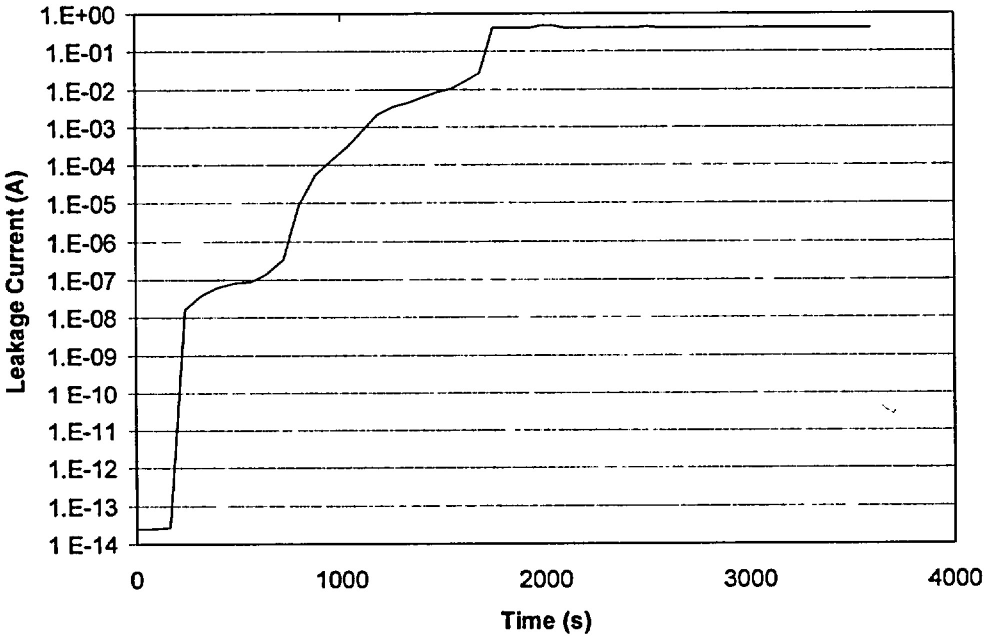

Figure 5-38. Leakage current resulting from IR changes between Conductors 1 and 2 during Test 9.

Based solely on the results of the IR measurements made during Test 9, it appears that the IR cable experienced fire-induced damage that allowed leakage currents high enough to cause device actuation in a DC control circuit. The modes of failure cannot, however, be determined with confidence.

5.3.2 Test 10

Test 10 was a 200-kW heat release rate fire with thermoset test cable bundles. The tray fill was limited to a single row of cables. The cables were installed in a vertical tray and exposed to the fire with the burner set 0.6 m (2 ft) behind the center of the tray. The IR sample bundle was, again, a seven-conductor cable but in this test, the multi-conductor was bundled with just one single-conductor cable. The cables were wired in the same manner as described for Test 4, except that there was only one external single-conductor cable (C8). The IR system was operated in an ungrounded DC mode. While substantial degradation in conductor IR was observed through the course of the test, all IR values remained in excess of 1000 Ω. Hence, using the same failure criteria applied to other tests (an IR of less than 100 Ω), no gross conductor failures were observed.

Figure 5-39 shows the time-temperature plots for two of the thermocouples monitored during the test. TC #23 was mounted on a tray rung at the top of the tray, and TC #49 was located at 15 cm (6 in.) from the bottom of the instrumented cable TC-4. These two thermocouples were chosen because they showed the worst-case temperature exposure conditions (highest recorded temperatures) for the air near the IR bundle and for the instrumented cable closest to the IR bundle. The peak tray temperature recorded was 508°C (946°F), whereas the peak cable temperature indication reached as high as 641°C (1186°F) at one point during the test.

The DC supply was set at 100 V for this test (the upper limit of the programmable power supply being used). In addition, since the IR measurement system is limited to monitoring only eight conductors in the DC operating mode, only one external single-conductor cable was bundled with the IR seven-conductor cable. This single external conductor was monitored as Conductor 8 of the IR measurement system.

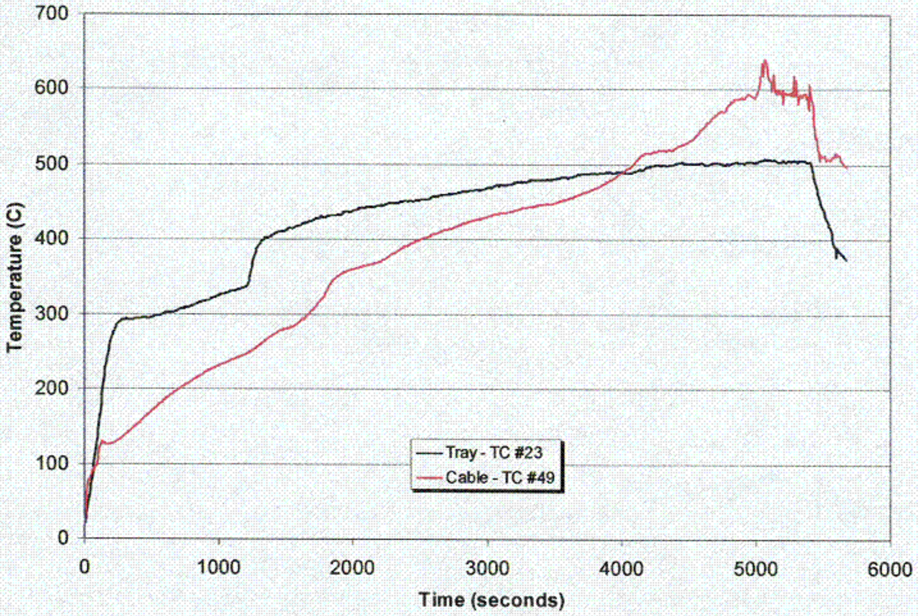

Figure 5-39. Representative tray and TC-4 cable temperatures recorded during Test 10.

Figure 5-40 shows the IR changes occurring between Conductor 1 and each of the other conductors during the test. Conductor 1 was the center conductor in the seven-conductor cable and the other six conductors surrounded Conductor 1 and were immediately adjacent to it. Conductor 8 is a single conductor cable bundled with the seven-conductor cable to make up the IR bundle for this test.

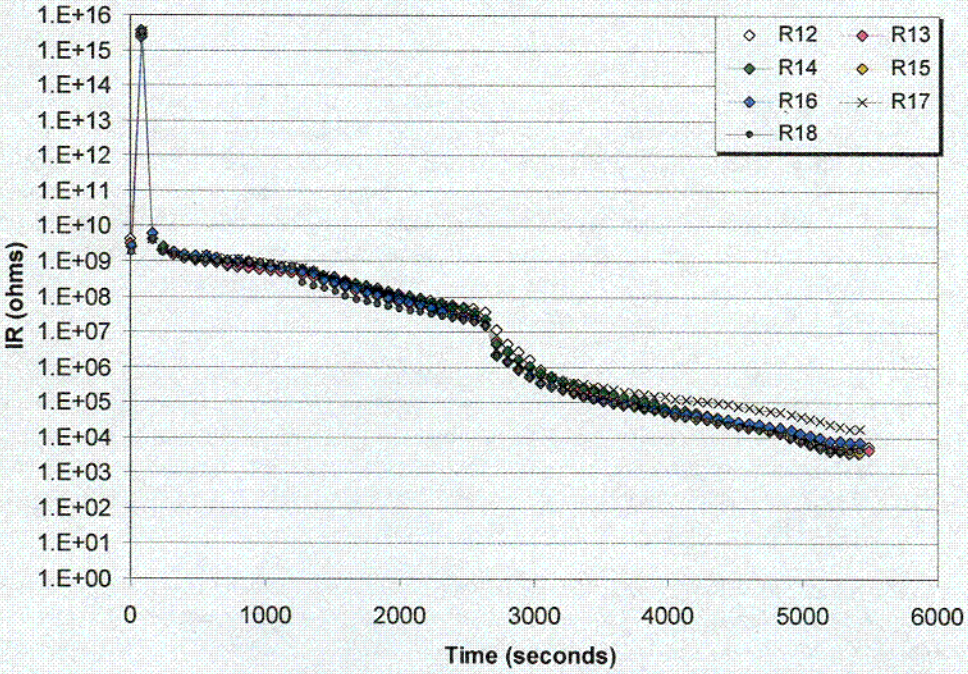

Figure 5-40. Representative conductor-to-conductor IRs obtained during Test 10. This plot shows the IR between Conductor 1 and the other seven conductors in the IR cable bundle.

C01

As shown in the figure, there was a very gradual decrease in IRs between the conductors from start to end of the test run (3×10^9 down to 1×10^4 Ω).

Figure 5-41 plots how the leakage current between Conductors 1 and 2 changed as the test progressed. The peak leakage current appears to be ~20 mA between the conductors.

Based solely on the results of the IR measurements made during Test 10, while the cable did show substantial IR degradation, the test appears to have stopped short of actual failure. That is, it does not appear that the IR cable experienced fire-induced damage that would allow leakage current high enough to cause device actuation in a DC control circuit.

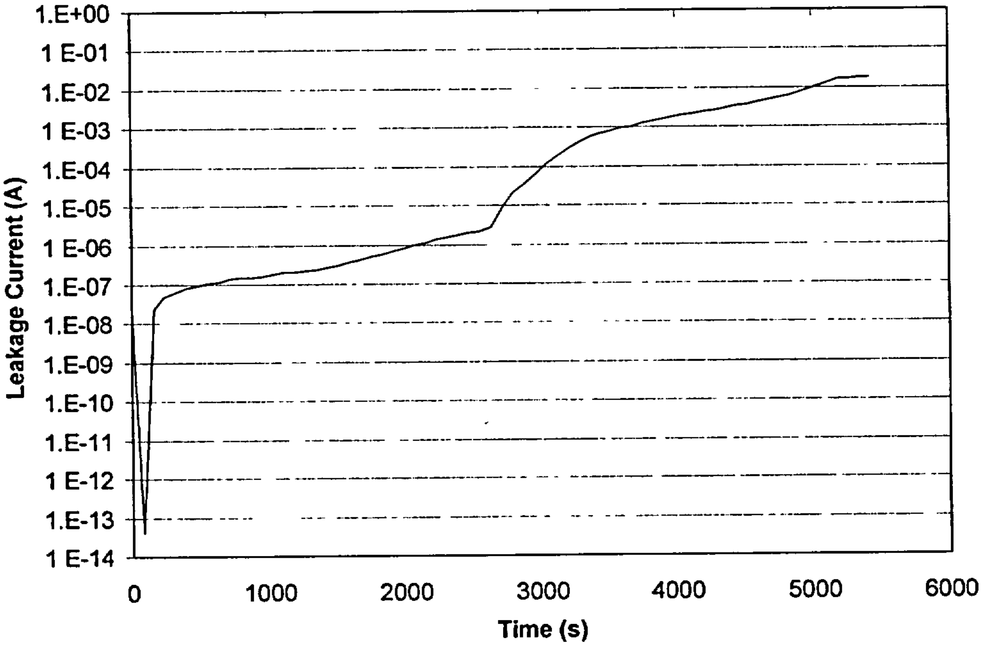

Figure 5-41. Leakage current resulting from IR changes between Conductors 1 and 2 during Test 10.

5.3.3 Test 11

Test 11 was a 145-kW heat release rate fire with thermoset test cable bundles. The tray was loaded with four full rows of cables. The cables were laid in a horizontal tray and exposed to the fire plume at the corner of the tray. The DC supply was set at 24 V for this test to simulate typical instrument signal conditions. In addition, the IR measurement system was connected to two separate instrumentation cables. One (IR1) was a shielded two-conductor cable; the other (IR3) was made up of three shielded pairs (six-conductor cable). Cable IR1 was laid in the top row of cables in the tray; IR3 was located in the bottom row of cables.

Based on the criteria applied to other tests (a conductor IR of less than 100 Ω), no gross failures were observed during this test – all IRs remained above 1000 Ω. However, substantial degradation was noted, particularly for the IR3 bundle. Given that these were instrument cables, alternate failure criteria may be appropriate. This report has not attempted to propose specific criteria for assessing the pass/fail behavior of an instrument cable.

Figure 5-42 shows the time-temperature plots for three of the thermocouples monitored during the test. TC #26 was mounted on a tray rung at the corner of the tray, TC #73 was located about the mid-position on the instrumented cable TC-4, and TC #46 was located about the mid-position on the instrumented cable TC-1. These

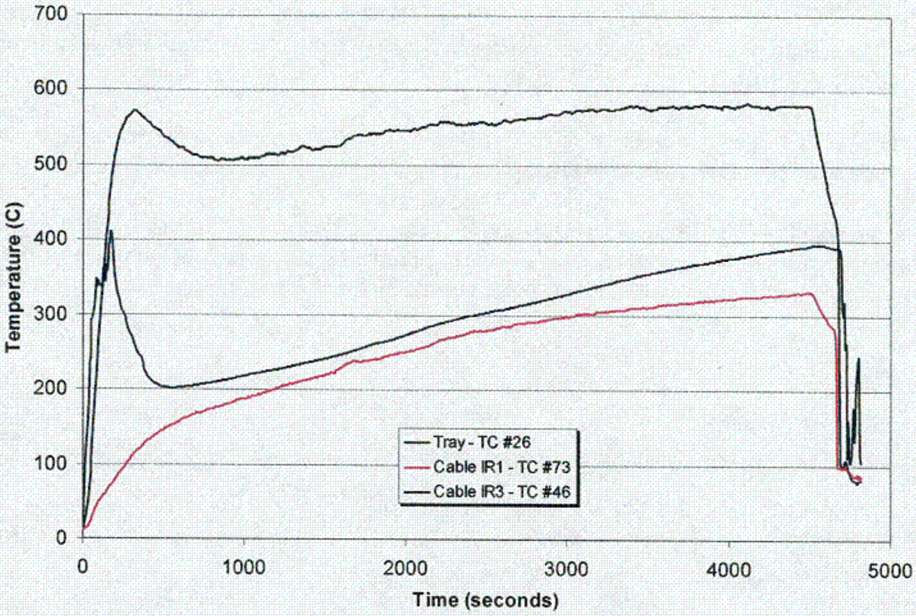

Figure 5-42. Representative tray and cable (TC-1 and TC-4) temperatures recorded during Test 11.

thermocouples were chosen because they showed the worst-case temperature exposure conditions (highest recorded temperatures) for the air near the IR bundle and for the instrumented cable closest to the IR bundle. Peak tray temperature was 584°C (1083°F), peak TC-1 cable temperature was 412°C (774°F), and the peak TC-4 cable temperature was 333°C (631°F).

Figure 5-43 shows the changes in IR occurring between Conductors 1 and 2 in the IR1 cable during the test. (Conductors 1 and 2 were the conductor pair within the IR1 cable.)

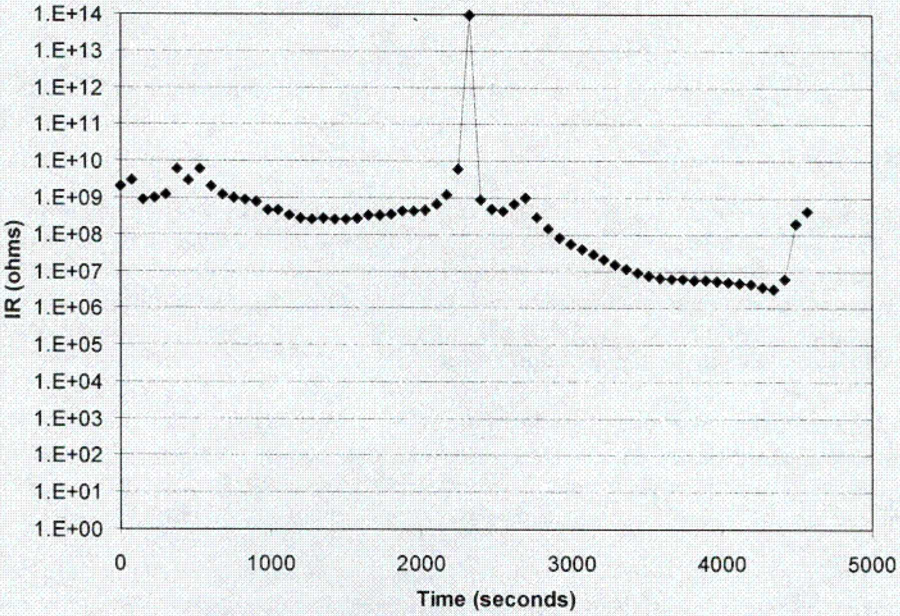

Figure 5-43. IR between Conductor 1 and 2 obtained during Test 11.

C02

As shown in the figure, the IR between Conductors 1 and 2 remains fairly constant with very small variations until ~2700 seconds into the test run. Then the conductor IR gradually decreases from ~10^9 to ~3×10^6 Ω at ~4400 seconds; it then seems to be recovering over the remaining time of the test.

Figure 5-44 shows the IR change between Conductor 3 and the other conductors in IR3 cable during the test. In general, the behavior is the same as shown above for Conductors 1 and 2; however, a definite change in the conductor-to-conductor IRs occurs at ~3600 seconds, when the cable IR3 conductor IRs decrease smoothly from 3×10^6 down to 3×10^3 Ω near the end of the test run.

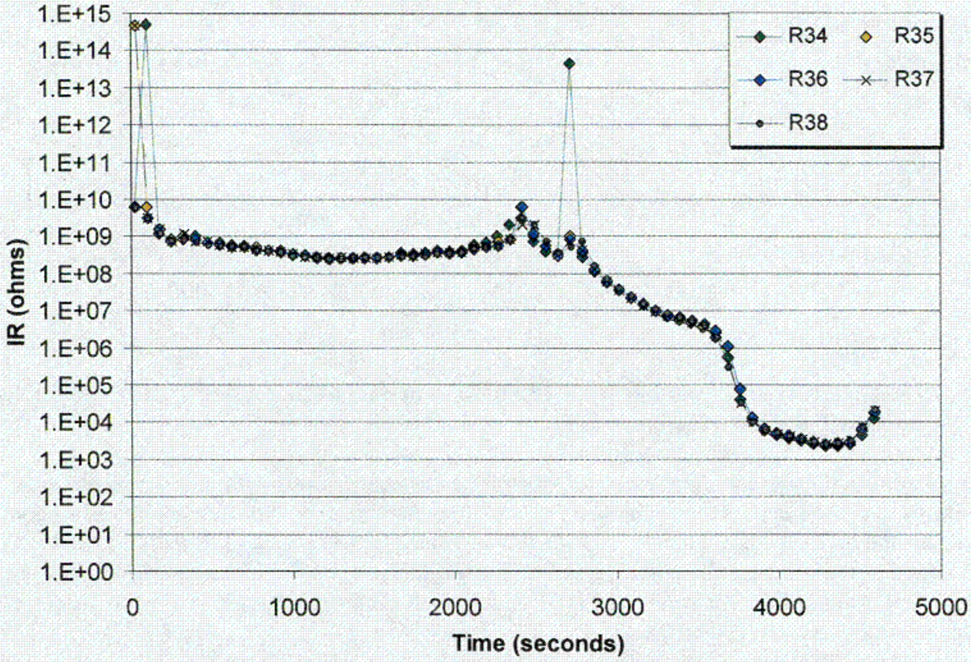

Figure 5-44. IRs between Conductor 3 and Conductors 4 through 8 obtained during Test 11.

Figure 5-45 plots how the leakage currents between Conductors 1 and 2, and 3 and 4 (a shielded pair within IR3), changed as the test progressed. The peak leakage current appears to be ~7 μA between Conductors 1 and 2, which is not enough to pose a serious problem, even to a typical instrument circuit. However, the peak leakage current between Conductors 3 and 4 is ~10 mA, which could cause a substantial instrument reading error in, for example, a 4-20 mA instrument circuit.

Based on the results of the IR measurements made during Test 11, it appears that the IR3 cable experienced substantial fire-induced degradation. While the IR did remain above 1000 Ω for the test duration, depending on the specific instrument circuit considered, this degradation might have been sufficient to cause incorrect instrument readings. The IR1 cable did not experience any substantial IR degradation.

5.3.4 Test 12

Test 12 was a 145-kW heat release rate fire with thermoset test cable bundles. The cables were laid in a horizontal tray positioned 1.8 m (6 ft) above the floor and exposed to the fire plume. The burner was positioned under the corner of the tray. The IR sample bundle was, again, a seven-conductor cable bundled with three single-conductor cables and wired in the same manner as described for Test 9 (i.e., the three external conductors were electrically ganged together and designated as Conductor 8). The IR system was operated in the DC mode at 100 V and the DC power supply was tied to ground on the negative terminal. Hence, both conductor-to-conductor and conductor-to-ground IR values can be determined. Various conductor failures were observed in this test.

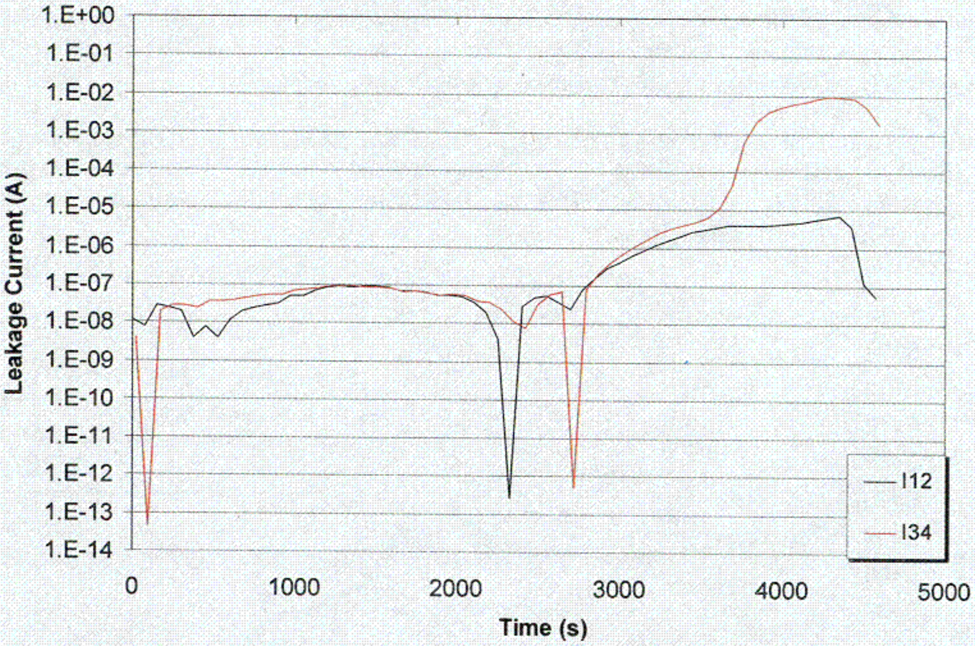

Figure 5-45. **Leakage currents resulting from IR changes between Conductors 1 and 2 and between Conductors 3 and 4 during Test 11.**

Figure 5-46 shows the time-temperature plots for two of the thermocouples monitored during the test. These two thermocouples were chosen because they showed the worst-case temperature exposure conditions (highest recorded temperatures) for the air near the IR bundle and for the instrumented cable closest to the IR bundle. TC #25 was mounted on a rung of the tray near the corner, and TC #64 was located about mid-way along the instrumented cable TC-3. The peak tray temperature was 611°C (1132°F) and then dropped and stabilized at 573°C (1063°F). The peak cable temperature was 465°C (869°F).

As Figure 5-47 shows, the change in IR occurring between Conductor 1 and the other conductors in the cable bundle was a fairly smooth transition from ~3 × 10^8 down to ~30 Ω beginning at ~1700 seconds and continuing throughout the rest of the test run. Conductor 1 was the center conductor in the seven-conductor cable and Conductors 2 through 7 surrounded Conductor 1 and were immediately adjacent to it. Conductor 8 was comprised of the ganged-together set of three single conductor cables bundled with the seven-conductor cable to make up the IR bundle.

The IR of the individual conductors to ground demonstrated three transitions in IR, as shown in Figure 5-48. The first occurred at 1140 to 1500 seconds; the next was between 1500 seconds and 1700 seconds; and finally the IRs shorted to ground in fairly smooth transitions.

Table **5-6** summarizes the conductor failure modes and times for Test 12. All of the initial failures observed involved the conductors shorting to ground. Initially, at about 1000 seconds, Conductor 8 (the three external conductors as a gang) shorts to ground. This short-to-ground failure is also manifested by the apparent reduction in IR between Conductor 8 and the other conductors in the cable bundle. A second ground short involving Conductor 3 is observed at about 1900 seconds. Over the period of 2200 to 3500 seconds, the rest of the conductors short to ground.

Figure 5-49 plots how the leakage currents for Conductors 1 and 2 changed in their relationship to one another and to ground as the test progressed.

C03A

Based solely on the results of the IR measurements made during Test 12, it appears that the IR cable experienced fire-induced damage that allowed leakage currents high enough to cause device actuation or blown fuses.

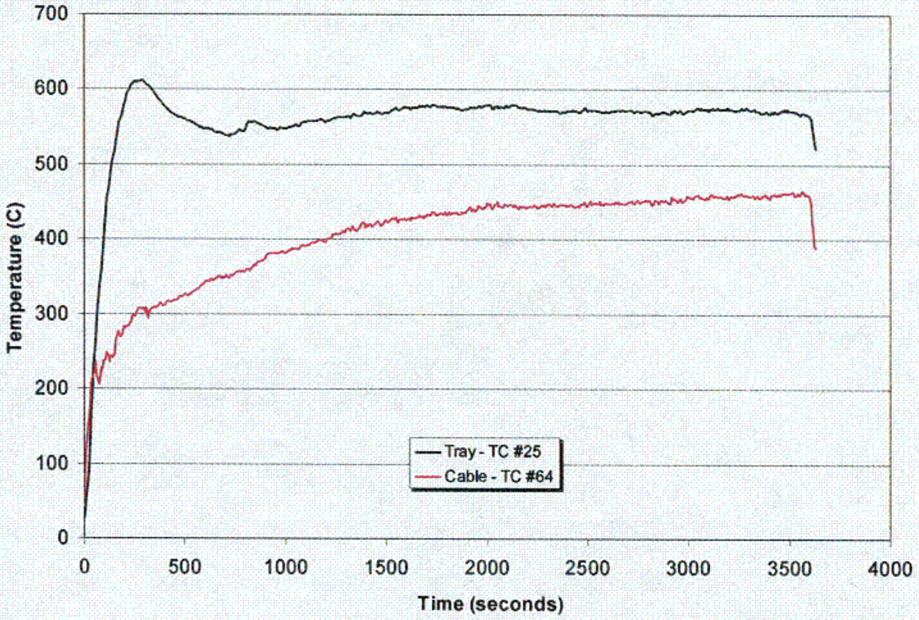

Figure 5-46. Representative tray and TC-3 cable temperatures recorded during Test 12

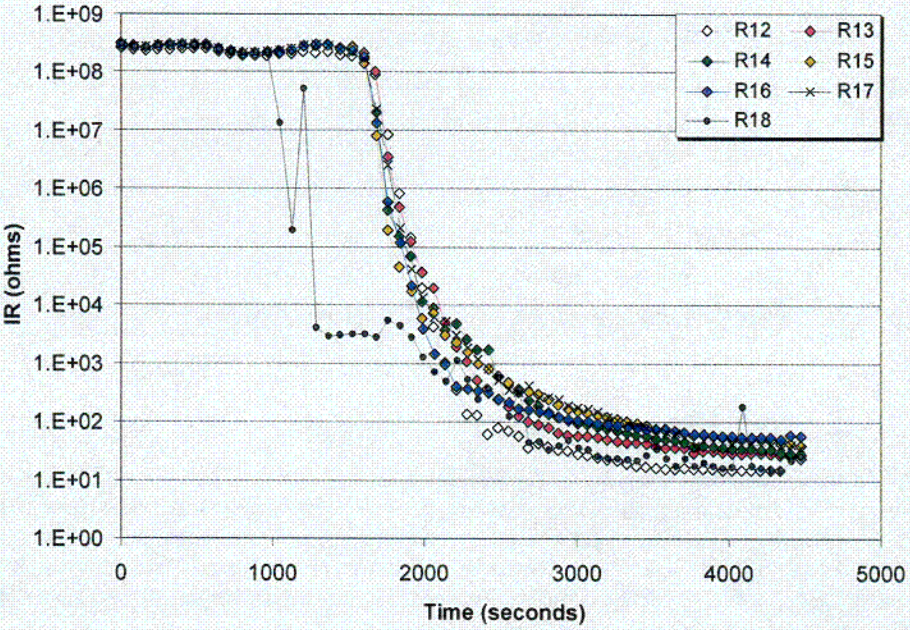

Figure 5-47. Representative conductor-to-conductor IRs obtained during Test 12. This plot shows the IR between Conductor 1 and the other seven conductors in the IR cable bundle.

C04

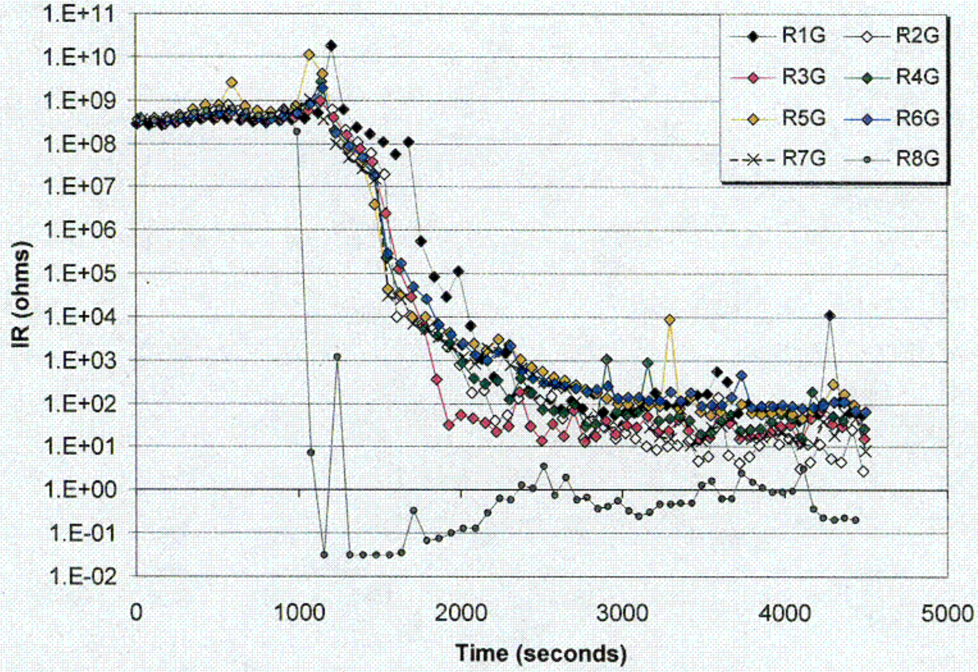

Figure 5-48. Conductor-to-ground IRs obtained during Test 12.

Table 5-6. Summary of Cable Failure Times and Modes during Test 12

Time (s)	Failure Mode Observed
~ 1000	Conductor 8 shorts to ground
~ 1900	Conductor 3 shorts to ground
~ 2200–2800	Conductors 1, 2, 4, and 7 short to ground
~ 3000	Conductor 5 shorts to ground
~ 3500	Conductor 6 shorts to ground – all conductors are grounded

5.4 Tests 13 through 18

Tests 13 through 18 were conducted using the SNL IR measurement system configured for AC operation. Unfortunately, the IR measurement system was miswired so that only the voltage supply side relays were operable during Tests 13 and 15 through 17. The measurement side relays were not properly connected to the relay control system. Also note that Tests 13 through 18 were not conducted in consecutive order; Tests 13 and 15 through 17 were conducted in April and Tests 14 and 18 were conducted in May. The problem with the IR measurement system was corrected before Tests 14 and 18 were run.

As a result of the wiring fault, for Tests 13 and 15 through 17, only the total change in IR for each conductor to ground can be determined. The specific initial failure mode cannot be ascertained.

C05

5.4.1 Test 13

Test 13 was a repeat of Test 1, but employing a cable tray with a much less severe bend radius than before. The armored cables were tested in a 350-kW heat release rate fire and exposed to the hot gas layer. The burner was placed in the center of the test cell. The cables were laid in a horizontal tray and the tray was filled with two rows of cables, five of which were being monitored along with a monitored instrument cable that was also included in the tray fill (see Section 6). The IR cable was an eight-conductor armored cable, not bundled with any external cables. In contrast to Test 1, the armor shield for the IR cable was connected to ground and was not monitored as a separate conductor.

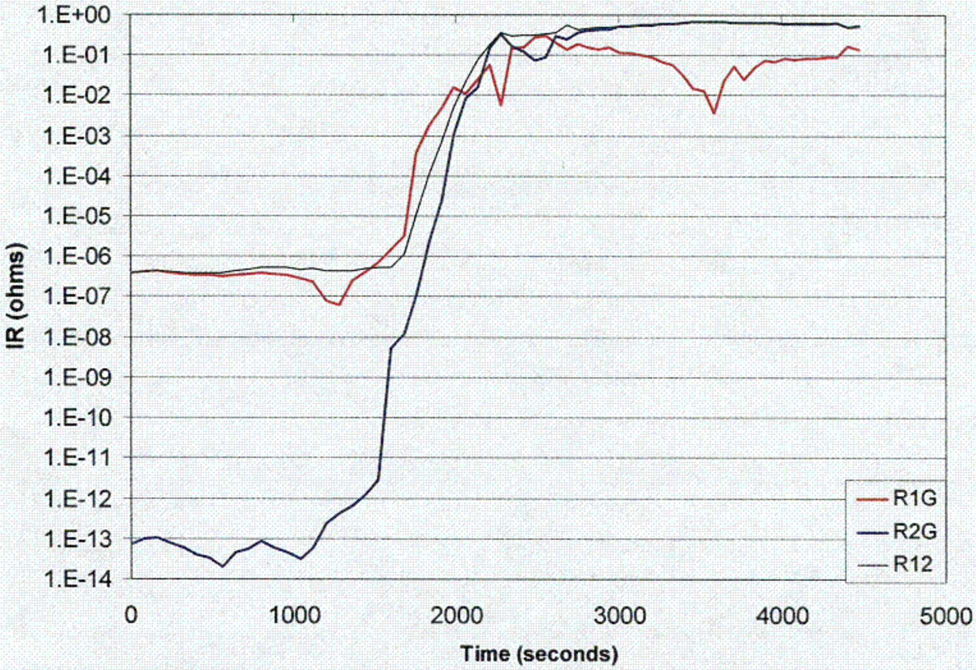

Figure 5-49. Leakage currents resulting from IR changes between Conductors 1 and 2 during Test 12.

shows the time-temperature plots for two of the thermocouples monitored during the test. TC #13 was mounted on the tray's side rail about 0.6 m (2 ft) from the corner of the tray, and TC #69 was located at the test cell doorway end of the instrumented cable TC-4. These two thermocouples were chosen because they showed the worst-case temperature exposure conditions (highest recorded temperatures) for the air near the IR cable and for the instrumented cable closest to the IR bundle. The peak tray temperature recorded during this test was 756°C (1393°F) and the cable temperature peaked at 772°C (1422°F) near the end of the run.

As noted previously, the IR measurement system was only capable of determining total IR to ground due to a wiring problem during Test 13. Figure 5-51 shows the time-dependent change in the total IR for each of the eight conductors in the IR cable measured during this test. The fact that the IR values fall to very low levels (<100 Ω) beginning at about 1900 seconds indicates that conductor failures have occurred. Figure 5-52 shows the associated leakage currents.

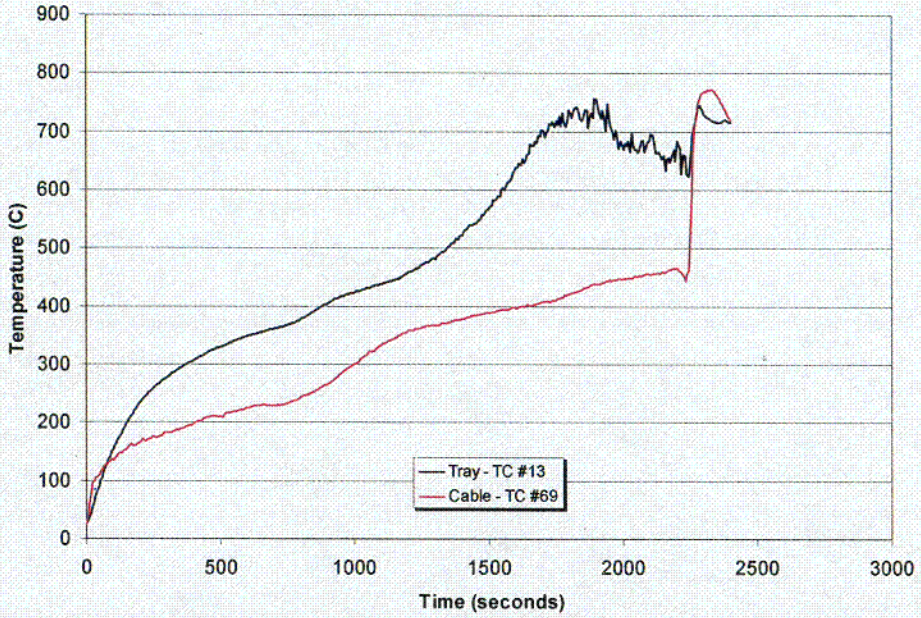

Figure 5-50. Representative tray and TC-4 cable temperatures recorded during Test 13.

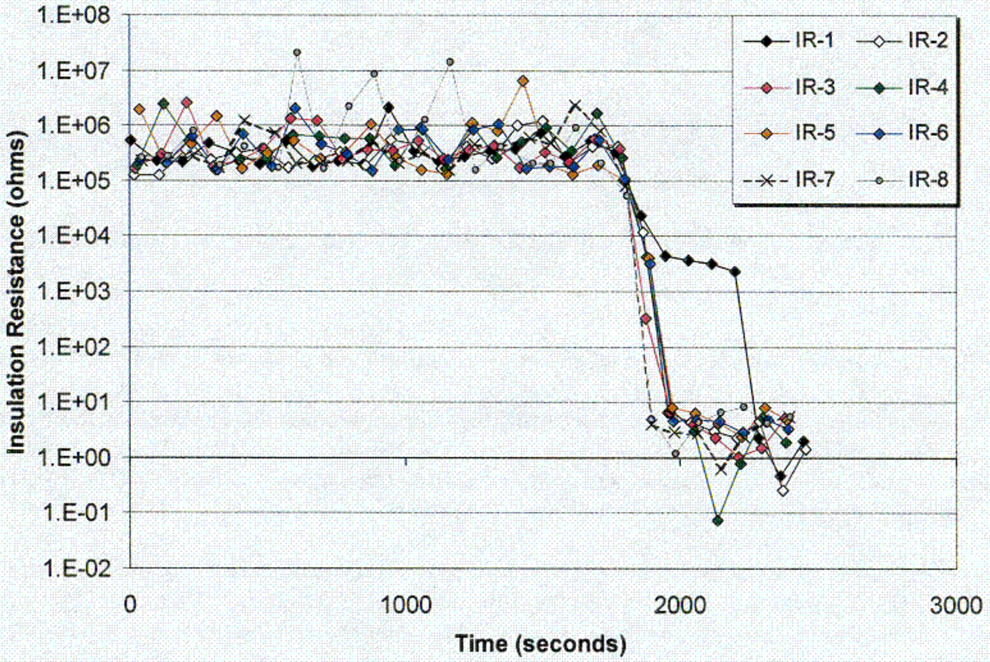

Figure 5-51. Total IR of each conductor recorded during Test 13.

C07

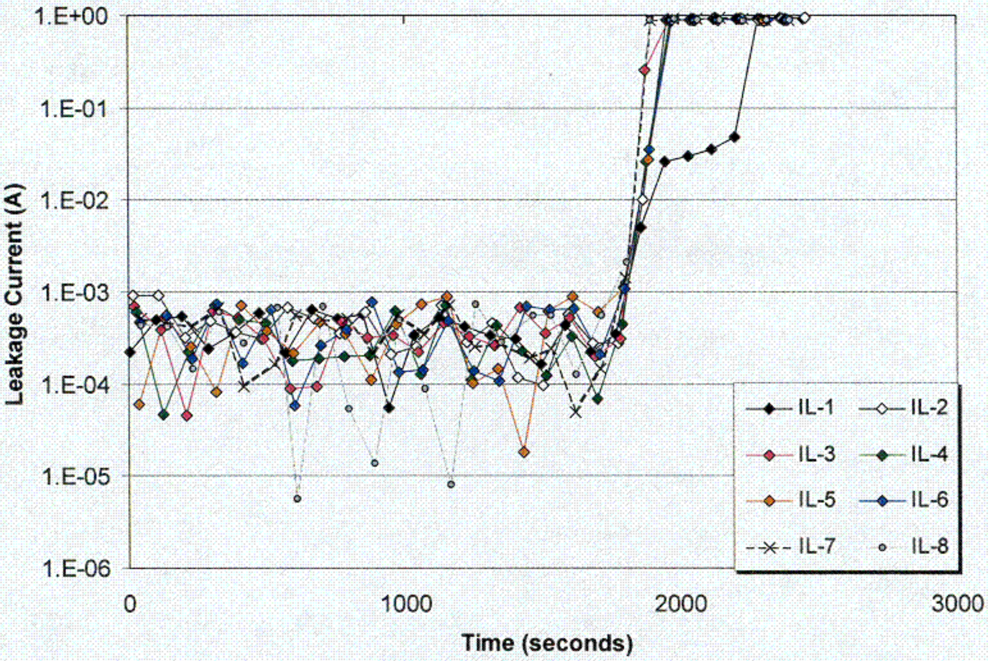

Figure 5-52. Total leakage currents resulting from IR changes for each conductor during Test 13.

5.4.2 Test 14

Test 14 was a 145-kW heat release rate fire with the cables exposed to the fire plume. The burner was placed under the corner of the cable tray and conduit. The IR cable bundle consisted of three thermoset three-conductor cables secured together and routed in the horizontal conduit. A thermoplastic instrument cable for the current loop circuit was also placed in the conduit (see Section 6). The wiring problem with the IR measurement system that had plagued Tests 13, 15, 16, and 17 had been diagnosed and corrected in time to allow its proper operation during this test.

No thermocouple-instrumented cable was routed in the conduit during this test; hence, there is no cable temperature data available. In addition, no direct measure of conduit temperature was made either. However, no failures of the IR cable bundle were identified based on the results of this test. Figure 5-53 shows a plot of the IRs between Conductor 1 and the other conductors in the IR bundle. Conductors 1 through 3 were enclosed in one of the three-conductor cables of the IR bundle, Conductors 4 through 6 were in a second cable, and Conductors 7 through 9 formed the third cable. As shown in the figure, the IRs declined very little over the course of the test run.

Figure 5-54 shows the values of IR between each of the IR cable conductors to ground recorded during Test 14. This figure also shows that the IRs to ground decreased very slightly during the test. Figure 5-55 presents the change in leakage current for Conductors 1 and 2 occurring during Test 14.

Based solely on the results of the IR measurements made during Test 14, it appears that the IR cable experienced virtually no damage and would not have caused any device actuation or blown fuses.

C08

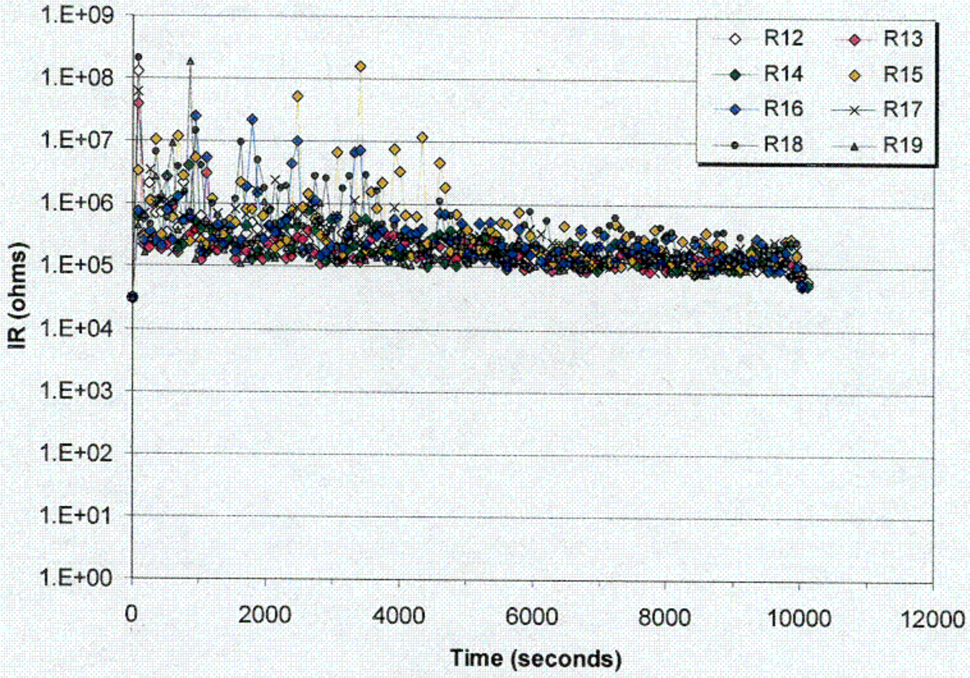

Figure 5-53. Representative conductor-to-conductor IRs obtained during Test 14.

5.4.3 Test 15

Test 15 was actually conducted prior to Test 14, and, like Test 13, was impacted by the problem with the IR measuring system. The IR cable bundle consisted of a seven-conductor thermoset control cable surrounded by three single-conductor thermoset cables. The test conditions for exposure consisted of a variable heat release rate fire where the flame intensity was adjusted from 350 kW to 200 kW and finally to 450 kW over the course of the test run. The cables were laid in a single row in a horizontal cable tray located 1.8 m (6 ft) above the floor and exposed to the hot gas layer generated by the fire. The burner was placed in the center of the test cell. A monitored instrument cable was also included in the tray for the current loop circuit (see Section 6).

Figure 5-56 shows the time-temperature plots for two of the thermocouples monitored during the test. TC #18 was mounted on the tray's side rail about 0.6 m (2 ft) from the end of the tray closest to the doorway, and TC #67 was located 0.6 m (2 ft) from the end of the of the instrumented cable TC-3 that ran parallel to the back wall of the test cell. These two thermocouples were chosen because they showed the worst-case temperature exposure conditions (highest recorded temperatures) for the air near the IR cable and for the instrumented cable closest to the IR bundle. The peak tray temperature recorded during this test was 573°C (1063°F) and the cable temperature was 540°C (1004°F).

As noted previously, the IR measurement system was only capable of determining total IR due to a wiring problem during Test 15. Figure 5-57 shows the time-dependent change in the total IR for each of the 10 conductors in the IR cable measured during this test. Table 5-7 summarizes the behavior of the cable in the test. Only five of the 10 conductors appear to have total IRs <100 Ω at the end of the test. The other conductors, while experiencing decreasing total IRs, did not reached the point of failure.

Figure 5-58 shows the resulting leakage currents allowed by the change in IR for each conductor. Although there is no direct evidence, the two external Conductors 8 and 10 may have been shorted together without ground interaction during the period of time their IRs decreased to and held at ~1000 Ω. This supposition is largely based on previous experience with conductors shorting together and the resulting voltage responses recorded on the IR system.

C09

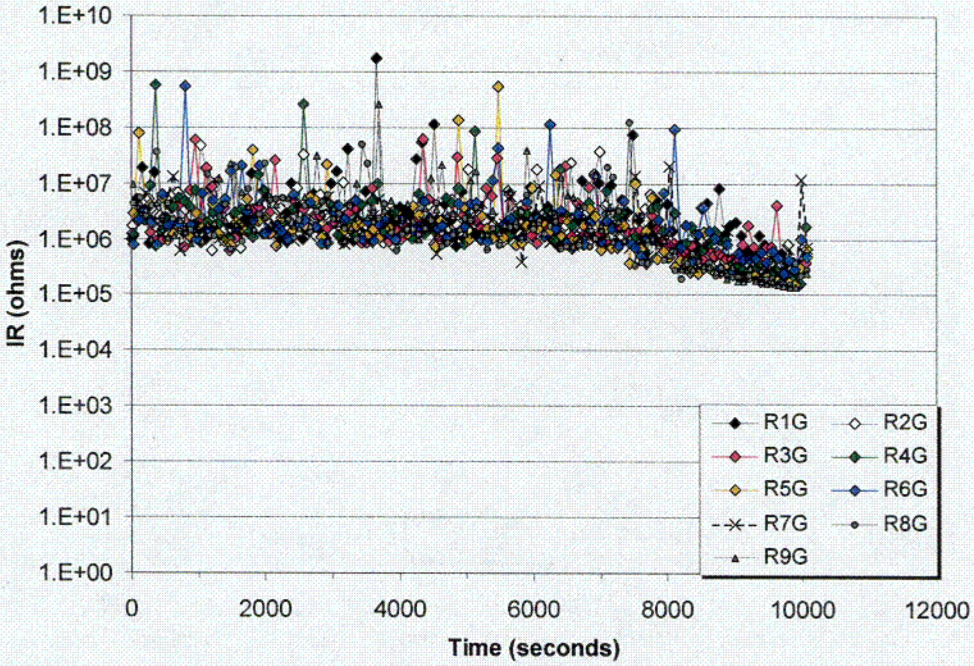

Figure 5-54. Conductor-to-ground IRs obtained during Test 14.

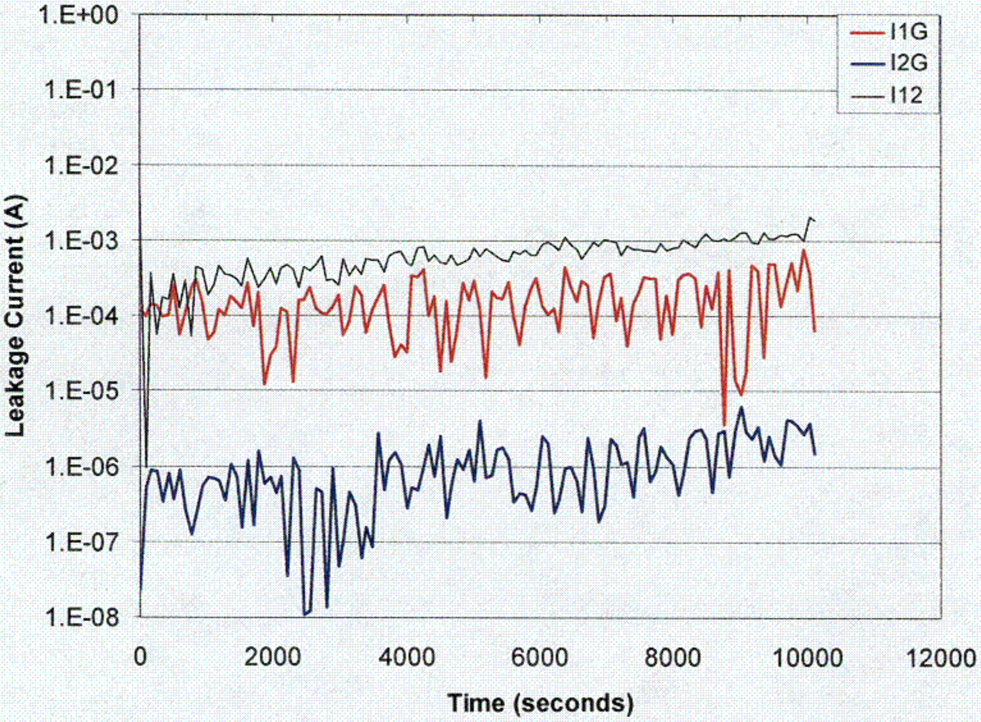

Figure 5-55. Leakage currents resulting from IR changes in Conductors 1 and 2 during Test 14.

C10

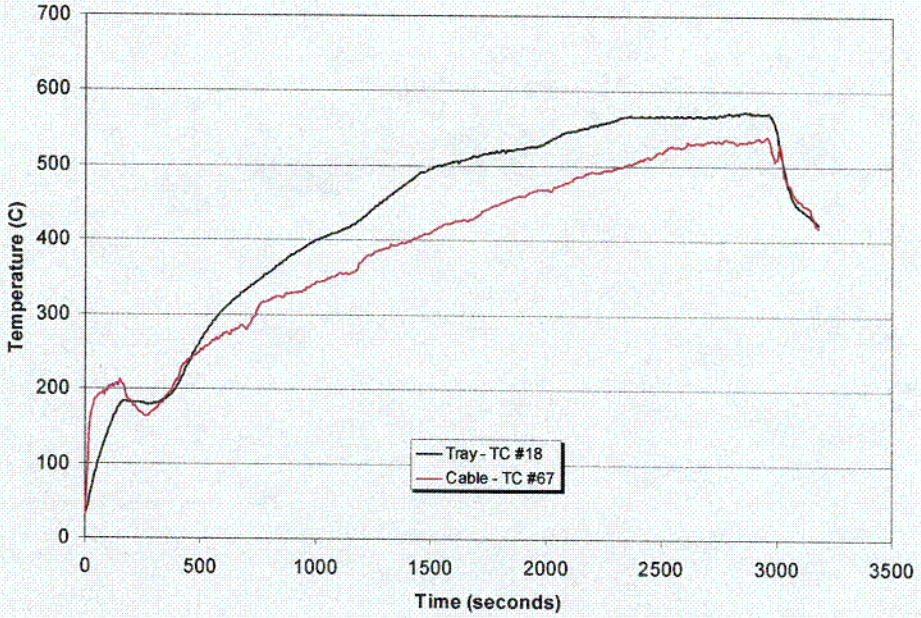

Figure 5-56. Representative tray and TC-3 cable temperatures recorded during Test 15.

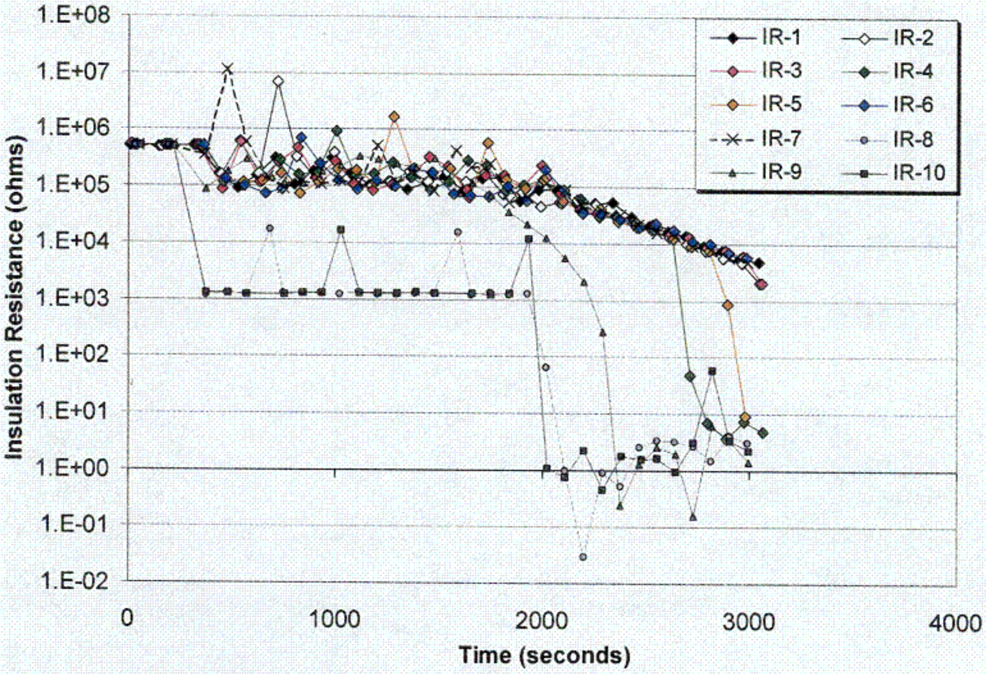

Figure 5-57. Total IR of each conductor recorded during Test 15.

C11

Table 5-7. Summary of Cable Behavior during Test 15

Time (s)	Observations
~ 1250	Conductors 8 and 10 IRs decrease to ~1000 Ω
~ 2020	Conductors 8 and 10 IRs decrease to ~1 Ω, perhaps indicating shorts to ground
~ 2400	Conductor 9 IR decreases to < 1 Ω, perhaps indicating a short to ground
~ 2700	Conductor 4 IR decreases to < 100 Ω, perhaps indicating a short to ground
~ 3000	Conductor 5 IR decreases to < 100 Ω, perhaps indicating a short to ground

5.4.4 Test 16

Test 16 was also impacted by the wiring problem with the IR measuring system and was conducted prior to Test 14. The IR cable bundle consisted of a nine-conductor thermoplastic control cable surrounded by three single-conductor thermoplastic cables. The three external cables were electrically ganged together and monitored on channel 10. The test conditions for exposure consisted of a 145-kW heat release rate fire with the test cables exposed to the fire plume. The IR cable bundle was routed inside a conduit located alongside the cable tray toward the center of the test cell. The cable tray and conduit were set 1.8 m (6 ft) above the floor. The burner was set directly under the corner of the cable tray. A monitored instrument cable was also included in the tray for the current loop circuit (see Section 6).

Figure 5-59 shows the time-temperature plots for two of the thermocouples monitored during the test. TC #27 was mounted on a tray rung at the corner of the tray, and TC #73 was located at the mid-point of the instrumented cable TC-4. These two thermocouples were chosen because they showed the worst-case temperature exposure conditions (highest recorded temperatures) for the air near the IR cable and for the instrumented cable closest to the IR bundle. The peak tray temperature recorded during this test was 550°C (1022°F) and the cable temperature was 276°C (529°F).

As previously mentioned, the IR measurement system was only capable of determining total IR due to a wiring problem during Test 16. Figure 5-60 shows the time-dependent change in the total IR for each of the 10 conductors in the IR cable measured during this test. Table 5-8 summarizes the behavior of the cable in the test. While some of the conductor IRs increase again (~1000 Ω) near the end of the test, it is believed that all experienced failure and the apparent recovery was due more to noise than to real healing. Figure 5-61 shows the resulting leakage currents allowed by the change in IR for each conductor.

Table 5-8. Summary of Cable Behavior during Test 16

Time (s)	Observations
~ 850	Conductors 5, 6, 7, 8, and 9 IRs decrease to ~10 Ω
~ 900	Conductors 1, 3, and 4 IRs decrease to ~10 Ω
~ 990	Conductor 2 IR decreases to ~10 Ω
~ 1450	Conductor 10 IR decreases to <1 Ω

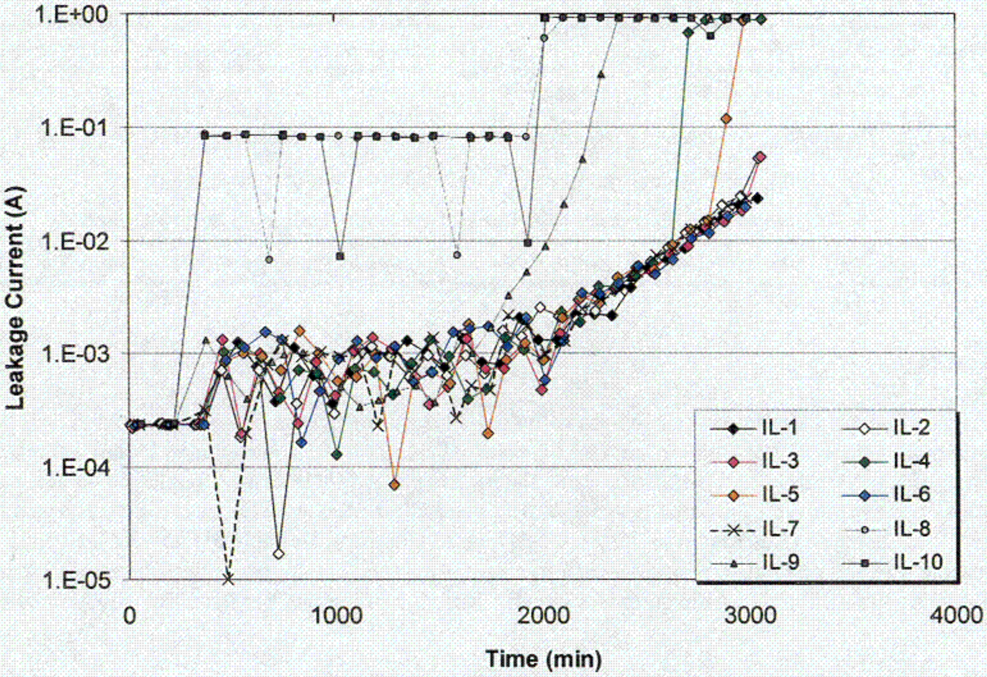

Figure 5-58. Total leakage currents resulting from IR changes for each Conductor during Test 15.

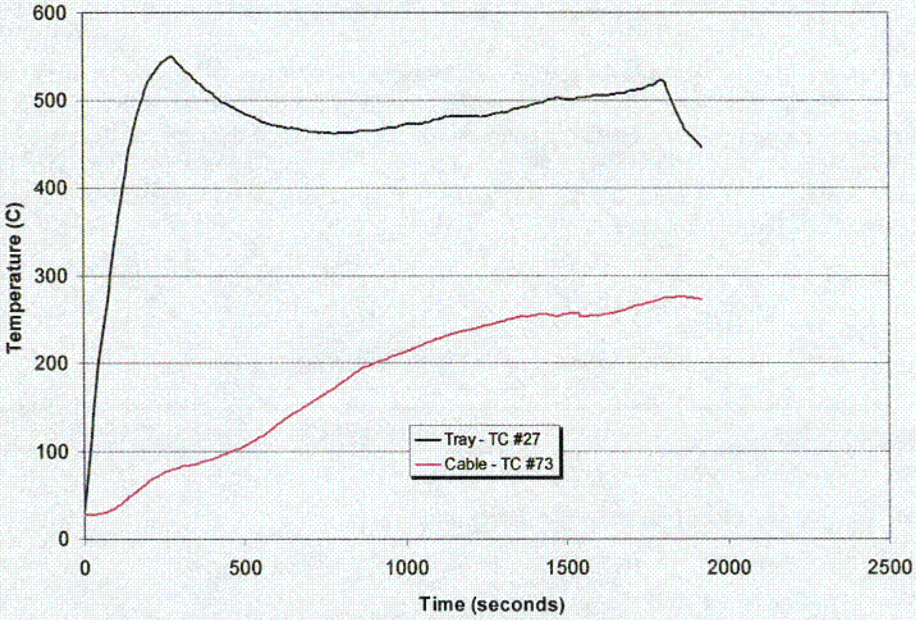

Figure 5-59. Representative tray and TC-4 cable temperatures recorded during Test 16.

C12

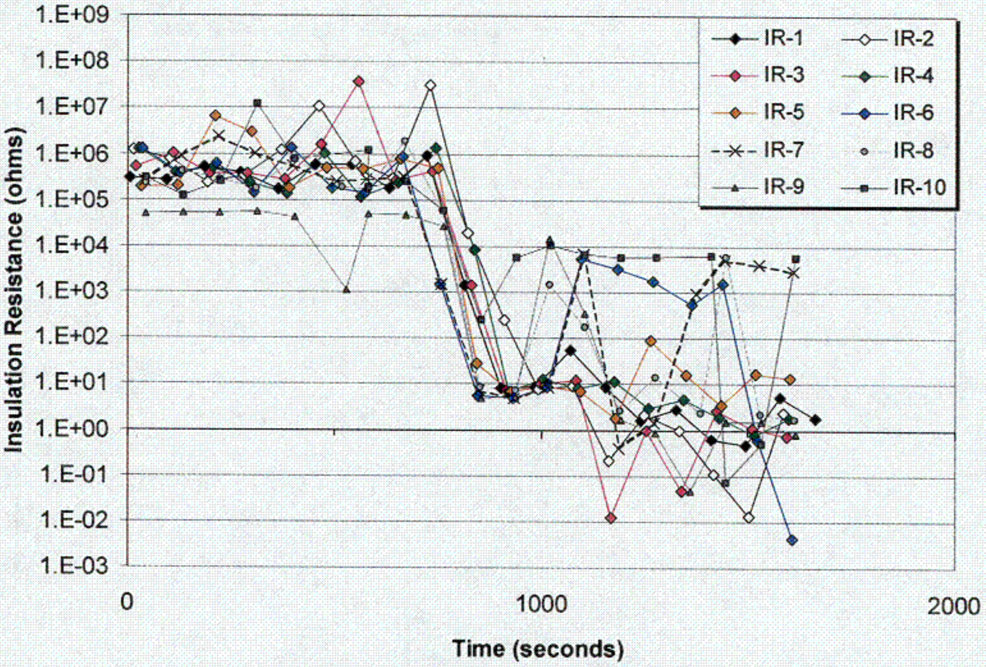

Figure 5-60. Total IR of each conductor recorded during Test 16.

5.4.5 Test 17

Test 17 was the last of the tests affected by the wiring problem with the IR measuring system and it was also conducted prior to Test 14. The IR cable bundle consisted of a nine-conductor thermoplastic control cable surrounded by three single-conductor thermoplastic cables. The three external cables were electrically ganged together and monitored on channel 10. The test conditions for exposure consisted of a 200-kW heat release rate fire with the test cables set in a vertical tray and exposed to a combined hot gas layer and radiant heat environment. The burner was set 0.6 m (2 ft) behind the center of the cable tray. A monitored instrument cable was also included in the tray for the current loop circuit (see Section 6).

Figure 5-62 shows the time-temperature plots for two of the thermocouples monitored during the test. TC #23 was mounted on a tray rung at the top of the vertical tray, and TC #56 was located at the top of the instrumented cable TC-4. These two thermocouples were chosen because they showed the worst-case temperature exposure conditions (highest recorded temperatures) for the air near the IR cable and for the instrumented cable closest to the IR bundle. The peak tray temperature recorded during this test was 482°C (900°F) and the peak cable temperature was 449°C (840°F).

Again, the IR measurement system was only capable of determining total IR due to a wiring problem during Test 17. Figure 5-63 shows the time-dependent change in the total IR for each of the 10 conductors in the IR cable measured during this test. Table 5-9 summarizes the behavior of the cable in the test. Figure 5-64 shows the resulting leakage currents allowed by the change in IR for each conductor.

C13

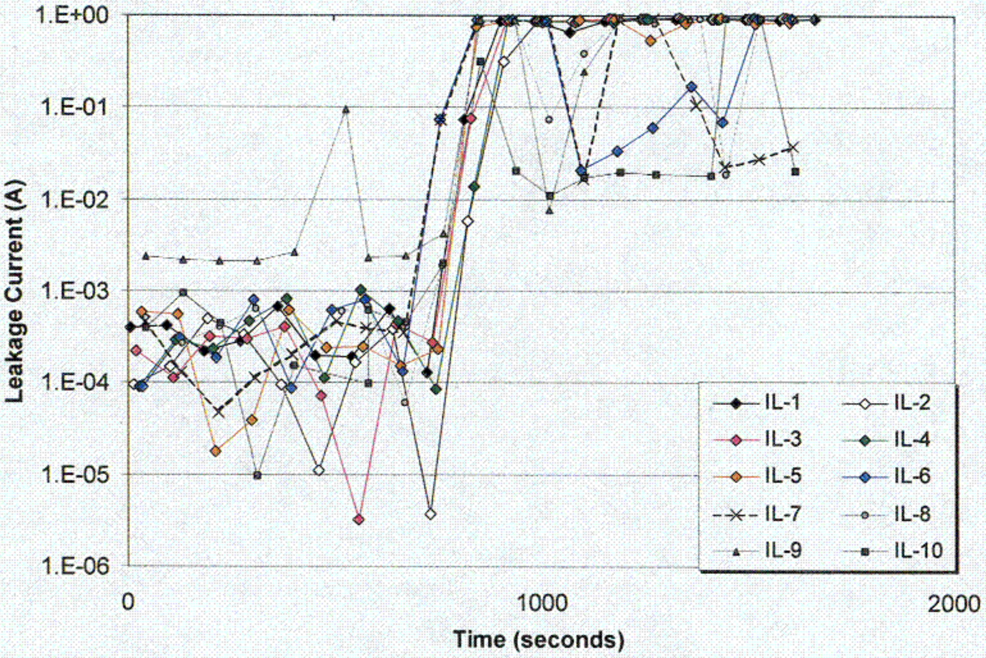

Figure 5-61. Total leakage currents resulting from IR changes for each conductor during Test 16.

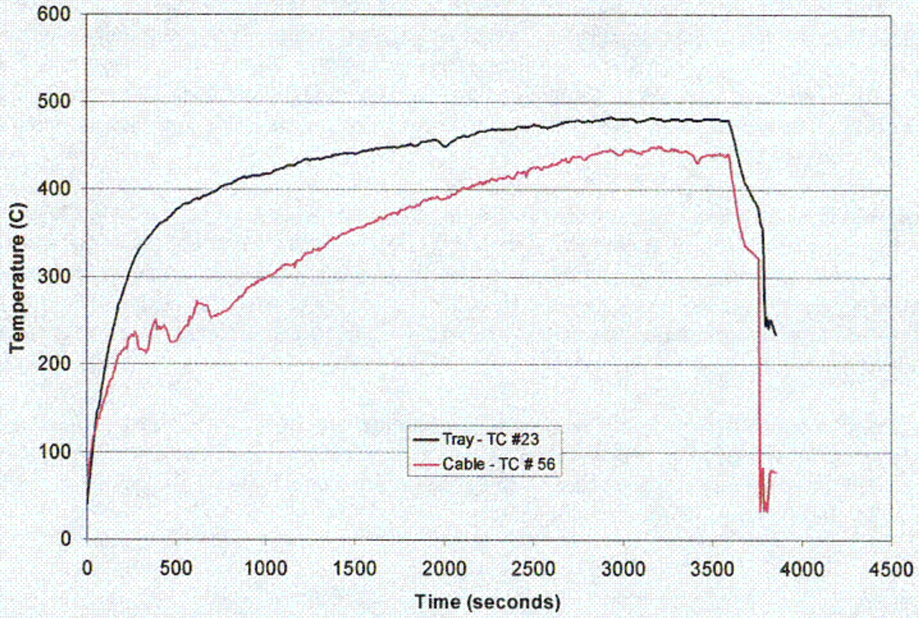

Figure 5-62. Representative tray and TC-4 cable temperatures recorded during Test 17.

C14

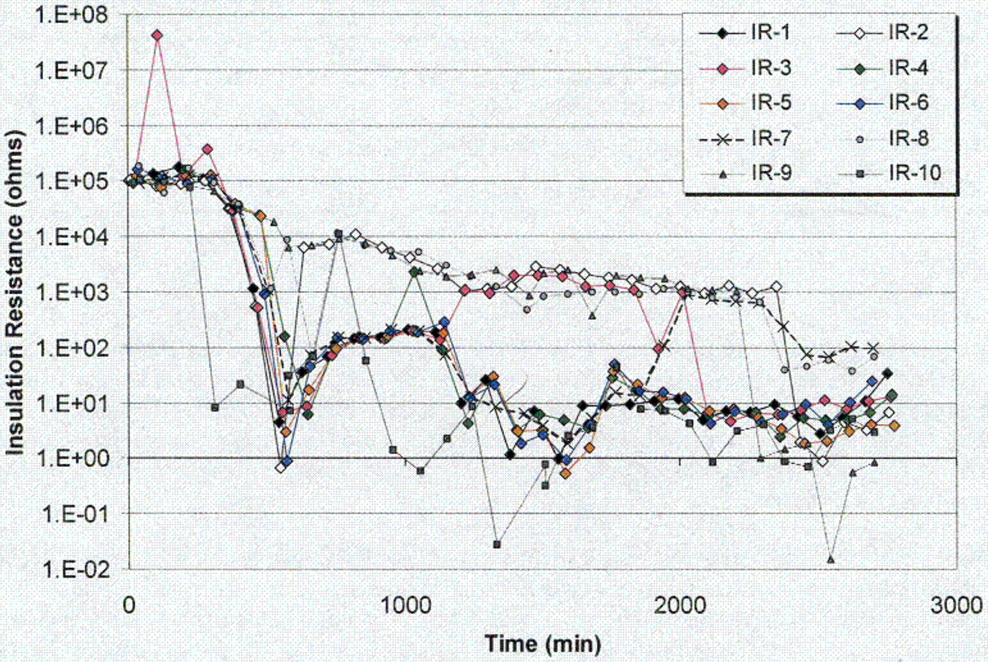

Figure 5-63. Total IR of each conductor recorded during Test 17.

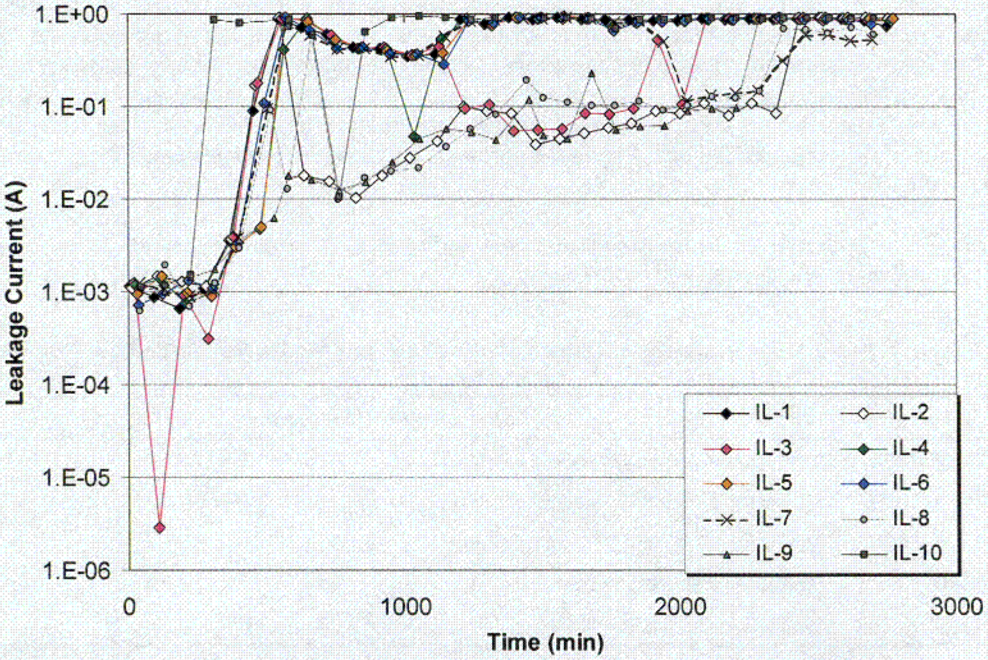

Figure 5-64. Total leakage currents resulting from IR changes for each conductor during Test 17.

C15

Table 5-9. Summary of Cable Behavior during Test 17

Time (s)	Observations
~ 315	Conductor 10 IR decreases to ~10 Ω
~ 550–650	Conductors 1, 2, 3, 4, 5, 6, 7, and 8 IRs decrease to 1 to 10 Ω
~ 2290	Conductor 9 IR decreases to <1 Ω

5.4.6 Test 18

Test 18 was the last test conducted in the test series. It was a 250-kW heat release rate fire with the cables exposed to the hot gas layer. The burner was placed in the center of the fire test cell. The IR cable bundle consisted of three thermoset three-conductor cables secured together and routed in the horizontal conduit. A thermoset instrument cable for the current loop circuit was also placed in the conduit (see Section 6). The wiring problem with the IR Measurement system that had plagued Tests 13, 15, 16, and 17 had been diagnosed and corrected in time to allow its proper operation during this test.

No thermocouple-instrumented cable was routed in the conduit during this test; hence, there is no cable temperature data available. In addition, no direct measure of conduit temperature was made either. Failures of the IR cable bundle were identified based on the results of this test. Figure 5-65 shows a plot of the IRs between Conductor 1 and the other conductors in the IR bundle. Conductors 1 through 3 made up one of the three-conductor cables of the IR bundle, Conductors 4 through 6 were in a second cable, and Conductors 7 through 9 formed the third cable. As shown in the figure, most of the IR values drop to < 100 Ω at ~3000 seconds.

Figure 5-66 shows the IR values between each of the IR cable conductors and ground recorded during Test 18. This figure shows a relatively gradual decline in IRs to ground from ~10^6 down to ~3000 Ω over the period 1500 to 2500 seconds. The almost simultaneous failure of Conductors 1, 3, and 9 followed this. The next conductor to fail was Conductor 7 at ~ 2900 seconds, then Conductors 8 and 4 failed. Conductors 5, 2, and 6 eventually failed during the course of the test. All conductors shorted to ground before interacting with any other conductor. Table 5-10 provides a summary of the conductor failures. Figure 5-67 presents the change in leakage current for Conductors 1 and 2 occurring during Test 18.

Based solely on the results of the IR measurements made during Test 18, it appears that the IR cable experienced significant damage and could have caused blown fuses.

Table 5-10. Summary of Cable Failure Times and Modes during Test 18

Time (s)	Failure Mode Observed
~ 2730–2830	Conductors 1, 3, and 9 short to ground
~ 2930	Conductor 7 shorts to ground
~ 3200–3400	Conductors 4, 5, and 8 short to ground
~ 3580	Conductor 2 shorts to ground
~ 4300	Conductor 6 shorts to ground

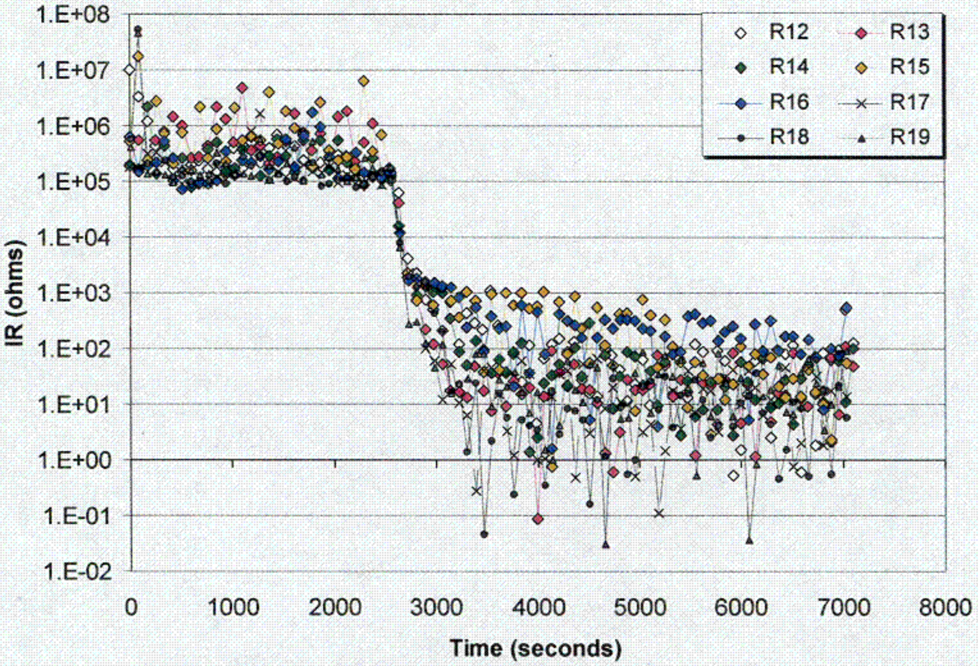

Figure 5-65. Representative conductor-to-conductor IRs obtained during Test 18. This plot shows the IR between Conductor 1 and the other eight conductors in the IR cable bundle.

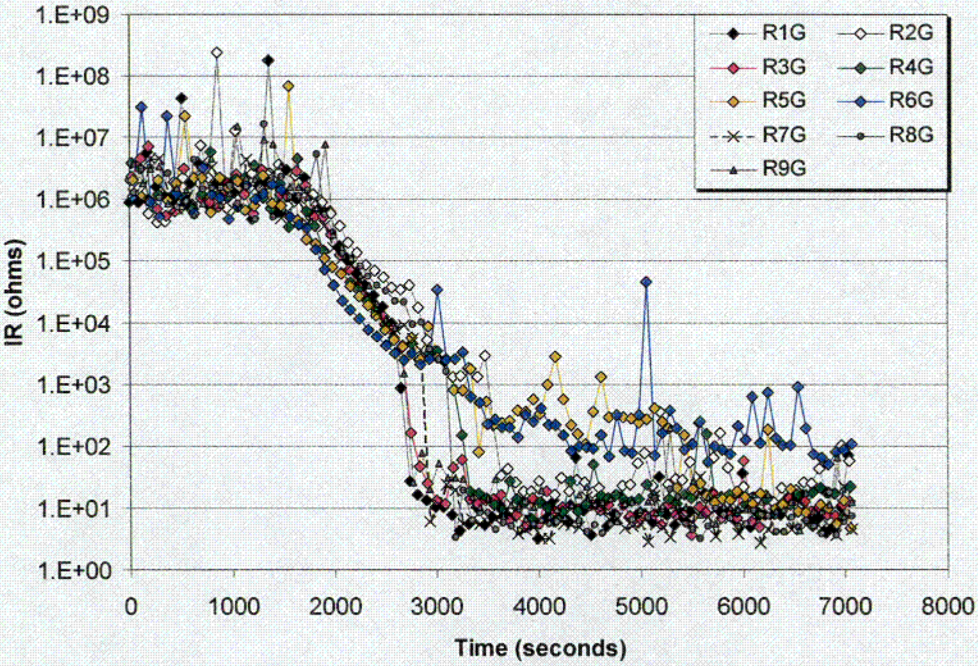

Figure 5-66. Conductor-to-ground IRs obtained during Test 18.

C16

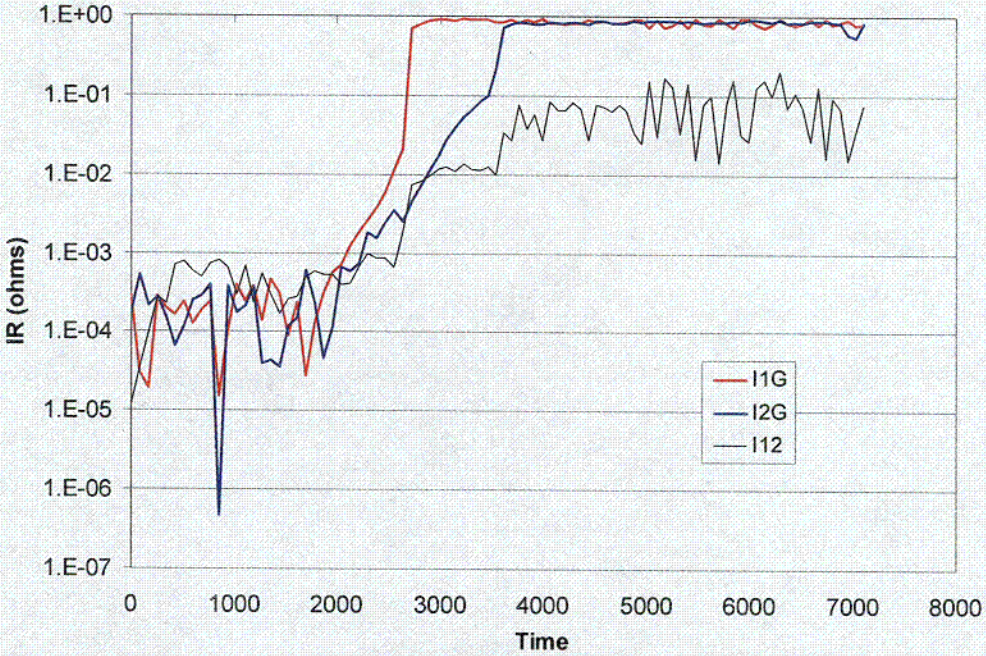

Figure 5-67. Leakage currents resulting from IR changes in Conductors 1 and 2 during Test 18.

C17

6. CURRENT LOOP DATA AND RESULTS

During the last six tests, a mockup of an instrument circuit was added to the SNL/NRC diagnostic system. This circuit was intended to simulate the operation of a typical 4 to 20 mA instrument loop. A schematic of the instrument loop circuit used during Tests 13 through 18 is presented in Figure 6-1. The instrument loop circuit was independent and separate from the IR measurements made concurrently during the tests. However, the current loop data was gathered and stored by the same computer data acquisition system as the IR data. The cables tested using this circuit were all standard instrument cables.

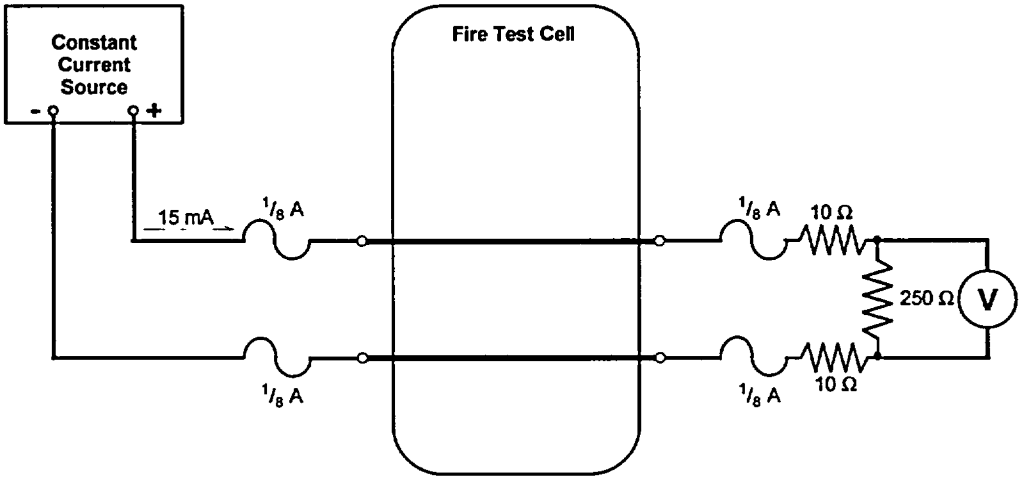

Figure 6-1. Instrument loop circuit.

The instrument loop circuit consists of a low-power current source, fuses to protect the components in the event of an unwanted voltage surge, two 10 Ω resistors to simulate a long run of instrument cable (~610 m (2000 ft) as opposed to the short length exposed during the fire test), a 250-Ω load resistor, and a voltmeter to provide the simulated readout circuit. Note that the 250-Ω load resistor is analogous to a shunt resistor in an output meter that would convert the 4 to 20 mA signal into a 1 to 5 V signal. Use of such a shunt resistor at the output device is typical of many instrumentation circuit designs.

The circuit was driven by a constant current output from the current source of 15 mA. It was anticipated that, as the fire degraded the instrument cable's IR, the apparent output signal would change. In particular, portions of the fixed current signal could leak directly from conductor to conductor bypassing the load/shunt resistor. This behavior would be reflected as an inaccurate reading at the load resistor/voltmeter assembly.

Note that in presenting the data result, the actual measured output voltage was converted to an equivalent 0 to 100% process variable scale to ease the interpretation of the results. That is, an output reading of 1 V corresponds to zero on the process variable scale, and an output reading of 5 V corresponds to 100% on the process variable scale. Given the 15 mA constant input current, a reading of about 68% on the process variable scale is expected. Also note that if the two conductors form a "hard" (or very low impedance) short, the reading would go off-scale low on the process variable scale.

6.1 Test Data and Results

6.1.1 Test 13

Figure 6-2 presents the current loop data obtained during Test 13. The cable used was a shielded two-conductor thermoset instrumentation cable exposed to the hot gas layer of a 350-kW flame. As shown in the figure, the output

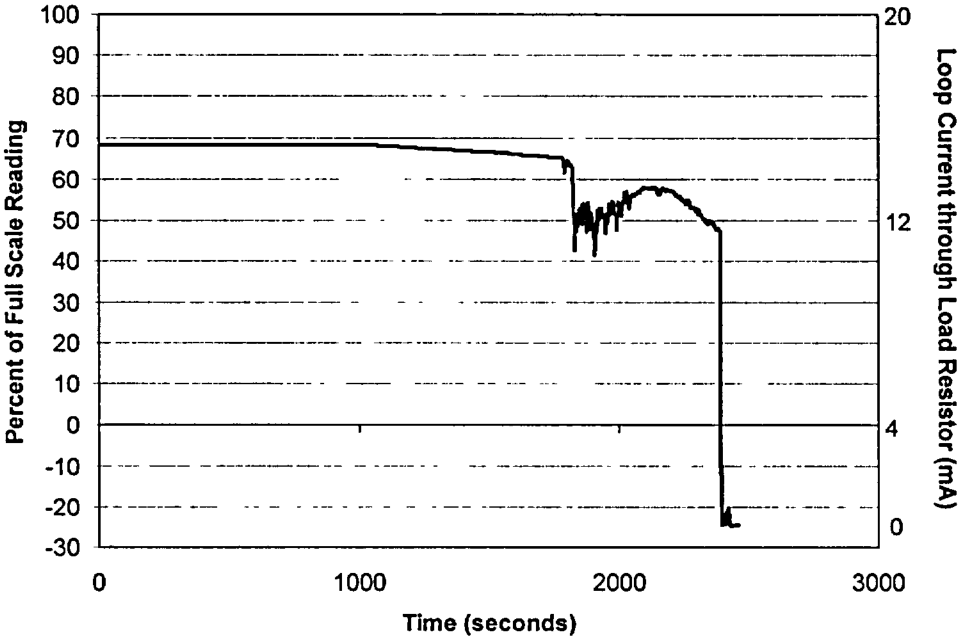

Figure 6-2. Current loop data obtained during Test 13.

signal of the circuit holds at a steady 68% (corresponding correctly to the 15 mA input signal) until ~1100 seconds. At that time, the signal begins to degrade to about 64% at ~1800 seconds. The signal then drops to ~50% and experiences several fluctuations between ~40% to ~53%. After some time, the signal climbs back up to ~57% and holds for a short time. The signal then decays to about 47% and is lost at ~2390 seconds.

This sort of behavior in an instrument circuit could provide an operator with misleading information. The operator would not be able to readily determine if the readout was an accurate indication of plant status or if it was the result of a fire. This is particularly true in this case, since the change in signal output varies rather slowly, and depending on the filtering on the input side of the readout device, the fluctuations occurring from 1800 to 2200 seconds may be damped so that the readout would remain stable. As noted below, a prolonged transition from "good signal" to obviously failed proved to be typical of the thermoset cables tested.

6.1.2 Test 14

Figure 6-3 presents the current loop data obtained during Test 14. The cable used was a two-conductor thermoplastic instrumentation cable routed in conduit and exposed to the plume of a 145-kW flame. As shown in the figure, the output signal remains at 68% until ~2225 seconds, whereupon the signal is abruptly lost. The signal briefly recovers to ~67% and is lost again for the remainder of the test.

Unlike the previous case, this sort of extremely rapid loss of signal would be an obvious indication that the instrument circuit had failed and was an unreliable source of plant information. As noted below, this abrupt failure behavior proved to be typical of the thermoplastic cables tested.

6.1.3 Test 15

Figure 6-4 presents the current loop data obtained during Test 15. The cable used was a shielded two-conductor thermoset instrumentation cable with a drain wire included. The cable was routed in a horizontal cable tray and exposed to a variable intensity flame (350/200/450 kW) during the test. As shown in the figure, the 68% output signal remains constant until ~1100 seconds. It then begins a slow decline to ~36% over the next 400 seconds. At this time, the signal is lost completely and remains so for the duration of the test.

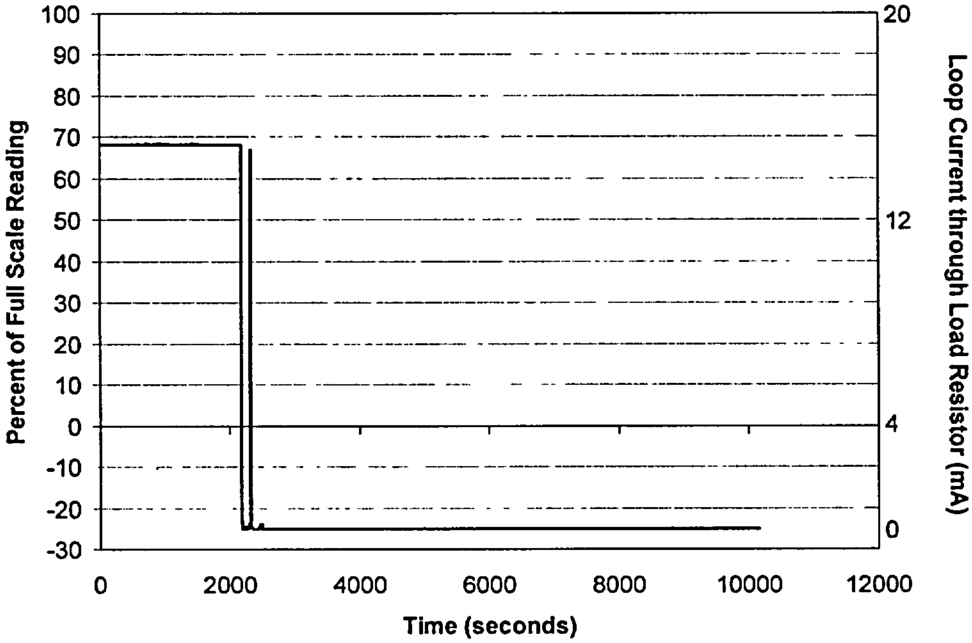

Figure 6-3. Current loop data obtained during Test 14.

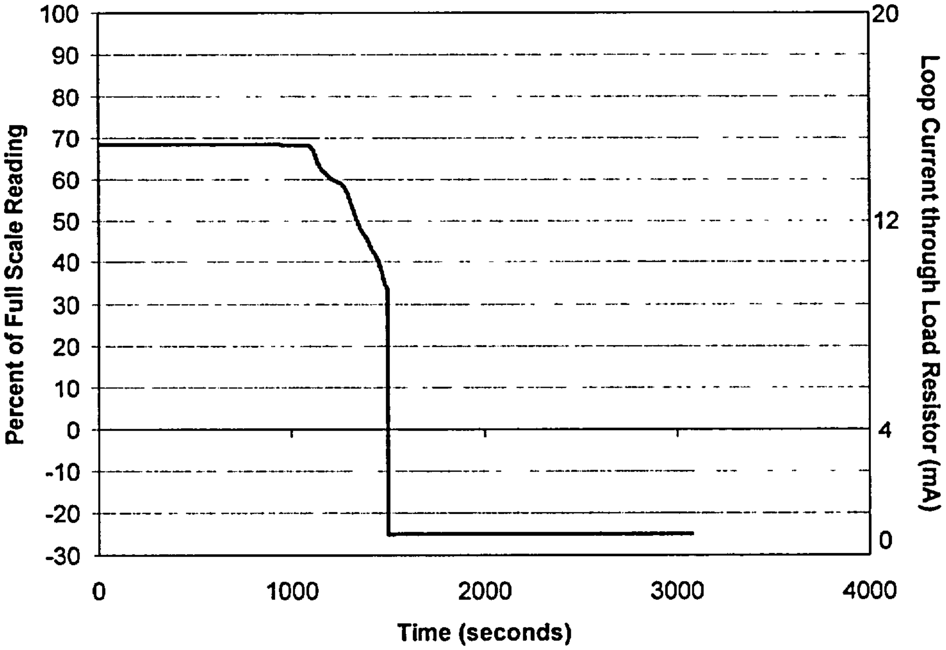

Figure 6-4. Current loop data obtained during Test 15.

Here again, as discussed above for Test 13, because of the rather slow, monotonic decay of the output signal, an operator may be misled into thinking that plant conditions are changing rather than that the instrument is being adversely affected by the fire.

6.1.4 Test 16

Figure 6-5 presents the current loop data obtained during Test 16. The cable used was a three-pair thermoplastic instrumentation cable with shield and drain wire. Only one pair of conductors was employed during this test. The instrument loop cable was routed in the cable tray and exposed to the plume of a 145 kW fire. As shown in the figure, this cable only lasted ~100 seconds before succumbing to damage and loosing the signal for the rest of the run.

As was the case for Test 14, above, this sort of extremely rapid loss of signal would make the operator realize that the instrument had been affected by the fire and was an unreliable source of plant information.

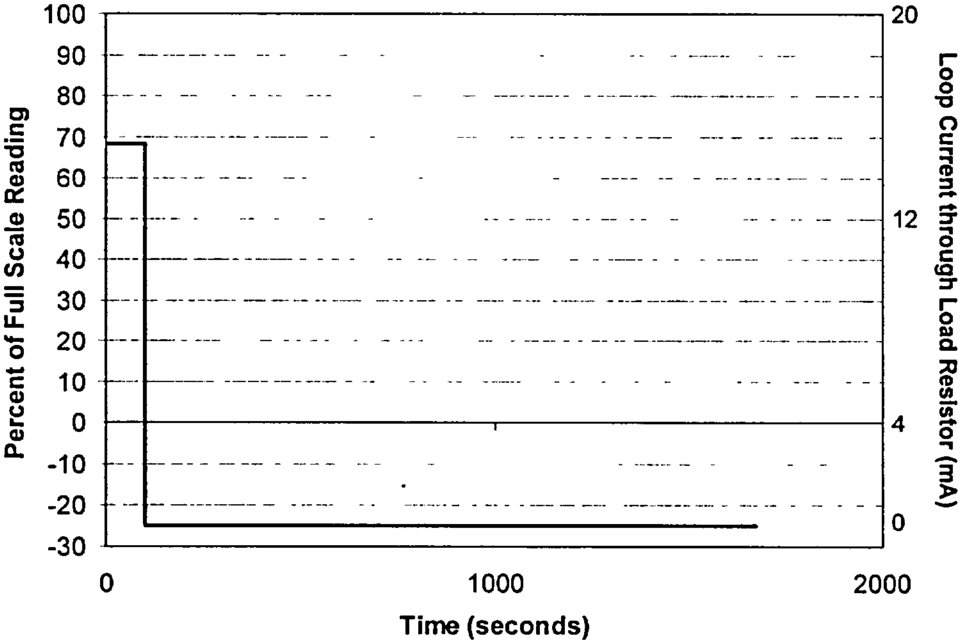

Figure 6-5. Current loop data obtained during Test 16.

6.1.5 Test 17

Figure 6-6 presents the current loop data obtained during Test 17. A two-conductor thermoset instrumentation cable was routed in a vertical cable tray and exposed to the hot gas layer and radiant heat from a 200-kW flame. As shown in the figure, the signal remains at a constant 68% until ~930 seconds when it degrades slightly to 67% at ~1420 seconds. The signal fluctuates very wildly over the period of 1420 to 1500 seconds, and then fluctuates again during the period of 1530 to 1600 seconds. The signal is then lost for the rest of the test.

This sort of extreme fluctuation and rapid loss of signal would make the operator realize that the instrument had been affected by the fire and was an unreliable source of plant information.

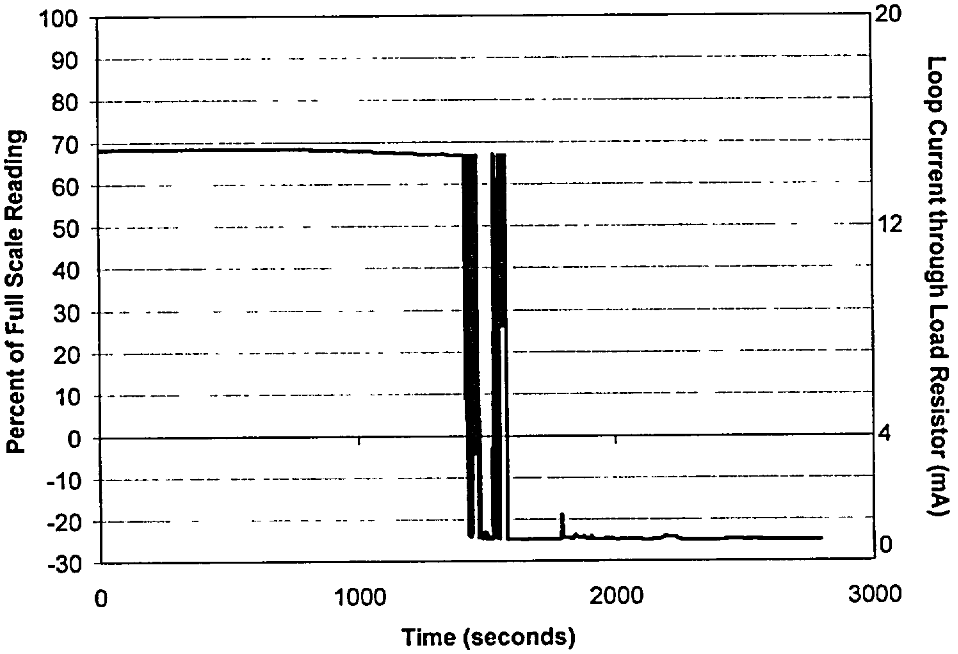

Figure 6-6. Current loop data obtained during Test 17.

6.1.6 Test 18

Figure 6-7 presents the current loop data obtained during Test 18. A two-conductor thermoset instrumentation cable was routed in the conduit. A 250-kW hot gas layer exposure fire was employed during this test. As shown in the figure, the current loop circuit output signal remains relatively constant at 68% until ~1140 seconds. The signal then decays down to ~40% at 1325 seconds. Afterwards, the signal fluctuates briefly and is ultimately lost for the duration of the test.

In this case, the signal degradation has some of the same "gentle" sloping characteristics of the other thermoset cables tested, giving rise to the concern about whether or not the operator would interpret the change as a change in plant status or as the effect of the fire.

6.2 Observations

The instrument loop cables failed at some time during each of these six tests. The most notable result of these tests is the pronounced behavioral differences observed between the failure of the thermoplastic cables and that of the thermoset cables. Thermoplastic cables generally displayed no characteristics of signal degradation prior to the complete loss of signal. On the other hand, the thermoset cables usually displayed some substantial amount of signal degradation for a relatively prolonged time period prior to the total loss of signal.

Table 6-1 presents the times for onset of signal degradation and complete loss of signal for each of the instrument cables tested.

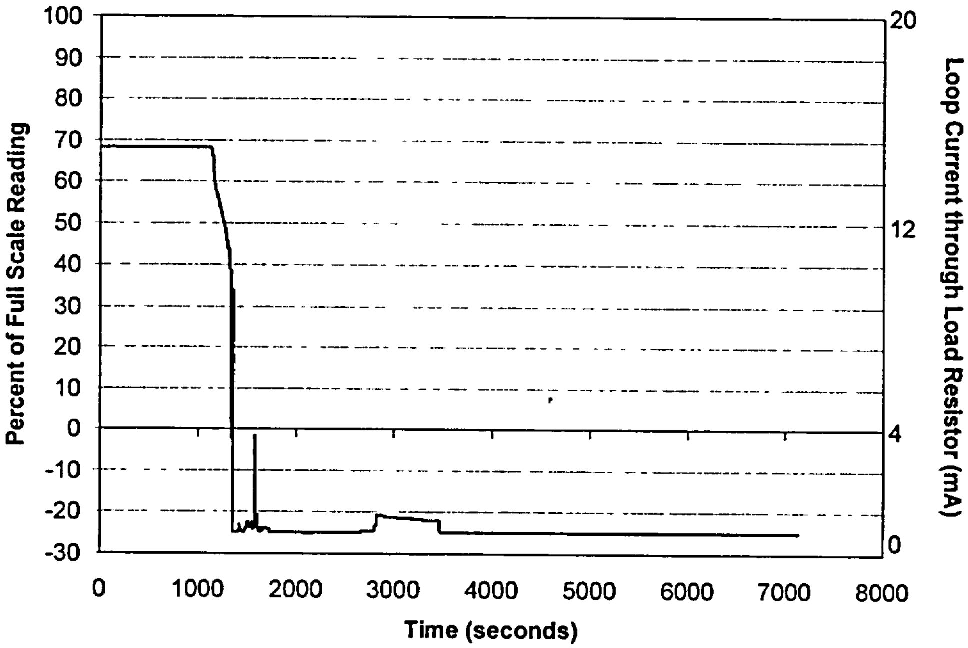

Figure 6-7. Current loop data obtained during Test 18.

Table 6-1. Current Loop Test Data

Test Number	Cable Material	Raceway Type	Time of Signal Degradation (s)	Time of Signal Loss (s)
13	Thermoset	Horiz. Tray	1100	2390
14	Thermoplastic	Conduit	—	2225
15	Thermoset	Horiz. Tray	1100	1500
16	Thermoplastic	Horiz. Tray	—	100
17	Thermoset	Vert. Tray	930	1600
18	Thermoset	Conduit	1140	1325

7. CONCLUSIONS

7.1 Insulation Resistance-Based Cable Failure Mode Results

Failures were observed in 12 of the 18 tests conducted. Tests 3, 4, and 6 through 9, 12, 13, and 15 through 18 all showed indications of cable failure based on the IR data collected. Of these 12 cases, the mode of initial failure can be discerned in seven cases (Tests 3, 4, 6 through 8, 12, and 18). The exceptions are as follows:

- Test 9 involved an ungrounded DC power source that made the IR system unable to detect shorts to ground. In total, three of the IR tests were run in the ungrounded DC power mode (Tests 9 through 11). (No failures were observed in Tests 10 and 11.) Inclusion of the failures observed during Test 9 in the overall statistics regarding failure mode would inappropriately bias the answer towards conductor-to-conductor hot shorts since conductor-to-ground shorts could not be detected. This is reflected in the "n/a" entries for Test 9 in Table 7-1.

- Tests 13 and 15 through 17 were impacted by a wiring fault in the IR system such that the approximate time of cable failure can be determined, but the mode of failure cannot. Hence, these tests also do not contribute to the failure mode statistics.

Most of the tested cable bundles involved a multiconductor cable surrounded by three single conductor cables. It has been concluded that independent treatment of the internal behavior of the multiconductor cables (intracable conductor-to-conductor hot shorts versus shorts to ground) versus the external single-conductor cables relative to each other and to the multiconductor cable (intercable conductor-to-conductor hot shorts versus shorts-to-ground) is appropriate. As discussed below, the multiconductor cables tended to display initial failures involving intracable hot shorts, which transitioned to shorts to ground at some later time. In contrast, the external single-conductor cables tended to short to ground first. These were clear distinctions in this regard; hence, the data have been parsed accordingly.

It should also be noted that in creating the IR cable bundles, three single-conductor cables typically would be bundled with one multiconductor cable using single wraps of fiberglass tape at approximately 30- to 46-cm (12- to 18-in.) intervals along the length of the bundle. This created a level of contact between the cables that may not be fully representative of in-plant conditions for all cases. Hence, some bias towards cable-to-cable shorts involving the single-conductor cables and the multiconductor cable is anticipated.

The failure modes observed in each of the 18 tests are summarized in Table 7-1. For the multiconductor cables, four of the seven observed failures involved intracable conductor-to-conductor hot shorts as the initial mode of failure (Tests 3, 4, 6, and 7). All four of these cases involved cables in a cable tray. In the fifth case involving a cable bundle in a cable tray (Test 12), the multiconductor cable displayed a short to ground as the initial failure mode. The cable bundle used in Test 12 was the same seven-conductor and three single-conductor cables configuration as used in Tests 3, 4, 6, and 7. The IR cable bundle in Test 12 was also routed in a horizontal cable tray. However, it alone of the tests employing this set of conditions exhibited shorting-to-ground failures. This is the only test conducted using the grounded DC power source. It is not clear whether or not the use of a DC source impacted the failure mode since there are no other comparable failure cases. The question of AC versus DC circuit behavior may, therefore, warrant further investigation.

The observed intracable conductor-to-conductor hot shorts involved a range of conductor combinations. In some cases, individual pairs shorted together. In others, rather complex failure transitions were observed involving progressively more conductors as the test progressed. In some cases, conductors shorted in independent groupings (e.g., four conductors shorting together and two other conductors forming an independent short circuit). In one case, all seven conductors became involved in a simultaneous hot short before a short to ground was observed. In all cases where failures were observed, the conductors did ultimately short to ground. The duration of the hot shorts observed ranged from a few seconds to four minutes. It is not clear what might have happened to the cables (e.g., whether or not a short-to-ground transition would still have been observed) had the fire been put out before such transitions occurred, as no such cases were observed during this test program (all the fires continued beyond such transitions).

Table 7-1. **Summary of Observed Initial Failure Modes for Conductors in the Multiconductor Cables and the Single-Conductor Cables. Failures are based on drop in conductor-to-conductor or conductor-to-ground IR to 100 Ω or less. The notation used indicates the number of cables failing in the mode defined by the column heading to the total number of cables involved in the test.**

Test #	Multiconductor Cable			Single-Conductor Cables		
	Short to Ground	Conductor-to-Conductor	No Failure	Short to Ground	Cable-to-Cable	No Failure
1(1)×	–	–	1/1	n/a	n/a	n/a
2	–	–	1/1	–	–	3/3
3	–	1/1	–	2/3	1/3	–
4	–	1/1	–	1/3	2/3	–
5	–	–	1/1	–	–	3/3
6	–	1/1(6)	–	2/3	1/3(6)	–
7	–	1/1	–	3/3	–	–
8(2)	1/2	–	1/2	n/a	n/a	n/a
9(3)	n/a	n/a	n/a	n/a	n/a	n/a
10	–	–	1/1	–	–	1/1
11(4)	n/a	n/a	n/a	n/a	n/a	n/a
12	1/1			1/1(8)		
13(5)	n/a	n/a	n/a	n/a	n/a	n/a
14(7)			3/3	n/a	n/a	n/a
15(5)	n/a	n/a	n/a	n/a	n/a	n/a
16(5)	n/a	n/a	n/a	n/a	n/a	n/a
17(5)	n/a	n/a	n/a	n/a	n/a	n/a
18(7)	3/3			n/a	n/a	n/a
Totals:	5/17	4/17	8/17	9/20	4/20	7/20

Notes

[1] One armored cable only, no single-conductor cables

[2] Two five-conductor cables (not collocated), no single conductors

[3] Ungrounded DC configuration could not detect shorts to ground

[4] Instrument cable not suitable for this comparison

[5] IR system miswired and unable to distinguish failure modes

[6] Both of these failures are indicative of the same occurrence in Test 6

[7] Three three-conductor cables bundled together, no single-conductor cables, routed in conduit

[8] Three single-conductor cables electrically ganged together

Two of seven multiconductor cable failures involved cables inside a conduit (Tests 8 and 18). In both of these particular cases, the multiconductor cables initially shorted to ground. These cases were also somewhat unique in that the cables monitored were a single five-conductor cable in one test (Test 8) and a bundled group of three three-conductor cables in the second (Test 18). This is compared to the seven-conductor with three single-conductor cable bundle configurations used in all of the other tests exhibiting failures. Overall, these results point to a pronounced difference in behavior for cables in conduits versus cables in cable trays. Cables in conduits appear more likely to display shorts to ground as the initial failure mode.

With regard to intercable conductor-to-conductor shorting behavior, there were six tests with a cable bundle of more than one cable where failures were observed and where the mode of failure could be discerned. Five of these six cases involved a seven-conductor cable surrounded by three single-conductor cables in a cable tray. In four of these five tests, there were three independently-monitored opportunities for failure (a total of 12 failure cases). Test 12 involved three external single-conductor cables electrically ganged together; thus, it is considered as only one external conductor and only one additional opportunity for an intercable failure. Of these 13 failure cases, four involved initial failures between a single-conductor cable and one or more conductors within the multiconductor cable. The remaining nine cases all involved initial shorts to ground.

The last case involving potential intercable interactions was Test 18. This test involved three three-conductor cables place in a conduit. As noted above, all of the individual conductors displayed shorts to ground as the initial fault mode. This is the only such case available for a conduit, but again, it appears to indicate a significant difference in behavior compared to cables in a tray.

No cases involving open circuit cable failures were observed. These results are consistent with the findings of the SNL Letter Report[3] in that open circuit failures have only been observed in cases involving cables energized with a high-energy (voltage and/or current) power source, and then only after repeated short-to-ground failures and arcing. The IR tests utilized a substantial voltage (i.e., 120 VAC or 100 VDC) but a very modest maximum current (<1 A). Hence, open circuit faults were not expected, and indeed were not observed.

The SNL Letter Report also reviewed the then-existing literature relating to cable failure modes observed in fire tests. It was found that the majority (at least 72%) of cable failures observed during various past fire tests where the mode of cable failure could be discerned involved initial intracable conductor-to-conductor shorts. That is, for multiconductor cables, the initial failure mode observed in about 72% (or more) of the past cases involved a short circuit between two (or more) conductors while less than one-third (28% or less) of the identified failures involved initial shorts-to-ground. (Note that one data set in particular dominated this analysis, and for that data set, all of the indeterminate cases were counted as shorts to ground.) Again, no cases of open circuit failures as the initial failure mode were found.

If the data from the cables routed in conduit are excluded (Tests 8 and 18), the IR data results are roughly consistent with these earlier findings and, in general, indicate a high likelihood that, if failure occurs, multiconductor cables will short internally before shorting to an external ground.

The data provides strong indications that the routing of cables in conduit tends to substantially reduce the likelihood of hot shorts (either intra- or intercable). During both tests where cable in conduit failures were observed, the multiconductor cables all shorted to ground as the initial failure mode. This is discussed further in Section 6.2.2.1.

7.2 Insulation Resistance Measurement Results Compared to SNL Influence Factors

In the SNL Letter Report, the authors speculated that a number of parameters related to a particular cable, its routing, and the exposure to which it was subjected, may impact the conditional probability that given a cable failure, a specific failure mode (i.e., conductor-to-conductor hot short, short-to-ground, or open circuit) might be observed. These parameters were identified as potential "influence factors." The SNL Letter Report also provided tentative assessments of each factor's potential significance and likely impact based on then-current knowledge and the author's judgment. The influence factors identified by SNL were grouped into four broad categories, each including a number of associated cable parameters. For convenience, the list of those influence factors is repeated here:

---

[3] Note that in the NEI tests, it is difficult to separate exposure mode (plume versus hot layer) from Exposure Intensity and Relative Fire Elevation Once the Exposure Intensity (the fire heat release rate) was determined, the Exposure Mode and Relative Fire Elevation was also determined for these tests For example, if the test involved a 200-kW or greater flame intensity, the exposure mode was set up as a hot gas layer exposure and the relative height of the horizontal cable tray was set at 2 1 m (7 ft) For heat release rates of less than 200 kW, the exposure mode was always in the fire plume and the trays were set at 1 8 m (6 ft) above the gas burner In the discussion that follows, the effects are combined under the headings of Exposure Mode and Exposure Intensity, but Relative Elevation is not separately discussed

Cable physical properties and configuration factors:

- Insulation/jacket composition
- Number of conductors in a multiconductor cable
- Armoring
- Shielding of conductor pairs
- Presence of an uninsulated ground conductor
- Aging condition
- Cable size
- Cable qualification status

Routing factors:

- Cable tray types versus conduits
- Overall raceway fill
- Maintained spacing installations
- Protective coatings
- Raceway orientation
- Bundling of cables

Electrical function factors:

- Circuit function (instrumentation, indication, power, or control)
- Cable ampacity load for power cables
- Circuit voltage

Fire exposure condition factors:

- Exposure mode (flame impingement, thermal radiation, or convection)
- Exposure intensity and duration
- Application of suppressants
- Relative fire elevation

Of these 21 influence factors, eight were addressed to some extent in the industry's test program. (Note that, by design, only a subset of the identified influence factors was addressed by this test program.) These eight factors are: Insulation/Jacket Composition, Number of Conductors, Armoring, Cable Tray versus Conduit, Raceway Fill, Raceway Orientation, Exposure Mode, and Exposure Intensity. The following subsections discuss the IR test results and the insights they lend to these seven influence factors and their significance with regard to the cable failure mode probability.

7.2.1 Cable Physical Properties and Configuration Factors

7.2.1.1 Insulation/Jacket Composition

Table 7-2 indicates the general types of cable insulation materials tested. With the exception of the armor cable in Tests 1 and 13 and the two five-conductor cables in Test 8, all of the others were composed of multiconductor cables bundled with one or more external cables (refer to Section 3.2.8). The thermoplastic multiconductor cables most often failed by initially shorting conductor-to-conductor, whereas the thermoplastic external cables were evenly split between cable-to-cable shorts and shorts to ground. Thermoset cables tended to short to ground first.

Table 7-2. Composition of Cables Tested Using the IR Measurement System

Test No.	Cable Insulation	No. of Cable Bundles	Configuration
1, 13	Armored	One in each test	One 8/c armored cable
2, 3, 5, 7, 9, 12, and 15	Thermoset	One in each test	One 7/c cable with 3-1/c external cables
4, 6	Thermoplastic	One in each test	One 7/c cable with 3-1/c external cables
8	Thermoset	Two	One 5/c cable in tray, one 5/c cable in conduit
10	Thermoset	One	One 7/c cable with 1-1/c external cable
11	Thermoset	Two	One 2/c instrument cable and one with three pairs (6/c) instrument cable
14, 18	Thermoset	One in each test	Three 3/c cables bundled together
16, 17	Thermoset	One in each test	One 9/c cable with 3-1/c external cables

A direct comparison can be made between Tests 4 and 6, involving thermoplastic cables, and Tests 3, 7, and 12, involving similar configurations of thermoset cables. Each of these five tests saw the failure of both the seven-conductor cable and all three of the single-conductor cables. With regard to the multiconductor cables, in four of the five cases, the initial mode of failure was internal conductor-to-conductor shorting. This nominally indicates a high probability of initial conductor-to-conductor failures for both materials, but provides little basis for distinction between materials.

With the single-conductor cables, there were a total of six failures for the thermoplastic cables and seven failures for the thermoset. In the case of the thermoplastic cables, half (three) of the initial failures involved cable-to-cable shorts and half (three) involved shorts to ground. For the thermoset cables, only one failure involved initial cable-to-cable shorts (in Test 3) and the other six failures were initial shorts to ground. These results indicate a potential bias toward shorts to ground for the thermoset materials as compared to the thermoplastic materials.

The SNL Letter Report ranked Insulation Composition as a 'Likely Weak' influence factor, especially in cases where the cables were of a common insulation type. For the internal failures of the multiconductor cables versus shorts to ground, this ranking appears to have been nominally borne out. However, based on the results obtained from the IR measurement system, it appears that the material type may be of more importance when the cable-to-cable shorting behavior is considered. Thermoset cables tended to short to ground more frequently than the thermoplastic cables.

7.2.1.2 Number of Conductors in a Multiconductor Cable

The types of multiconductor cables tested using the IR system included two five-conductor cables in Test 8; one seven-conductor cable in each of the Tests 2, 3, 4, 5, 6, 7, 10, and 12; one eight-conductor armored cable in Tests 1 and 13, and three three-conductor cables each in Tests 14 and 18. However, the configurations for the tests in which failures were observed are quite different, making an assessment of the conductor count effects difficult.

One of the two five-conductor cables tested did not fail. The other five-conductor cable was a cable in conduit, which may have impacted the results more than the conductor count. Similarly, of the three-conductor cables tested, one bundle exhibited no failures and the one that failed by shorting to ground was also routed in conduit. The eight-conductor cables were armored and did not show signs of IR failure during the two tests in which they were used. Hence, these results provide little or no insight into this influence factor as related to multiconductor cables.

One interesting, though perhaps expected, result appears when comparing the number and types of failures experienced by the external single-conductor cables to the failures of all the multiconductor cables. As noted in Section 7.1, multiconductor cables showed a high likelihood of internal conductor-to-conductor failures, whereas single-conductor cables tended to favor shorts to ground over cable-to-cable shorts.

The number of conductors in a cable was ranked in the SNL Letter Report as "significant" on the basis that the conductors in a multiconductor cable would tend to short to each other more readily than short to ground. Based on the results of the IR measurement system obtained during these tests, when failures occurred, multiconductor cables tended to short internally more often than by other failure modes; however, there is not sufficient evidence to suggest that the probability of such failure modes happening depended on the specific number of conductors in a cable.

7.2.1.3 Armoring

The results of the IR tests indicate that the armored cable used in Test 1 did not fail. Although the IR system could only determine the change in total IR during Test 13, the data obtained strongly hint at a short-to-ground failure. Unfortunately, this assessment is based more on experience with the indications of cable failures from other tests than on direct evidence available from Test 13. Hence, given no failures, it is not possible to assess the impact of the armor on the mode of failure.

Armoring of cable was ranked as a significant influence factor in the SNL Letter Report. The IR results are inconclusive about this factor. The armored cables monitored by the IR measurement system during the tests did not fail or could not indicate the actual initial failure mode, so the preferred failure mode for this type of cable is uncertain.

7.2.2 Routing Factors

7.2.2.1 Cable Tray Types Versus Conduits

The SNL Letter Report ranked Raceway Type as a "likely significant" influence factor. One particular aspect of the question was the impact of a tray configuration versus a conduit configuration on the hot-short probability. The authors speculated that there were two competing effects that would likely influence the failure mode. One effect was the presence of a more prevalent ground plane in a metal conduit, as compared to the rungs of a cable tray, which might enhance the probability for shorts to ground. The second effect was the potential that the more uniform weight support provided for a cable in a conduit might promote internal shorting, as compared to a cable tray where the rungs of the tray impose periodic sharp loading points on the cables.

Five of the seven cable failure cases were observed for seven-conductor cables in cable trays (Tests 3, 4, 6, 7, and 12). All of the cable trays used during these tests had a standard ladder-back design. Conduit effects were investigated using the IR system during Tests 8 and 18. In these tests, the IR measurement system detected failures in a five-conductor cable and the bundle of three three-conductor cables placed in a length of conduit.

The IR test results for Test 8 show that the cable in the conduit shorted to ground first (a sporadic short to ground on two of the five conductors) rather than displaying conductor-to-conductor hot shorts as the initial failure mode. All of the conductors eventually shorted to ground as the fire test progressed. (Note that there were no external conductors bundled with the IR measurement cable in this test.) In Test 18, the IR data shows that all nine conductors in the cable bundle shorted to ground before interacting with another conductor. In contrast, four of five multiconductor cables routed in the cable tray were observed to initially fail by internal conductor-to-conductor shorts. The remaining multiconductor cable routed in a tray did, however, initially fail by shorting to ground.

The IR results obtained during the fire tests provide limited evidence relevant to the tray versus conduit question. Nominally, it would appear that the conduit does introduce a greater likelihood of shorts to ground as the initial failure mode of a multiconductor cable. However, the data are somewhat sparse.

7.2.2.2 Overall Raceway Fill

The IR results were inconclusive. Most tray tests were run with two rows of cable fill. One test, Test 8, contained three rows of cables but the IR cable was located in the top row, had no external cables bundled with it, and did not fail in any case. The cable bundle in Test 12 was part of a single-row filled tray and experienced a short to ground failure. In Tests 3, 4, 6, and 7, the cable bundles were part of a two-row filled tray condition and all experienced internal conductor-to-conductor or, in the case of Test 6, cable-to-cable shorts first.

The SNL Letter Report ranked tray fill as a significant influence factor. The IR results indicate that tray fill is a significant factor, but this is based on a very limited variety of tray fill cases.

7.2.2.3 Raceway Orientation

Although Tests 10 and 17 consisted of cables installed in vertical trays, the results of these test cannot be compared directly to the results from tests conducted using horizontal trays because the IR system was set up for the ungrounded DC input operation in Test 10 and was unable to determine any specific failure mode in Test 17. Thus, this influence factor cannot be evaluated based on the results of these tests.

7.2.3 Fire Exposure Condition Factors

As previously mentioned, three of the influence factors in this category were intimately connected in the conduct of the industry's cable tests. Once an exposure mode was selected, both the flame intensity and the relative height of the cable tray above the floor were also determined. Plume exposures were only made at 145-kW heat release rates and with the tray elevated 1.8 m (6 ft) above the test cell floor. Hot gas layer exposures were used for heat release rates greater than or equal to 200 kW and the trays were located at 2.1 m (7 ft) above the floor for these cases.

7.2.3.1 Exposure Mode (flame impingement, thermal radiation, or convection)

Two primary exposure modes were exercised in the NEI tests; namely, plume and hot gas layer exposures. One test (Test 10) involved a vertical tray exposed to both the hot gas layer and radiant heating, but no failures were observed. None of the NEI tests involved direct flame exposures. Hence, insights relating to exposure mode are somewhat limited.

A comparison can be made between Tests 3, 4, and 12 (plume exposures) and Tests 6 and 7 (hot gas layer). The multiconductor cable showed that in four of the five tests, the initial failure modes involved conductor-to-conductor shorts. The failure mode experienced by the multiconductor cable in Test 12 was shorting to ground. For the single conductor cables, the plume exposure cases were nearly evenly split – three involved initial cable-to-cable faults and four involved conductor-to-ground shorts. For the two hot gas layer tests, only one cable-to-cable short occurred, compared to five conductor-to-ground faults. These results are rather sparse, especially given that the cable type also changed in these four tests. However, it appears that the more intense plume exposures nominally favored hot shorts in comparison to the slower hot gas layer exposures.

The SNL Letter Report characterized Exposure Mode as a "likely significant" influence factor in their circuit analysis report. From the IR results obtained during the industry tests, only two modes of exposure were assessed, and even then the results were rather sparse. Overall, it appears that exposure mode between plume and hot gas layer exposures is present but relatively weak as an influence factor. Direct flame impingement was not evaluated.

7.2.3.2 Exposure Intensity and Duration

The exposure intensity and duration clearly had an impact on the overall likelihood that some failure would be observed. For example, no cable failures were identified during Test 2 at the 70-kW heat release rate. However, the tests are inconclusive regarding fire intensity and exposure duration as influence factors associated with failure mode. There is simply not enough variety in this parameter, and the variety that is provided is inextricably linked with other influence factors (e.g., cable type, plume versus hot gas layer, tray orientation, etc.).

Flame Intensity was ranked in the SNL Letter Report as "likely significant." The relative significance of this factor cannot be clearly discerned from the IR results obtained during the industry tests.

8. REFERENCES

8.1 J. LaChance, S. Nowlen, F. Wyant, V. Dandini, "Circuit Analysis—Failure Mode and Likelihood Analysis," A Letter Report to the NRC, Sandia National Laboratories, May 8, 2000. This letter report is available through the NRC Public Document Room under a NRC cover memorandum from T. L. King, NRC/RES/DRAA to G. M. Halogen, NRC/NRR/DSSA and M.E. Mayfield, NRC/RES/DET, dated June 13, 2000.

8.2 S. Nowlen, "Ampacity Derating and Cable Functionality for Raceway Fire Barriers," SAND2000-1825, NUREG/CR-6681, Sandia National Laboratories, August 2000.

NRC FORM 335
(2-89)
NRCM 1102,
3201, 3202

U S NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC, Add Vol , Supp Rev , and Addendum Numbers, if any)
NUREG/CR- 6776
SAND2002-0447P

2. TITLE AND SUBTITLE

Cable Insulation Resistance Measurements Made During Cable Fire Tests

3 DATE REPORT PUBLISHED

MONTH	YEAR
June	2002

4 FIN OR GRANT NUMBER

Y6037

5 AUTHOR(S)

Francis J. Wyant
Steven P. Nowlen

6 TYPE OF REPORT

Technical

7. PERIOD COVERED *(inclusive Dates)*

8. PERFORMING ORGANIZATION – NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U S Nuclear Regulatory Commission, and mailing address, if contractor, provide name and mailing address)*

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0744

9 SPONSORING ORGANIZATION – NAME AND ADDRESS *(If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U S Nuclear Regulatory Commission, and mailing address)*

Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES
H. W. Woods, NRC Project Manager

11. ABSTRACT *(200 words or less)*

An insulation resistance diagnostic system was recently developed and exercised during a series of cable fire tests. This insulation resistance measurement system was able to identify and quantify the changes in insulation resistance occurring between the separate conductors and the conductors to ground in cable bundles as they were being exposed to fires. Eighteen separate fire tests were conducted and included a variety of cable and fire exposure conditions. The insulation resistance measurement system was operated at 120 VAC for 14 of those test runs and at 100 VDC for three of the runs. One test was run with the insulation resistance measurement system providing 24 VDC to two separate instrument cables being exposed to the fire. The results obtained by the insulation resistance measurement system during these tests showed that cables will fail during a fire in one of three ways: by internal shorting of the conductors in a multiconductor cable, by shorting of the conductors in different cables bundled together, or by individual conductors shorting to ground. A mockup of a simple 4 to 20 mA DC current loop instrument circuit was included in six of the later tests.

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

Electric Cables, Electrical Faults, Electrical Insulation, Electrical Testing, Failure Mode Analysis, Fires

13 AVAILABILITY STATEMENT
Unlimited

14. SECURITY CLASSIFICATION
(This Page)
Unclassified
(This Report)
Unclassified

15. NUMBER OF PAGES

16 PRICE

ISBN 0-16-051155-0

90000

9 780160 511554

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001