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Equipment Qualification Methodology Research: Tests of RTDs

F. J. Wyant, E. E. Minor

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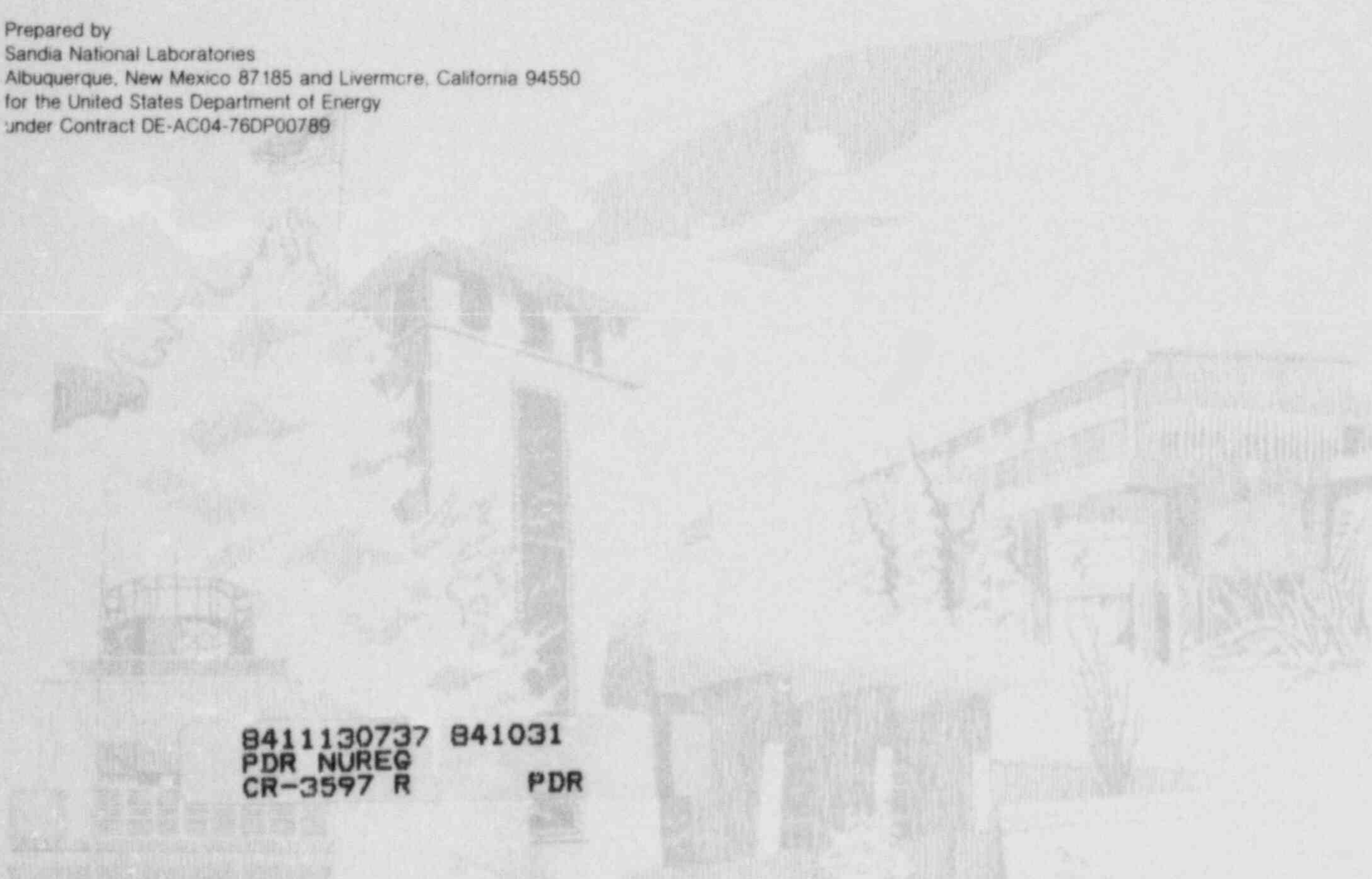

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EQUIPMENT QUALIFICATION METHODOLOGY RESEARCH: TESTS OF RTDs

Francis J. Wyant
Earl E. Minor

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Sandia National Laboratories
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ABSTRACT

Ten resistance temperature detectors (RTDs), from three manufacturers, were subjected to an abbreviated loss-of-coolant accident (LOCA) environment (saturated steam and chemical spray) simulation test as part of the NRC-sponsored Equipment Qualification Methodology Research Test Program (A-1355). The test was a "screening test" on unaged specimens that lasted about 24 hours and was of short duration to isolate any obvious problem areas. The LOCA environment caused functional failures and some physical damage in four of the RTDs tested. One RTD failed early in the test, two others of the same type produced erroneous temperature readings 7.5 hours into the test. Post-test investigations revealed that water leakage into the head areas of the three affected RTDs (as well as one other of the same model) may have contributed to the anomolous behavior.

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EXECUTIVE SUMMARY

Ten resistance temperature detectors (RTDs), from three manufacturers, were subjected to an abbreviated loss-of-coolant accident (LOCA) environment (saturated steam and chemical spray) simulation test as part of the NRC-sponsored Equipment Qualification Methodology Research Test Program (A-1355). The Equipment Qualification Branch, Office of Nuclear Reactor Regulation, USNRC, chose RTDs as generic equipment candidates for tests which would be used to generate data to evaluate qualification test methods for accident conditions. The choice was based on the wide use of RTDs throughout the nuclear power industry.

The purpose of this test was to "screen" RTDs from three different suppliers to assess the functional capabilities of <u>unaged</u> equipment and to determine the primary failure modes of RTDs. Ten unaged RTDs were exposed to the LOCA environment, which consisted of saturated steam and chemical spray.

Supplier A RTDs (No. 1-No.4) contain two 100-ohm platinum elements with three leads coming from each element. The elements are connected to a terminal board located in a cast-iron body ("head") at the top of the RTD unit. Both Supplier B (No. 5-No.8) and Supplier C (No. 9 and No. 10) RTDs are four-wire, single-element RTDs with 200-ohm elements.

The LOCA environment test was conducted in a stainless steel cylindrical chamber. Chamber temperature was monitored by calibrated thermocouples, and chamber pressure by calibrated pressure transducers. The tests were performed in the following sequence:

Pretest Visual Inspection and Functional Check
LOCA Environment
Post-test Visual Inspection and Functional Check

Soon after the first 15-psig pressure plateau was reached (seconds), chemical spray was introduced into the chamber. The spray was introduced primarily to provide a conductive medium so that leaks would be more easily recognized by aberrant readings caused by electrical short circuits in the system. The exposure was terminated at the end of 24 hours as scheduled.

The LOCA environment caused functional failures and some physical damage in four of the RTDs tested. Within the first minute of the test, a large steam leak was apparent around the cable of RTD No. 1 where the cable came out of the chamber, and its readings had begun to diverge from the chamber temperature. Two minutes into the test RTD No. 1 was clearly producing erroneous temperature indications.

During the same time period, RTD No. 2 and RTD No. 3 also gave erroneous readings, suggesting that water had leaked into these RTDs as well.

RTD No. 1 was isolated from the instrumentation and data recording system, the steam leak was plugged, and the test was restarted an hour later. During the course of the test, Supplier B and Supplier C RTDs functioned properly. At some time during the test, every RTD from Supplier A gave erroneous (low) readings. At other times they recovered and provided reasonably accurate (i.e., within 5°C) temperature indications. Post-test inspection revealed that moisture had entered all four Supplier A units.

Post-exposure functional tests were performed with the RTD sensing element immersed first in an ice bath then in hot water at approximately 50 degrees C. Supplier B and Supplier C RTDs functioned satisfactorily. RTD No. 2 and RTD No. 4 functioned properly during this post-LOCA functional; however, RTD No. 1 and RTD No. 3 gave readings far below the temperature being measured.

Insulation resistance measurements at 10 volts were taken of all units while they were still mounted in the test chamber head. All readings were above $1x10^{10}$ ohms for the Supplier B and Supplier C RTDs. RTD No. 1 leads had been cut and this test could not be applied. RTD No. 2 had one channel which tested at $1.5x10^{7}$ ohms; the other channel tested below the range of the IR tester ($0.5x10^{6}$ ohms) but tested in the range of 15 to 17 kilohms with a multimeter. RTD No. 3 (both channels) readings were in the 1 to 2 kilohm range. RTD No. 4 readings were all around 1 megohm.

During post-test inspection of the head castings, RTD No. 2 was found to have a small hole through the body; RTD No. 3 appeared to have a leak around the ground screw in the cast body; and RTDs No. 1, No. 2, and No. 4 had leaked at the gasket.

The results show that the gasket material used in RTDs No. 1-4 is inadequate to protect the electrical connectors in the head from water intrusion, and thus shorting. Additionally, the head casting process appears to have inadequate quality controls to prevent the occurrence of pin-holes and through body leakage paths.

1.0 INTRODUCTION

This report discusses the results of a loss-of-coolant accident (LOCA) environment simulation test made on resistance temperature detectors (RTDs) procured from three different manufacturers. The test was performed as part of the Equipment Qualification Research Testing (EQRT) Methodology Program,[1] conducted by Sandia National Laboratories on behalf of the Office of Nuclear Regulatory Research, United States Nuclear Regulatory Commission (USNRC). Detailed test plans[2,3] for the test were submitted to, reviewed, and approved by NRC staff prior to execution of the test. The objective of the overall program is the assessment of qualification test methodologies through the testing of safety-related equipment, in this case, RTDs.

The purpose of this test was to "screen" unaged RTDs from the three suppliers to (1) determine the advisability of proceeding with the extended test program outlined in Reference 2; (2) evaluate basic designs and assess the general functional capabilities of the equipment when subjected to design-basis event environments; and (3) identify the primary failure modes. Ten RTDs were exposed to a LOCA environment (saturated steam and chemical spray), simulated by using a step-function profile for the temperature and pressure, beginning at low (15 psig) temperature/pressure conditions, increasing in small (10-psig) increments to a high (115 psig) temperature/pressure condition, and returning to the low temperature/pressure conditions for the duration of the test.

To evaluate the results of the test, the following criteria were established as being indicative of potential problems:

1. Evidence of moisture intrusion.

2. Temperature indications which differed from the thermocouple readings far enough (greater than 5°C) that the difference could not be reasonably explained by thermal lag in the system.

3. Temperature indications which differed by more than five or six degrees from those obtained by other RTDs, when the RTDs were in a "steady-state" environment.

4. For dual-element RTDs, a difference of more than 3°C between the temperatures indicated by the two elements.

Generally, when a short occurred, the divergence of the affected element was of sufficient magnitude and occurred on repeated readings so that it gave a clear indication of problems.

A Quick Look report,[4] outlining the results of this screening test, was issued soon after completion of the post-test activities.

2.0 EQUIPMENT SELECTION

The Equipment Qualification Branch, Office of Nuclear Reactor Regulation, USNRC, chose RTDs as generic equipment candidates for tests which would be used to generate data to evaluate qualification test methods for accident conditions.[5] The choice was based on the wide use of this type of equipment throughout the nuclear power industry. Because of the wide use of these or similar models of RTDs, NRR recommended[6] three models of Supplier A, four models of Supplier B RTDs, and also requested that three models of Supplier C RTDs be tested. Supplier C RTDs are no longer available but were added because of their extensive use in older plants. Because of the unavailability of certain components and procurement problems, the diversity of RTDs available for testing was reduced to one model from Supplier A, two models from Supplier B, and one model from Supplier C. Table 1 provides a listing of the RTDs tested in this screening test.

At the time of this screening test, Supplier A was in the process of planning and conducting qualification tests on their components; their test was nearing completion. Supplier B components of the same design as those used in the tests described herein have been purchased and qualified by another corporation. Supplier C has not qualified their RTDs to the current standards for nuclear use and does not plan to do so.

TABLE 1. RTDs TESTED DURING SCREENING TEST

RTD No.	Description	Serial No.
1	Supplier A	9409
2	Supplier A	9410
3	Supplier A	9412
4	Supplier A	9415
5	Supplier B, Model 1	102
6	Supplier B, Model 1	103
7	Supplier B, Model 2	101
8	Supplier B, Model 2	102
9	Supplier C	8138
10	Supplier C	8147

3.0 TEST SPECIMENS

References 7 and 8 (as well as many other sources) will provide the interested reader with information concerning the general theory and use of RTDs in current temperature measurement applications.

Supplier A RTDs contain two 100-ohm platinum elements with three leads coming from each element. The elements are connected to a terminal board located in a cast-iron body at the top of the RTD unit. The outgoing leads are assembled in this body, then a cast-iron cap is screwed onto the body to seal the assembly (the seal is provided by a Thermotorq CN 9000--Armstrong gasket). We connected the RTDs with four wires to make them compatible with our data collection instruments. The port through which the leads pass must be sealed, and Supplier A leaves this responsibility to the firm installing the RTDs. In this test, the ports were sealed using flexible metal conduit and heat-shrinkable tubing.

Both Supplier B and Supplier C RTDs are four-wire, single-element RTDs with 200-ohm elements. Neither supplier uses the cast body and cap design; instead the leads feed from the element through a sealed connection into a cable which is covered with a stainless steel braided flexible hose. The "outboard" end of the flexible hose is terminated in a fitting from which the leads protrude. This end must then be protected by a junction box or by some other means.

Figure 1 shows the RTD test assembly configuration prior to installation in the test chamber.

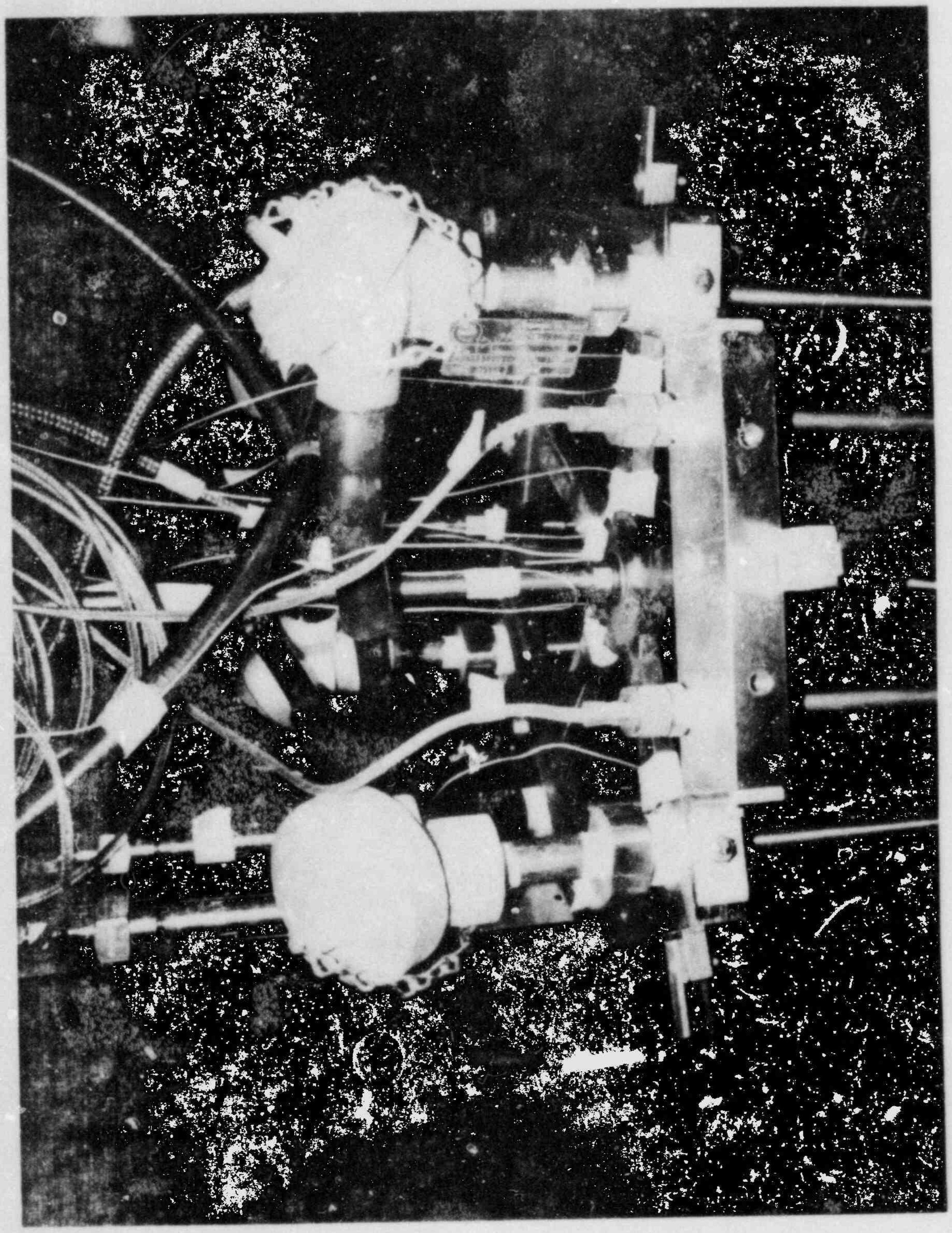


Figure 1. RTD test assembly prior to installation in test chamber.

4.0 TEST APPARATUS

The LOCA environment test was conducted in a stainless steel cylindrical chamber (Figure 2) with an inside diameter of 0.52 m. The test chamber consists of two sections; an upper section which is 0.51 m long and a 0.96 m long lower section. The chamber has a free volume of 0.3 cubic meters.

Located in the upper section are nine penetrations which provide access into and out of the test chamber for steam, chemical spray, power, and monitoring cables, etc.

Chamber temperature was monitored by thermocouples (calibrated to within 1°C), and chamber pressure by pressure transducers (0-200 psig and 0-30 psig). Data was collected by an Acurex Autodata Ten/10 datalogger.

Table 2 lists the diagnostic equipment used during this test.

Post-test insulation resistances (IRs) were measured with a Hewlett-Packard, model 4329A IR tester; however, when IRs were below the lower limit of the 10-volt scale of the IR tester, IRs were estimated with multimeters.

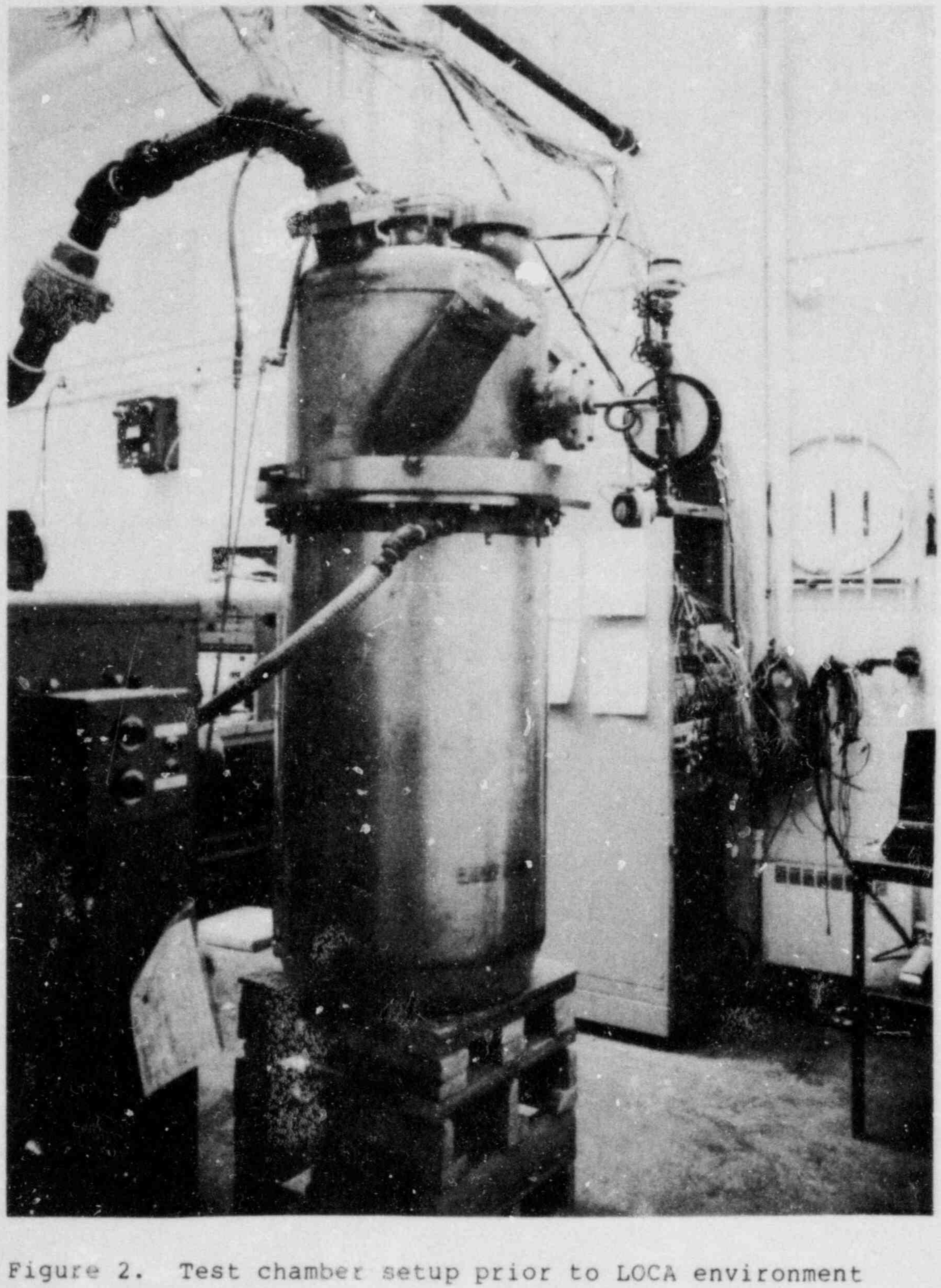


Figure 2. Test chamber setup prior to LOCA environment simulation test.

TABLE 2. List of Diagnostic Equipment

	Calibration Expiration Date	Cal. Certificate No.
Accurex Auto-Data 10	4/20/83	3-210-1/12793
Heise Pressure Gauge	2/28/84	26953
Heise Digital Pressure Transducer	3/31/84	S7-5982
Hewlett-Packard 4329A (IR Tester)	10/14/83	02898/9496
*Simpson 260L Multimeter	---	---
*Fluke 8040A Multimeter	---	---

* The multimeters had not been calibrated. Readings taken by these instruments are considered approximations. These instruments were used when insulation resistance readings were below the lower limit of the 10-volt scale of the HP 4329A (approximately 0.5×10^6 ohms).

5.0 EXPERIMENTAL

5.1 Sequence of Tests

Tests were conducted in accordance with Reference 3, and were performed in the following sequence:

Pretest Visual Inspection and Functional Check
LOCA Environment
Post-test Visual Inspection and Functional Check

5.2 Visual Inspection and Functional Check

Visual inspection consisted of an examination for obvious damage of external parts only. All pipe joints were securely tight- ened. After wiring was completed, the cap threads of the Supplier A RTDs were lubricated with a nuclear grade anti-seize compound (Never-Seez). They were then installed onto the RTD bodies and tightened to a torque of 50 to 60 foot-pounds. (This torqu e value was obtained from Supplier A by telephone on August 19, 1982, and reconfirmed by telephone on January 25, 1983.) Pipe joints were not checked for torque values. The tightness of pipe joints is generally defined in terms of the number of threads engaged. These data were not determined. Instead, Supplier B assemblies were checked (as assemblies) to a minimum torque of 40 foot-pounds and a maximum of 60 foot pounds. This verified that all pipe threads were tightened to a torque of at least 40 foot-pounds. During visual inspection, the only damage observed were the marks left on the stainless steel pipe nipples from tightening the assembly into the test fixture. This damage had no effect on the test results. It should be noted that Supplier A RTDs used in this test were modified by replacing the three inch nipple-union-nipple assem- bly with a three-inch black iron nipple. The threads of this nipple were wrapped with teflon tape for assembly. Otherwise, the RTDs were tested as they came from the suppliers.

Functional checks consisted of comparing each RTD's reading with readi ngs obtained from reference thermocouples in the same environment. The thermocouples had been calibrated against NBS secondary standards. In addition, prior to closing the test chamber and after connecting the RTDs to the data recording system, each RTD in turn was first immersed in an ice water bath then heated with an air gun to determine that it responded to the approximately correct temperature and that it was connected to the proper channel of the data recording system.

5.3 Preparation for LOCA Environment Test

Supplier A RTDs were received without cables. Prior to tighten- ing the caps to the required torque, the caps were removed and the necessary leads were installed. In addition, a grounded-junction thermocouple was welded to the inside head of each of the four Supplier A RTDs to record the temperature as close to the sealing gasket as possible. A flexible steel hose was installed around the leads from each Supplier A RTD, extending from the RTD body to the cover plate through which the leads exited from the exposure chamber. Each end of the flexible hose was covered with heat-shrinkable tubing to ensure a well-sealed interface.

Supplier B RTDs included their own armored cables. These were securely connected to fittings at the cover plates.

Supplier C RTDs also included their own armored cables. However, to protect the open end of the cables, a length of beta-ucriptite-filled epoxy was molded around the cables at the point where the cables exited from the exposure chamber. A short length of 1/2-inch stainless steel tubing was placed over the cables and molded into the outboard end of the betaucriptite-filled epoxy. This was secured in a Swagelok fitting as it exited the chamber to protect the cables at that interface and to prevent steam from leaking.

Figure 3 shows the RTD cable connections existing prior to installation in the test chamber. See, also, Figure 1.

5.4 LOÇA Environment Exposure

Figure 4 shows the planned pressure profile the RTDs were to be exposed to during the LOCA Harsh Environment test, and the chamber pressure profile achieved during the test, as read by pressure transducers attached to the chamber. Saturated steam was used to maintain the profile. The primary control was pressure; the temperature attained at each level was the temperature associated with saturated steam at the given chamber pressure. The gage pressure values shown are relative to atmospheric pressure for the altitude of the test facility -5440 feet above sea level - or 12.15 psia).

As soon as possible after the first 15-psig pressure plateau was reached, chemical spray was introduced into the chamber. Spray was continued throughout the period of exposure. The spray was introduced primarily to provide a conductive medium so that leaks would be more easily recognized by aberrant readings caused by electrical short circuits in the system. The exposure was terminated at the end of 24 hours.

Chemical spray composition was as follows (per IEEE 323-1974):[9]

0.28 molar H_3BO_3 (3000 ppm boron)
0.064 molar $Na_2S_2O_3$
NaOH to maintain pH between 10.0 and 11.0 at 25° C.

Figure 5 shows the placement of thermocouples used to measure the internal test-chamber temperatures. Thermocouple position measurements, on Figure 5, were taken downward from the top flange of the container head.

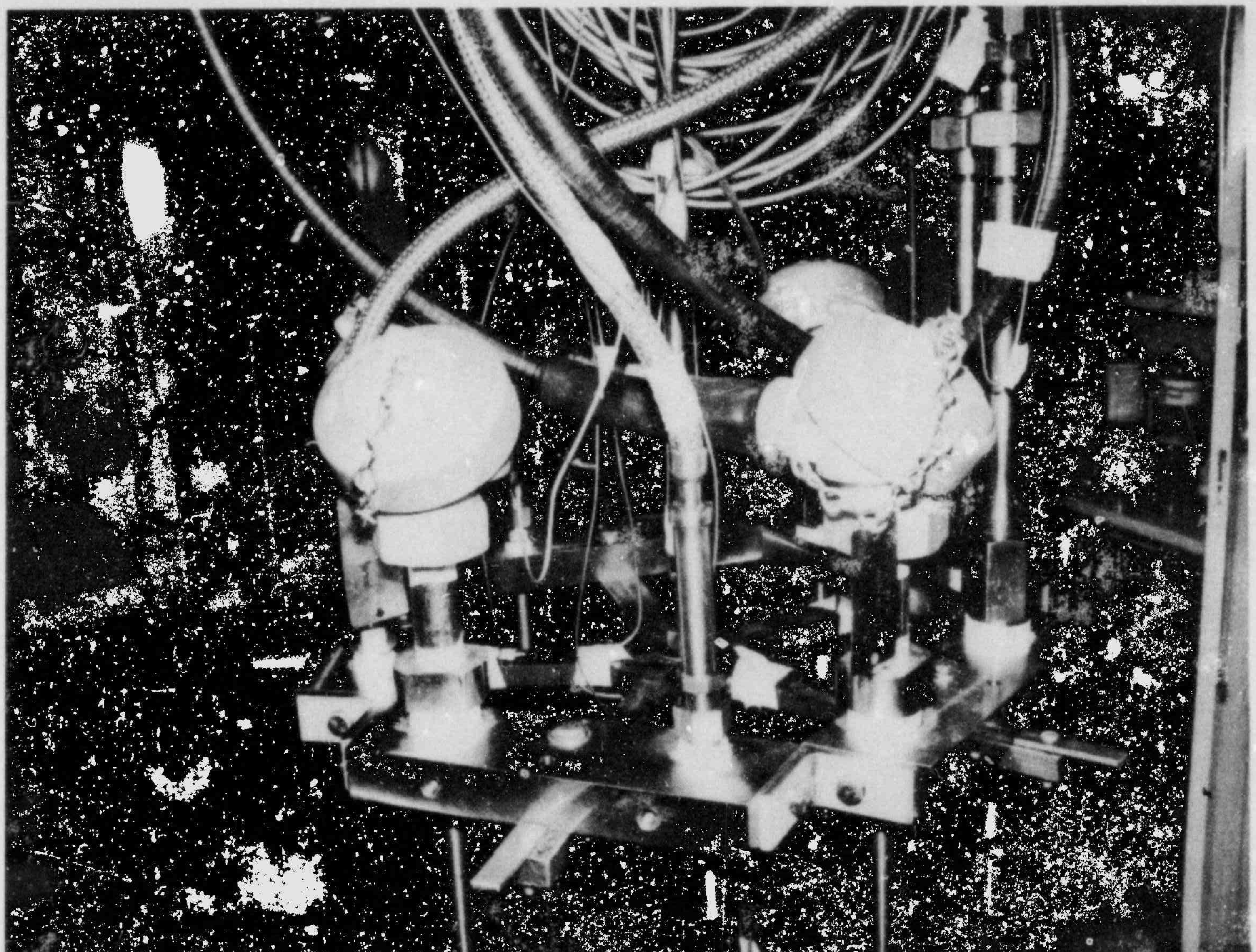


Figure 3. RTD cable interfaces prior to installation in test chamber. (Also see Figure 1.)

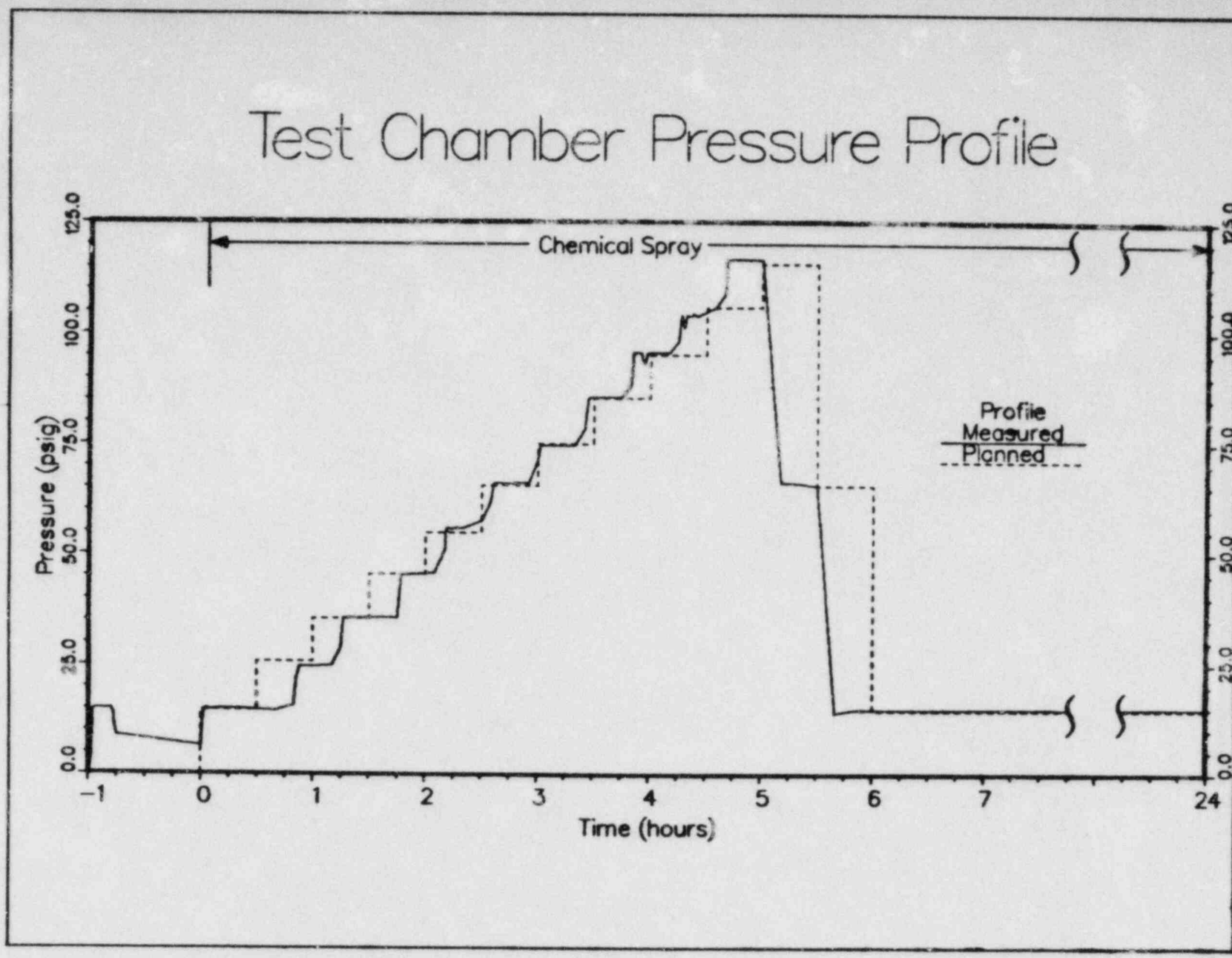


Figure 4. Screening test pressure profiles: as planned (dashed curve) and as measured (solid curve) during the LOCA environment simulation test.

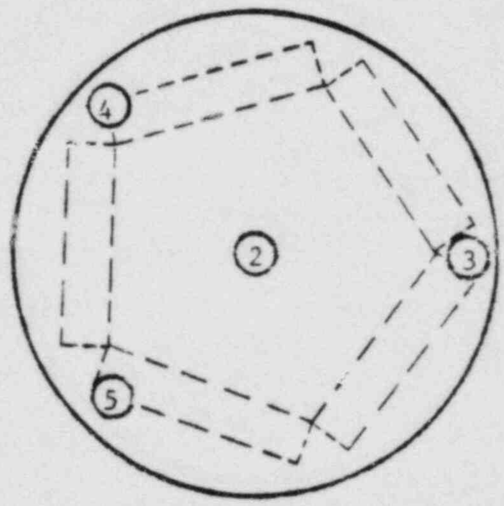
TC1 - Level with flange in center of container head

TC2 - 11.5 in. at center

TC3 - 12.5 in.

TC4 - 16.5 in.

TC5 - 14.0 in.



TC6 - 18.0 in. at center

TC7 - 24.0 in.

TC8 - 23.0 in.

TC9 - 23.0 in.

TC10 - 24.0 in.

TC11 - 29.5 in. at center

TC12 - 33.5 in. at center

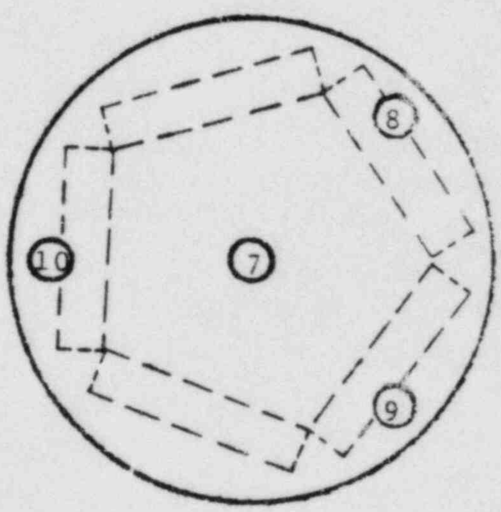


Figure 5. Position of Thermocouples in Chamber. Measurements are taken downward from the test chamber flange interface.

6.0 RESULTS

6.1 LOCA Test Results

Exposure was begun at 0830, March 16, 1983. Within the first minute, a large steam leak was apparent around the cable of RTD No. 1 where the cable came out of the chamber. Post-test examinations revealed that the leak was around the screw cap sealing gasket at the RTD head. By 0831, RTD No. 1 readings had begun to diverge from the chamber temperature, and by 0832 it was clearly producing erroneous temperature indications. (Figure 6 shows the output for both circuits of RTD No. 1, and the average chamber temperature versus time, for this period.) By 0846 (16 minutes into the test - see the measured pressure drop in Figure 4) the test was temporarily shut down, the cables were cut on RTD No. 1 and the steam leak was sealed.

During the same time period, RTD No. 2 and RTD No. 3 also gave erroneous readings, suggesting that water had leaked into the RTDs (Figures 7 and 8). (After the conclusion of the exposure, RTD No. 2 was found to be leaking at the head gasket and also to have a small hole through the body casting. RTD No. 3 was found to have a small leak in the head gasket and a small leak in the flexible hose used to protect the cable.) By the end of the test, RTD No. 3 was also leaking at the flexible metal connector at the chamber head because the heat-shrinkable tubing had shrunk too far and had uncovered the connector. The problems with flexible hose and heat-shrinkable tubing are not attributable to Supplier A, as these elements were Sandia-furnished. (The flexible hose was supplied as nuclear-grade material, and the heat-shrinkable tubing had been used in the same way in previous Sandia tests.[10])

As shown in Figures 9 thru 15, the other RTDs (No. 4 thru No. 10) appear to have functioned properly during the first 15 minutes of the LOCA exposure.

At 0930, March 16, the test was restarted. Supplier B and Supplier C RTDs continued to function properly. At some time during the test, every RTD from Supplier A gave erroneous (low) readings. At other times they recovered and provided reasonably accurate temperature indications. Post-test inspection revealed that moisture had entered all four Supplier A units.

Table 3 provides a running account of significant events throughout the harsh environment exposure. After RTD No. 1 was cut out of the test and the chamber resealed, the three remaining Supplier A RTDs functioned adequately during portions of the test. Figures 16-24 depict the temperature response of each RTD (No. 2 - No. 10) during the 24 hour harsh environment exposure.

Table 4 lists the times and RTDs which deviated from the average chamber temperature (TC) by more than 5°C during the steady state conditions; note that all RTDs listed are from Supplier A. Table 5 lists the times and 2-element RTDs involved where the temperature output of one element deviated from the temperature output of the other element by more than 3° C, during steady-state conditions.

6.2 Post-test Functionals and Inspection

The results described below follow the sequence in which the inspections were performed. The initial configuration was with all RTDs still mounted in the chamber head, but with the lower part of the chamber removed.

Post-exposure temperature readings were taken with each RTD immersed first in an ice bath then in hot water at approximately 50 degrees C. Supplier B and Supplier C RTDs functioned satisfactorily. RTD No. 2 and RTD No. 4 also functioned properly during this test. RTD No. 1 and RTD No. 3 gave readings far below the temperature being measured. Table 6 lists the RTD outputs and thermocouple (TC) readings for each of these post-test functional checks.

Insulation resistance measurements at 10 volts were taken of the external cable leads on all units while they were still mounted in the test chamber head. All readings were above $1x10^{10}$ ohms for Supplier B and Supplier C RTDs. RTD No. 1 leads had been cut and this test could not be applied. RTD No. 2 had one channel which tested at $1.5x10^{7}$ ohms; the other channel tested below the range of the IR tester ($0.5x10^{6}$ ohms) but tested from 15 to 17 kilohms with a Simpson Model 250L Multimeter. RTD No. 3 (both channels) tested below the range of the IR tester; readings taken with the Simpson meter were in the 1 to 2 kilohm range. RTD No. 4 readings were all around 1 megohm.

During the assembly of the test specimens, the caps of all four Supplier A RTDs had been tightened to a minimum torque of 50 foot-pounds with a breakover torque wrench. A post test check of the torque on each cap was made in the tightening direction first, then breaking torque was measured. In the tightening direction, RTD No. 2 read 50 foot-pounds; breakaway torque was approximately 35 foot-pounds. (Note that breakaway torque values are generally less reliable.) RTDs No. 1, 3, and 4 showed no movement in the tightening direction with 60 foot-pounds applied. Breakaway torque for these units were read as approximately 100 foot-pounds, approximately 55 foot-pounds, and approximately 30 foot-pounds, respectively.

After removal from the test fixture, insulation resistance (IR) measurements at 10 volts were again taken (see Table 7). All readings were above 1×10^{10} ohms for Supplier B and Supplier C RTDs. On RTD No. 1, all leads were shorted. Readings taken with a multimeter were less than 100 ohms for all leads of both elements. RTD No. 2 circuit-1 channel IR readings were all less than 0.5×10^{6} (the lower limit of the instrument). With a Simpson Multimeter Model 250L the circuit-1 channel resistance readings were in the 15 to 17 kilohm range. RTD No. 3 leads all read less than 0.5×10^{6} ohms with the IR tester. With a Simpson Multimeter the resistance readings on one channel were 1 to 2 kilohms. RTD No. 4 IR readings were in the 1×10^{6} ohm range. These tests were made first through the cables, then through the elements with cables removed but element leads still connected to the terminal boards.

After the above tests were completed, the element leads were disconnected from the terminal boards and IR readings were taken from the element leads to ground (Table 8). RTD No. 1 readings were still below the lower limit of the IR tester. A Fluke Model 8040A Multimeter was used to measure the two elements. The circuit-1 element read approximately 500 kilohms and the circuit-2 element read approximately 150 kilohms. (When the elements were removed from their thermowell, it was found to be full of water, see Figure 25.) RTD No. 2 readings were in the $1\text{-}4 \times 10^{7}$ ohm range with the IR tester, RTD No. 3 readings were in the $3\text{-}4 \times 10^{6}$ ohm range, and RTD No. 4 readings were in the $2\text{-}3 \times 10^{7}$ ohm range.

During inspection of the castings, RTD No. 2 was found to have a small hole through the body (Figure 26). Examination revealed that one of the tapped holes used for mounting the terminal board into the casting had a small break-through. Discoloration inside the casting indicated that water had leaked through this external hole into the tapped hole and then into the RTD body (Figure 27).

RTD No. 3 appeared to have a leak around the ground screw, in the cast body, as indicated by discoloration around the screw (Figures 28 and 29).

RTDs No. 2 and No. 3 were inspected with dye penetrant, but no definitive results could be obtained to show a leak through either casting. They were then x-rayed with the machine set to 240 kV. RTD No. 2 did not show a through hole on the x-ray negative because, in the region through which the exposure had to be made, too much metal was present for the small hole to show on the x-ray negative. However, after the non-destructive test methods failed to show the hole, a small pin was pushed into the hole from the outside of the body and the tip of the pin could be seen in the threaded hole inside the body, providing conclusive evidence that the tapped hole had broken through the casting. RTD No. 3, when x-rayed in the proper orientation, showed a small hole from outside going into a region of high porosity in the casting. The high porosity region was adjacent to the threaded ground-screw hole. It is reasonable to assume that this provided the leakage path for water, resulting in the discoloration around the ground screw and the moisture inside the RTD.

RTDs No. 1, No. 2, and No. 4 had leaked at the gasket (Figures 30 - 32). Before head-cap removal, a low-pressure air source (less than 4 psig) was held to the end of the flexible hose as it exited the chamber and Leak-Tec solution was applied to each RTD and cable system to determine the leak area. The areas found to be leaking by this test were those areas where discoloration occurred in the RTDs. RTD No. 1 had leaked very severely immediately upon admission of steam into the chamber. Leakage into RTD No. 4 was much less severe (see Figure 33).

The heat-shrinkable tubing and flexible metal conduit on RTDs No. 1, 2, and 4 was inspected and no evidence of leakage was found.

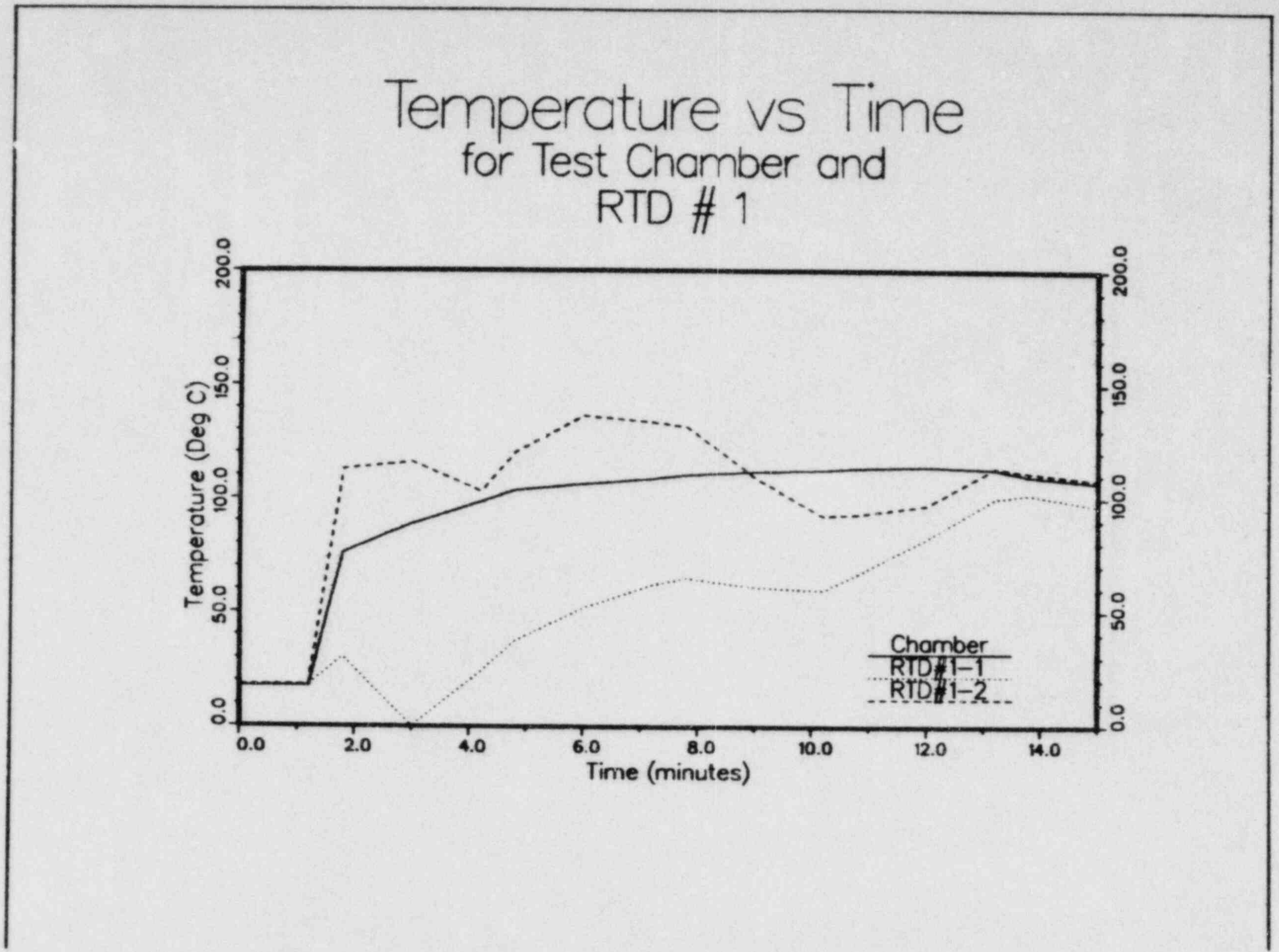


Figure 6. Test chamber and RTD #1 (circuit-1, and circuit-2) temperature profiles for the first 15 minutes of the LOCA test.

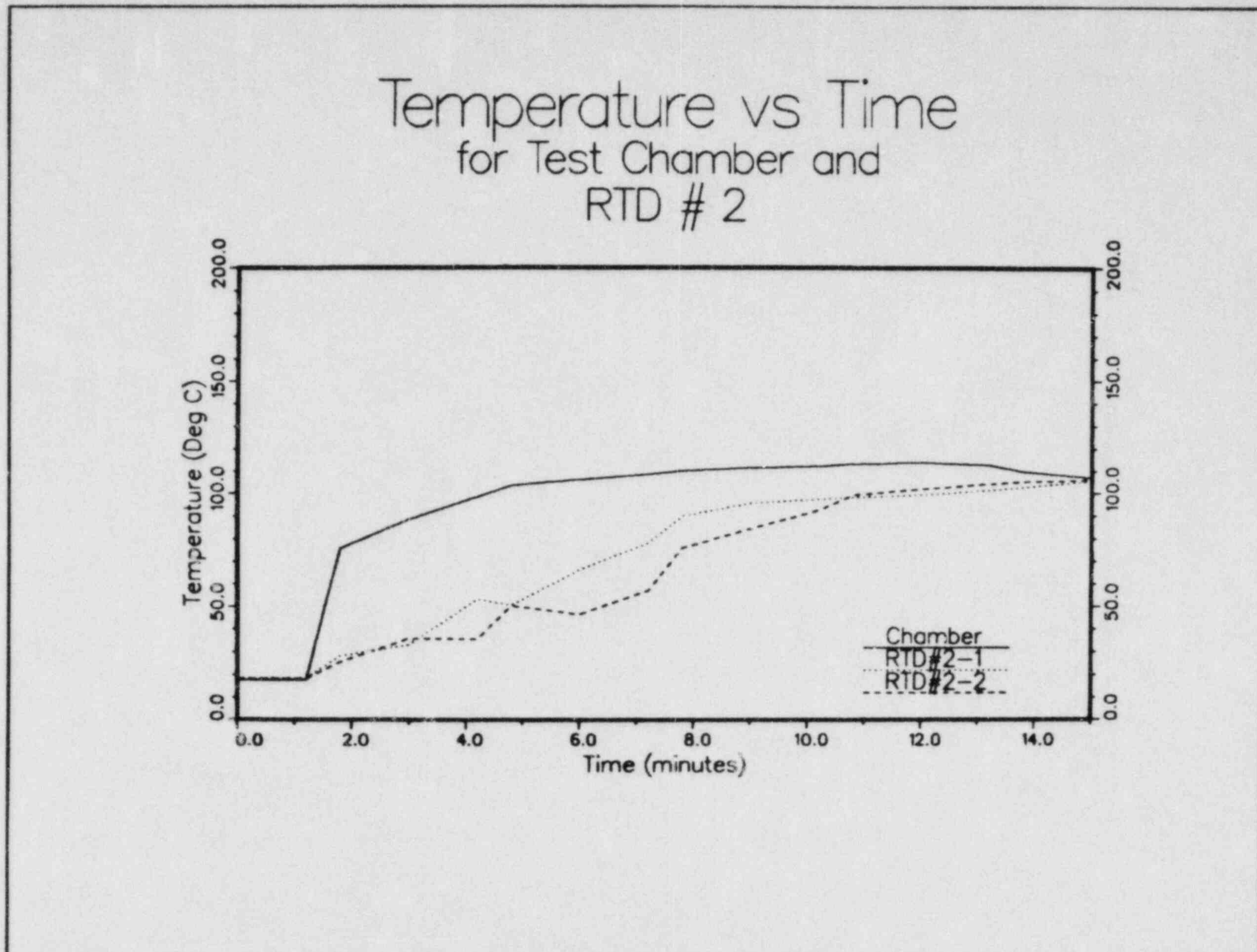


Figure 7. Test chamber and RTD #2 (circuit-1, and circuit-2) temperature profiles for the first 15 minutes of the LOCA test.

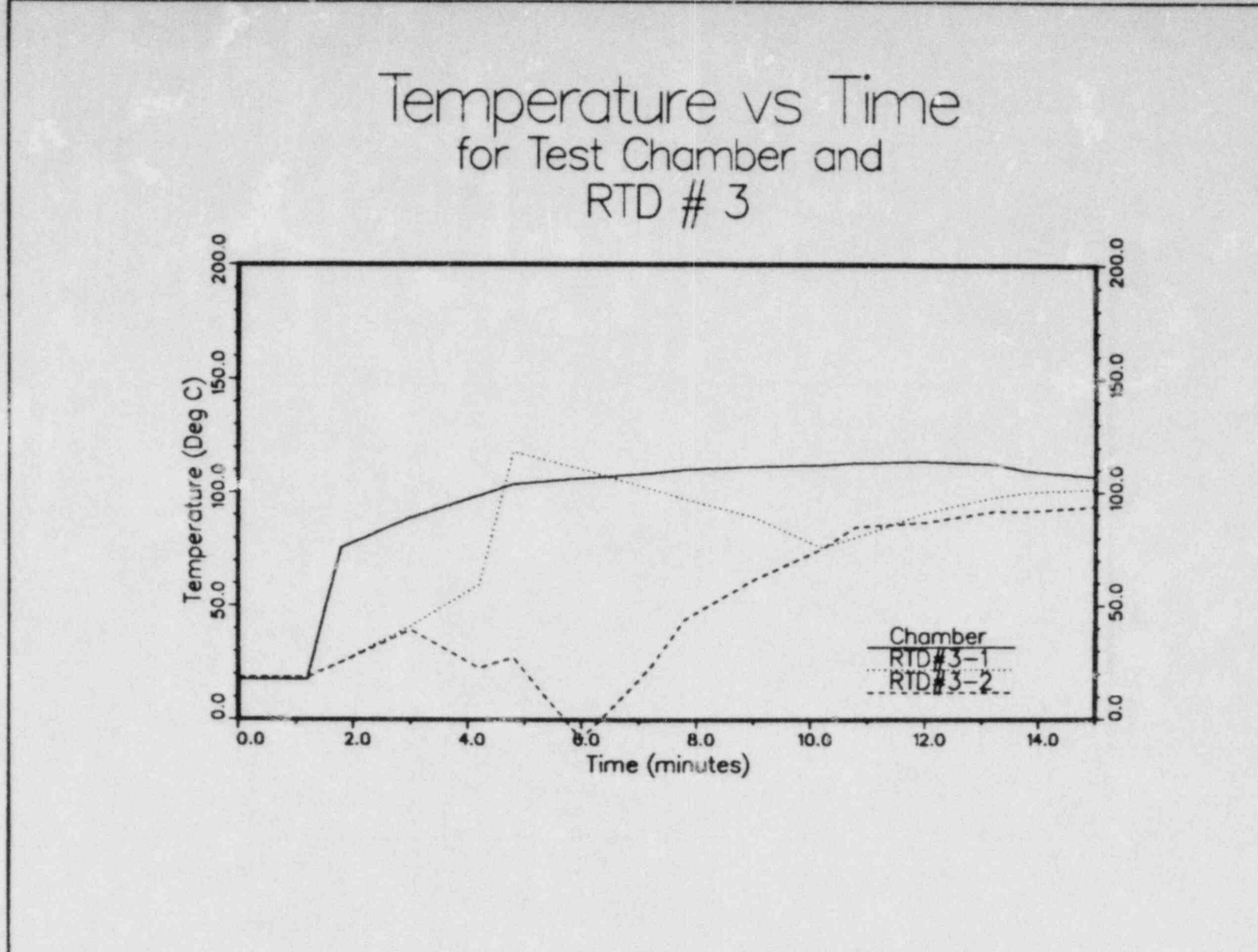


Figure 8. Test chamber and RTD #3 (circuit-1, and circuit-2) temperature profiles for the first 15 minutes of the LOCA test.

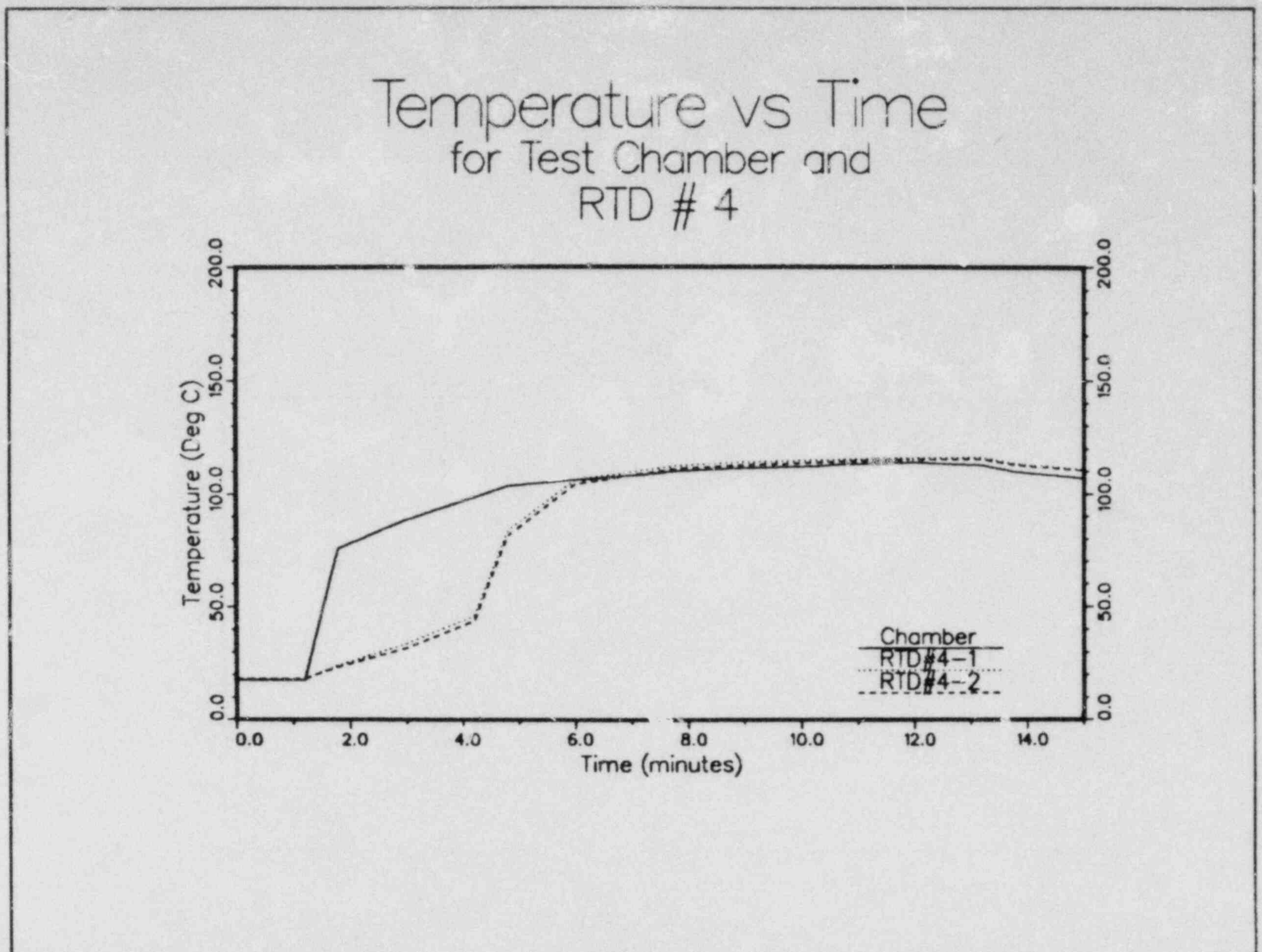


Figure 9. Test chamber and RTD #4 (circuit-1, and circuit-2) temperature profiles for the first 15 minutes of the LOCA test.

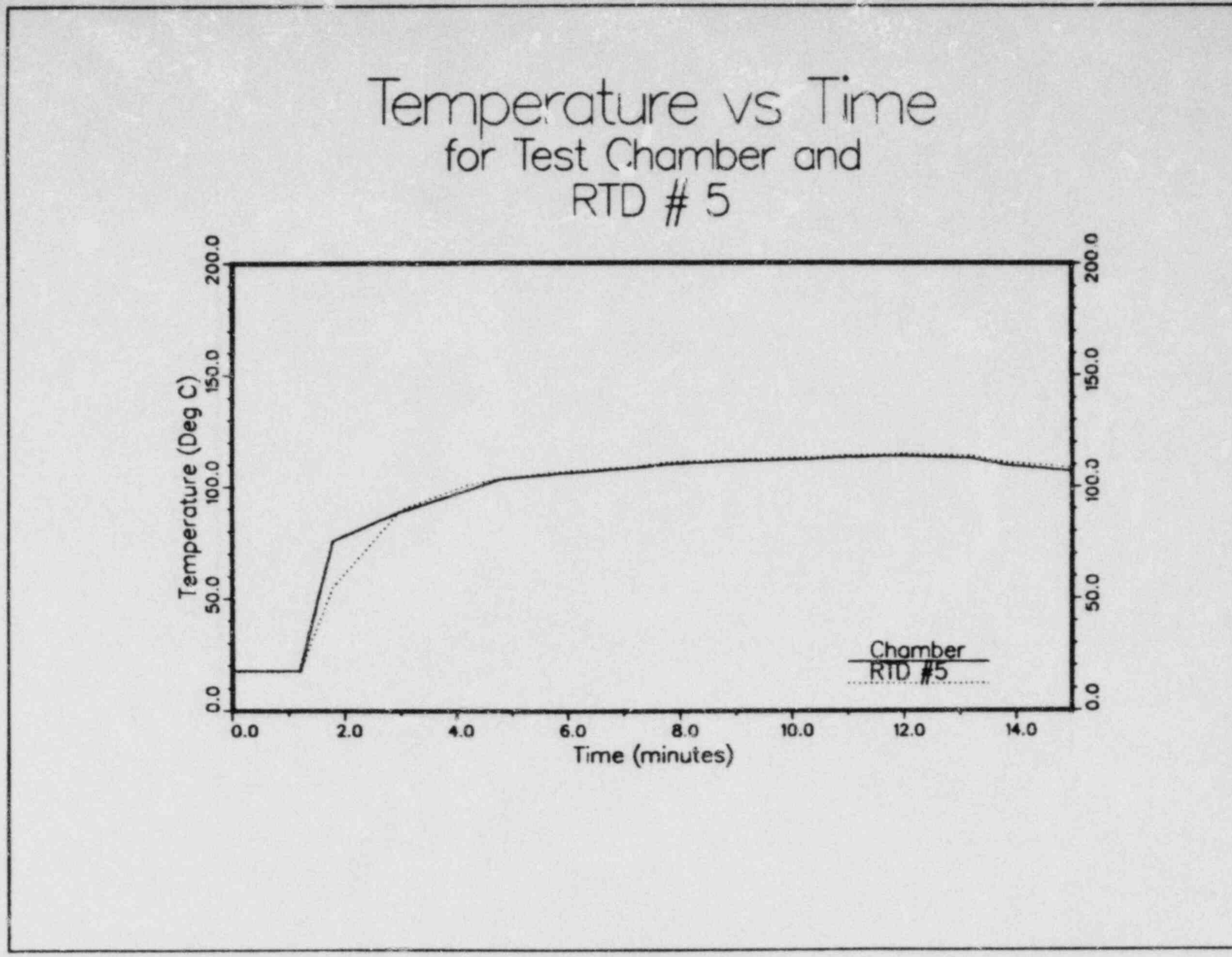


Figure 10. Test chamber and RTD #5 temperature profiles for the first 15 minutes of the LOCA test.

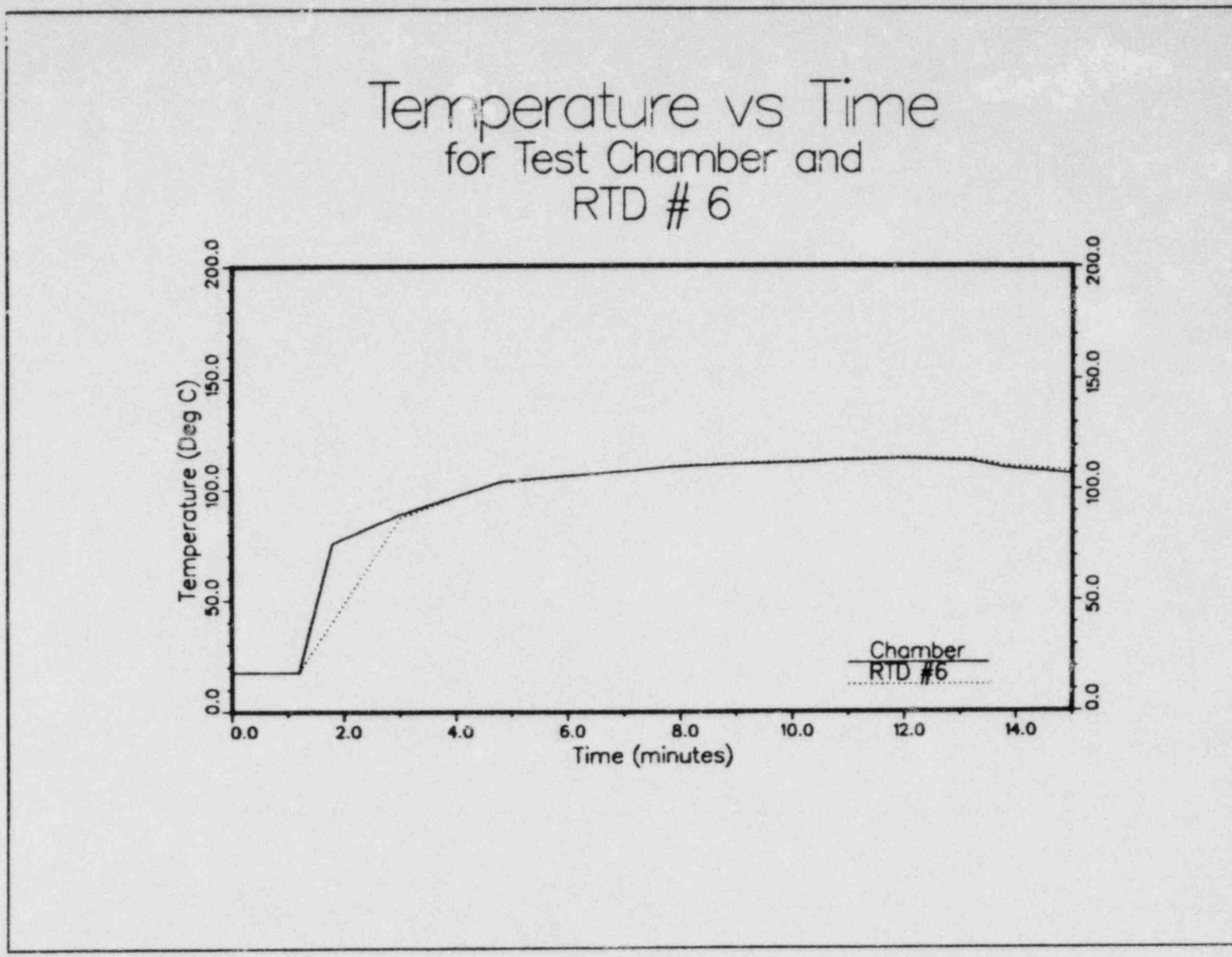


Figure 11. Test chamber and RTD #6 temperature profiles for the first 15 minutes of the LOCA test.

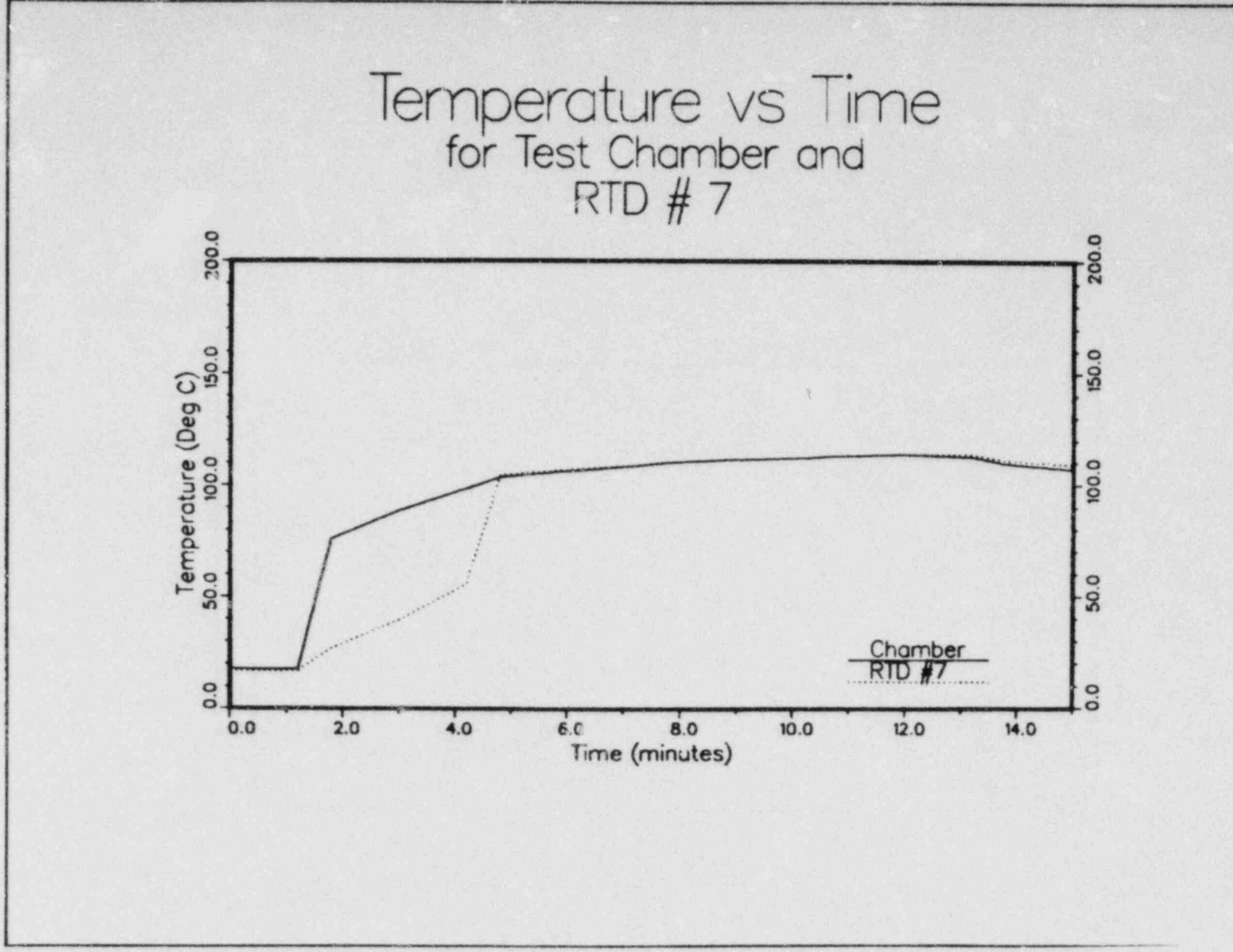


Figure 12. Test chamber and RTD #7 temperature profiles for the first 15 minutes of the LOCA test.

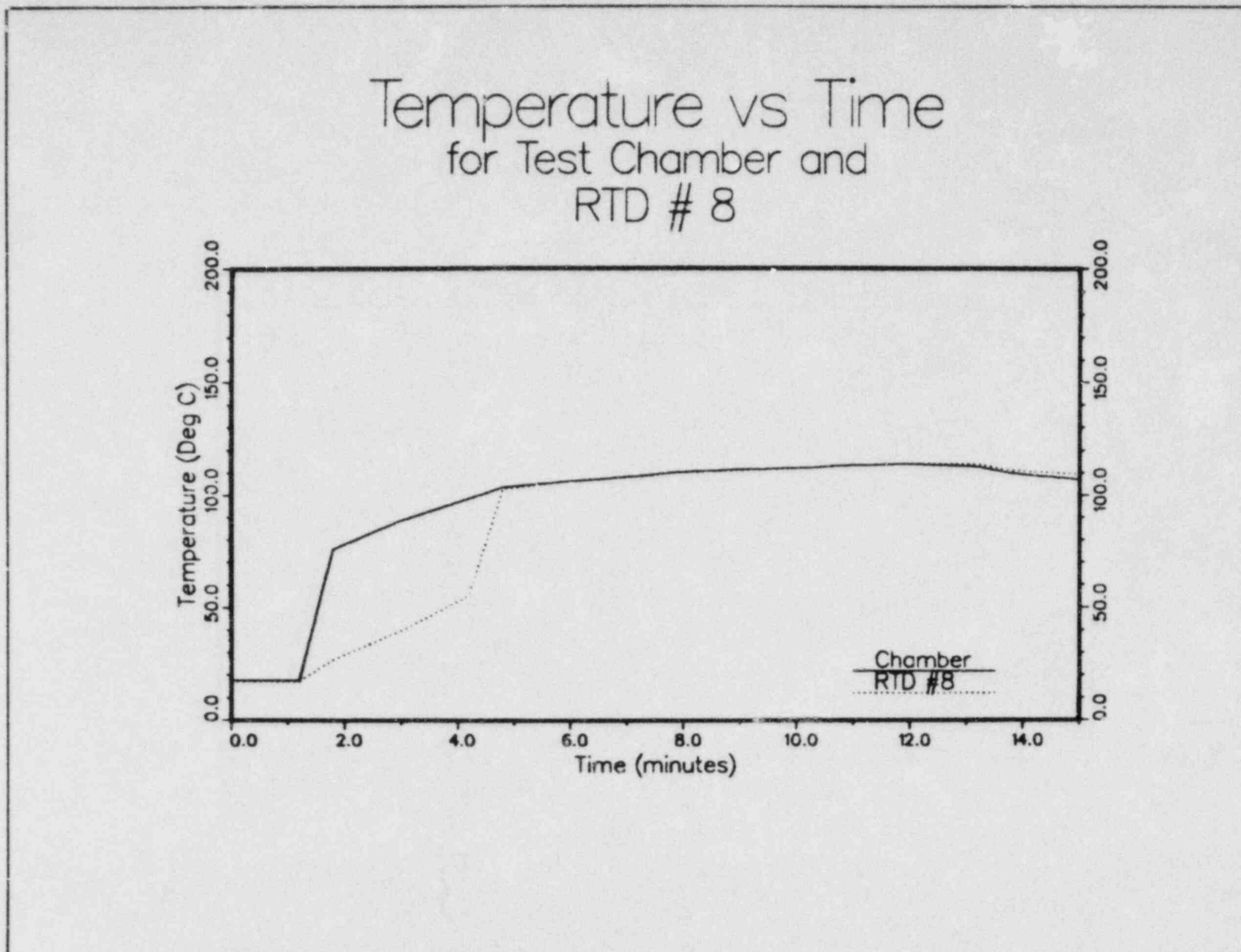


Figure 13. Test chamber and RTD #8 temperature profiles for the first 15 minutes of the LOCA test.

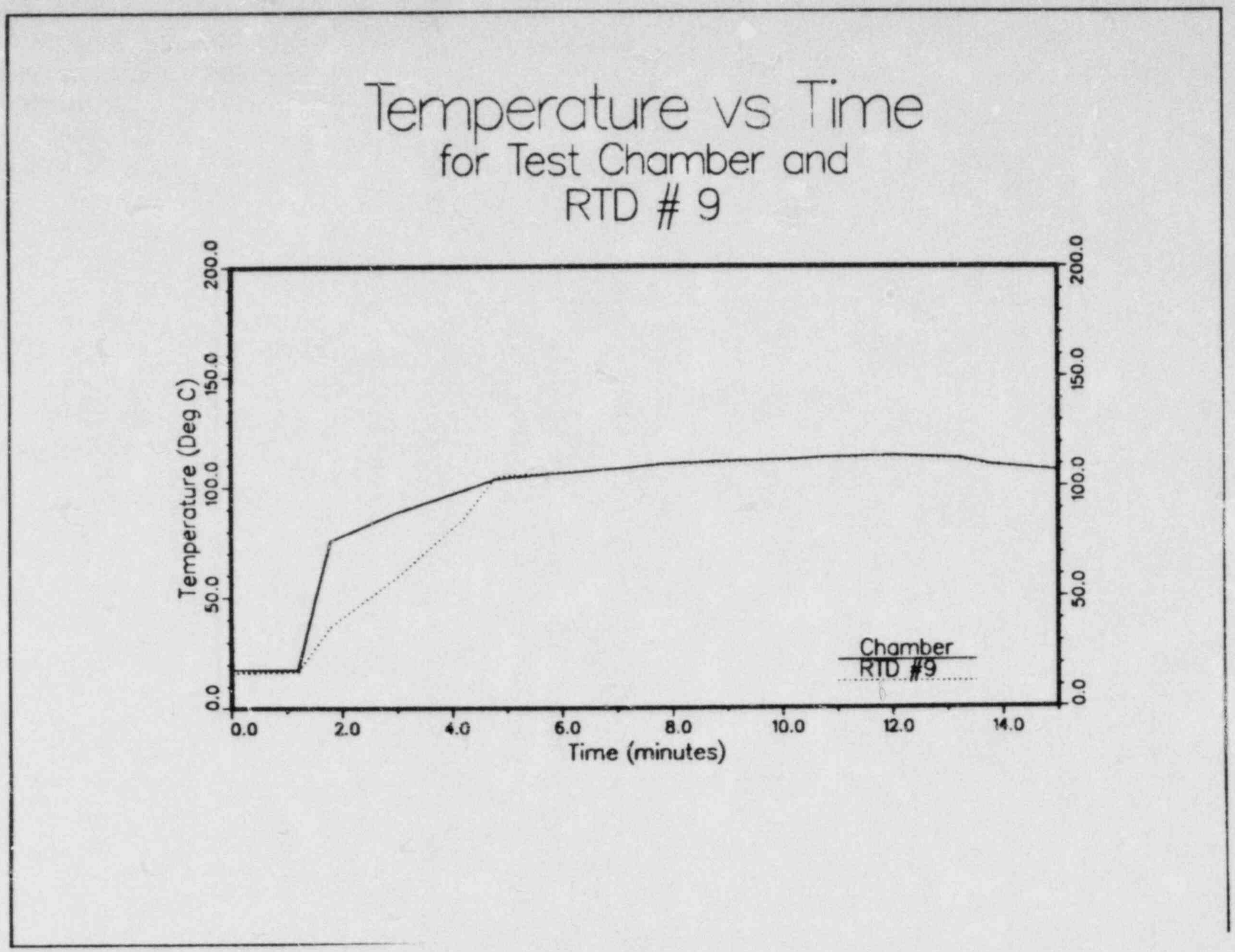


Figure 14. Test chamber and RTD #9 temperature profiles for the first 15 minutes of the LOCA test.

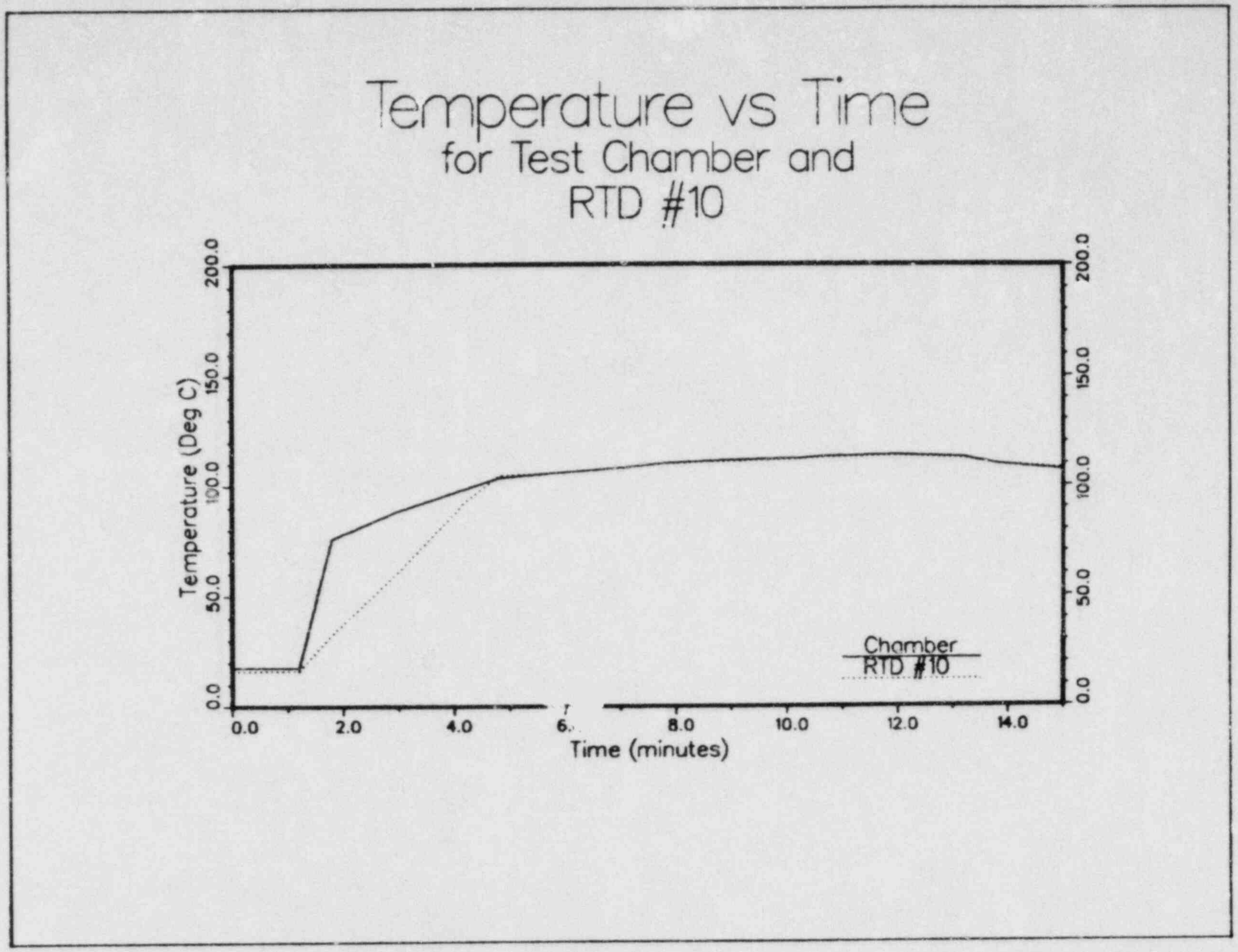


Figure 15. Test chamber and RTD #10 temperature profiles for the first 15 minutes of the LOCA test.

TABLE 3. Sequence of Significant Events

0830 Test begun

0831 Chamber pressure: 10.7 psig. RTD No. 1 measurements appeared slightly different than other Supplier A RTDs. Channel 1 read slightly low (17.9°C) and channel 2 read slightly high (21.5°C). Other Supplier A RTDs read from 18.3°C to 18.6°C. Steam was leaking from the chamber around the cable of No. 1.

0832 Chamber pressure: 14.6 psig. RTD No. 1, channel 1 read 16.8°C; channel 2 read 101.9°C. Other Supplier A RTDs read from 23.9°C to 29.0°C. Thermocouple in No. 1 head: 95.0°C.

0833 RTD No. 1, channel 1, read -53.2°C; channel 2 read 112.8°C. At this time, No. 3 appeared abnormal: channel 1 read 42.5°C; channel 2 read 15.2°C.

0834 RTD No. 1, channel 1, read 26.4°C; channel 2 read 103.7°C. No. 3, channel 1, read 49.7°C; channel 2 read 35.3°C. RTD No. 2 began to show abnormal readings at this time with channel 1 reading 61.4°C, channel 2 reading 22.6°C.

0835 No. 1, No. 2, and No. 3 continued to give abnormal readings. No. 4 continued normally. This situation continued to exist until the test was shut down to seal the steam leak around No. 1.

0843 Steam lines were closed and pressure was removed from the vessel.

0846 No. 1 leads were cut and the exit port was sealed.

0930 Test was restarted. No. 1 was no longer being monitored. No. 2, channel 1, read 70.2°C; channel 2 read 72.9°C. No. 3, channel 1, read 84.8°C; channel 2 read 77.9°C. Both channels of No. 4 read 91.4°C, which corresponded with the thermocouple readings throughout the chamber of 96.1°C in the steam inlet area to 86.2°C at the bottom portion of the chamber.

0931 Chamber temperature had risen to approximately 109°C and the pressure transducer indicated 14.8 psig. No. 4, channel 1, read 98.8°C; channel 2 read 98.7°C. No. 2 read 61.2°C and 61.6°C on channels 1 and 2, respectively. No. 3 read 71.6°C and 68.4°C on channels 1 and 2.

0932 Chamber temperature stabilized at about 108.5°C with a pressure of 14.8 psig. No. 4 read 107.8°C on both channels. No. 2 read 85.3°C and 88.3°C; No. 3 read 85.5°C and 80.8°C.

TABLE 3. Sequence of Significant Events (contd)

0933 Chamber temperature: 109°C; pressure: 15.4 psig. No. 4, channel 1, read 109.4°C; channel 2 read 109.2°C. No. 2 read 99.7°C and 103.1°C; No. 3 read 96.8°C and 93.9°C.

0934 No. 4, channel 1, 109.8°C, channel 2, 109.6°C. No 2: 105.3°C, 106.9°C. No. 3: 104.4°C, 102.5°C. Chamber temperature as monitored by thermocouples: approximately 109°C.

0935 No. 4, channel 1, 109.2°C; channel 2, 109.5°C. No. 2: 106.8°C, 107.5°C. No. 3: 106.7°C, 104.6°C.

0936 No. 4, channel 2, 106.1°C; channel 2, 109.4°C. Channel 1 had dropped 3°C in one minute, with chamber temperature remaining stable. This was the first apparent anomaly for No. 4.

0937 No. 2 now read 107.7°C and 108.0°C (very close to chamber thermocouples). No. 3, channel 1, read 107.8°C; channel 2 still read low (105.7°C). No. 4, channel 1, read 105.3°C (low); channel 2 read 109.1°C.

0938 No. 2: 108.3°C, 108.3°C; No. 3: 108.2°C, 106.0°C; No. 4: 106.9°C, 109.5°C.

0939 No. 2: 108.3°C, 108.2°C; No. 3: 108.1°C, 105.9°C; No. 4: 108.8°C, 109.4°C.

All Supplier A units remained relatively stable at the above levels until 1000.

1000 This was the time designated to raise the pressure to 25 psig. However, because of difficulty with a clogged steam trap, this step was postponed until 1020. Chamber temperature was about 107.4°C. At 1000, No. 2, channel 1, read 106.8°C; channel 2 read 107.2°C. No. 3, channel 1, read 107.2°C; channel 2 read 106.3°C. No. 4, channel 1, read 102.7°C; channel 2 read 104.3°C. Note that No. 4 now gave evidence of enough difference from the chamber temperature to suggest a steam leak.

1020 Pressure was increased to 25 psig. Temperature was rising accordingly. At 1020, chamber temperature was approximately 111°C. No. 2, channel 1, read 107.1°C; channel 2 read 107.9°C. No. 3, channel 1, 107.9°C; channel 2, 106.4°C. No. 4 channel 1, 104.4°C; channel 2, 104.8°C. When the chamber stabilized at about 121°C, all RTDs appeared to be reading at or near the correct temperature.

1045 Pressure was increased to 35 psig with a corresponding rise in temperature. All RTDs appeared to be functioning properly (i.e., reading correct temperatures).

TABLE 3. Sequence of Significant Events (contd)

1115 Pressure was increased to 45 psig. All RTDs were functioning normally.

1140 Pressure was increased to 55 psig. All RTDs were functioning properly.

1205 Pressure was increased to 65 psig. All RTDs ok.

1230 Pressure was increased to 75 psig. All RTDs ok.

1255 Pressure was increased to 85 psig. All RTDs ok.

1320 Pressure was increased to 95 psig. All RTDs ok.

1345 Pressure was increased to 105 psig. All RTDs ok.

1410 Pressure was increased to 115 psig. All RTDs ok.

1435 Pressure was reduced to 65 psig. All RTDs ok.

1500 Pressure was reduced to 15 psig. All RTDs ok.

1700 No. 2, channel 1, read 102.3°C; channel 2 read 118.2°C. Thermocouples read about 118.5°C. Evidently this unit had begun to leak again. About this time a small steam leak was observed around the No. 2 cable where it left the chamber. This steam leak continued for the remainder of the test.

Channel 1 of No. 2 continued to read low for the remainder of the test. Channel 2 remained at or near the correct temperature.

2200 No. 3, channel 2, read 116.7°C (about 2°C low). Channel 1 of No. 2 was still low at 105.9°C.

2230 No. 3, channel 2, read 114.4°C. This condition persisted throughout the test.

0100 Both channels of No. 3 were low with channel 1 reading 115.0°C and channel 2 reading 114.4°C. The chamber temperature was approximately 118.5°C. This RTD continued to read low throughou t the remainder of the test.

0930 Pressure was reduced to zero (i.e., steam was shut off) and chemical spray was turned off. Channel 2 of No. 2 was still indicating properly and both channels of No. 4 were still indicating properly. Channel 1 of No. 2 and both channels of No. 3 were giving false readings.

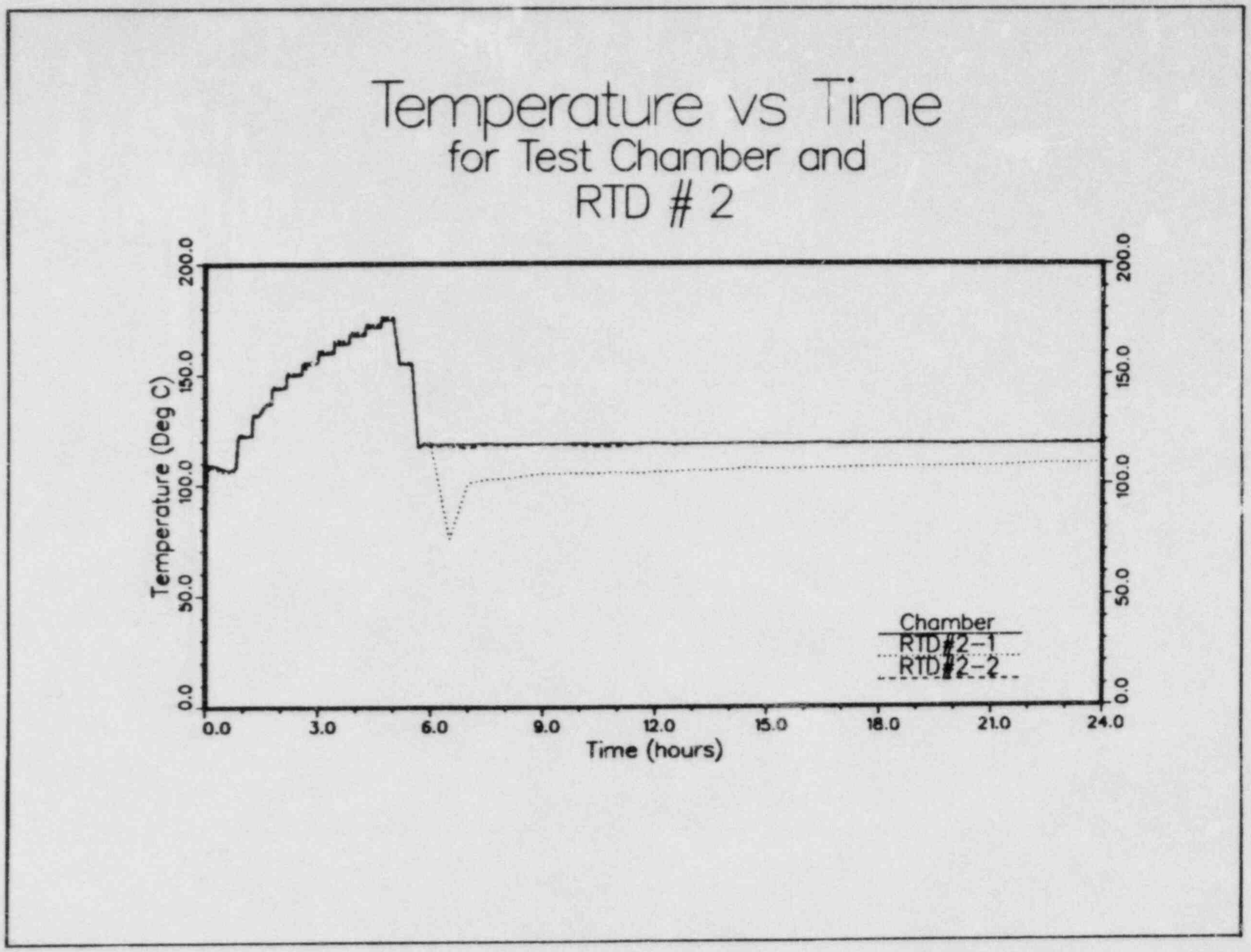


Figure 16. Comparison of test chamber and RTD #2 (circuit-1, and circuit-2) temperature profiles during the 24-hour LOCA test.

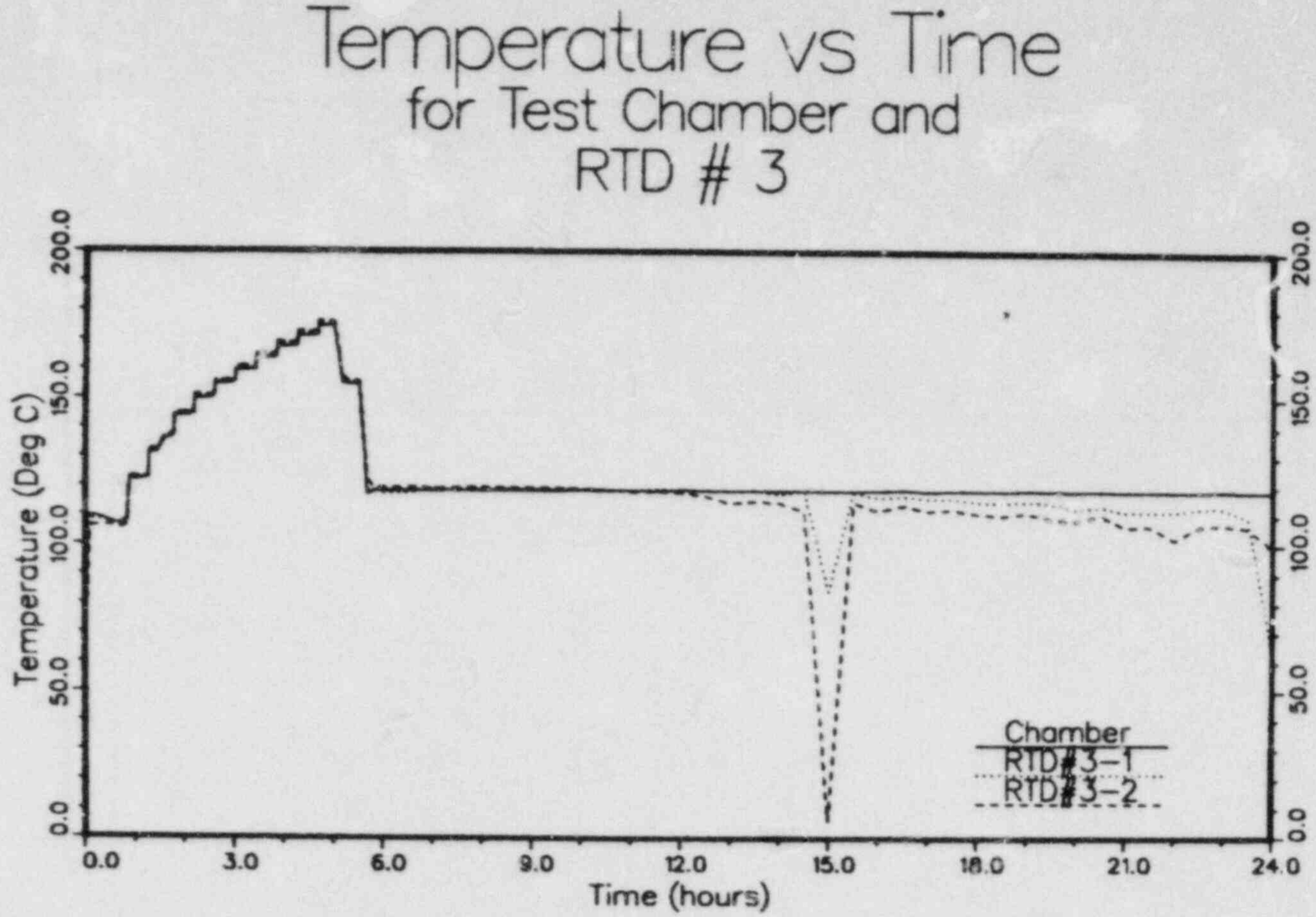


Figure 17. Comparison of test chamber and RTD #3 (circuit-1, and circuit-2) temperature profiles during the 24-hour LOCA test.

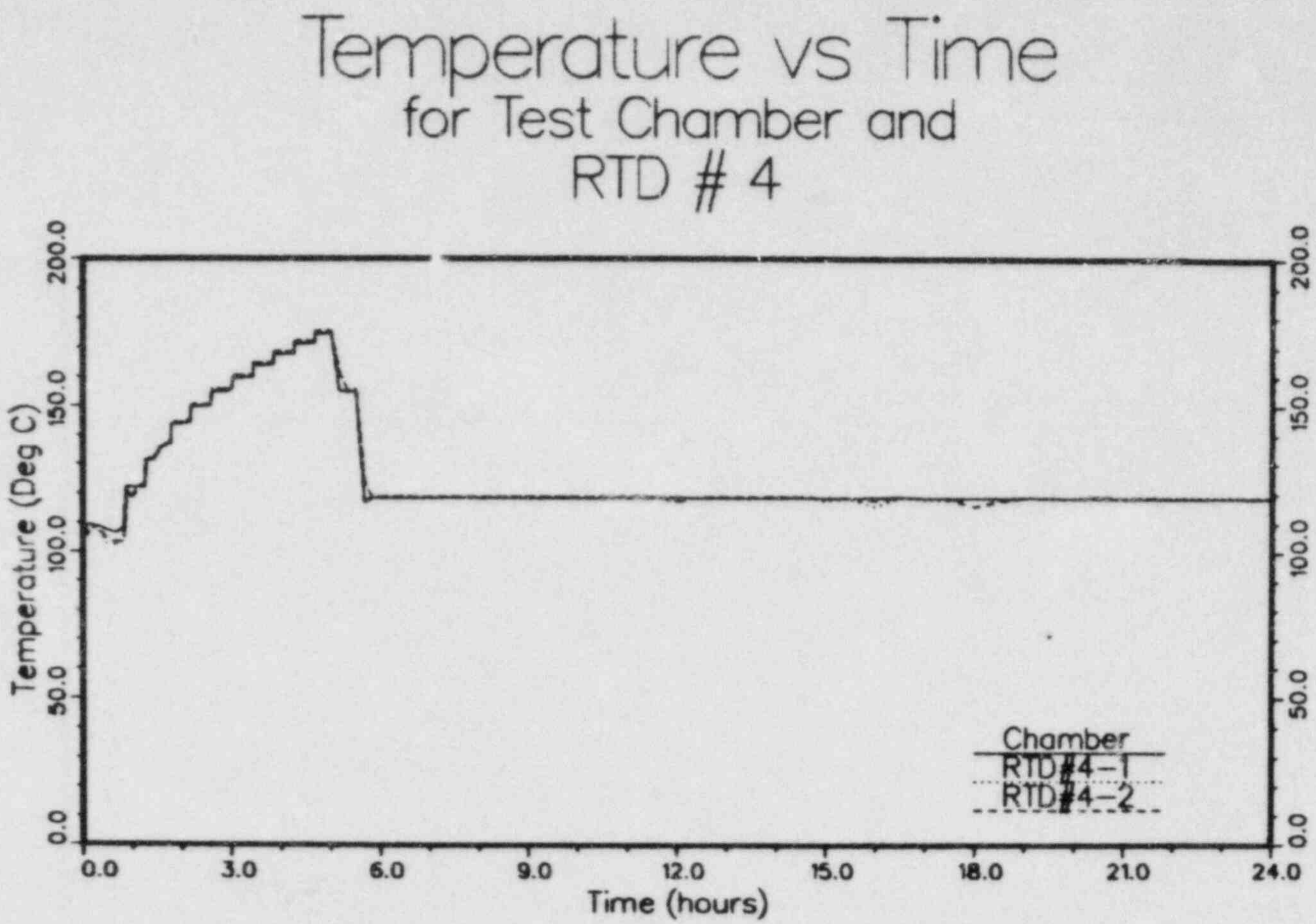


Figure 18. Comparison of test chamber and RTD #4 (circuit-1, and circuit-2) temperature profiles during the 24-hour LOCA test.

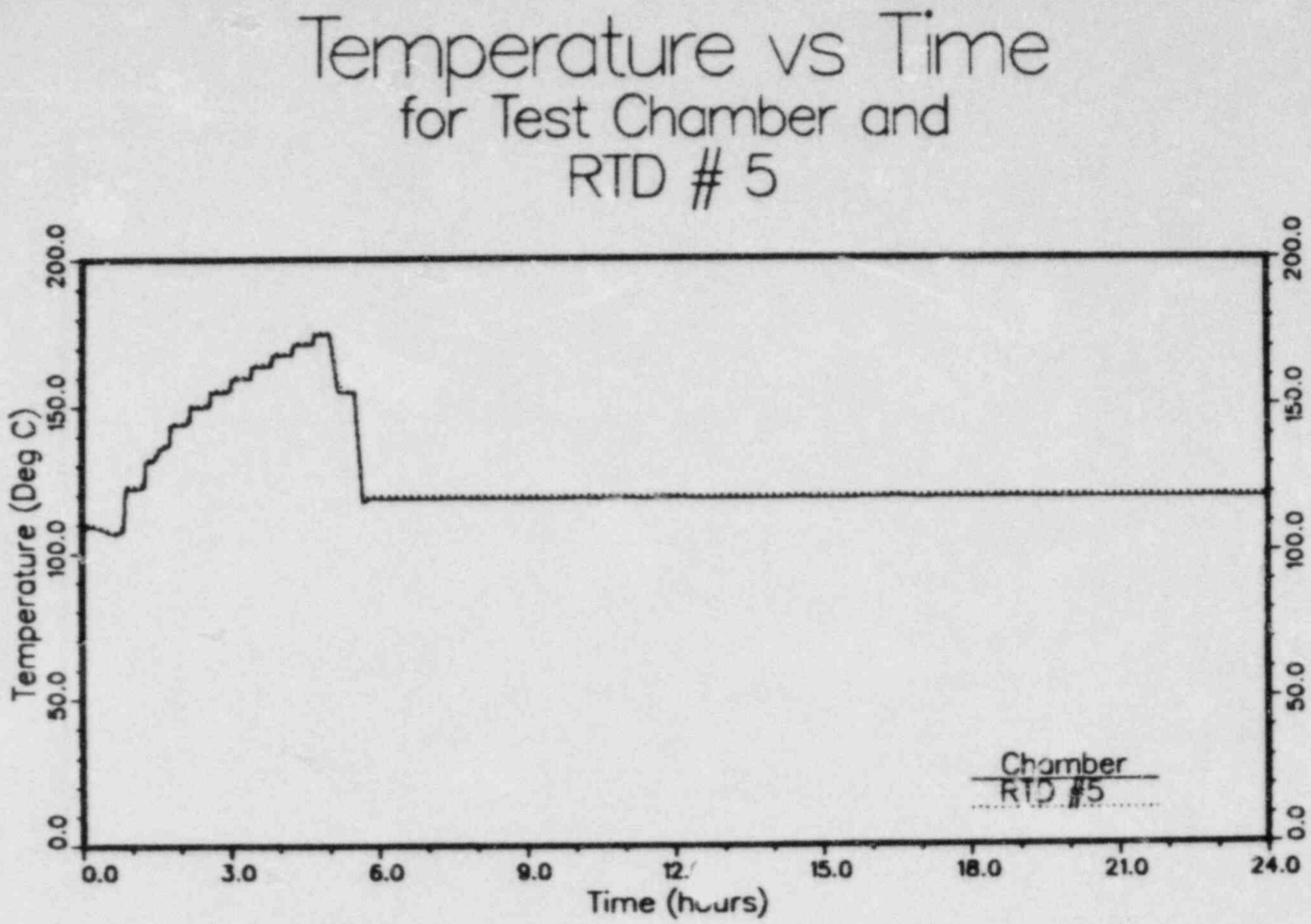


Figure 19. Comparison of test chamber and RTD #5 temperature profiles during the 24-hour LOCA test.

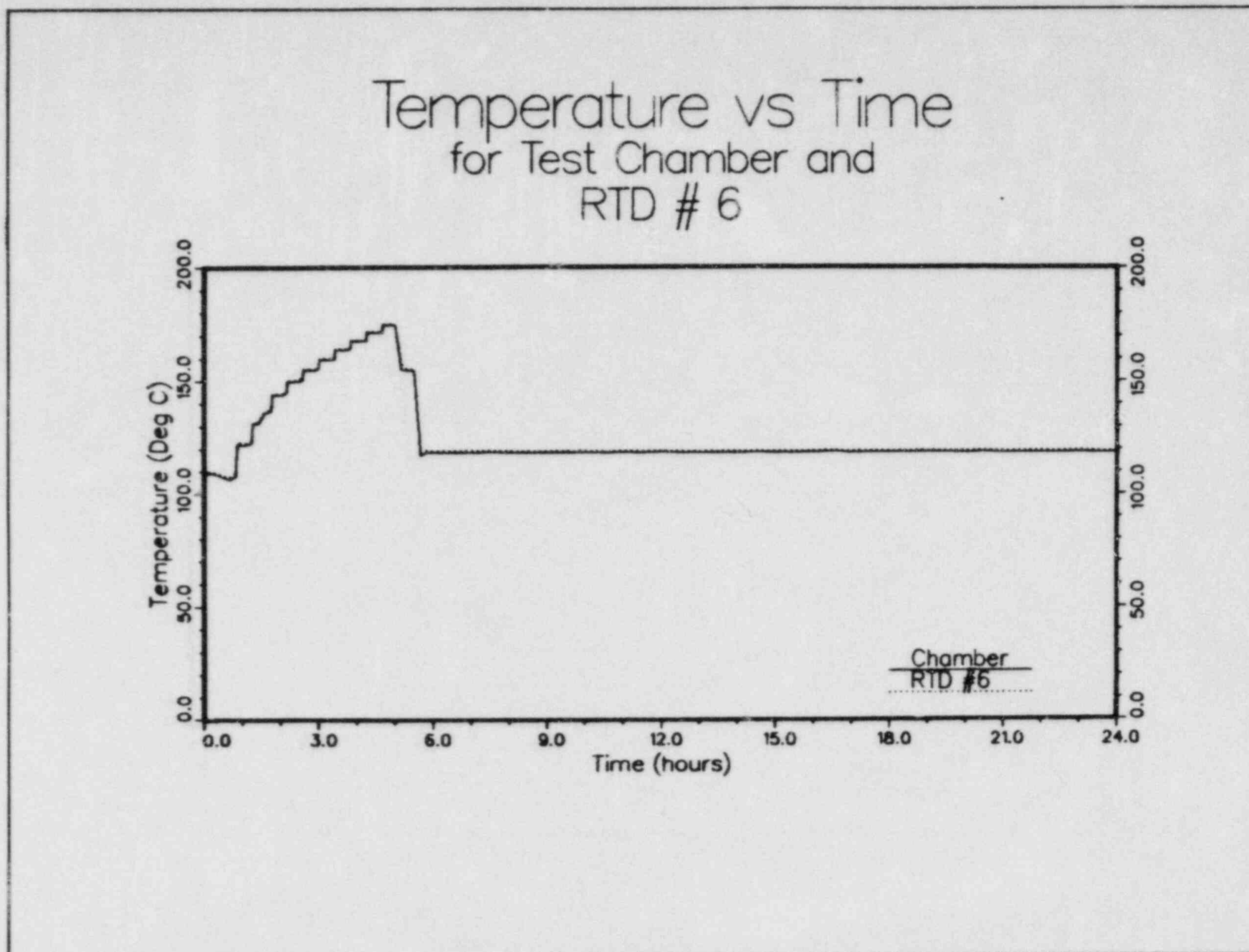


Figure 20. Comparison of test chamber and RTD #6 temperature profiles during the 24-hour LOCA test.

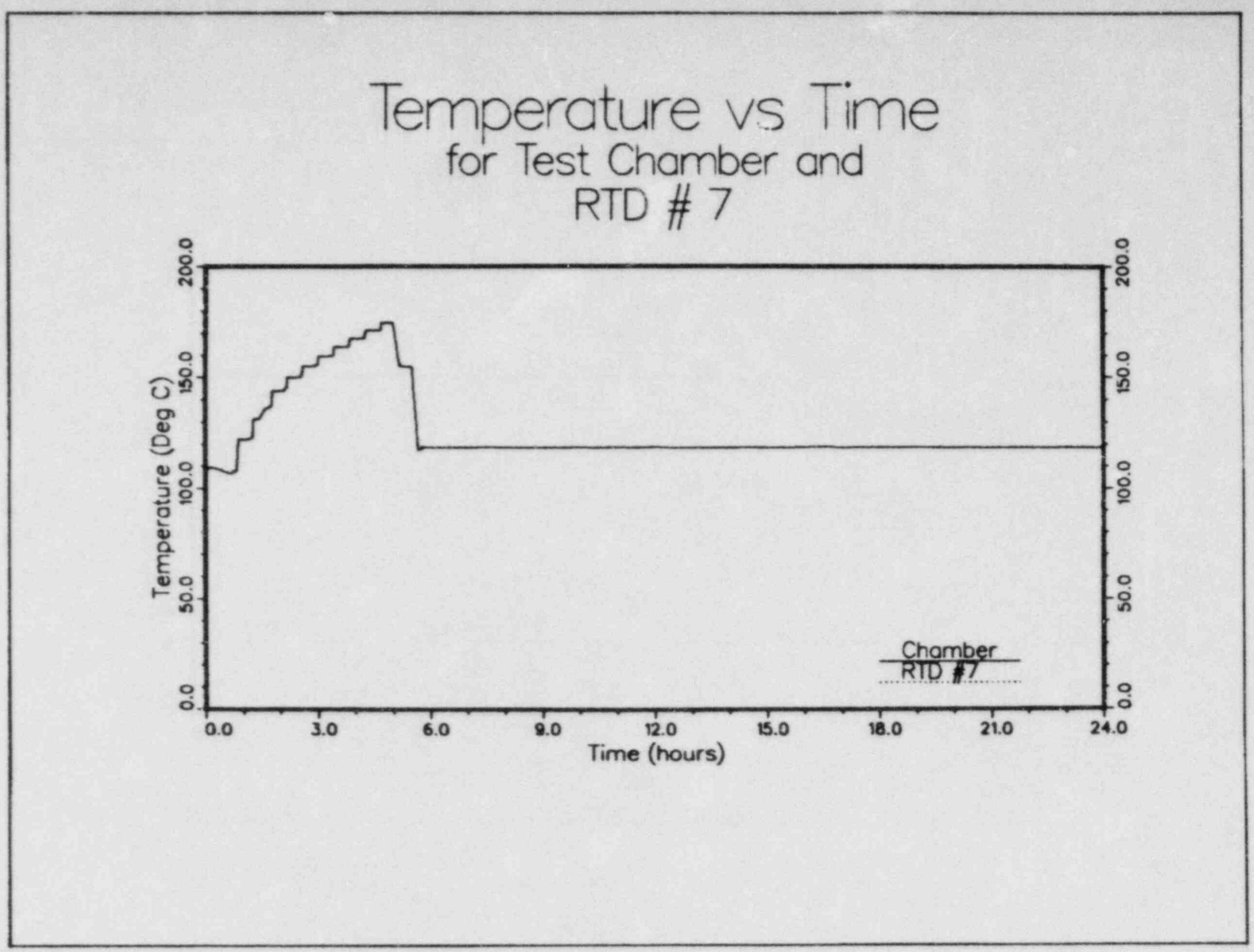


Figure 21. Comparison of test chamber and RTD #7 temperature profiles during the 24-hour LOCA test.

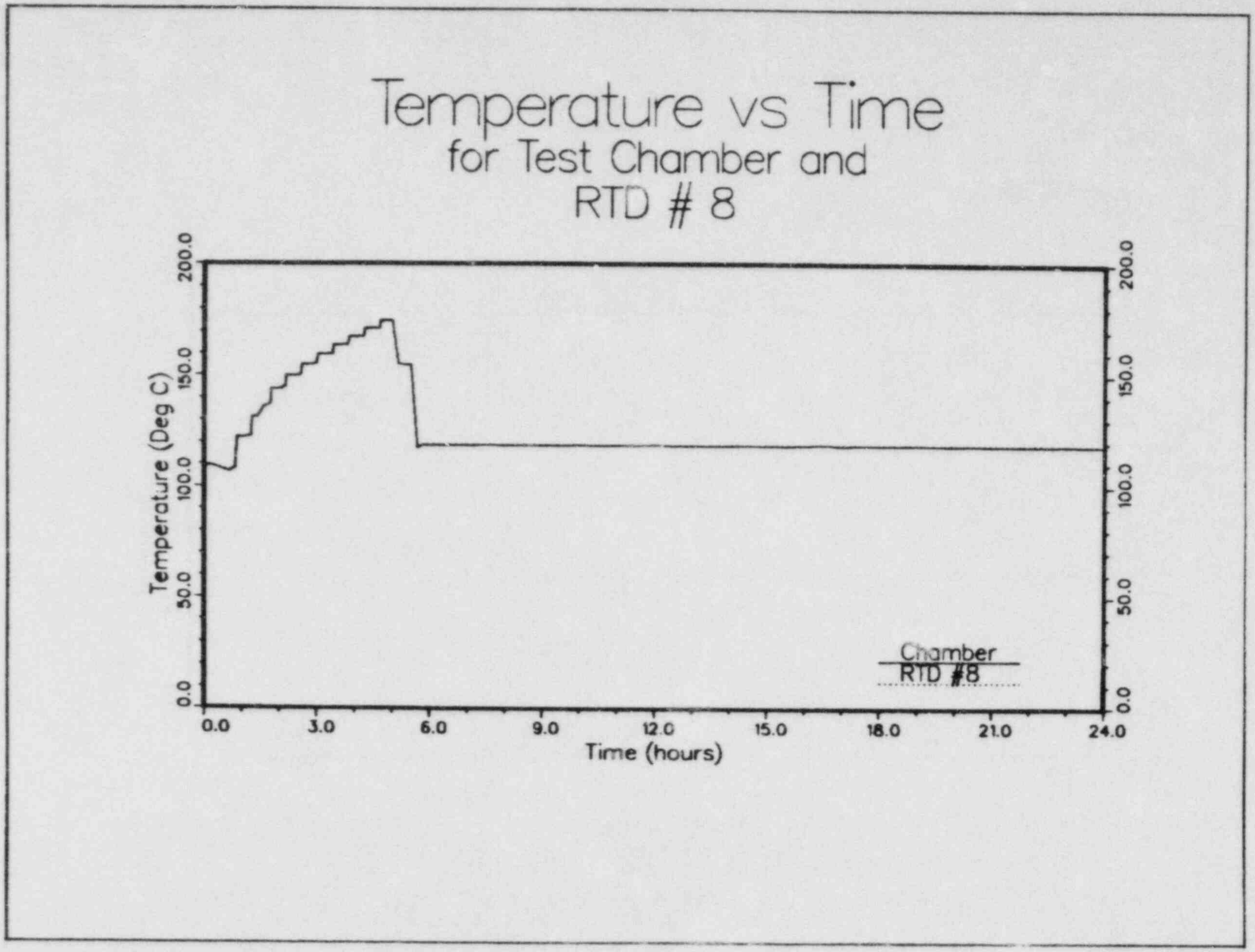


Figure 22. Comparison of test chamber and RTD #8 temperature profiles during the 24-hour LOCA test.

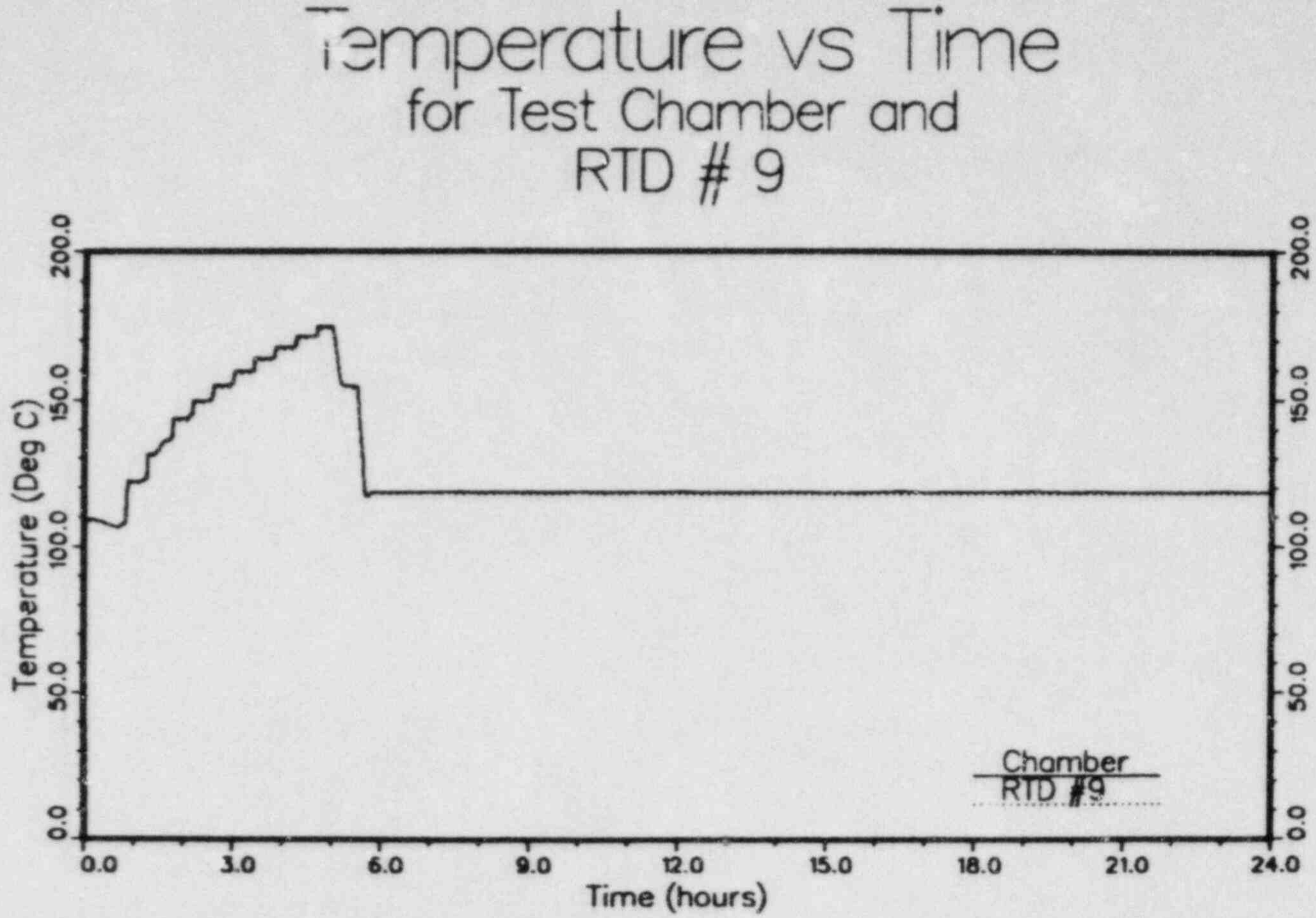


Figure 23. Comparison of test chamber and RTD #9 temperature profiles during the 24-hour LOCA test.

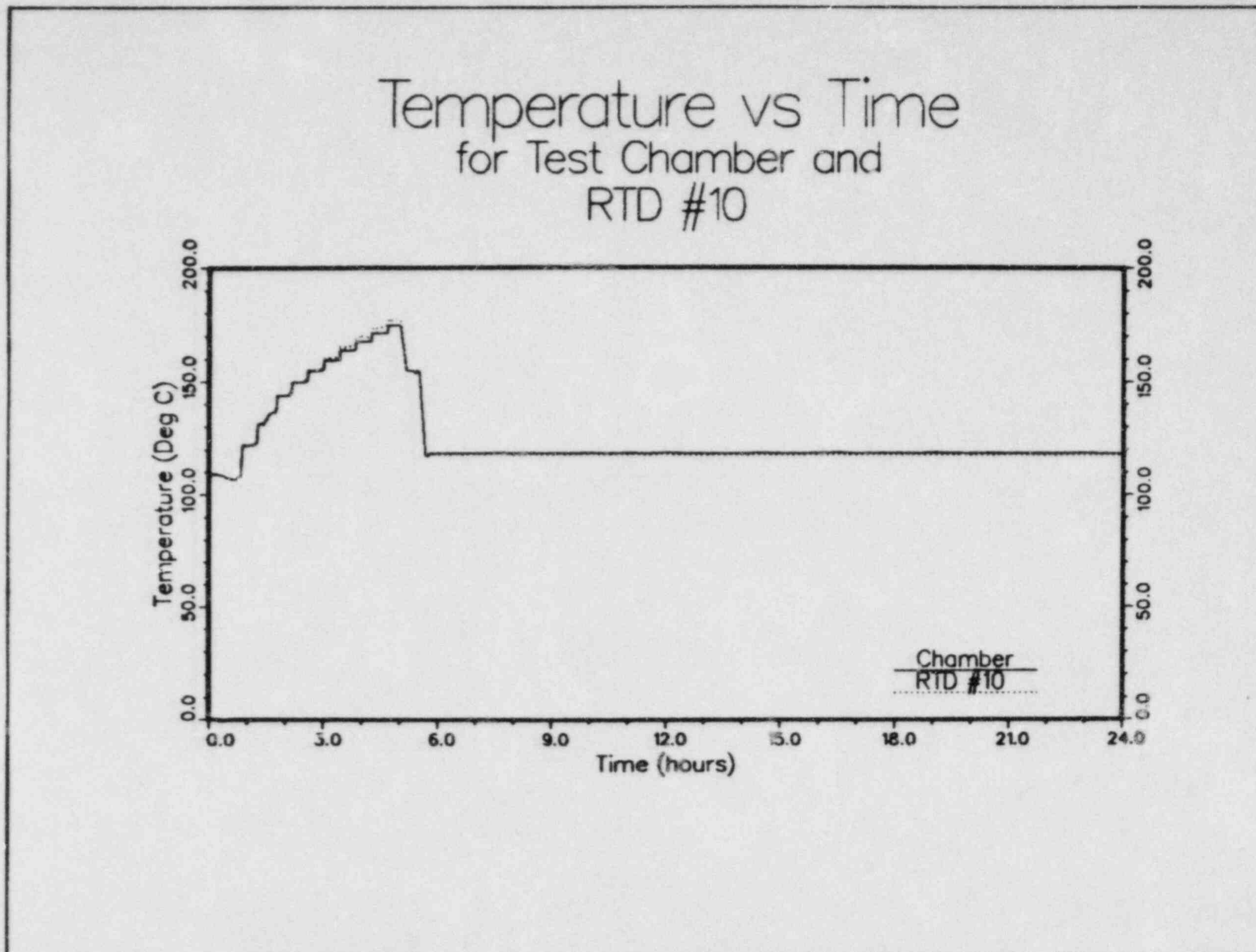


Figure 24. Comparison of test chamber and RTD #10 temperature profiles during the 24-hour LOCA test.

TABLE 4. RTDs Which Deviated from Average Chamber Temperature By More Than 5°C During Steady-State Conditions

TIME (hr)	TC TEMP (°C)	RTD TEMP (°C)	DELTA T	RTD ID
6.50	118.4	75.6	42.8	RTD #2-1
7.00	118.5	100.7	17.8	RTD #2-1
7.50	118.6	102.3	16.3	RTD #2-1
8.00	118.4	102.8	15.6	RTD #2-1
8.50	118.5	103.8	14.7	RTD #2-1
9.00	118.5	105.0	13.5	RTD #2-1
9.50	118.5	104.8	13.7	RTD #2-1
10.00	118.6	105.2	13.4	RTD #2-1
10.50	118.5	105.0	13.5	RTD #2-1
11.00	118.6	105.5	13.1	RTD #2-1
11.50	118.5	104.9	13.6	RTD #2-1
12.00	118.7	105.7	13.0	RTD #2-1
12.50	118.5	105.9	12.6	RTD #2-1
13.00	118.5	106.4	12.1	RTD #2-1
13.50	118.5	106.3	12.2	RTD #2-1
14.00	118.5	106.7	11.8	RTD #2-1
14.50	118.6	107.6	11.0	RTD #2-1
"		111.5	7.1	RTD #3-2
15.00	118.5	107.1	11.4	RTD #2-1
"	"	84.2	34.3	RTD #3-1
"	"	5.9	112.6	RTD #3-2
15.50	118.5	107.1	11.4	RTD #2-1
16.00	118.6	107.1	11.5	RTD #2-1
"	"	111.7	6.9	RTD #3-2

TABLE 4. Continued

TIME (hr)	TC TEMP (°C)	RTD TEMP (°C)	DELTA T	RTD ID
16.50	118.8	107.6	11.2	RTD #2-1
"	"	113.6	5.2	RTD #3-2
17.00	118.5	107.6	10.9	RTD #2-1
"	"	111.7	6.8	RTD #3-2
17.50	118.6	108.0	10.6	RTD #2-1
"	"	112.1	6.5	RTD #3-2
18.00	118.6	108.0	10.6	RTD #2-1
"	"	110.8	7.8	RTD #3-2
18.50	118.6	108.0	10.6	RTD #2-1
"	"	110.2	8.4	RTD #3-2
19.00	118.7	108.3	10.4	RTD #2-1
"	"	111.2	7.5	RTD #3-2
19.50	118.6	108.3	10.3	RTD #2-1
"	"	109.1	9.5	RTD #3-2
20.00	118.5	108.2	10.3	RTD #2-1
"	"	112.4	6.1	RTD #3-1
"	"	108.4	10.1	RTD #3-2
20.50	118.6	108.5	10.1	RTD #2-1
"	"	113.3	5.3	RTD #3-1
"	"	110.4	8.2	RTD #3-2
21.00	118.5	108.3	10.2	RTD #2-1
"	"	111.6	6.9	RTD #3-1
"	"	106.3	12.2	RTD #3-2
21.50	118.5	108.5	10.0	RTD #2-1
"	"	111.6	6.9	RTD #3-1
"	"	106.6	11.9	RTD #3-2
22.00	118.5	109.1	9.4	RTD #2-1
"	"	111.6	6.9	RTD #3-1
"	"	102.0	16.5	RTD #3-2
22.50	118.5	109.4	9.1	RTD #2-1
"	"	112.8	5.7	RTD #3-1
"	"	106.5	12.0	RTD #3-2

TABLE 4. Continued

TIME (hr)	TC TEMP (°C)	RTD TEMP (°C)	DELTA T	RTD ID
23.00	118.6	109.5	9.1	RTD #2-1
"	"	112.8	5.8	RTD #3-1
"	"	107.1	11.5	RTD #3-2
23.50	118.5	109.5	9.0	RTD #2-1
"	"	109.4	9.1	RTD #3-1
"	"	106.2	12.3	RTD #3-2
24.00	118.4	109.7	8.7	RTD #2-1
"	"	63.8	54.6	RTD #3-1
"	"	99.4	19.0	RTD #3-2

TABLE 5. Dual-element RTDs Where One Circuit Output Deviated from the Other Circuit Output By More Than 3°C During Steady-State Conditions.

TIME (hr)	CKT-1 (°C)	CKT-2 (°C)	DELTA T	RTD ID
6.50	75.6	117.7	42.1	RTD #2
7.00	100.7	116.7	16.0	RTD #2
7.50	102.3	118.3	16.0	RTD #2
8.00	102.8	117.8	15.0	RTD #2
8.50	103.8	118.2	14.4	RTD #2
9.00	105.0	118.3	13.3	RTD #2
9.50	104.8	118.3	13.5	RTD #2
10.00	105.2	117.8	12.6	RTD #2
10.50	105.0	117.4	12.4	RTD #2
11.00	105.5	117.4	11.9	RTD #2
11.50	104.9	118.3	13.4	RTD #2
12.00	105.7	118.6	12.9	RTD #2
12.50	105.9	117.9	12.0	RTD #2
13.00	106.4	118.4	12.0	RTD #2
"	118.5	114.2	-4.3	RTD #3
13.50	106.3	118.4	12.1	RTD #2
"	118.7	115.0	-3.7	RTD #3
14.00	106.7	118.6	11.9	RTD #2
14.50	107.6	118.7	11.1	RTD #2
"	118.6	111.5	-7.1	RTD #3
15.00	107.1	118.7	11.6	RTD #2
"	84.2	5.9	-78.3	RTD #3
15.50	107.1	118.6	11.5	RTD #2
"	117.9	114.5	-3.4	RTD #3

TABLE 5. Continued

TIME (hr)	CKT-1 (°C)	CKT-2 (°C)	DELTA T	RTD ID
16.00	107.1	118.7	11.6	RTD #2
"	116.3	111.7	-4.6	RTD #3
16.50	107.6	118.8	11.2	RTD #2
"	116.8	113.6	-3.2	RTD #3
17.00	107.6	118.8	11.2	RTD #2
"	116.0	111.7	-4.3	RTD #3
17.50	108.0	118.9	10.9	RTD #2
"	116.0	112.1	-3.9	RTD #3
18.00	108.0	118.7	10.7	RTD # 2
"	114.9	110.8	-4.1	RTD # 3
18.50	108.0	118.8	10.8	RTD # 2
"	114.6	110.2	-4.4	RTD # 3
19.00	108.3	118.9	10.6	RTD # 2
"	115.1	111.2	-3.9	RTD # 3
19.50	108.3	118.7	10.4	RTD # 2
"	114.5	109.1	-5.4	RTD # 3
20.00	108.2	118.1	9.9	RTD # 2
"	112.4	108.4	-4.0	RTD # 3
20.50	108.5	118.6	10.1	RTD # 2
21.00	108.3	118.5	10.2	RTD # 2
"	111.6	106.3	-5.3	RTD # 3
21.50	108.5	118.6	10.1	RTD # 2
"	111.6	106.6	-5.0	RTD # 3
22.00	109.1	118.7	9.6	RTD # 2
"	111.6	102.0	-9.6	RTD # 3
22.50	109.4	118.6	9.2	RTD # 2
"	112.8	106.5	-6.3	RTD # 3
23 00	109.5	119.0	9.5	RTD # 2
"	112.8	107.1	-5.7	RTD # 3
23.50	109.5	119.0	9.5	RTD # 2
"	109.4	106.2	-3.2	RTD # 3
24.00	109.7	119.0	9.3	RTD # 2
"	63.8	99.4	35.6	RTD # 3

TABLE 6. Post-test Functional Results*

RTD NO.	ICE BATH TC** Output	ICE BATH RTD Output	ICE BATH $T_{RTD}-T_{TC}$	HOT WATER BATH TC** Output	HOT WATER BATH RTD Output	HOT WATER BATH $T_{RTD}-T_{TC}$
1	23.0	-152.6	175.6			
2-1	-0.1	0.5	0.6	50.7	51.1	0.4
2-2	-0.1	0.8	0.9	50.7	51.6	0.9
3				47.0	-12.3	-59.3
4-1	0.0	1.1	1.1	47.5	48.2	0.7
4-2	0.0	1.1	1.1	47.5	48.0	0.5
5	0.6	-0.2	-0.8	49.4	49.9	0.5
6	0.6	0.0	-0.6	47.1	49.6	2.5
7	2.8	2.0	-0.8	46.6	46.6	0.0
8	1.6	1.2	-0.4	45.9	44.3	-1.6
9	-0.1	-1.7	-1.6	50.6	50.1	-0.5
10	0.5	-1.3	-1.8	50.7	50.6	-0.1

* All values in degrees Celsius
** Thermocouple

TABLE 7. Post-test Insulation Resistance Measurements Made on External Cable Leads.*

RTD No.	Lead ID	Insulation Resistance
1-1	A	<100
"	B	"
"	C	"
"	D	"
1-2	A	<100
"	B	"
"	C	"
"	D	"
2-1	A	$1.7x10^4$
"	B	$1.7x10^4$
"	C	$1.5x10^4$
"	D	$1.5x10^4$
2-2	A	$1.5x10^7$
"	B	1.7 "
"	C	2.0 "
"	D	2.4 "
3-1	A	$<0.5x10^6$
"	B	"
"	C	"
"	D	"
3-2	A	1000
"	B	1100
"	C	1150
"	D	2000
4-1	A	$0.85x10^6$
"	B	0.95 "
"	C	1.15 "
"	D	1.10 "
4-2	A	$0.67x10^6$
"	B	0.61 "
"	C	0.75 "
"	D	0.75 "

* All Insulation Resistance values in ohms.

TABLE 7. Continued

RTD No.	Lead ID	Insulation Resistance
5	A	2.6×10^{11}
"	B	52. "
"	C	50. "
"	D	70. "
6	A	3.0×10^{12}
"	B	4.0 "
"	C	5.0 "
"	D	5.0 "
7	A	3.6×10^{10}
"	B	4.2 "
"	C	4.0 "
"	D	4.5 "
8	A	5.0×10^{11}
"	B	8.0 "
"	C	7.8 "
"	D	8.5 "
9	A	$>1.0\times10^{10}$
"	B	"
"	C	"
"	D	"
10	A	1.6×10^{10}
"	B	1.5 "
"	C	1.9 "
"	D	1.8 "

TABLE 8. Post-test Insulation Resistance Measurements Made on Dual-element Leads Removed from Terminal Board*

RTD No.	Lead ID	Insulation Resistance
1-1	A	5.0×10^5
"	B	"
"	C	"
1-2	A	1.5×10^5
"	B	"
"	C	"
2-1	A	1.1×10^7
"	B	1.4 "
"	C	0.9 "
2-2	A	3.5×10^7
"	B	4.0 "
"	C	2.6 "
3-1	A	2.7×10^6
"	B	2.7 "
"	C	2.6 "
3-2	A	4.0×10^6
"	B	4.0 "
"	C	3.8 "
4-1	A	2.6×10^7
4-2	B	2.4×10^7

* All Insulation Resistance values in ohms.

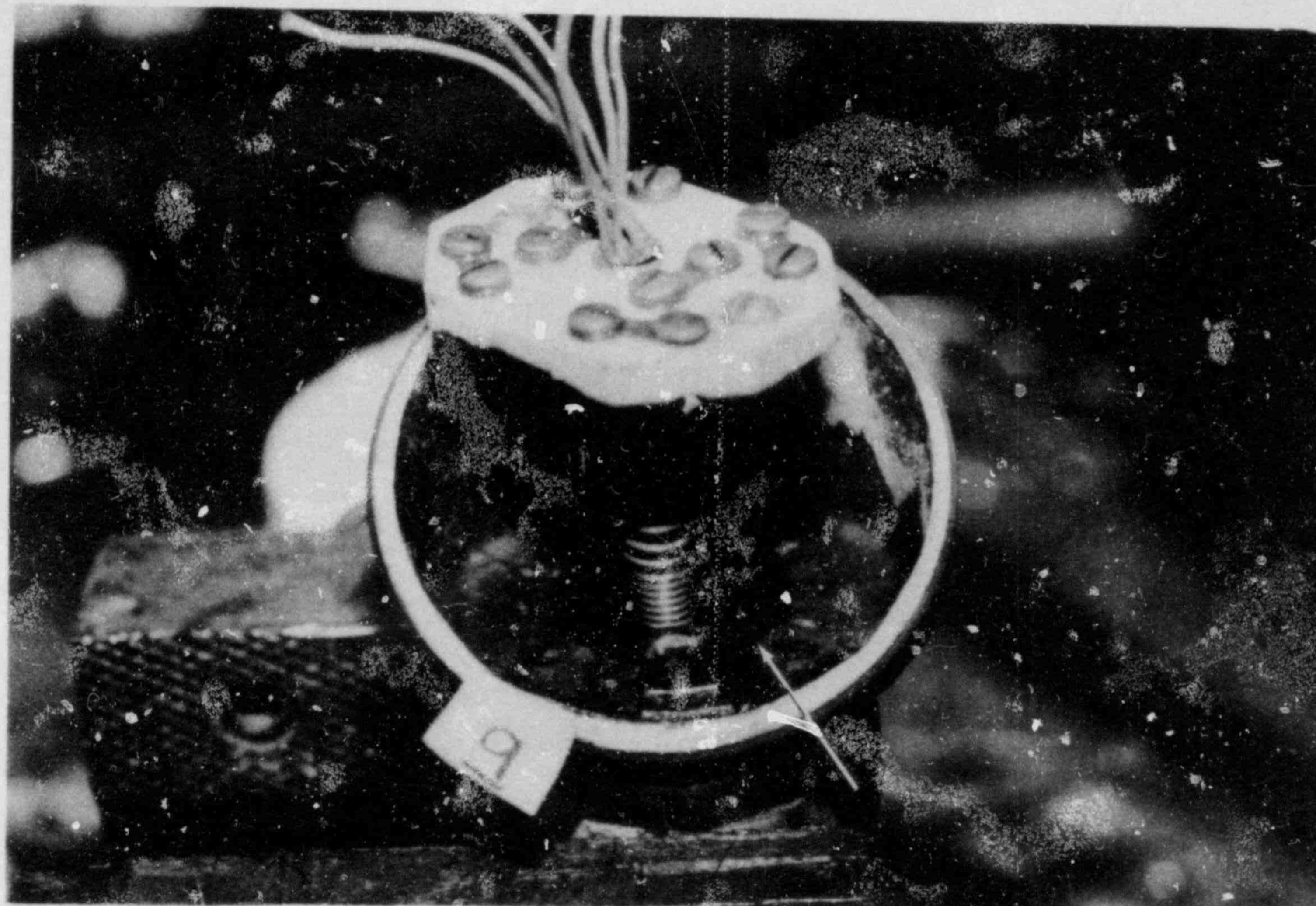


Figure 25. RTD No. 1, showing water inside the thermowell (arrow).

Figure 26. RTD No. 2, showing hole in the body.

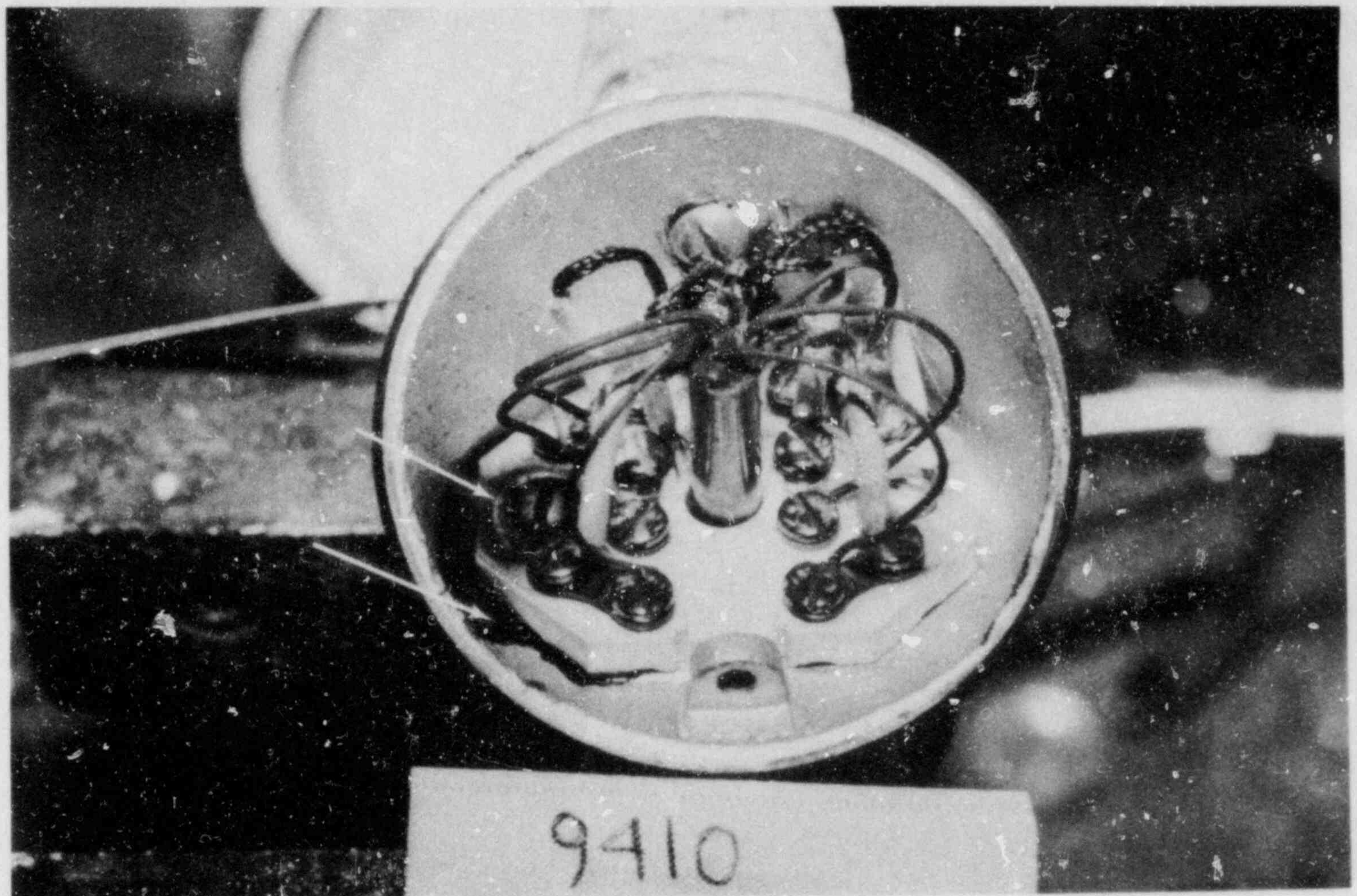


Figure 27. RTD No. 2, showing wet areas under the terminal board.

Figure 28. RTD No. 3, showing discoloration around the ground screw.

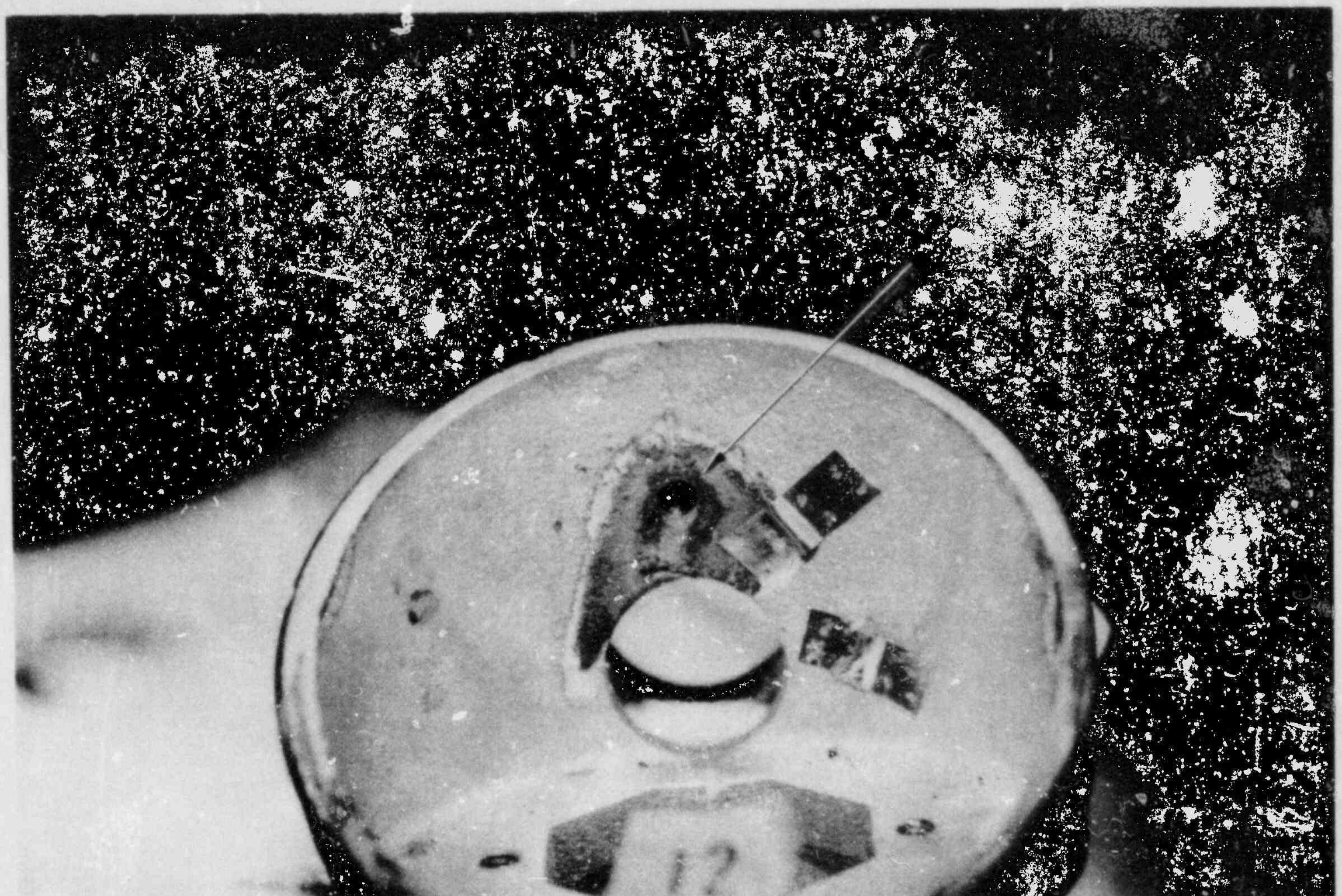


Figure 29. RTD No. 3, with terminal board elements removed, showing leak area around the ground screw hole.

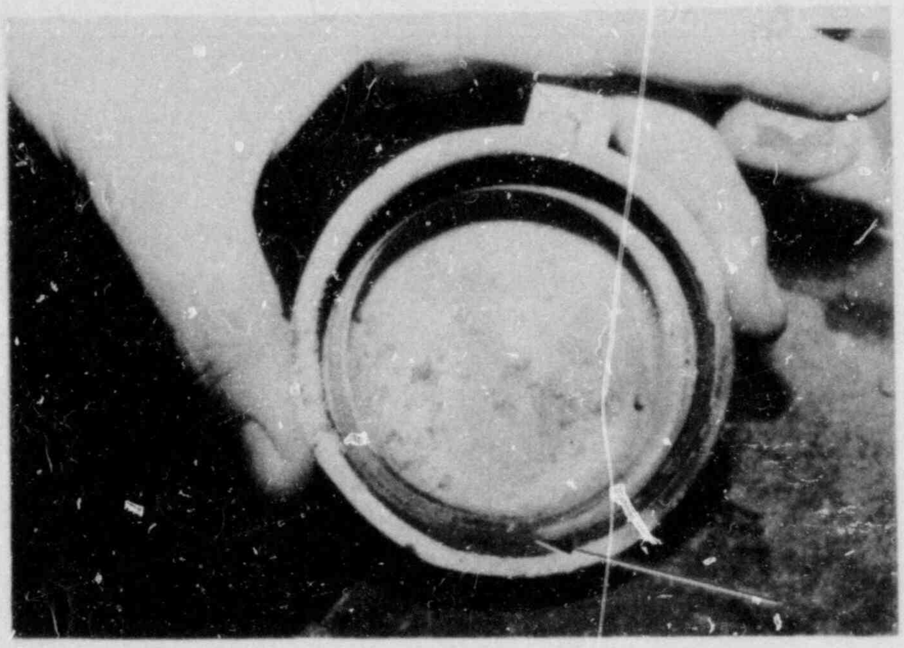


Figure 30. RTD No. 1, showing discoloration of cap seal.

Figure 31. RTD No. 2, showing discoloration of cap seal.

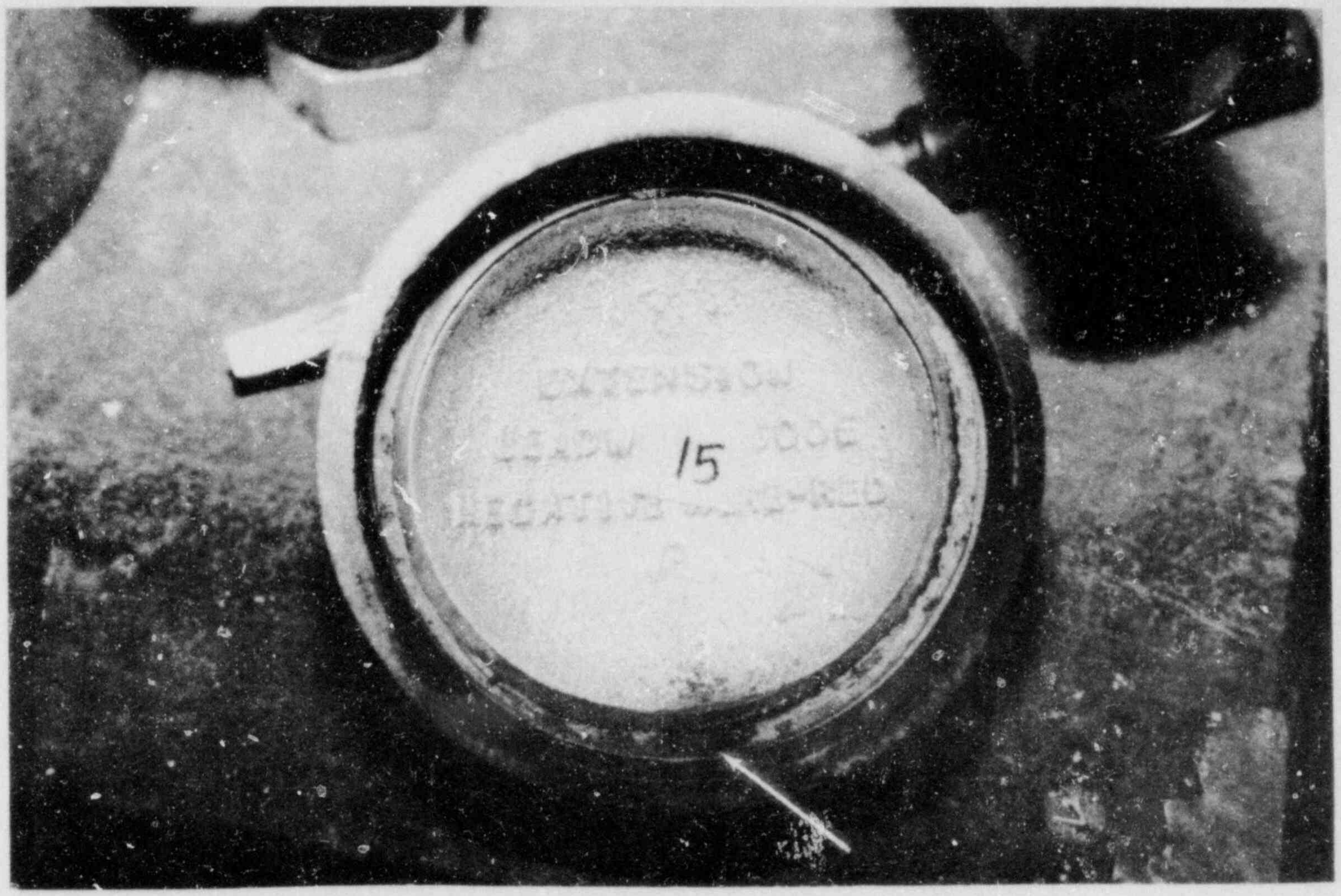


Figure 32. RTD No. 4, showing discoloration of cap seal.

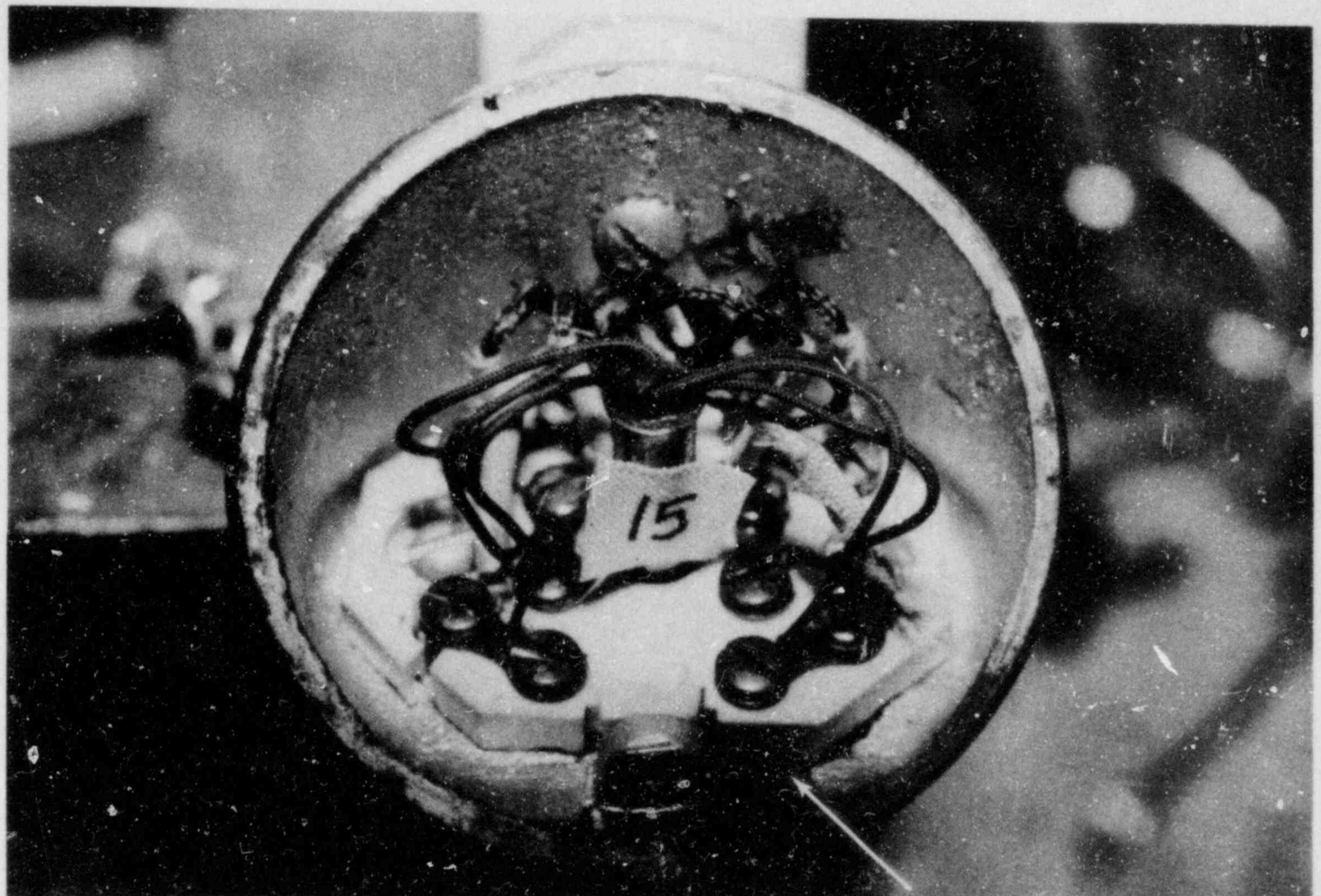


Figure 33. RTD No. 4, showing wet area under the terminal board.

7.0 CONCLUSIONS

The results show that the primary mode of failure for Supplier A RTDs to be the leakage allowed by the head seal gasket material. In one case the failure occurred at 15 psia pressure; in two cases the failures probably did not occur until after the peak (115 psig) pressure condition had passed. The failures were manifested by shorting of the electrical connectors in the RTD head.

Considering the failure mode of these unaged components, it appears that the failures are related to the seal material rather than seal design (a contributing cause also appears to be poor quality control in the head casting process).

Supplier B and Supplier C RTDs functioned properly throughout all phases of this test.

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Ten resistance temperature detectors (RTDs), from three manufacturers were subjected to an abbreviated loss-of-coolant accident (LOCA) environment (saturated steam and chemical spray) simulation test as part of the NRC-sponsored Equipment Qualification Methodology Research Test Program (A-1355). The test was a "screening test" on unaged specimens that lasted about 24 hours and was of short duration to isolate any obvious problem areas. The LOCA environment caused functional failures and some physical damage in four of the RTDs tested. One RTD failed early in the test, two others of the same type produced erroneous temperature readings 7.5 hours into the test. Post-test investigations revealed that water leakage into the head areas of the three affected RTDs (as well as one other of the same model) may have contributed to the anomolous behavior.

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