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Transient Fire Environment Cable Damageability Test Results: Phase I

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TRANSIENT FIRE ENVIRONMENT CABLE DAMAGEABILITY TEST RESULTS: PHASE I

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ABSTRACT

The results of a series of 13 cable tests using IEEE-383 qualified and unqualified cable are discussed in this report. The purpose of these tests was to determine cable damage response (as indicated by electrical failure) to transient fire environments (temperature vs. time only).

The major insights gained from these tests were that (a) cables terminated in a fire environment are more likely to fail: (b) cable geometry plays a significant role in determining if a cable will fail; (c) convective heat transfer, i.e., high air flow regions, leads to severe cable damage; and (d) based on simulated, air cooled down suppression, neither qualified nor unqualified cables would fail given the suppression actuation times and test profiles used in these tests. This assumes that suppression agents (e.g., water) do not cause damage.

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Executive Summary

As part of the cable damageability test program being performed at Sandia National Laboratories for the U.S. Nuclear Regulatory Commission (USNRC), a series of 13 tests was performed to assess cable damage response in transient fire environments. The objectives of these tests were (1) to determine electrical failure times for cables in transient fire environments (temperature versus time) similar to those transients observed in the 20-foot separation tests #1 and #2[1], and (2) to determine whether interruption of the temperature transients to simulate suppression activities could prevent cable damage. The data obtained from these tests is intended to be used in conjunction with fire Probabilistic Risk Assessments (PRAs) to help determine cable fragility values and to reduce the uncertainties associated with cable damage.

The instrumented cables used in these tests were the same qualified and unqualified cables used in the 20-foot separation tests (to aid in comparing failure data). Specifically, the IEEE-383 qualified cable was a 3 conductor, Number 12 AWG, with a 30 mil (0.76 mm) crosslinked polyethylene insulation, silicon glass tape, and a 65 mil (1.65 mm) crosslinked polyethylene jacket rated at 600 V (XPE/XPE). The unqualified cable was a 3 conductor, Number 12 AWG, with 20/10 polyethylene/polyvinylchloride insulation and a 45 mil (1.14 mm) polyvinylchloride jacket (PE/PVC).

All cables were tested in a temperature controlled chamber with a maximum heatup rate of approximately 200°F/minute and a cooldown rate of 65°/minute. A fan was located in the test chamber to provide air flows similar to those observed in fires. To determine when electrical failure occurred in the cables, each conductor in a cable was connected to one phase of a three phase, 120 VAC power supply. Because of the phase differences between conductors, combinations of internal conductor shorts could be determined.

Three different cable geometries were tested as follows:

1. Cable tray (12.5% fill) with three instrumented cables in the tray. One end of each instrumented cable physically terminated in the test chamber.

2. Cable tray (12.5% fill) with two instrumented cables looped into and out of the test chamber (i.e., no instrumented cable ends were in the chamber).

3. Three individual cables, insulated from any metal surfaces, ran lengthwise through the test chamber. The ends of these cables were physically located outside the test chamber.

In the first test configuration (item 1 above), the unqualified cables failed at times close to those for the unqualified cable in the 20-foot tests. However, the qualified cables had failure times consistently less than those observed in the 20-foot tests. Because one end of the instrumented cables was in the test chamber for these tests, it was determined that jacket shrinkage around individual conductors at their ends, as well as the flexing of the conductors, probably led to electrical shorts. These "end effects" probably led to the early failures that were observed.

The second set of tests (item 2) bore out the fact that end effects are important. In these tests, only the unqualified cable failed (at times comparable to the 20-foot tests). This indicated that the unqualified cable had a low fire resistance, regardless of whether cable ends were in or out of the chamber. These tests also pointed out two other interesting facts. First, geometry plays an important role in determining if a cable will be damaged (i.e., the qualified cable did not fail in these tests, whereas it did in the 20-foot separation tests). Second, when suppression was simulated by interrupting the test temperature transient, no failures were observed. This indicates that suppression activity (as long as it occurs) could prevent damage to the cables, assuming that suppression agents themselves do not cause damage.

The last series of tests, which used individual cables, demonstrated that for each cable type, failures of all three individual cables in the chamber occurred at essentially the same time and temperature (dependent on the cable type), and that the qualified cable was more fire resistant than the unqualified cable (as indicated by failure times on the average of 8.00 and 4.85 minutes respectively). These tests also showed, most graphically for the qualified cables, that in regions of high air flow, severe cable damage occurs.

The major conclusions reached from these tests are summarized below:

1. End effects are significant. If a cable terminates at a location in the fire environment, it is more likely to experience an electrical failure.

2. Cable geometry, especially for qualified cable, plays a significant role in determining if a cable will be damaged by a fire.

3. Areas with a high air flow (i.e., large convective heat transfer), produce severe cable damage, as compared to low air flow regions. This implies that convective, as well as radiative heat transfer mechanisms, must be considered when determining cable damage.

4. Based on simulated, air cooled down suppression, neither the qualified nor unqualified cables would fail given the suppression actuation times and test profiles recorded in the 20-foot separation tests. This assumes that suppression agents (e.g., water) do not cause damage.

1. INTRODUCTION

1.1 Program Purpose and Objectives

Based on plant operating experience over the last 20 years, it has been observed that nuclear power plants will have three to four significant fires over their operating lifetimes. Probabilistic risk assessments (PRAs) that have determined the risks to a plant caused by a fire have shown that fires are significant contributors to the overall core melt probability (contributing from 7% to 50% of the total). The parameters used by these PRAs to assess the threat of a fire have historically included the fire occurrence frequency for the location of interest, the fire's growth and spread, suppression activities, and the damage caused by the fire to critical safety equipment (generally limited to cables). The key parameter used to assess cable damage has been the temperature that the cable experiences. Cable damage temperatures have been based on steady-state temperature environments. However, fires create transient and not steady-state temperature environments. Therefore, to further resolve the question of cable damage and thus reduce the uncertainty associated with this damage and ultimately the risk a fire poses to a plant, transient fire environment cable damage data is needed.

The tests described herein are part of the Fire Protection Research Program for the U.S. Nuclear Regulatory Commission (USNRC), which includes both steady-state and transient fire environment test conditions. This report will describe the results of Phase I of the transient fire environment cable tests. The purpose of these tests was to assess cable damage response to transient fire environments. Specifically, the objective of these tests was (1) to determine electrical failure times for cables in transient fire environments (T vs t) similar to those transients observed in the 20-foot separation tests #1 and #2[1], and (2) to determine whether interruption of the temperature transients to simulate suppression activities could prevent cable damage. The Phase I tests were carried out in a temperature controlled chamber that was capable of closely replicating the temperature environments seen during the 20-foot tests. Water suppression effects will be evaluated in Phase II of the transient fire environment tests.

2. TRANSIENT FIRE ENVIRONMENT CABLE DAMAGE TESTS, PHASE I

2.1 Scope of Phase I Tests

Instrumented cables were monitored for electrical failure in transient fire environments following the T vs t profiles of tests #1 and 2 of the 20-foot tests.[1] The effects of suppression were also evaluated; however, Phase I looked at simulated suppression by air cooldown rather than by actual water suppression. Phase II of this test program will examine the effects caused by water suppression. By studying the effects of suppression in this way, it may be possible to identify the separate influences on cable failure of stopping a transient temperature increase versus stressing cables with a water environment.

For the tests conducted in Phase I, <u>both</u> cable-tray arrangements and individual cables were subjected to the fire environments of interest to determine the cable responses. Individual cables were included because it became apparent while running the first several cable tray tests that geometry plays an important role in how cables fail. Thus to understand a complicated geometry, simple geometric configurations needed to be assessed so that their response could be understood and then extrapolated to a complex tray arrangement.

2.2 Chamber Capabilities and Response

The chamber used to produce the transient temperature test profiles has a heatup rate of approximately 200°F/min. The cooldown rate of the chamber is on the order of 65°F/min with the door shut. With the door open, an initial large cooldown rate can be obtained; however, it lasts only a short time and the cooldown rate reverts to the above-mentioned value.

The temperature profile of the chamber along its length, next to where the cable tray and cables are positioned, is fairly uniform. Figures 1 through 3 show the right, left and center line temperature profiles in the chamber as compared to the temperature sensed by the chamber for control purposes. The test profile used for this characterization was the Test 1 profile of the 20-foot separation tests. From the curves in Figures 1 through 3, it can be seen that by time shifting all the curves with respect to the control profile by 30 seconds, that the profiles overlap. (See Figure 4 for an example of this.) This observation demonstrates that throughout the chamber all temperature transients are nearly identical.

2.3 Voltage Failure Criteria

All cables were connected to one phase of a three-phase 120 VAC power supply. Because the phases were different, combinations of internal conductor shorts could be determined, including which conductors short to each other or to the tray.

Failures were indicated by a significant decrease in the measured voltage. Figure 5 (lower plot) shows an example of how the voltages change when failure occurs. In this example, electrical failure is indicated when the voltage (for the WHITE Conductor) goes to zero. (Note: The voltages have been scaled in this example to provide a more readable graph. SUB 4 pertains to a thermocouple placed underneath the jacket of the cable.)

An interesting finding during the first few cable tests involved the way thermocouple leads can cause erroneous voltage failure indications. This can occur if a thermocouple touches both a copper conductor and the cable tray. This condition is not present at the start of a test, because all the thermocouples placed under the cable jackets are verified both electrically and by X-ray photography not to be touching copper conductors (except in Tests A and B where the thermocouple leads were intentionally touching copper, but were insulated to prevent them from causing erroneous shorts). However, as a test progresses, there is a chance that a thermocouple will come in contact with a copper conductor. A method for determining if this occurs has been developed and is based on comparing the derivative of the subsurface thermocouple temperatures to the indicated voltage failures. It is assumed that when a thermocouple touches a copper conductor, its temperature will change rapidly. By taking a simple derivative of this temperature profile, when the thermocouple touches the copper, it should be highlighted by a spike in the curve. By superimposing the electrical failure times onto this curve, a correlation can be made to identify thermocouple shorts. Figure 5 (upper plot) shows how this was used in Test 1 to determine that the white conductor short was in all probability caused by a thermocouple. Note that a large temperature spike (at approximately 250 seconds) occurred at the same time that the electrical failure was occurring.

Note however, shorts to the cable tray are also possible for those cables resting on the tray, and due to thermal expansion, they may intermittently short, just like a thermocouple short. Therefore care had to be taken in determining exactly what kind of shorts actually occurred. The electrical failure times presented in Section 2.5 of this report reflect actual conductor shorts and not thermocouple-induced shorts.

2.4 Test Setups

Two basic test setups were used. One setup involved a 12.5% fill cable tray, while the other setup entailed the use of three individual cables being passed longitudinally through the test chamber. The following paragraphs describe in more detail the actual setups used.

2.4.1 Cable Trays

Two installation methods were used to place instrumented cables (cables with thermocouples placed on or in them and that were monitored for electrical continuity during a test) in cable trays. Each method used a basic cable tray configuration as described below:

> Forty-three straight cable segments, approximately 19 inches long, were arranged so as to give 3 levels of cable in a cable tray (14 segments in the top and bottom layer, 15 segments in the middle layer). Each

layer was placed at slightly different horizontal orientations so that they would lie in place on the layer below them as shown in Figure 6. This placement provided for a well-ventilated cable arrangement similar to the 20-foot test configurations. The ends of the cable segments were wrapped in an insulation blanket designed to prevent the ends of the segment from conducting appreciable heat down the cable and to make them look like a continuous cable passing through a room, with no ends terminating in the room. This arrangement also provided a means of keeping the cables in place.

The first method used in installing the instrumented cables was to run three instrumented cables into the above cable tray arrangement with one cable per level. The bottom layer had a straight instrumented cable installed, which touched the center cable tray rung, while the middle and top layers had cables that had gentle 90-degree bends with the ends of the cables being wrapped in an insulation jacket and butting up against the side of the cable tray. (See Figure 7.) This configuration was used for two tests since it was felt that tests done with one end terminating in a chamber, or at a terminal block in an actual application, would be more susceptible to failure. Thus for testing purposes it was expected that having an end in the chamber would induce failures that in reality would not have occurred or have occurred as quickly if the cable end was not present. Two tests were used to verify this theory.

The second method used in installing the instrumented cables was to run two cables into the cable tray arrangement previously discussed and loop them in and out of the chamber. In this arrangement, a gentle 180° bend in the instrumented cables was used. The bottom cable was allowed to touch the cable trays center rung. The other cable was placed on top of the second row of cable segments and then covered by a row of cable segments. Thus the "top" instrumented cable in this arrangement was partially shielded by another layer of cables, as shown in Figure 8.

In each of these cable tray configurations, the instrumented cables were wrapped with an insulating blanket inside the chamber except where they actually laid in the cable tray. This was done to prevent the cables from failing except in the cable tray region.

Temperature measurements for the instrumented cables were made using 20-mil thick, shielded, K-type thermocouples. These thermocouples were placed under the jacket of the instrumented cables or on their surfaces (indicated by SUB or SURF respectively on figures found in this report).

To measure electrical failure of the cables, each of the three conductors in the cables was connected to one phase of a nominal 120 VAC, three phase power supply. Because the phase relationship between each conductor was different (by 120 degrees), this measurement technique detected all of the conductor-to-conductor and conductor-to-tray short-circuit combinations that could possibly occur, independent of their failure sequence. This represents an improvement over the measurements taken in the 20-foot tests, which could only detect the first occurring conductor or tray short.

2.4.2 Individual Cables

The test setup used during these tests was to run three individual cables through the chamber. This meant that each end of the cable was physically located outside the chamber so that no end effects could take place. The cables were run longitudinally through the chamber and were supported by a cable tray to keep them from sagging. However, wherever the cable could touch any metal in the chamber (i.e., the chamber walls, cable tray), this point was covered with an insulating blanket. (See Figure 9.) In this way, the cable was essentially only responding to heating from air in the chamber, and any electrical faults occurring were due to conductor-to-conductor faults and not cable-tray shorts. Only chamber temperatures were monitored, no thermocouples were implanted in the cables. Electrical failures were monitored in the same manner as for the cable tray tests.

2.4.3 Cables Tested

The instrumented cables used in all tests were the qualified and unqualified cables used in the 20-foot separation tests. Specifically, the IEEE-383 qualified cable was a 3-conductor, No. 12 AWG, with a 30-mil (0.76 mm) crosslinked polyethylene insulation, silicon glass tape, and a 65 mil (1.65 mm) crosslinked polyethylene jacket rated at 600 V (XPE/XPE). The unqualified cable was a 3-conductor, No. 12 AWG, with 20/10 polyethylene/polyvinylchloride insulation and a 45-mil (1.14 mm) polyvinylchloride jacket (PE/PVC).

2.5 <u>Results of Phase I Tests</u>

Thirteen tests were performed using the test configurations previously described. The test profiles used are summarized in Table 1. Table 2 shows for which tests electrical failure occurred. The results of these tests are discussed below.

2.5.1 Cable Trays--End Effects

Two tests were performed where one end of the cables terminated in the chamber. These two tests were performed to verify that

Table 1

Transient Cable Damage Testing Matrix
Phase I

Test #	Cable Type	Environment Cables Subjected To
Cable Tray-One End Terminates in Chamber		
A	UQ	Follow Test #1 profile,* at 20-ft, 1 ft from ceiling, for 15 min
B	Q	Follow Test #2 profile,* at 20 ft, 1 ft from ceiling, for 15 min
Cable Tray - Looped Cables (both ends of cable outside the chamber)		
1	UQ	Follow Test #1 profile, at 20 ft, 1 ft from ceiling, for 15 min
2	Q	Follow Test #2 profile, at 20 ft, 1 ft from ceiling, for 15 min
3	UQ	Follow Test #1 profile, at 20 ft, 2 ft from ceiling, for 15 min
4	Q	Follow Test #2 profile, at 20 ft, 1 ft from ceiling, for 15 min
5	UQ	Follow Test #1 profile, at 20 ft, 1 ft from ceiling, for 112 sec, then air cooldown at 120°C/min
6	UQ	Follow Test #2 profile, at 20 ft, 1 ft from ceiling, for 200 sec, then air cooldown at 120°C/min
Individual Cables		
7	UQ	Same as #1
8	Q	Same as #2+
9	Q	Same as #2
10	UQ	Same as #6
11	Q	Same as #6

* Refers to the temperature profiles recorded during Test 1 and 2 of the 20-foot separation tests.

\+ This test was not able to meet the desired temperature profile because of electrical power supply malfunctions.

Table 2

Transient Cable Damage Testing Matrix
Phase I

Electrical Failure Summary

Test #	Cable Type	Electrical Failure Yes	Electrical Failure No	Comments
A	UQ	X		Heavy smoke, cables fused together.
B	Q	X		Heavy smoke, cables brittle, blistered.
1	UQ	X		Heavy smoke, cables fused together.
2	Q		X	Heavy smoke, cables brittle, blistered.
3	UQ	X		Same as # 1.
4	Q		X	Test performed as verification of # 2 results. Same results, effects observed.
5	UQ		X	No smoke produced, no apparent physical damage observed.
6	UQ		X	Light smoke produced. Cables closest to fan had some swelling, browning occur.
7	UQ	X		Heavy smoke, cables severely damaged. Upon removal from chamber, only bare conductors left.
8	Q		X	Light smoke, cables blistered.+
9	Q	X		Heavy smoke, cables severely damaged along one third of their length (closest to fan).
10	UQ		X	Light smoke, outer jacket showed some melting.
11	Q		X	No smoke produced, no apparent physical damage observed.

+ This test was not able to meet the desired temperature profile because of electrical power supply malfunctions.

end effects could in fact have a detrimental impact in causing electrical failure of cables. The major concern in using this type of arrangement was that electrical faults could be induced at the end of the cable. Some cable jacket shrinkage was expected during the tests. This shrinkage could be most apparent at the end of a cable terminating in the chamber, thus exposing the individual conductors. In a similar fashion, the individual conductor jackets could also be expected to shrink. Also, electrical conductors have been shown to physically move as evidenced by electrical healing during fire tests. Thus the probability of the bare conductors touching at the end would be high, inducing electrical shorts. However, if the cable ends are not exposed to fire, such as a continuous cable running through a room, the ends should not experience the above phenomenon and should not be expected to fail. We believed though that the end effect could occur even if the ends were thermally insulated from the environment, i.e., sufficient jacket shrinkage and movement could occur leading to electrical shorts. The results of these two tests, based on both visual observations and electrical failure times, as compared to the follow-on tests, seem to verify our concern that end effects are significant and can induce failures.

Test A involved the use of unqualified (PE/PVC) cabling, while Test B used qualified (XPE/XPE) cabling. In each test, three instrumented cables were monitored. Each test had a straight cable (which touched the center rung of the cable tray) and a middle and top cable. The middle and top cable each had gentle 90-degree bends so that they entered the cable tray on one side and the end of the cable terminated on the other side of the cable tray. These ends were then wrapped with an insulating blanket.

Figure 10 shows a pictorial sequence of what the cable-tray arrangement looked like prior to running Test A, while Figure 11 shows what the cables looked like after the test. Figures 12 and 13 show similar pictorial information only for Test B.

Figure 14 shows the desired and actual time-temperature profiles obtained during Test A, while Figure 15 shows the same information for Test B. Note that in Figure 14 the actual profile deviates slightly from the desired profile. The deviation is due to chamber capabilities (see section 2.2).

Table 3 summarizes the times that conductors first indicated electrical failure. Figures 16 through 18 show the actual test results indicating when electrical failure occurred based on voltage measurements taken for Test A, while Figures 19 through 21 show the failures for Test B. Note that an examination of Table 3 indicates that a majority of the unqualified cables failed at times close to the unqualified cable failure time in the 20-foot tests (i.e., 4.07 minutes). However, for the qualified cabling, it consistently indicated failure times of less than that observed in the 20-foot tests (12.92 minutes) or no failures at all. In fact the straight cable, which physically touched the tray and might have been expected to fail, showed no failures at all. However, the top and middle cables failed early. (Note: The ends of these two cables were wrapped, yet the end assembly was exposed to the full chamber temperature, while the straight cable was shielded by both insulation material and other cable segments.)

Table 4 summarizes the temperatures (based on the chamber temperature) at which the electrical failures occurred. Note that for those cases where a thermocouple was suspected of leading to an erroneous failure, no temperatures are reported for that conductor.

Figures 22 through 24 show the temperatures that were monitored for the instrumented cables in Test A. From these time-temperature plots, it is observed that almost all the failures for the unqualified cabling occur prior to the peak of the time-temperature curve. The chamber temperature band of failures for these two tests is 720 to 930°F. Based on the narrow failure band reported for individual cable tests, to be discussed in Section 2.5.3, the difference in failure temperatures in the cable tray configuration is probably due to the geometry seen by the different instrumented cables (i.e., shielded by other cables). Note that the thermocouples placed in the ends of the cables (END TOP and END MID) indicate that the cables may have ignited. However, this had to be only a small localized fire because the chamber environment thermocouple never responded to these fires. (Another plausible reason for the temperature increase for these ends is that they may have experienced smoldering combustion.)

Figures 25 through 27 are similar temperature profiles for Test B, qualified cabling. As contrasted to Test A, all failures occurred after the time-temperature curves peak, indicating, as expected, that higher temperatures and longer exposure times are required to fail qualified cables. Maximum recorded surface temperatures compare favorably with those observed in the 20-foot test (i.e., 785°F versus 720°F for the straight cable). However, failure times are considerably less, indicating that end effects are important, i.e., end effects seem to accelerate or induce failures.

Figures 28 and 29 show why end effects are important and can lead to failure. These two figures show the end of the unqualified and qualified cabling that was wrapped. Not only end effects but also the effects of wrapping the cable are seen in these two figures. In Figure 28, the unqualified cable "looks" like it has been completely consumed by fire. This may have been caused by the fact that the end was wrapped. One possible explanation for this end wrapping effect is that as the temperature in the chamber heated up, the PVC produced more and more pyrolyzates. At every location in the chamber, except on the

Table 3

Electrical Conductor Failure Times (Tests A and B)

	Time of Conductor Failure (seconds/minutes)		
Test A	White	Red	Black
Straight	320/5.33	270/4.5	270/4.5
Middle	430/7.17	430/7.17	200/3.33*
Top	310/5.17	290/4.83	345/5.75
Test B			
Straight	-	-	-
Middle	545/9.08	505/8.42	545/9.08
Top	-	250/4.17	615/10.25

* Thermocouple induced short
\- No electrical failure

Table 4

Chamber Temperatures at Which Electrical Failure Occurred
(Tests A and B)

	Failure Temperature (deg F)		
Test A	White	Red	Black
Straight	870	720	720
Middle	825	825	*
Top	850	750	930
Test B			
Straight	-	-	-
Middle	750	780	750
Top	-	620	690

* Thermocouple induced short
\- No electrical failure

cable ends, the pyrolyzates were quickly swept away from the cable by the air flow in the chamber, thus a build-up of pyrolyzates was not possible. However, on the cable ends, where the wrapping was present, the pyrolyzates were in essence trapped by the air voids in the insulating blanket. The pyrolyzates may have then chemically reacted in an exothermic reaction that heated the end up until its autoignition temperature was reached. The plots in Figures 22 and 23 seem to bear this out since initially the cable end temperature was lower than any of the other monitored temperatures (i.e., the insulation blanket was keeping the cable end cool). As the temperature in the chamber rose, the production of pyrolyzates would be expected to increase, and the the end temperature rose (due to the build up of pyrolyzates in the insulation blanket). The cable end temperature continued to rise while other temperatures fell, indicating ignition may have occurred under the insulation blanket. This may explain, at least for the unqualified cable, why the wrapped cable ends were completely consumed. The fact that the ignition was contained under the insulation may explain why the chamber thermocouples never responded to the fire. However, despite the fact that the end insulation may have eventually caused severe end damage, electrical failure occurred well before the ends experienced any rapid temperature excursions.

The same type of explanation as above is applicable to the qualified cable with one exception. The rate of pyrolysis of the qualified cable is less than the unqualified cable as evidenced by the fact that given the same temperature profile the qualified cable evolves considerably less smoke than the unqualified cabling (see Table 2, results of tests 10 and 11). Therefore, the build up of pyrolyzates in the wrapped end for the qualified cables is significantly less. For the qualified cable the data indicates that the end wrap does tend to cool and protect the end of the cable. The fact that pyrolyzates do not build up in the same manner as for the unqualified cable is seen in Figure 25, where the cable end temperature is only slightly elevated over all other temperatures near the end of the test. In addition, Figure 29 shows that the wrapping did protect the end of the cable, i.e., the end is not as damaged looking as the rest of the cable. However, this figure does show the end effect due to jacket shrinkage occurring and exposing the individual conductors.

Both the wrapping effects and end effects appear to be capable of leading to failures that may be relevant to certain nuclear power plant applications (e.g., connectors, terminal blocks, junctions). However, to focus on the failure of the continuous cable runs most often found throughout nuclear power plants, all follow-on tests listed in Table 1 positioned cable ends outside the chamber to ensure that end effects would not induce electrical failures.

2.5.2 Cable Trays--Looped Cables

The cable tray arrangement used in this series of tests was similar to that in the previous section; however, there were only two instrumented cables that entered and exited the chamber on the same end (through different accesses). The bottom loop, which will be referred to as the big loop, physically touched the cable tray center rung and ran approximately halfway into the cable tray assembly. The top loop, which will be referred to as the small loop, had cables supporting it both on top and bottom, and was separated from the big loop by one layer of cables, and extended approximately three quarters of the way into the cable tray assembly. The 180° bend radius of the small loop was smaller than the big loop, so it could be thought of as being "inside" the big loop. Figures 30 and 31 show how the cable tray arrangements looked for unqualified and qualified cable prior to the tests. Tests 1, 2, 3 and 4 of this series of tests involved exposing the cable trays to the full time-temperature environments of those seen in the 20-foot tests. The damage for these tests was identical to Tests A and B, see Figures 11 and 13. Tests 5 and 6 simulated suppression based on the suppression actuation times recorded in the 20-foot tests. Cooldown rates were based on Reference 2.

Figures 32 through 37 show the desired and actual time-temperature profiles obtained for Tests 1 through 6.

Table 5 summarizes the times that conductors first indicated electrical failure. Note that in this series of tests, only Tests 1 and 3, with unqualified cabling showed electrical failures. Figures 38 through 41 show the actual test results indicating when electrical failure occurred based on voltage measurements for Tests 1 and 3 respectively. Similar figures are not included for the other tests since no failures were indicated. In comparing Test A to Test 1, where the only difference is that the ends were either in or out of the chamber, the times to failure for Test 1 have a slightly wider variation than in Test A. (i.e., 270 to 490 seconds versus 270 to 430 seconds.) However, this difference is probably insignificant compared to the overall failure range and the fact that unqualified cable generally failed quickly in both tests. Test 3, which had a slightly less severe profile, had failures occurring later than Test 1, and were consistent with the 20-foot tests. These results indicate that unqualified cable is susceptible to failure regardless of the geometry it is found in. Tests 2 and 4, where qualified cabling was used, do appear to verify that end effects are important. In neither test did the cables indicate failure; however, in Test B, five failures were recorded. The cable tray geometry and fire environment the cables were subjected to were essentially the same, but the end terminations were different. It appears, based on a comparison of these three qualified cable tray tests, that end effects <u>are</u> important, at least for qualified cable, which is now predominately used in nuclear power plants. This implies

Table 5

Electrical Conductor Failure Times (Tests 1-6)

Test #	Loop	Time of Conductor Failure (seconds/minutes) White	Red	Black
1	Small	270/4.50	490/8.17	415/6.92
	Big	245/4.08*	390/6.50	360/6.00
2		No electrical failures in either loop		
3	Small	495/8.25	260/4.33*	555/9.25
	Big	405/6.75	294/4.92+	360/6.00*
4		No electrical failures in either loop		
5		No electrical failures in either loop		
6		No electrical failures in either loop		

* Thermocouple induced short
\+ Cable tray short

Table 6

Chamber Temperatures at Which Electrical Failure Occurred (Tests 1 and 3)

Test #	Loop	Failure Temperature (deg F) White	Red	Black
1	Small	750	760	825
	Big	*	920	950
3	Small	690	*	630
	Big	800	735	*

* Thermocouple induced short

that cable termination points may be more susceptible to electrical failures than cable runs.

Table 6 summarizes the temperatures (based on chamber temperature) at which the electrical failures occurred. For those cases where a thermocouple was suspected of leading to an erroneous failure, no temperatures are reported for that conductor.

In comparing Test 1 chamber failure temperatures to those of Test A, although the chamber failure temperature ranges are similar (i.e., 720 to 930°F for Test A, and 750 to 950°F for Test 1) the time to reach failure was, in general, longer for Test 1. The average time-to-conductor failure (not considering thermocouple induced shorts) in Test 1 was 6.4 minutes, while in Test A it was 5.5 minutes. This is attributed to the end effects previously mentioned for Test A, which accelerated the time to failure.

A comparison of Test 1 and 3 failure times to those of the 20-foot tests also indicates that these tests took longer to fail cable than in the 20-foot tests. This is most likely due to the geometry being different than in the 20-foot tests for the instrumented cables. In the 20-foot tests a continuous strand of cable was used. Thus a failure occurring on one of the exposed loops of this single cable was treated the same as if it failed deep in the cable tray arrangement. However, in Tests 1 and 3, and the same can be said for Tests 2 and 4 of the qualified cable tests, both instrumented cables were shielded by at least one layer of cable, or the cable tray. In all likelihood, the cables did not see the same temperature extremes as the topmost layer of instrumented cable in the 20-foot tests. This is partially verified by noting that for the unqualified cabling, the maximum cable surface temperature recorded was 860°F in the 20-foot tests, but only 720°F for this series of tests. Thus the geometry that a cable is placed in has a great deal to do with how and when it will experience failure. The discussion in the next section concerning individual cables bears this assertion out.

Tests 5 and 6 simulated suppression system actuation. Suppression was simulated by air cooldown rather than the actual introduction of a suppression agent. This was done to determine if the cables would survive a less severe temperature profile that was based on when the suppression systems electrically initiated in the 20-foot tests. Air cooldown was used to ensure that any failures that might occur at these temperatures could be attributed to temperature and not suppression agents. In both tests, no electrical failure was noted. Test 5, which interrupted the Test #1 profile of the 20-foot separation tests, did not even produce any smoke. After the test the cables were barely warm to the touch. Although no failures occurred in Test 6, some smoke was produced, the cables near the front of the chamber (i.e., near the fan) showed some signs of blistering, were brown, and were warm and pliable after the test. Thus, based on these tests, it would appear that for Test 5, if water suppression had occurred, it would not have caused damage. In Test 6, because of the blistering and browning of the cable, the application of water might have led to electrical failure.

2.5.3 Individual Cables

In this series of tests, five sets of three cables were placed longitudinally in the test chamber. The ends of each cable were located physically outside the chamber. In addition, the cables were insulated from any metal surfaces inside the chamber. No thermocouples were implanted in any of the cables; however, electrical failure was monitored as in the previous cases. The three cables will be referred to as the left cable, middle cable, and right cable (based on looking into the chamber with the door open). Figures 42 and 43 show how the unqualified and qualified cable respectively were placed in the chamber. Tests 7, 8, and 9 of this series of tests involved exposing the cables to the full time-temperature environments of Tests 1 and 2 of the 20-foot separation tests. Tests 10 and 11 involved following the Test 2 profile of the 20-foot tests for 200 seconds, and then cooling down as rapidly as possible to simulate suppression.

The desired and actual time-temperature profiles obtained for Tests 7 through 11 are shown in Figures 44 through 48.

Table 7

Electrical Conductor Failure Times (Tests 7-11)

		Time of Conductor Failure (seconds/minutes)		
Test #	Cable	White	Red	Black
7	Left	305/5.08	305/5.08	305/5.08
	Middle	285/4.75	285/4.75	295/4.92
	Right	280/4.67	280/4.67	280/4.67
8		No electrical failure*		
9	Left	515/8.58	485/8.08	485/8.08
	Middle	530/8.03	480/8.00	480/8.00
	Right	480/8.00	480/8.00	480/8.00
10		No electrical failures		
11		No electrical failures		

* This test was not able to meet the desired temperature profile because of electrical power supply malfunctions.

Table 7 summarizes the times that conductors first indicated electrical failures. Note that for these tests, unlike the previous tests, no interpretation of the data due to thermocouple induced failures is required. Figures 49 through 54 show the actual test results indicating when electrical failure occurred based on voltage measurements for Tests 7 and 9. Similar figures for the other tests are not included because no failures occurred.

In examining the results presented in Table 7, several major insights become apparent. First, the failure times for either type of cable are narrow (compared to the tests with full cable trays). The unqualified cabling of Test 7 failed with an average time of 291 seconds (4.85 minutes). This time is close to the time that electrical failure occurred during the 20-foot tests (i.e., 4.07 minutes).

The qualified cabling of Test 9 failed with an average time of 491 sec (8.18 minutes). These failure times, which are about 4.5 minutes less than those observed in the 20-foot tests, reinforce the point that the geometry a cable is tested in makes a big difference as to how it fails (i.e., the qualified cable provides the most conclusive example of this assertion since in the cable tray arrangement of section 2.5.2, it did not fail, but it failed in this case.) Figures 55 and 56 show what the cables looked like after Tests 7 and 9. This leads to the second major insight of the individual cable tests.

In examining the two figures mentioned above, it is apparent that major damage occurs to the cables. In addition, Figure 56 shows that the most severe damage occurs close to the chambers installed fan. Convective heat transfer apparently has a large effect on cable failure. Figure 57 is a plot of the air flow (in feet per minute) measured along the left cable. Note that the air flow rate is highest near the chamber fan and drops off rapidly toward the other end of the chamber. Figure 58 is a composite view showing the left cable and its damage versus the air flow rate measured directly above it. This figure graphically indicates that convective heat transfer plays a vital role in damaging cables. It also indicates why the electrical failure times that were observed in Section 2.5.2 (cable tray tests) were different than the individual cable tests. During the cable tray tests, instrumented cabling was exposed to a much lower air flow region (since it was shielded by other cables and exposed cable was approximately 12 inches from the fan), thus convective heat transfer was less. In fact, several air flow measurements taken inside the cable tray configuration show even smaller air flows than the smallest observed air flow in the single cable tests.

Because the failure times of the cables do not have a wide time dispersion, the temperature at which failure occurs is fairly well defined also (compared to the cable tray tests). Table 8 summarizes the temperatures (based on the chamber control temperature) when electrical failures occurred. Also included in this table are the high and low temperatures recorded near the cables at the failure times. Note that the importance of convective heat transfer is seen by examining Tables 7 and 8 and by considering the air flow profile of the chamber. Several air flow measurements were made on the right-hand side of the chamber, but not in as great a detail as that done for the left side of the chamber. Air flow on the right side had the same type of profile; i.e., high air flow near the fan, that rapidly dropped off. However, the magnitudes were slightly greater (on the order of 15% greater than the left side). In examining Table 8, the right side fails at temperatures less than the left side. Similarly, the time to failure is generally less for the right-side cable as compared to the left-side cable when Table 7 is examined. As a further check of the effect of air velocity induced convective heating of the cables, temperature measurements were made throughout the test chamber. These measurements showed that, although air velocities varied by a factor of over eight, temperatures throughout the chamber only varied by a factor of 1.3. Based on simple heat transfer coefficient correlations for cylindrical surfaces, the observed velocity variations can account for as much as a factor of 2 difference in heat transfer from one end of the cables to the other. On these bases, convective heat transfer seems to play a major role in determining when a cable will fail.

Table 8

Chamber Temperatures at Which Electrical Failure Occurred (Tests 7 and 9)

		Failure Temperature (deg F)		
Test #	Cable	Control Temp	High Temp	Low Temp
7	Left	1020	1050	980
	Middle	920	970	900
	Right	920	970	900
9	Left	850	850	840
	Middle	850	850	840
	Right	850	850	830

Test 8, which used qualified cabling, had no electrical failures; however, as seen from Figure 45, the actual temperatures the cables were exposed to were considerably lower than desired. This was due to electrical generator fluctuations that prevented full power from being applied to the chamber. The cable produced a large amount of smoke and was blistered;

however, no failures occurred. The usefulness of this test, however, is that it serves to bound where failure occurs for the qualified cable.

In Tests 10 and 11, no electrical failures were recorded. The qualified cable generated no smoke, and after the test looked just like it did before the test. The unqualified cable, even though it did not fail, in the region near the fan, did have the jacket material run and produced globs of PVC on the cable. Figure 59 shows what the cable looked like after the test. In addition, the cable did produce some smoke, but as previously stated, no failures occurred.

3. CONCLUSIONS

Several major conclusions can be reached from Phase I of the transient fire environment cable damageability tests and are discussed below.

1. End effects are significant.

   For those situations where a cable terminates at a location in the fire environment, failure is more likely at this point than other locations in the cable. This also implies for test purposes that for those tests done with cables where one end terminates in the test chamber, the interpretation of electrical failure must be done very carefully since the end of the cable may <u>induce</u> an unwanted or untrue failure indication.

2. Geometry plays a significant role in determining if a cable will fail.

   The shielding effects afforded by multiple cables can prevent a cable from electrically failing. The cable geometry can mask failures that would occur if simple changes to the geometry were made. In comparing the cable tray tests performed in this phase of the testing program to the 20-foot tests, specifically the qualified cable, the placement of one layer of cables over the instrumented cable as compared to its being completely exposed to the environment was the difference between no failures and failure.

3. Convective heat transfer plays a major role in damaging cables.

   The individual cable tray tests vividly show that where high air flow regions exist, cable damage is most severe. This implies that component damage tests and fire environment models must not only consider radiative heat transfer, but also convective heat transfer to determine the response of cables and components in a fire.

4. Based on simulated, air cooled down suppression, neither the qualified nor unqualified cables would fail with the suppression actuation times and test profiles recorded in the 20-foot separation tests.

   None of the simulated air cooldown suppression tests experienced electrical failures. However, the unqualified cabling did blister and bubble when the Test 2 profile of the 20-foot tests was used and suppression was simulated at 200 sec. Water and high humidity might therefore lead to electrical failure in this case. Phase II of this test program will specifically investigate this situation.

Two other, less significant conclusions are worth mentioning:

1. Both qualified and unqualified cables "heal" themselves to some extent.

   In all the cases where failure occurred, and usually while the chamber was still cooling down, some of the electrical failures would become less severe, or completely disappear. This was attributed to the thermal expansion and then contraction of the copper conductors. As a result, cable or component damage tests that measure operability only <u>after</u> a test may have no relationship to operability <u>during</u> a test.

2. Subsurface thermocouple temperatures are affected by whether they are sleeved or unsleeved.

   The 20-mil thick thermocouples used to monitor temperatures either were unsleeved (i.e., were implanted under the jacket as is) or sleeved (had a six-inch long glass braid insulation sleeve placed over them that was sealed to the cable). For the qualified cables, unsleeved thermocouples read approximately 50°F different than sleeved thermocouples. This temperature difference may cause erroneous temperature readings and may accelerate cable damage by conducting heat into the test cables.

4. REFERENCES

1. D. D. Cline, W. A. von Riesemann, J. M. Chavez, <u>Investigation of Twenty-Foot Separation Distance as a Fire Protection Method as Specified in 10 CFR 50, Appendix R</u>, Sandia National Laboratories, NUREG/CR-3192, SAND83-0306, October 1983.

2. J. M. Chavez, <u>Evaluation of Suppression Methods for Electrical Cable Fires</u>, Sandia National Laboratories, NUREG/CR-3656, SAND83-2664, (to be published).

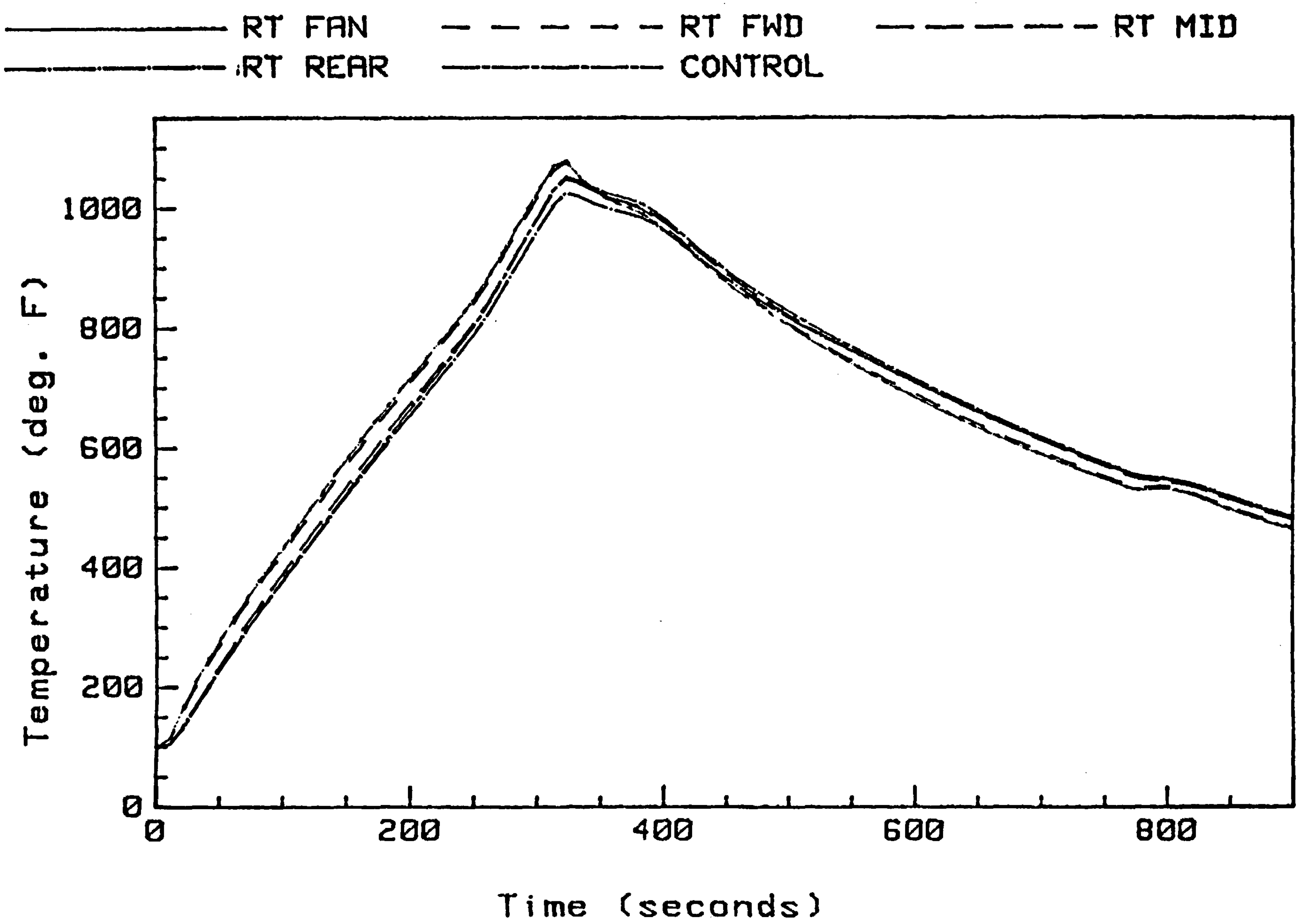


Figure 1. Temperature Profile--Chamber Right Side

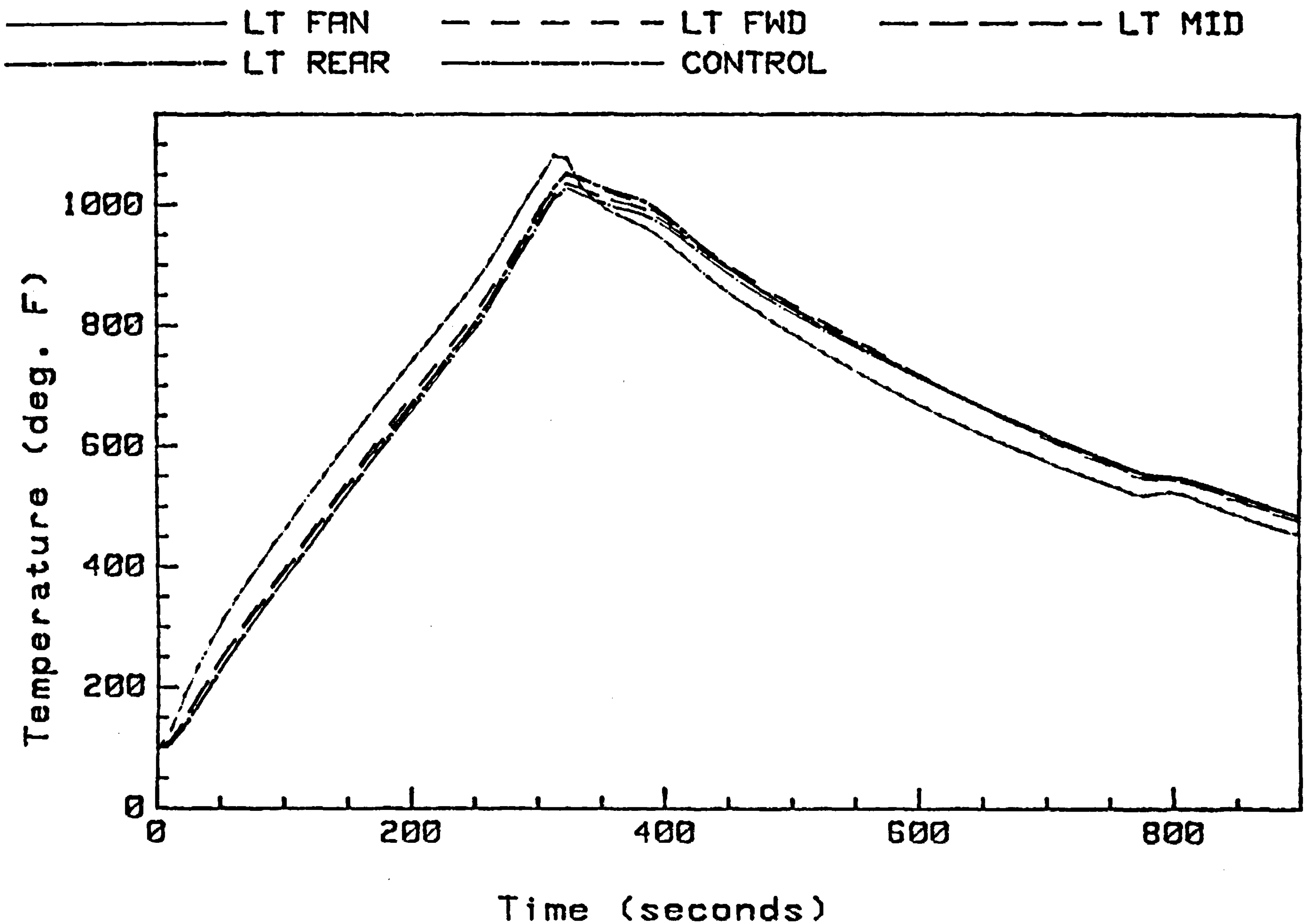


Figure 2. Temperature Profile--Chamber Left Side

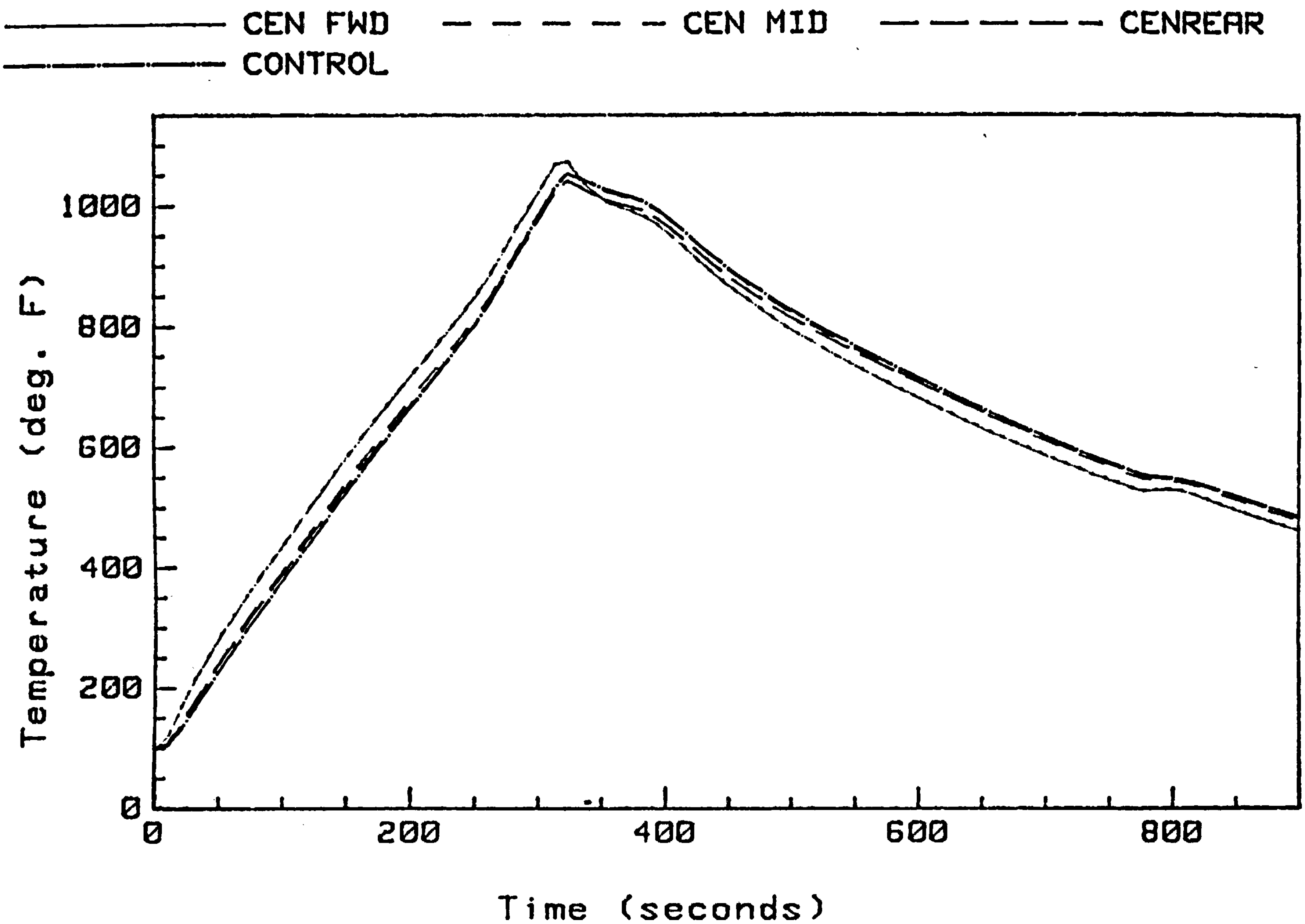


Figure 3. Temperature Profile--Chamber Center Line

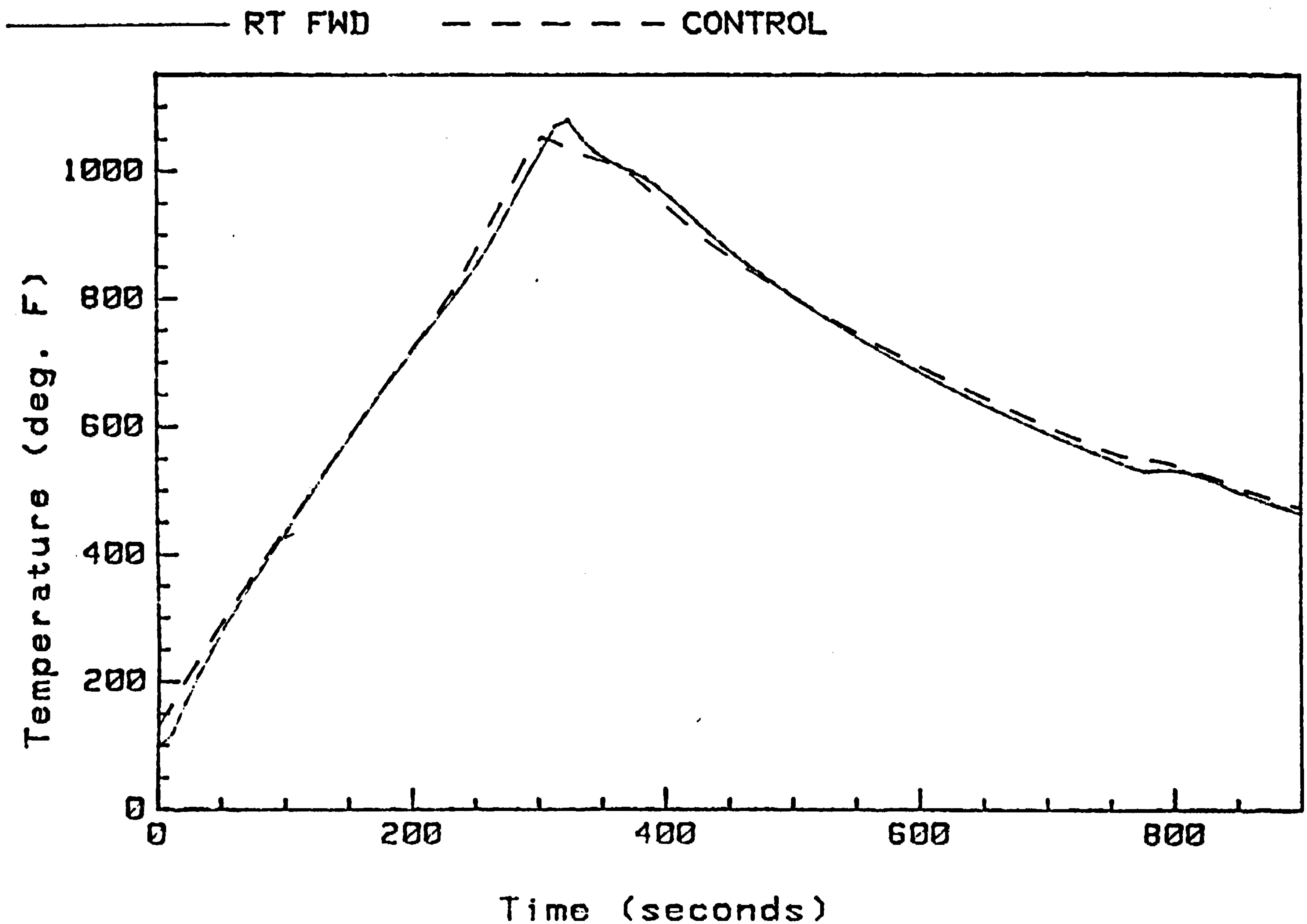


Figure 4. Thermal Lag--30 Second Time Shift

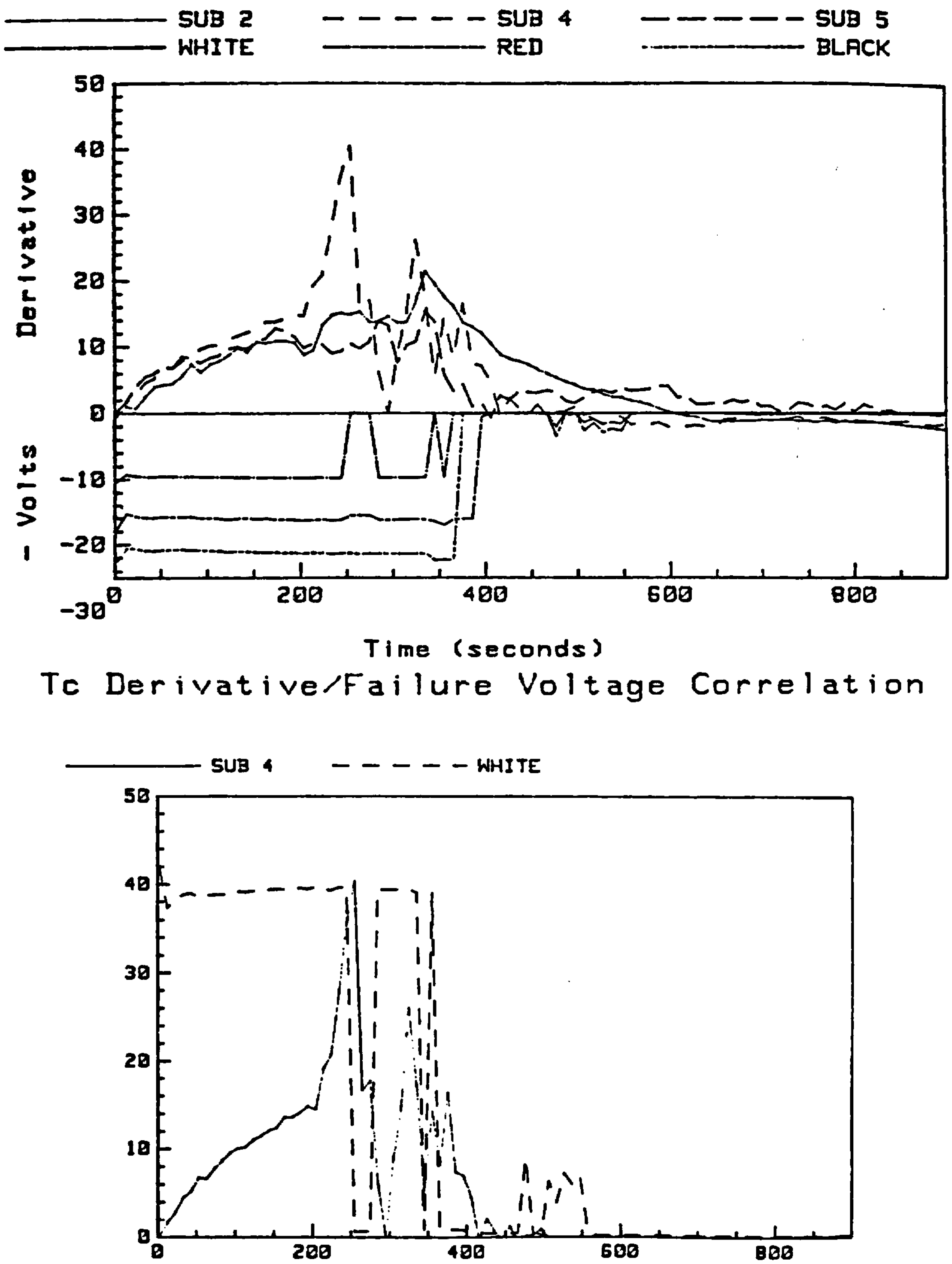


Figure 5. Temperature Derivatives Versus Failure Voltages, Correlation for Cable Conductors (Top) and Cable Temperature Under the Jacket (SUB4) Versus White Conductor Voltage Profile (Bottom)

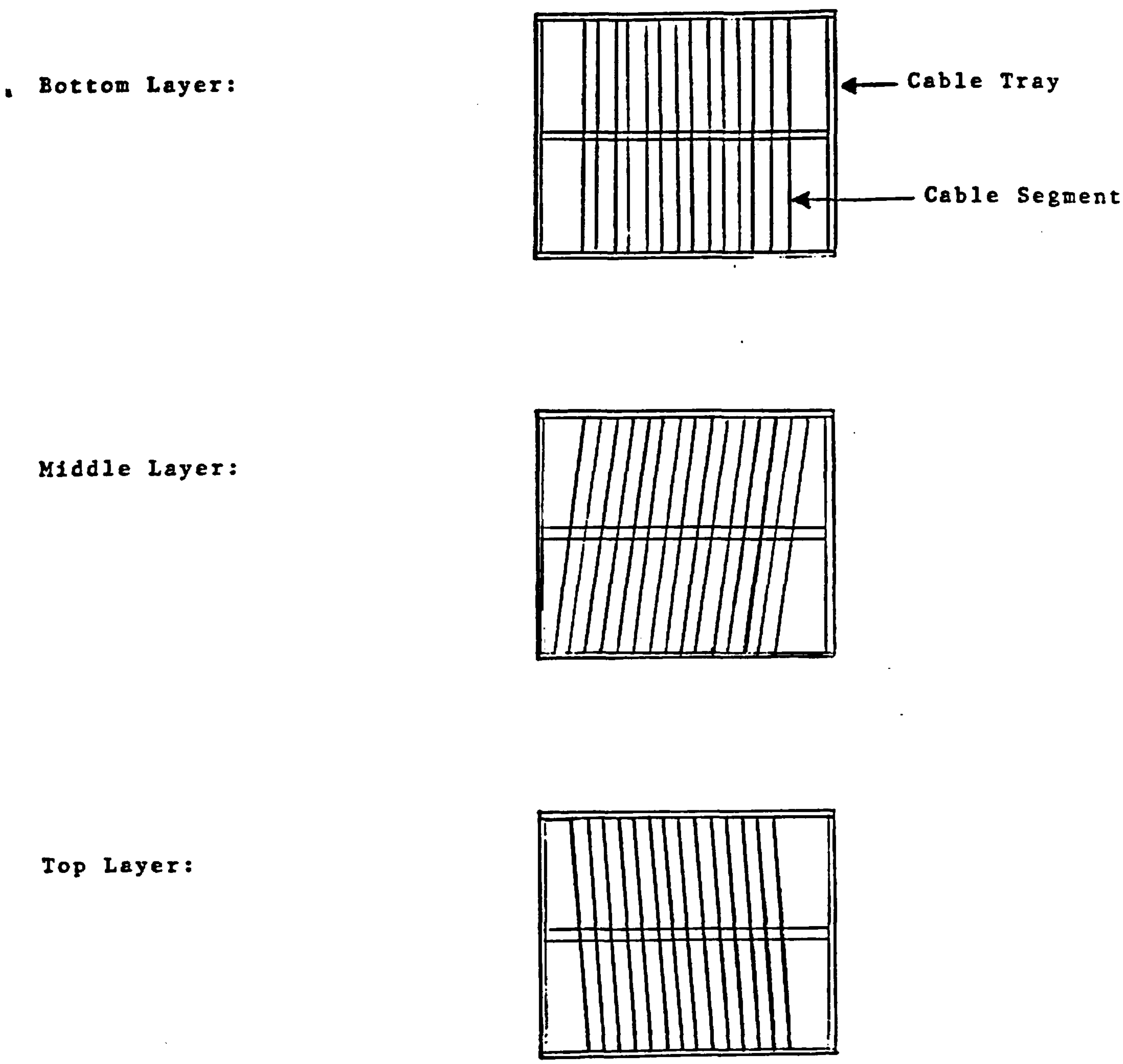
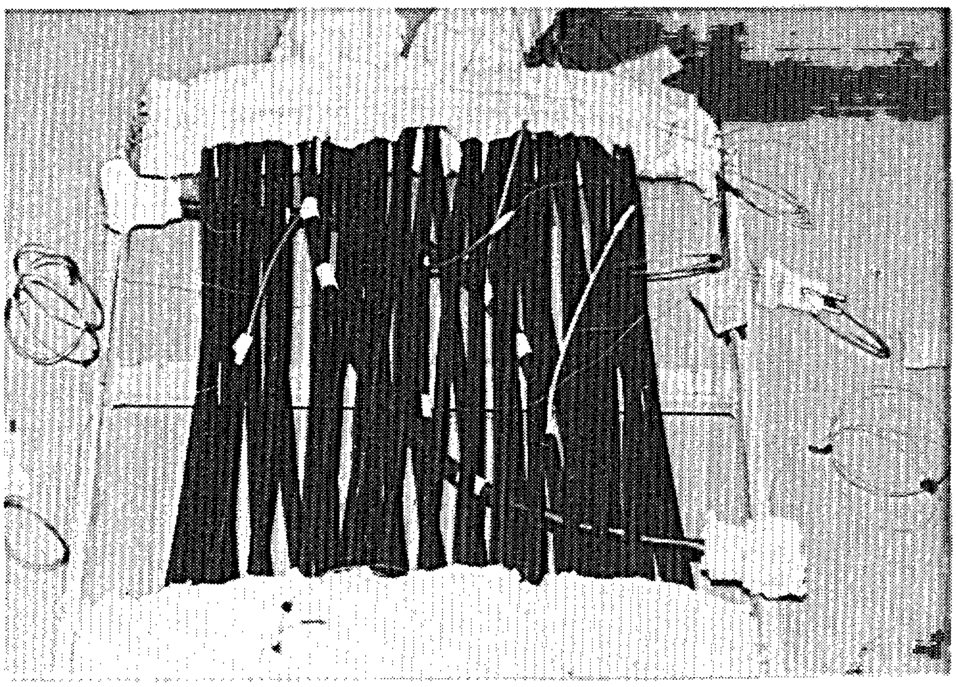


Figure 6. Cable Tray Cable Segment Layout



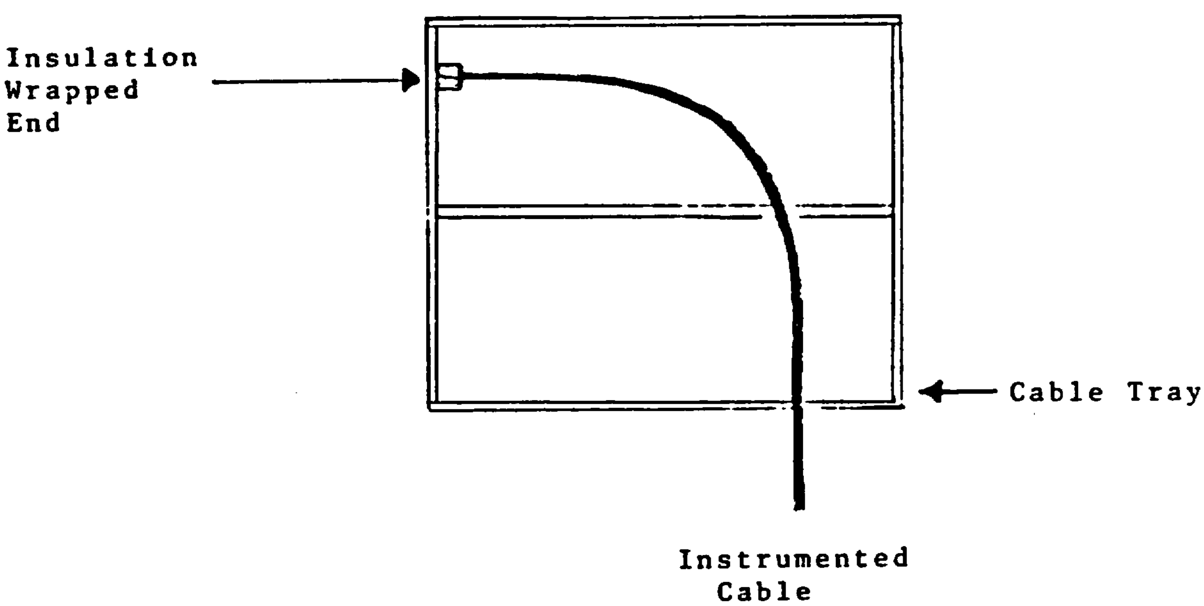
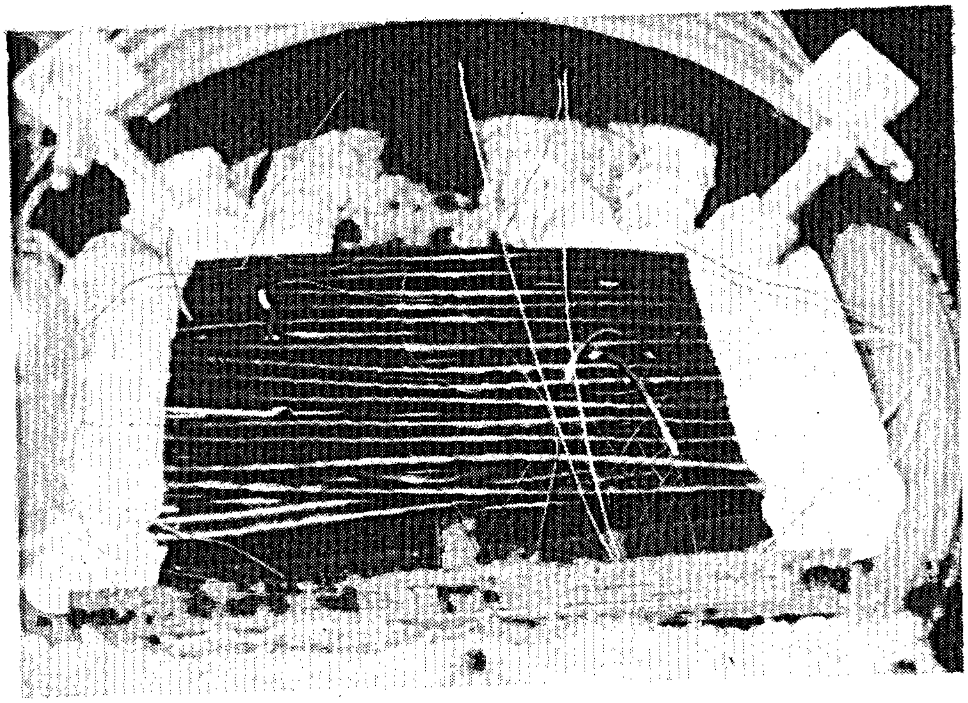


Figure 7. Instrumented Cable Placement in Cable Tray (Tests A and B)



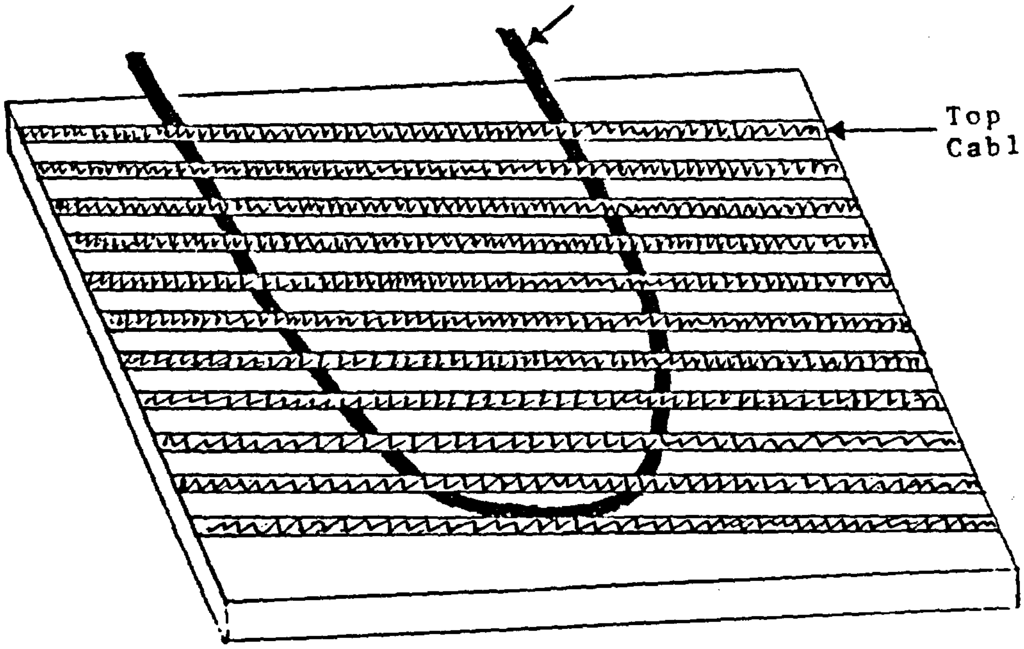
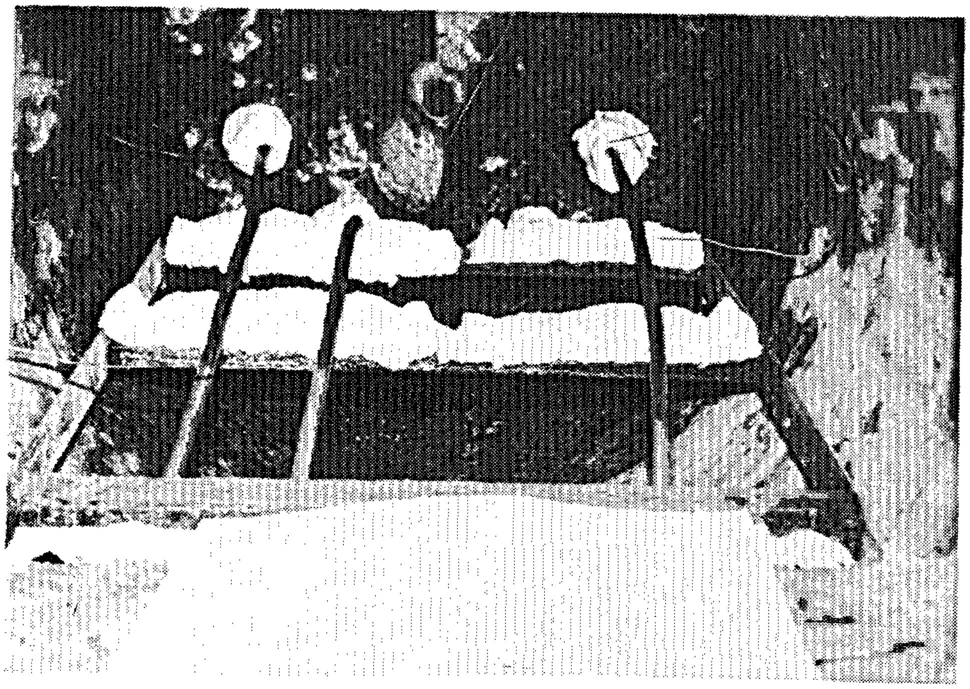


Figure 8. Instrumented Cable Placement in Cable Tray (Tests 1-6)



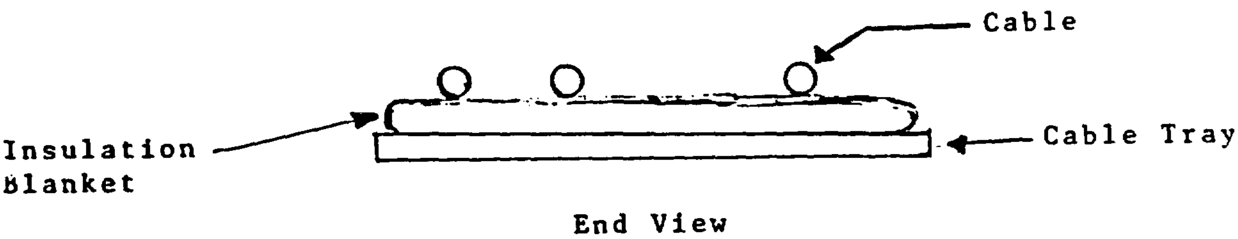
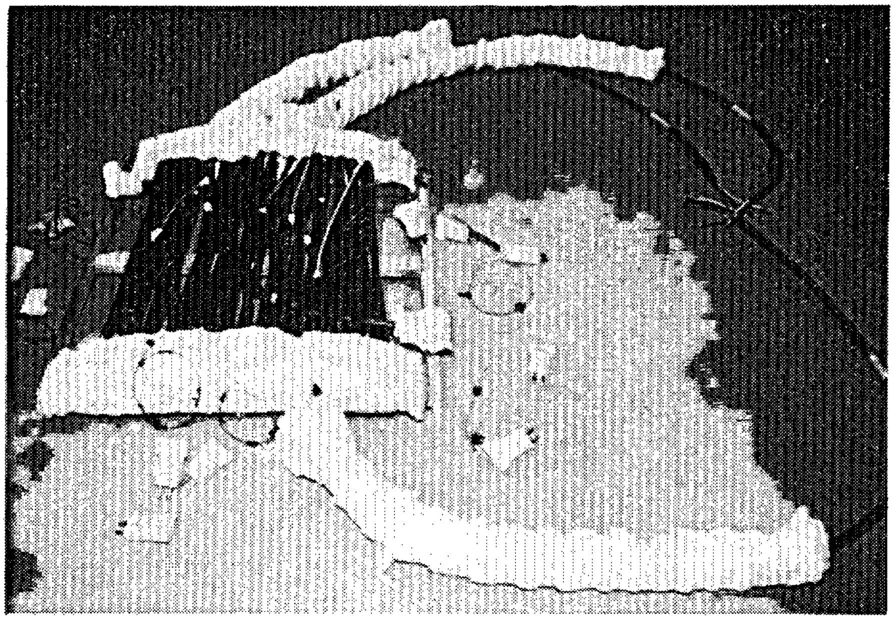


Figure 9. Insulation Blanket Placement for Individual Cable Tests



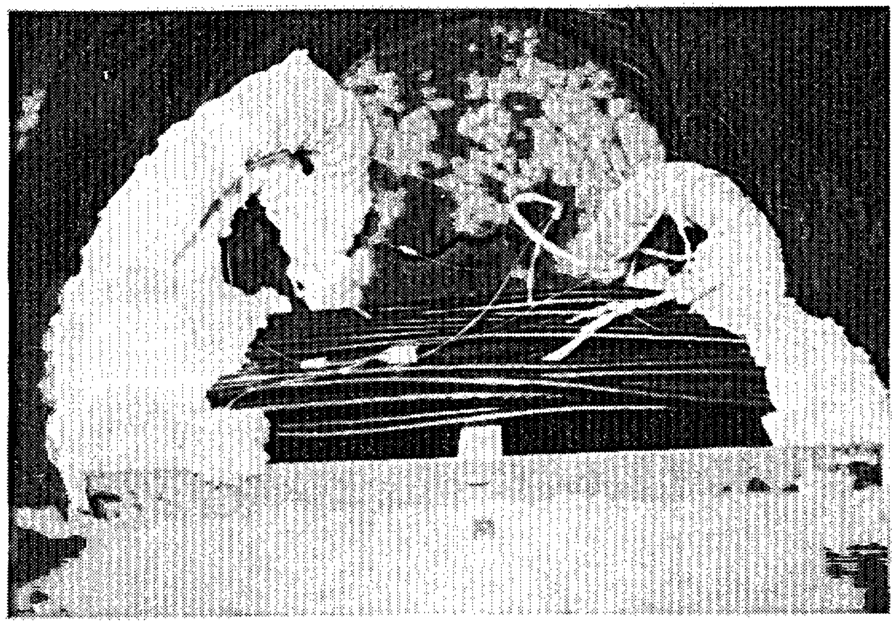
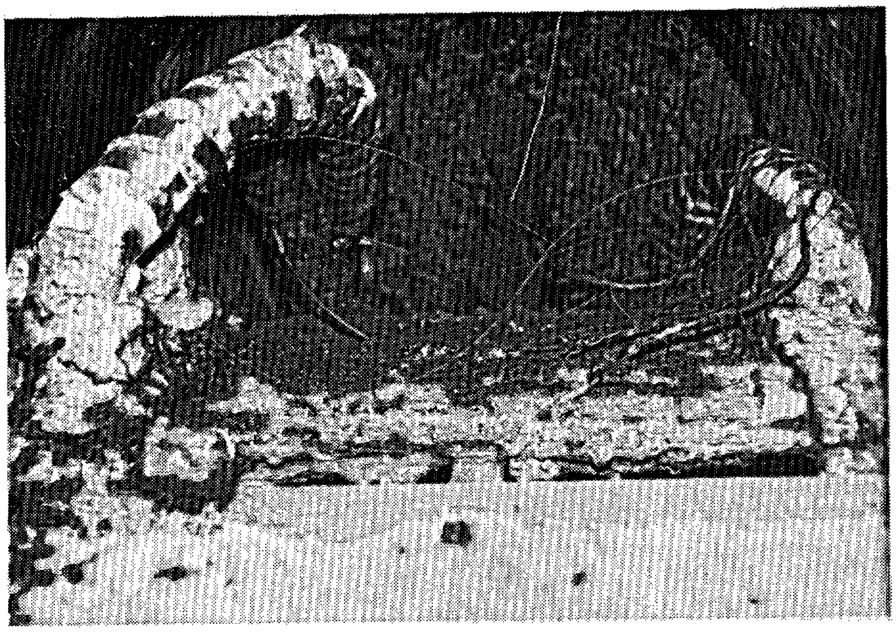


Figure 10. Unqualified Cable Prior to Exposure, Test A



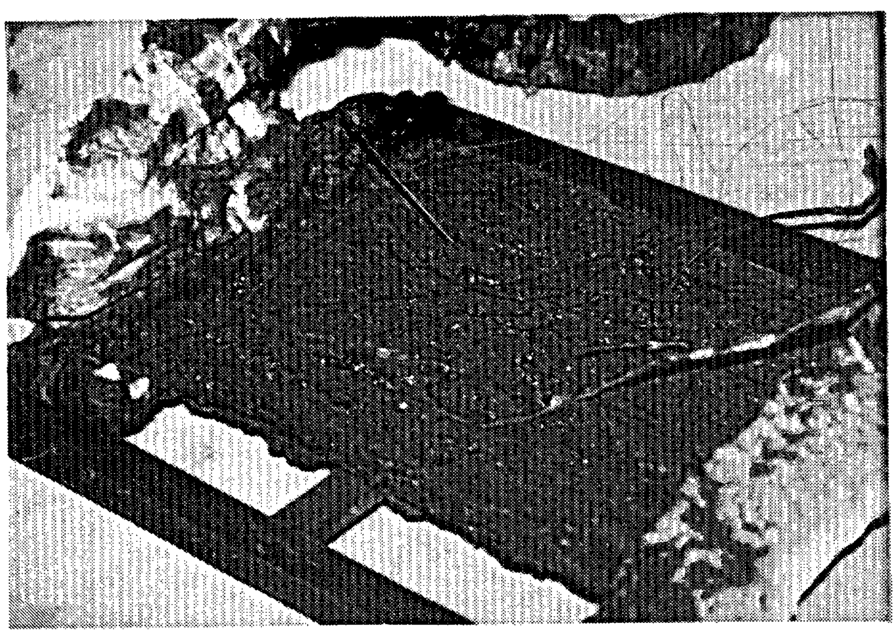
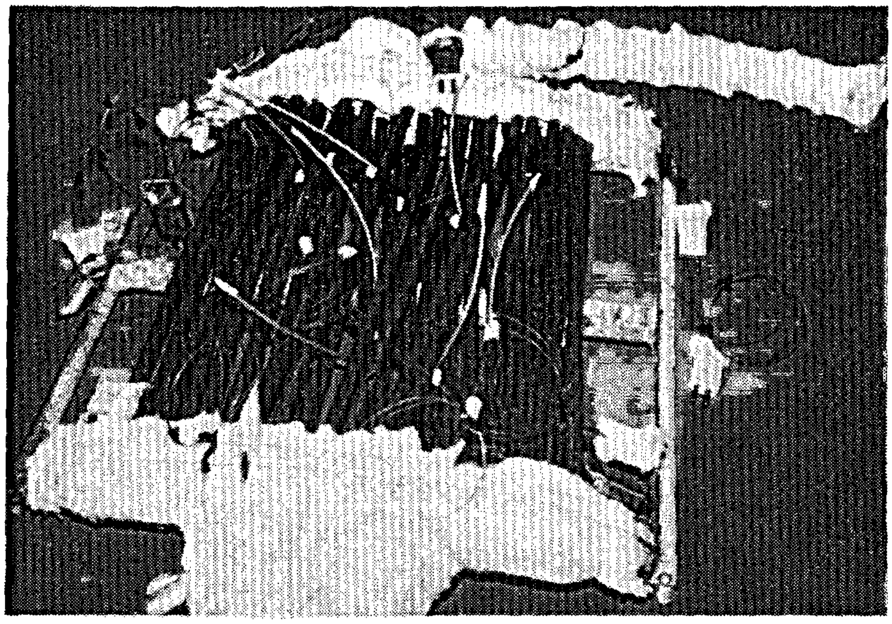


Figure 11. Unqualified Cable After Exposure, Test A



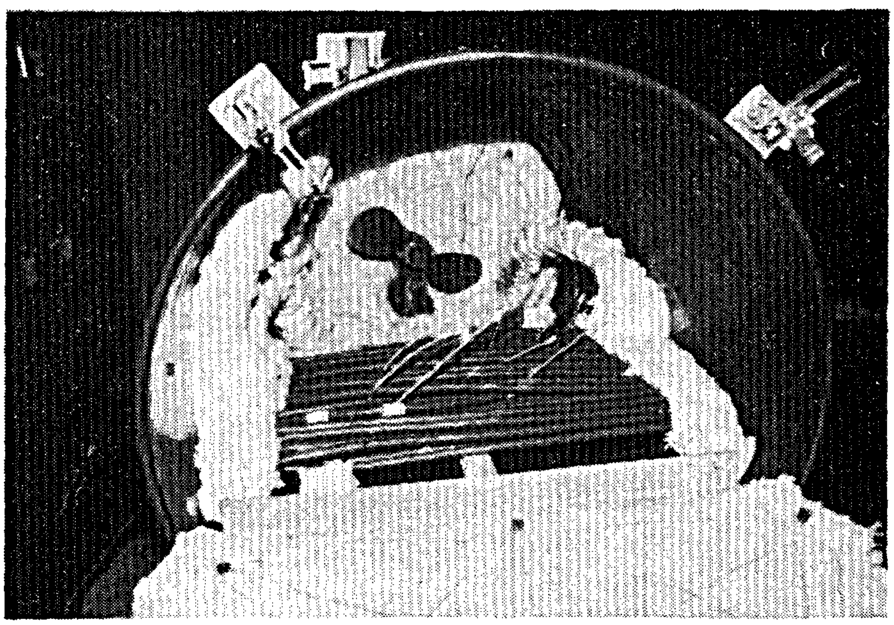
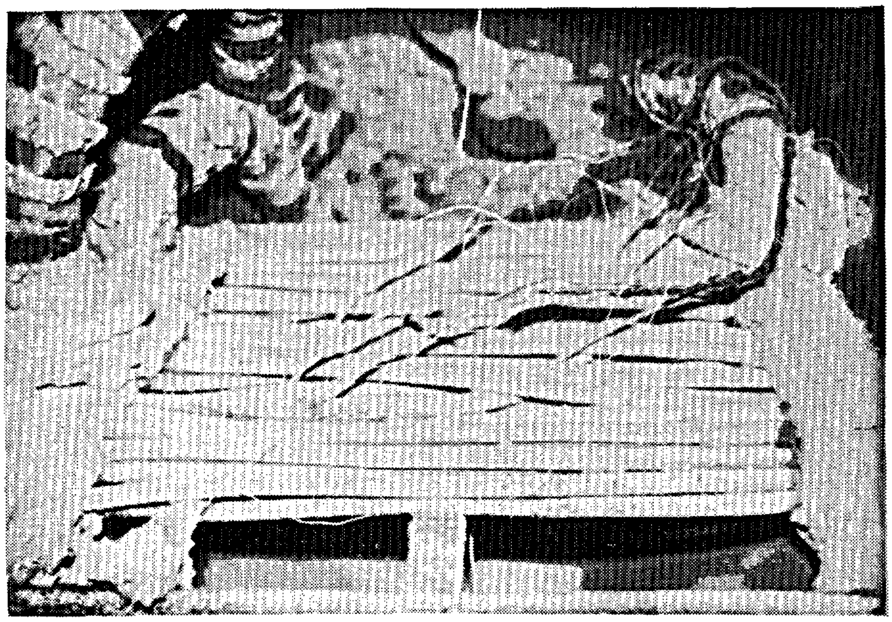


Figure 12. Qualified Cable Prior to Exposure, Test B



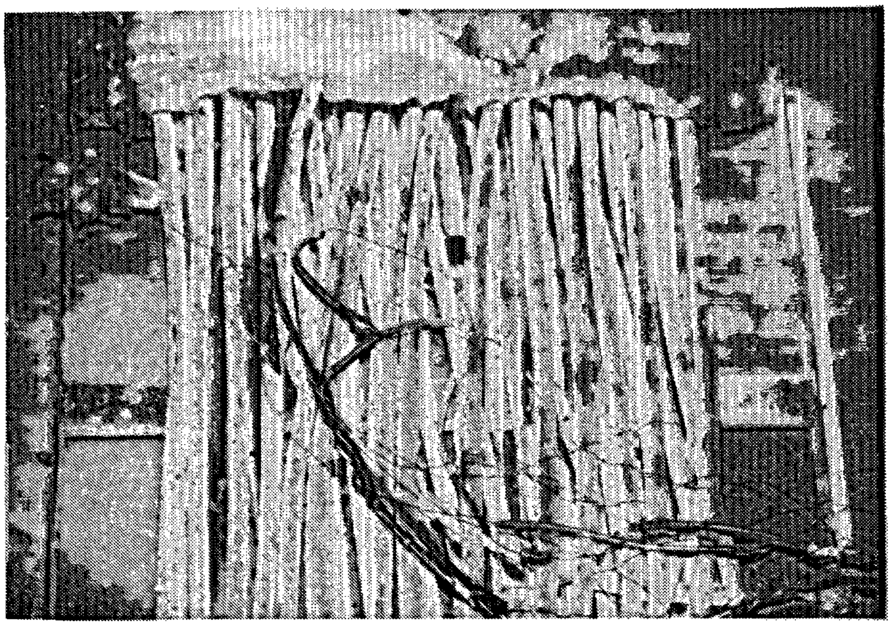


Figure 13. Qualified Cable After Exposure, Test B

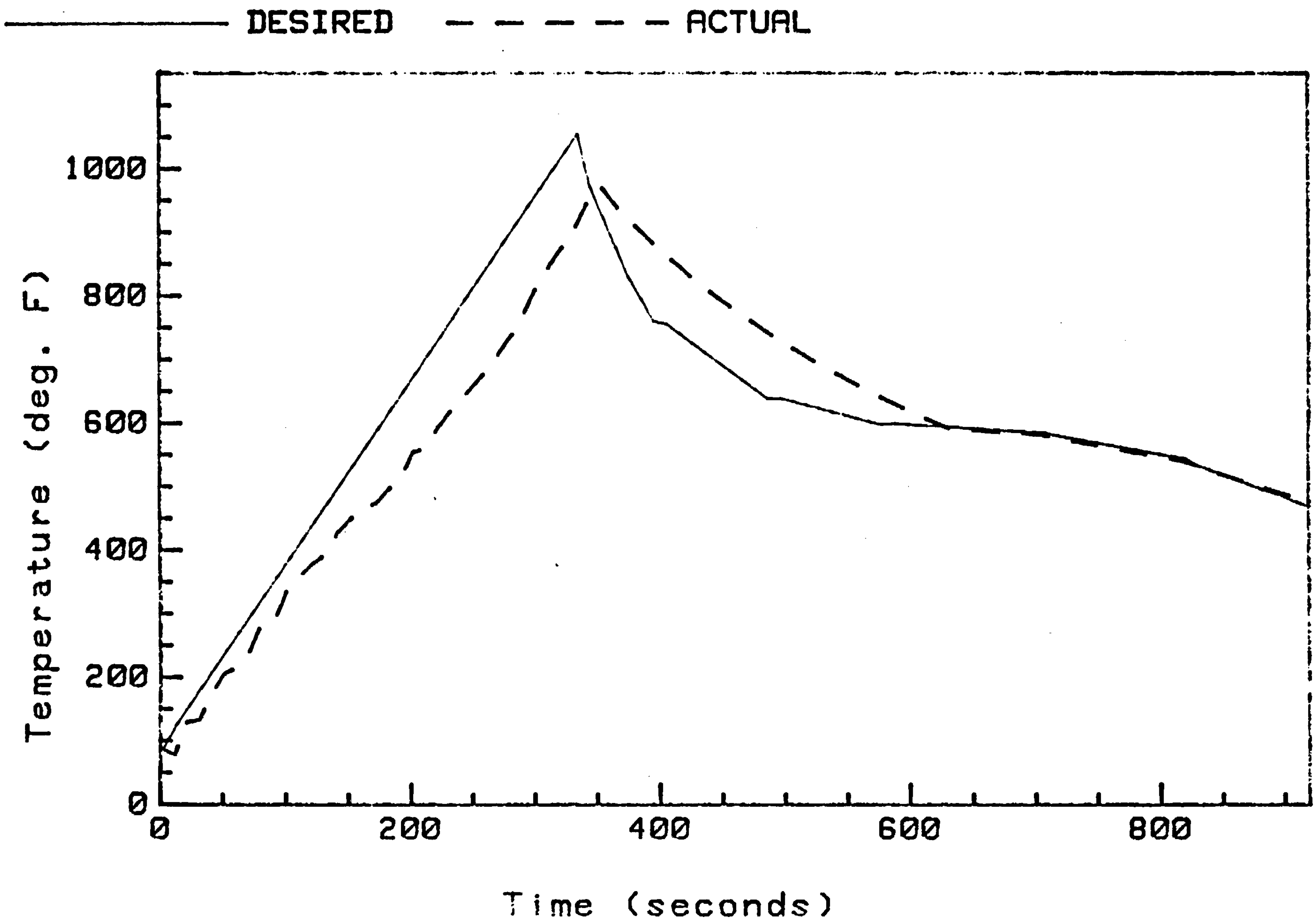


Figure 14. Test A: Temperature Profiles

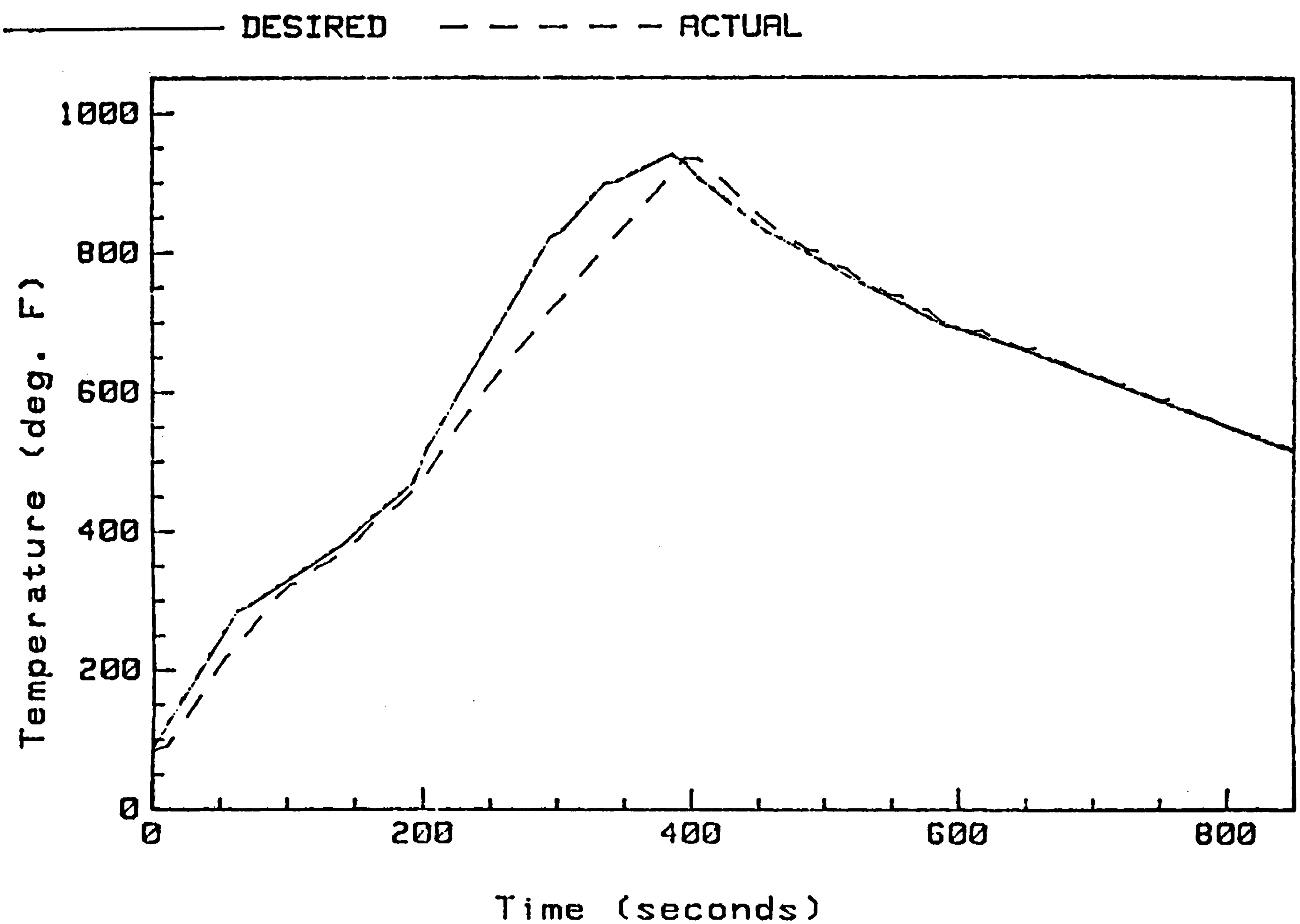


Figure 15. Test B: Temperature Profiles

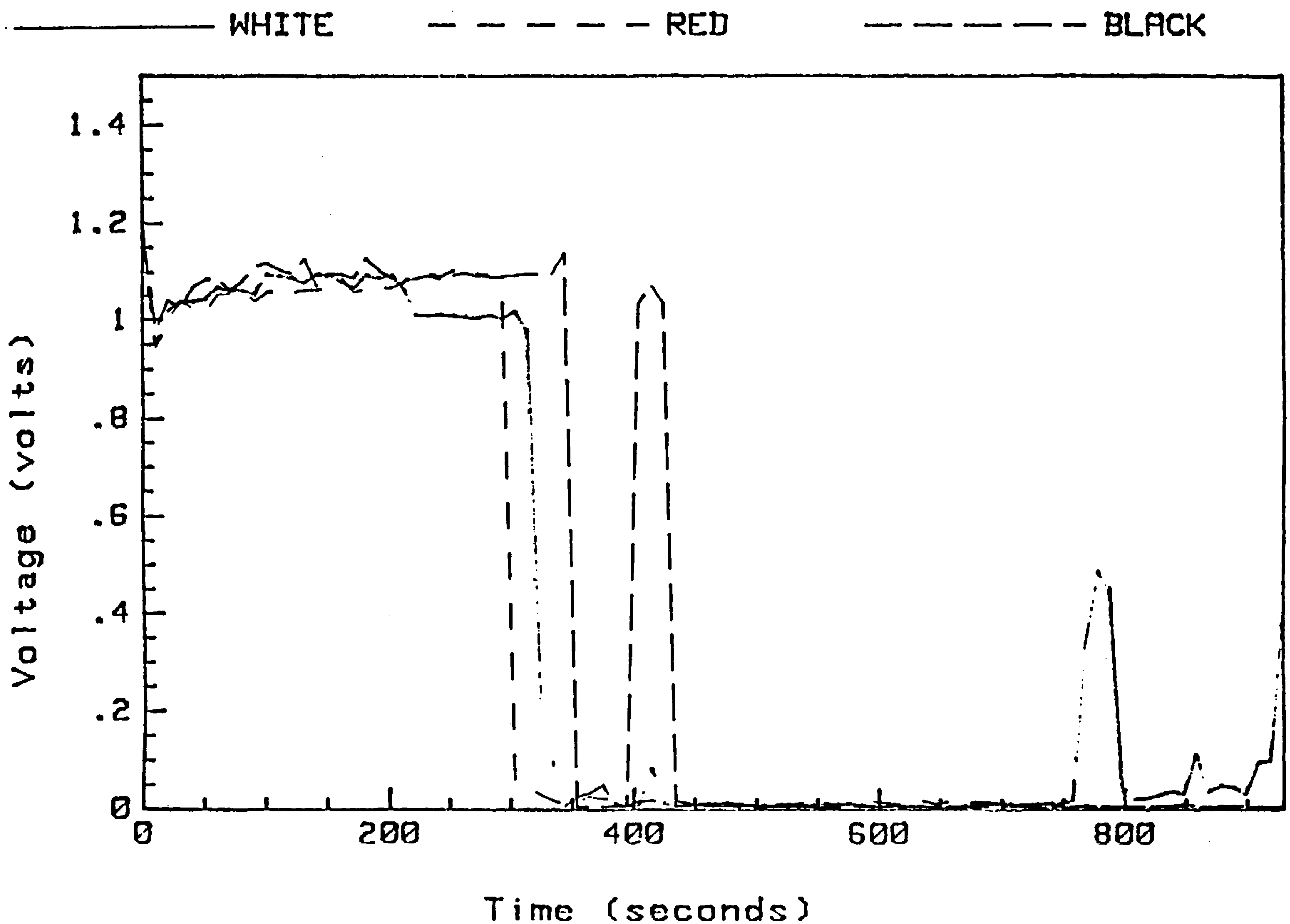


Figure 16. Test A: Top Cable Voltages

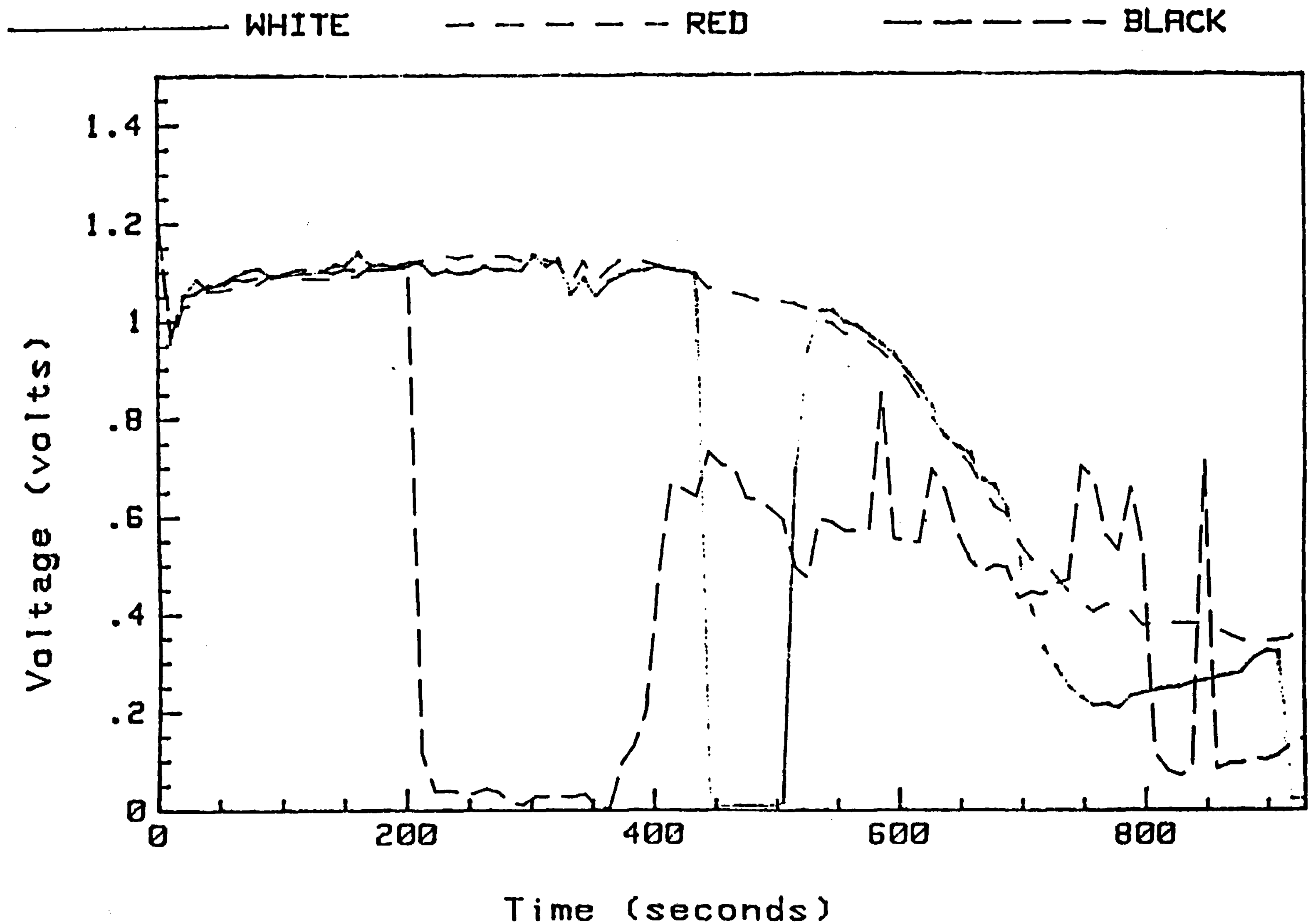


Figure 17. Test A: Middle Cable Voltages

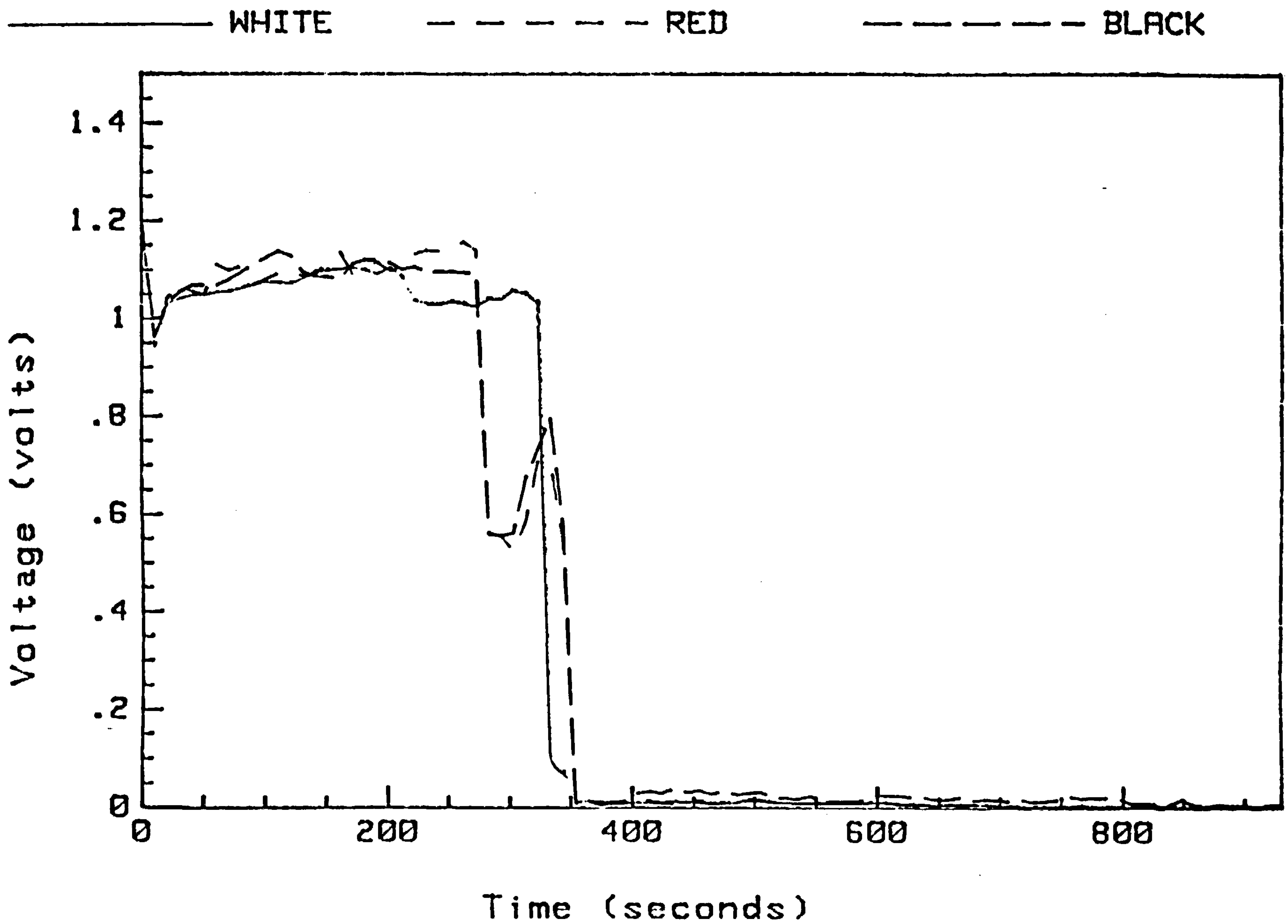


Figure 18. Test A: Straight Cable Voltages

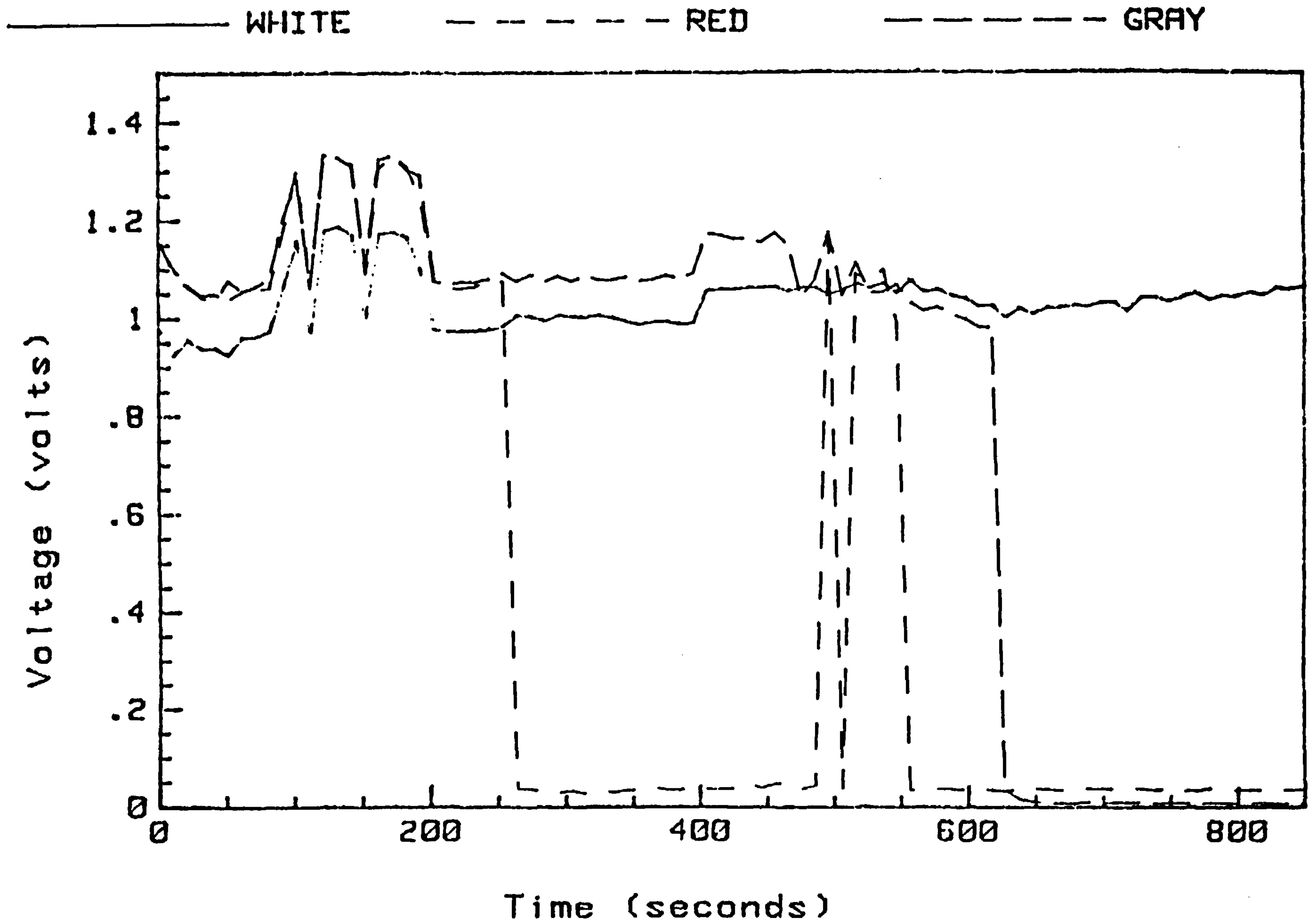


Figure 19. Test B: Top Cable Voltages

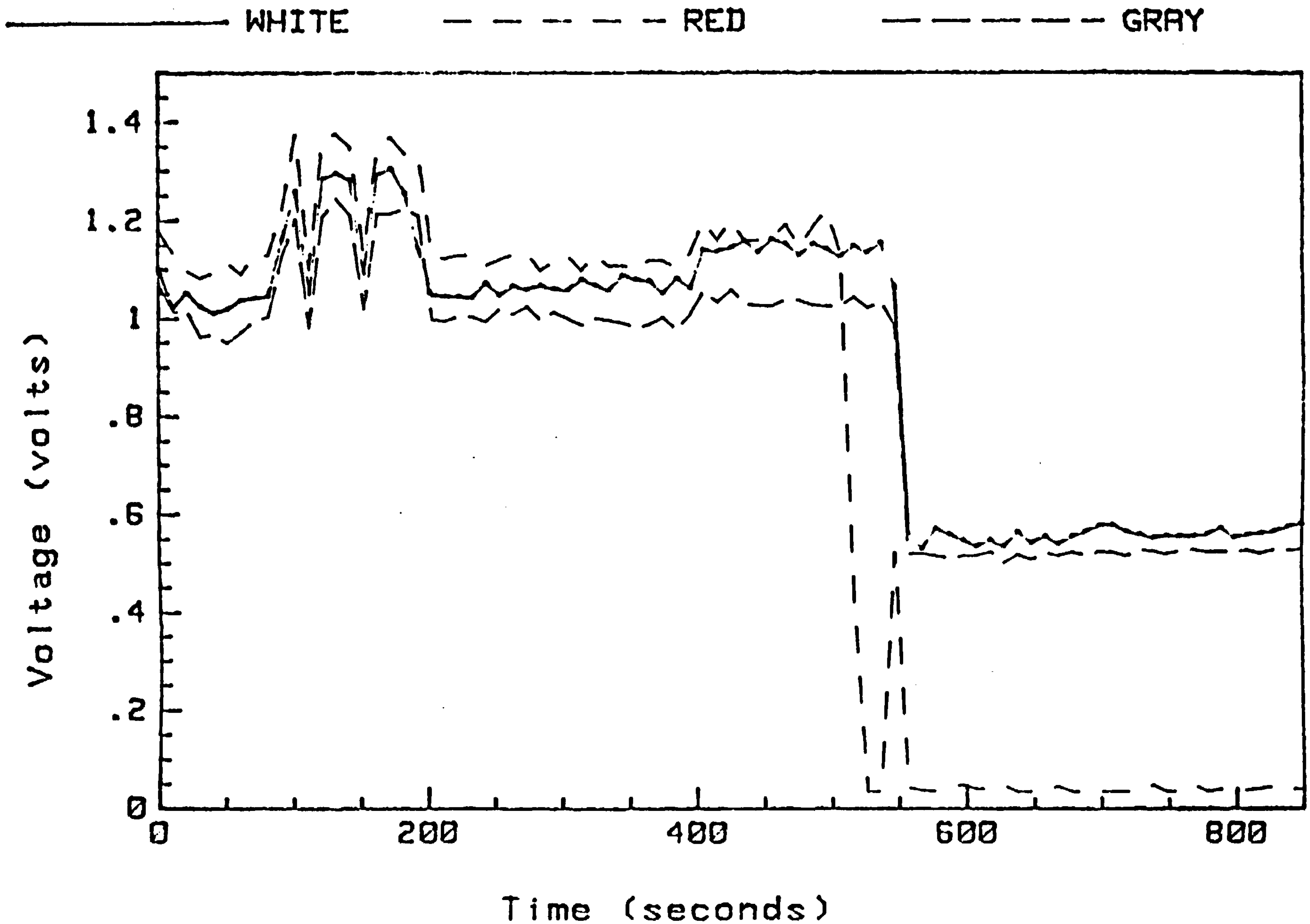


Figure 20. Test B: Middle Cable Voltages

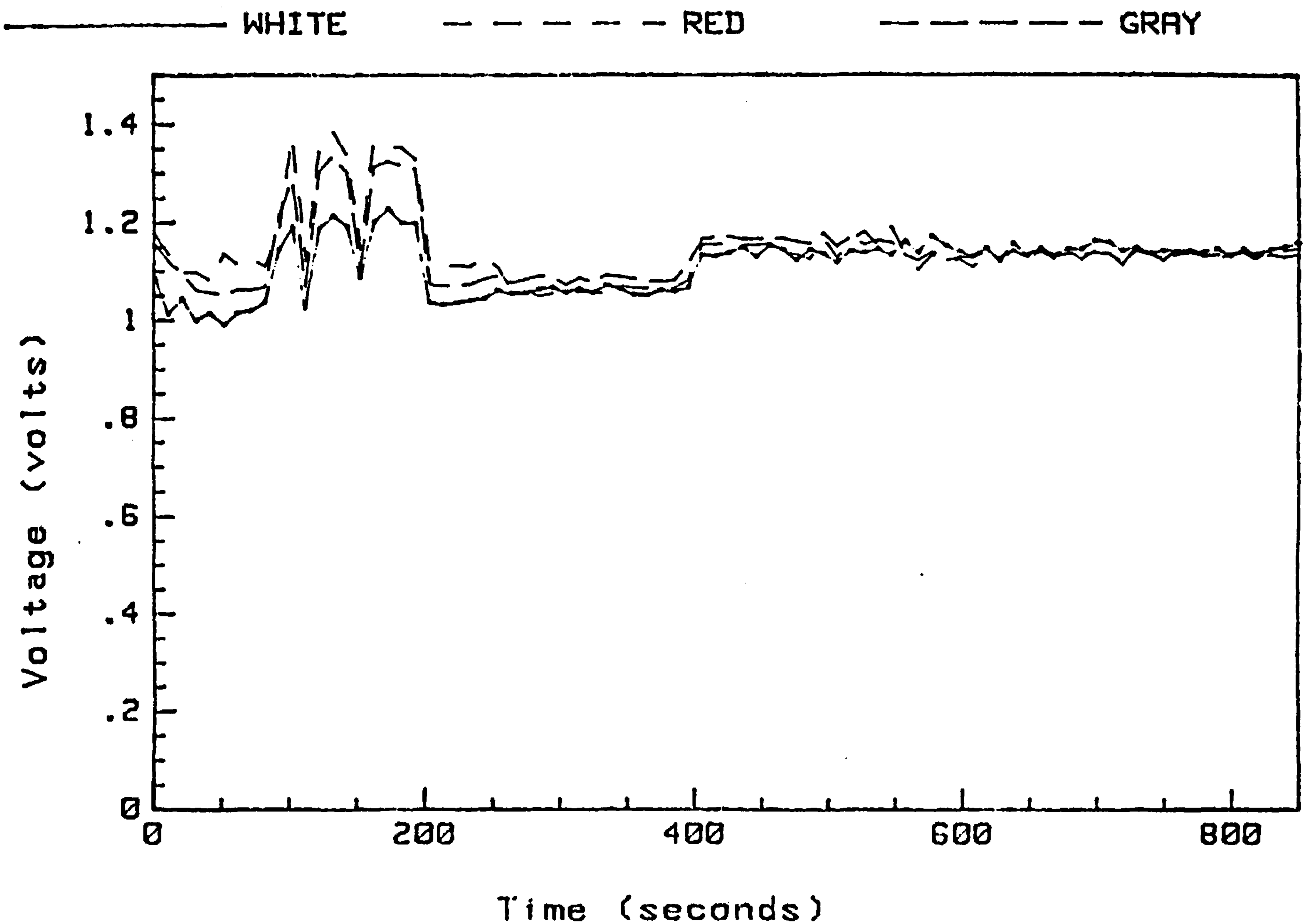


Figure 21. Test B: Straight Cable Voltages

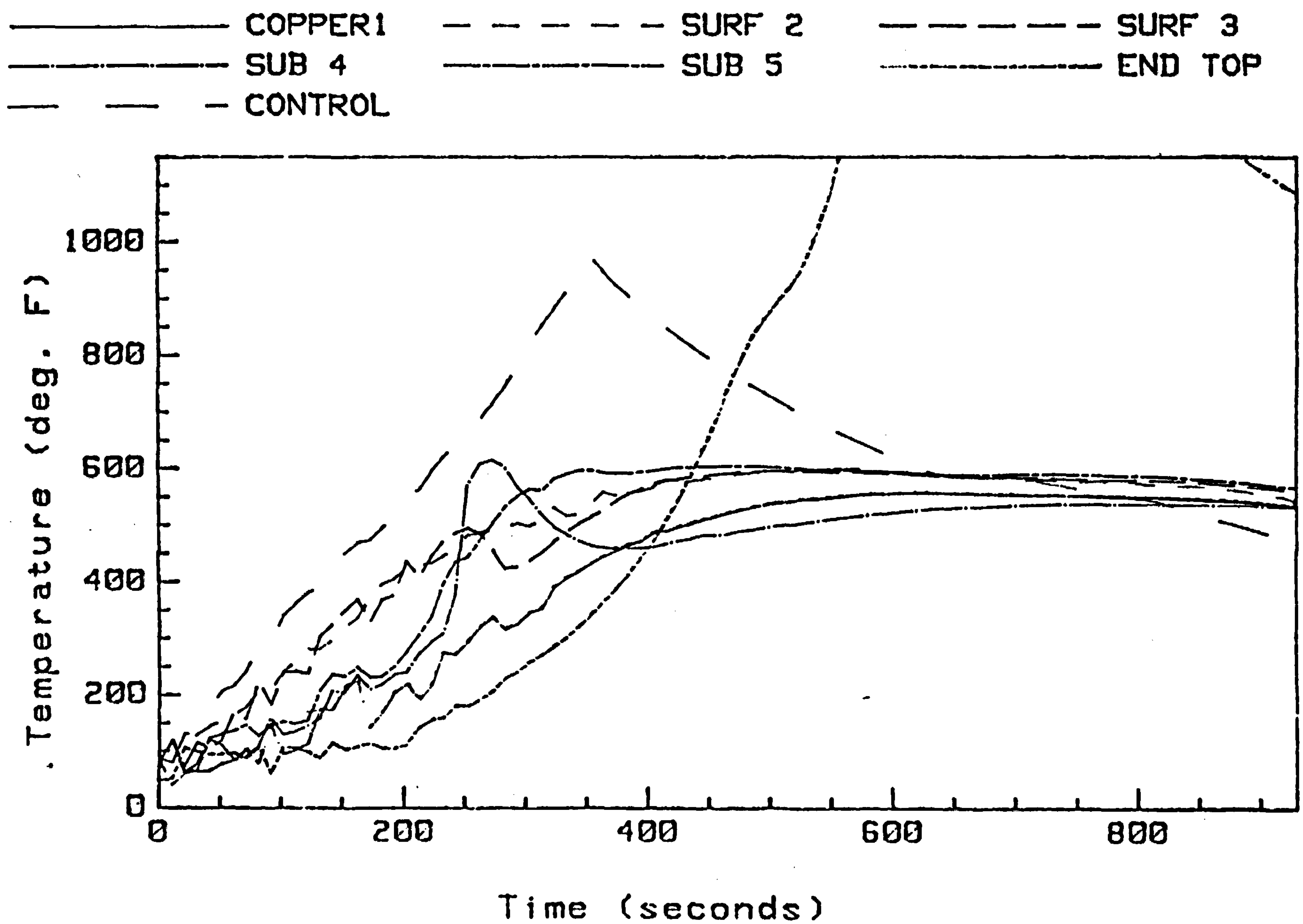
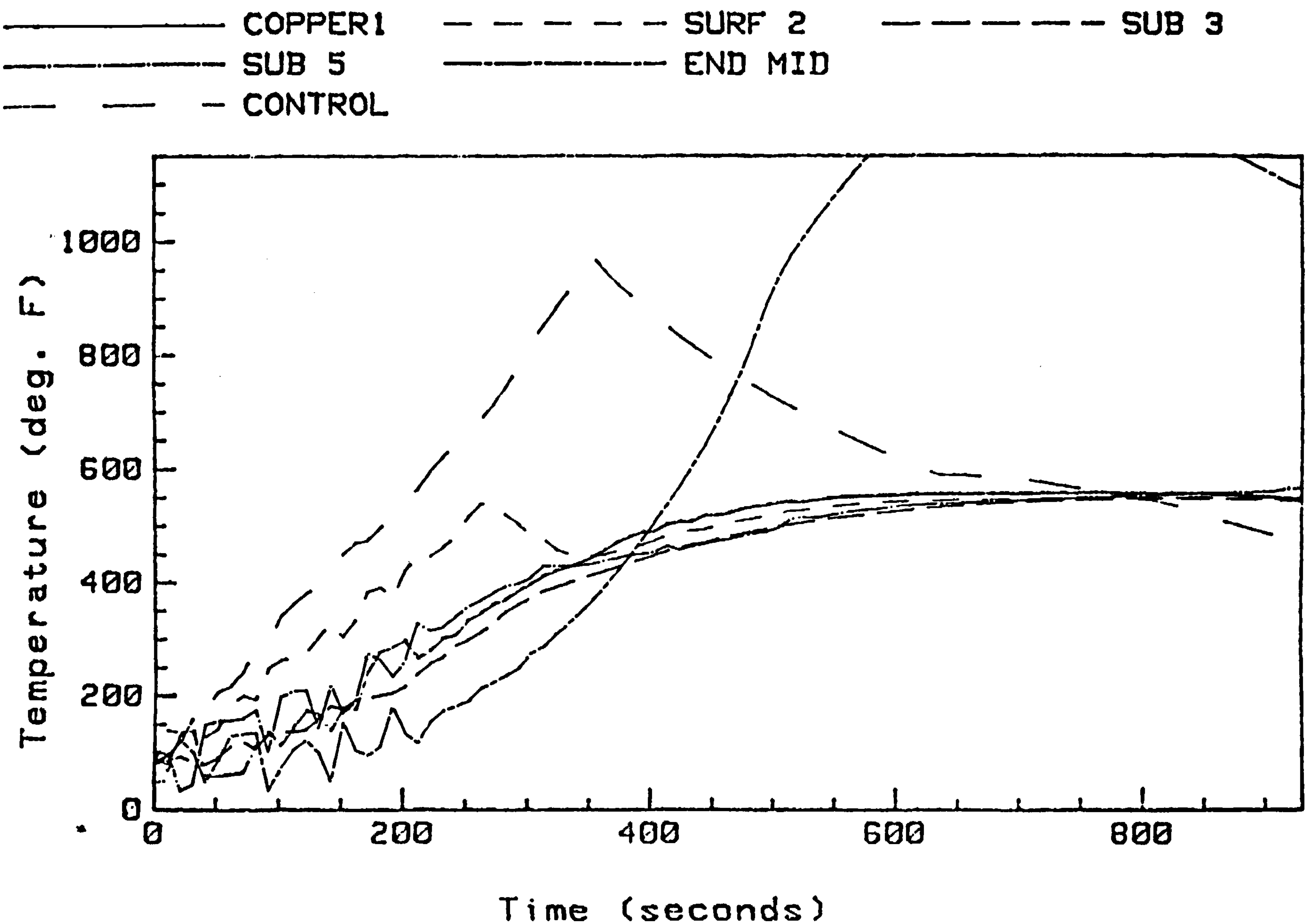


Figure 22. Test A: Top Cable Temperatures



Figures 23. Test A: Middle Cable Temperatures

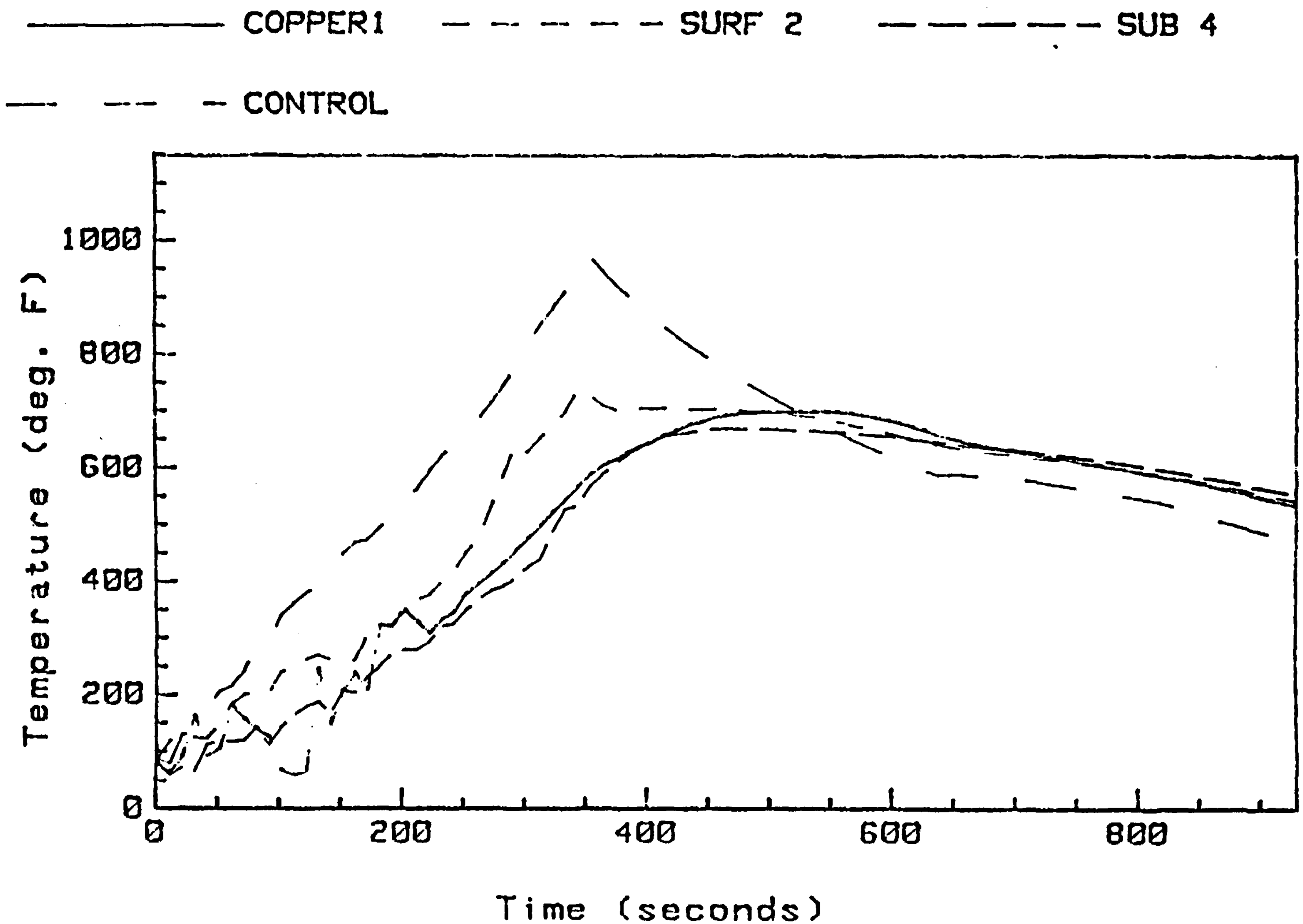


Figure 24. Test A: Straight Cable Temperatures

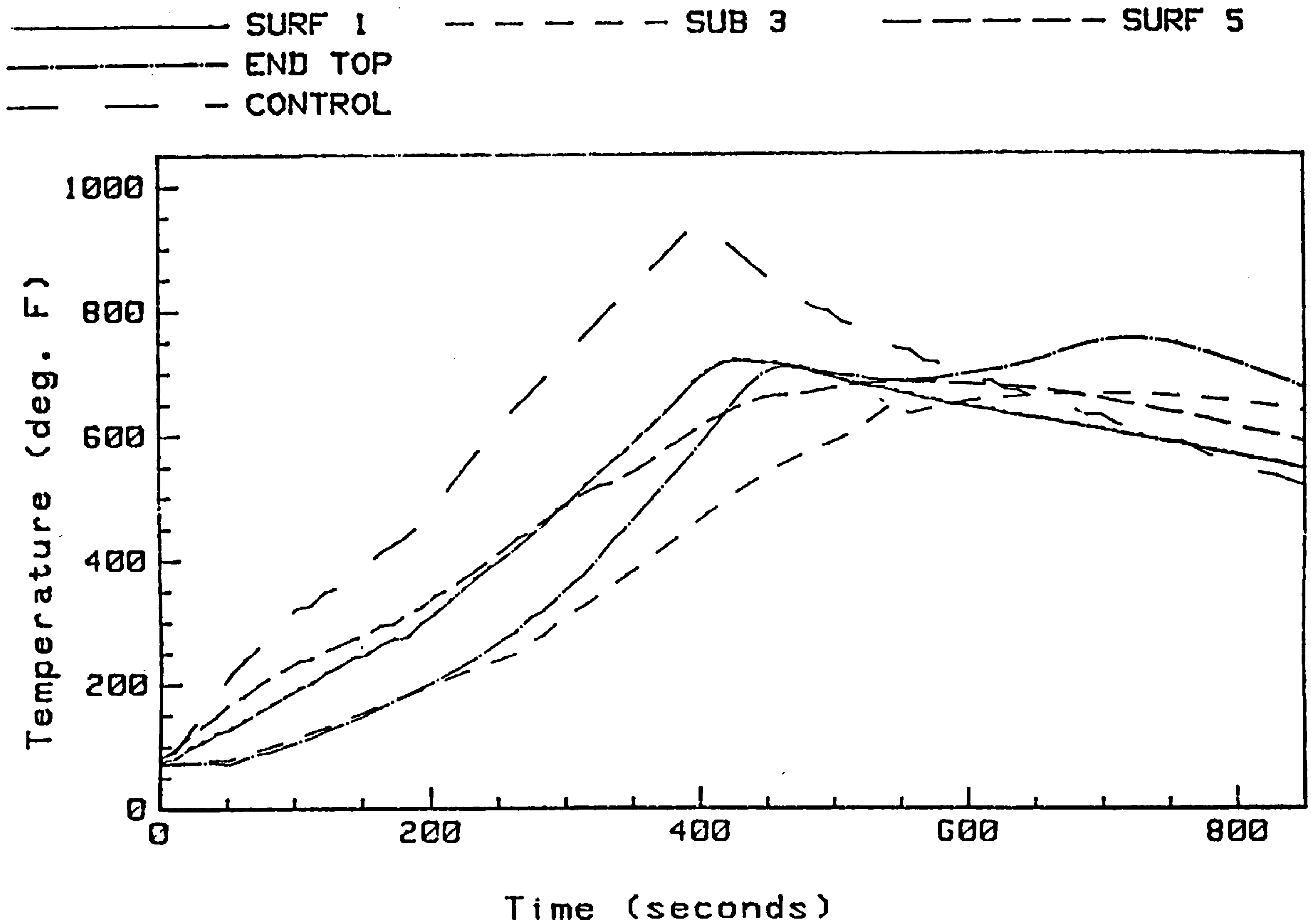


Figure 25. Test B: Top Cable Temperatures

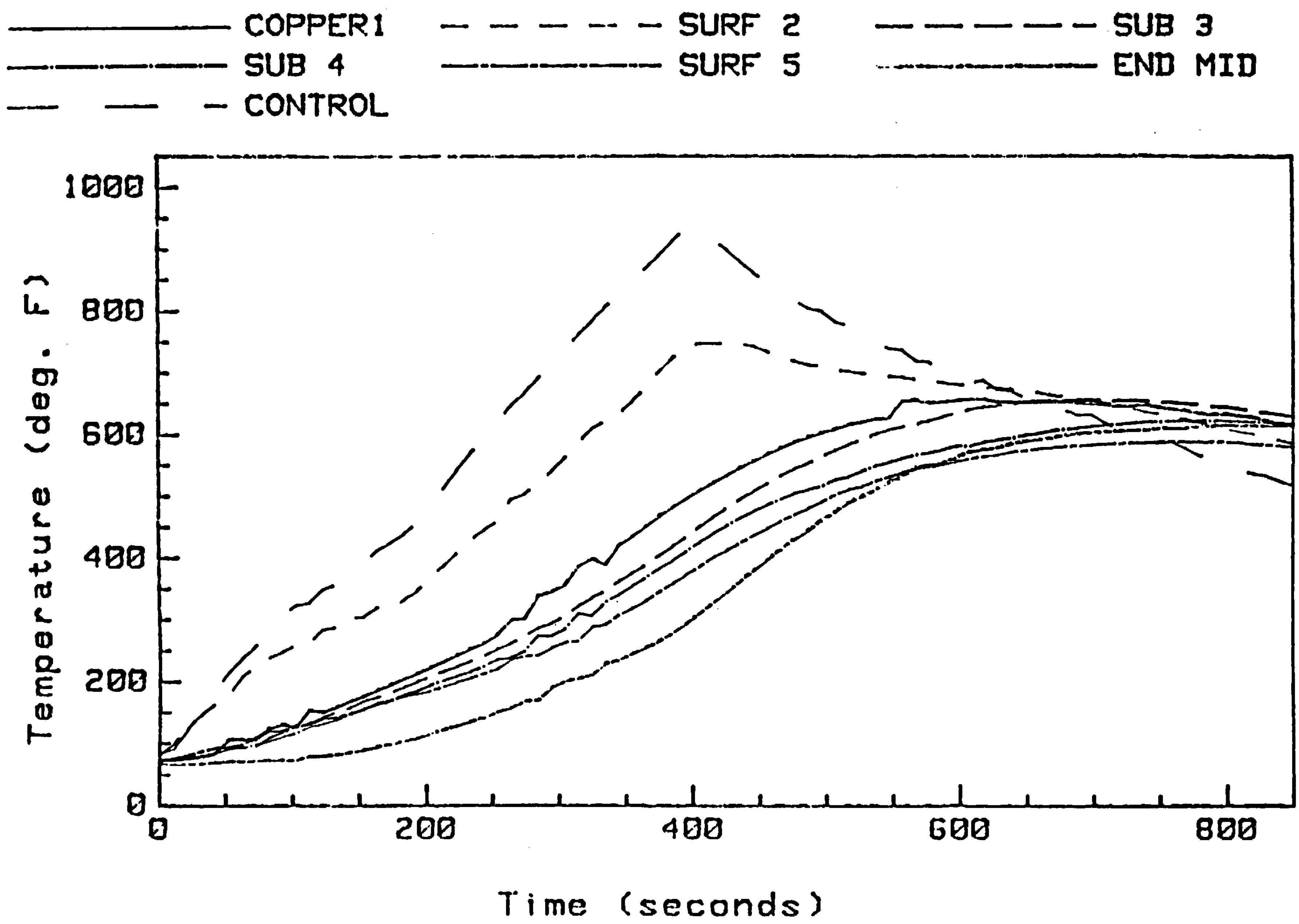


Figure 26. Test B: Middle Cable Temperatures

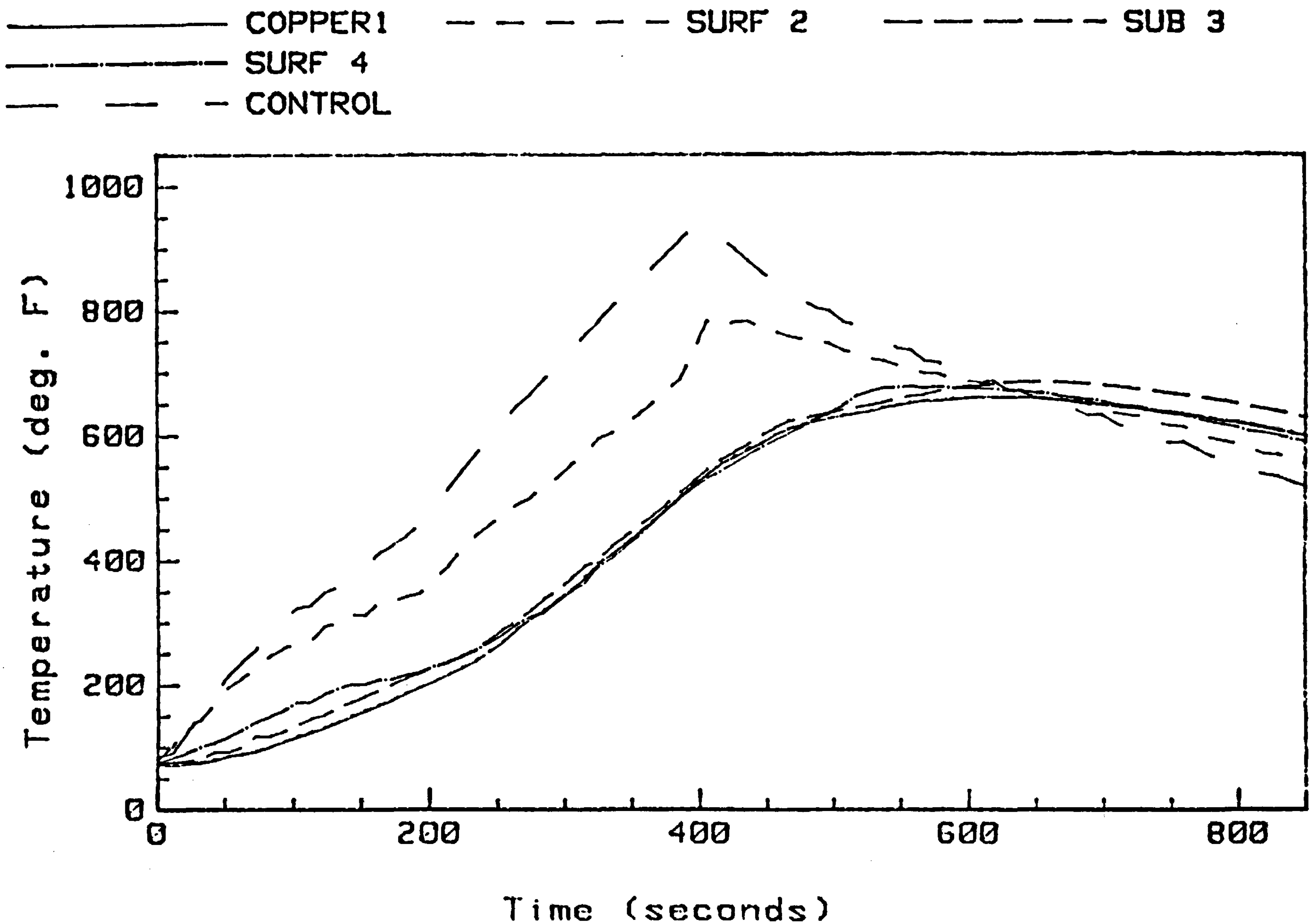


Figure 27. Test B: Straight Cable Temperatures

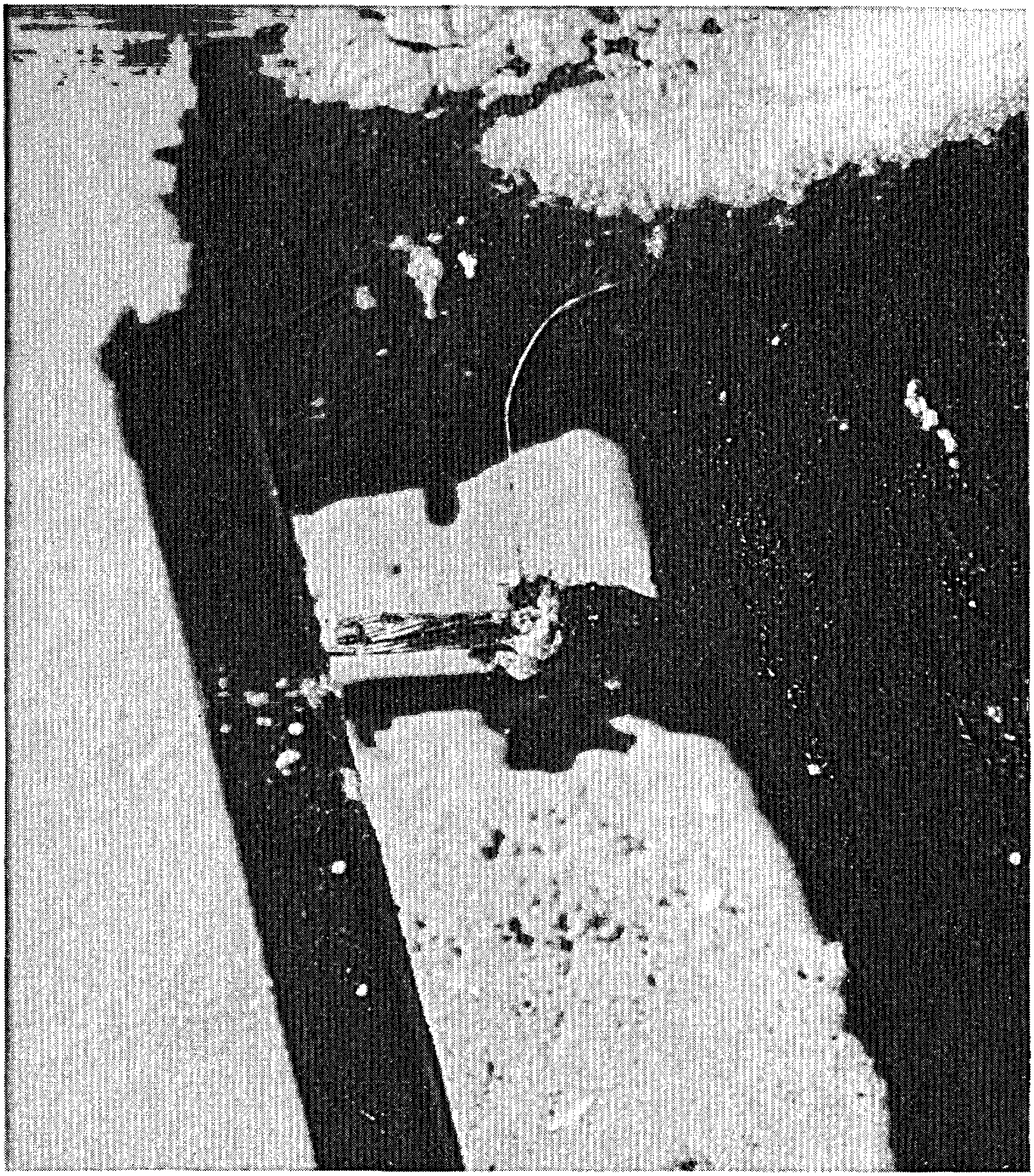


Figure 28. End Effect for Unqualified Cable, Test A

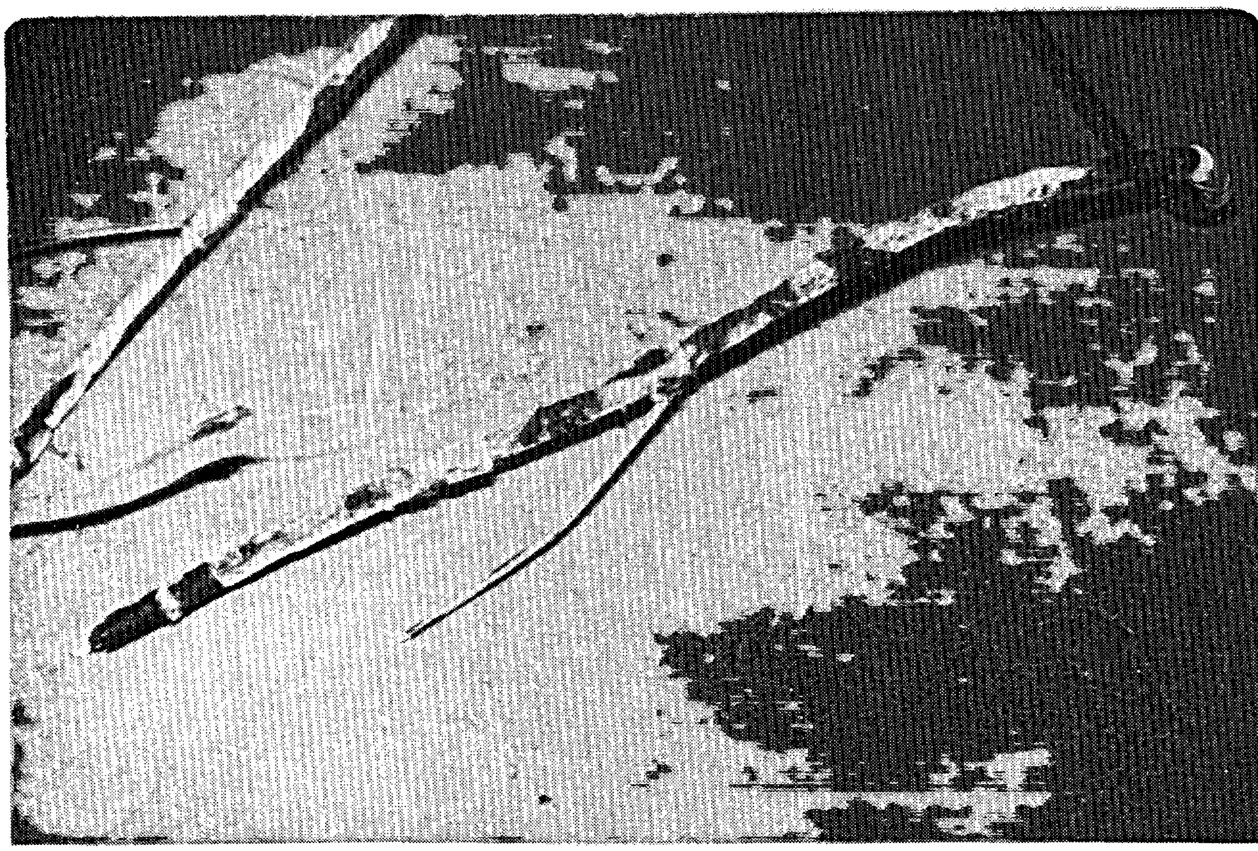
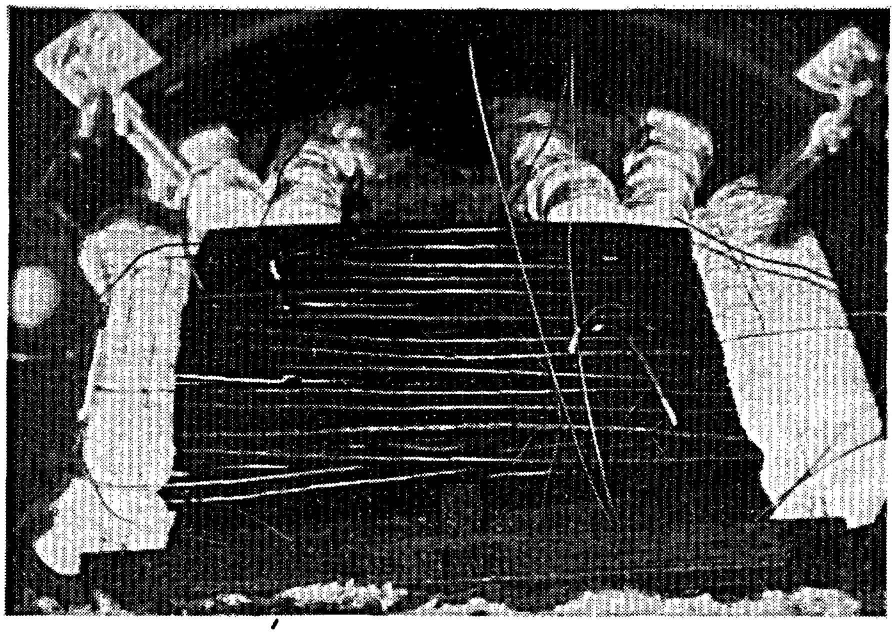


Figure 29. End Effect for Qualified Cable, Test B



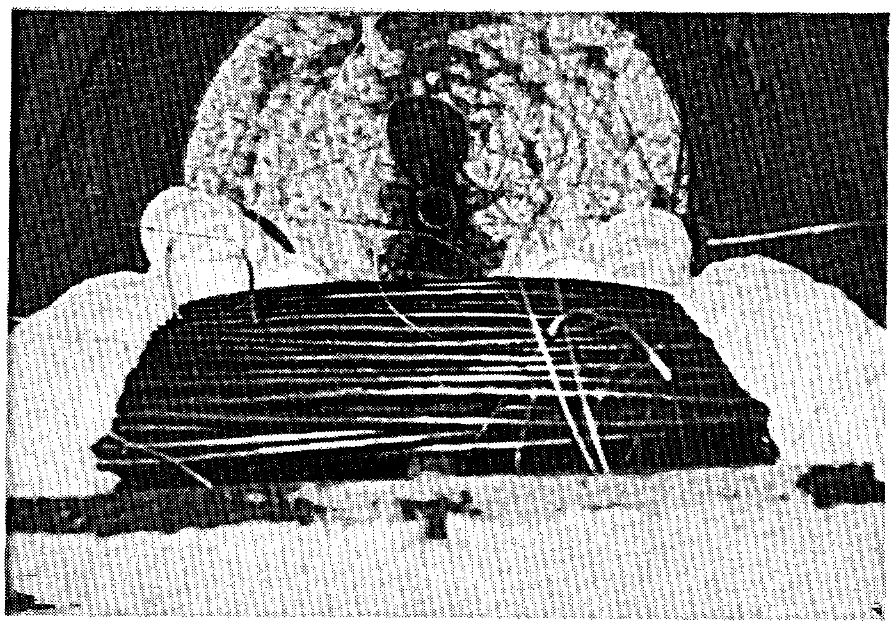


Figure 30. Unqualified Cable Prior to Exposure, Test 1

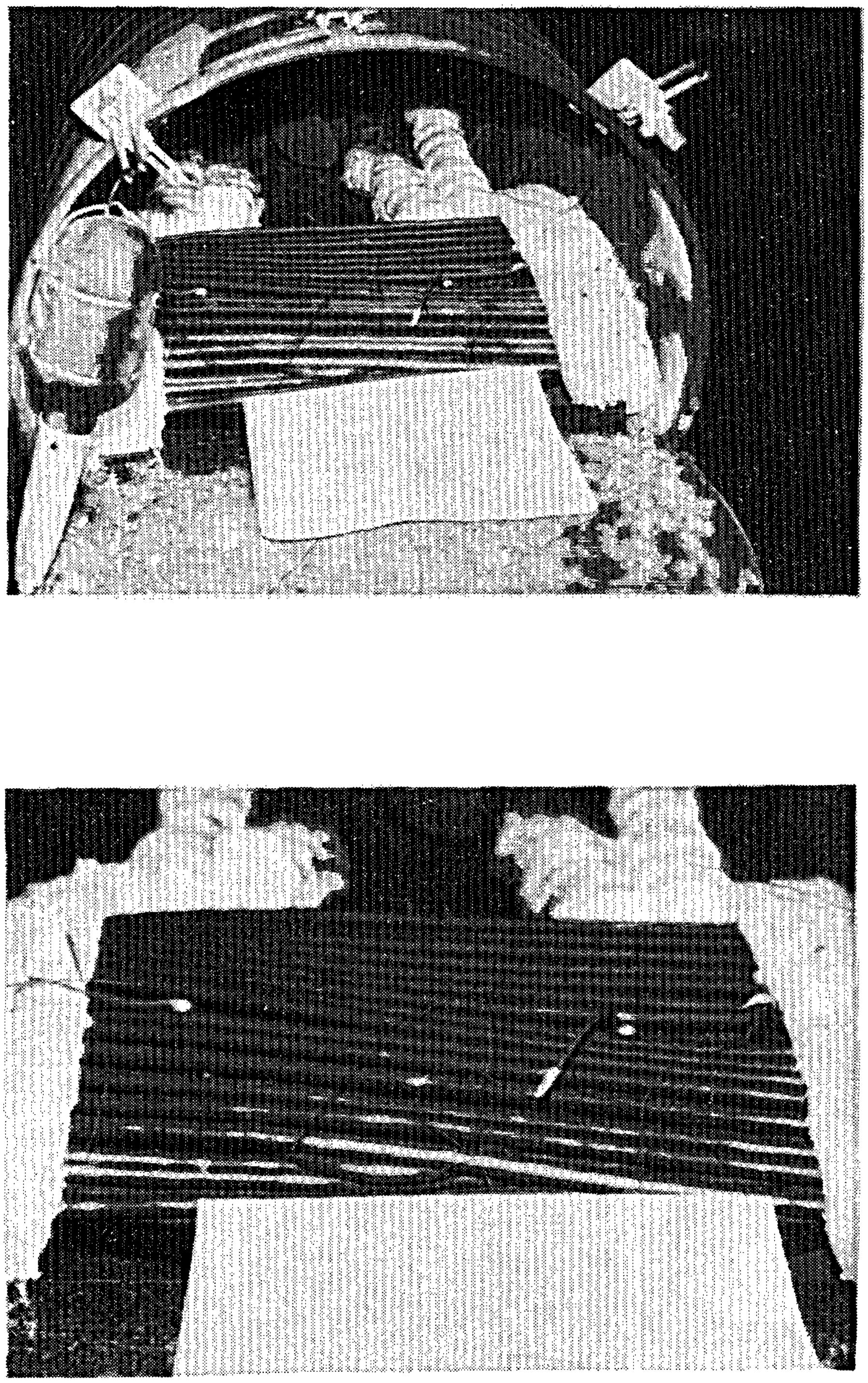


Figure 31. Qualified Cable Prior to Exposure, Test 2

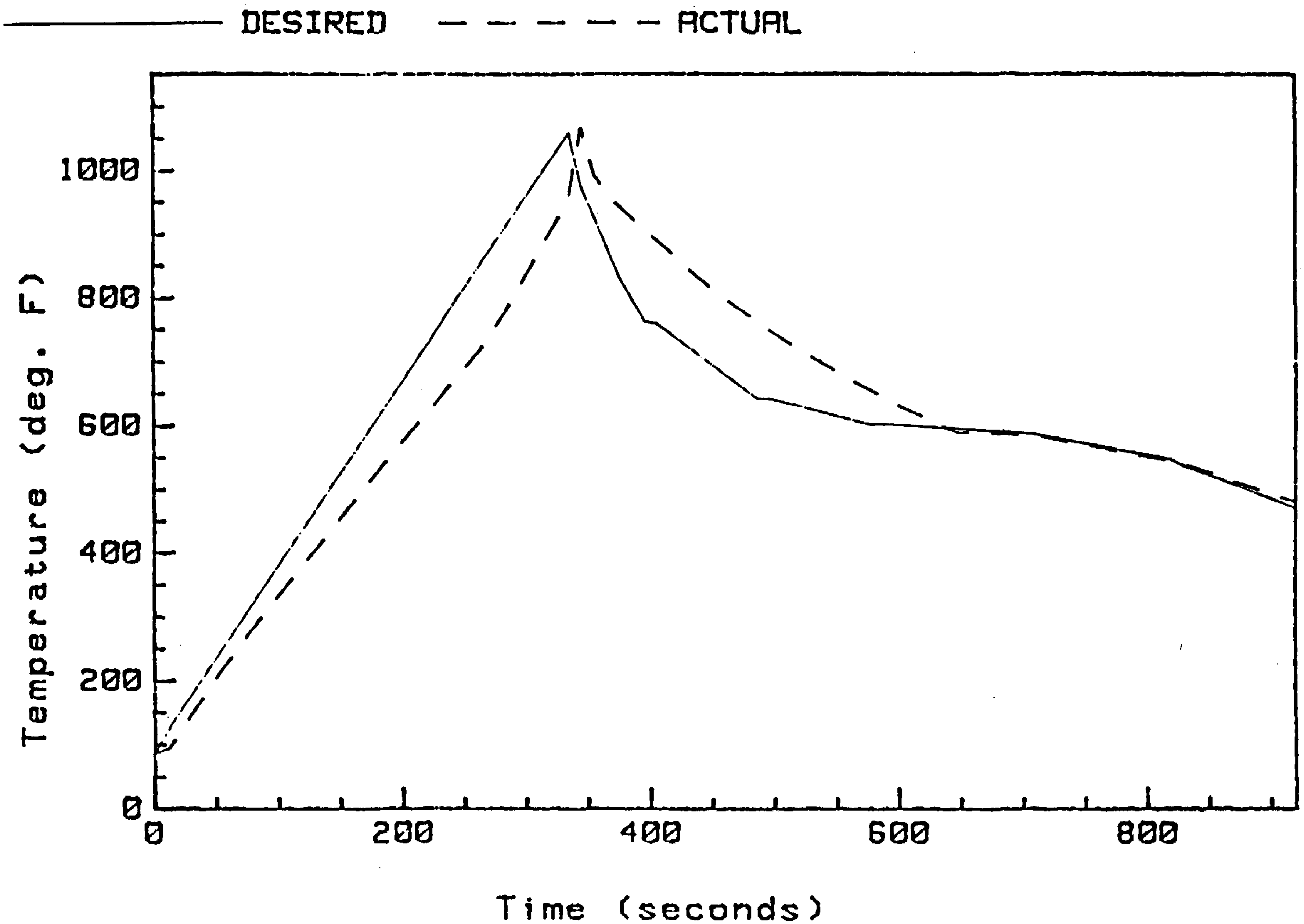


Figure 32. Test 1: Temperature Profiles

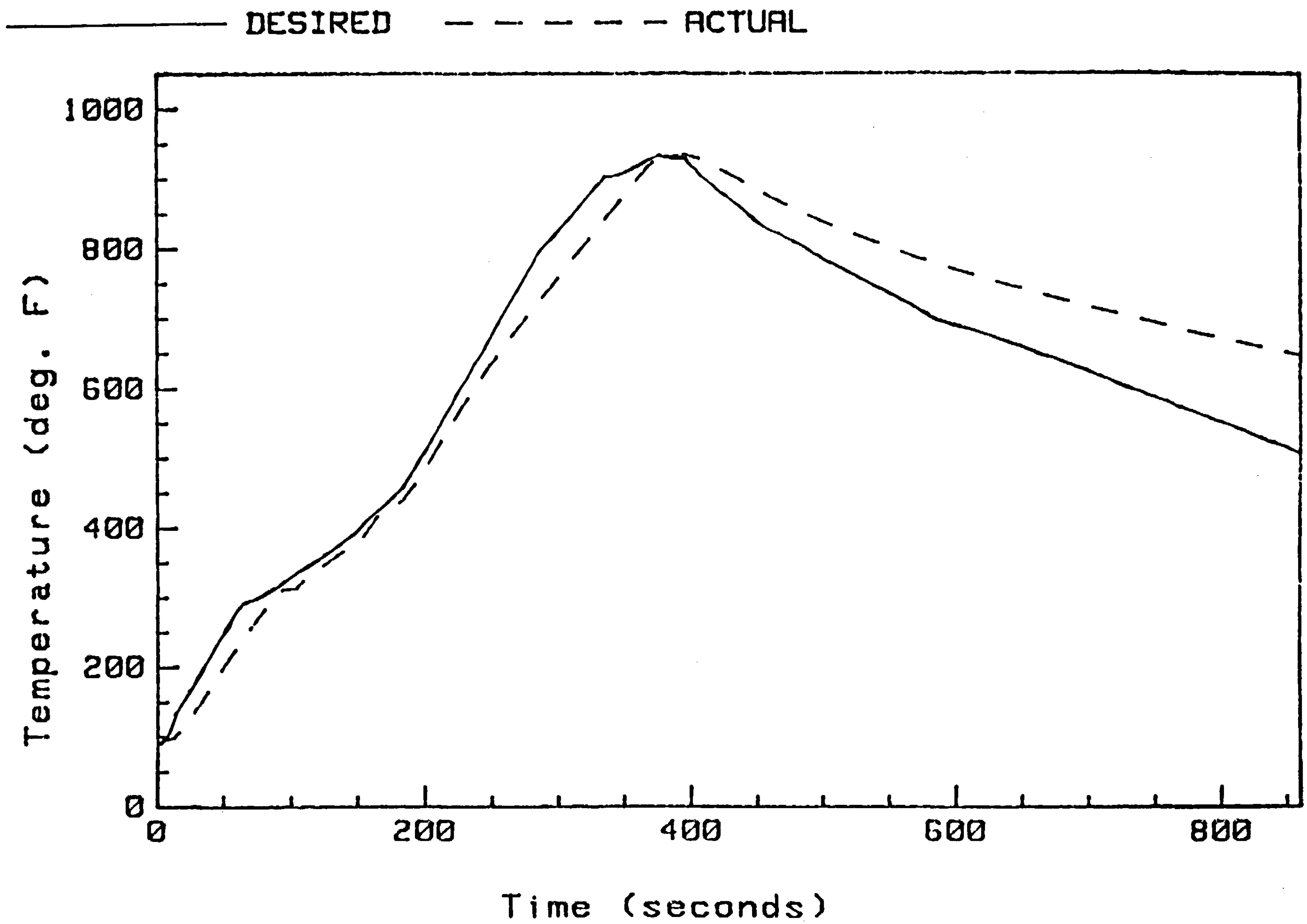


Figure 33. Test 2: Temperature Profiles

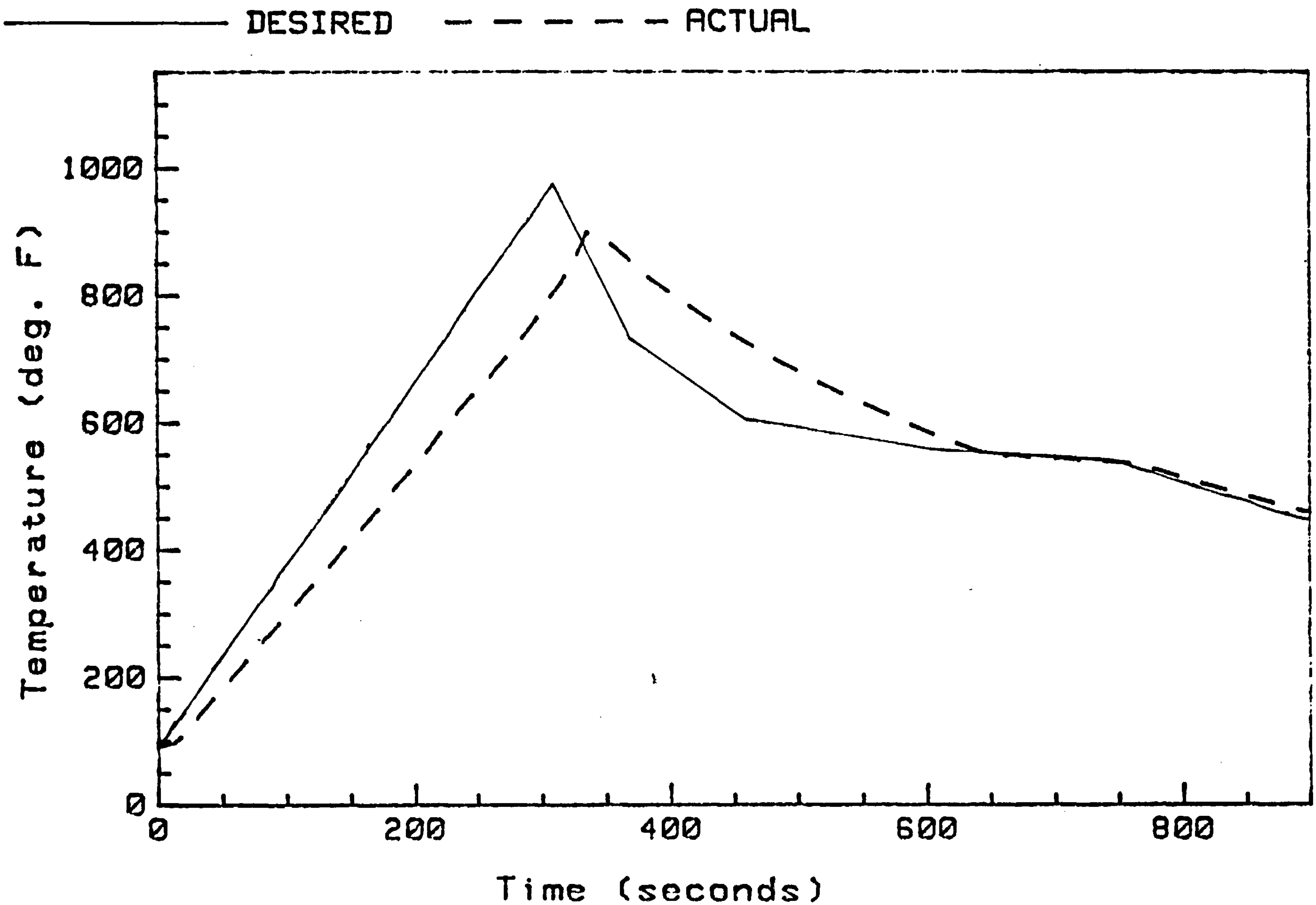


Figure 34. Test 3: Temperature Profiles

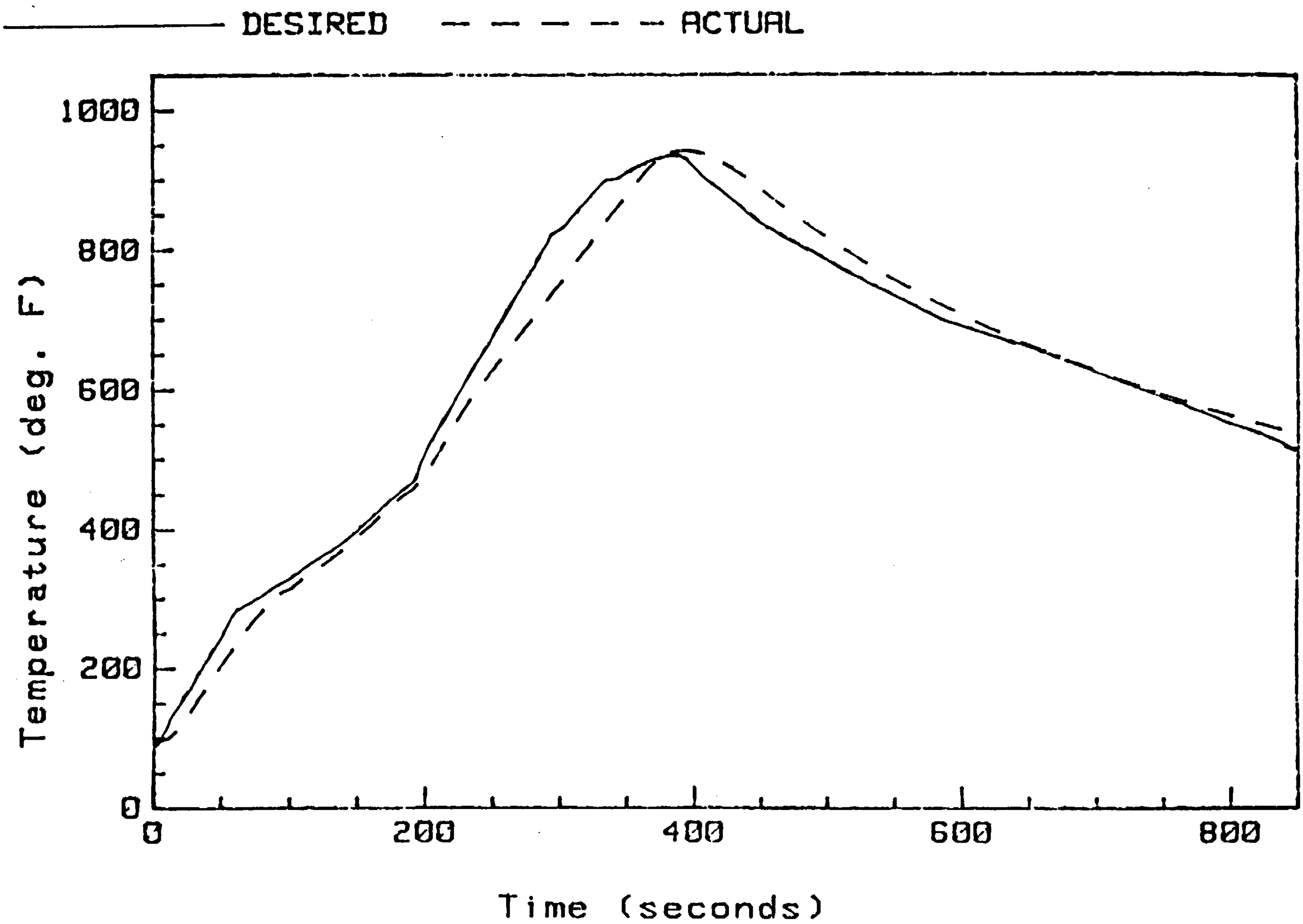


Figure 35. Test 4: Temperature Profiles

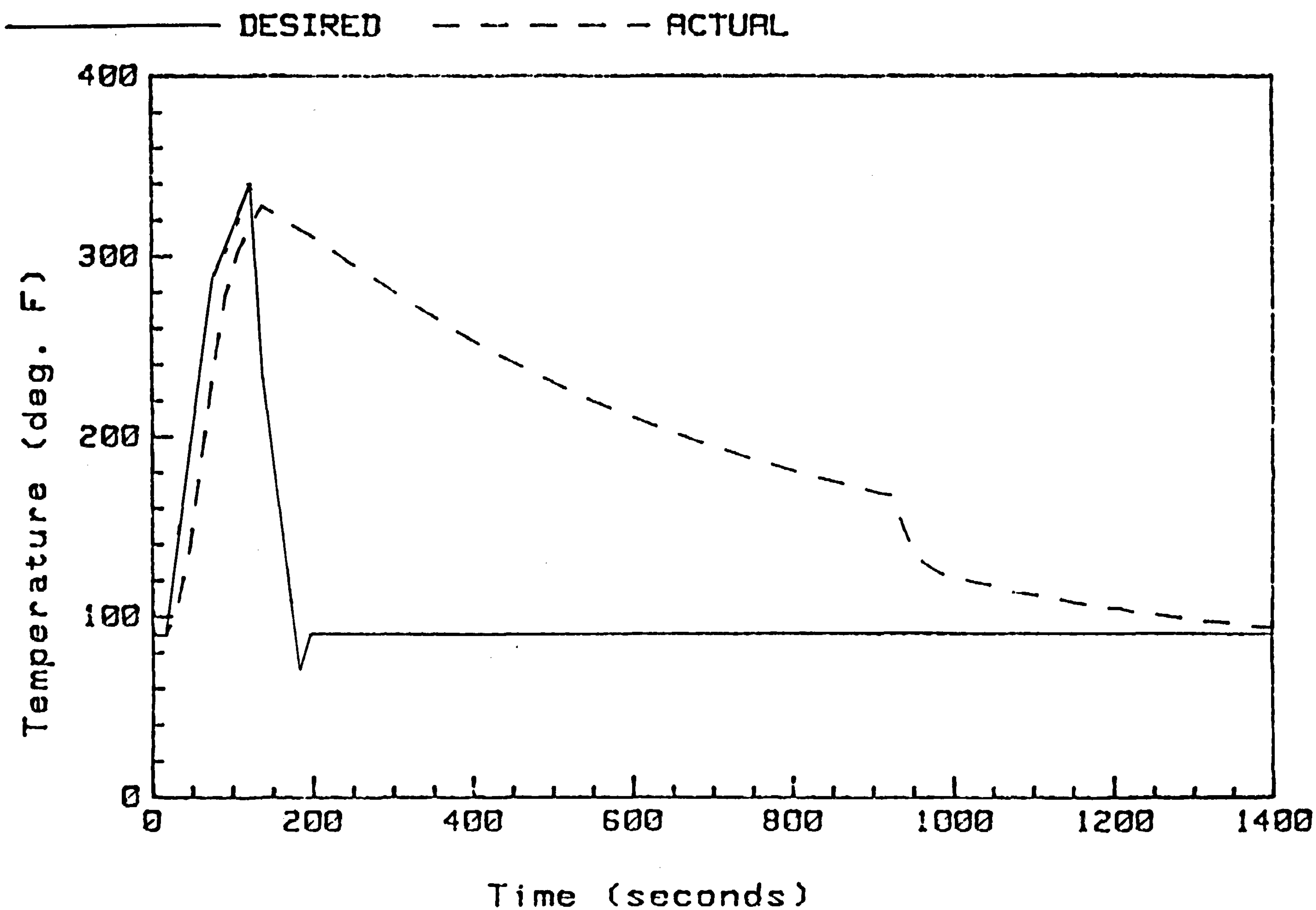


Figure 36. Test 5: Temperature Profiles

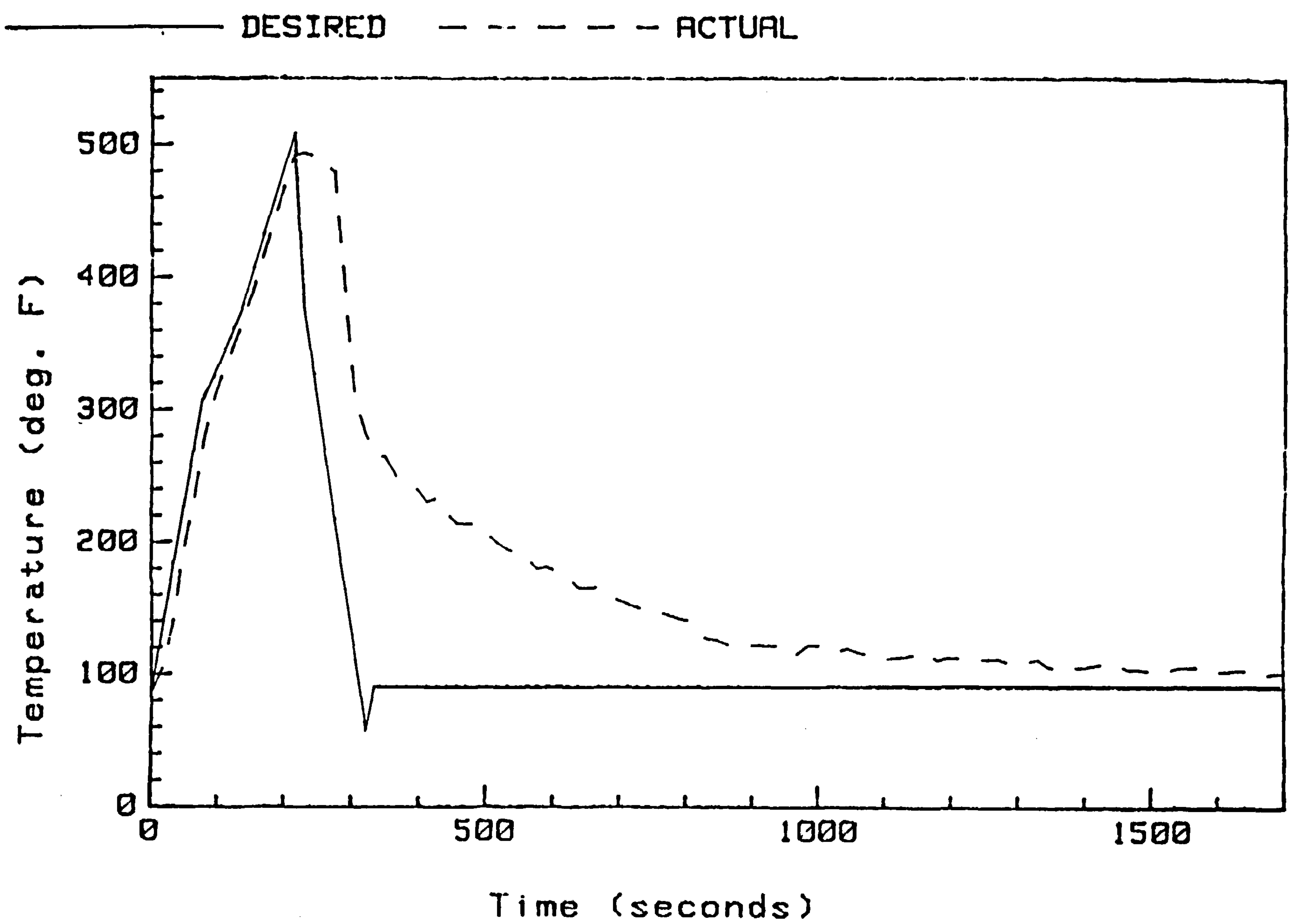


Figure 37. Test 6: Temperature Profiles

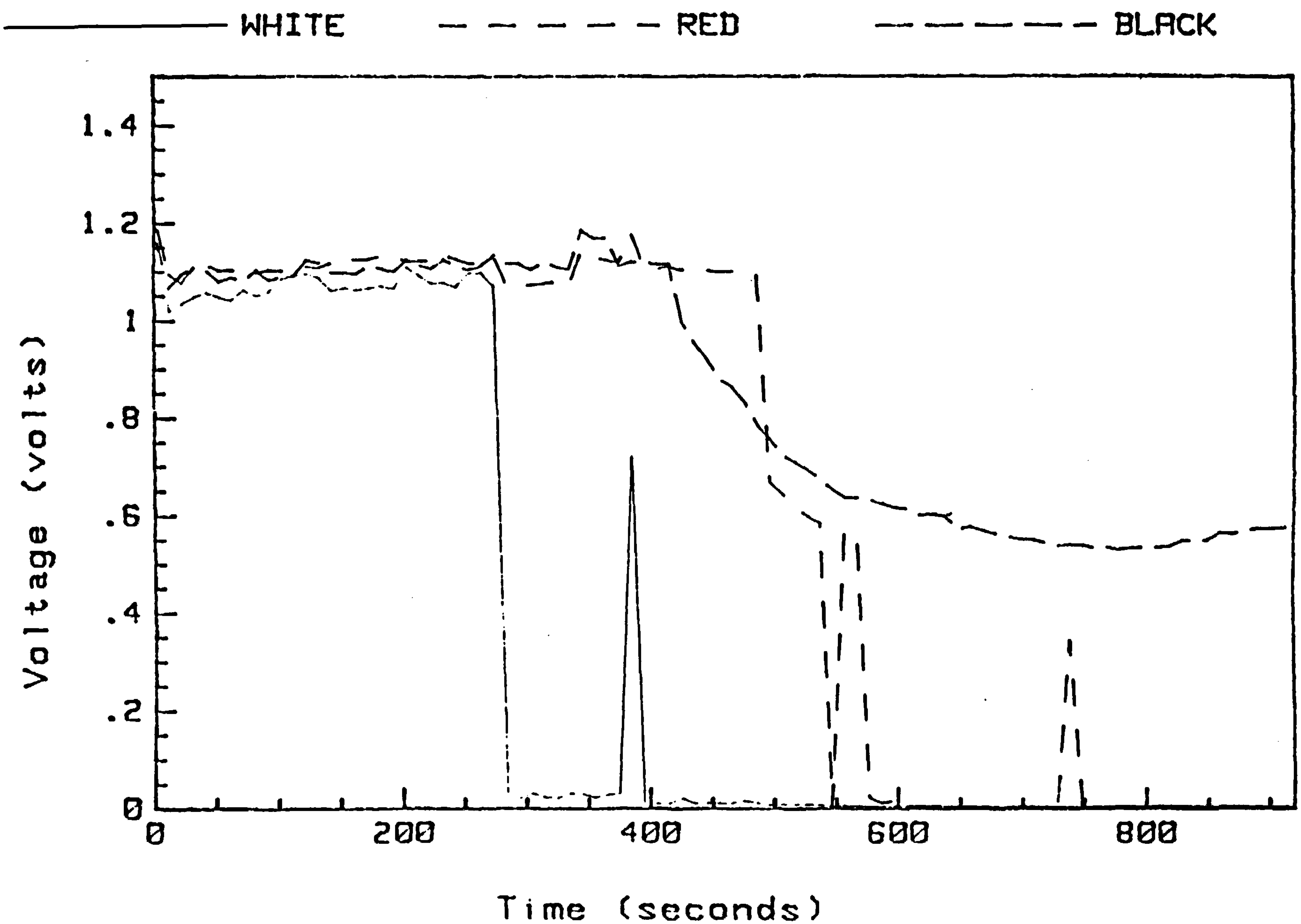


Figure 38. Test 1: Small Loop Voltages

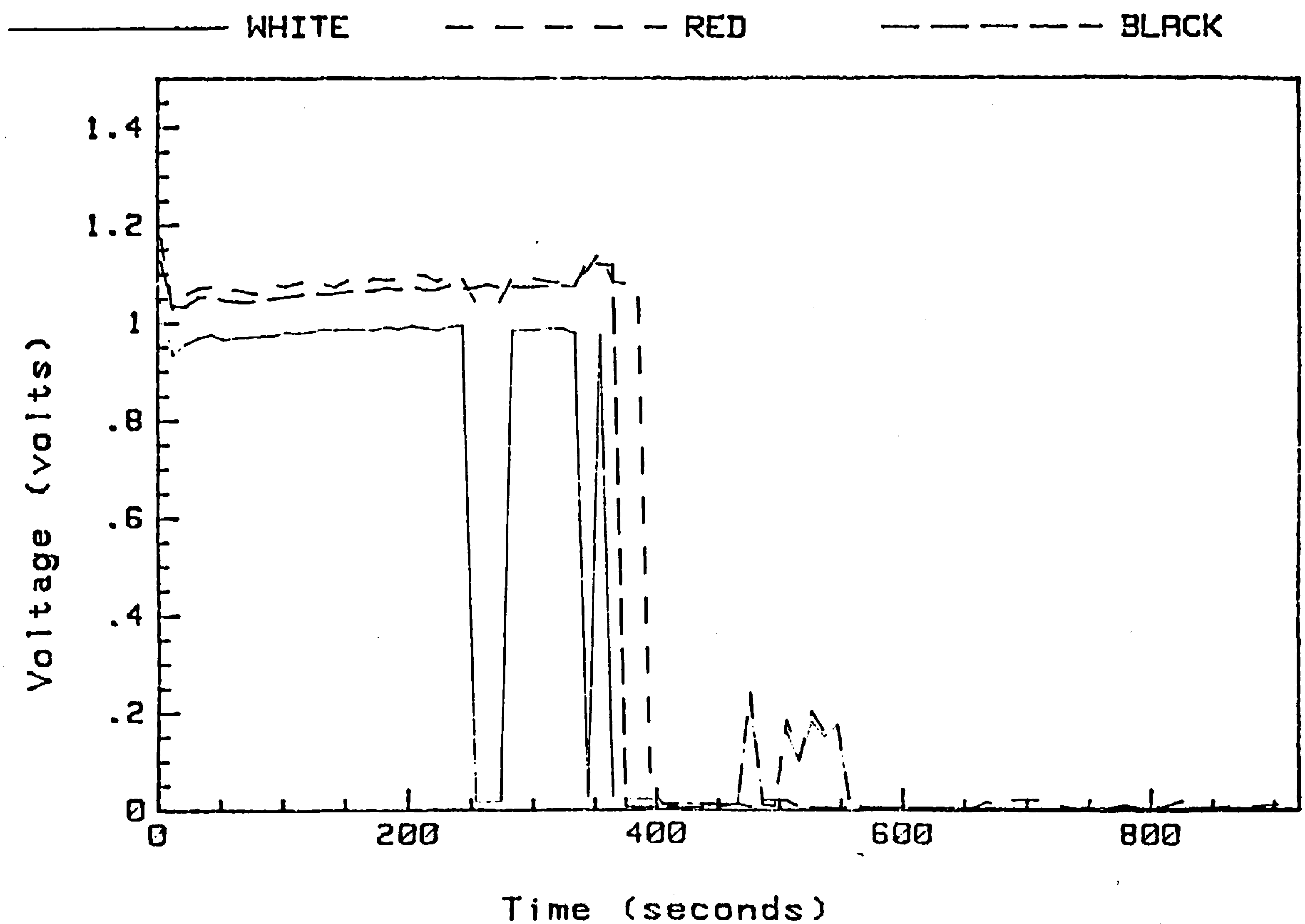


Figure 39. Test 1: Big Loop Voltages

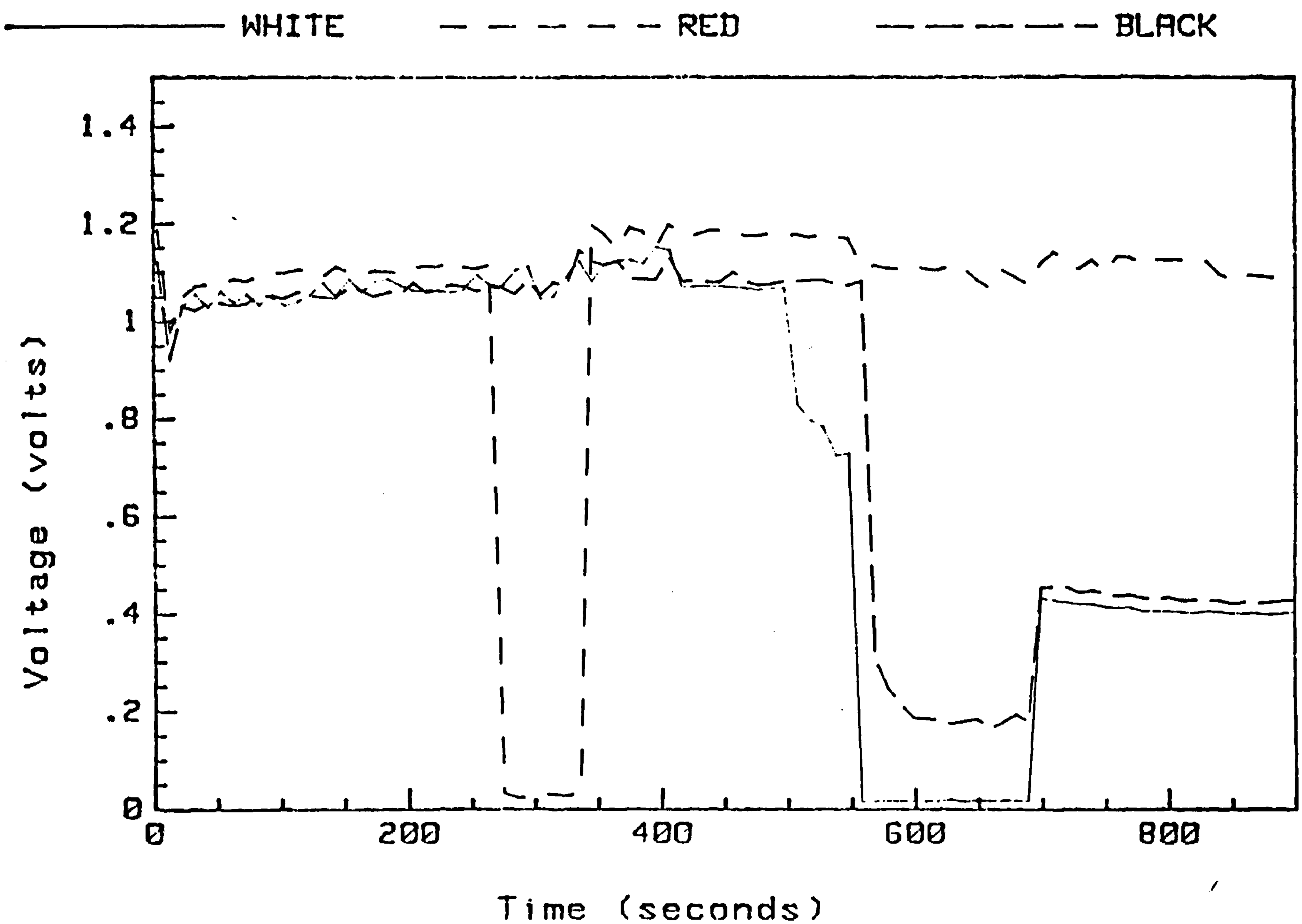


Figure 40. Test 3: Small Loop Voltages

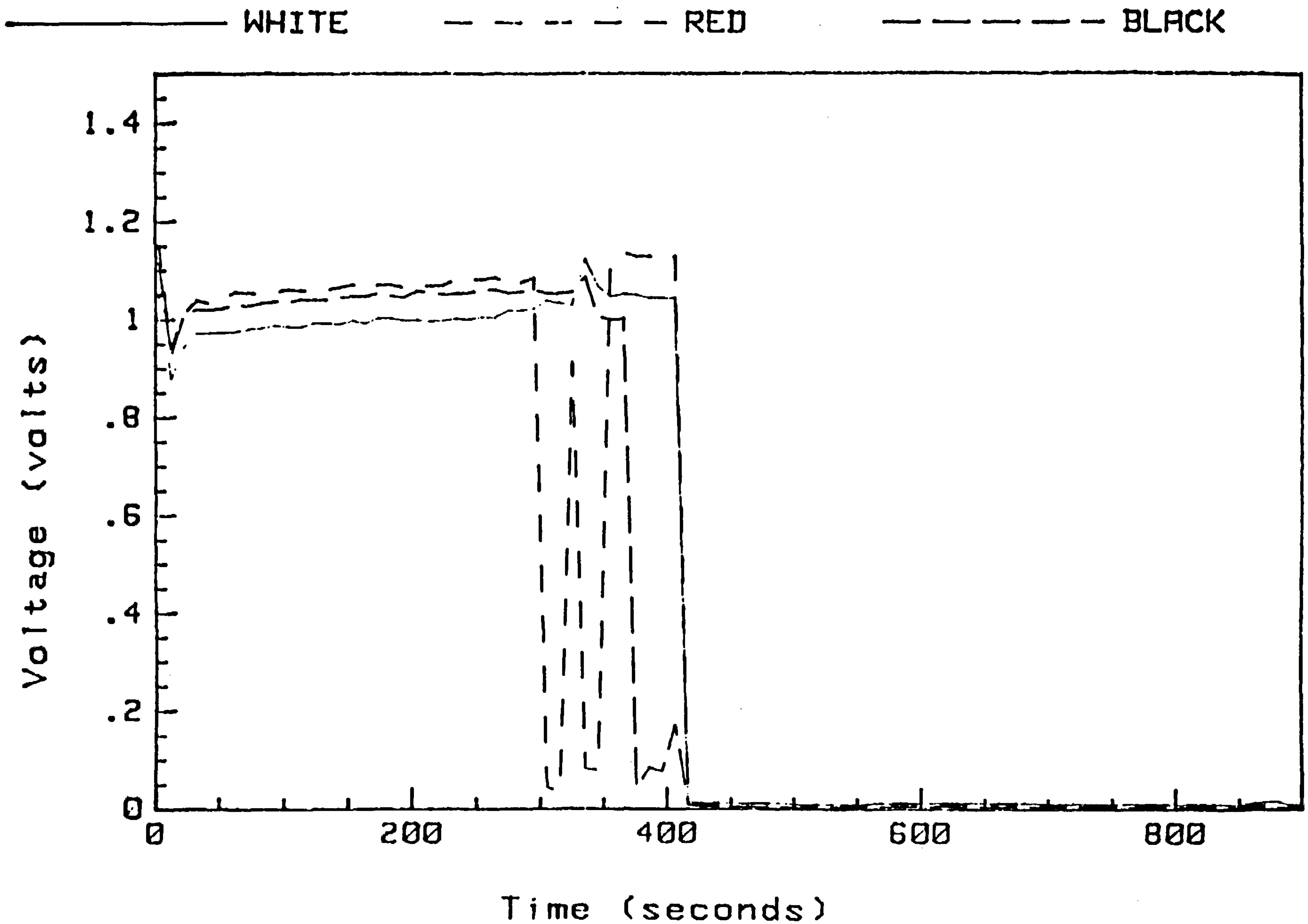


Figure 41. Test 3: Big Loop Voltages

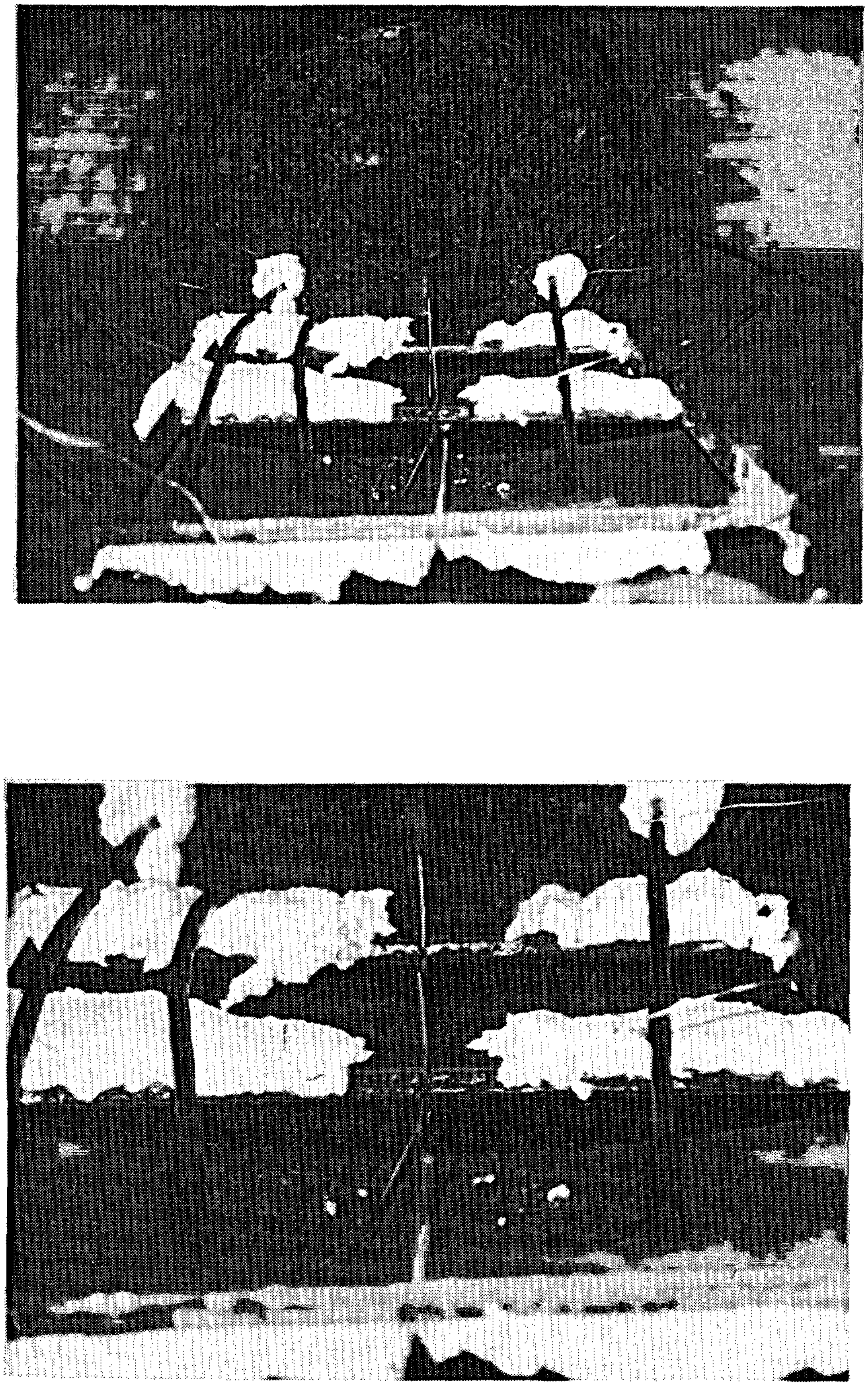
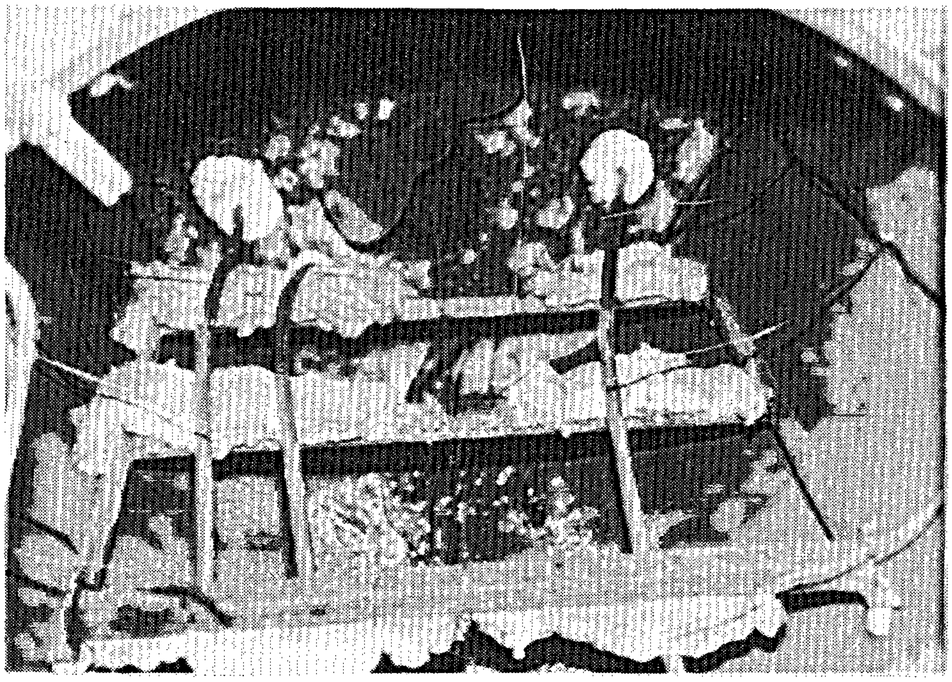


Figure 42. Single Cable Placement in the Chamber, Unqualified Cable (applicable to Tests 7 and 10)



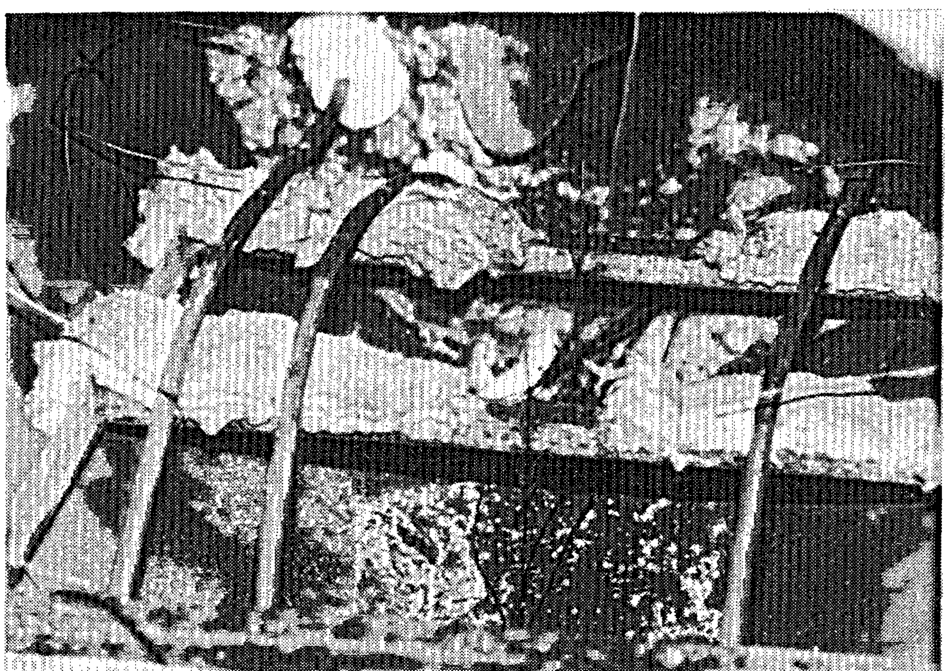


Figure 43. Single Cable Placement in the Chamber, Qualified Cable (applicable to Tests 8, 9, and 11)

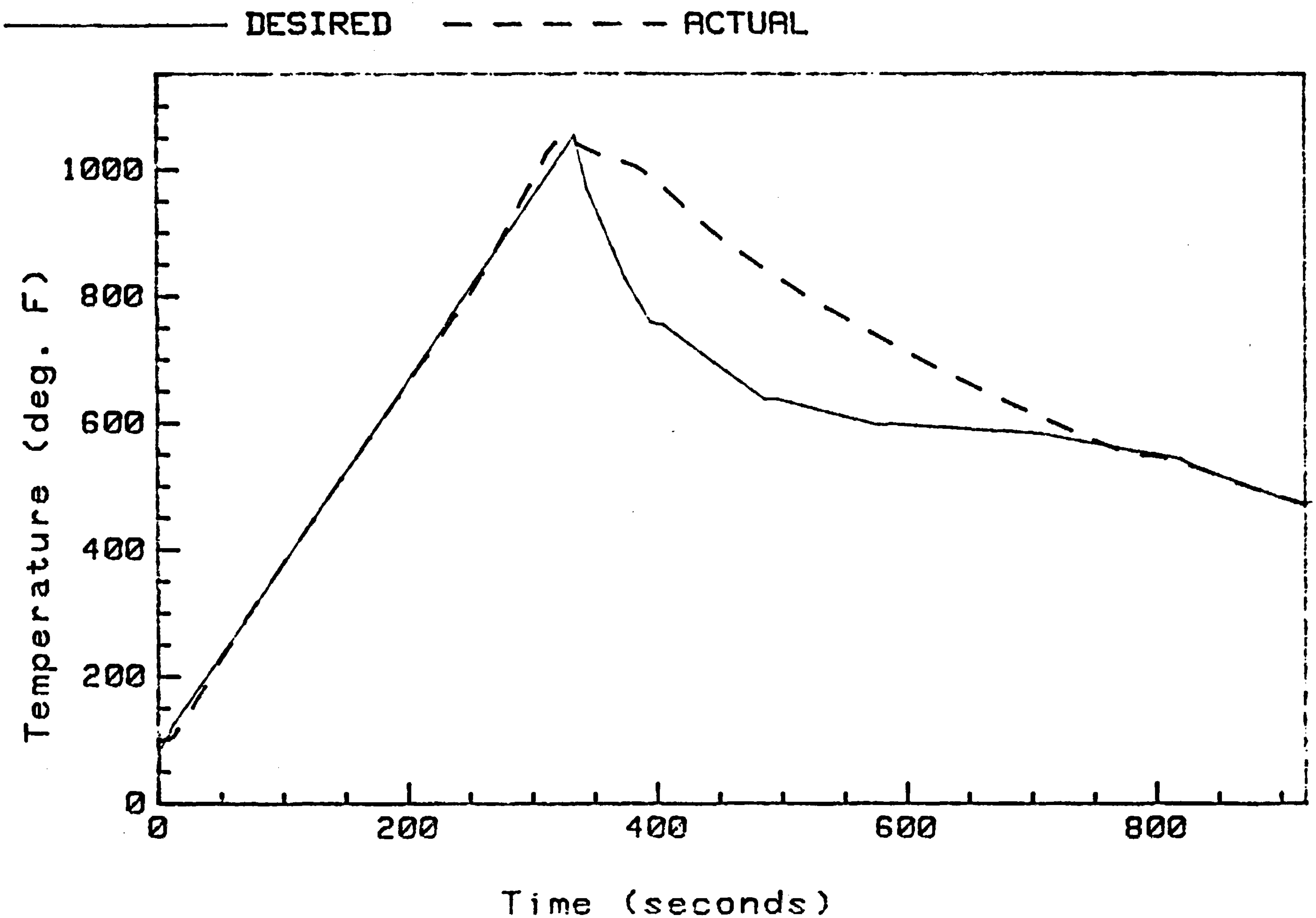


Figure 44. Test 7: Temperature Profiles

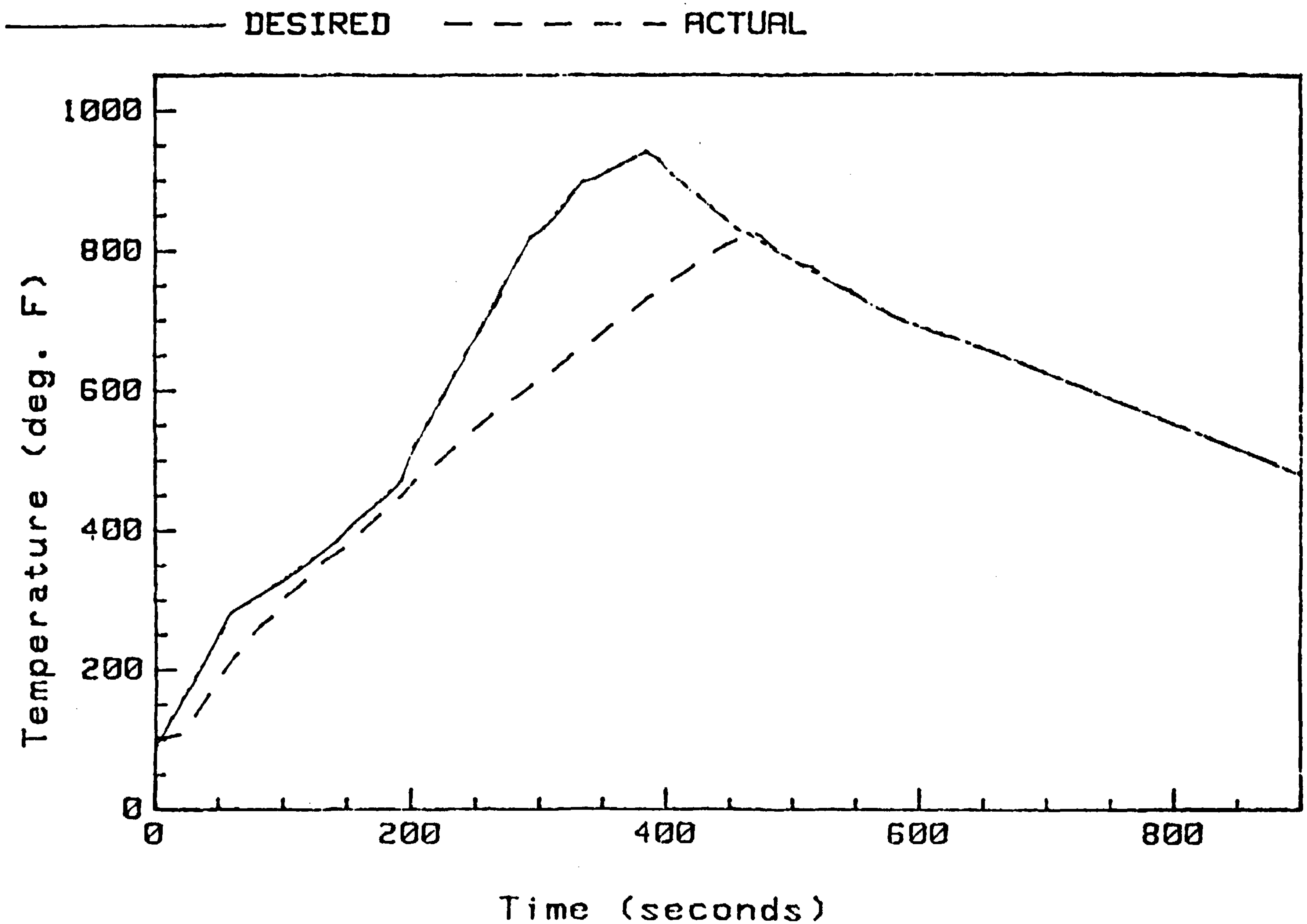


Figure 45. Test 8: Temperature Profiles

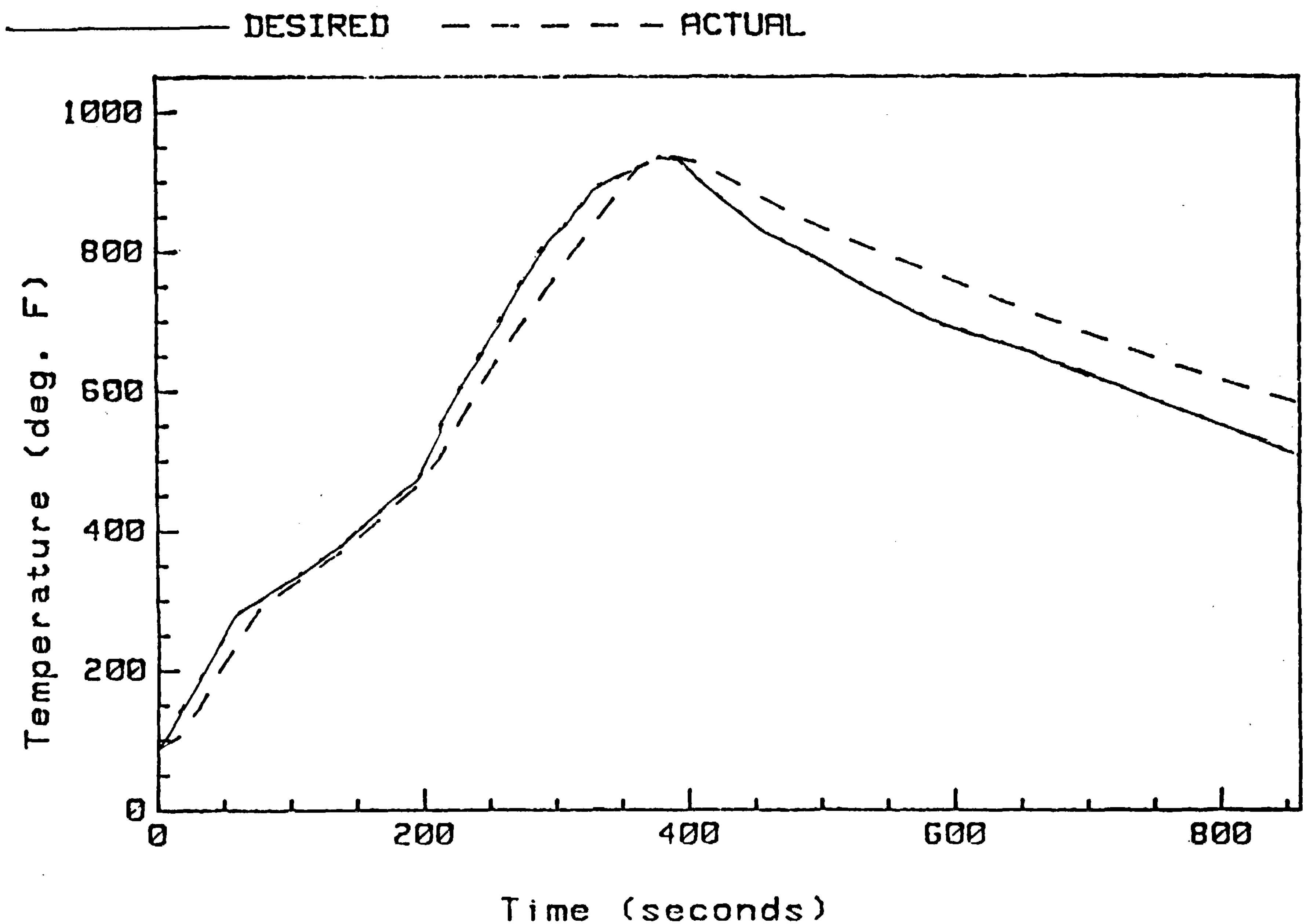


Figure 46. Test 9: Temperature Profiles

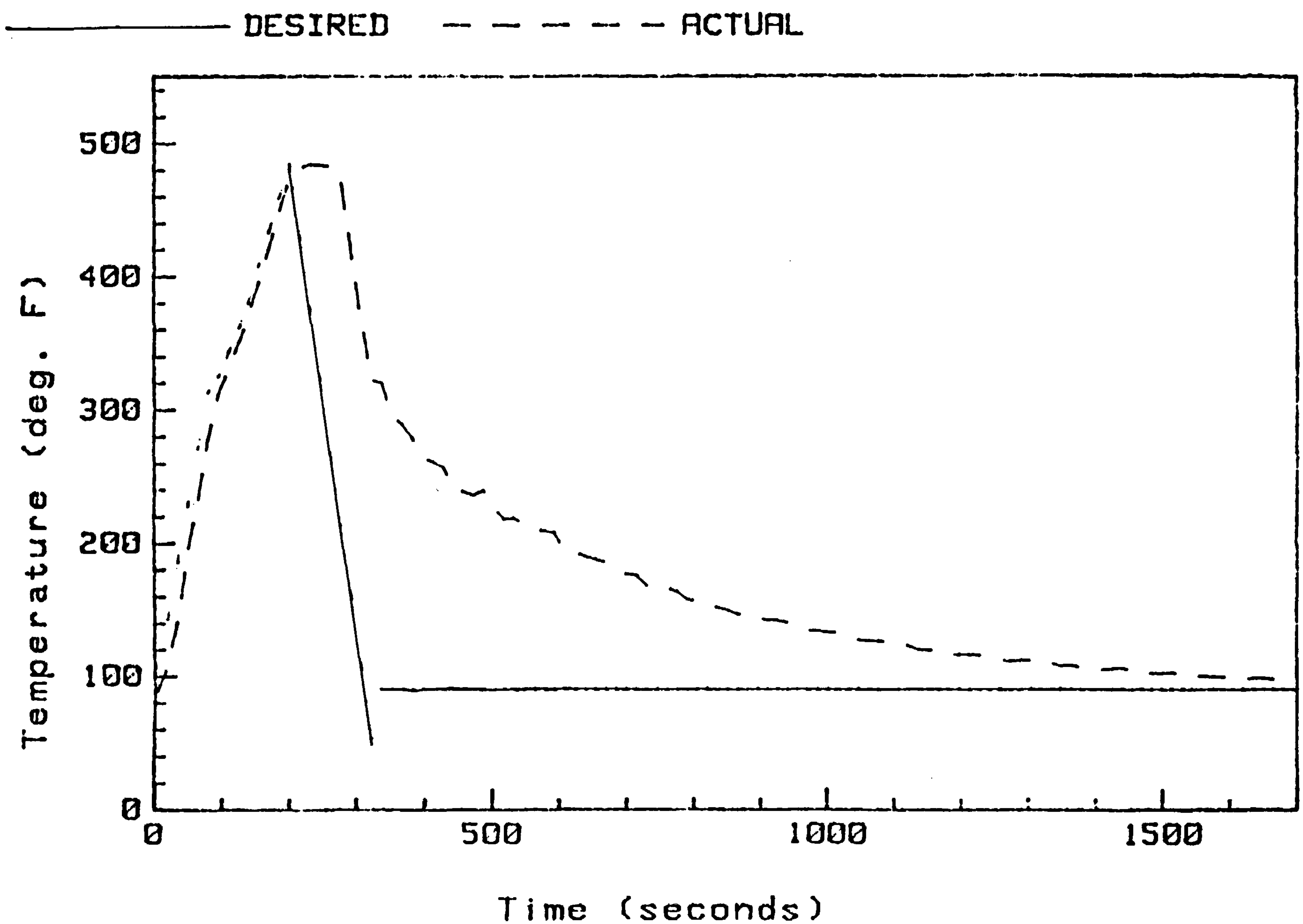


Figure 47. Test 10: Temperature Profiles

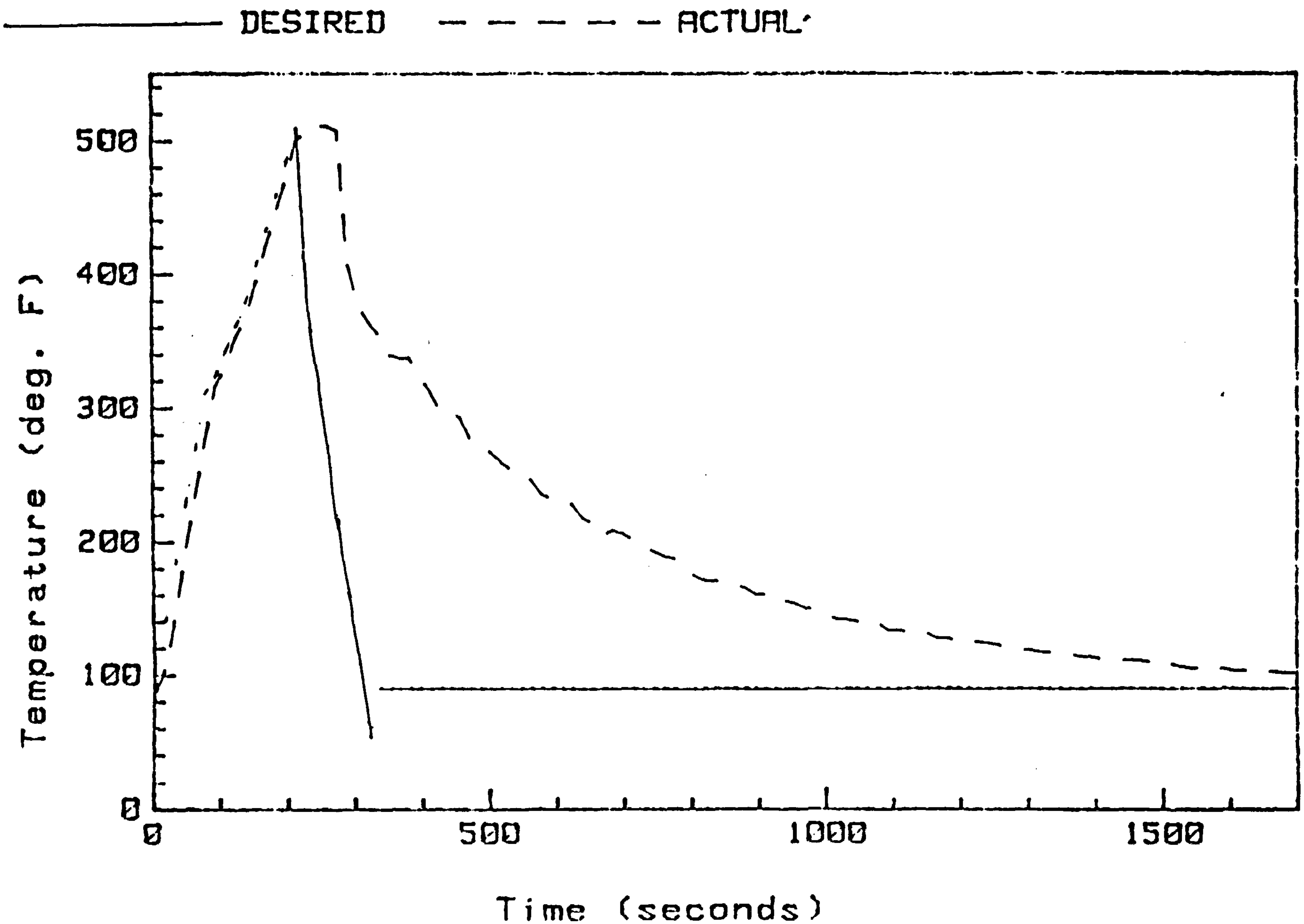


Figure 48. Test 11: Temperature Profiles

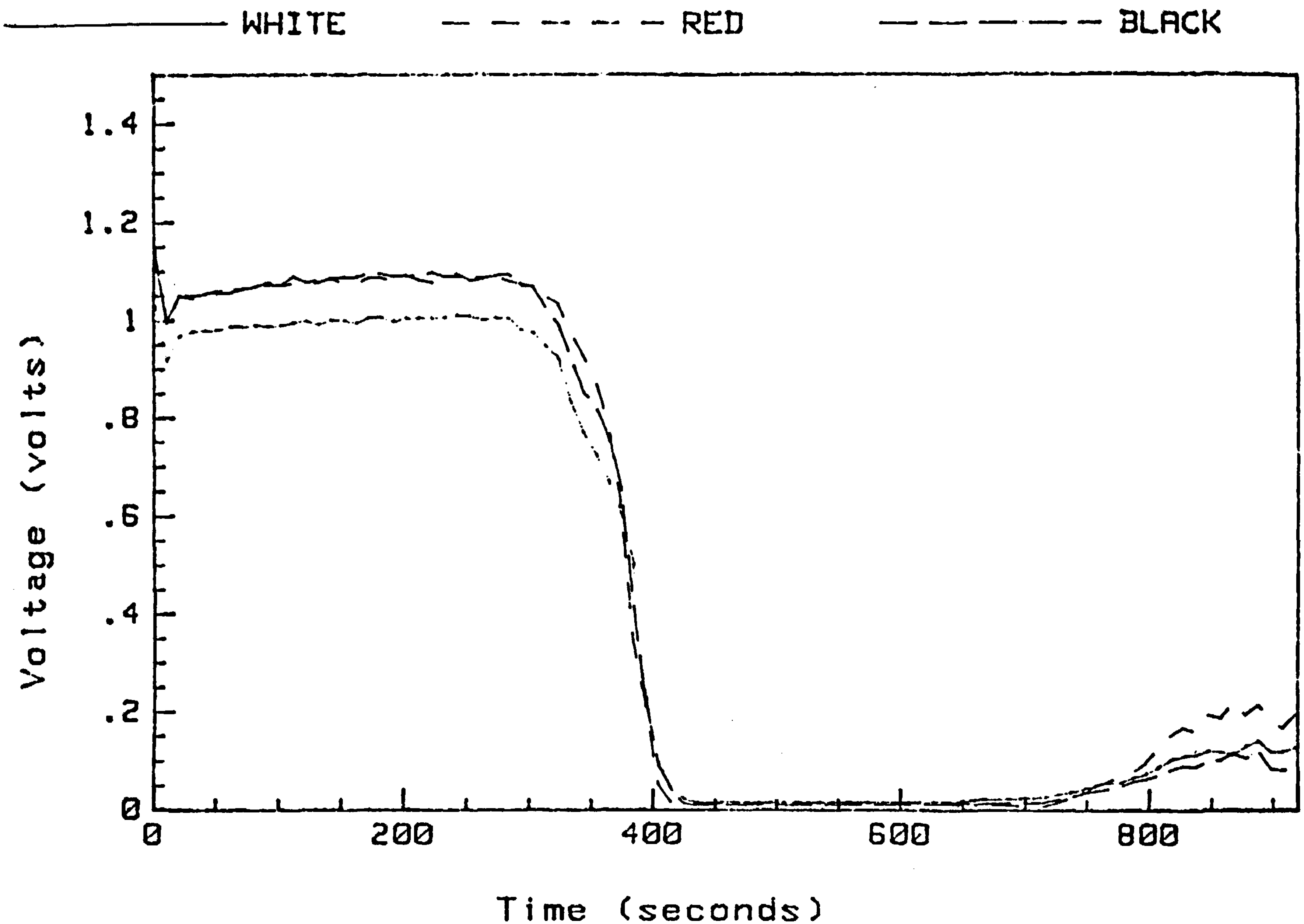


Figure 49. Test 7: Left Cable Voltages

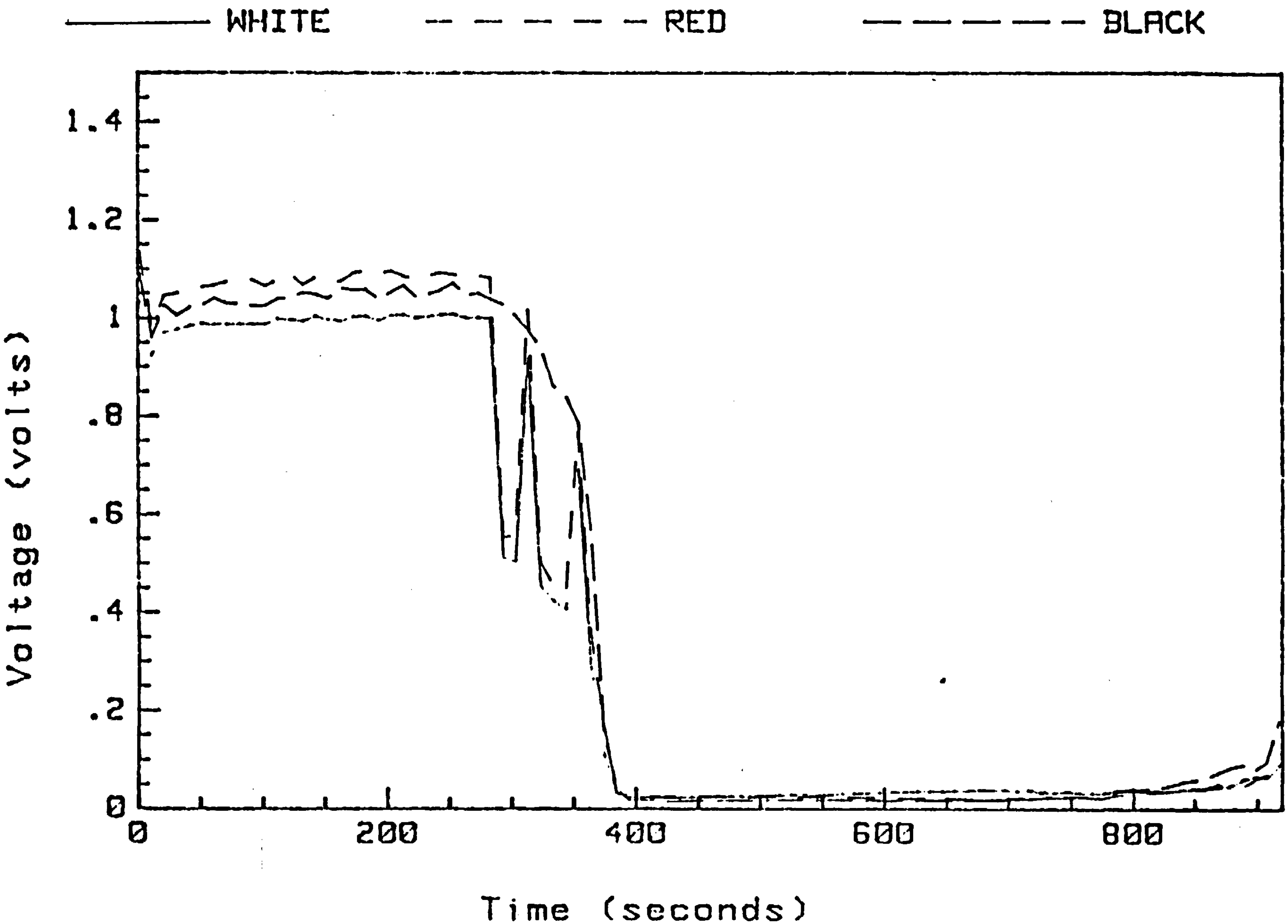


Figure 50. Test 7: Middle Cable Voltages

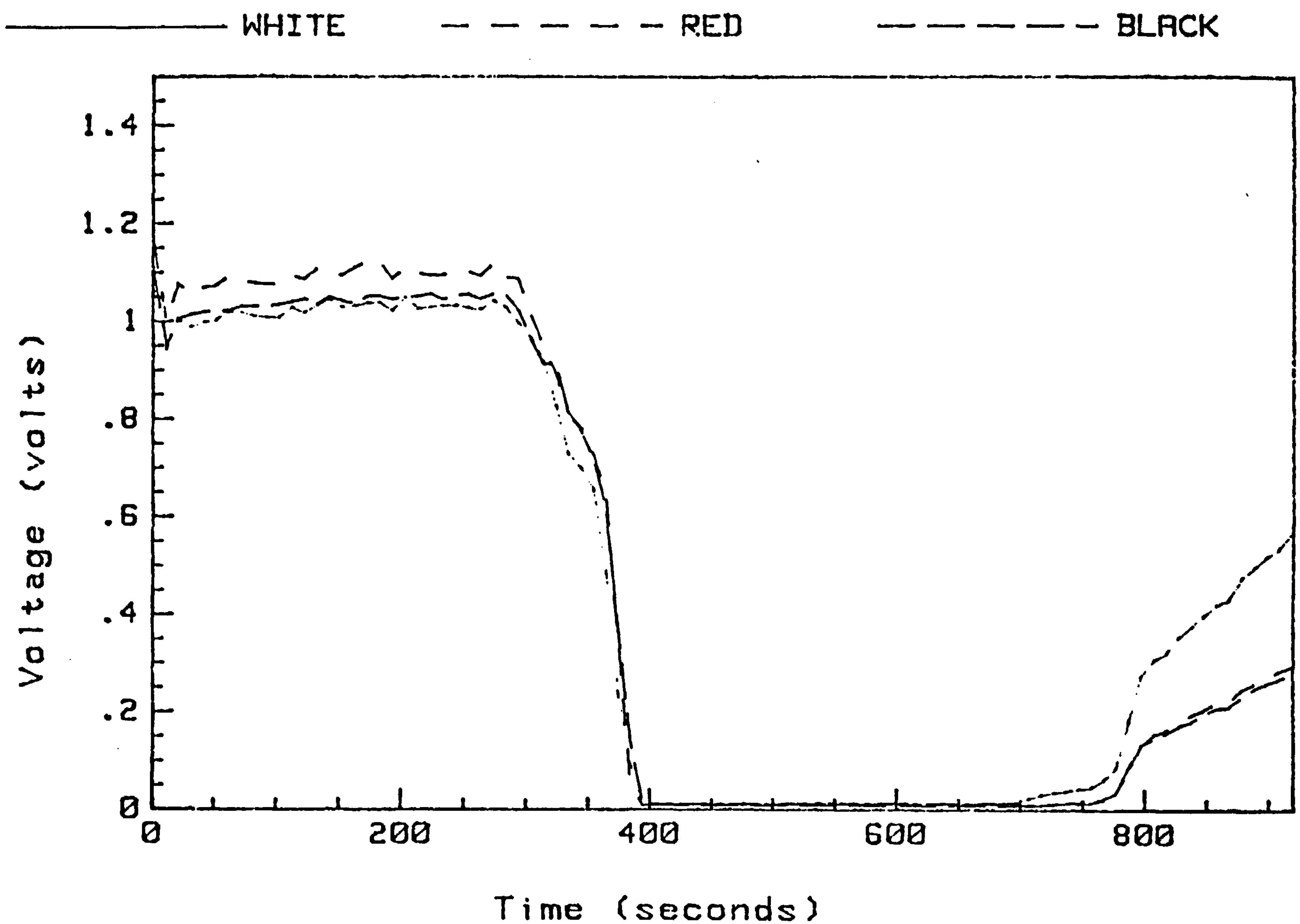


Figure 51. Test 7: Right Cable Voltages

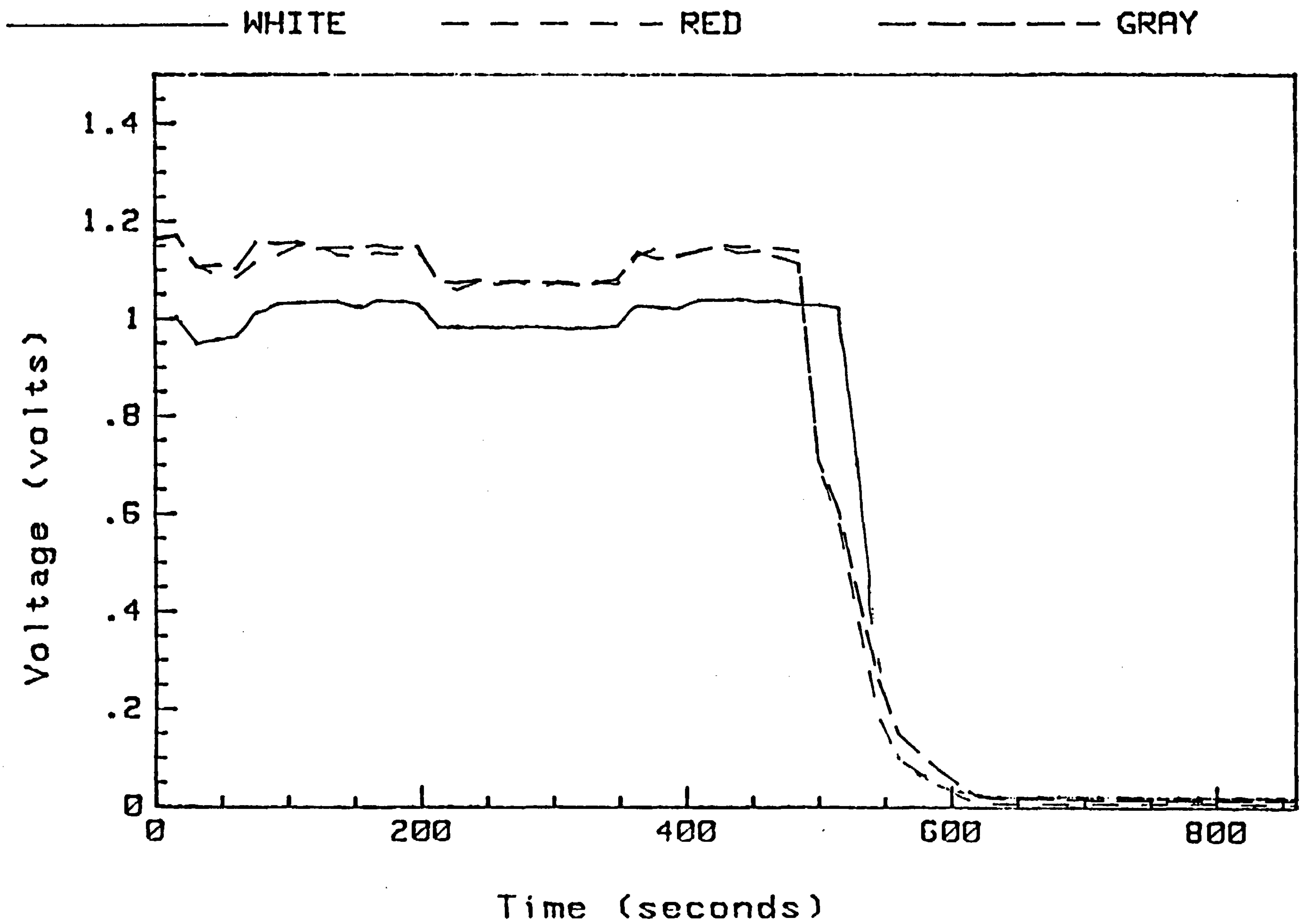


Figure 52. Test 9: Left Cable Voltages

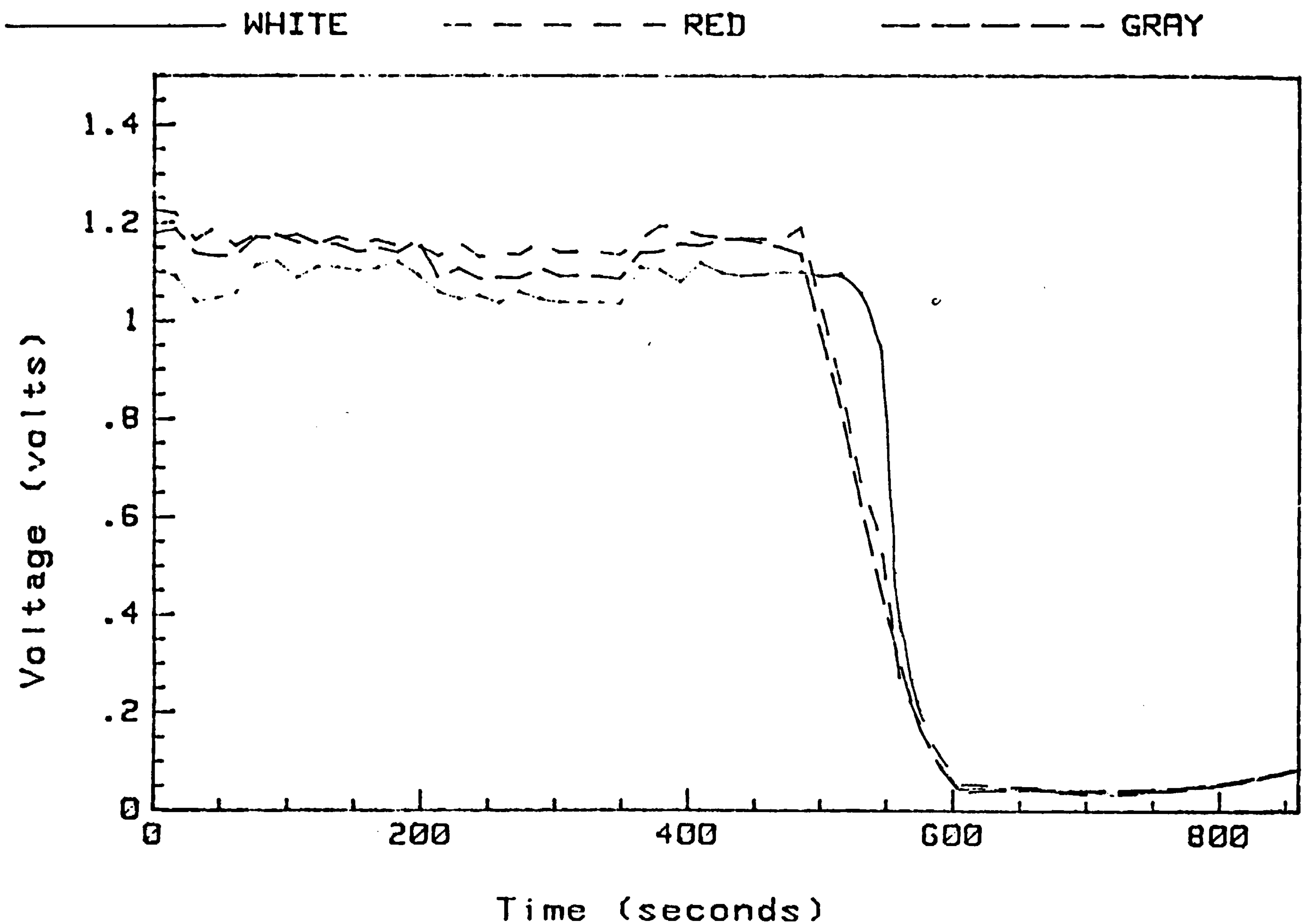


Figure 53. Test 9: Middle Cable Voltages

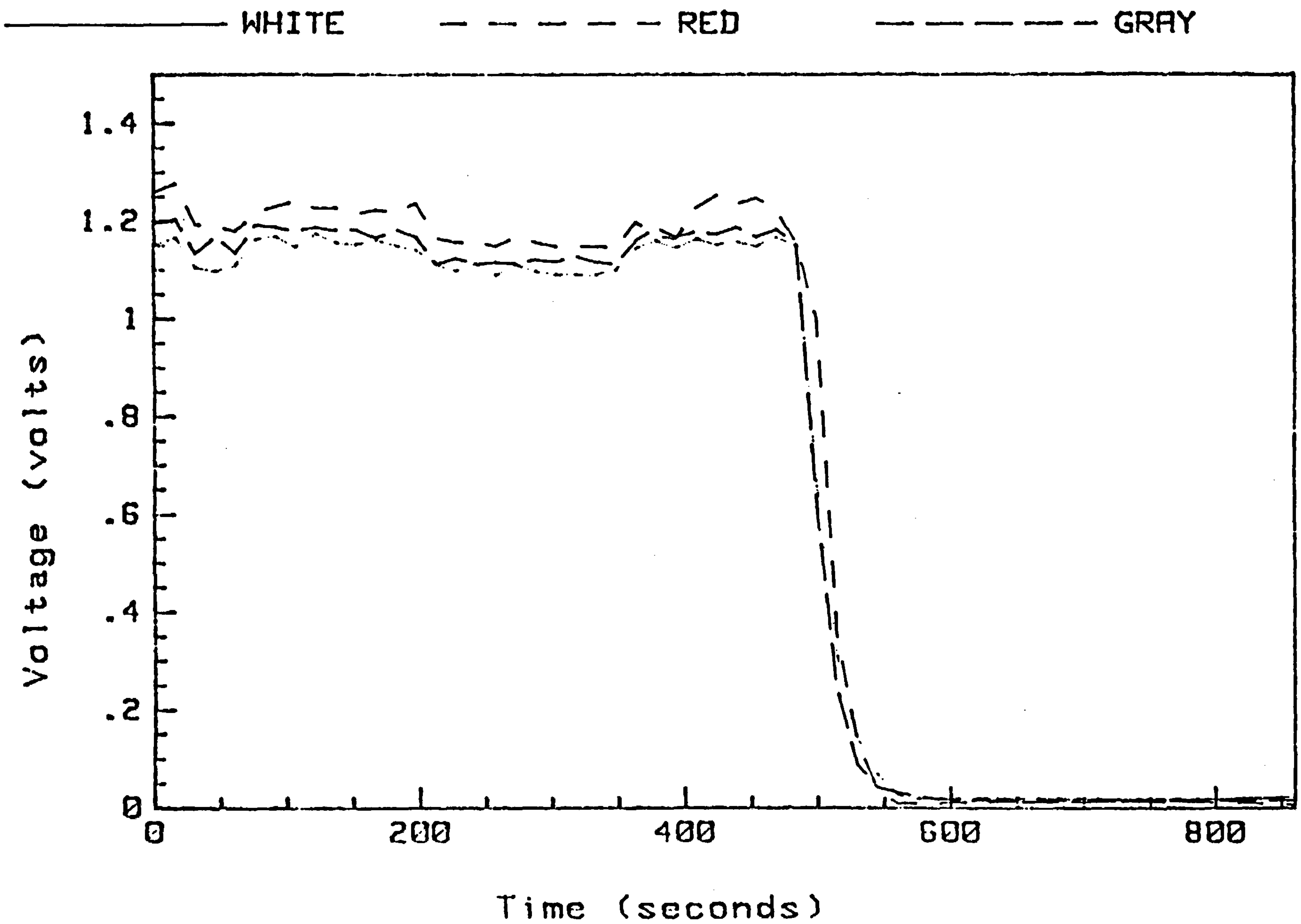


Figure 54. Test 9: Right Cable Voltages

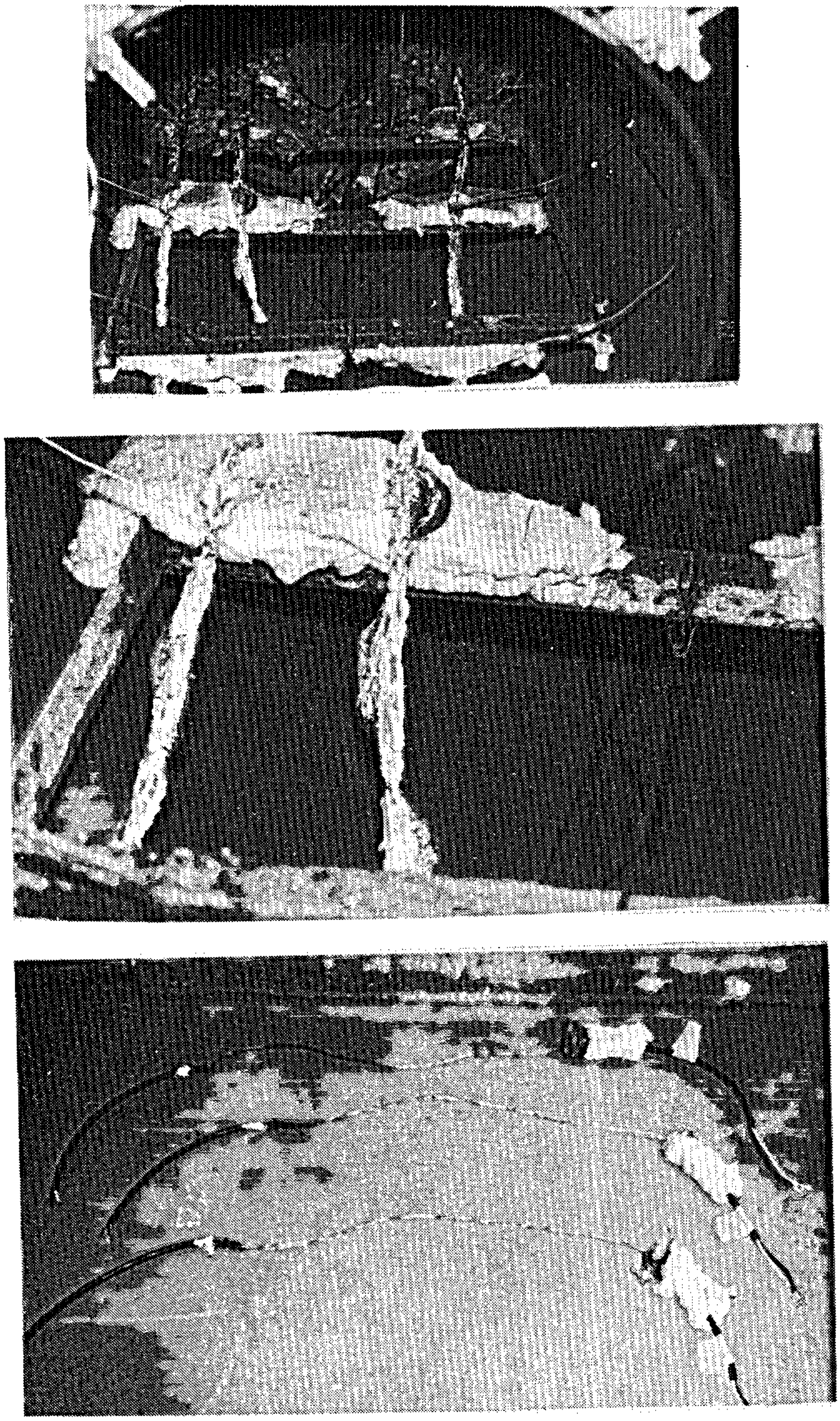


Figure 55. Unqualified Cable After Exposure, Test 7

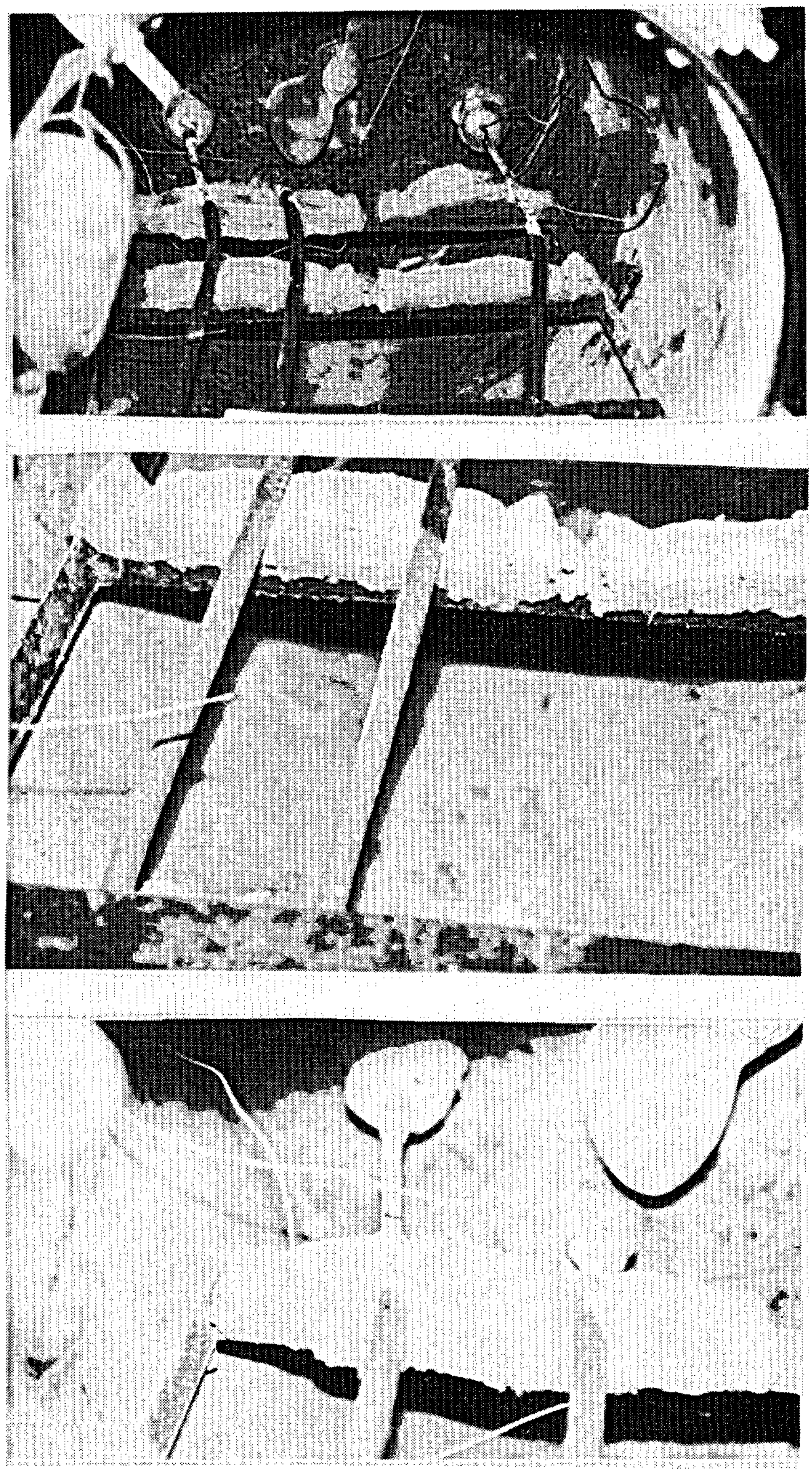


Figure 56. Qualified Cable After Exposure, Test 9

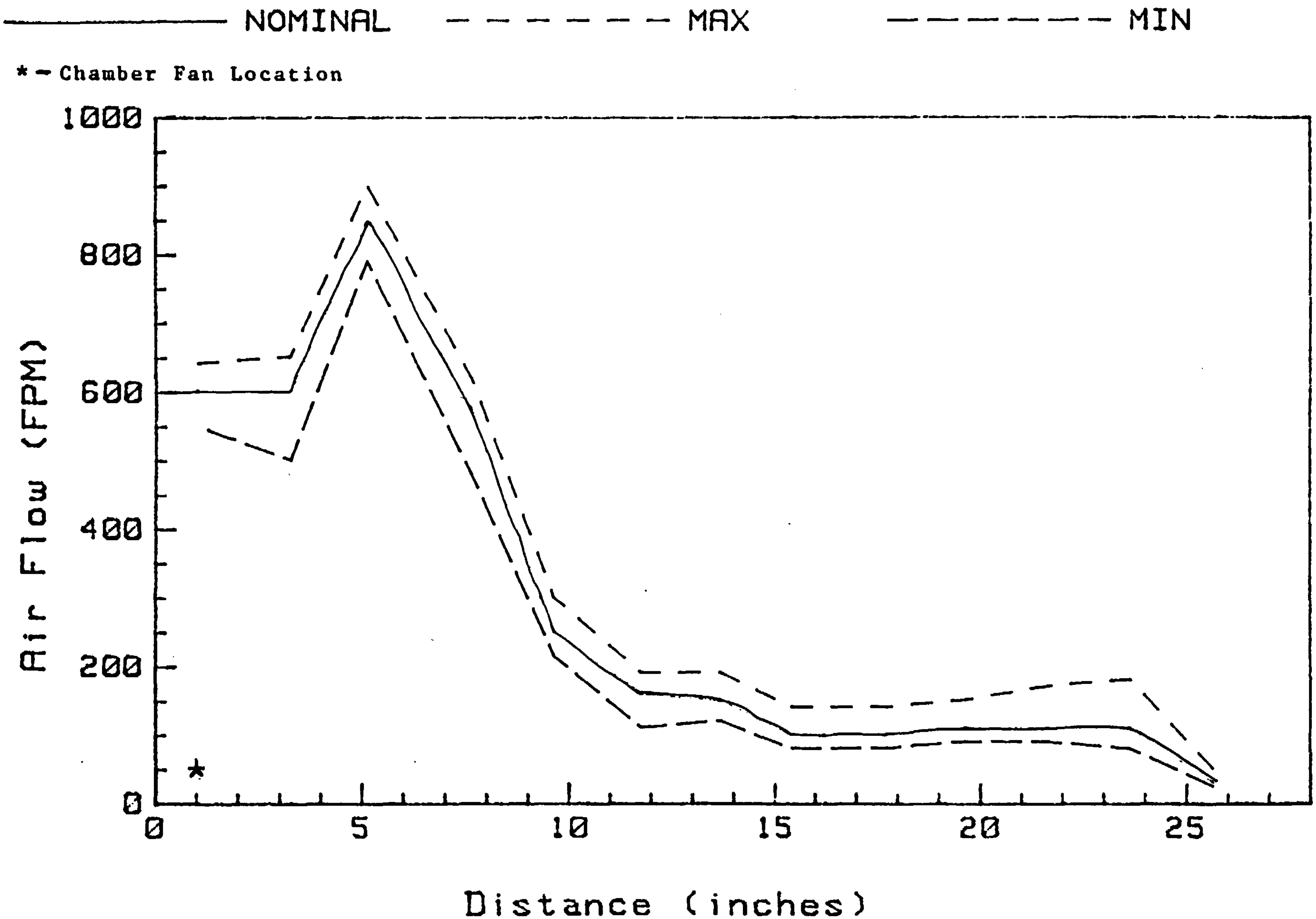


Figure 57. Chamber Left Side Air Flow Profile

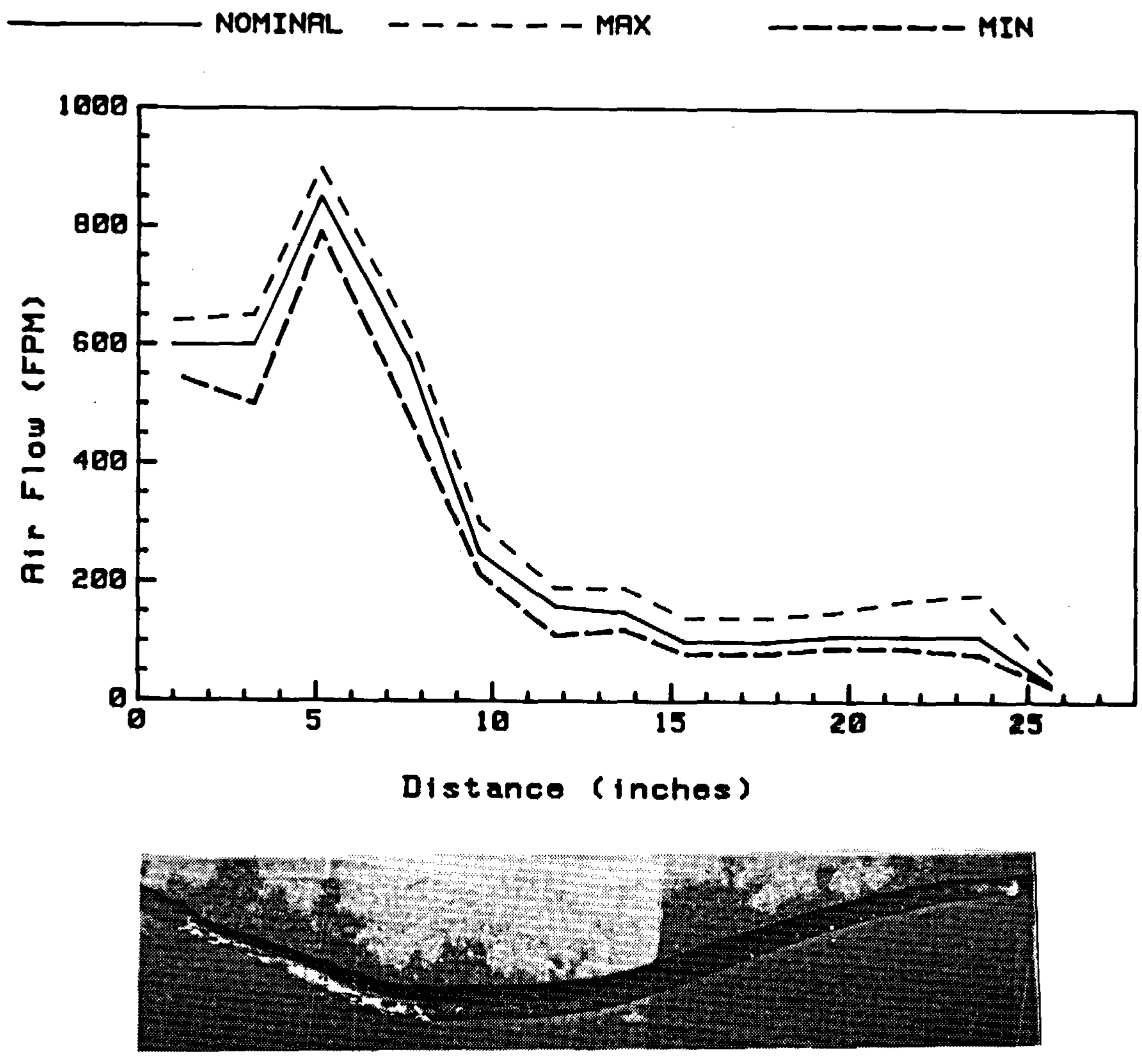


Figure 58. Comparison of Chamber Air Flow and Qualified Cable Damage, Test 9

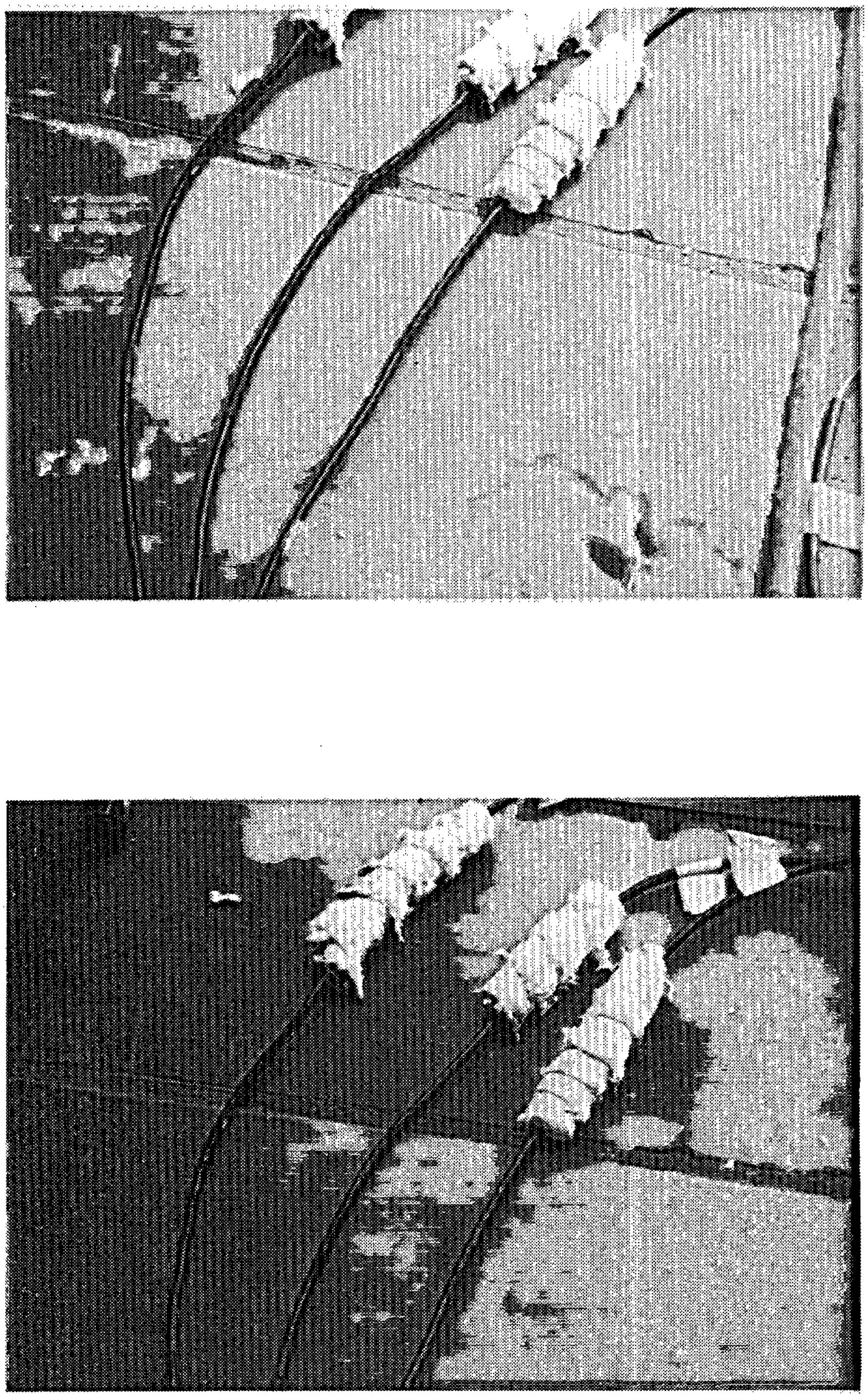


Figure 59. Unqualified Cable After Simulated Suppression, Test 10

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13. ABSTRACT (200 words or less)

The results of a series of 13 cable tests using IEEE-383 qualified and unqualified cable are discussed in this report. The purpose of these tests was to determine cable damage response (as indicated by electrical failure) to transient fire environments (temperature vs time only).

The major insights gained from these tests were that (a) cables that have terminated in a fire environment are more likely to fail; (b) cable geometry plays a significant role in determining if a cable will fail; (c) convective heat transfer, i.e., high air flow regions, leads to severe cable damage; and (d) based on simulated, air cooled down suppression, neither qualified nor unqualified cables would fail given the suppression actuation times and test profiles used in these tests. This assumes that suppression agents (e.g., water) do not cause damage.

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