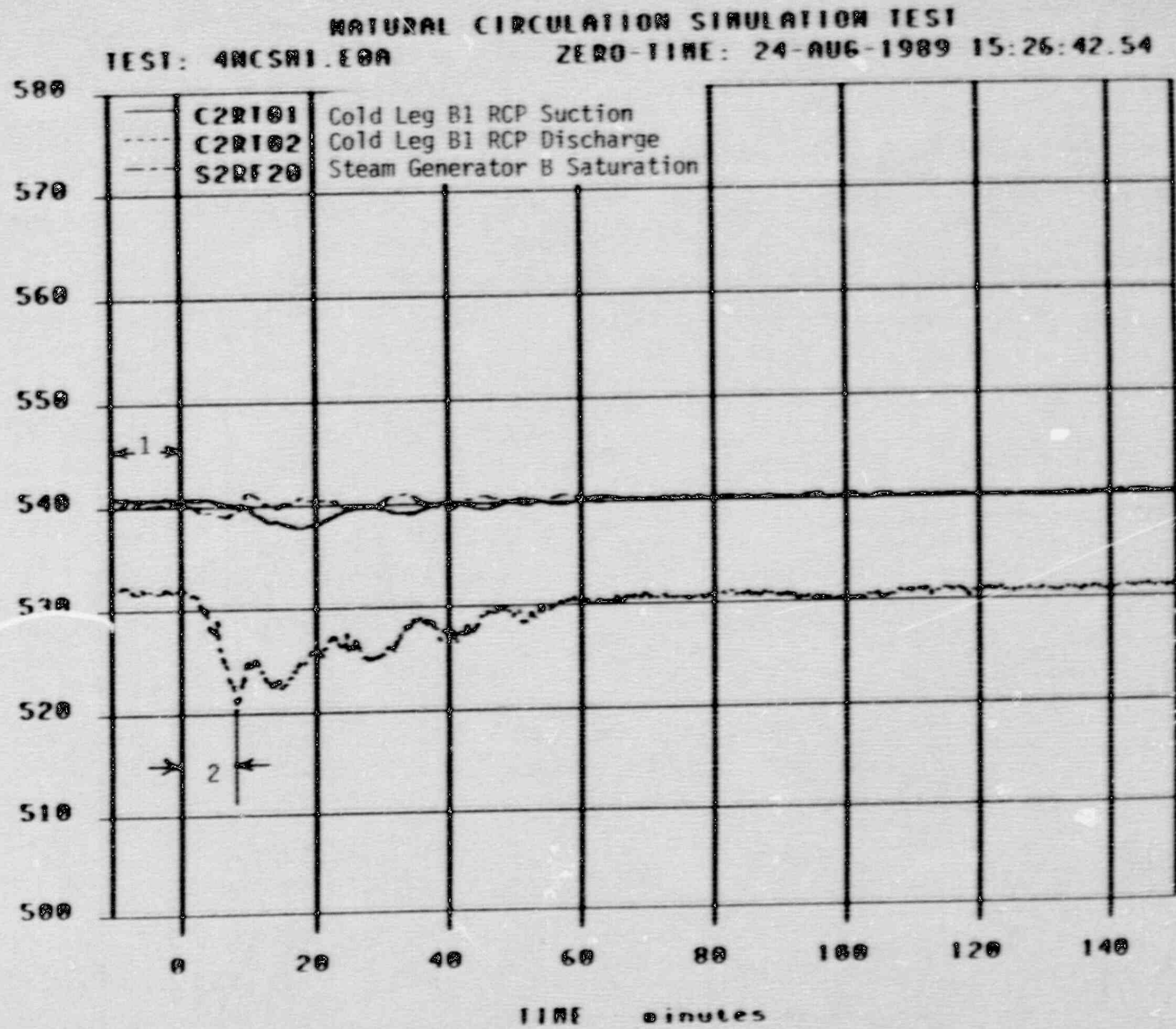


Figure 4.155 Steam Generator B Saturation Temperature And Cold Leg B1 Reactor Coolant Pump Suction And Discharge Temperature

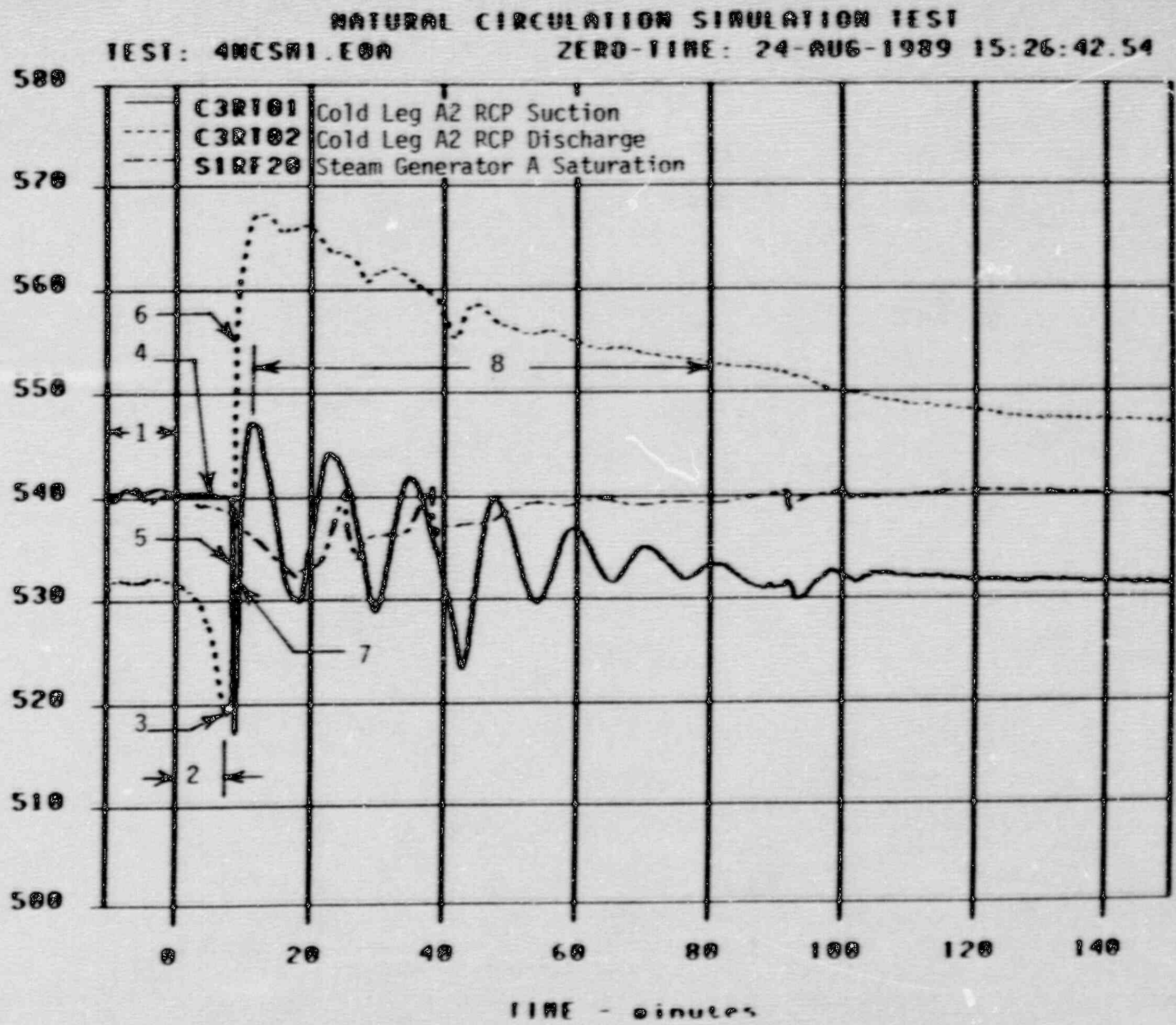


Figure 4.156 Steam Generator A Saturation Temperature And Cold Leg A2 Reactor Coolant Pump Suction And Discharge Temperature

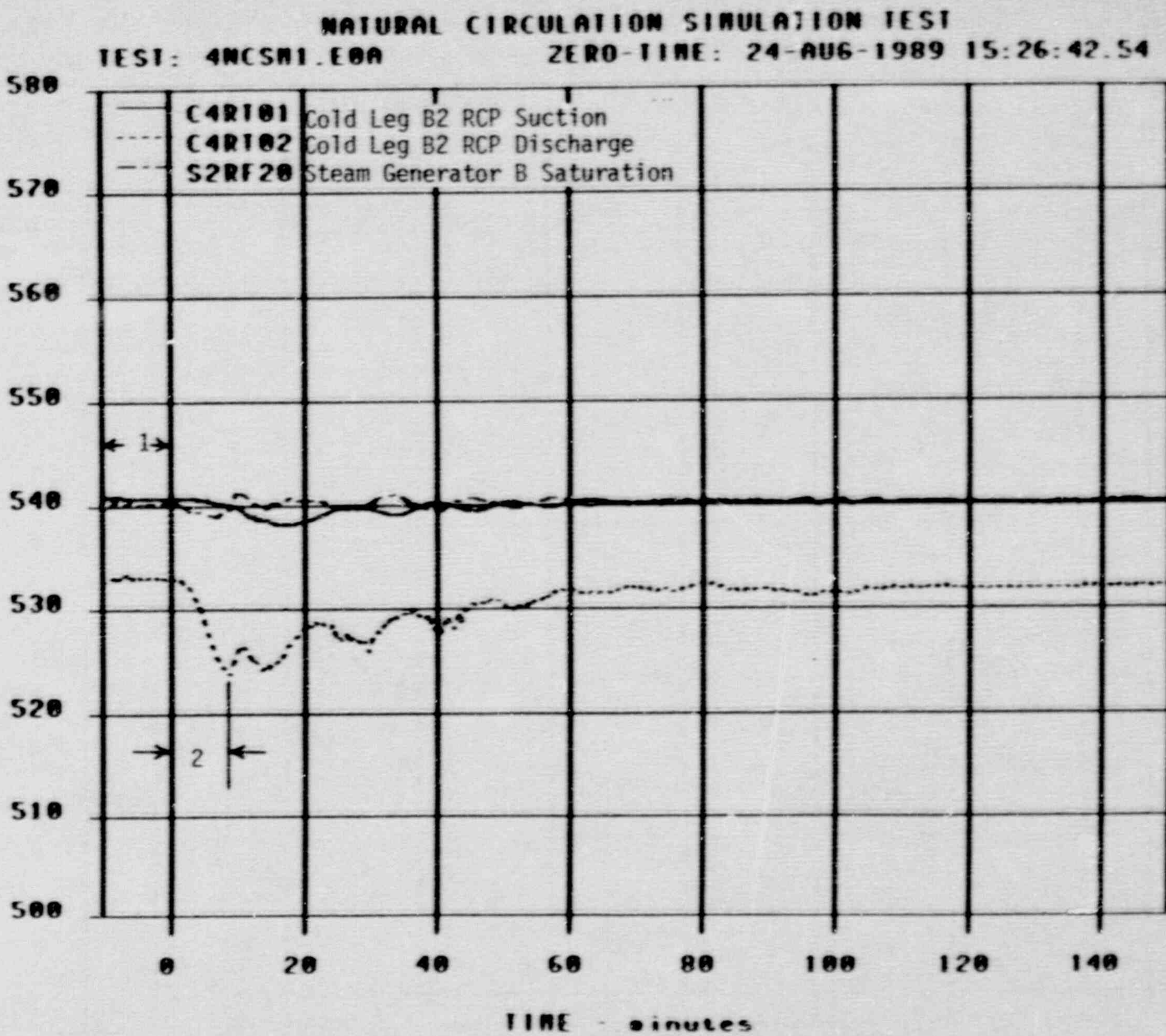


Figure 4.157 Steam Generator B Saturation Temperature And Cold Leg B2 Reactor Coolant Pump Suction And Discharge Temperature

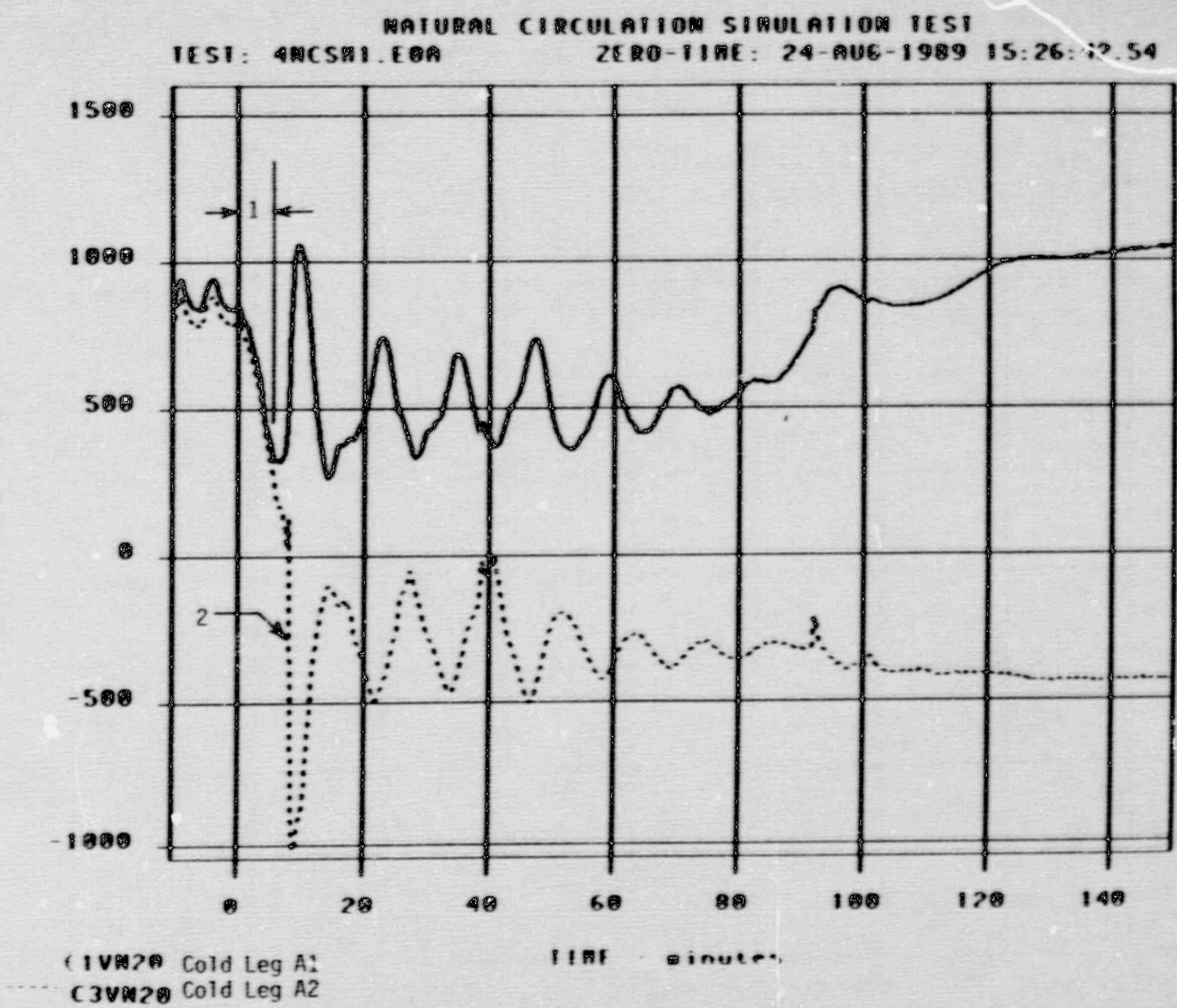


Figure 4.158 Cold Leg A1 And A2 Flow Rate

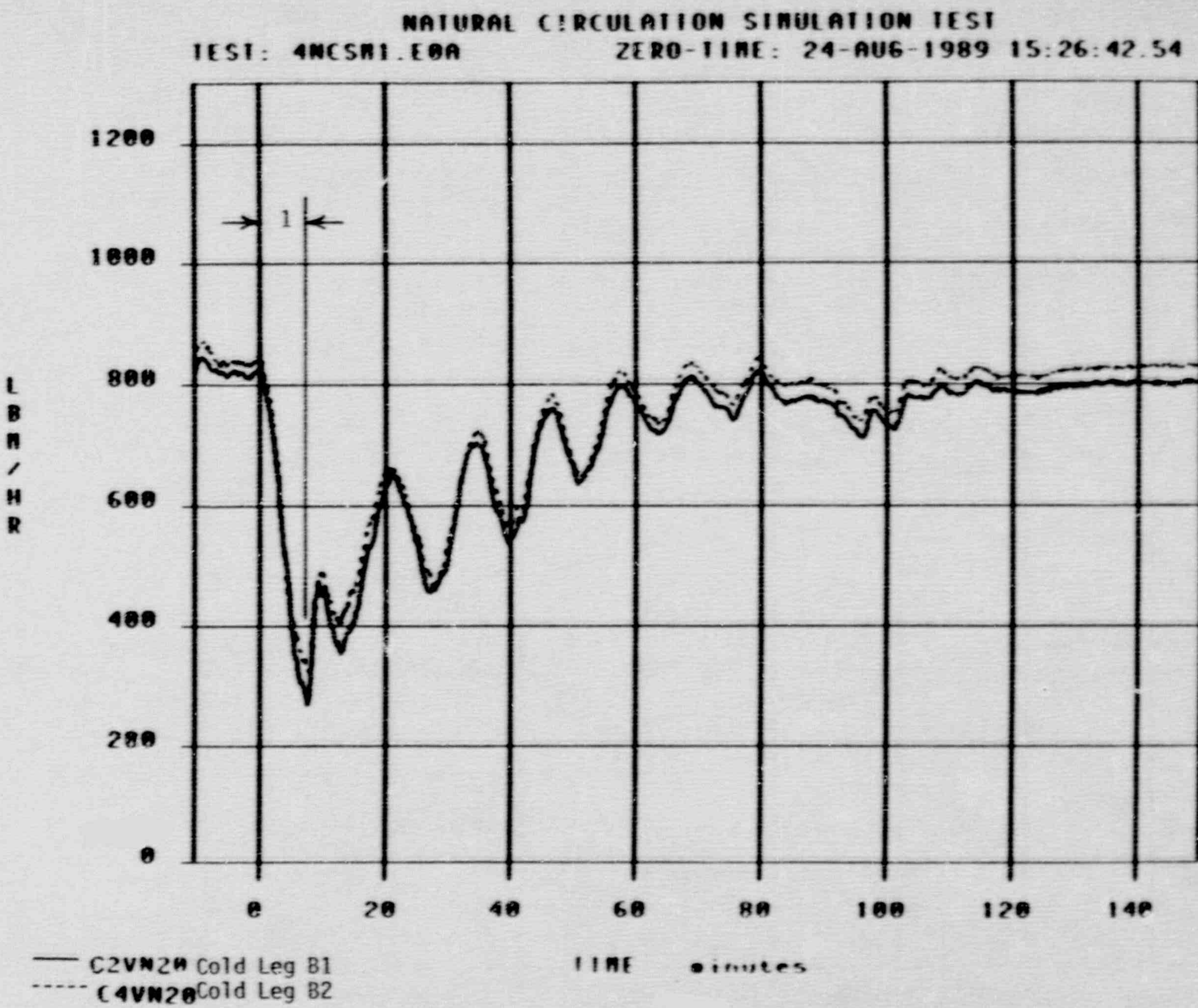


Figure 4.159 Cold Leg B1 And B2 Flow Rate

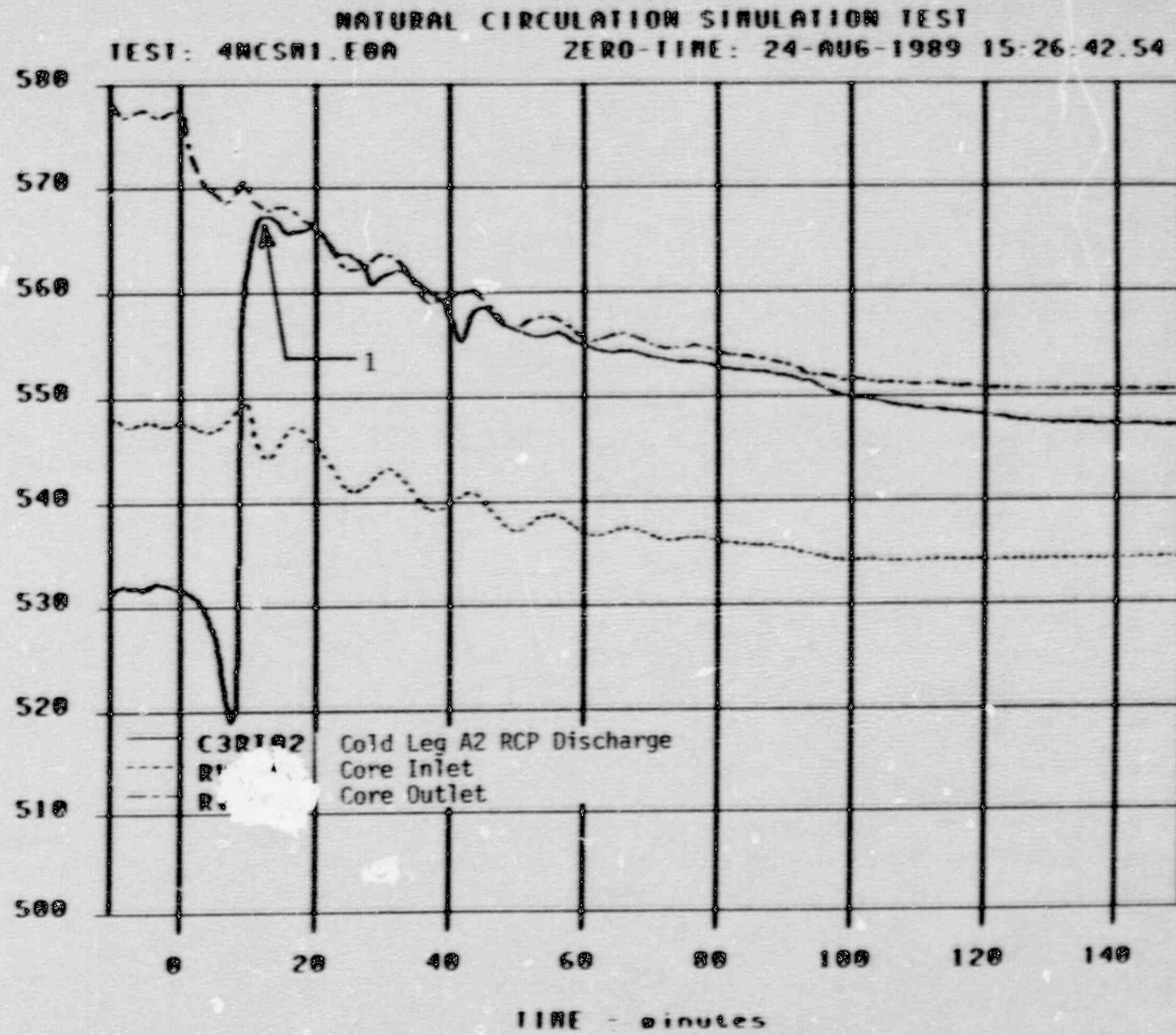


Figure 4.160 Core Inlet And Outlet Temperature And Cold Leg A2 Reactor Coolant Pump Discharge Temperature

5.0 SUMMARY

The MIST Natural Circulation Tests confirmed that the MIST facility exhibits phenomena similar to those observed during actual plant natural circulation events. The "cold leg temperature anomaly" that was first identified during the natural circulation testing conducted at the TMI-1 plant (Appendix A) and subsequently observed during natural circulation transients that occurred at other plants, e.g., Oconee 1, Appendix B and Crystal River 3, Appendix C, was replicated on the MIST facility.

The key observations from the MIST natural circulation tests are:

- The MIST Natural Circulation Tests showed that the "cold leg temperature anomaly" was a flow interruption followed by backflow in the cold leg(s) and was caused by a combination of the following:
  - A reduction in the primary loop (up the hot legs) natural circulation driving head.
  - Heat loss in the vicinity of the reactor coolant pump.
  - The existence of a flow path from the core exit to the cold leg nozzle by way of the reactor vessel internal vent valves.
- Makeup and letdown flow, by themselves, cannot induce flow reversal. Makeup and letdown can influence the location of the reversal in a situation that is otherwise marginal.
- Core Power Increase - increase in core power by as little as 0.5% of full power restores forward flow.
- High point vent actuation - did not provide conclusive results in regard to restoration of forward flow in loop with open HPV.
- Reactor coolant pump restart may lead to primary pressure increase or decrease, depending on core power level and fluid conditions at the time of restart.

Note: The MIST test did not address the impact of increased SG heat removal on the reestablishment of a natural circulation driving head.

This phase of the MIST program exhibited similar flow interruption phenomena that were particularly observed during the MIST Phase III Mapping Tests and the MIST Phase IV Small Break LOCA Tests. The MIST Natural Circulation Tests provide insight into the flow interruption phenomena and, since the primary system was maintained in single phase liquid conditions for these tests, have shown that phase separation in the hot legs was not necessary for the occurrence of primary loop flow interruption. Simultaneous with the flow interruptions, core cooling was not interrupted for the conditions tested.

Screening tests were performed to establish the MIST boundary conditions necessary to demonstrate the cold leg phenomena observed during plant transients. The results of the screening tests and the four formal tests indicated that the primary system response was highly dependent upon the boundary conditions and facility operator actions. The screening tests indicated that any parameter that influences the fluid density in the cold legs can have an effect on the system response. Several dominant parameters found to affect cold leg flow reversal/interruption in MIST were:

- Rate of change of core power
  - Abrupt power decrease necessary for occurrence (for conditions tested).
  - Atypically high elevation tube wetting with cold AFW in MIST prevented flow reversal. Main feedwater reproduced cold leg flow reversal phenomena.
- Steam generator level
  - No flow reversal with AFW at any level tested in MIST.
  - Cold leg flow reversal was sensitive to level with main feedwater operation. 50% on Operate Range appears to be a threshold of one loop vs. two loop reversal/interruption.

The observations and results of the MIST Natural Circulation Tests are of course limited to the particular conditions tested. The atypicalities of MIST due to scaling compromise must be considered.

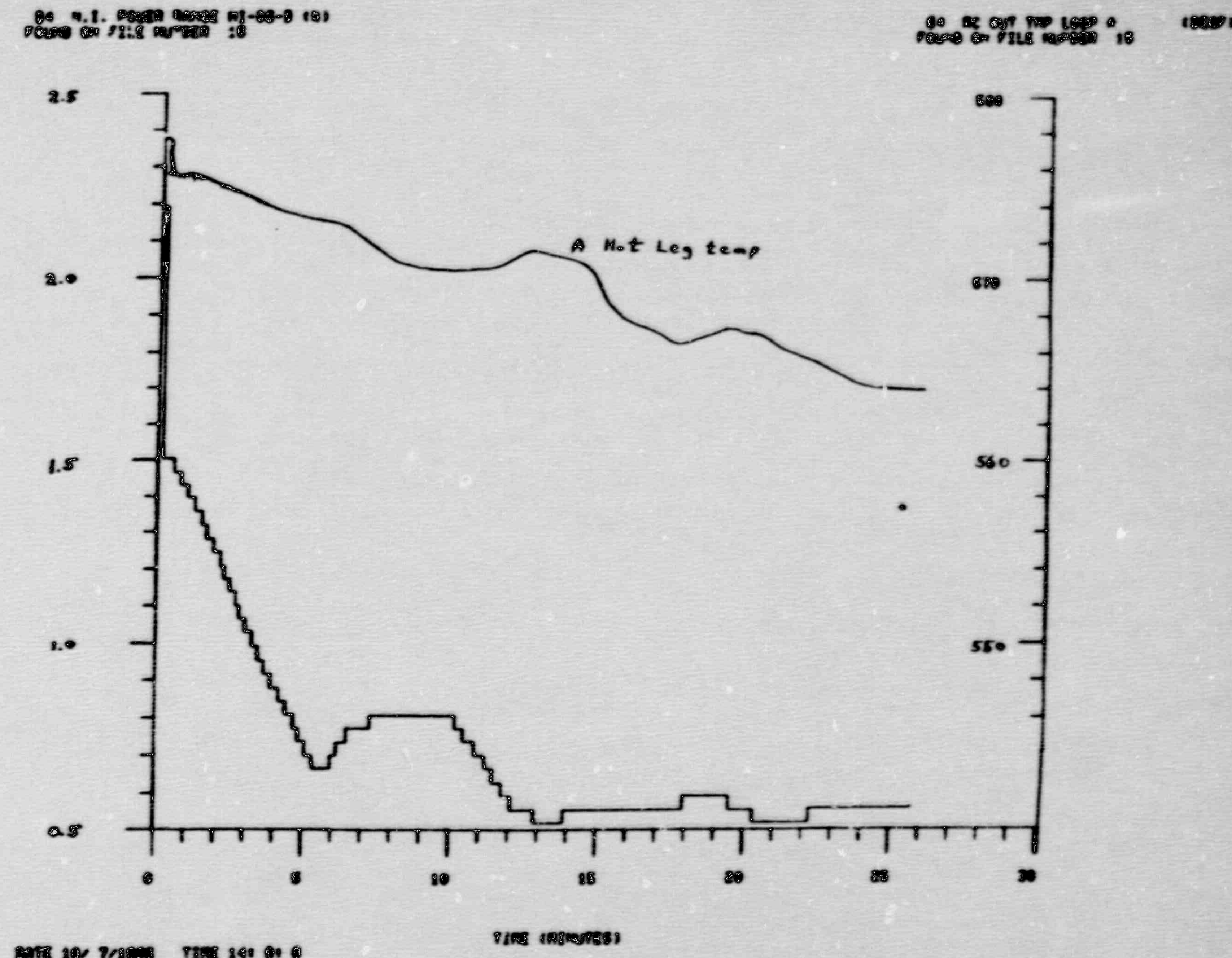
The MIST single phase natural circulation tests did exhibit a considerable degree of similarity to actual plant transients. The MIST natural circulation test results provide insights which should be considered in the preparation of training packages for natural circulation cooldown.

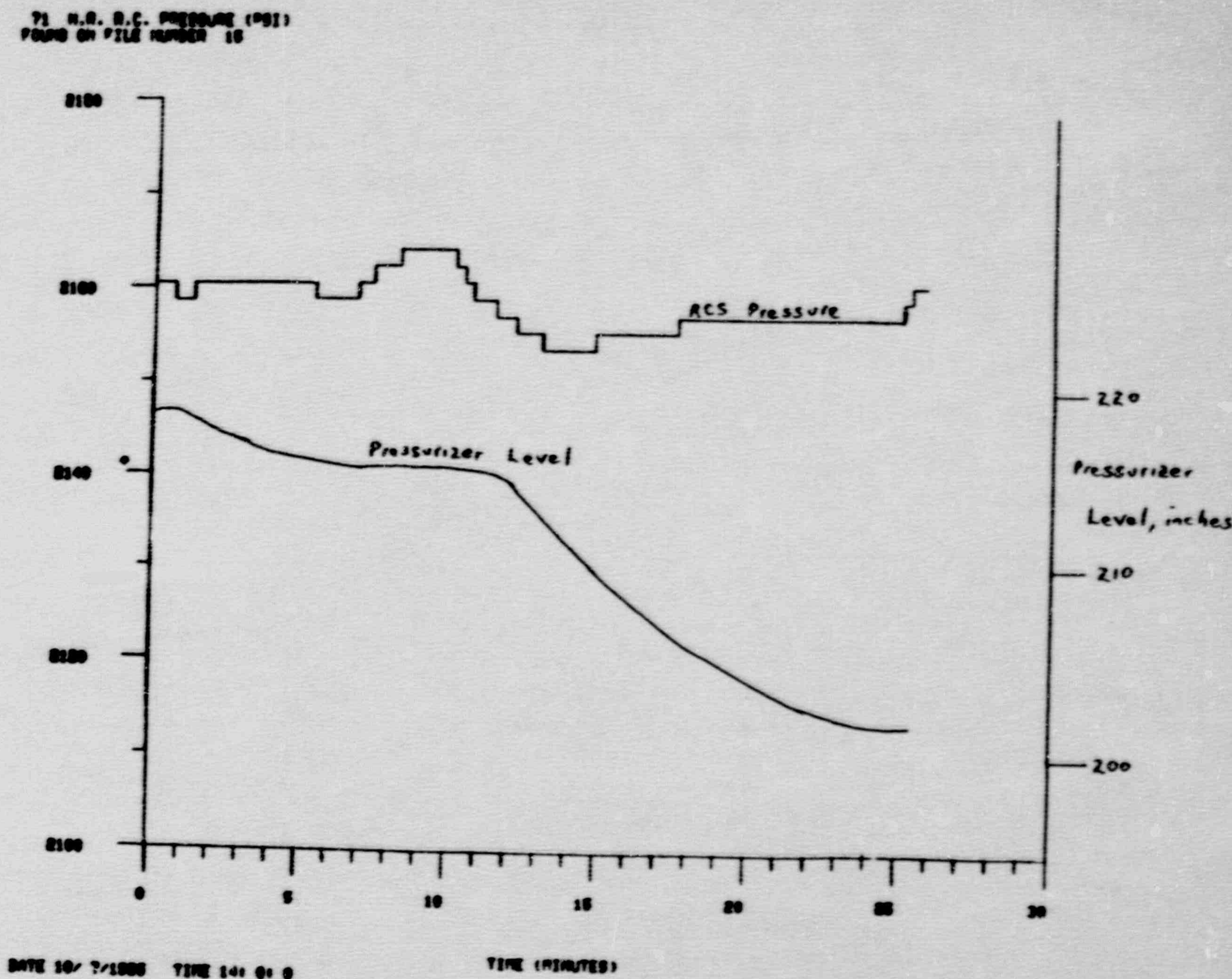
6. REFERENCES

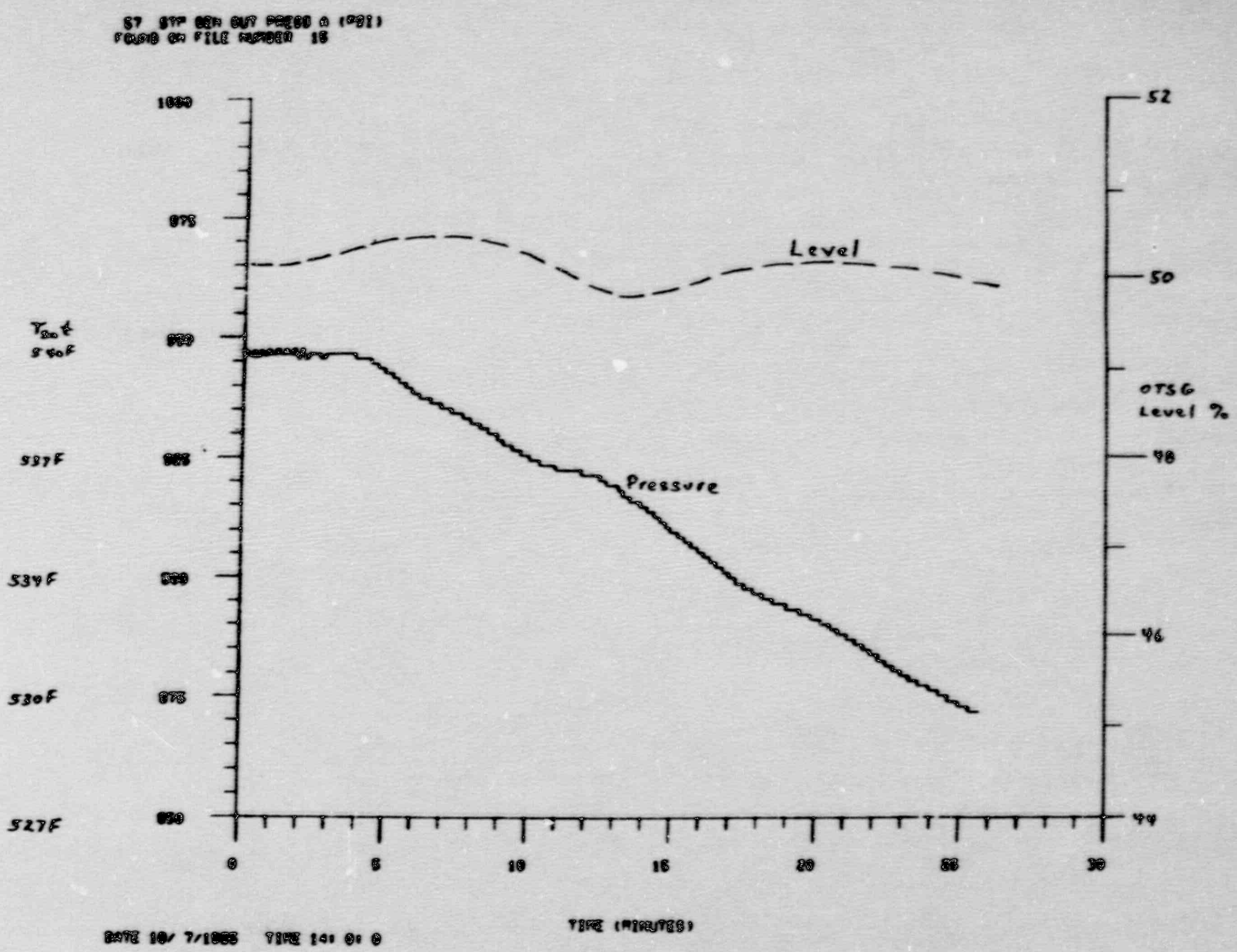
1. MIST Natural Circulation Test Specifications, BAW-2090, Rev. 1, August 1989.
2. "MIST Test Specifications", G.O. Geissler et al., BAW-1984, Babcock & Wilcox Co., Nuclear Power Generation Division, Lynchburg Va., October 1985.

APPENDIX A

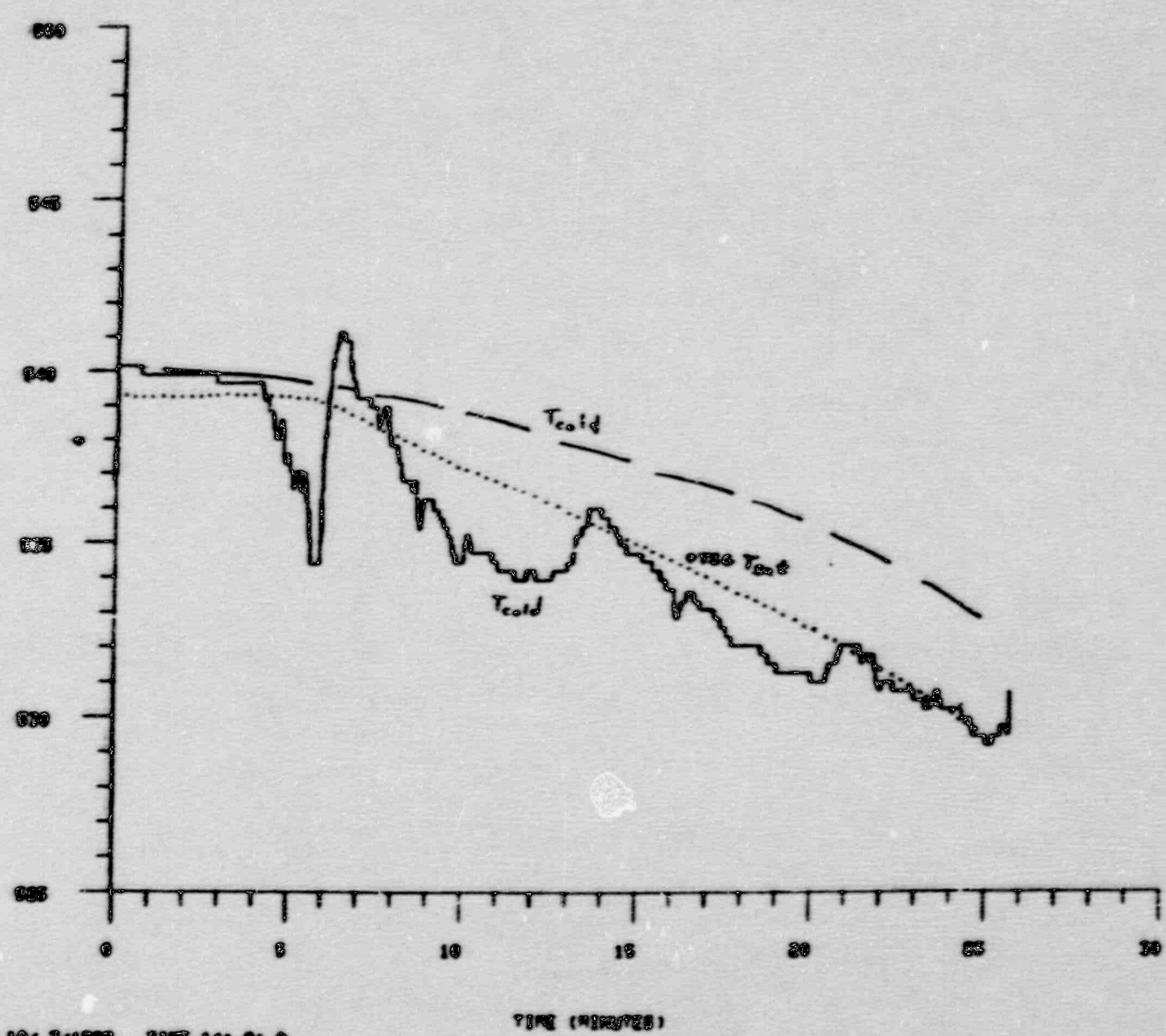
Data Plots from the TMI-1 Natural
Circulation Test October 1985


A Hot Leg temp
2.5
2.0
1.5
1.0
0.5
0
5
10
15
20
25
30
560
550

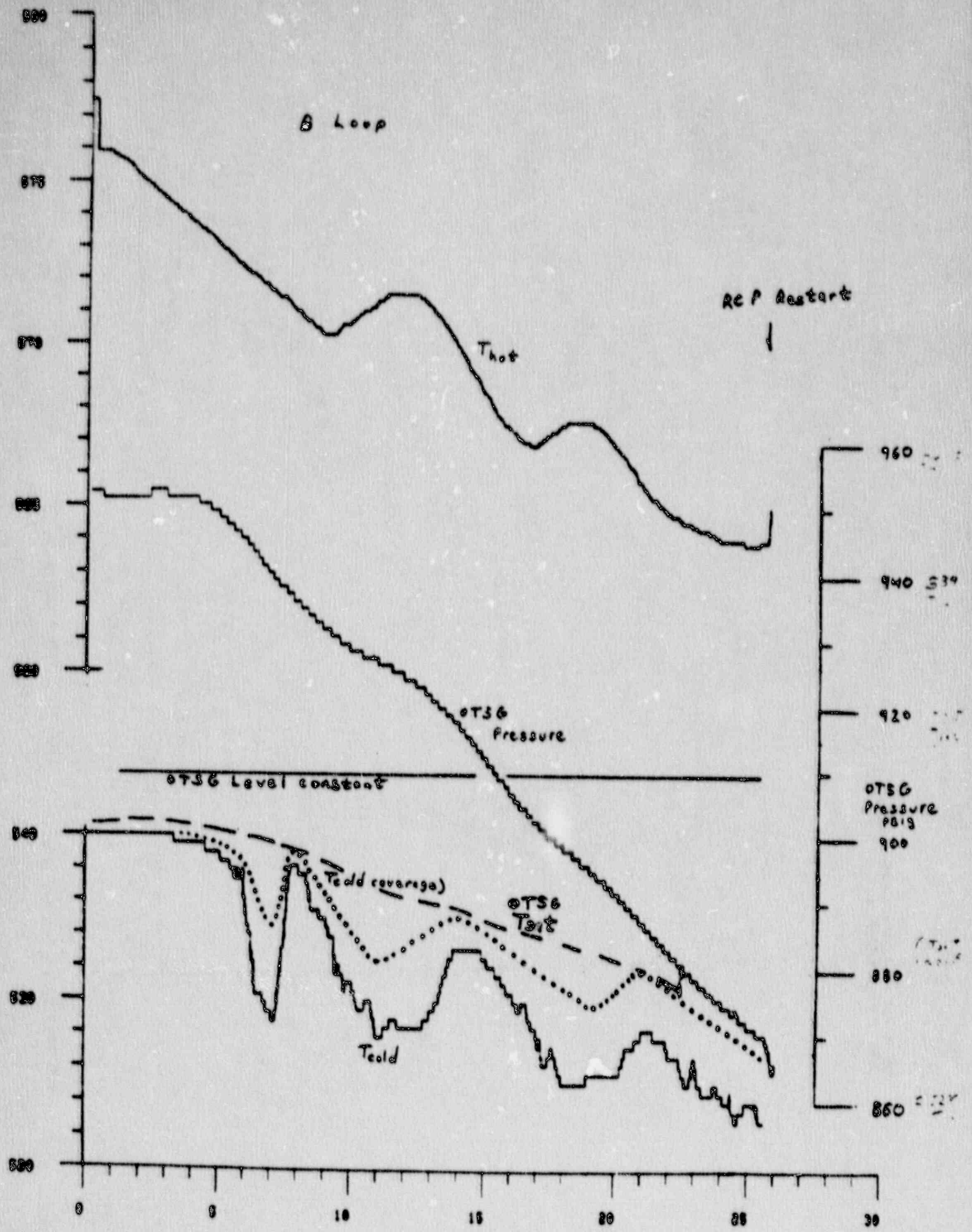

RCS Pressure
Pressurizer Level
220
Pressurizer
Level, inches
210
200
0
5
10
15
20
30



Level
Pressure
OTSG Level %
52
50
48
46
540F
537F
534F
530F
527F
0
5
10
15
20
30

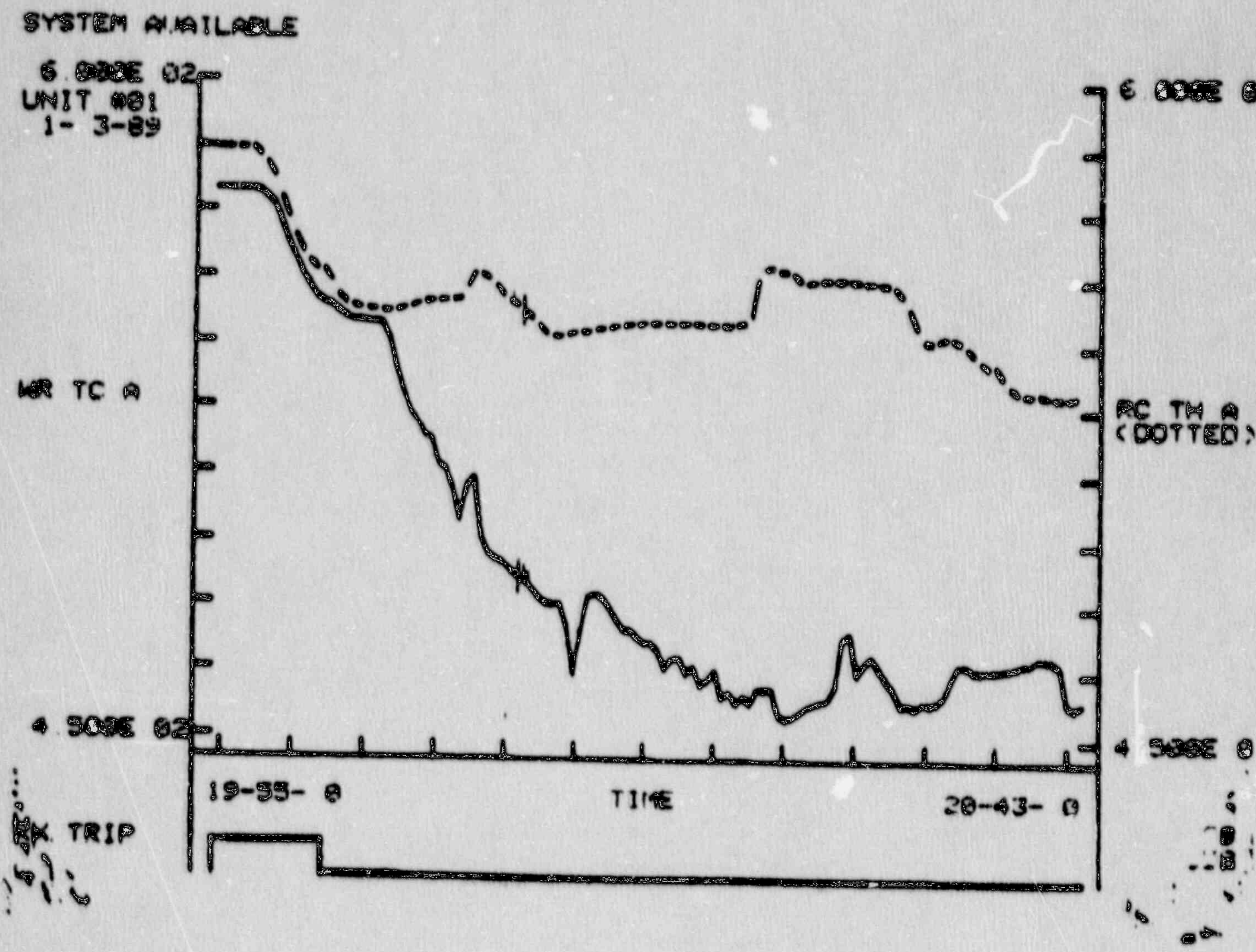


Tcold
OTSG Tout
Tcold
0
5
10
15
20
25
30
TIME (MINUTES)

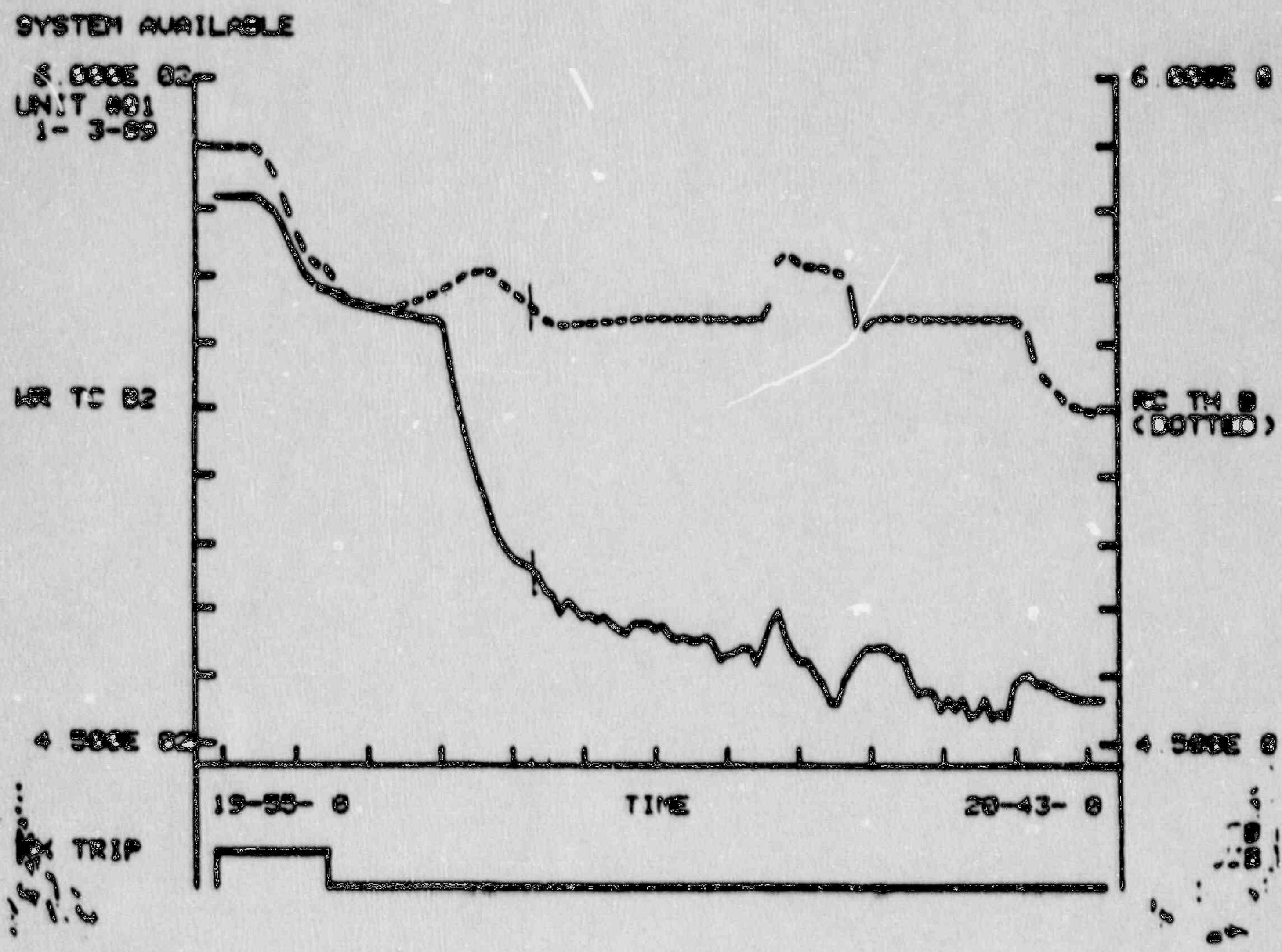

B Loop
RCP Restart
Thot
OTSG
Pressure
OTSG Level constant
Tcold (average)
OTSG
Tsat
Tcold
960
940
920
900
880
860
OTSG
Pressure
PSIG
0
10
15
20
30
TIME (MINUTES)

APPENDIX B

Data Plots from the Oconee 1 Transient
That Occurred on January 3, 1989



SYSTEM AVAILABLE
6.000E 02
UNIT #01
1- 3-89
WR TC A
4.500E 02
6.000E 0
RC TH A (DOTTED)
4.500E 0
19-55- 0
TIME
20-43- 0
RX. TRIP



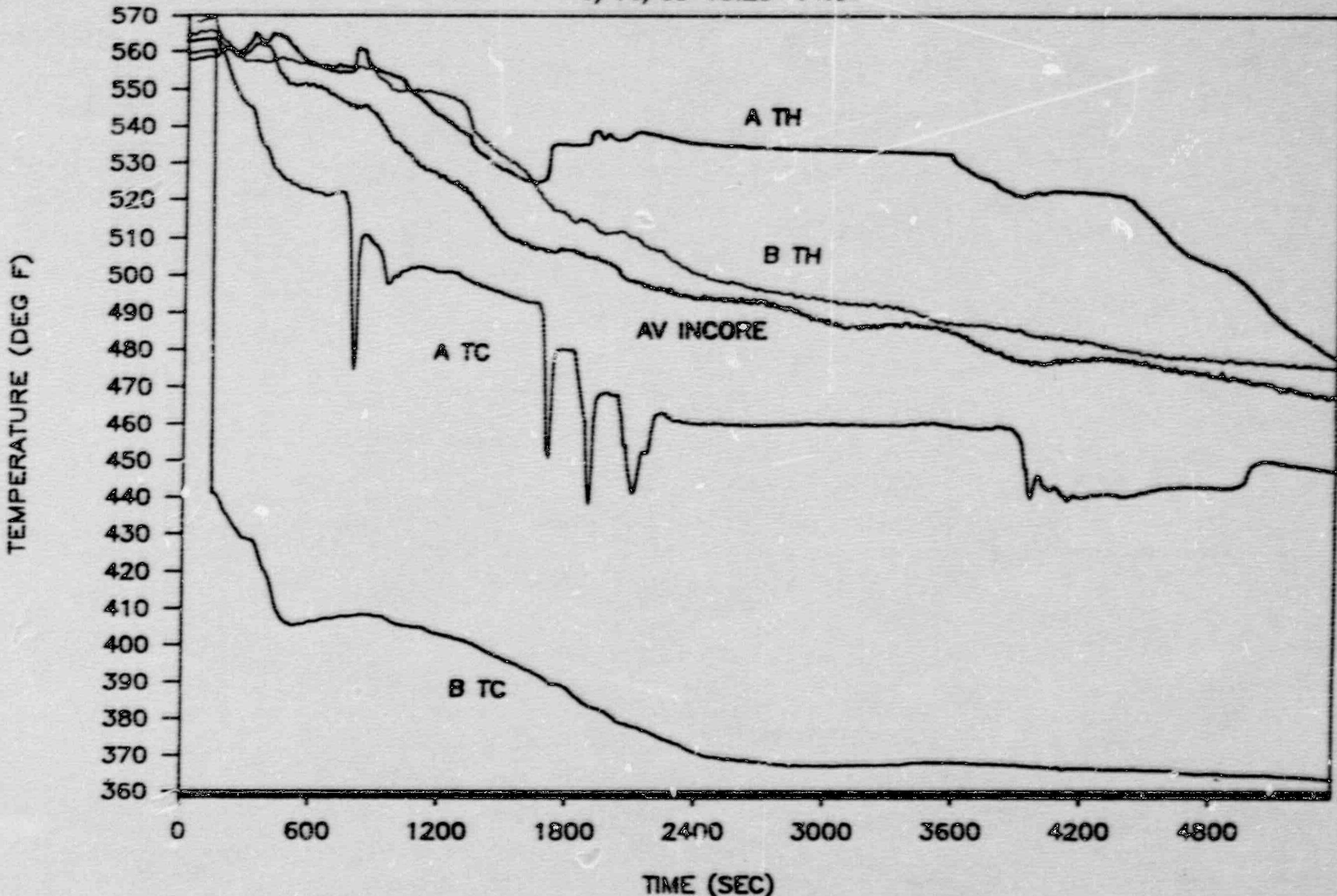
SYSTEM AVAILABLE
1- 3-89
TIME
TRIP
(DOTTED)

APPENDIX C

Data Plots from the Crystal River 3
Loss of Offsite Power Transient
That Occurred on June 16, 1989

RCS TEMPERATURE

6/16/89 13:25–14:55



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1562 Beeson Street
Alliance, OH 44601

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

The Multiloop Integral System Test (MIST) is part of a multiphase program started in 1983 to address small-break loss-of-coolant accidents (SBLOCAs) specific to Babcock and Wilcox designed plants. MIST is sponsored by the U. S. Nuclear Regulatory Commission, the Babcock & Wilcox Owners Group, the Electric Power Research Institute, and Babcock and Wilcox. The unique features of the Babcock and Wilcox design, specifically the hot leg U-bends and steam generators, prevented the use of existing integral system data or existing integral facilities to address the thermal-hydraulic SBLOCA questions. MIST and two other supporting facilities were specifically designed and constructed for this program, and an existing facility--the Once Through Integral System (OTIS)--was also used. Data from MIST and the other facilities will be used to benchmark the adequacy of system codes, such as RELAP5 and TRAC, for predicting abnormal plant transients.

The MIST program is reported in 11 volumes. The program is summarized in Volume 1; Volumes 2 through 8 describes groups of tests by test type; Volume 9 presents inter-group comparisons; Volume 10 provides comparisons between the calculations of RELAP5/MOD2 and MIST observations, and Volume 11 presents the later Phase 4 tests. This Volume 11 addendum pertains to MIST natural circulation tests.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

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steam generator (once through)
natural circulation
Two-phase flow

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