Cable Failure Modes and Effects Experiments and Data

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Sandia National Laboratories

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Key Points of Presentation

- Numerous tests have been conducted on cables
- Multi-conductor cables in trays tend to short conductor to conductor first before shorting to ground
- Single conductor cables tend to short to ground first - but not always
- The IR test cables routed in conduit failed by shorting to ground during the EPRI-NEI tests
- No open circuit initial failures have been detected or reported
- Thermoplastic instrument cables failed catastrophically during the EPRI-NEI tests
- Thermoset instrument cables had degraded outputs prior to failure during the EPRI-NEI tests

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OUTLINE

- Terminology
- Cable Failure Modes & Circuit Effects
- Results of Literature Reviews
- SNL IR Measurement System
- IR Test Results
- Sandia Current Loop Simulation & Test Results
- Summary of Findings

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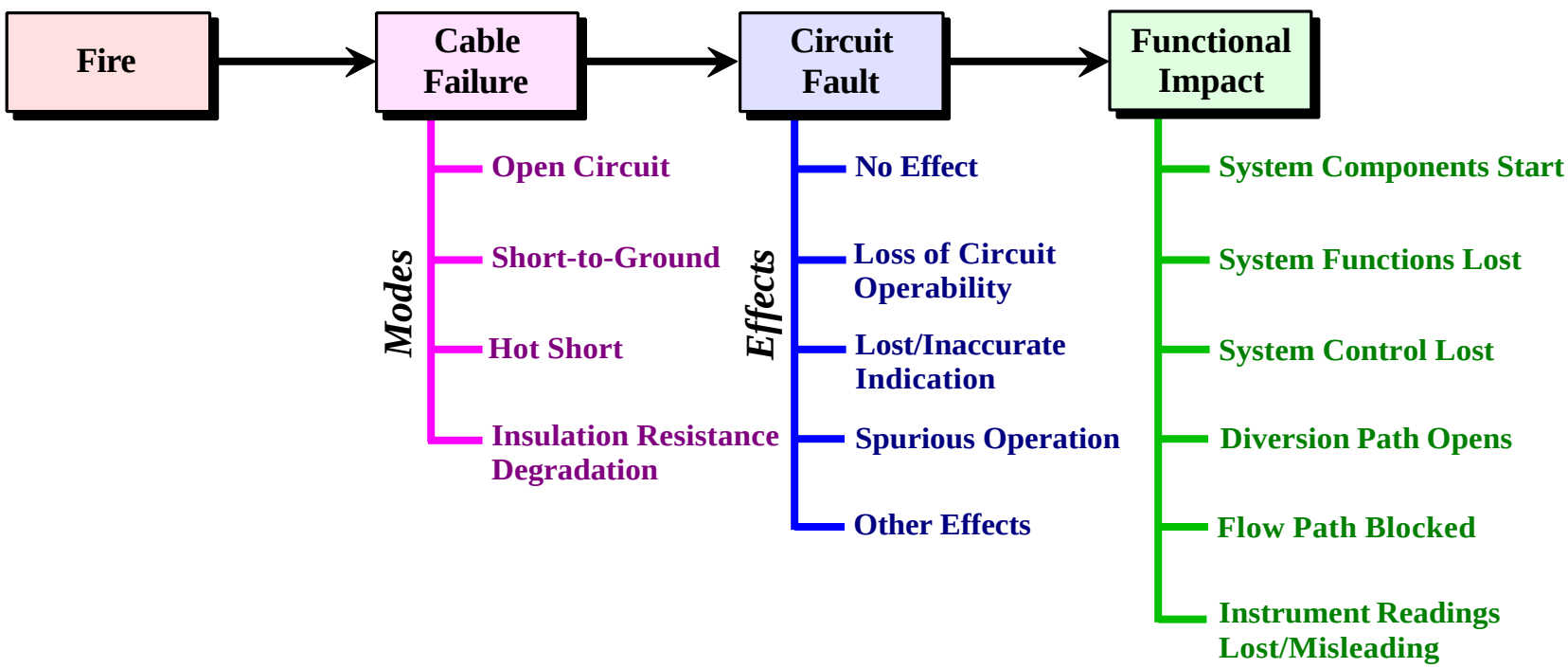
Terminology



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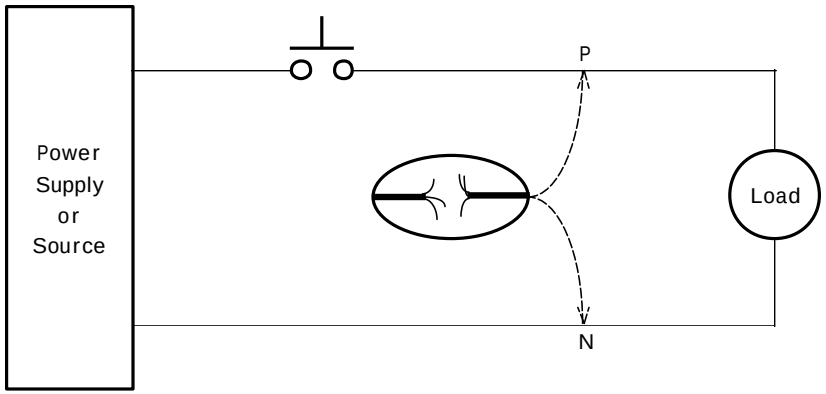
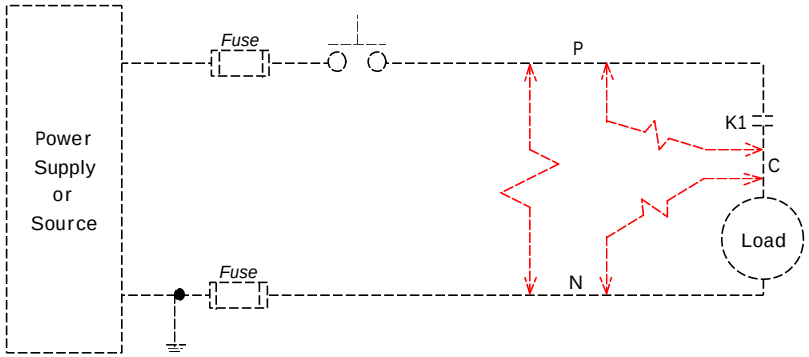
Cable Failure Modes and Circuit Effects

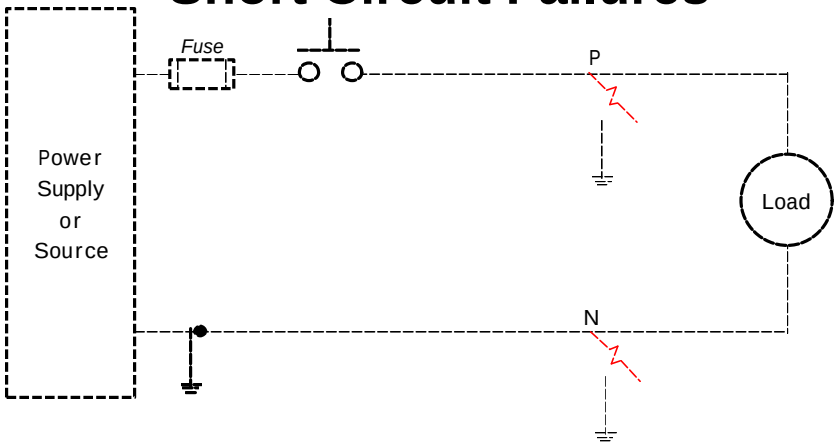
Open Circuit Failures



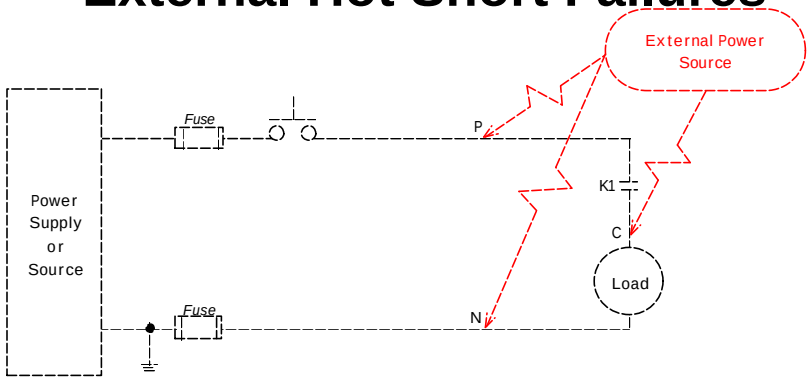
Internal Hot Short Failures



Short Circuit Failures



External Hot Short Failures



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Results of Cable Failure Mode Lit. Review

(for multi-conductor cables)

Source	#Shorts-Ground	#Hot Shorts	#Open Circuits
NUREG/CR-0833	12/12	0/12	0/12
NUREG/CR-3192	4/8	4/8	0/8
NUREG/CR-0596	0/1	1/1	0/1
EPRI NP-1881	1/3	2/3	0/3
ENS-IN-99-00412	0/1	1/1	0/1
UL File NC555	35/161	126/161	0/161
Totals	**52/186**	**134/186**	**0/186**

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Cable Failure Mode Influence Factors

Cable Physical Properties and Configuration Factors:

- Insulation/jacket composition
- Number of conductors
- Armoring
- Shielding of conductor pairs
- Presence of an un-insulated ground conductor
- Aging condition
- Cable size
- Cable qualification status

Routing Factors:

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

Electrical Function Factors:

- Circuit function
- Cable ampacity load for power cables
- Circuit voltage

Fire Exposure Condition Factors:

- Exposure mode
- Exposure intensity and duration
- Application of suppressants
- Relative fire elevation

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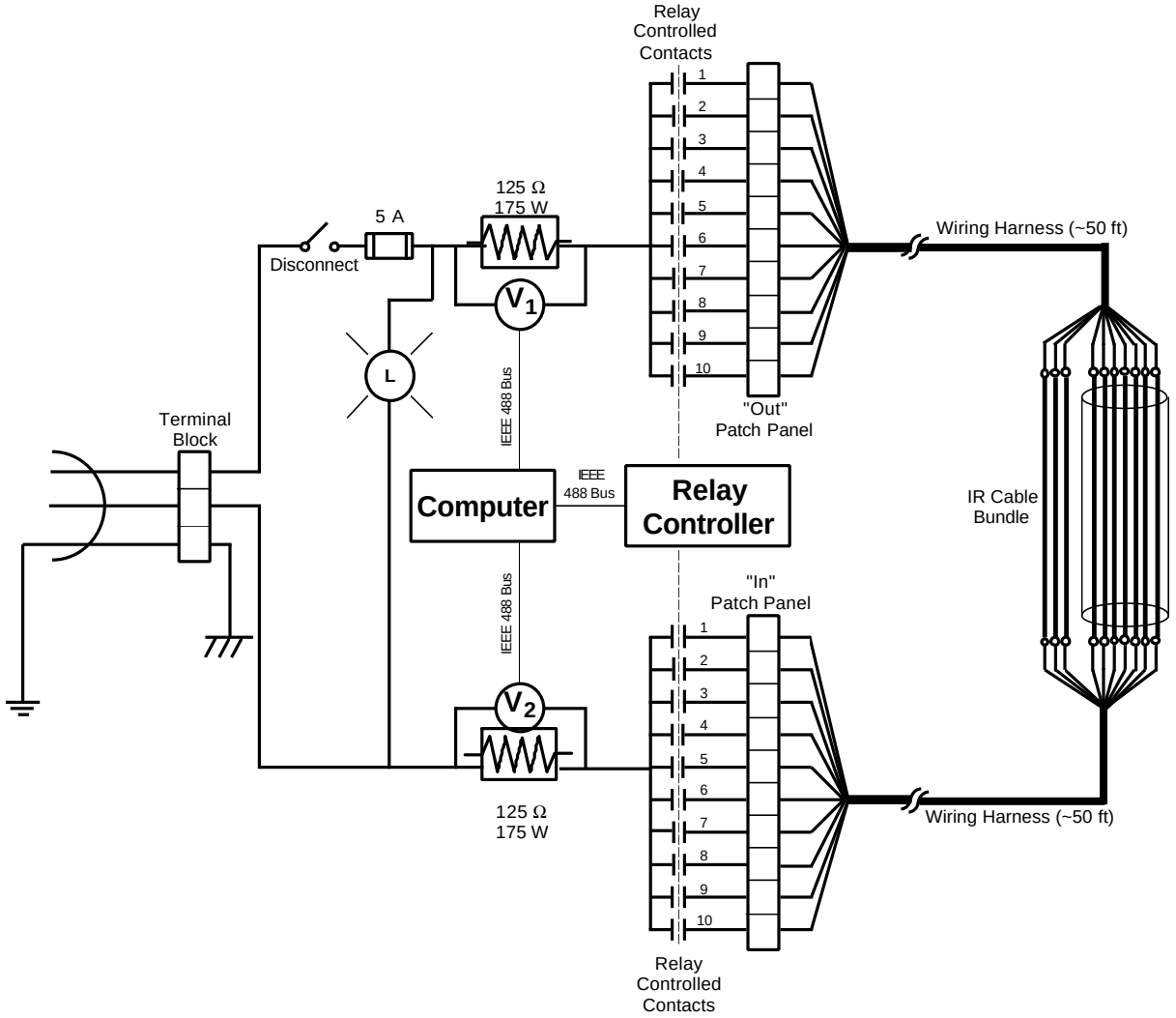
Sandia's IR Measurement System



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Prototype IR Measurement System

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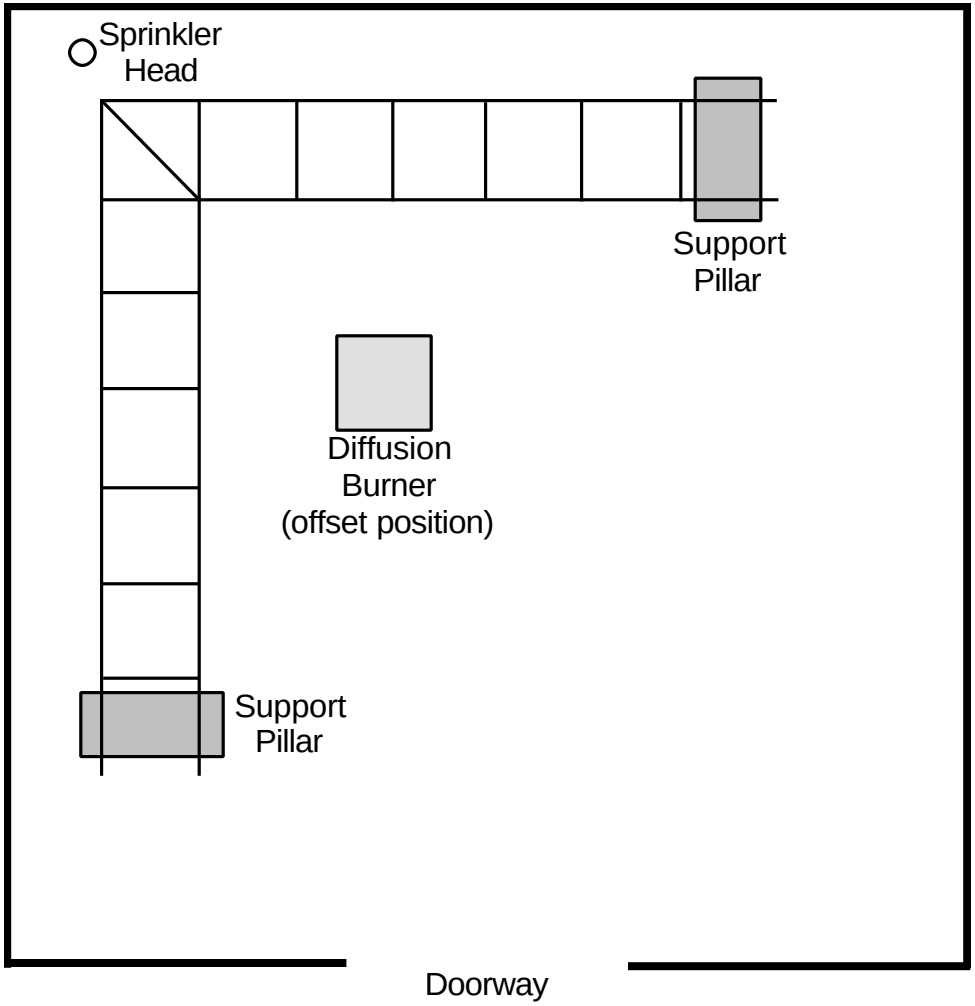
Test Cell Configuration



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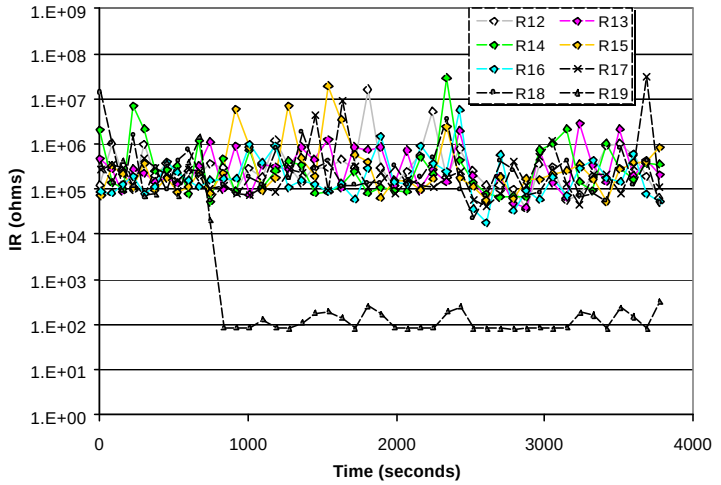
Test #1

Armored Cable (#1-8), Armor Shield (#9)

Heat Release Rate = 350 kW

Peak Tray Temperature = 820ºF

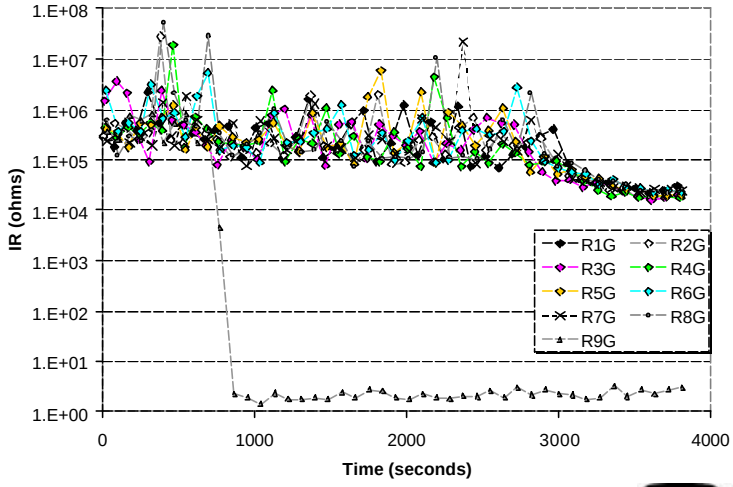
Peak Cable Temperature = 680ºF



Results:

Armor shield shorted to ground at ~865 s.

No failures identified.



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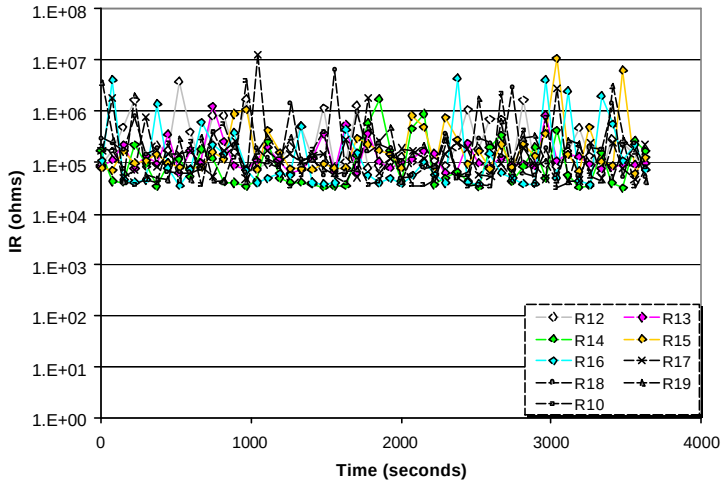
Test #2

7/c Thermoset Cable, 3 External Cables

Heat Release Rate = 70 kW

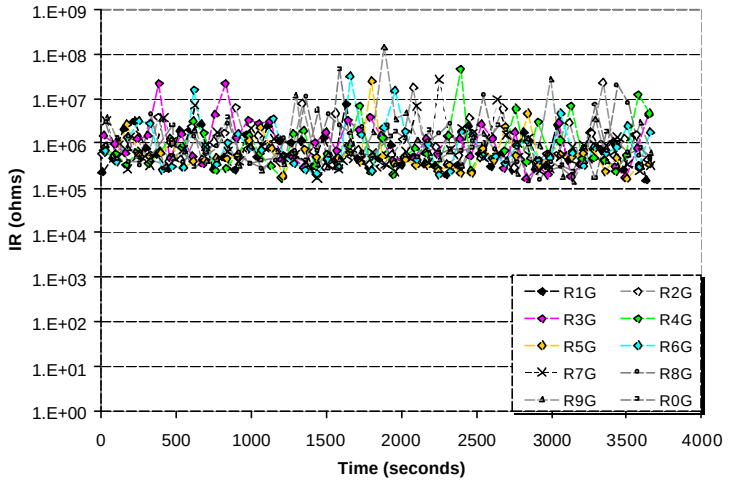
Peak Tray Temperature = 760ºF

Peak Cable Temperature = 570ºF



Results:

No failures identified.



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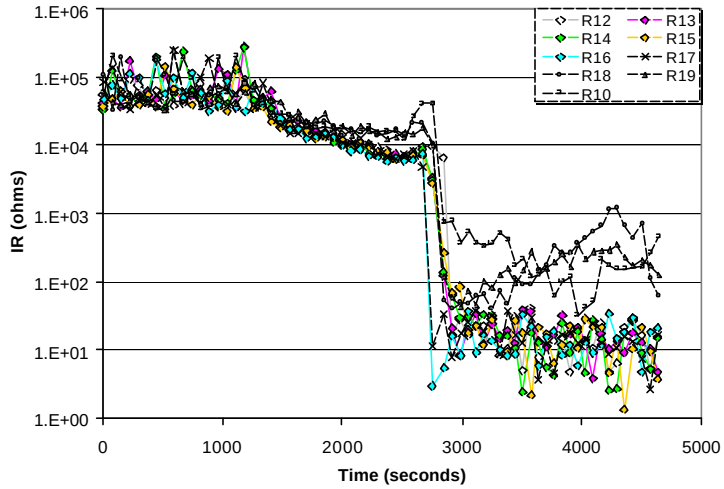
Test #3

7/c Thermoset Cable, 3 External Cables

Heat Release Rate = 145 kW

Peak Tray Temperature = 940ºF

Peak Cable Temperature = 760ºF



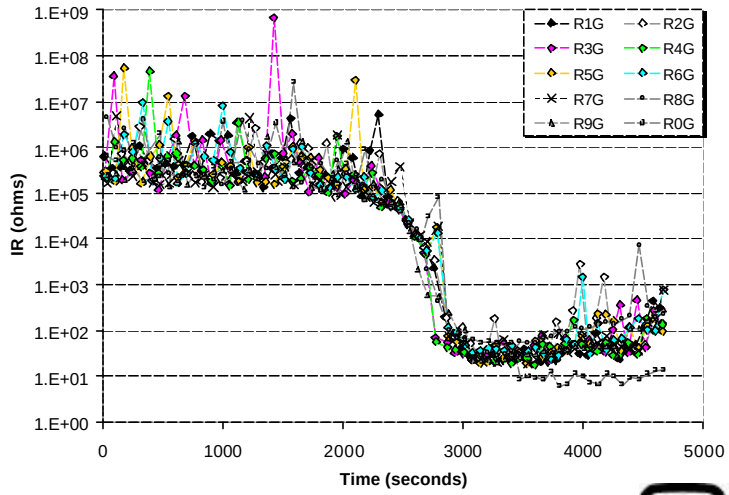
Results:

2750 s: Conductor 1 shorts to 6 & 7

2770 s: Conductor 3 shorts to 4 & ground

2860 s: Conductor 8 shorts to 1, 2, 3, & 4

3000 s: All conductors shorted to ground



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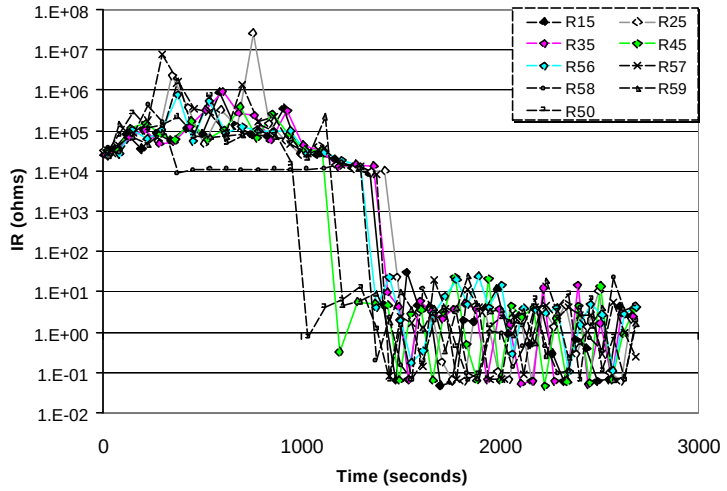
Test #4

7/c Thermoplastic Cable, 3 External Cables

Heat Release Rate = 145 kW

Peak Tray Temperature = 780ºF

Peak Cable Temperature = 550ºF



Results:

374 s: Conductor 8 shorts to ground

1030 s: Conductor 10 shorts to 5

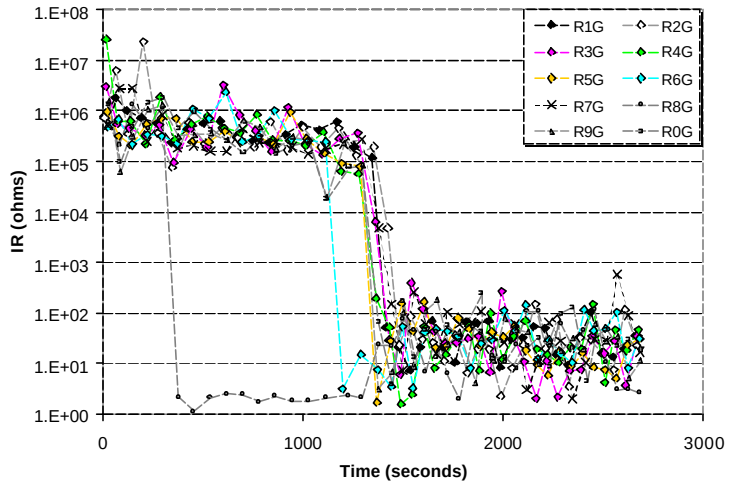
1190 s: Conductor 4 shorts to 9 & 5, 10

1200 s: Conductor 6 shorts to ground

1350 s: Conductor 1 shorts to 7

1370 s: #4, 5 & 10 short to ground

1480 s: All conductors have shorted to ground



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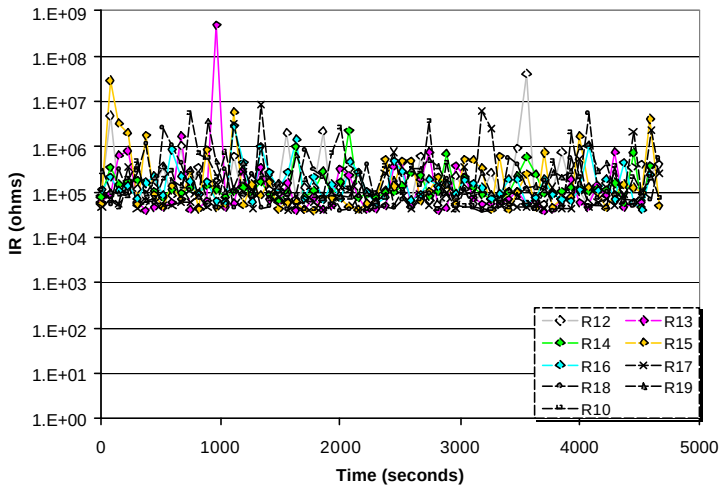
Test #5

7/c Thermoset Cable, 3 External Cables

Heat Release Rate = 200 kW

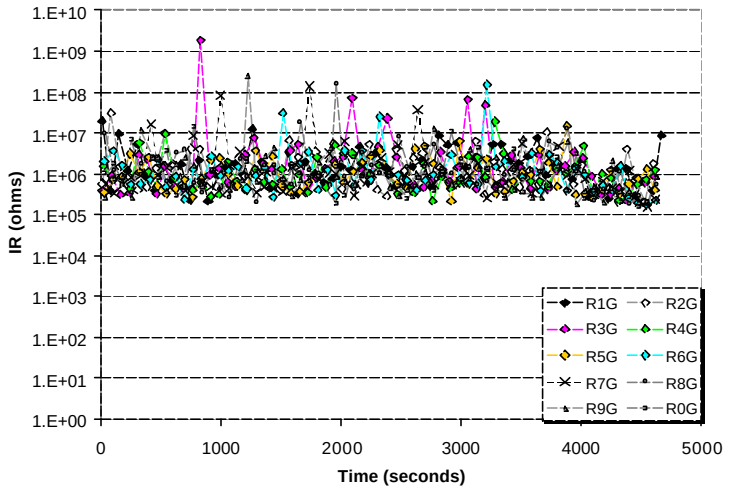
Peak Tray Temperature = 675ºF

Peak Cable Temperature = 625ºF



Results:

No failures identified.



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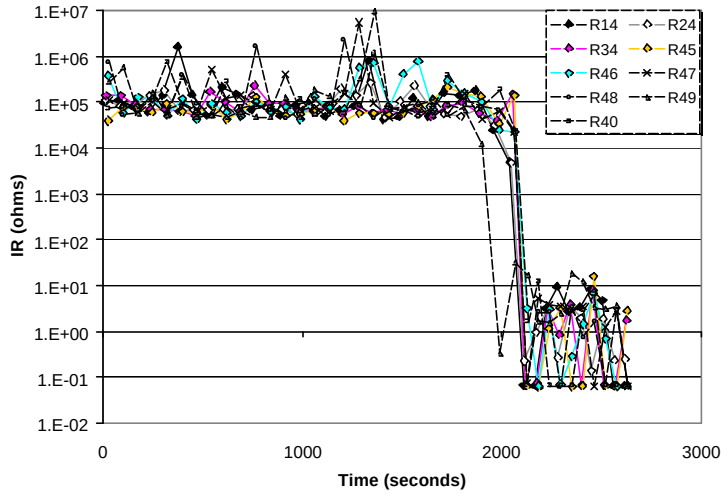
Test #6

7/c Thermoplastic Cable, 3 External Cables

Heat Release Rate = 200 kW

Peak Tray Temperature = 670ºF

Peak Cable Temperature = 570ºF



Results:

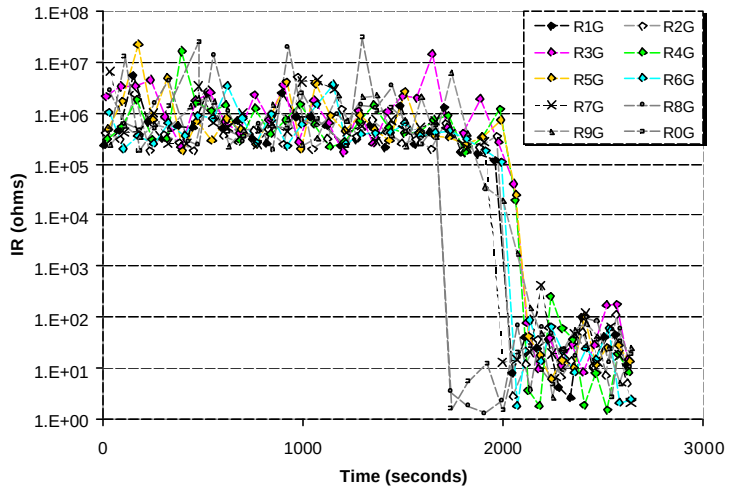
1700 s: Conductors 8 & 10 short to ground

1990 s: Conductor 4 shorts to 9

1995 s: Conductor 7 shorts to ground

2080 s: Conductors 1, 2, 3, 5, & 6 short to ground

2130 s: Conductors 4 & 9 short to ground



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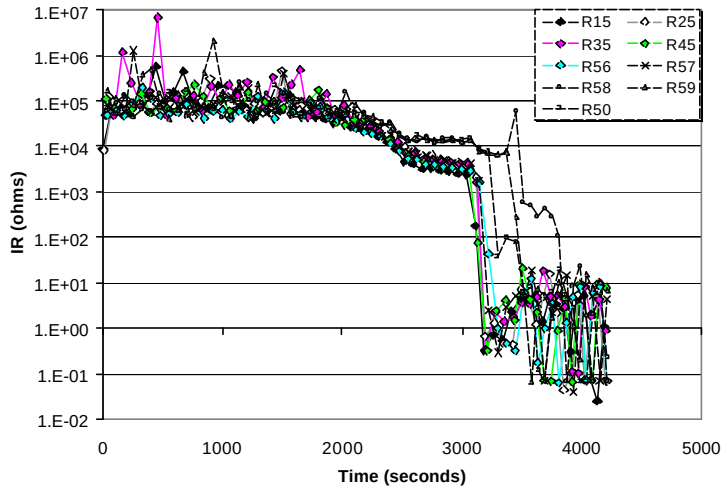
Test #7

7/c Thermoset Cable, 3 External Cables

Heat Release Rate = 350 kW

Peak Tray Temperature = 980ºF

Peak Cable Temperature = 900ºF



Results:

3130 s: Conductor 4 shorts to 5

3190 s: Conductors 1 & 3 short to 4 & 5

3195 s: Conductor 2 shorts to 1, 3, 4, & 5

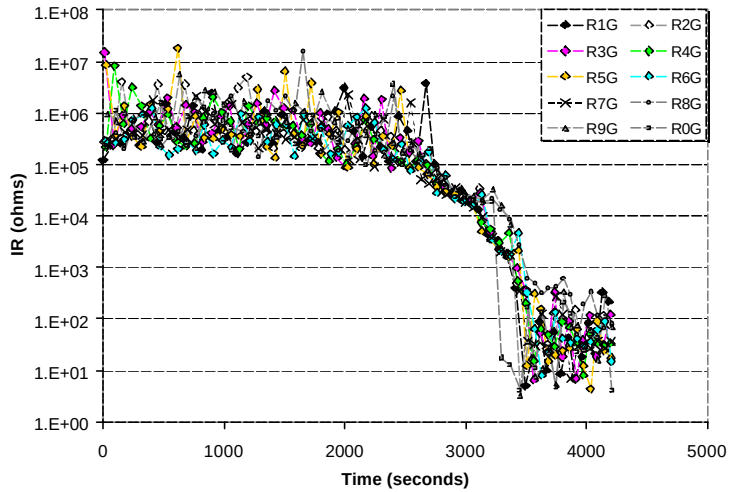
3230 s: Conductor 6 shorts to 7

3265 s: All conductors in M/c cable shorted

3300 s: Conductor 10 shorts to ground

3470 s: Conductors 1-7 & 9 short to ground

3870 s: Conductor 8 shorts to ground



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Test #8

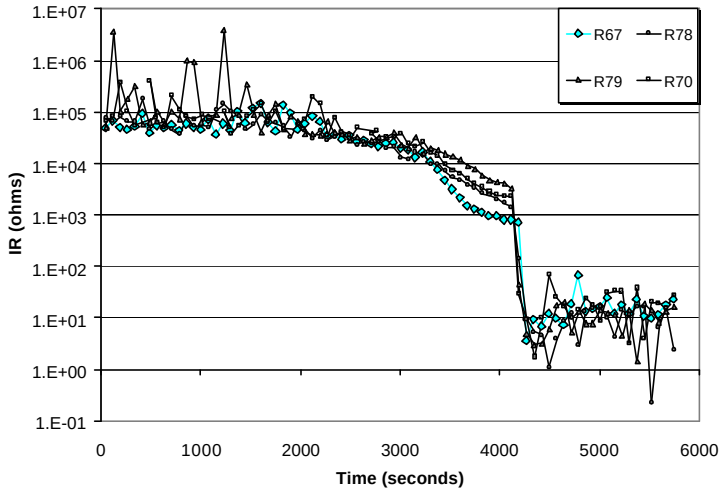
Tray and *Conduit* Exposure

Two 5/c Thermoset Cables: Tray & Conduit

Heat Release Rate = 145 kW

Peak Temperatures: Tray = 1000ºF, Conduit = 770ºF

Peak Temperature: Cable = 900ºF, Cable = 800ºF

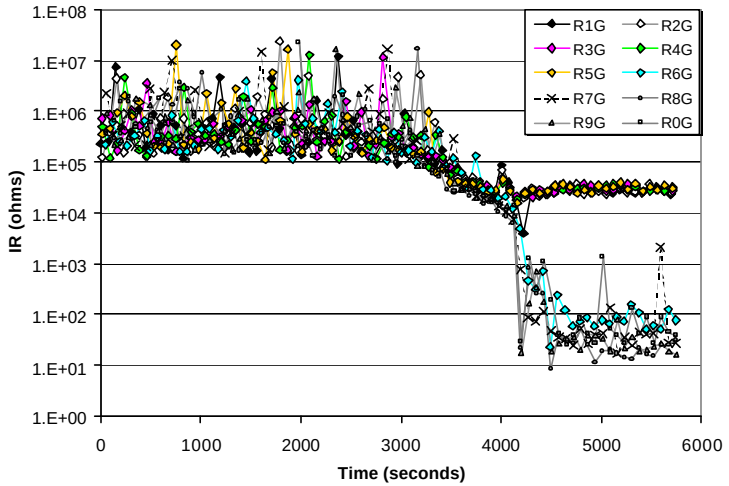


Results:

4200 s: Conductors 8, 9, & 10 short to ground

4300 s: Conductor 7 shorts to ground

4500 s: Conductor 6 shorts to ground



Note: Indications of IR2 cable interacting with DA1 cables at 69.3-95 min.

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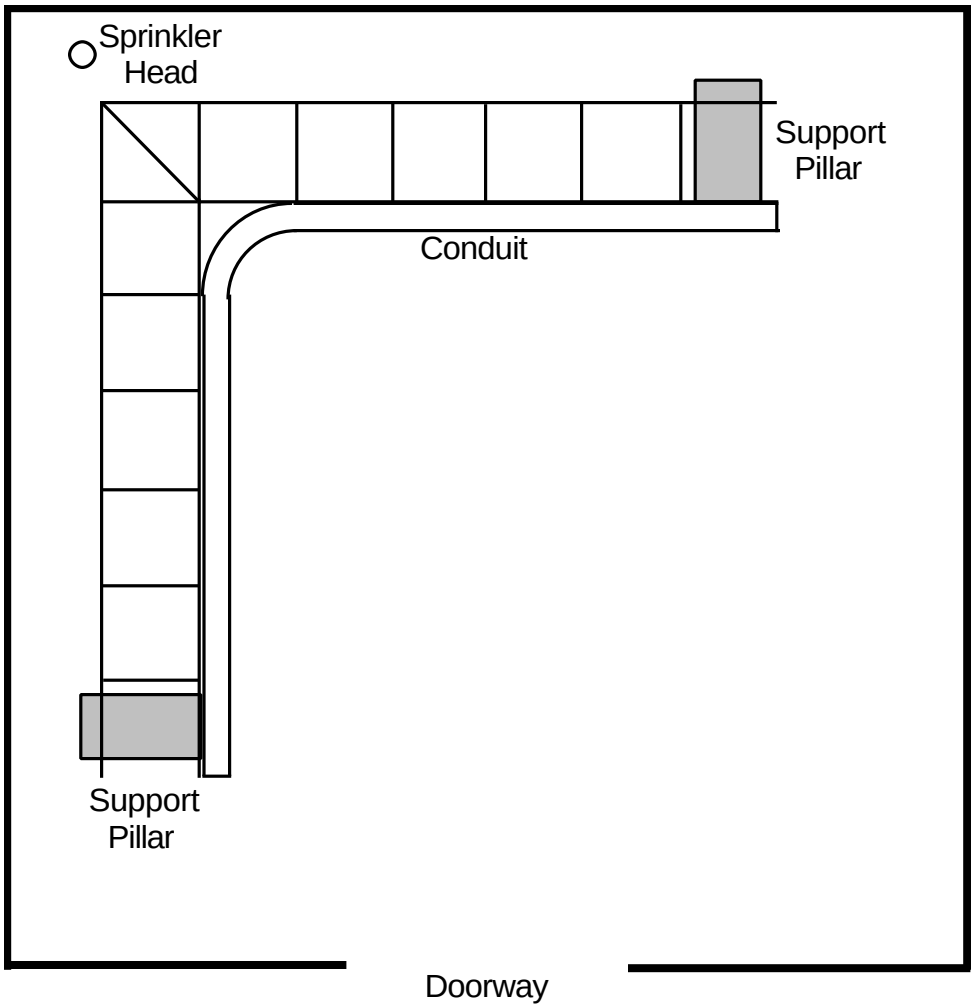
Conduit Location in Test Cell



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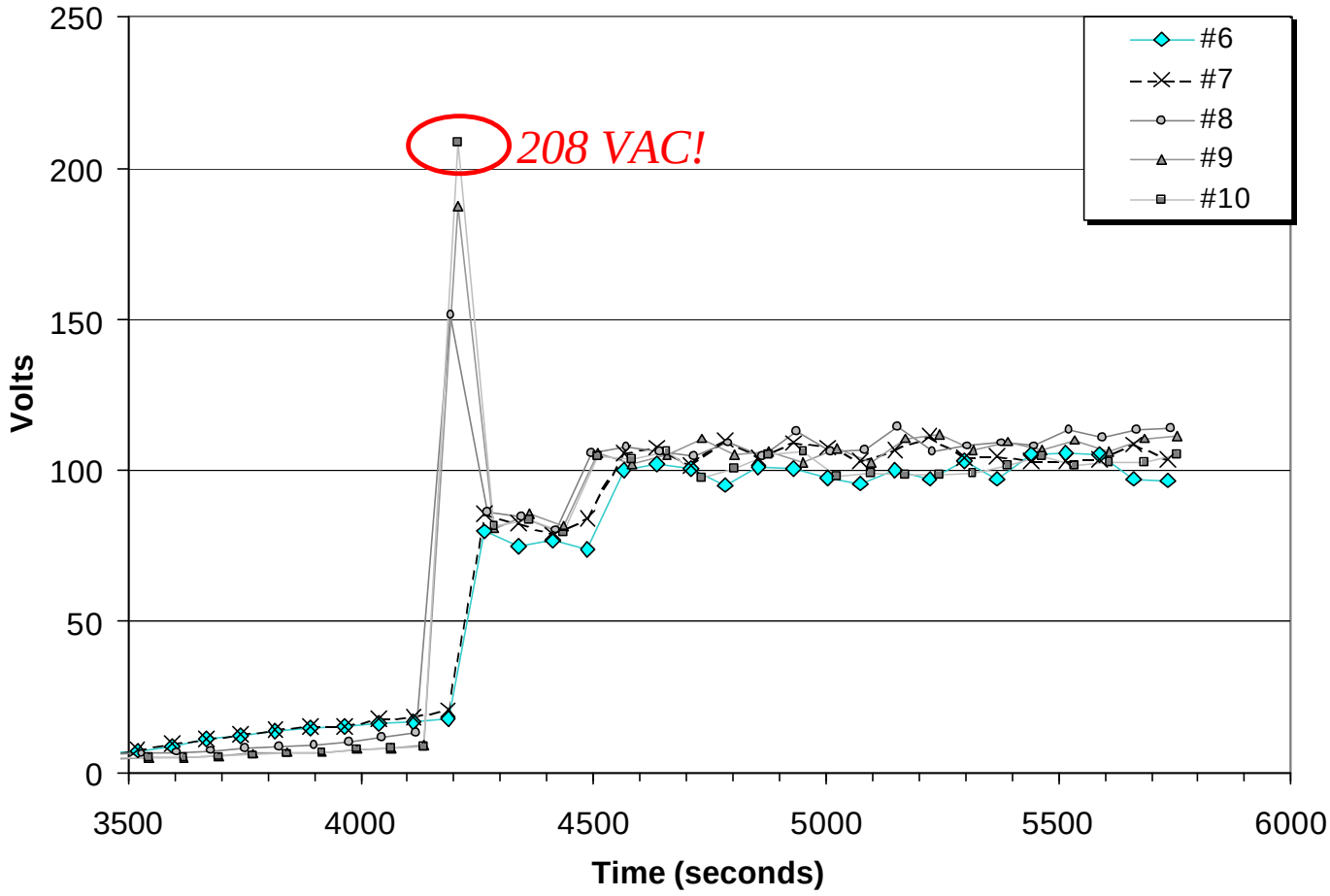
Test #8
IR2 Conductor Voltages



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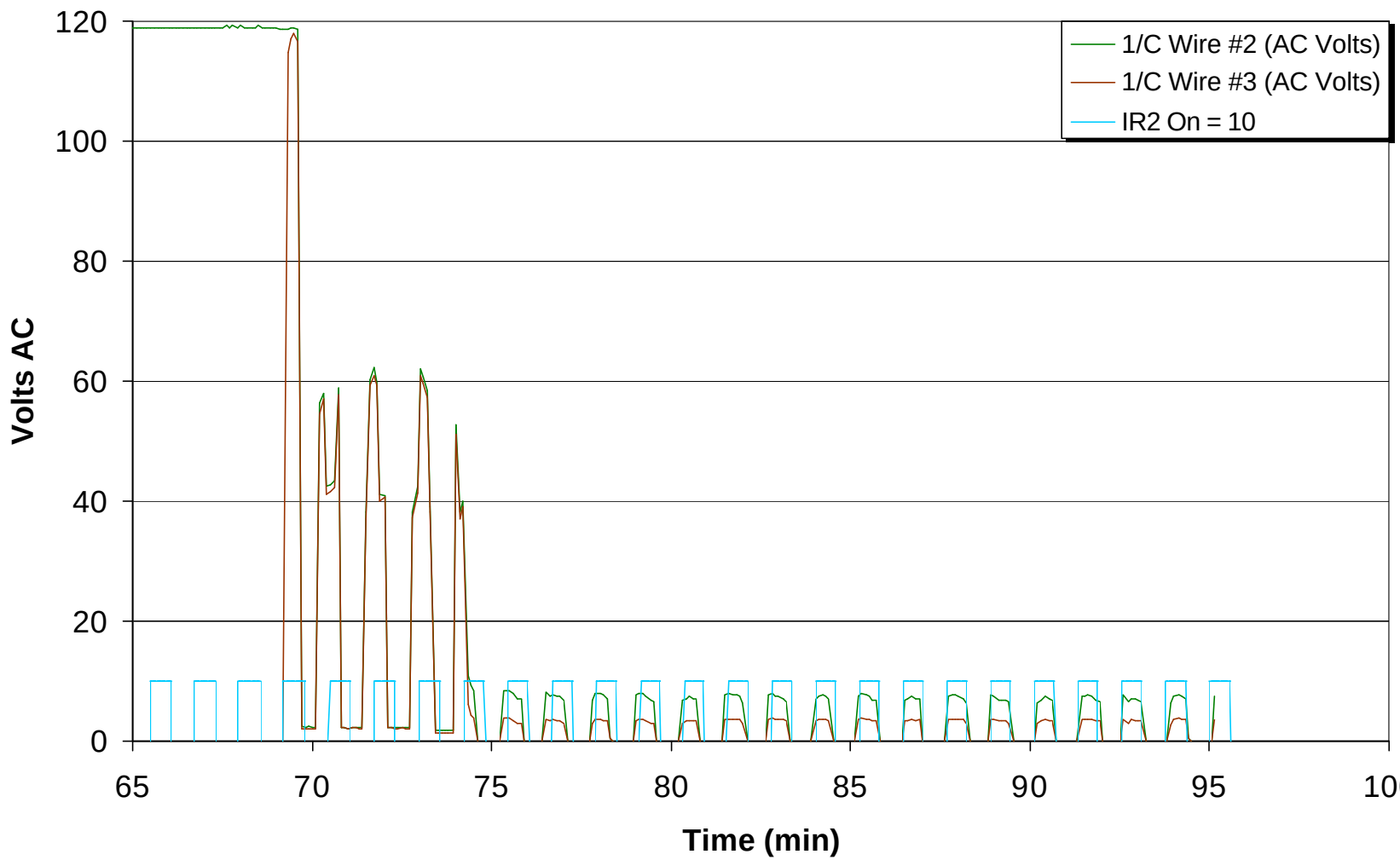
Test #8

DA-1 External Conductors Voltage Response



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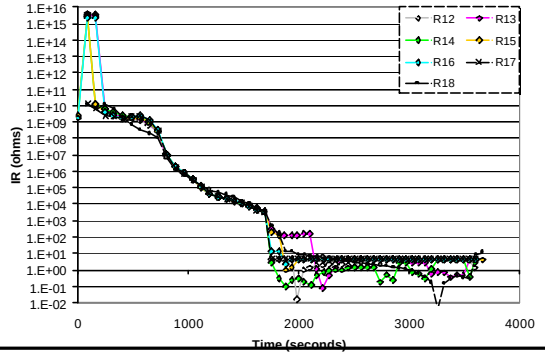
Tests #9, 10 & 11

IR Sys in <u>Ungrounded</u> DC mode

Test #9:

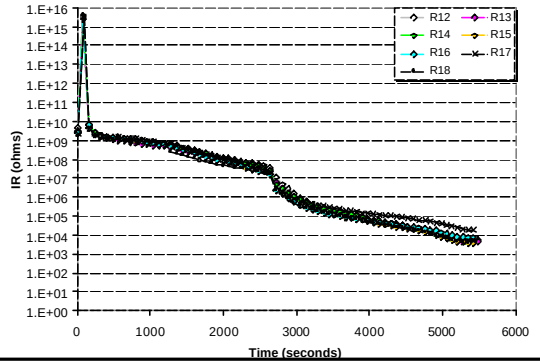
- 7/c Thermoset Cable Bundled w/ 3 1/c cables
- Heat Release Rate = 145 kW
- Peak Tray Temperature = 1020ºF
- Peak Cable Temperature = 1020ºF



100 VDC

Test #10:

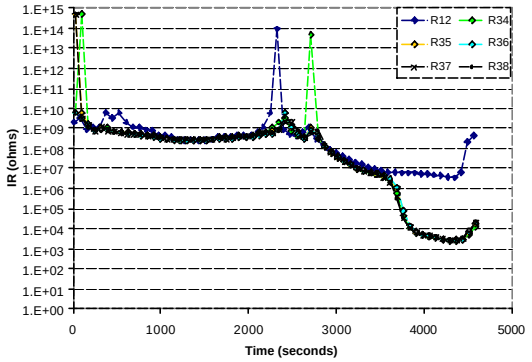
- Vertical Cable Tray
- 7/c Thermoset Cable Bundled w/ 1 1/c cable
- Heat Release Rate = 200 kW
- Peak Tray Temperature = 950ºF
- Peak Cable Temperature = 1200ºF



100 VDC

Test #11:

- 2/c Thermoset Instrument Cable &
- 6/c Thermoset Instrument Cable (no bundles)
- Heat Release Rate = 145 kW
- Peak Tray Temperature = 1080ºF
- Peak Cable Temperature = 750ºF



24 VDC

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Test #12

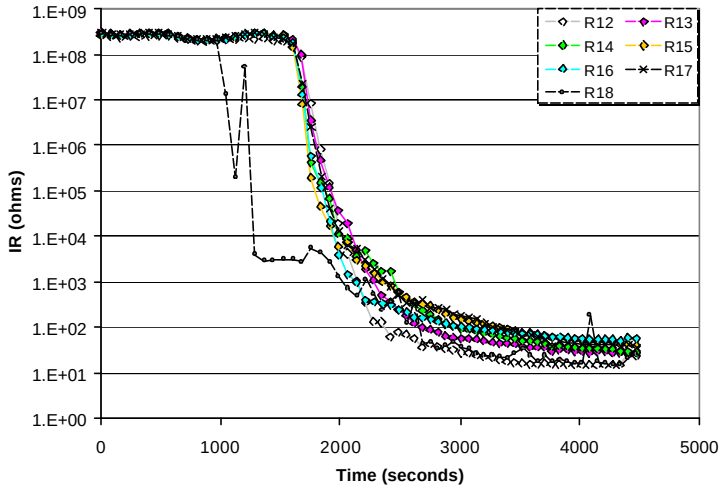
IR Sys in Grounded DC mode (100 VDC)

7/c Thermoset Cable w/ 3 1/c Cables

Heat Release Rate = 145 kW

Peak Tray Temperature = 1130ºF

Peak Cable Temperature = 860ºF



Results:

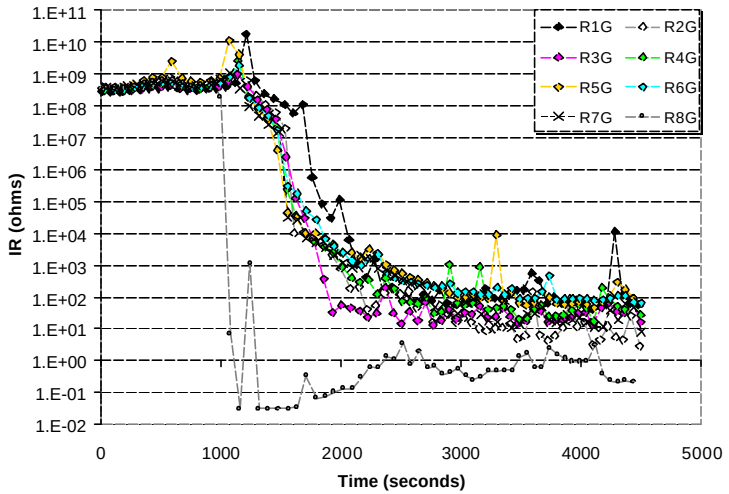
1000 s: Conductor 8 shorts to ground

1900 s: Conductor 3 shorts to ground

2500 s: Conductors 1, 2, 4, & 7 short to ground

3000 s: Conductor 5 shorts to ground

3500 s: All conductors are shorted to ground



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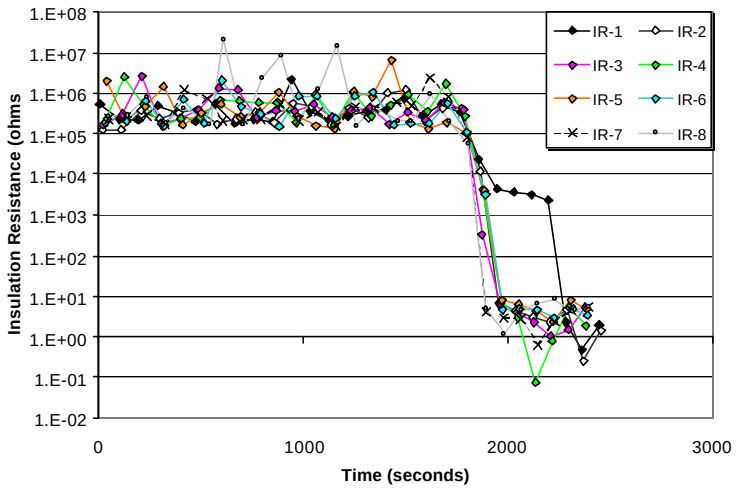
Test #13

Armored Cable with Shield Grounded

Heat Release Rate = 350 kW

Peak Tray Temperature =1400ºF

Peak Cable Temperature =870ºF



Results:

Conductor insulation resistances fall to <100 ohms at ~1900 s.

IR System not wired correctly

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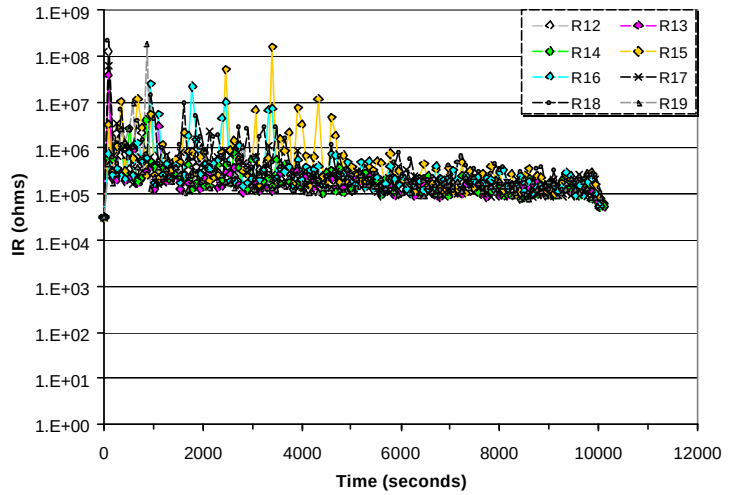
Test #14

Three 3/c cables in one bundle

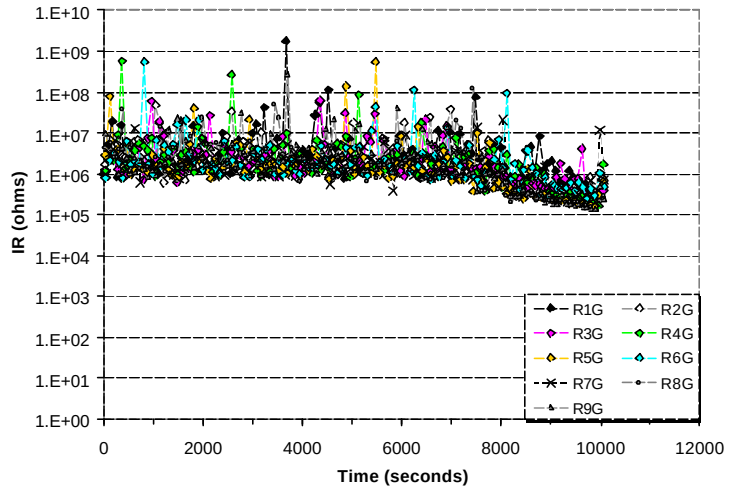
Routed in grounded conduit

Heat Release Rate = 145 kW



Results:

No failures identified.



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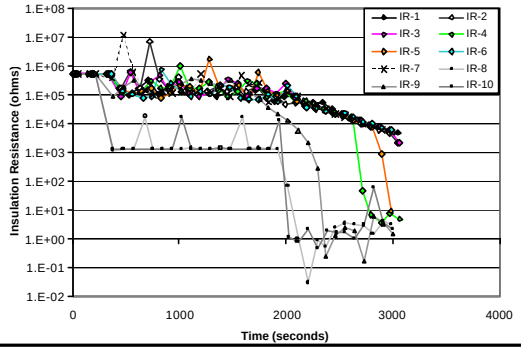
Tests #15, 16 & 17

IR System not wired correctly

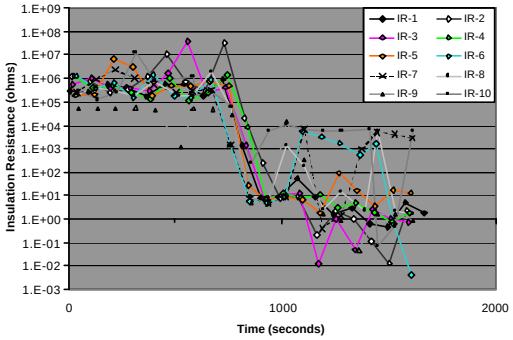
Test #15:

- 7/c Thermoset Cable Bundled w/ 3 1/c cables
- Variable Heat Release Rate = 350-200-450 kW
- Peak Tray Temperature = 1060ºF
- Peak Cable Temperature = 1000ºF



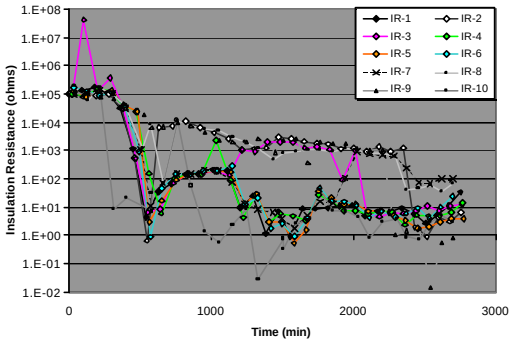
Test #16:

- 9/c Thermoplastic Cable Bundled w/ 3 1/c cables
- Heat Release Rate = 145 kW
- Peak Tray Temperature = 1020ºF
- Peak Cable Temperature = 530ºF



Test #17:

- 9/c Thermoplastic Cable Bundled w/ 3 1/c cables
- Heat Release Rate = 200 kW
- Peak Tray Temperature = 900ºF
- Peak Cable Temperature = 840ºF



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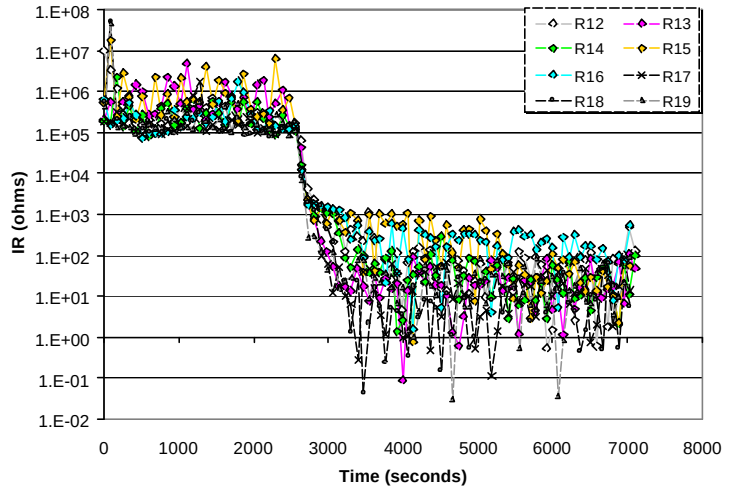
Test #18

Three 3/c cables in one bundle

Routed in grounded conduit

Heat Release Rate = 250 kW



Results:

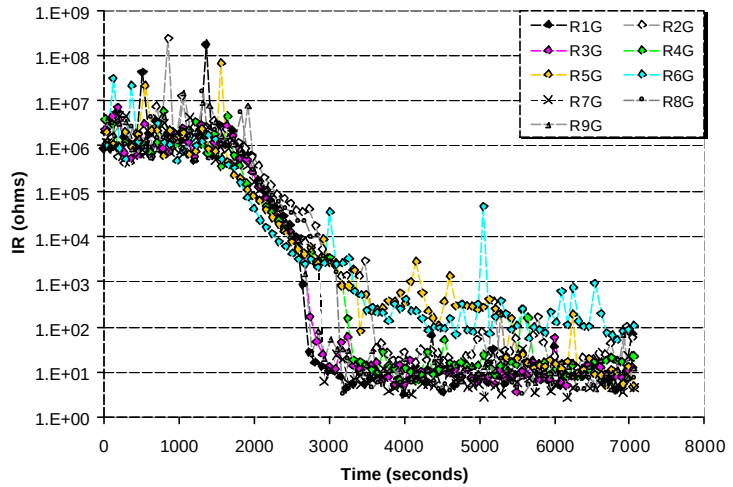
2800 s: Conductors 1, 3 & 9 short to ground

2930 s: Conductor 7 shorts to ground

3300 s: Conductors 4, 5 & 8 short to ground

3600 s: Conductor 2 shorts to ground

4300 s: Conductor 6 shorts to ground



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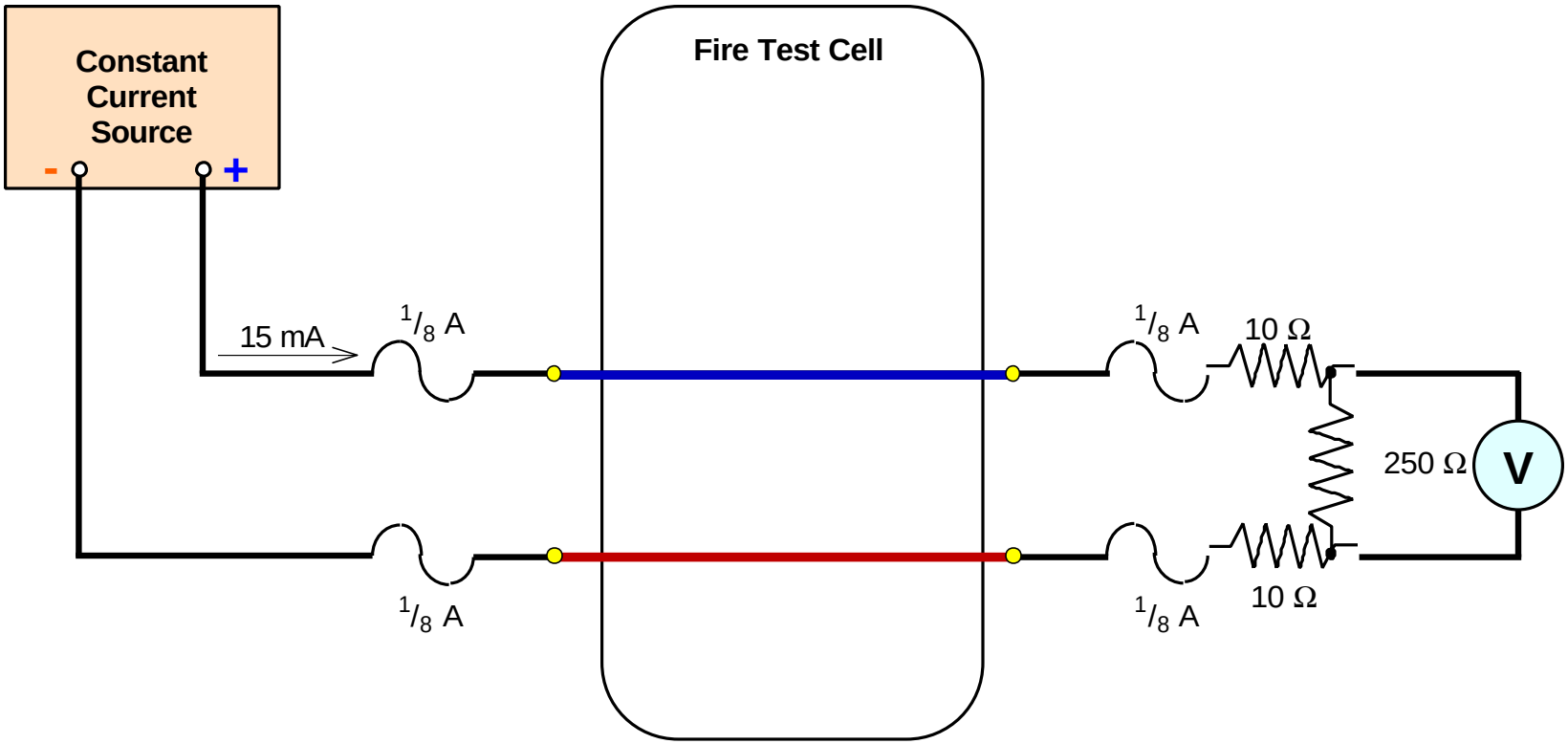
Sandia's Current Loop Circuit



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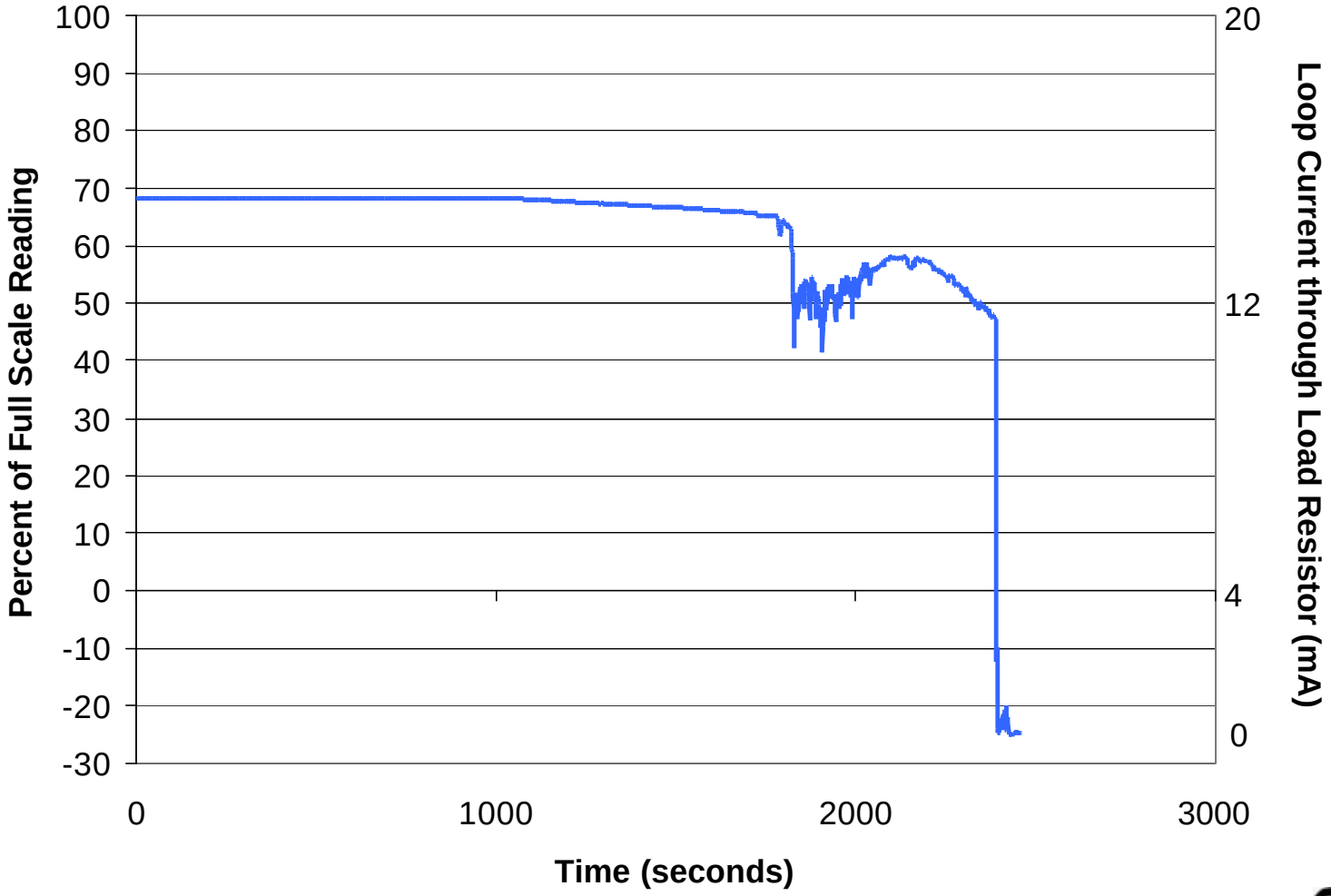
Test #13
Current Loop Data



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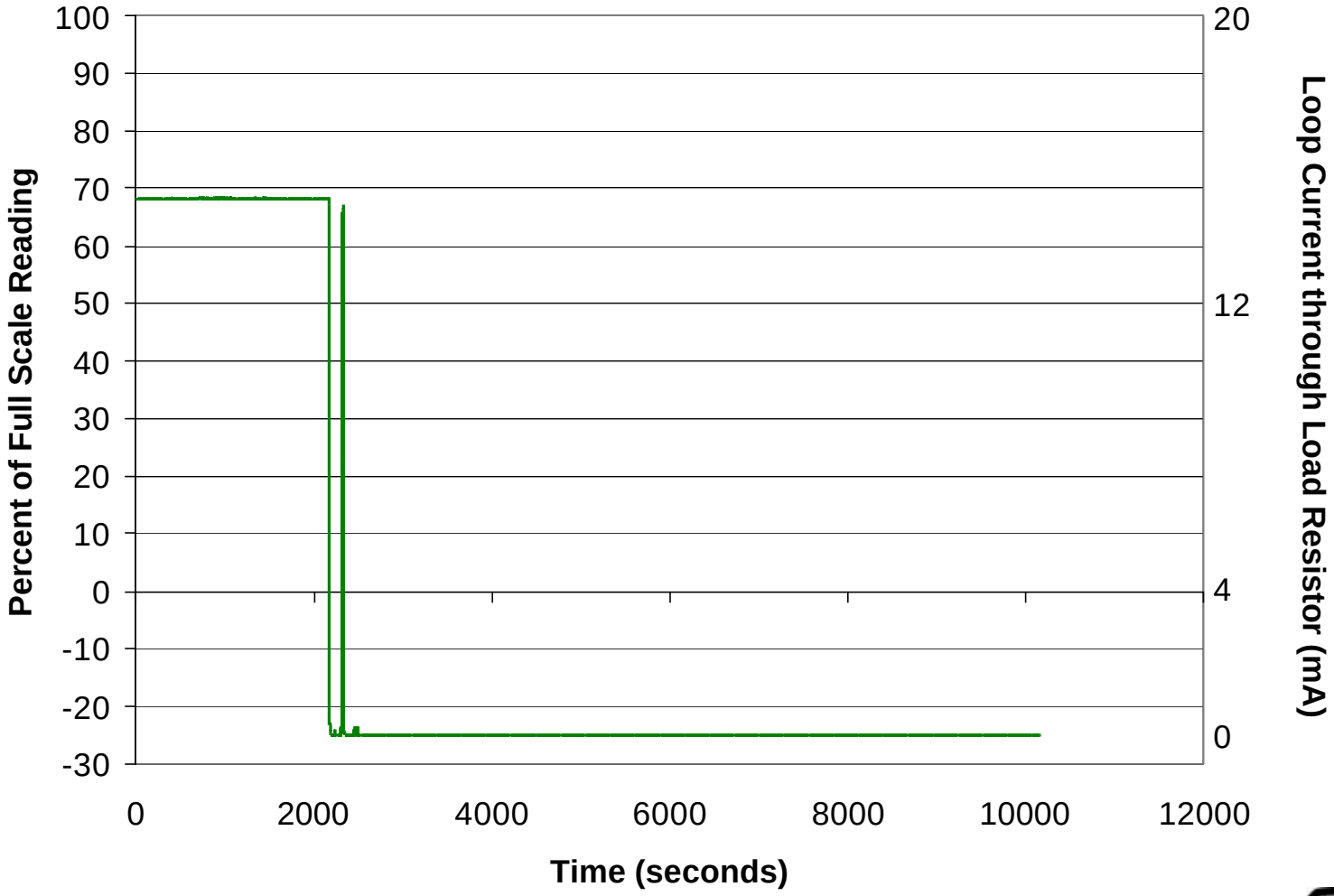
Test #14
Current Loop Data



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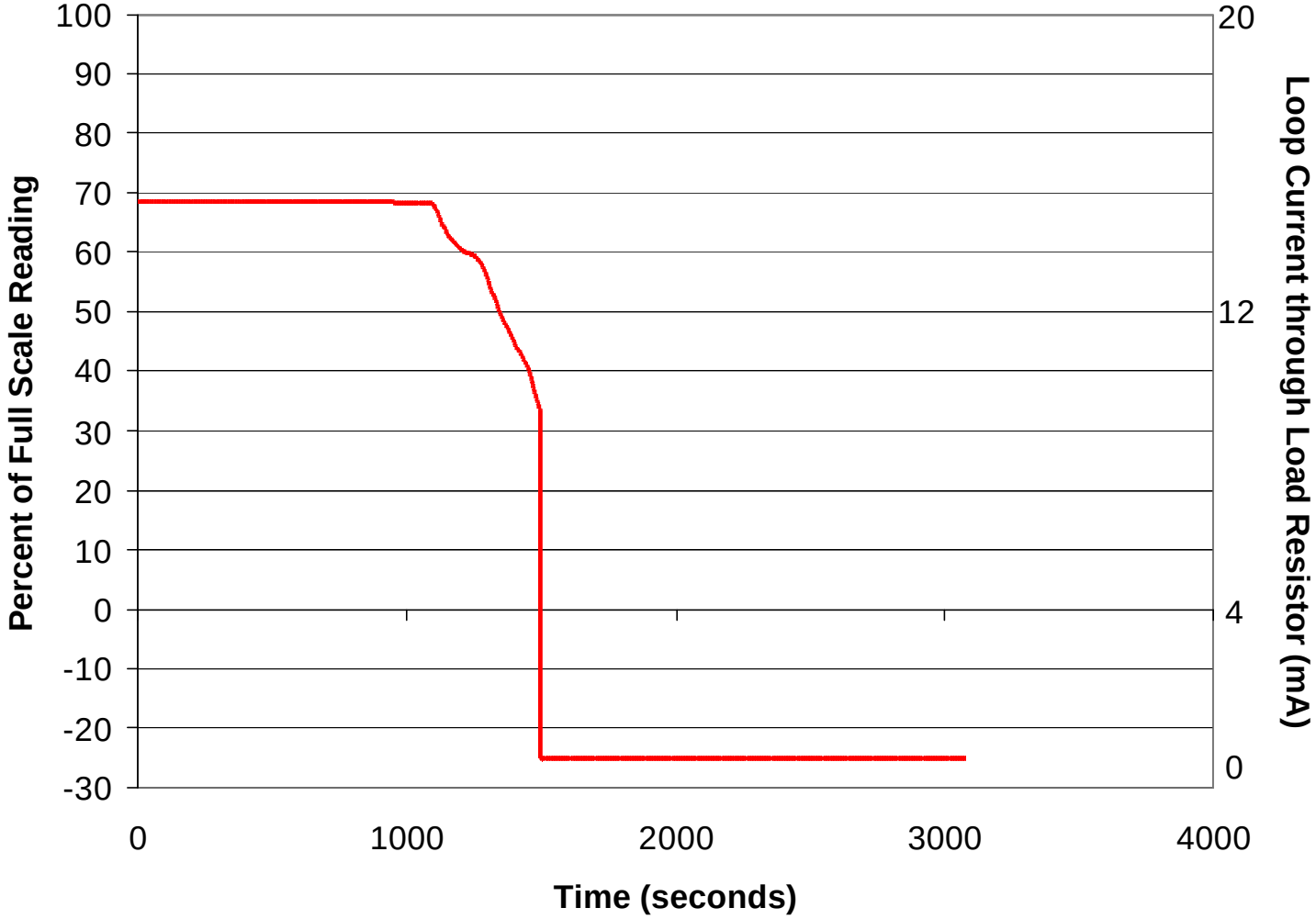
Test #15
Current Loop Data



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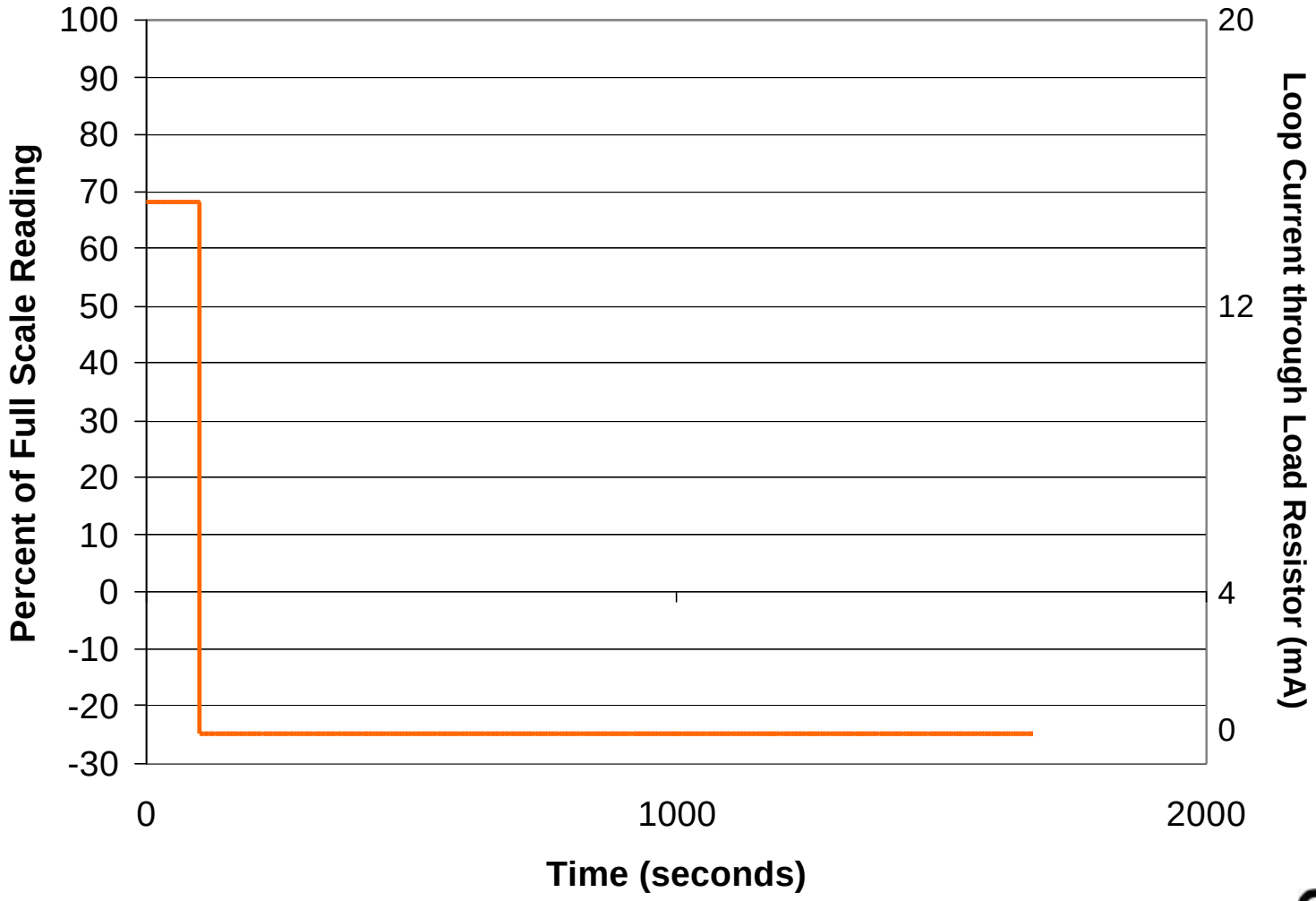
Test #16
Current Loop Data



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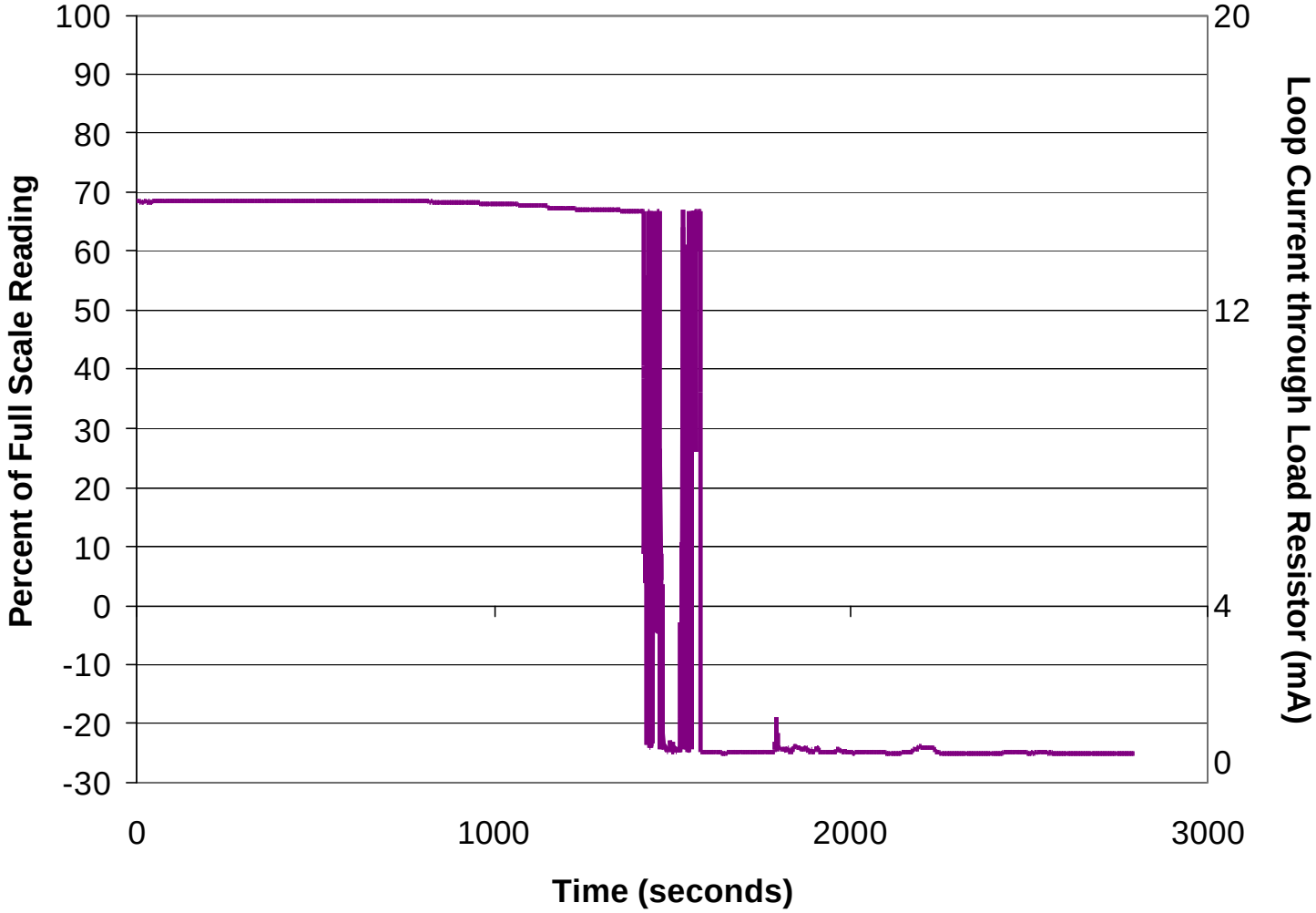
Test #17
Current Loop Data



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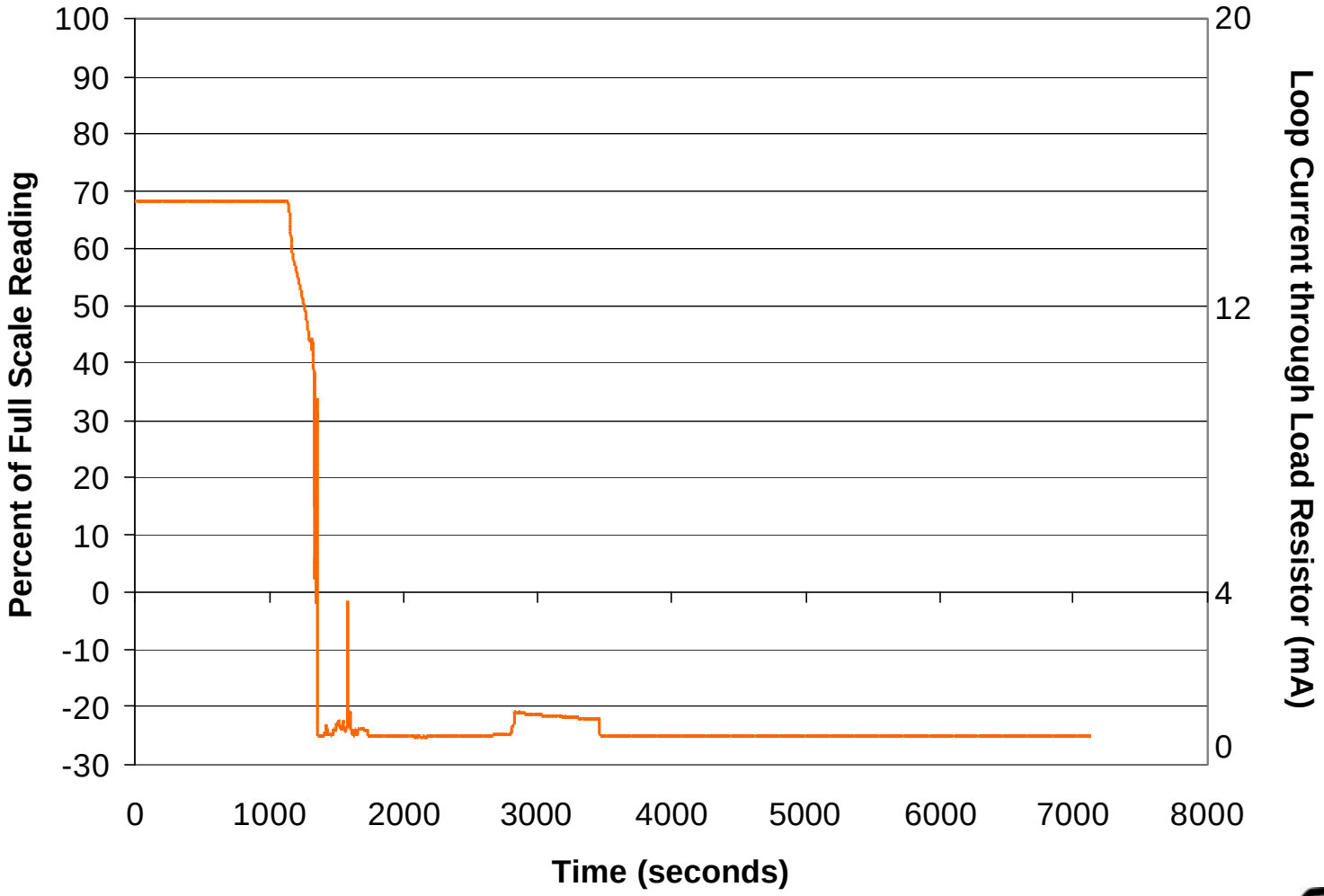
Test #18
Current Loop Data



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Summary of IR Measurement Results

- **For the tests where we can differentiate**

Initial Cable Failure Mode in Cable Trays:

	Multi-conductor cables		*Single cables*	
	Cond-Cond	Cond-Ground	Cable-Cable	Cable-Ground
Tests 1 – 7	4	0	4	8
Test 12	0	1	0	1
Total	4	1	4	9
Relative Probabilities	80%	20%	31%	69%

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Summary continued

- For the tests where we can differentiate

Initial Cable Failure Mode in Conduit:

	Multi-conductor cables		*Single cables*	
	Cond-Cond	Cond-Ground	Cable-Cable	Cable-Ground
Test 8	0	1	n/a	n/a
Test 18	0	3	n/a	n/a
Total	0	4		
Relative Probabilities	0%	100%		

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Summary continued

- **<u>NO</u> open circuits detected**

- **For the instrument current loops tested:**
  - **☑All six instrument cables failed**
  - **☑Thermoplastic cables failed catastrophically**
  - **☑Thermoset cables had degraded signal outputs prior to failing**

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