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Kansas Aviation Research and Technology (KART) Program

Effect of Chemical Composition of Battery on Safety During Thermal Runaway

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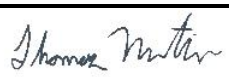
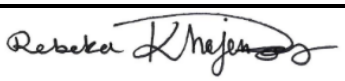
Written by: Thomas Martin 	Date: 6/7/2024
Reviewed by: Rebeka Khajehpour 	Date: 7/16/2024
Section	Description
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TABLE OF CONTENTS

SECTION	TITLE	PAGE
1.0	Scope	13
2.0	Thermal Runaway	14
2.1	General Test Setup and Methodology	14
2.2	Thermal Runaway Results	21
2.2.1	N1-X (Tadiran™ TLM 1530M T)	22
2.2.2	N2-X (UltraLife® UHR-CR34610)	37
2.2.3	R3-X (Lithium Werks™ ANR26650M1B)	58
2.2.4	R4-X (Samsung INR21700-50S)	79
2.2.5	R5-X (Molicel® 20700B)	100
2.2.6	R6-X (Sanyo 20700B)	122
2.3	Safety & Chemical Hazards	142
3.0	References	145

List of Abbreviations, Acronyms, and Symbols

A	Amperes
C	Celsius
ETL	Environmental Test Laboratory
KART	Kansas Aviation Research and Technology
Li-Ion	Lithium Ion
NIAR	National Institute for Aviation Research
PSIA	Pounds per Square Inch Absolute
SLPM	Standard Liters Per Minute
PPM	Parts Per Million
°	Degrees
WH	Watt Hours
TC	Thermocouple
CO	Carbon Monoxide
CO_2	Carbon Dioxide
C_2H_4	Ethylene
H_2	Hydrogen
H_2S	Hydrogen Sulfide
H_2SO_4	Sulfuric Acid
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HF	Hydrogen Fluoride
HNO_3	Nitric Acid
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
SO_2	Sulfur Dioxide

LIST OF TABLES

TABLE **TITLE** **PAGE**

Table 1: Test Matrix of Batteries for Thermal Runaway 13
Table 2: Equipment Used For Thermal Runaway Testing 17
Table 3: Cell Trial Validity List 19
Table 4: Detected Gases Summary 21
Table 5: Failure Modes Summary 21
Table 6: Cell and Chamber Temperatures Summary 22
Table 7: N1-X Mass Change Summary 22
Table 8: N1-X Detected Gases 22
Table 9: N1-X Failure Modes 23
Table 10: N2-X Mass Change Summary 37
Table 11: N2-X Detected Gases 38
Table 12: N2-X Failure Modes 38
Table 13: R3-X Mass Change Summary 58
Table 14: R3-X Detected Gases 59
Table 15: R3-X Failure Modes 59
Table 16: R4-X Mass Change Summary 79
Table 17: R4-X Detected Gases 80
Table 18: R4-X Failure Modes 80
Table 19: R5-X Mass Change Summary 100
Table 20: R5-X Detected Gases 101
Table 21: R5-X Failure Modes 101
Table 22: R6-X Mass Change Summary 122
Table 23: R6-X Detected Gases 122
Table 24 R6-X Failure Modes 122
Table 25: Gas Safety & Chemical Hazards 142
Table 26: Chemical and Physical Hazards Key 144

LIST OF FIGURES

FIGURE **TITLE** **PAGE**

Figure 1: Nichrome Wire Resistive Heating Installation 15
Figure 2: Diagram of Thermocouple Array Positions 15
Figure 3: Thermocouple Fixture Mounted at the Top of the Thermal Runaway Chamber 16
Figure 4: Thermal Runaway Chamber Diagram 16
Figure 5: N1-1 Pre-Test 23
Figure 6: N1-1 Venting 24
Figure 7: N1-1 Post-Test 1 24
Figure 8: N1-1 Post-Test 2 25
Figure 9: N1-3 Pre-Test 25
Figure 10: N1-3 Venting 26
Figure 11: N1-3 Post-Test 1 26
Figure 12: N1-4 Pre-Test 27
Figure 13: N1-4 Post-Test 1 27
Figure 14: N1-4 Post-Test 2 28
Figure 15: N1-5 Pre-Test 28
Figure 16: N1-5 Venting 29
Figure 17: N1-5 Post-Test 1 29
Figure 18: N1-5 Post Test 2

..... 30
Figure 19: N1-6 Pre-Test 30
Figure 20: N1-6 Venting 31
Figure 21: N1-6 Post-Test 1 31

Figure 22: N1-6 Post-Test 2 32
Figure 23: N1-1 Temperature Graph 32
Figure 24: N1-1 Pressure and Voltage Graph 33
Figure 25: N1-3 Temperature Graph 33
Figure 26: N1-3 Pressure and Voltage Graph 34
Figure 27: N1-4 Temperature Graph 34
Figure 28: N1-4 Pressure and Voltage Graph 35
Figure 29: N1-5 Temperature Graph 35
Figure 30: N1-5 Pressure and Voltage Graph 36
Figure 31: N1-6 Temperature Graph 36
Figure 32: N1-6 Pressure and Voltage Graph 37
Figure 33: N2-1 Pre-Test 39
Figure 34: N2-1 Leaking and Fire 39
Figure 35: N2-1 Post-Test 1 40
Figure 36: N2-1 Post-Test 2 40
Figure 37: N2-2 Pre-Test 41
Figure 38: N2-2 Leaking & Venting 41
Figure 39: N2-2 Post Test 1 42
Figure 40: N2-2 Post Test 2 42
Figure 41: N2-5 Pre-Test 43
Figure 42: N2-5 Venting 43
Figure 43: N2-5 Post-Test 1 44
Figure 44: N2-5 Post-Test 2 44
Figure 45: N2-7 Pre-Test 45
Figure 46: N2-7 Venting, Leaking, and Fire 45
Figure 47: N2-7 Post-Test 1 46
Figure 48: N2-7 Post-Test 2 46
Figure 49: N2-8 Pre-Test 47
Figure 50: N2-8 Venting, Leaking, and Fire 47
Figure 51: N2-8 Post-Test 1 48
Figure 52: N2-8 Post-Test 2 48
Figure 53: N2-1 Temperature Graph 1 49
Figure 54: N2-1 Temperature Graph 2 49
Figure 55: N2-1 Temperature Graph 3 50
Figure 56: N2-1 Pressure and Voltage Graph 50
Figure 57: N2-2 Temperature Graph 1 51
Figure 58: N2-2 Temperature Graph 2 51
Figure 59: N2-2 Temperature Graph 3 52
Figure 60: N2-2 Pressure and Voltage Graph 52
Figure 61: N2-5 Temperature Graph 1 53
Figure 62: N2-5 Temperature Graph 2 53
Figure 63: N2-5 Pressure and Voltage Graph 54
Figure 64: N2-7 Temperature Graph 1 54
Figure 65: N2-7 Temperature Graph 2 55
Figure 66: N2-7 Temperature Graph 3 55
Figure 67: N2-7 Pressure and Voltage Graph 56
Figure 68: N2-8 Temperature Graph 1 56
Figure 69: N2-8 Temperature Graph 2 57

Figure 70: N2-8 Temperature Graph 3 57
Figure 71: N2-8 Pressure and Voltage Graph 58
Figure 72: R3-3 Pre-Test 60
Figure 73: R3-3 Venting and Rupture 60
Figure 74: R3-3 Post Test 1 61
Figure 75: R3-3 Post-Test 2 61
Figure 76: R3-4 Pre-Test 62
Figure 77: R3-4 Venting and Fire 62
Figure 78: R3-4 Post-Test 1 63
Figure 79: R3-4 Post-Test 2 63
Figure 80: R3-5 Pre-Test 64
Figure 81: R3-5 Venting 64
Figure 82: R3-5 Post-Test 1 65
Figure 83: R3-5 Post-Test 2 65
Figure 84: R3-11 Pre-Test 66
Figure 85: R3-11 Venting 66
Figure 86: R3-11 Post-Test 1 67
Figure 87: R3-12 Pre-Test 67
Figure 88: R3-12 Venting 68
Figure 89: R3-12 Post-Test 1 68
Figure 90: R3-12 Post-Test 2 69
Figure 91: R3-3 Temperature Graph 1 69
Figure 92: R3-3 Temperature Graph 2 70
Figure 93: R3-3 Temperature Graph 3 70
Figure 94: R3-3 Pressure & Voltage Graph 71
Figure 95: R3-4 Temperature Graph 1 71
Figure 96: R3-4 Temperature Graph 2 72
Figure 97: R3-4 Temperature Graph 3 72
Figure 98: R3-4 Pressure & Voltage Graph 73
Figure 99: R3-5 Temperature Graph 1 73
Figure 100: R3-5 Temperature Graph 2 74
Figure 101: R3-5 Temperature Graph 3 74
Figure 102: R3-5 Pressure & Voltage Graph 75
Figure 103: R3-11 Temperature Graph 1 75
Figure 104: R3-11 Temperature Graph 2 76
Figure 105: R5-11 Temperature Graph 3 76
Figure 106: R3-11 Pressure & Voltage Graph 77
Figure 107: R3-12 Temperature Graph 1 77
Figure 108: R3-12 Temperature Graph 2 78
Figure 109: R3-12 Temperature Graph 3 78
Figure 110: R3-12 Pressure & Voltage Graph 79
Figure 111: R4-1 Pre-Test 81
Figure 112: R4-1 Venting 81
Figure 113: R4-1 Post-Test 1 82
Figure 114: R4-1 Post-Test 2 82
Figure 115: R4-2 Pre-Test 83
Figure 116: R4-2 Venting 83
Figure 117: R4-2 Post-Test 1 84

Figure 118: R4-2 Post-Test 2 84
Figure 119: R4-3 Pre-Test 85
Figure 120: R4-3 Venting 85
Figure 121: R4-3 Post-Test 1 86
Figure 122: R4-3 Post Test 2 86
Figure 123: R4-4 Pre-Test 87
Figure 124: R4-4 Venting and Fire 87
Figure 125: R4-4 Post-Test 1 88
Figure 126: R4-4 Post-Test 2 88
Figure 127: R4-5 Pre-Test 89
Figure 128: R4-5 Venting and Rupture 89
Figure 129: R4-5 Post-Test 1 90
Figure 130: R4-5 Post-Test 2 90
Figure 131: R4-1 Temperature Graph 1 91
Figure 132: R4-1 Temperature Graph 2 91
Figure 133: R4-1 Temperature Graph 3 92
Figure 134: R4-1 Pressure and Voltage Graph 92
Figure 135: R4-2 Temperature Graph 93
Figure 136: R4-2 Temperature Graph 2 93
Figure 137: R4-2 Temperature Graph 3 94
Figure 138: R4-2 Pressure and Voltage Graph 94
Figure 139: R4-3 Temperature Graph 1 95
Figure 140: R4-3 Temperature Graph 2 95
Figure 141: R4-3 Temperature Graph 3 96
Figure 142: R4-3 Pressure and Voltage Graph 96
Figure 143: R4-4 Temperature Graph 1 97
Figure 144: R4-4 Temperature Graph 2 97
Figure 145: R4-4 Temperature Graph 3 98
Figure 146: R4-4 Pressure and Voltage Graph 98
Figure 147: R4-5 Temperature Graph 1 99
Figure 148: R4-5 Temperature Graph 2 99
Figure 149: R4-5 Pressure and Voltage Graph 100
Figure 150: R5-2 Pre-Test 102
Figure 151: R5-2 Venting 102
Figure 152: R5-2 Post-Test 1 103
Figure 153: R5-2 Post-Test 2 103
Figure 154: R5-4 Pre-Test 104
Figure 155: R5-4 Venting and Fire 104
Figure 156: R5-4 Post-Test 1 105
Figure 157: R5-4 Post-Test 2 105
Figure 158: R5-5 Pre-Test 106
Figure 159: R5-5 Venting and Fire 106
Figure 160: R5-5 Post-Test 1 107
Figure 161: R5-5 Post-Test 2 107
Figure 162: R5-6 Pre-Test 108
Figure 163: R5-6 Venting and Fire 108
Figure 164: R5-6 Post-Test 1 109
Figure 165: R5-6 Post-Test 2 109

Figure 166: R5-7 Pre-Test 110
Figure 167: R5-7 Venting and Fire 110
Figure 168: R5-7 Post-Test 1 111
Figure 169: R5-7 Post-Test 2 111
Figure 170: R5-2 Temperature Graph 1 112
Figure 171: R5-2 Temperature Graph 2 112
Figure 172: R5-2 Temperature Graph 3 113
Figure 173: R5-2 Pressure and Voltage Graph 113
Figure 174: R5-4 Temperature Graph 1 114
Figure 175: R5-4 Temperature Graph 2 114
Figure 176: R5-4 Temperature Graph 115
Figure 177: R5-4 Pressure and Voltage Graph 115
Figure 178: R5-5 Temperature Graph 1 116
Figure 179: R5-5 Temperature Graph 2 116
Figure 180: R5-5 Temperature Graph 3 117
Figure 181: R5-5 Pressure and Voltage Graph 117
Figure 182: R5-6 Temperature Graph 1 118
Figure 183: R5-6 Temperature Graph 2 118
Figure 184: R5-6 Temperature Graph 3 119
Figure 185: R5-6 Pressure and Voltage Graph 119
Figure 186: R5-7 Temperature Graph 1 120
Figure 187: R5-7 Temperature Graph 2 120
Figure 188: R5-7 Temperature Graph 3 121
Figure 189: R5-7 Pressure and Voltage Graph 121
Figure 190: R6-1 Pre-Test 123
Figure 191: R6-1 Venting 123
Figure 192: R6-1 Post-Test 1 124
Figure 193: R6-1 Post-Test 2 124
Figure 194: R6-2 Pre-Test 125
Figure 195: R6-2 Venting 125
Figure 196: R6-2 Post-Test 1 126
Figure 197: R6-2 Post-Test 2 126
Figure 198: R6-3 Pre-Test 127
Figure 199: R6-3 Venting 127
Figure 200: R6-3 Post-Test 1 128
Figure 201: R6-3 Post-Test 2 128
Figure 202: R6-4 Pre-Test 129
Figure 203: R6-4 Post-Test 1 129
Figure 204: R6-4 Post-Test 2 130
Figure 205: R6-5 Pre-Test 130
Figure 206: R6-5 Venting 131
Figure 207: R6-5 Post-Test 1 131
Figure 208: R6-5 Post-Test 2 132
Figure 209: R6-1 Temperature Graph 1 132
Figure 210: R6-1 Temperature Graph 2 133
Figure 211: R6-1 Temperature Graph 3 133
Figure 212: R6-1 Pressure and Voltage Graph 134
Figure 213: R6-2 Temperature Graph 1 134

Figure 214: R6-2 Temperature Graph 2 135
Figure 215: R6-2 Temperature Graph 3 135
Figure 216: R6-2 Pressure and Voltage Graph 136
Figure 217: R6-3 Temperature Graph 1 136
Figure 218:R6-3 Temperature Graph 2 137
Figure 219: R6-3 Temperature Graph 3 137
Figure 220: R6-3 Pressure and Voltage Graph 138
Figure 221: R6-4 Temperature Graph 1 138
Figure 222: R6-4 Temperature Graph 2 139
Figure 223: R6-4 Temperature Graph 3 139
Figure 224: R6-4 Pressure and Voltage Graph 140
Figure 225: R6-5 Temperature Graph 1 140
Figure 226: R6-5 Temperature Graph 2 141
Figure 227: R6-5 Temperature Graph 3 141
Figure 228: R6-5 Pressure and Voltage 142

1.0 Scope

This document contains a summary of the test results for the thermal runaway testing of the test articles in Table 1. This test was performed in accordance with the test methods defined in NIAR Document 24-2152-TP007, DO-227A, and DO-311A. Testing took place at the National Institute for Aviation Research (NIAR) Environmental Test Laboratory (ETL) located at 3800 S. Oliver Wichita, Kansas 67210 from November 29, 2023 to May 8, 2024.

Table 1: Test Matrix of Batteries for Thermal Runaway

Cell Type	Manufacturer	Chemistry	Size	Shape	Wh	Product Code	Test Article ID
Non-rechargeable	Tadiran™	LiNixCoyAlzO2	2/3 AA	Cylindrical	0.8	TLM 1530M T	N1-X
	UltraLife®	Li/MnO_2	D	Cylindrical	33.3	UHR-CR34610	N2-X
Rechargeable	Lithium Werks™	$LiFePO_4$	26650	Cylindrical	8.25	ANR26650M1B	R3-X
	Samsung	Li-Ion	21700	Cylindrical	18	INR21700-50S	R4-X
	Molicel®	Li-Ion	21700	Cylindrical	15.3	INR21700-P45B	R5-X
	Sanyo	Li Metal Oxide	20700	Cylindrical	15.3	20700B	R6-X

This test was designed to determine the failure modes of various battery cells and the resulting temperatures, pressures, and gases produced as a result of thermal runaway events. This public dataset contains the data obtained from this effort and relevant safety information. Data listed in the results sections includes:

- Tables listing the pre and post-test cell masses, gas concentrations, and cell failure modes
- Test photos
- Temperature graphs – some graphs are shown multiple times at different scales to better show the data.
- Chamber pressure and cell voltage graphs

Safety hazards associated with the gasses detected can be found in section 2.3.

2.0 Thermal Runaway

2.1 General Test Setup and Methodology

All rechargeable cells were fully charged prior to testing as this would result in the worst-case scenario. Non-rechargeable cells were tested at the state of charge in which they were received. The cell being tested was stripped of the factory jacket and wrapped in polyimide tape to isolate the heater element from the cell body. The cell was then weighed. Once wrapped in polyimide tape, a nichrome wire heater coil was formed in a switchback pattern axial to the cell. The cell heater was installed and bound to the cell body via polyimide tape as well. Lastly, three thermocouples were affixed to the cell; one at the positive terminal (or the end of the cell where the venting was expected to begin), one at 2/3 the length of the cell, and one at 1/3 the length of the cell via polyimide tape and located such that they were spaced off the heater element. The cell to be tested was placed into a holder. An array of 11 thermocouples was used to measure the temperature at various positions in the chamber. One thermocouple was placed 6” behind the negative terminal of the battery. The remaining thermocouples were arranged in a spiral pattern, moving away from the terminal where the venting was expected to take place, as shown in Figure 2. Steel tubing was used to protect each thermocouple from damage and to help keep them in the desired location through the duration of the thermal runaway event. The tip of the thermocouples was exposed at the end of the tube to get more accurate temperature data. Figure 3 shows this thermocouple fixture. A list of test equipment can be found in Table 2. A schematic of the thermal runaway chamber and test setup can be seen in Figure 4.

Figure 1: Nichrome Wire Resistive Heating Installation

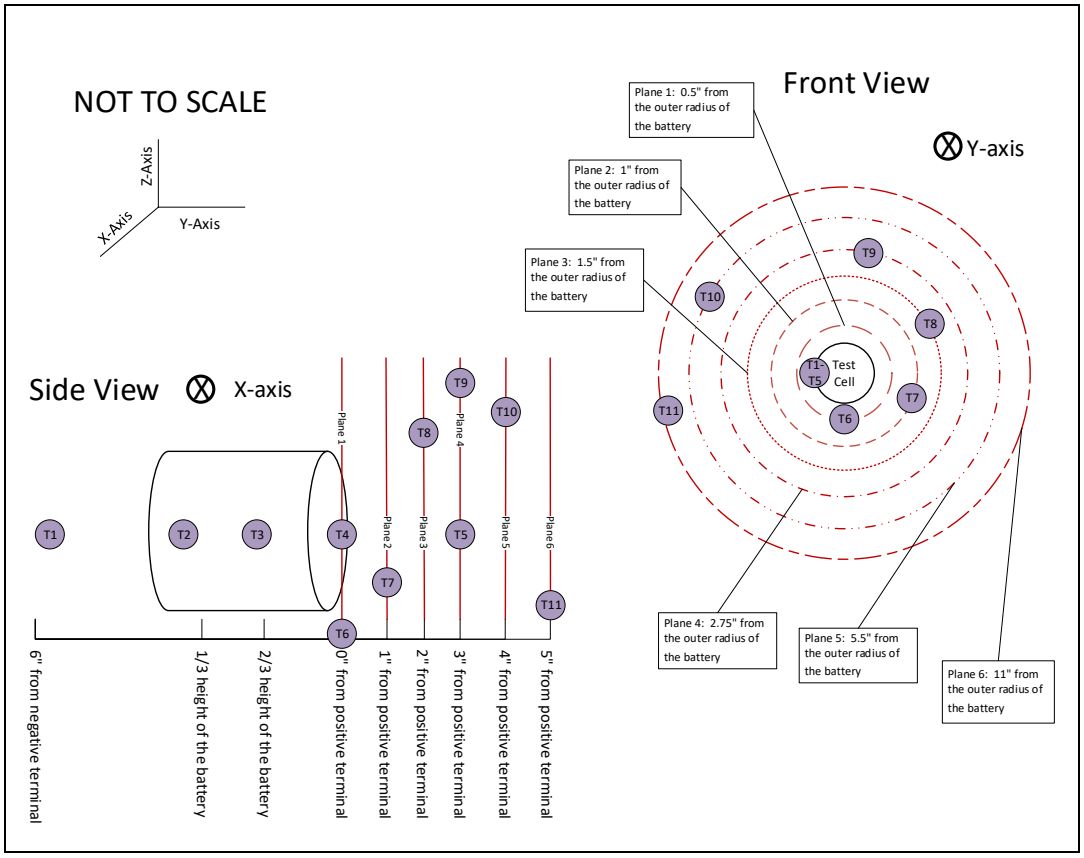

Figure 2: Diagram of Thermocouple Array Positions

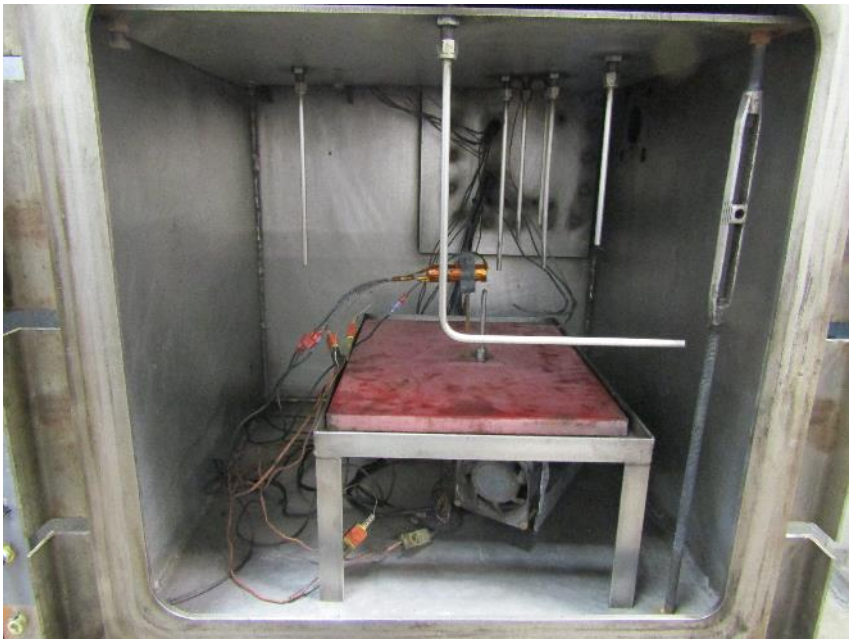

Figure 3: Thermocouple Fixture Mounted at the Top of the Thermal Runaway Chamber

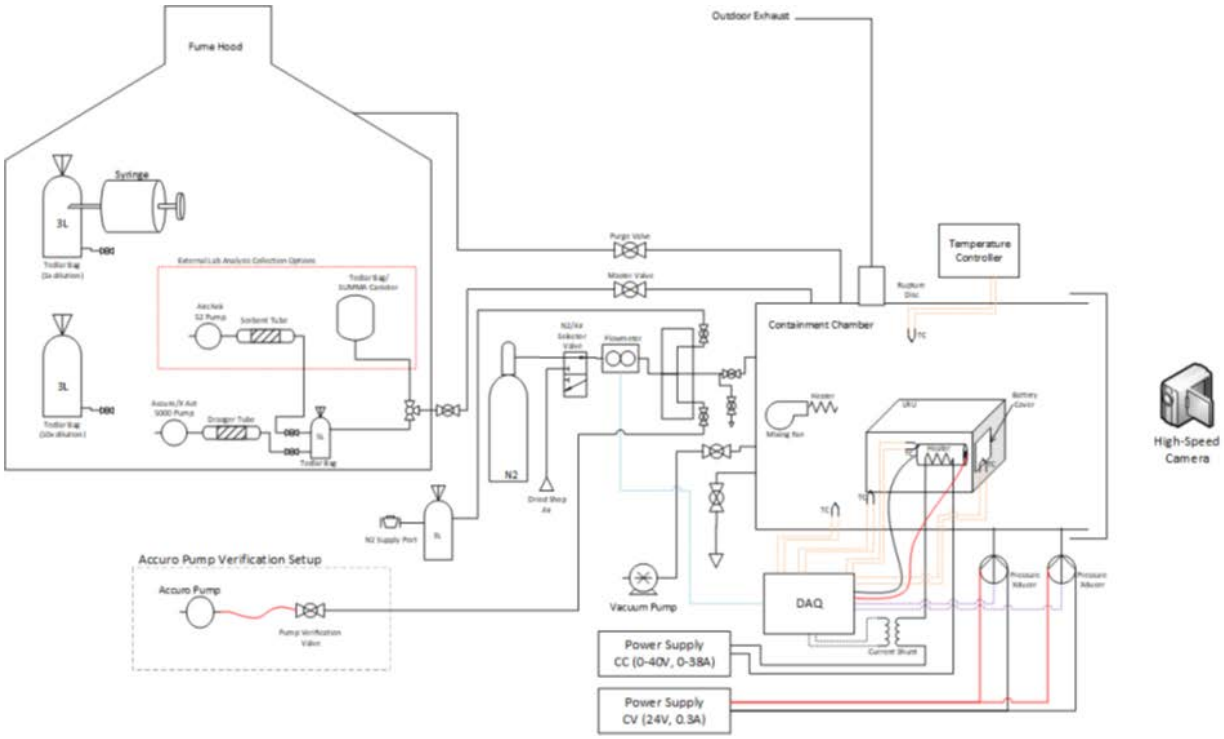

Figure 4: Thermal Runaway Chamber Diagram

Table 2: Equipment Used For Thermal Runaway Testing

Description	Manufacturer	Model Number	Qty
K-Type Thermocouple	Omega	5SRTC-TT-K-30-72-ROHS	29
T-Type Thermocouple	Omega	T-Type	10
Power Supply: 40V, 0.3A / 20V, 0.6A, 20W, Dual Range	Hewlett Packard	6205B	1
Data Logger	Omega	OM-24	1
Camera System: 8-Ch, 2TB, HD Wi-Fi NVR	Lorex	N842A8-Z	1
Thermal Runaway Containment Chamber	NIAR	EITR	1
Mass Flowmeter: 0-100SLPM	Omega	FMA-1610A	1
Pressure Sensor: 0-30 PSIA	Omega	PX429-030A5V	1
Pressure Transducer: 0-300 PSIA	Omega	PX309-300A5V	1
Pressure Transducer: 0-30 PSIA	Omega	PX309-030A5V	1
DAQ Module: ±78mV, 75S/s, 24 Bit, 16-Ch Thermocouple Input, Compact	National Instruments	NI-9213	1
DAQ Module: Universal, 4-Ch Analog Input, Compact	National Instruments	NI-9219	3
DAQ Module: ±60V, 12-Bit, 8-Ch Analog Input, Compact	National Instruments	NI-9221	1
DAQ Chassis: 4-Module, Compact, USB	National Instruments	cDAQ-9174	1
DAQ Module: ±78mV, 75S/s, 24 Bit, 16-Ch Thermocouple Input, Compact	National Instruments	NI-9213	1
Current Shunt: 15A, 50MV	Wacline	15AMP-50MV	1
Current Shunt: 30A, 50mV	Elreco	MS91586-1	1

Once a cell was placed in the chamber and all thermocouples were connected, the chamber was sealed, and the pretest and verification procedures were performed. Those procedures included a chamber volume injection/leak check, tube pump verification, and an atmosphere replacement through vacuum. Once the pretest safety checks and verification procedures were complete the chamber temperature was raised to 55 °C and stabilized for at least 1-hour. After stabilization was established, the cell was heated via the installed cell heater element at a rate of 10 °C/min until thermal runaway occurred. Thermal runaway for this testing was determined as rapid self-

heating of a battery cell driven by exothermic chemical reactions of the materials within the cell evidenced by a sharp increase in temperature (> 20 °C/min) and pressure and a drop in cell voltage, without acceleration to the rate of current draw of the heating source.

For the gas collection procedure, the chamber was pressurized with dry shop air to motivate the sample gas to flow into the sampling bag. This was done to ensure all sampling was done at ambient pressure and temperature. Each gas was sampled similarly using colorimetric detector tubes. These detector tubes work best at ambient temperatures and pressures. Because the thermal runaway event creates a pressure wave and an increase in temperature, the gases were not immediately collected. Rather, the chamber temperature was allowed to return to 55 °C before the gases could be moved into a collection bag where the pressure was then adjusted for use with the detector tubes. Tube ends come sealed from the factory. The ends were broken, and the tube installed between the sampling bag and the tube pump. The pump draws a specific bolus (100 mL) of gas through the tube. Each tube requires a specific number of boluses. Once the total volume required was drawn, the tube scale measurement was recorded on the gas collection datasheet and a photograph of the detector tube was taken. The temperature and pressure inside and outside the chamber, the volume of the chamber, and the detected concentration of each gas were used to calculate the total moles of each gas released by the thermal runaway reaction. Gas detector tubes were used to determine the presence and concentration of the following gases:

- CO (carbon monoxide)
- CO_2 (carbon dioxide)
- C_2H_4 (ethylene)
- H_2 (hydrogen)
- H_2S (hydrogen sulfide)
- H_2SO_4 (sulfuric acid)
- HCl (hydrogen chloride)
- HCN (hydrogen cyanide)

- HF (hydrogen fluoride)
- HNO_3 (nitric acid)
- NO (nitric oxide)
- NO_2 (nitrogen dioxide)
- SO_2 (sulfur dioxide)

The gas detector tubes contain specific indicators that change colors in the presence of the specific gas they are designed to detect and based on the concentration of said gas. For this reason, the measurement has a certain degree of subjectivity involved. The error ranges of the detector tubes are listed in the detected gases table for each cell type in Section 2.2.

Upon completion of all gas sampling the chamber was purged with dry shop air for at least 30 minutes. Then, the chamber was opened and the cell was inspected, removed, photographed, and weighed. Once the post-test inspection was complete the chamber was cleaned and reset for subsequent tests.

Test articles included both non-rechargeable and rechargeable cells that were all lithium based but had varying chemical compositions. All test articles were cylindrical in shape. Additional information for each test article is shown in Table 1. A list of the test equipment used is detailed in Table 2. Table 3 shows which cells resulted in valid test points and why certain cell data was omitted from this report.

Table 3: Cell Trial Validity List

Cell Type	Cell Number	Valid?	Notes
N1	N1-1	Y	
	N1-2	N	Heater shorted. Cell did not go into thermal runaway
	N1-3	Y	
	N1-4	Y	
	N1-5	Y	
	N1-6	Y	
N2	N2-1	Y	
	N2-2	Y	

Cell Type	Cell Number	Valid?	Notes
	N2-3	N	Invalid TC data
	N2-4	N	Invalid TC data
	N2-5	Y	
	N2-6	N	Cell was used in the initial development run
	N2-7	Y	
	N2-8	Y	
R3	R3-1	N	Invalid TC data
	R3-2	N	Invalid TC data
	R3-3	Y	
	R3-4	Y	
	R3-5	Y	
	R3-6	N	Invalid TC data
	R3-7	N	Invalid TC data
	R3-8	N	Cell was used in a development run
	R3-9	N	Cell was used in a development run
	R3-11	Y	
	R3-12	Y	
	R3-13	Y	Valid but not included in report, extra data point
R4	R4-1	Y	
	R4-2	Y	
	R4-3	Y	
	R4-4	Y	
	R4-5	Y	
R5	R5-1	N	Invalid TC data
	R5-2	Y	
	R5-3	N	Invalid TC data
	R5-4	Y	
	R5-5	Y	
	R5-6	Y	
	R5-7	Y	
R6	R6-1	Y	
	R6-2	Y	
	R6-3	Y	
	R6-4	Y	
	R6-5	Y	

2.2 Thermal Runaway Results

Summaries of temperatures, detected gases, and failure modes for each cell type are shown in Table 4 through Table 6. The failure modes listed in Table 5 are defined as follows:

- Leak – liquid electrolyte escapes the cell
- Vent – gaseous electrolyte escapes the cell
- Fire – flames were observed to be originating from the cell
- Rupture – a physical/structural failure of the cell

Table 6 shows a summary of the average temperature data and the corresponding standard deviations. Cell peak temperature was the highest temperature recorded by T3. Thermal runaway onset temperature was the temperature reading from T3 at the onset of the reaction. Chamber peak temperature was the highest temperature recorded by any thermocouple that was not directly attached to the cell (T1, T5-T11) and was not damaged during the test. All of the average measurements used the measured value for each of the five duplicate battery cells. Specific data from each cell are separated by cell type in the following sections.

Table 4: Detected Gases Summary

Gas Species	Average Moles of Gas Detected N1	Average Moles of Gas Detected N2	Average Moles of Gas Detected R3	Average Moles of Gas Detected R4	Average Moles of Gas Detected R5	Average Moles of Gas Detected R6
CO	1.7E-3	0.064	5.0E-3	0.099	2.7E-2	0.048
CO_2	5.6E-3	0.30	0.099	0.33	2.1E-1	0.24
C_2H_4	2.1E-4	0.030	9.4E-3	3.8E-3	1.3E-3	5.0E-3
H_2	0	0	0.017	0	0	0
H_2S	0	0	0	0	0	0
H_2SO_4	5.3E-6	9.6E-6	4.3E-5	5.4E-6	8.0E-6	6.0E-6
HCl	0	2.2E-6	0	0	0	0
HCN	2.4E-6	2.6E-5	1.1E-4	6.4E-6	7.2E-6	7.7E-6
HF	0	0	0	0	0	0
HNO_3	0	0	0	0	0	0
NO	1.1E-6	1.9E-4	1.6E-5	2.1E-4	2.0E-4	2.3E-4
NO_2	0	3.0E-5	2.2E-6	1.4E-5	4.3E-5	1.5E-5
SO_2	0	0	9.5E-6	0	0	0

Table 5: Failure Modes Summary

Cell Type	Leak	Vent	Fire	Rupture
N1	0/5	5/5	0/5	3/5
N2	5/5	5/5	5/5	5/5
R3	5/5	5/5	1/5	3/5
R4	0/5	5/5	5/5	5/5
R5	0/5	5/5	5/5	5/5
R6	4/5	5/5	5/5	4/5

Table 6: Cell and Chamber Temperatures Summary

Cell Type	Average Thermal Runaway Onset Temperature (°C)	Average Cell Peak Temperature (°C)	Average Chamber Peak Temperature (°C)
N1	188.5 ± 14.0	277.0 ± 32.8	67.1 ± 2.7
N2	181.5 ± 6.9	994.9 ± 435.4	894.3 ± 352.4
R3	224.1 ± 31.4	348.5 ± 36.6	361.4 ± 335.9
R4	172.1 ± 4.6	348.4 ± 77.6	391.4 ± 80.8
R5	178.3 ± 5.5	365.7 ± 101.6	712.9 ± 306.9
R6	184.3 ± 8.2	458.5 ± 179.0	778.0 ± 230.2

2.2.1 N1-X (Tadiran™ TLM 1530M T)

The N1-X cells were relatively benign compared to the other cell types, which was expected as they were the smallest in terms of size and watt hours. The reaction resulted in an average cell peak temperature of 277°C and an average chamber peak temperature of 67.1°C, the lowest of all the cell types tested. Each cell released similar amounts of carbon monoxide, carbon dioxide, ethylene, and sulfuric acid. Hydrogen cyanide and nitric oxide were only released by two and one of the cells, respectively. The cells lost an average of 2.800g of mass, which translates to a 27% loss in initial mass.

Table 7: N1-X Mass Change Summary

Cell	Pre-Test Mass (g)	Post-Test Mass (g)
N1-1	10.421	7.540
N1-3	10.628	7.754
N1-4	10.389	7.426
N1-5	10.485	7.647
N1-6	10.621	8.178

Table 8: N1-X Detected Gases

Gas Species	Detector Tube Error Range	Moles of Gas Detected N1-1	Moles of Gas Detected N1-3	Moles of Gas Detected N1-4	Moles of Gas Detected N1-5	Moles of Gas Detected N1-6
CO	±10 - 15%	2.1E-3	2.1E-3	1.2E-3	1.6E-3	1.7E-3
CO_2	±10%	6.3E-3	5.1E-3	3.4E-3	7.1E-3	6.2E-3
C_2H_4	±5 - 10%	3.2E-4	3.1E-4	1.3E-4	2.7E-4	2.2E-05
H_2	±15 - 20%	0	0	0	0	0
H_2S	±10%	0	0	0	0	0
H_2SO_4	±10%	1.3E-06	1.3E-05	3.5E-06	5.6E-06	2.9E-06
HCl	±15%	0	0	0	0	0
HCN	±10 - 15%	0	5.2E-06	0	0	6.7E-06
HF	±10%	0	0	0	0	0
HNO_3	±15%	0	0	0	0	0
NO	±10%	0	0	5.6E-06	0	0
NO_2	±10%	0	0	0	0	0
SO_2	±10%	0	0	0	0	0

Table 9: N1-X Failure Modes

Cell	Leak	Vent	Fire	Rupture
N1-1		Y		Y
N1-2		Y		
N1-3		Y		Y
N1-4		Y		Y
N1-6		Y		

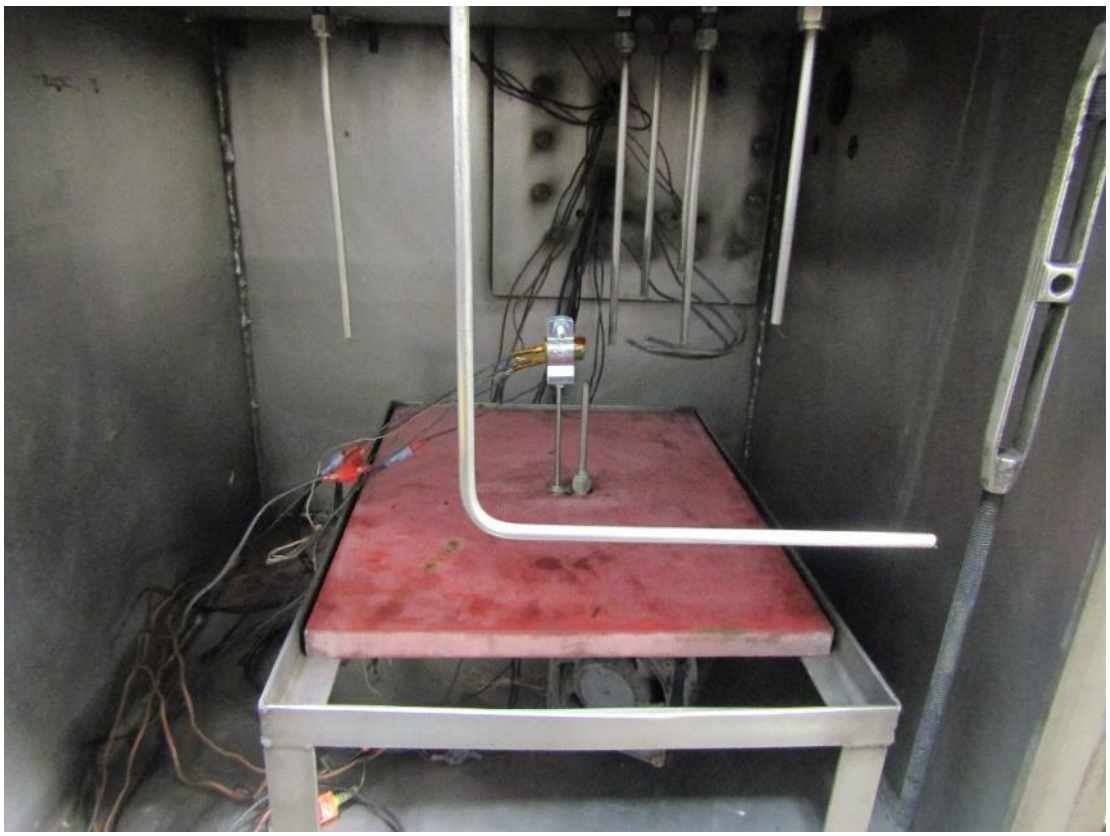

Figure 5: N1-1 Pre-Test

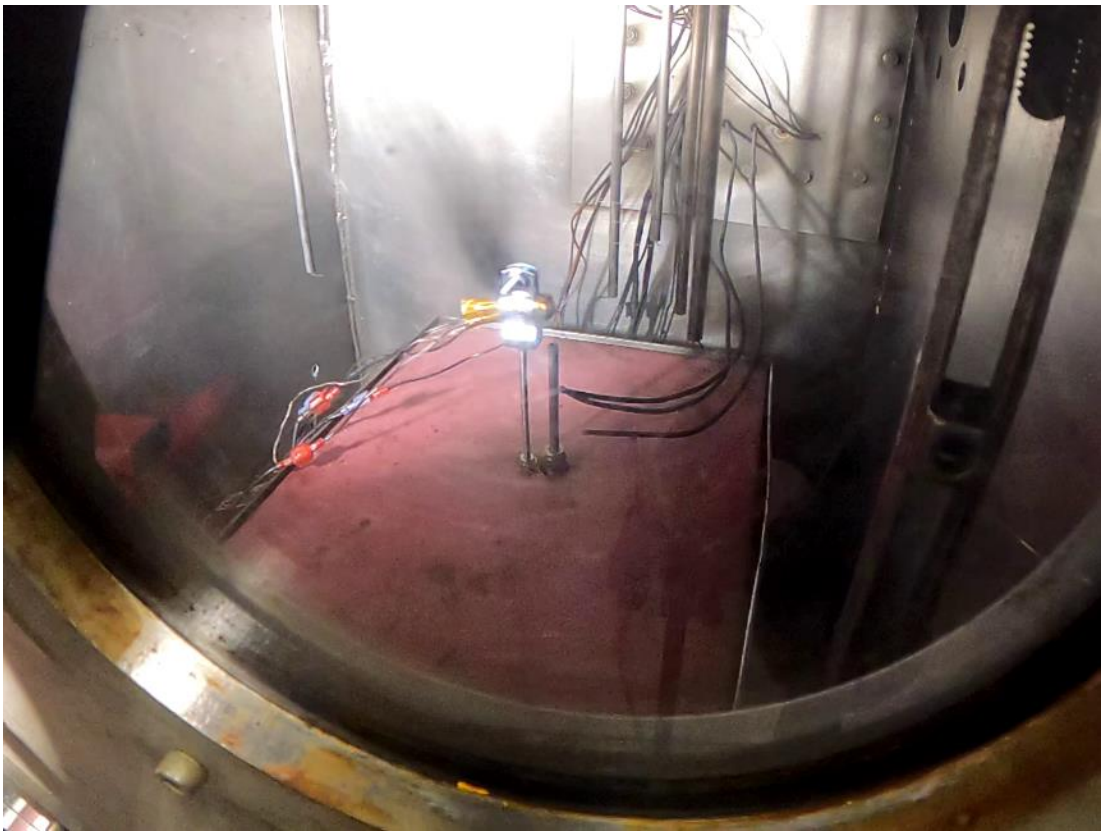

Figure 6: N1-1 Venting

Figure 7: N1-1 Post-Test 1

Figure 8: N1-1 Post-Test 2

Figure 9: N1-3 Pre-Test

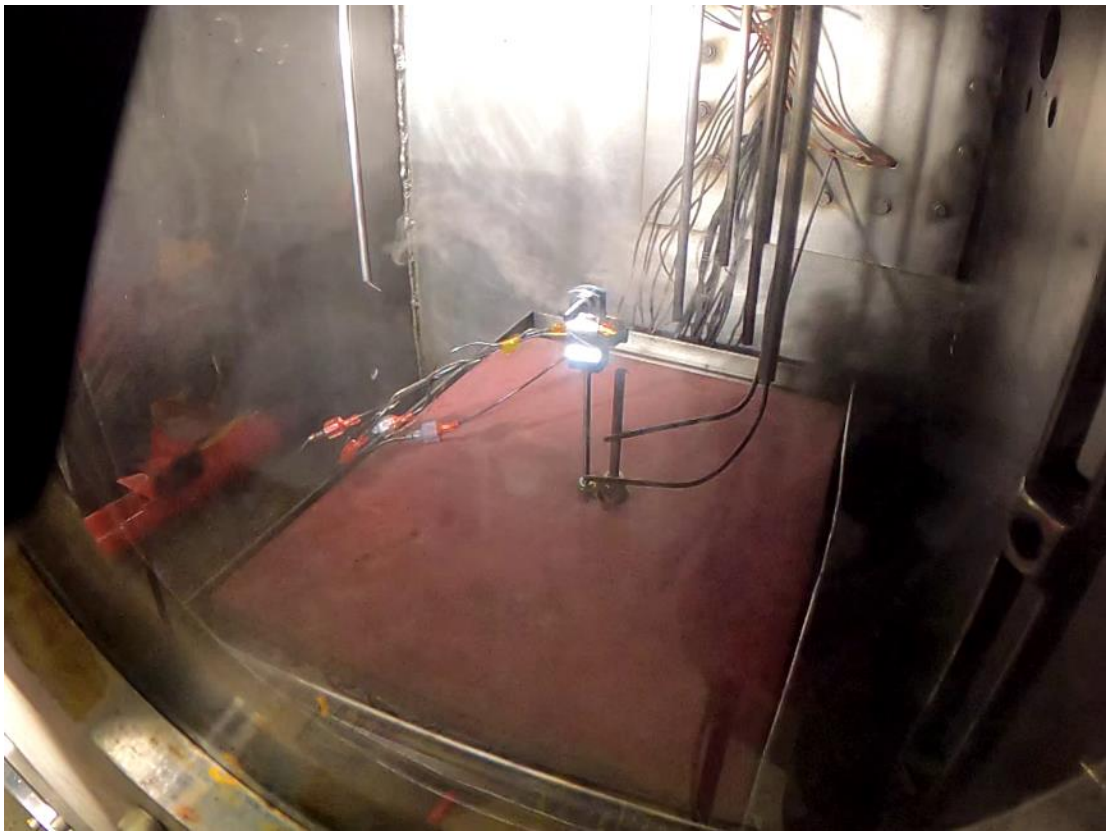

Figure 10: N1-3 Venting

Figure 11: N1-3 Post-Test 1

Figure 12: N1-4 Pre-Test

Figure 13: N1-4 Post-Test 1

Figure 14: N1-4 Post-Test 2

Figure 15: N1-5 Pre-Test

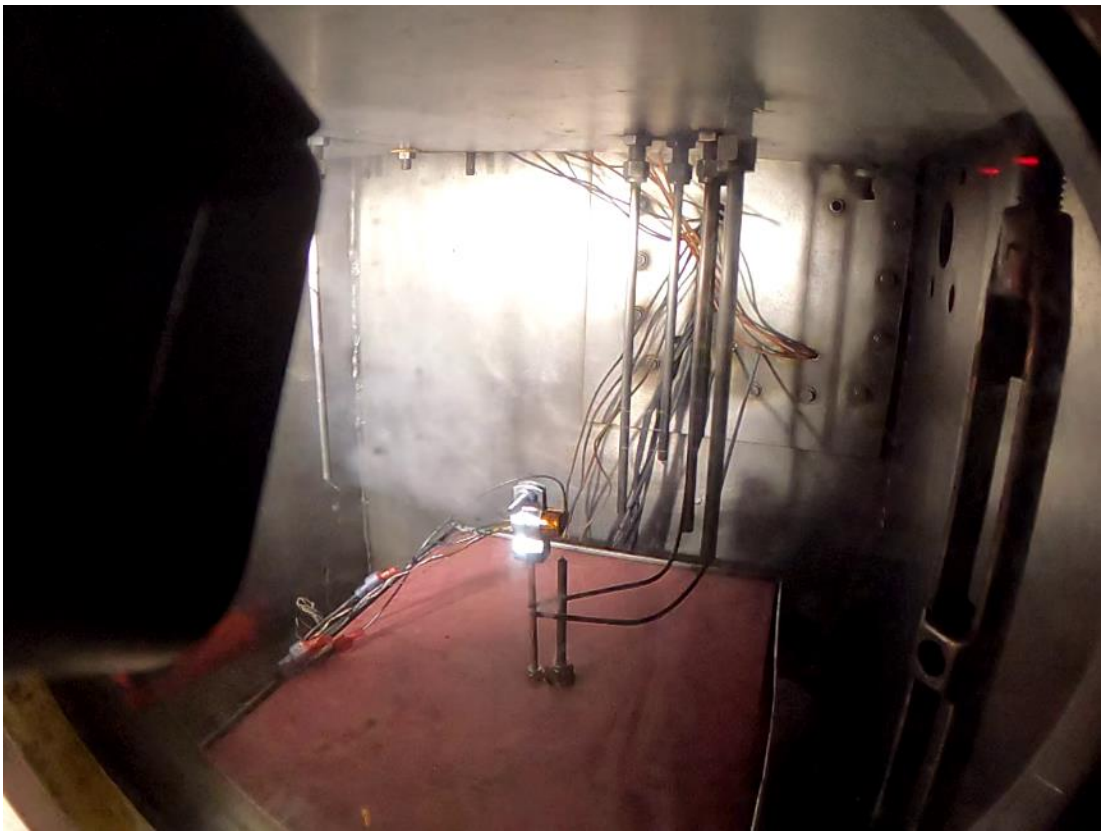

Figure 16: N1-5 Venting

Figure 17: N1-5 Post-Test 1

Figure 18: N1-5 Post Test 2

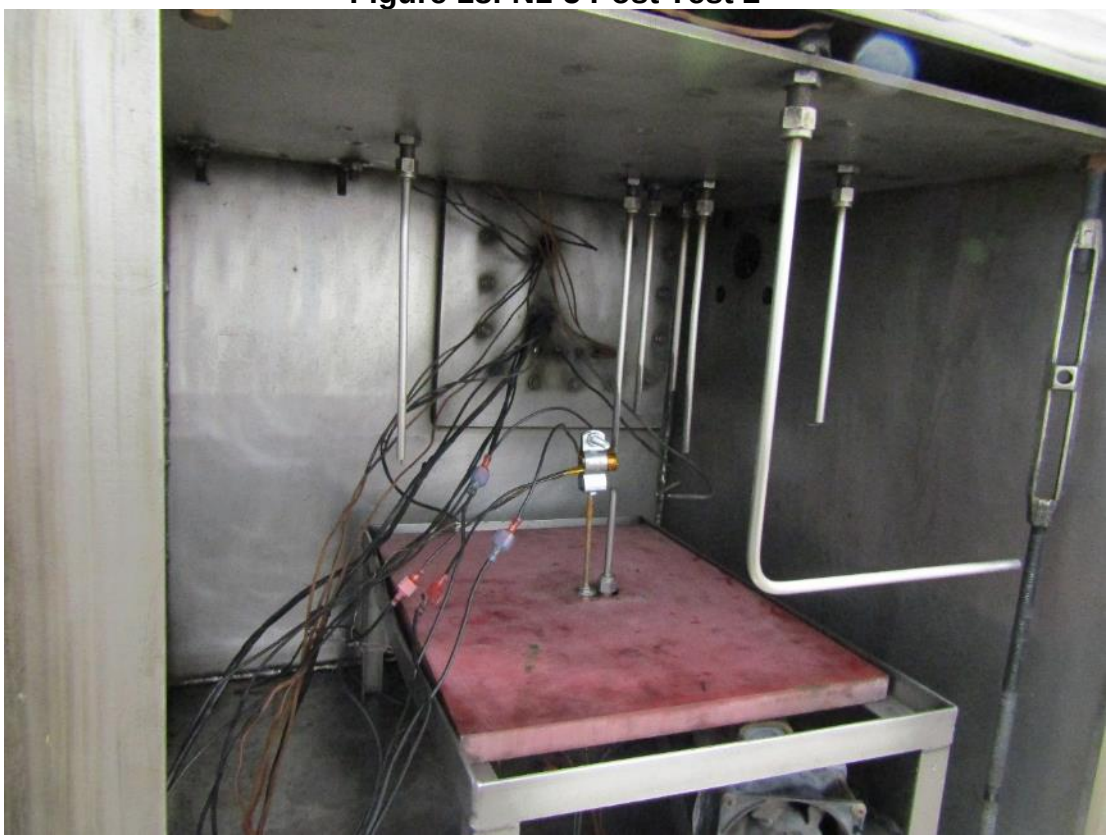

Figure 19: N1-6 Pre-Test

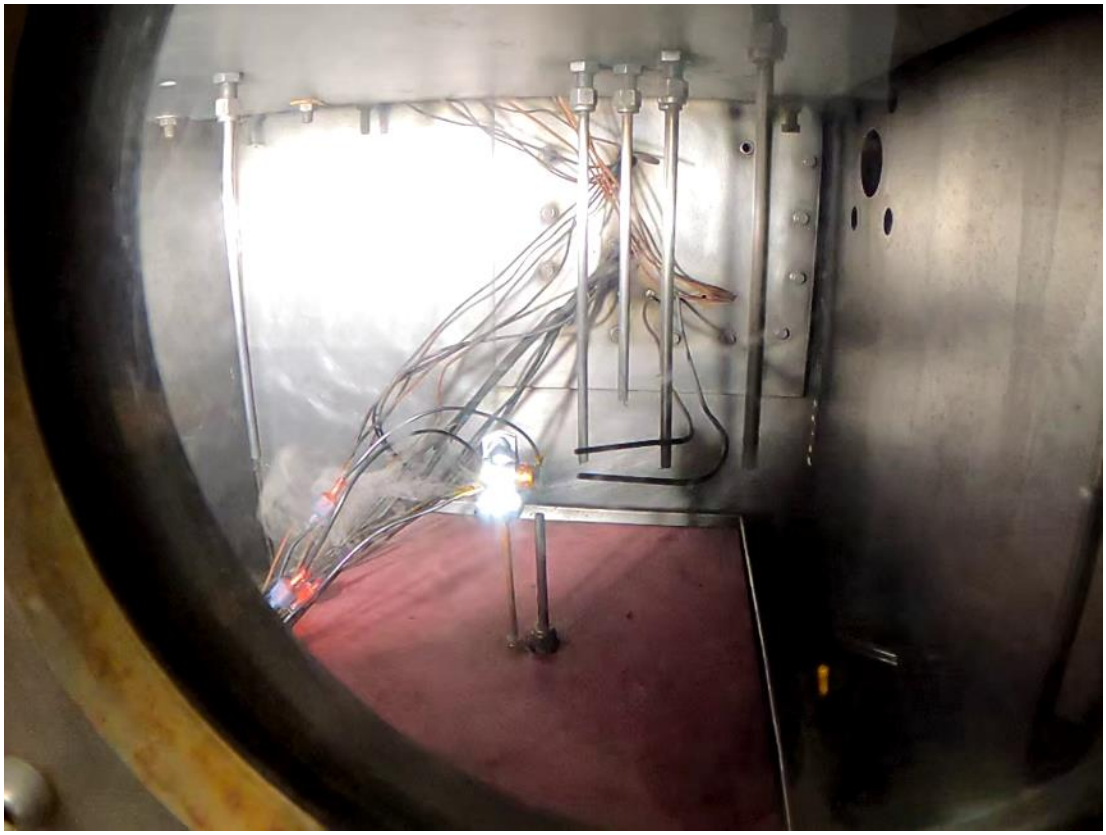

Figure 20: N1-6 Venting

Figure 21: N1-6 Post-Test 1

Figure 22: N1-6 Post-Test 2

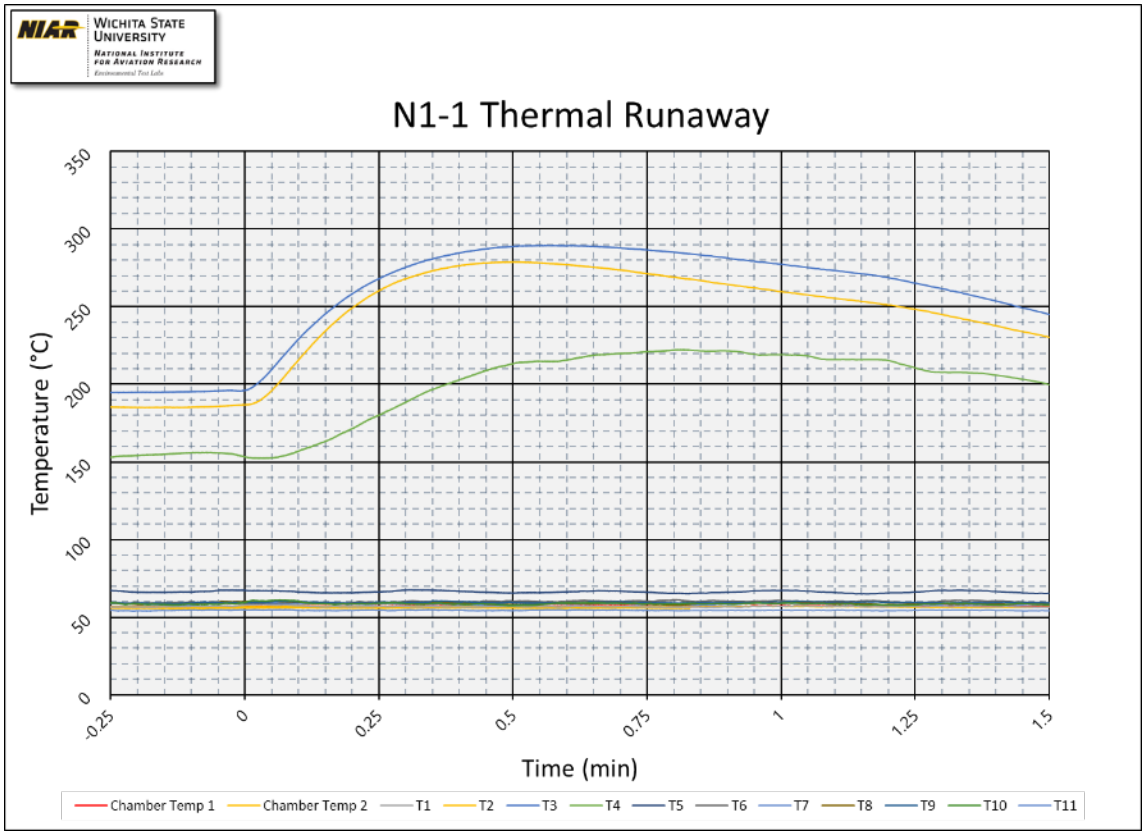

Figure 23: N1-1 Temperature Graph

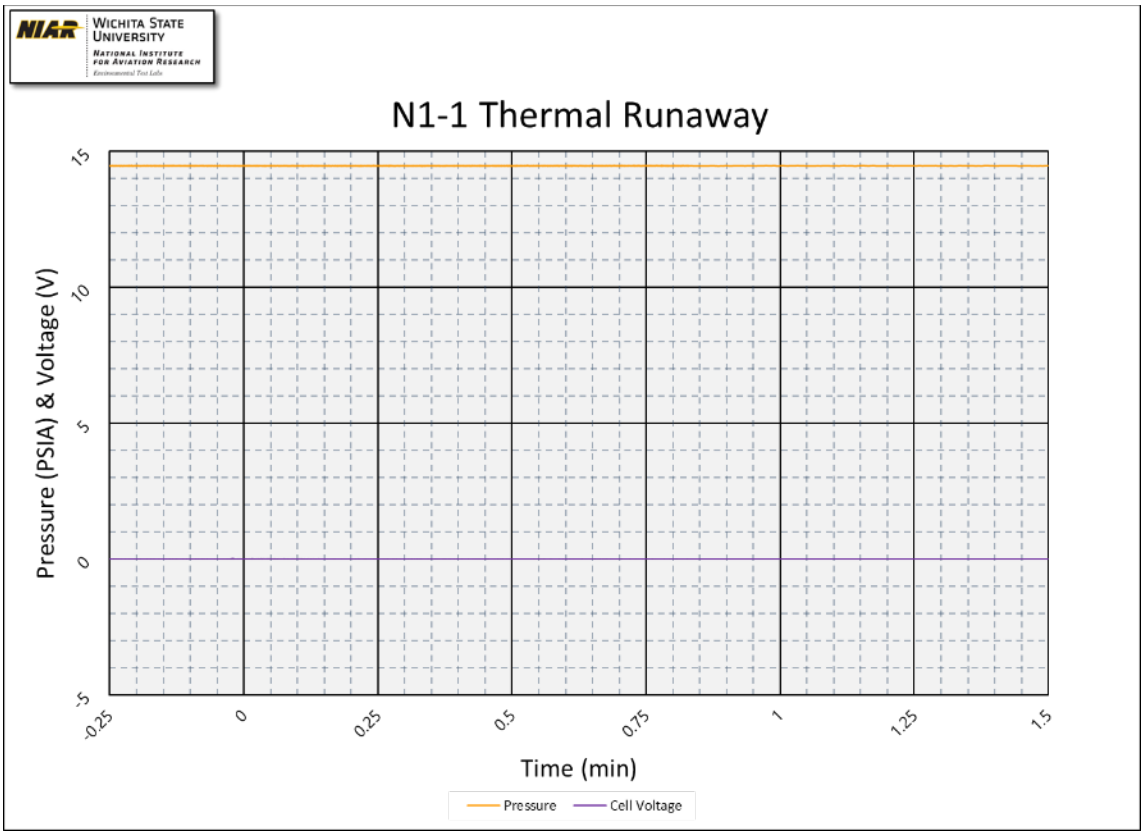

Figure 24: N1-1 Pressure and Voltage Graph

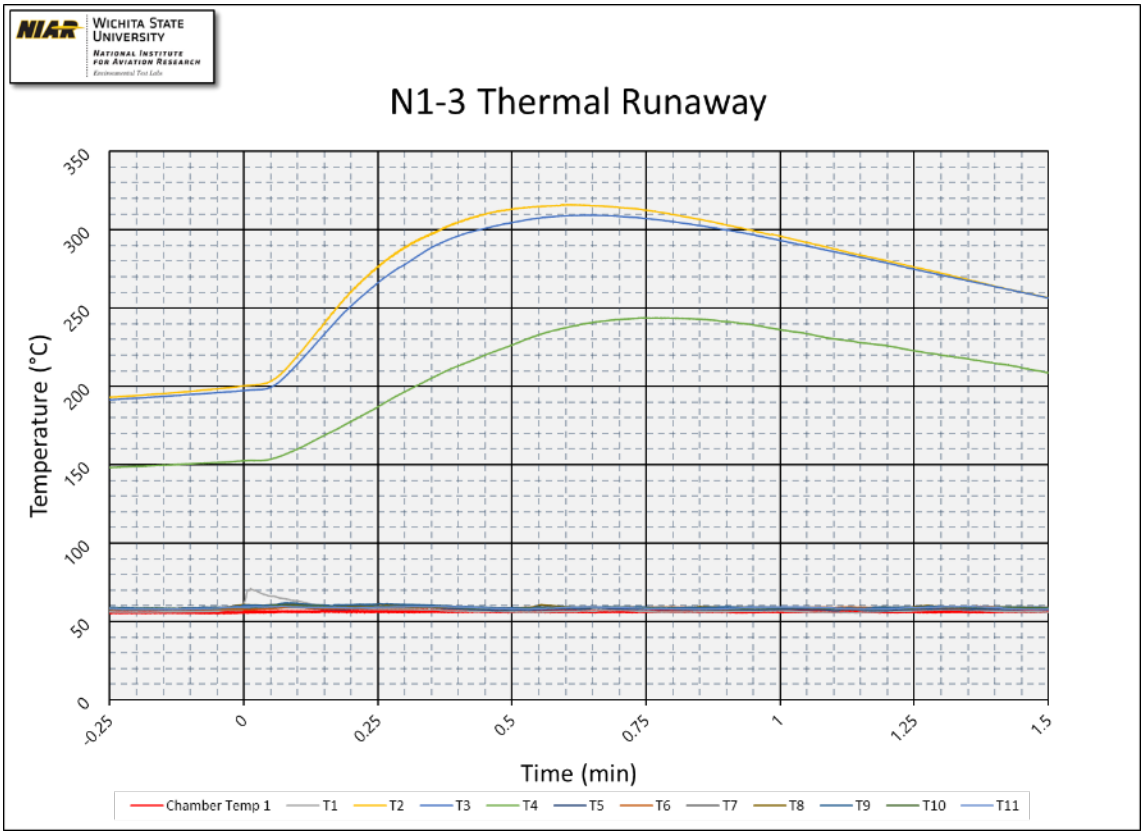

Figure 25: N1-3 Temperature Graph

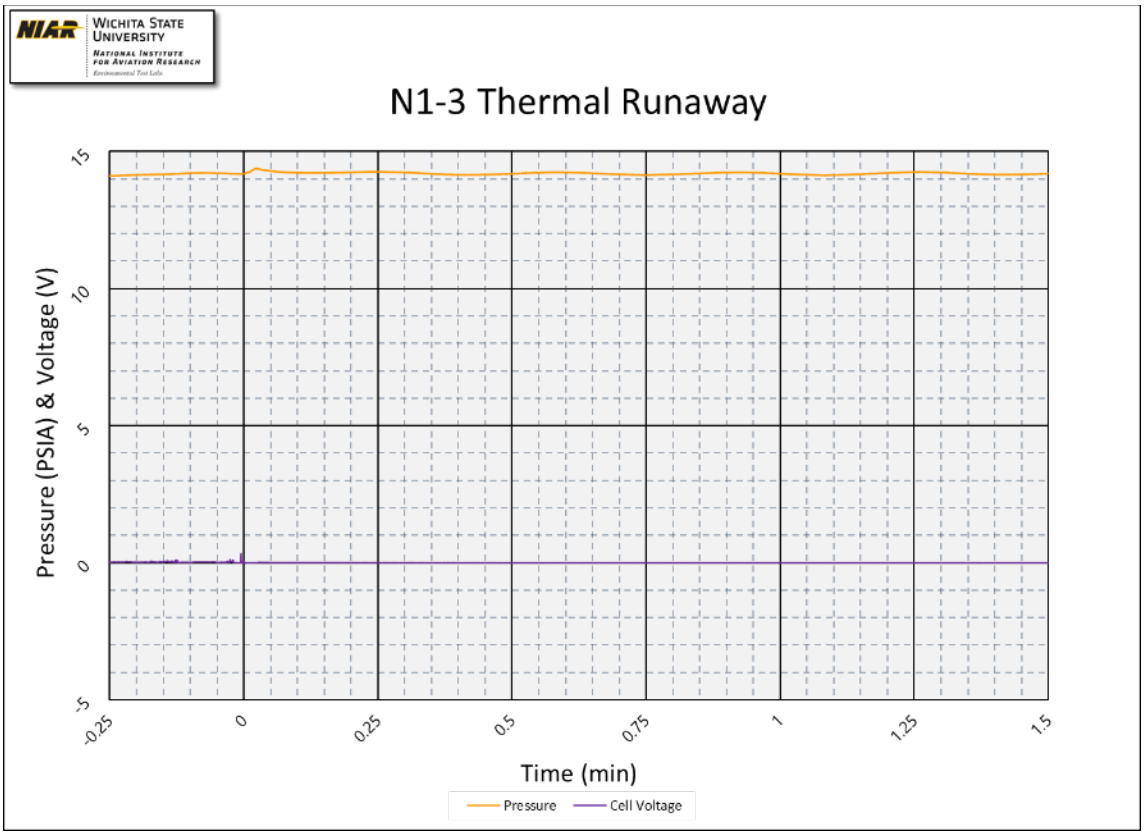

Figure 26: N1-3 Pressure and Voltage Graph

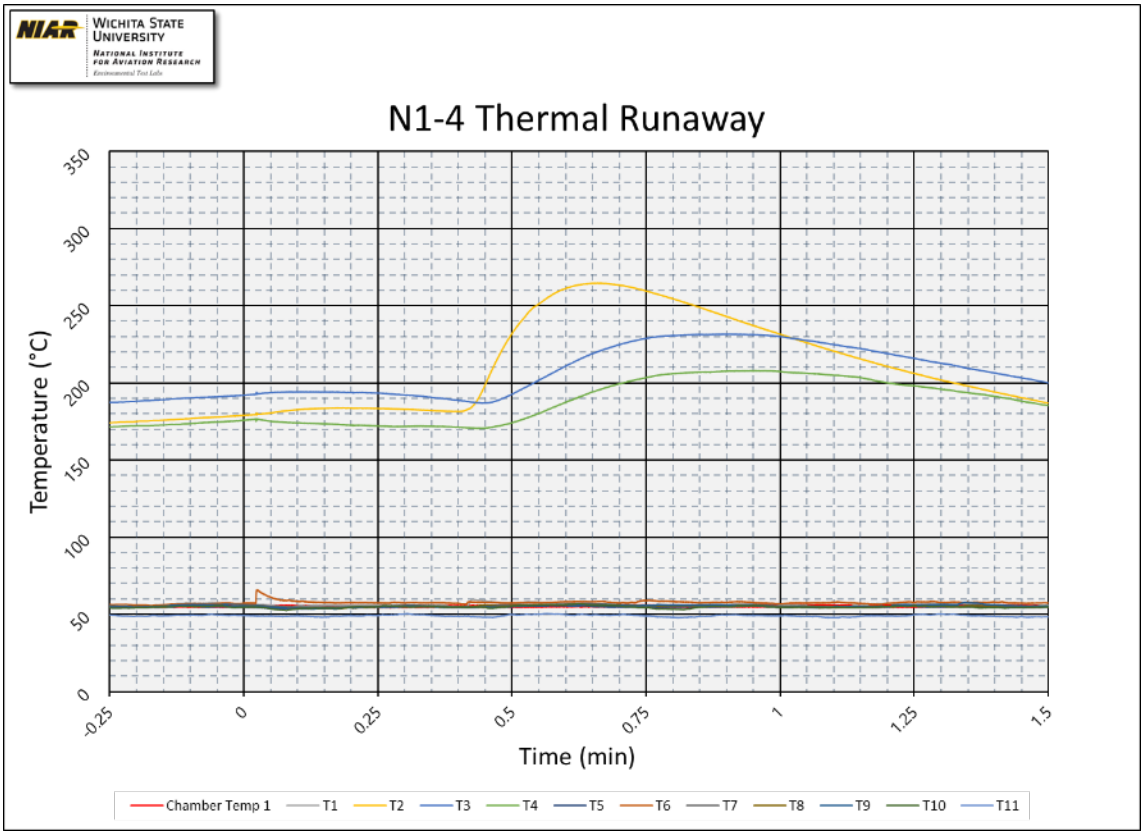

Figure 27: N1-4 Temperature Graph

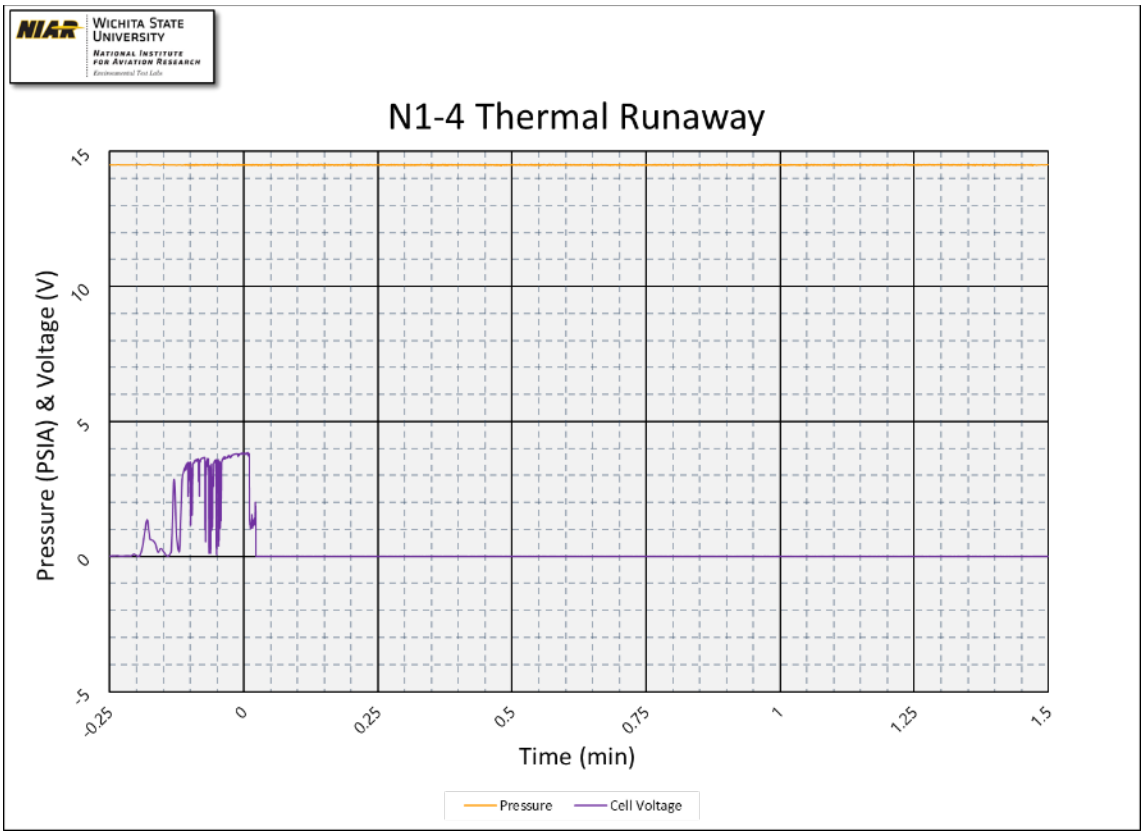

Figure 28: N1-4 Pressure and Voltage Graph

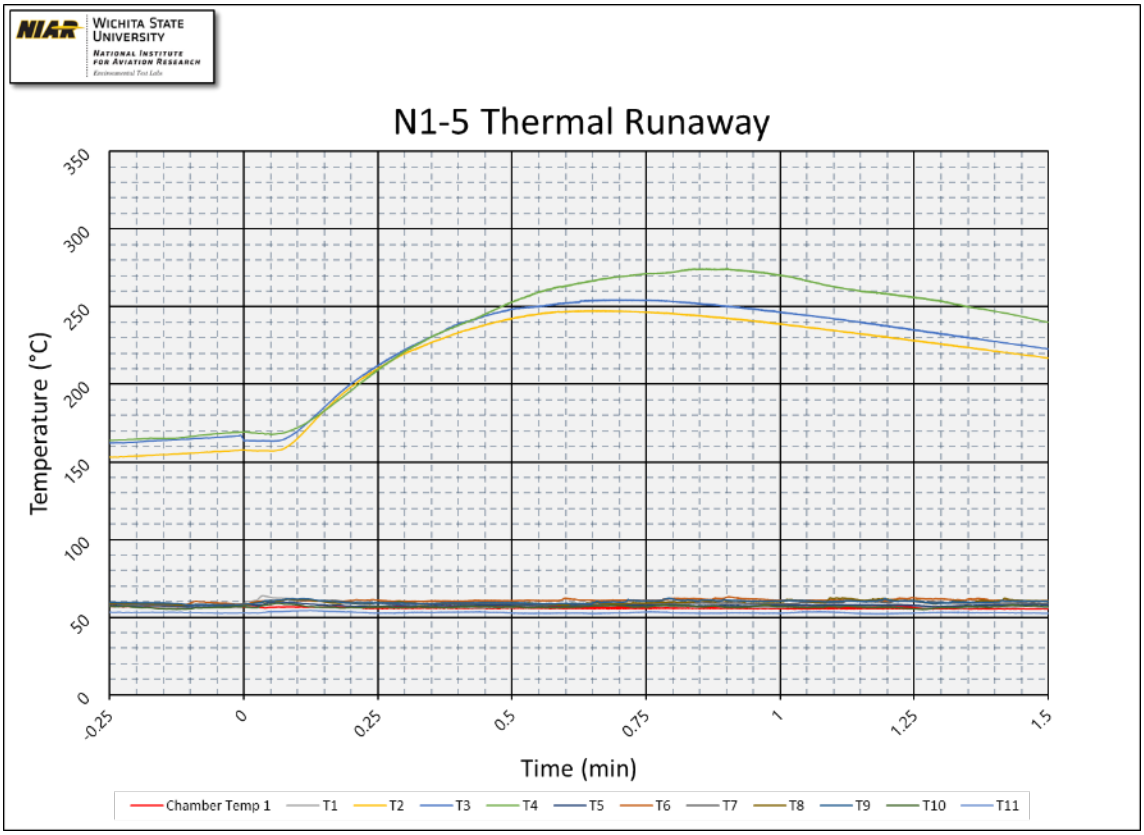

Figure 29: N1-5 Temperature Graph

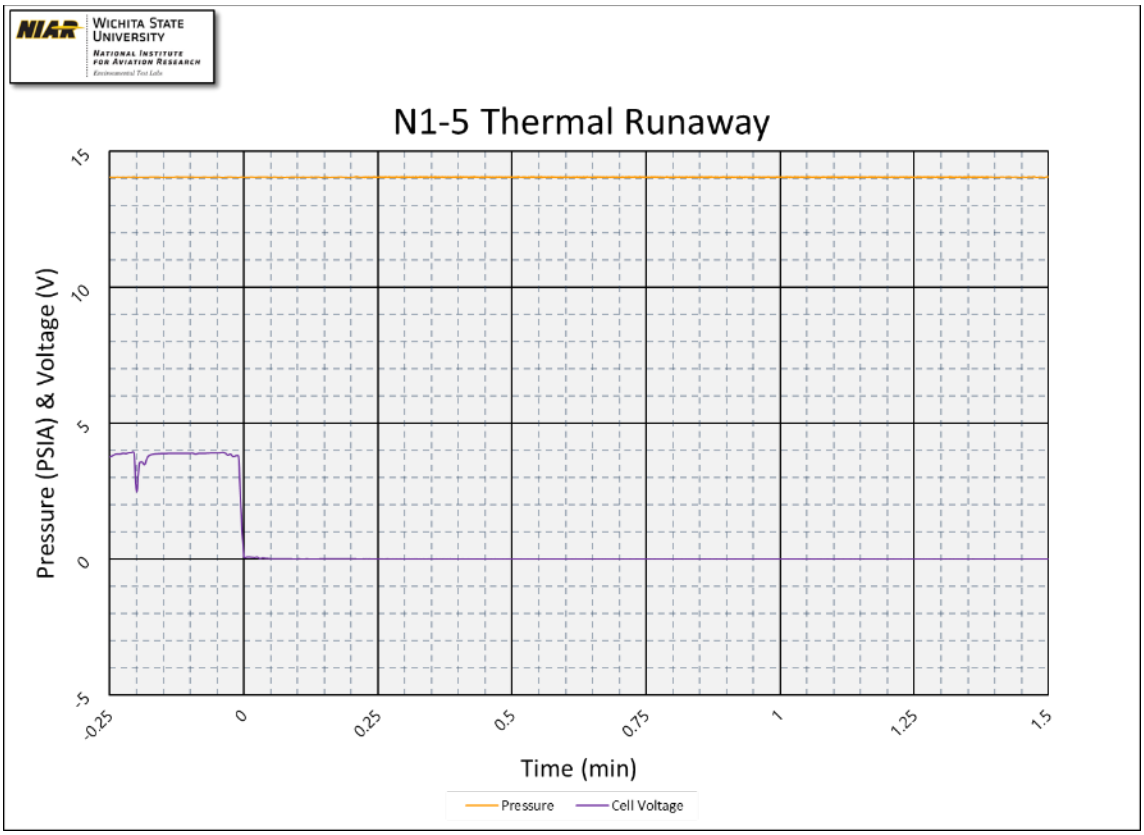

Figure 30: N1-5 Pressure and Voltage Graph

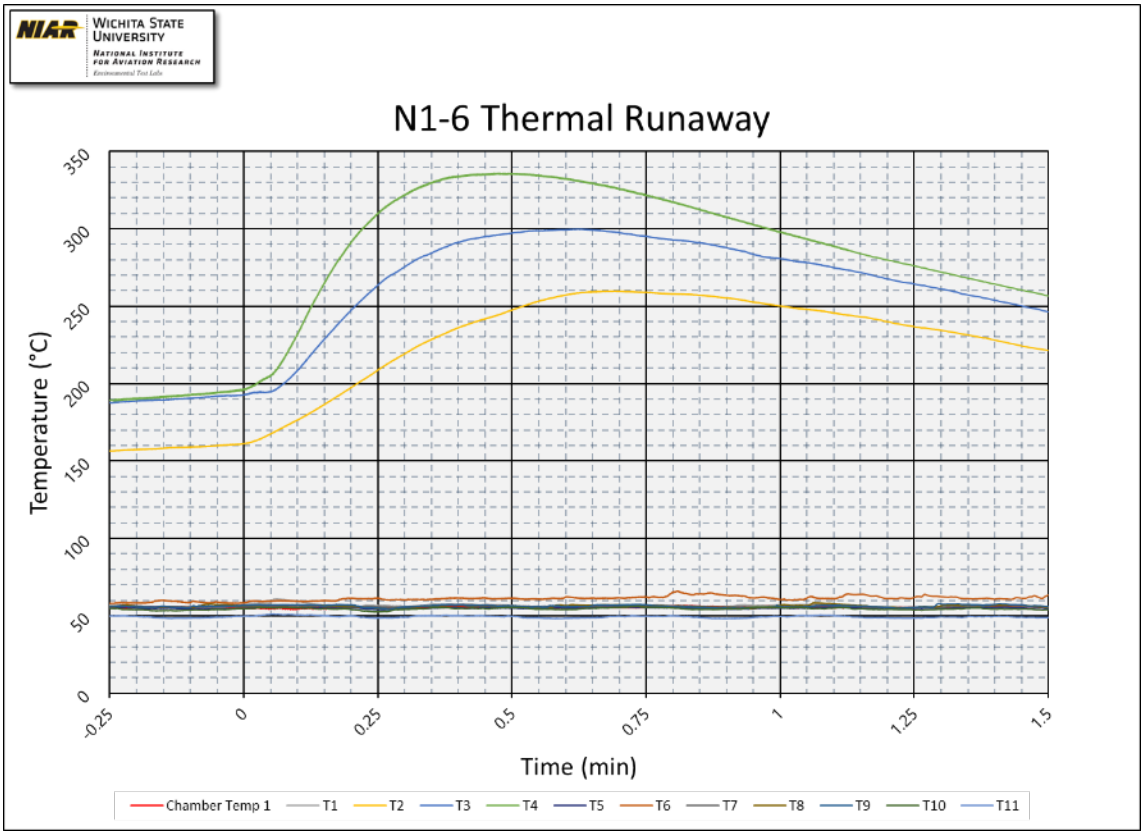

Figure 31: N1-6 Temperature Graph

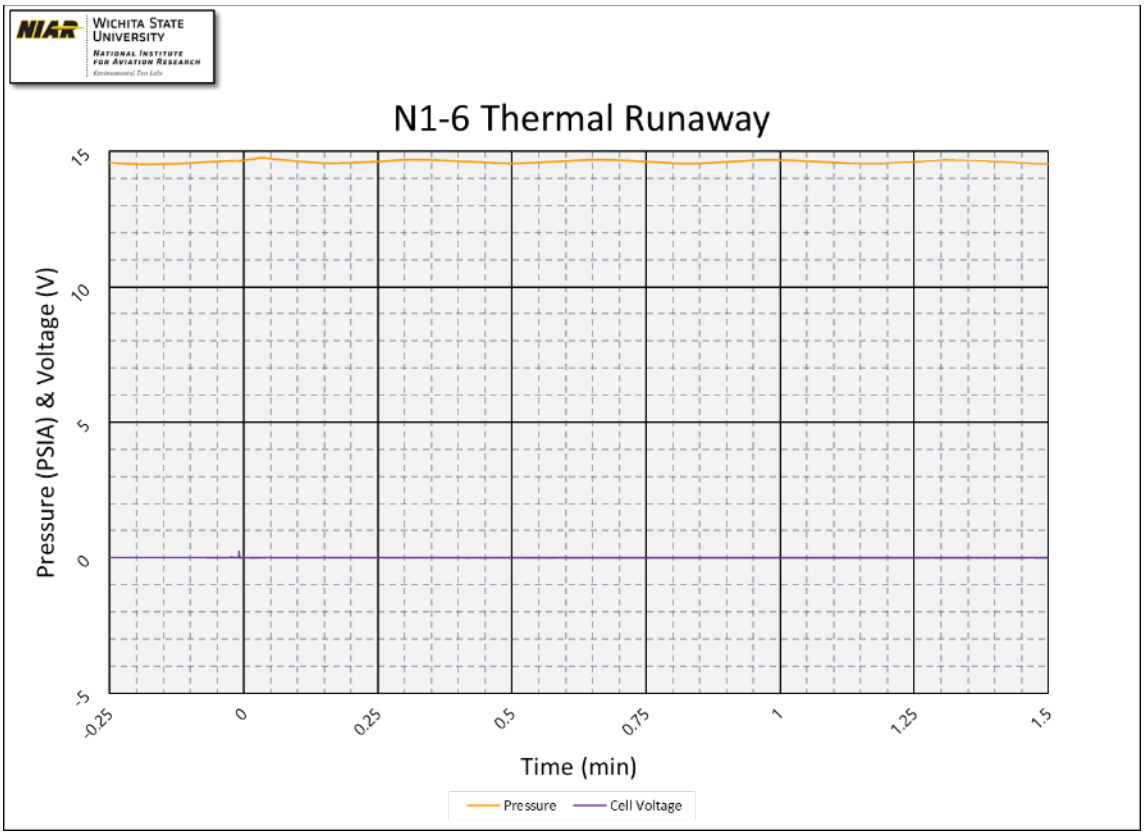

Figure 32: N1-6 Pressure and Voltage Graph

2.2.2 N2-X (UltraLife® UHR-CR34610)

The N2-X cells resulted in the most violent reactions of all the cell types tested, which was expected as they were the largest in terms of size and watt hours. The reaction resulted in an average cell peak temperature of 994.9°C and an average chamber peak temperature of 894.3°C, the highest of all the cell types tested. All five valid trials released carbon monoxide, carbon dioxide, ethylene, and sulfuric acid, although the amounts of carbon dioxide and ethylene released varied greatly between trials. Hydrogen cyanide, nitric oxide, and nitrogen dioxide were detected in 4 of the 5 trials, while hydrogen chloride was only detected in 1 of the 5. The cells on average lost 64.159 g of mass, which translates to a 52% loss in mass.

Table 10: N2-X Mass Change Summary

Cell	Pre-Test Mass (g)	Post-Test Mass (g)
N2-1	124.362	41.764
N2-2	121.265	64.483
N2-5	122.247	61.062
N2-7	121.006	55.809
N2-8	122.280	67.246

Table 11: N2-X Detected Gases

Gas Species	Detector Tube Error Range	Moles of Gas Detected N2-1	Moles of Gas Detected N2-2	Moles of Gas Detected N2-5	Moles of gas Detected N2-7	Moles of gas Detected N2-8
CO	±10%	0.055	0.045	0.065	0.044	0.11
CO_2	±10%	0.77	0.45	0.14	5.4E-3	0.11
C_2H_4	±20 - 30%	5.5E-3	2.1E-3	0.018	0.090	0.036
H_2	±15 - 20%	0	0	0	0	0
H_2S	±25%	0	0	0	0	0
H_2SO_4	±10%	8.5E-06	1.08E-05	1.25E-05	1.14E-05	5.01E-06
HCl	±15%	0	0	0	0	1.09E-05
HCN	±10 - 15%	5.49E-06	1.1E-4	5.4E-06	1.1E-05	0
HF	±10%	0	0	0	0	0
HNO_3	±15%	0	0	0	0	0
NO	±5%	7.5E-4	3.2E-05	5.4E-06	0	1.5E-4
NO_2	±10%	7.7E-05	2.1E-05	3.8E-05	0	1.6E-05
SO_2	±10%	0	0	0	0	0

Table 12: N2-X Failure Modes

Cell	Leak	Vent	Fire	Rupture
N2-1	Y	Y	Y	Y
N2-2	Y	Y	Y	Y
N2-5	Y	Y	Y	Y
N2-7	Y	Y	Y	Y
N2-8	Y	Y	Y	Y

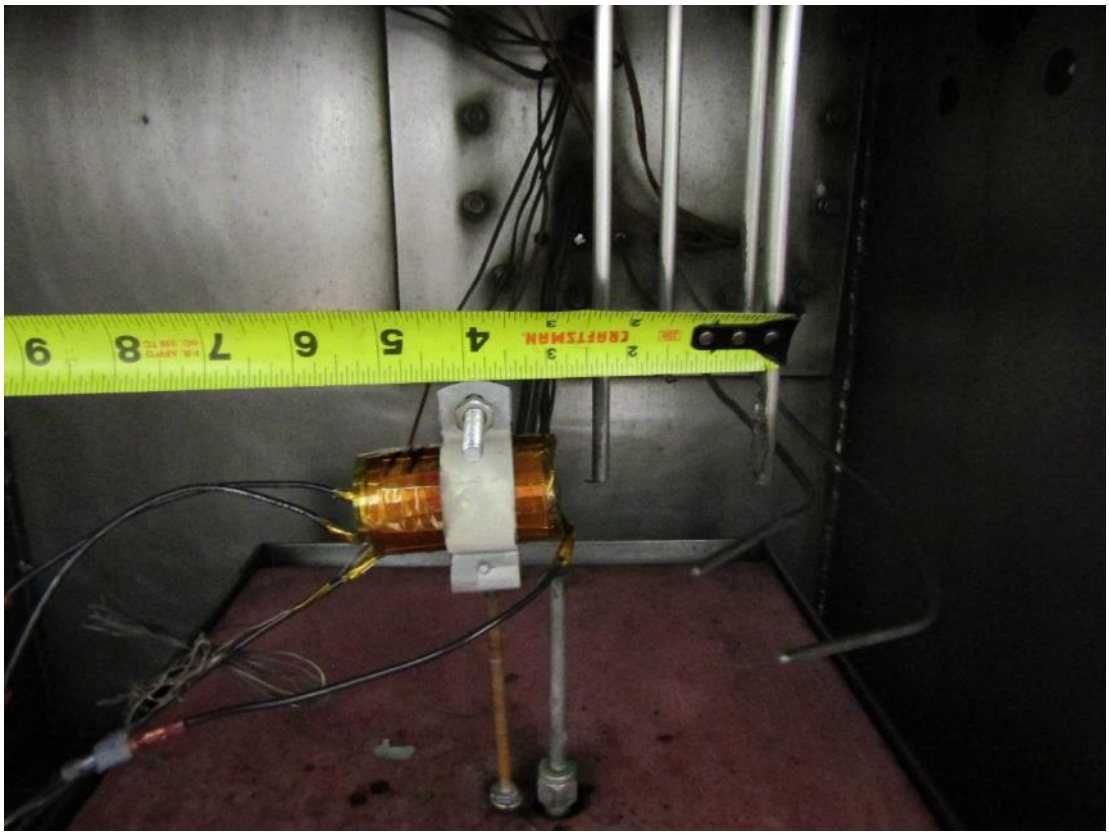

Figure 33: N2-1 Pre-Test

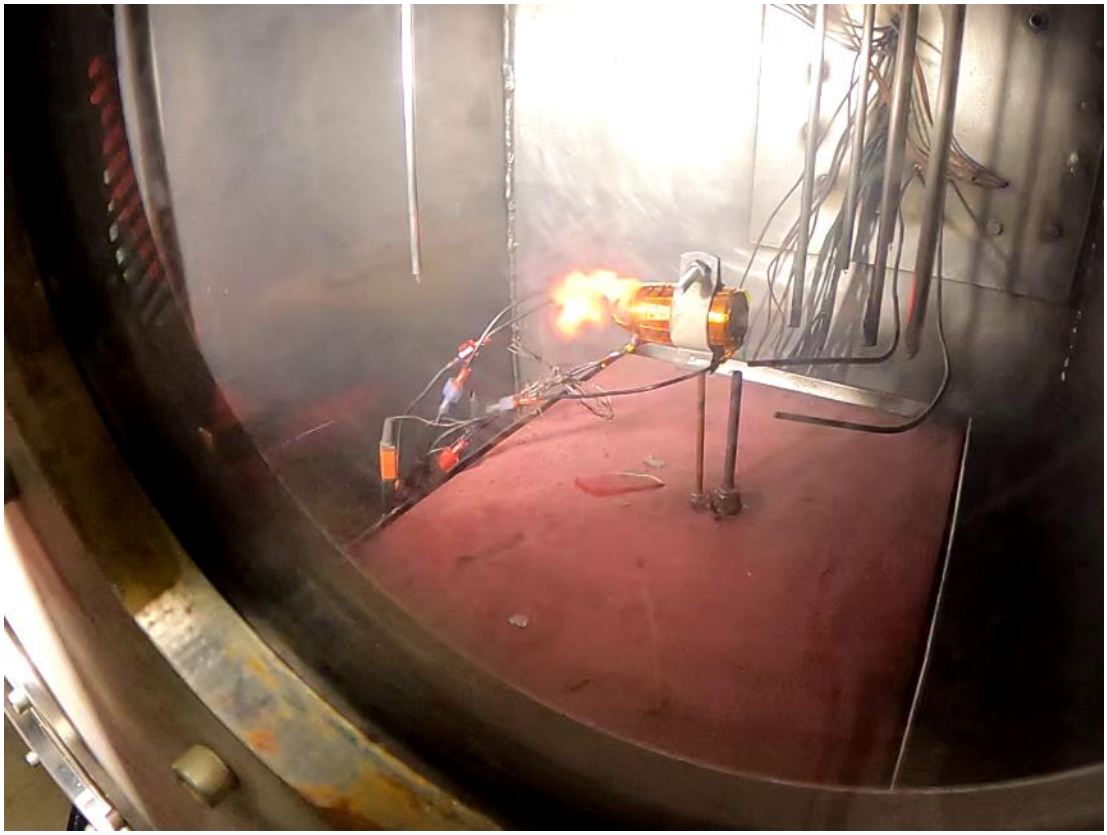

Figure 34: N2-1 Leaking and Fire

Figure 35: N2-1 Post-Test 1

Figure 36: N2-1 Post-Test 2

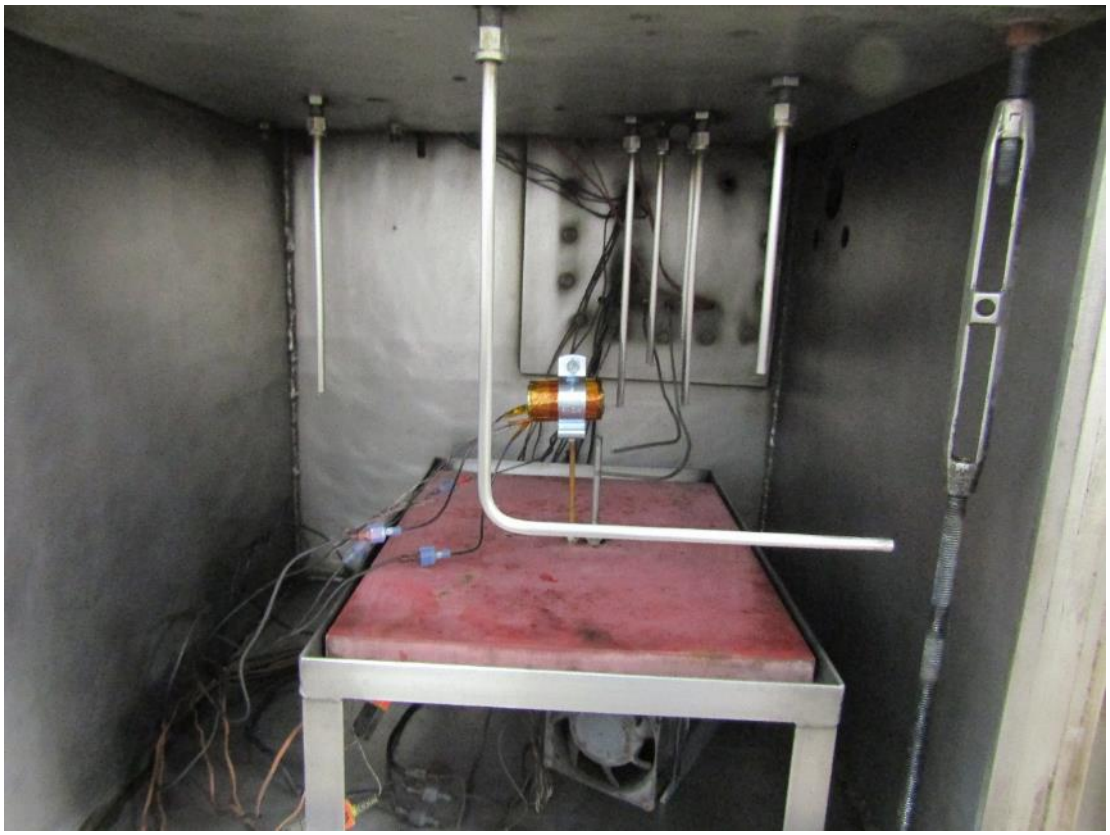

Figure 37: N2-2 Pre-Test

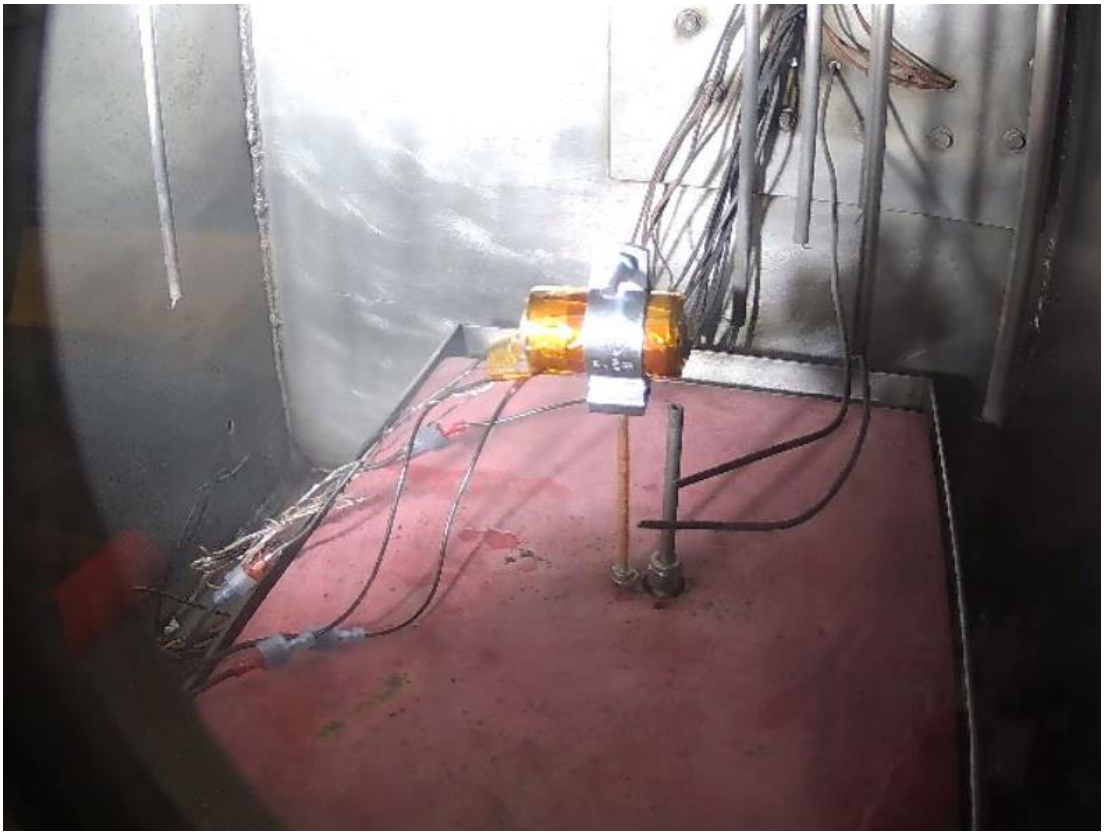

Figure 38: N2-2 Leaking & Venting

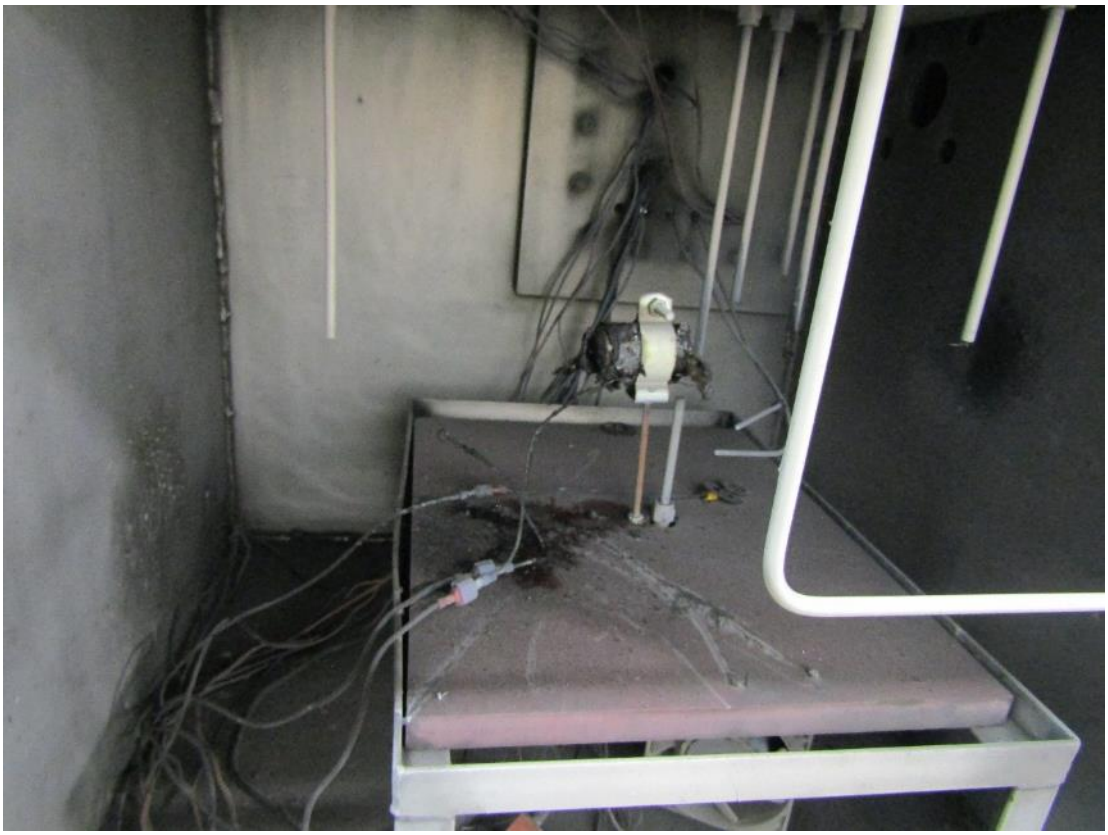

Figure 39: N2-2 Post Test 1

Figure 40: N2-2 Post Test 2

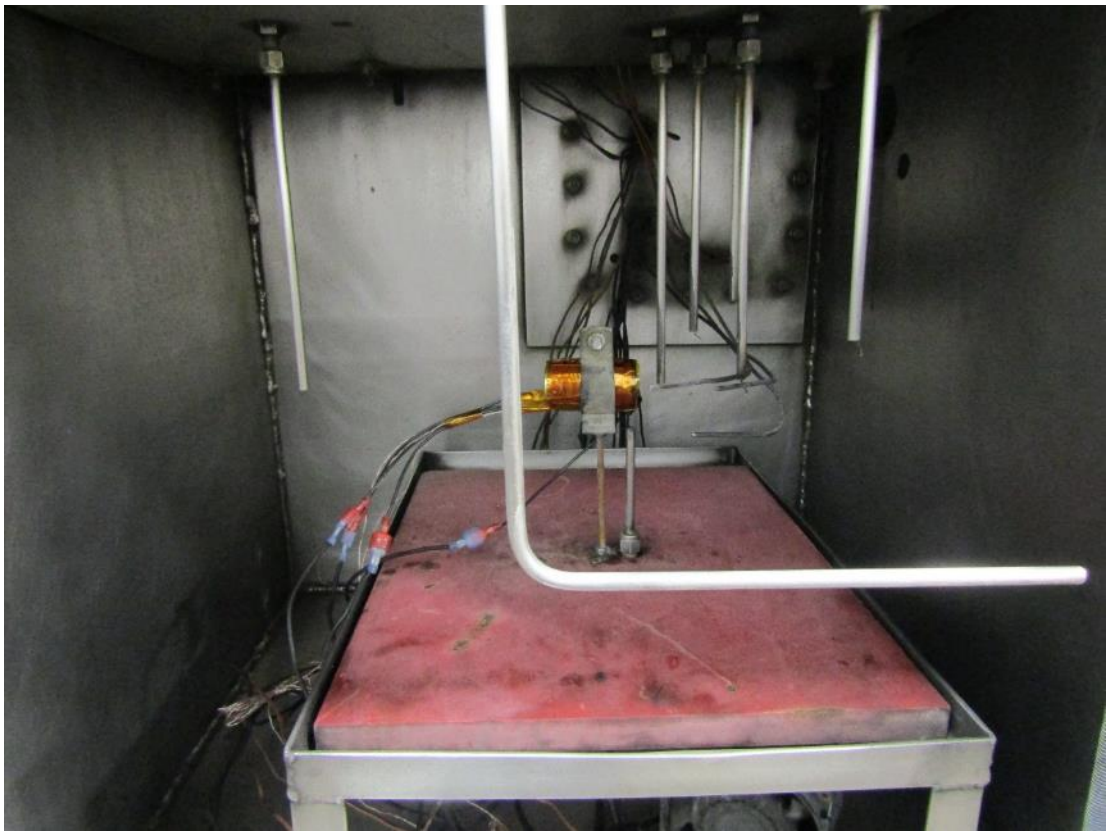

Figure 41: N2-5 Pre-Test

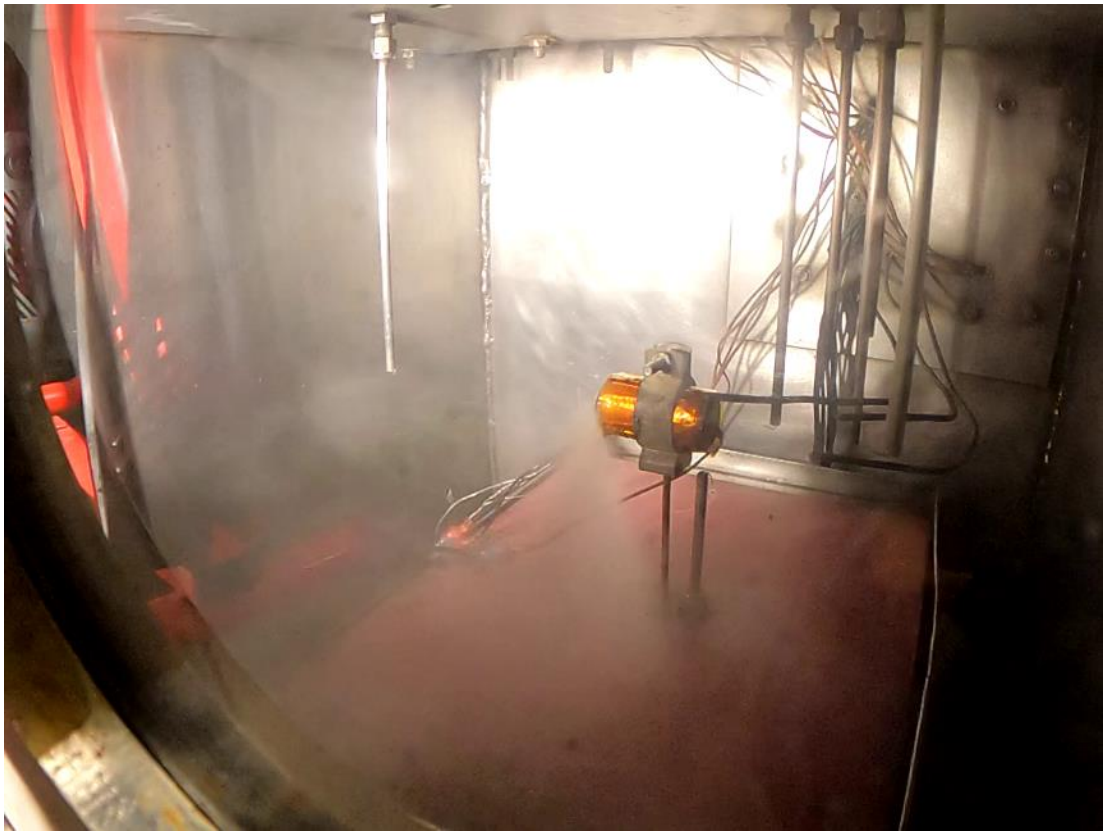

Figure 42: N2-5 Venting

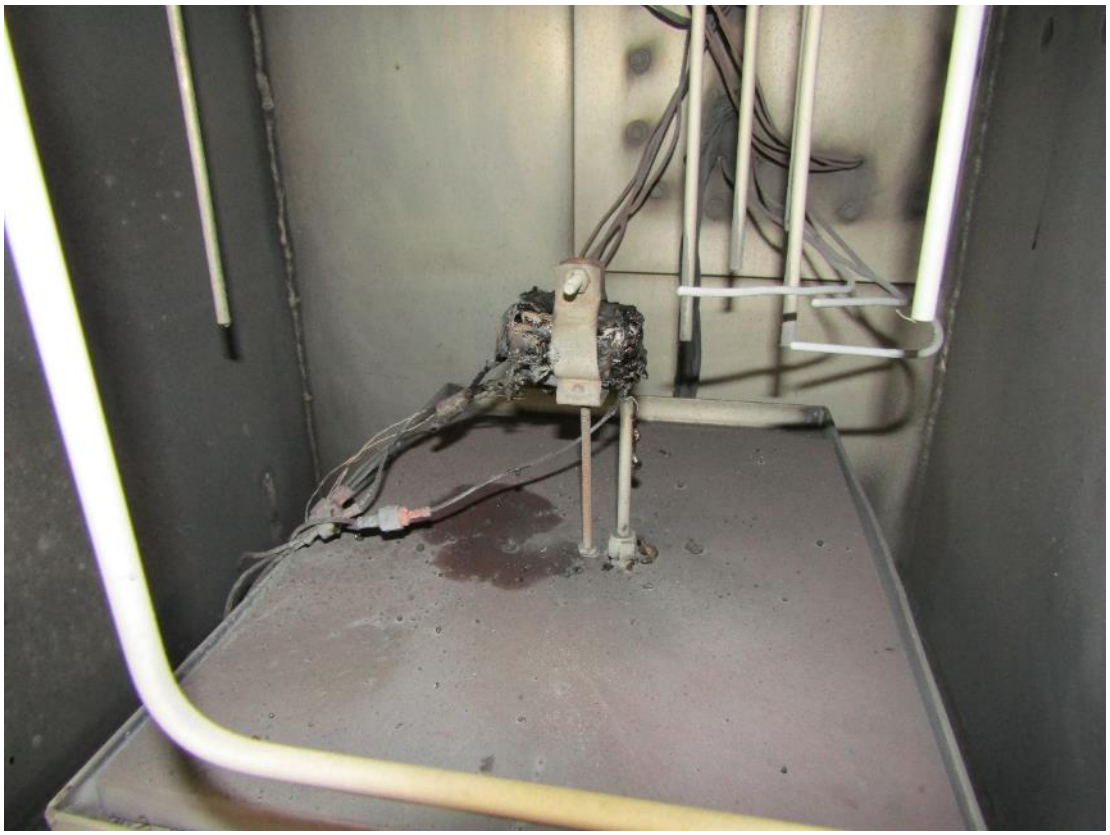

Figure 43: N2-5 Post-Test 1

Figure 44: N2-5 Post-Test 2

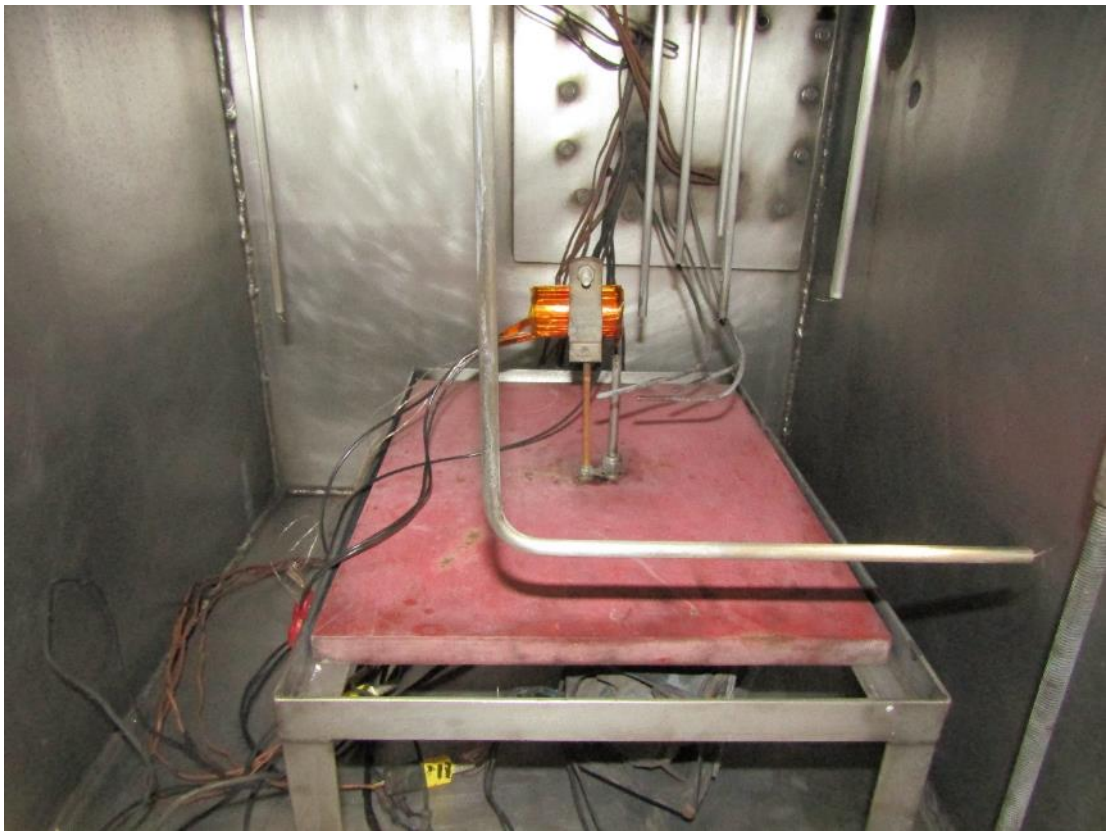

Figure 45: N2-7 Pre-Test

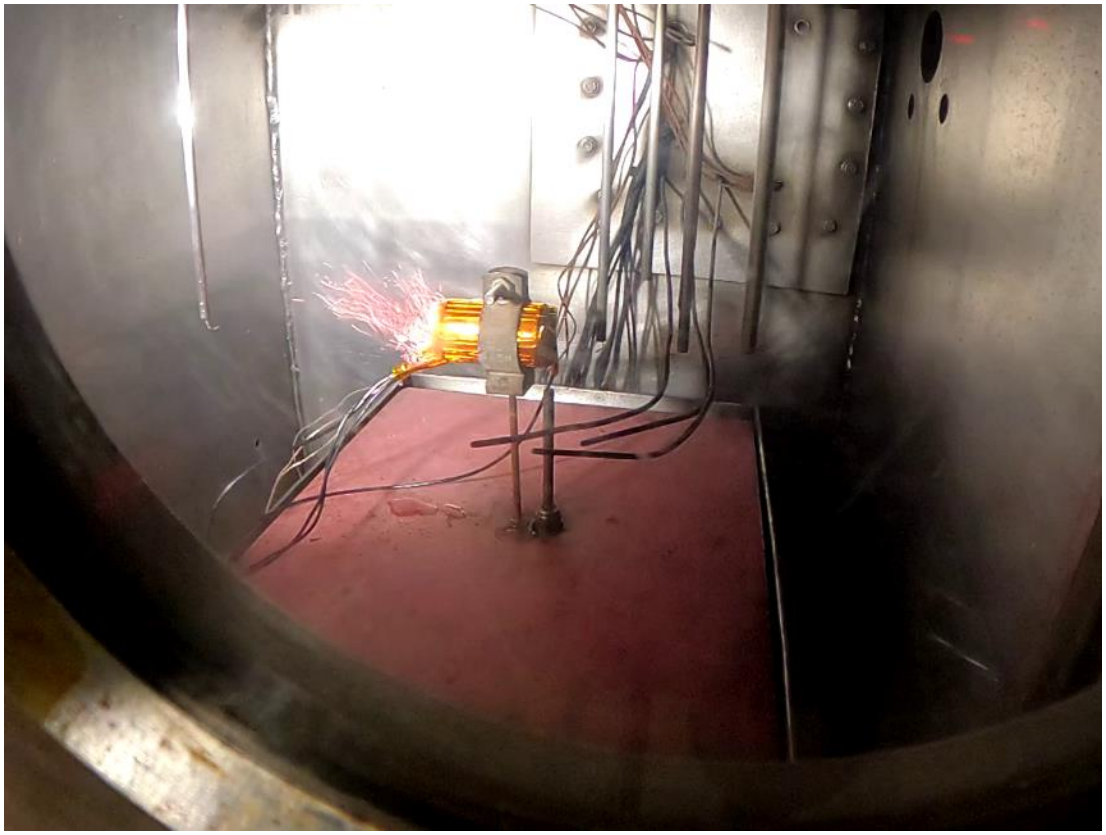

Figure 46: N2-7 Venting, Leaking, and Fire

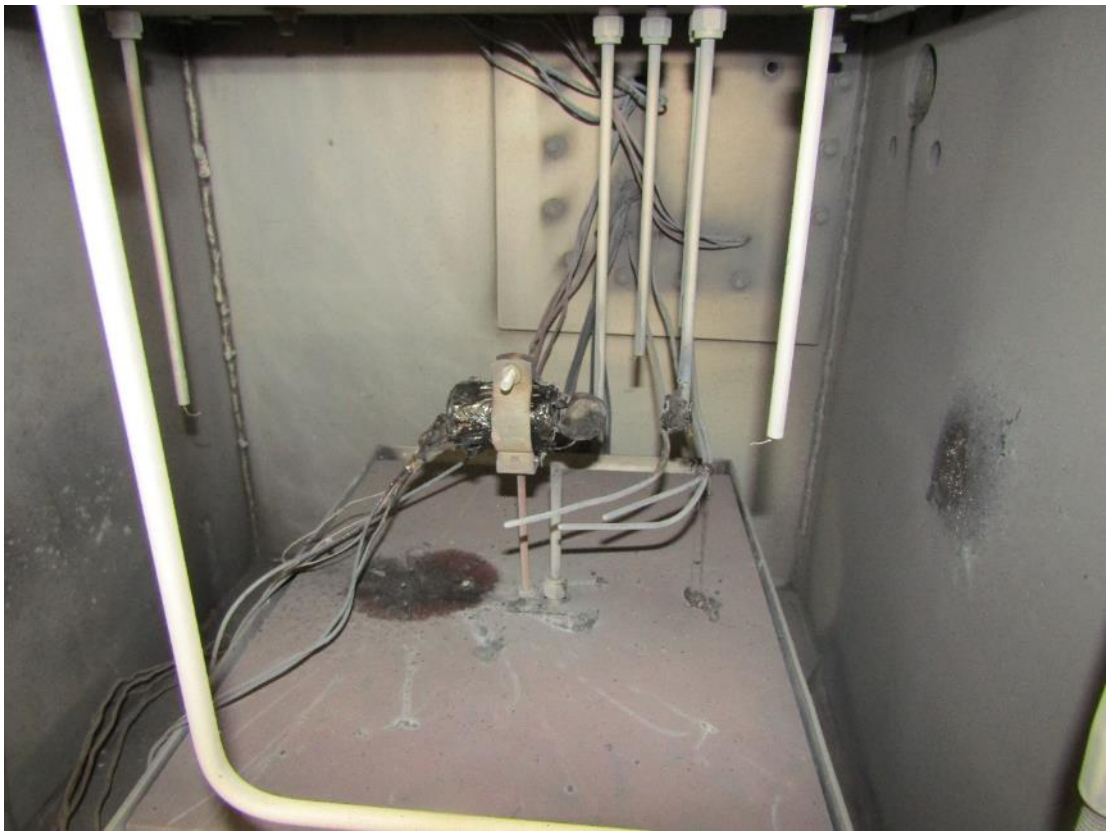

Figure 47: N2-7 Post-Test 1

Figure 48: N2-7 Post-Test 2

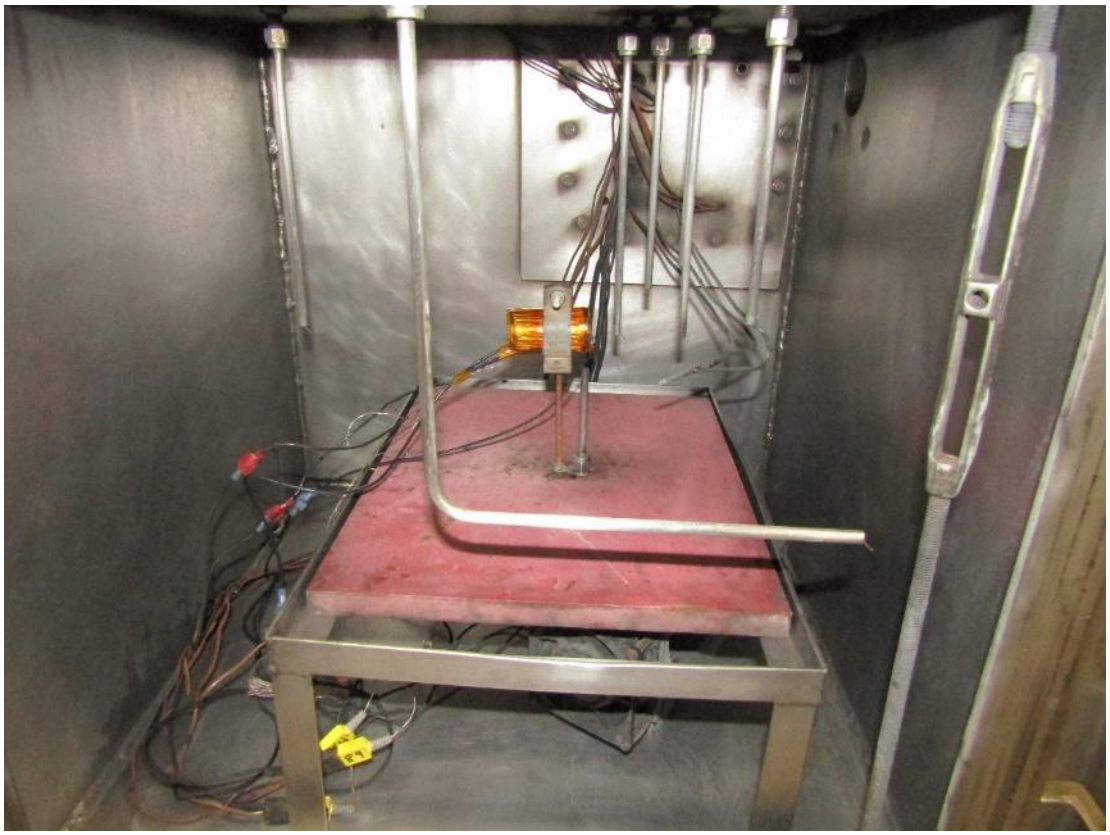

Figure 49: N2-8 Pre-Test

Figure 50: N2-8 Venting, Leaking, and Fire

Figure 51: N2-8 Post-Test 1

Figure 52: N2-8 Post-Test 2

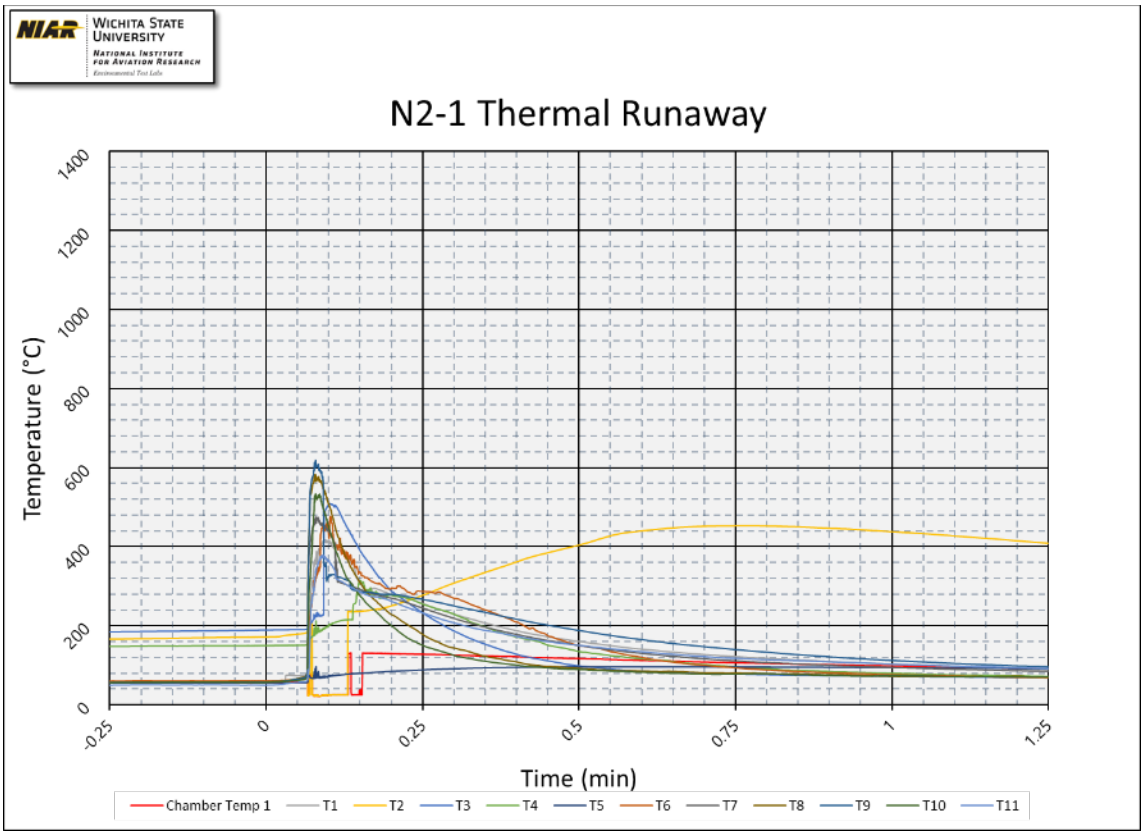

Figure 53: N2-1 Temperature Graph 1

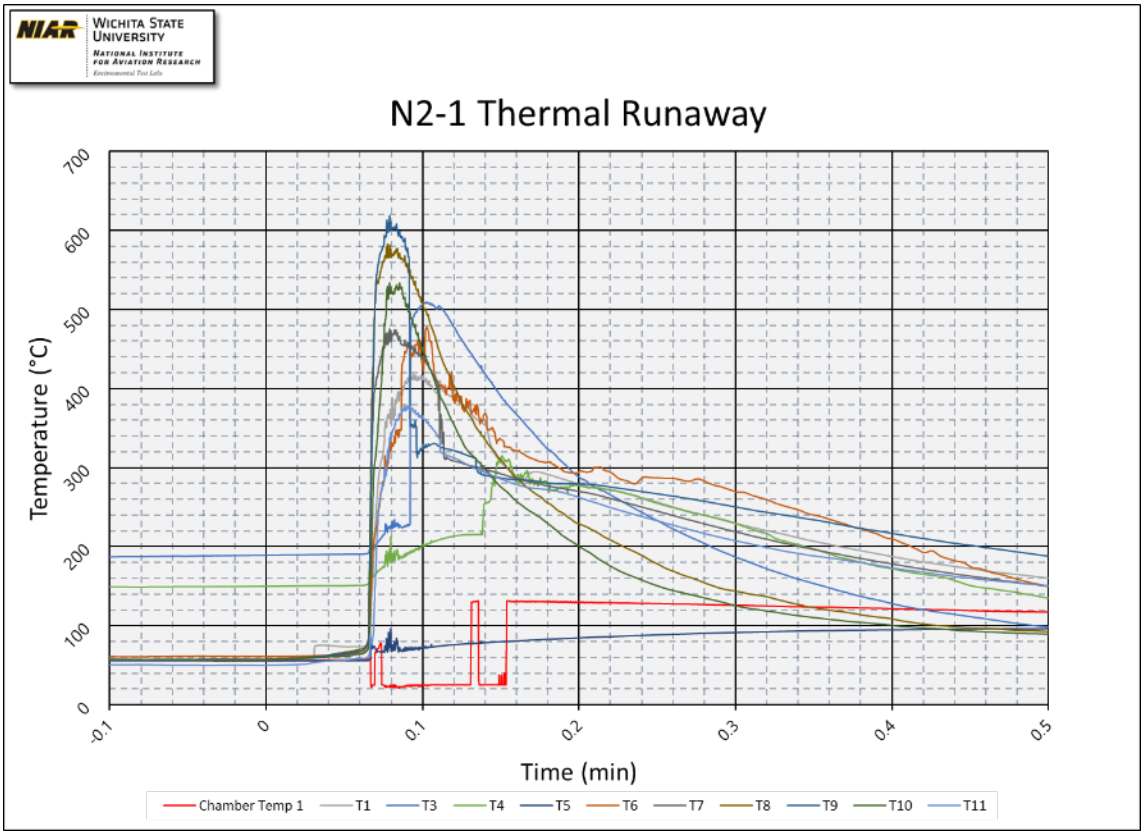

Figure 54: N2-1 Temperature Graph 2

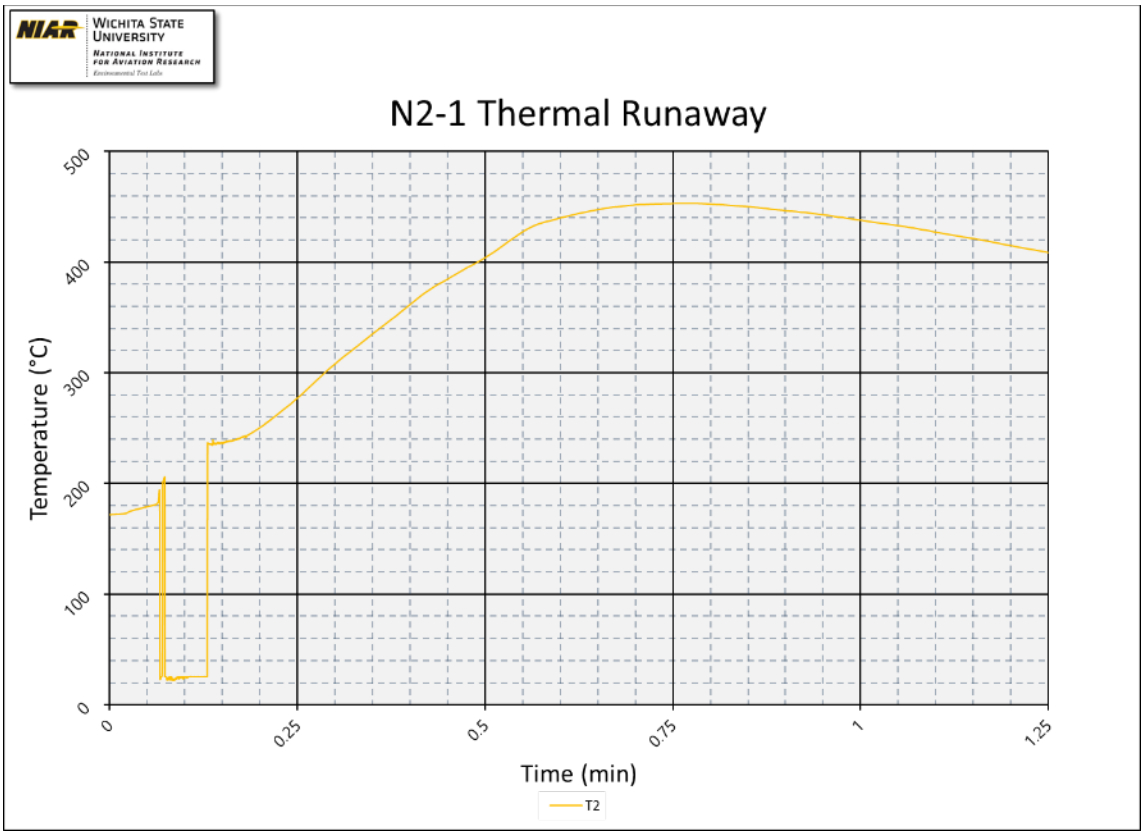

Figure 55: N2-1 Temperature Graph 3

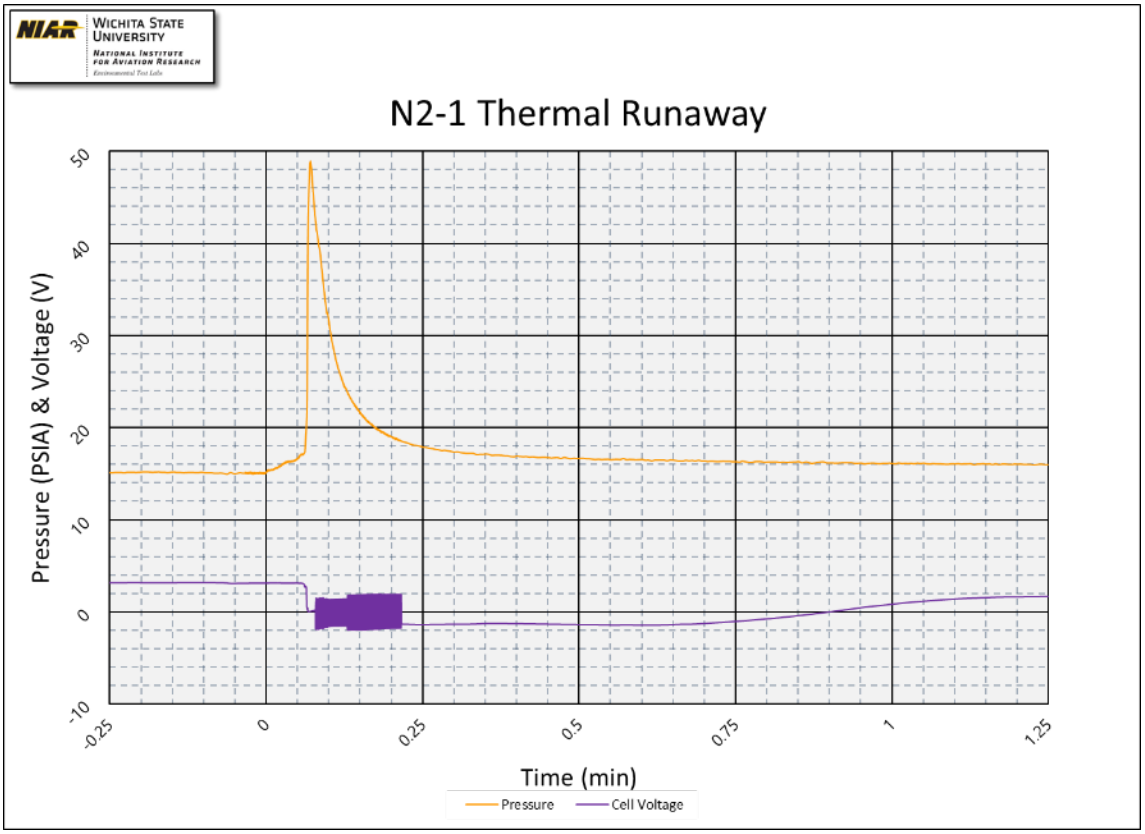

Figure 56: N2-1 Pressure and Voltage Graph

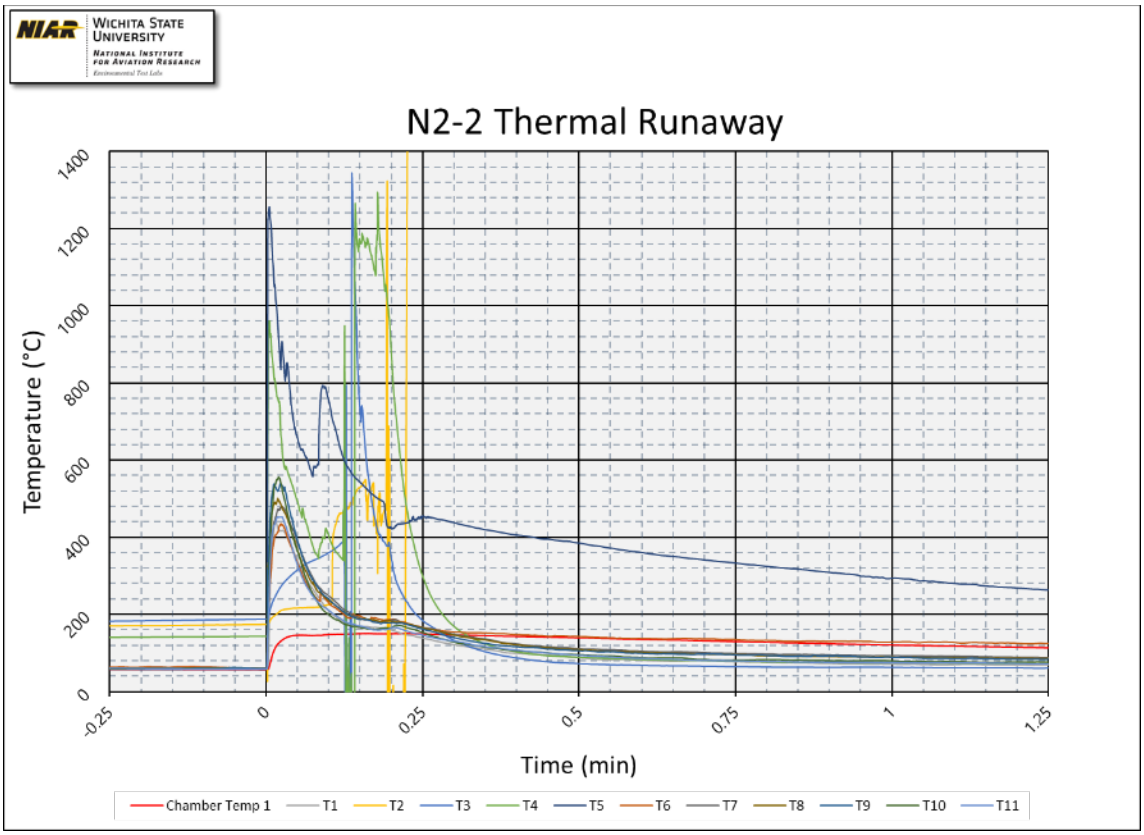

Figure 57: N2-2 Temperature Graph 1

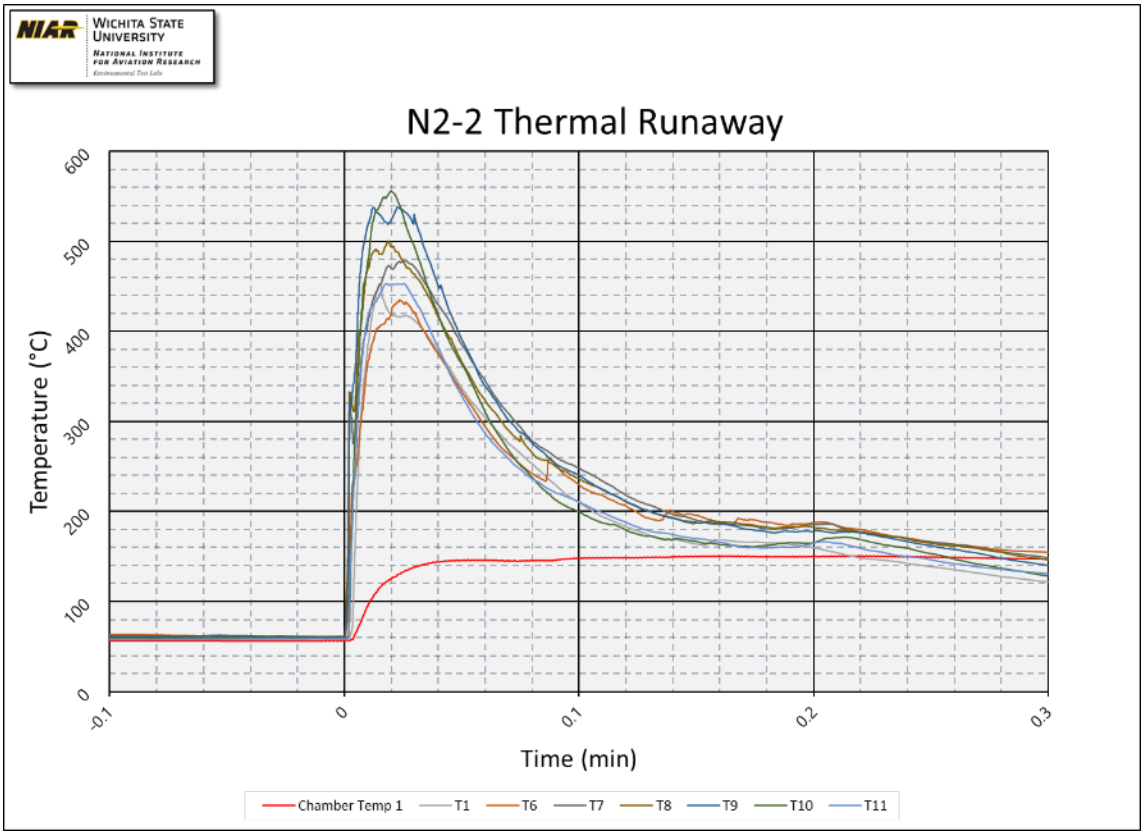

Figure 58: N2-2 Temperature Graph 2

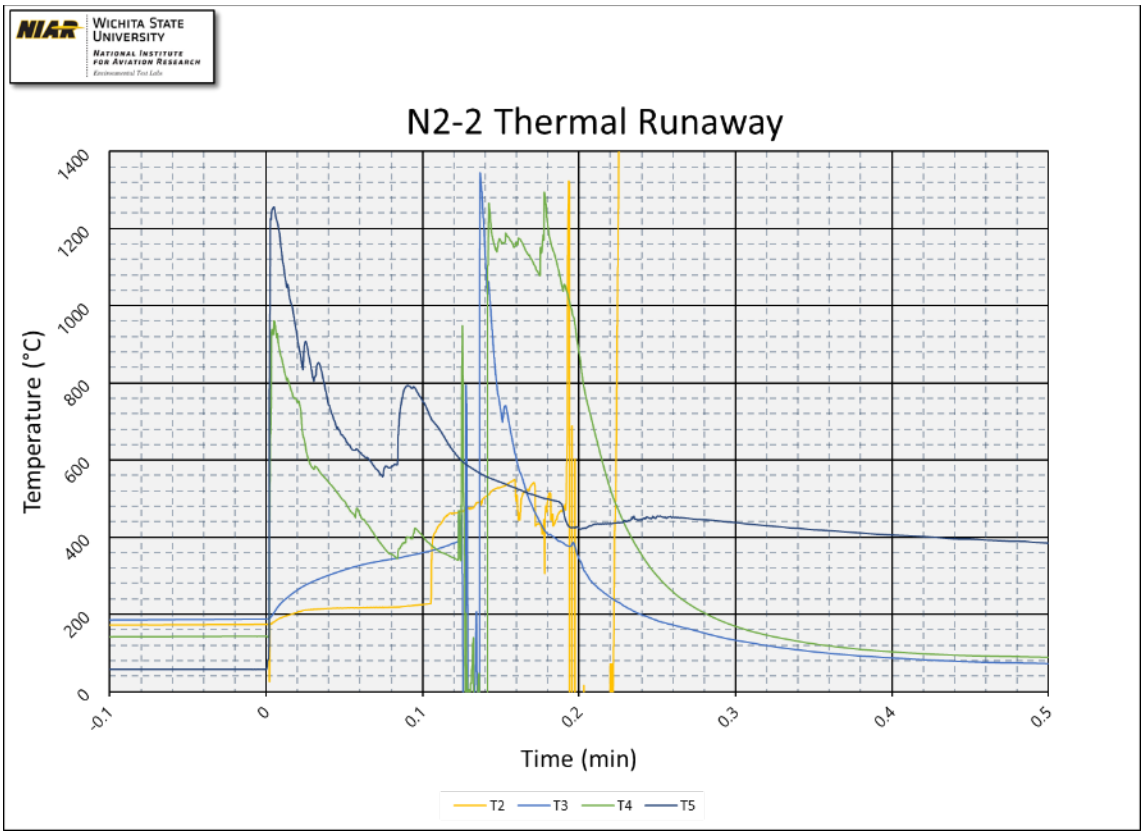

Figure 59: N2-2 Temperature Graph 3

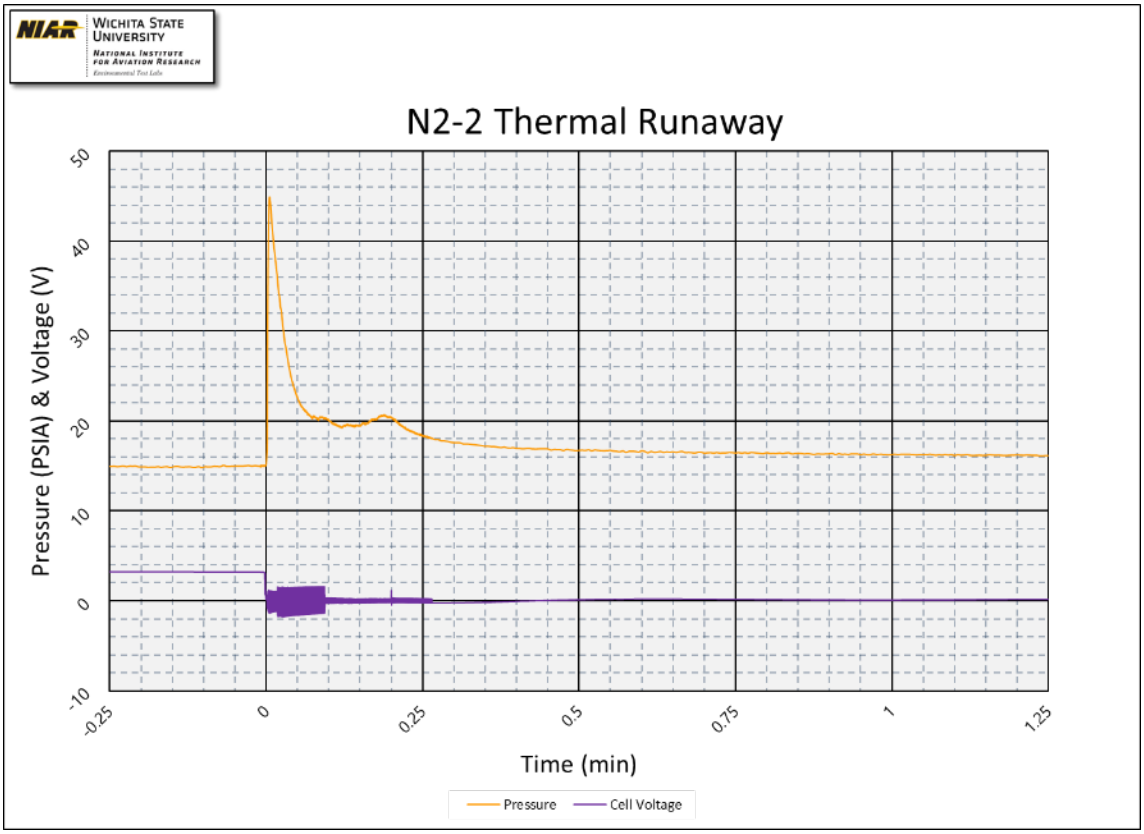

Figure 60: N2-2 Pressure and Voltage Graph

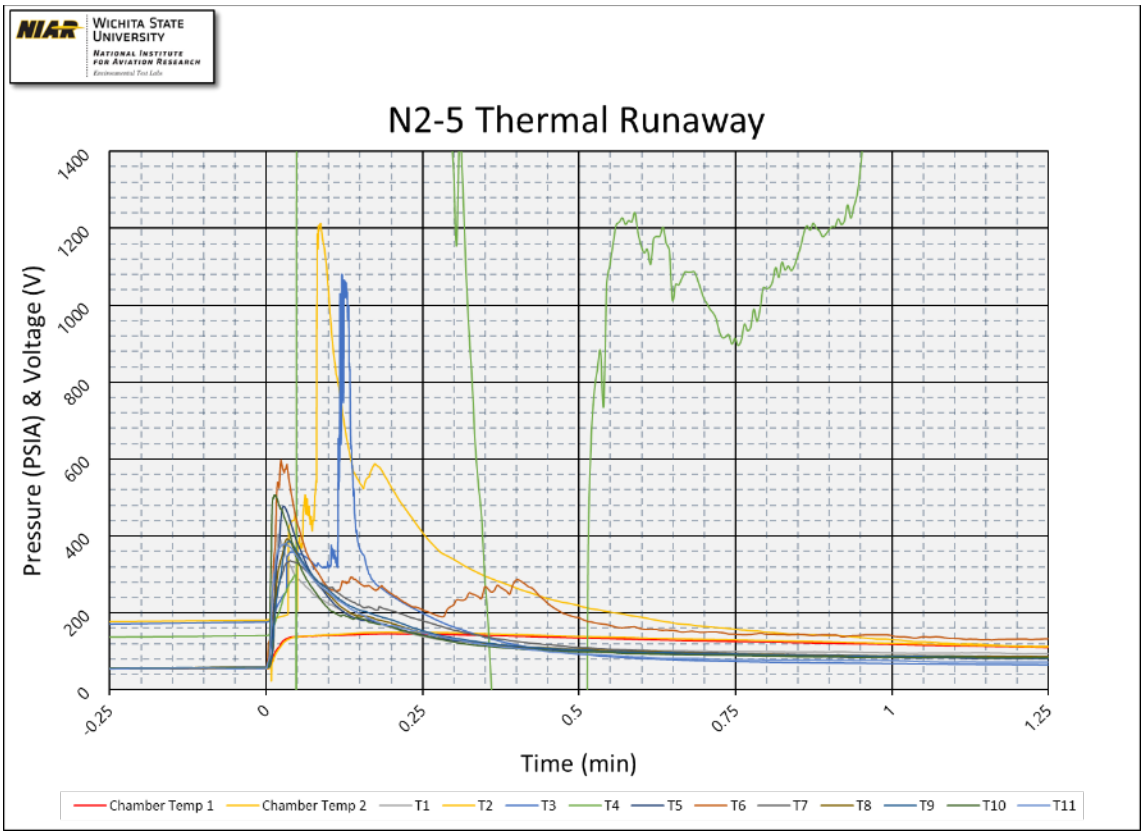

Figure 61: N2-5 Temperature Graph 1

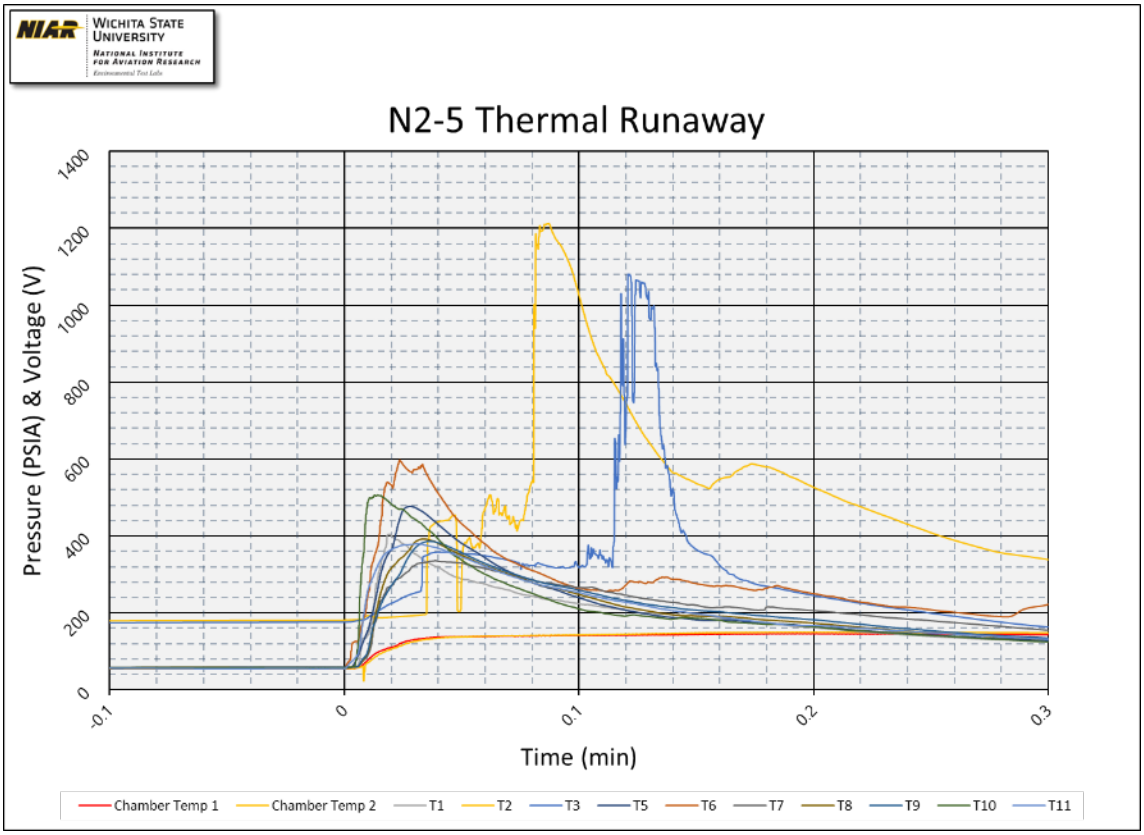

Figure 62: N2-5 Temperature Graph 2

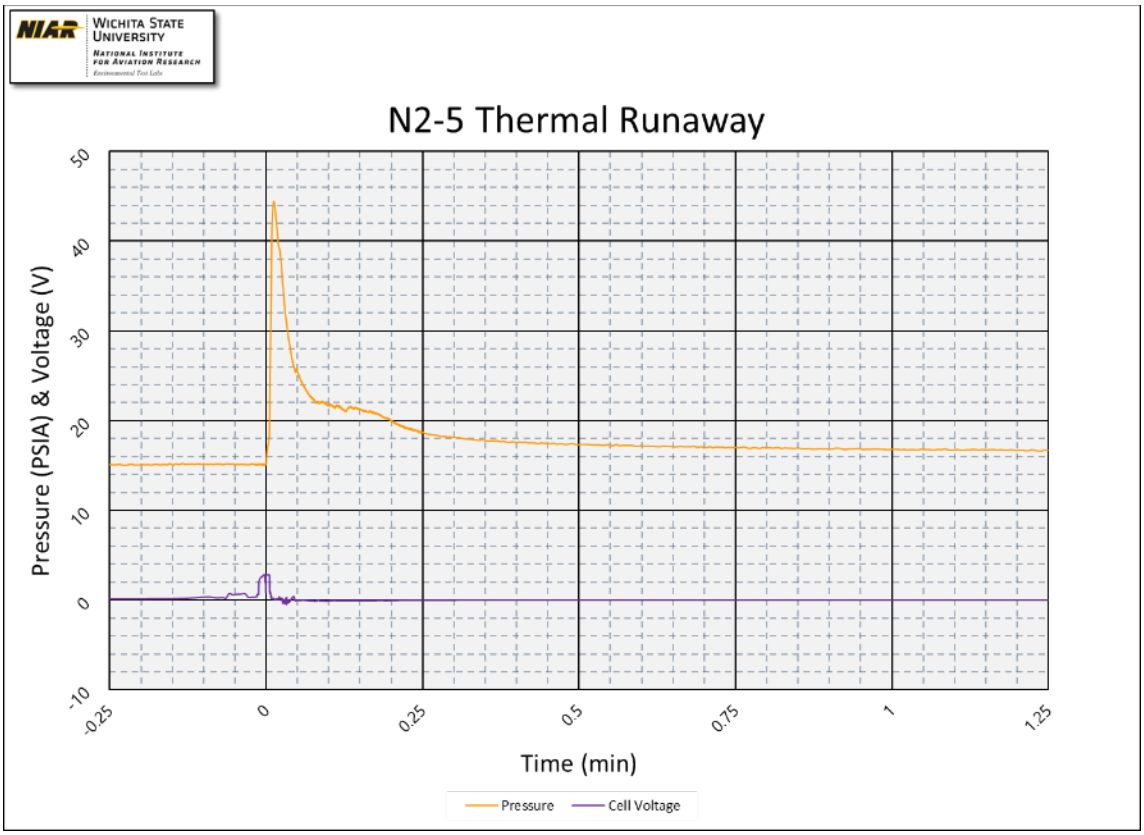

Figure 63: N2-5 Pressure and Voltage Graph

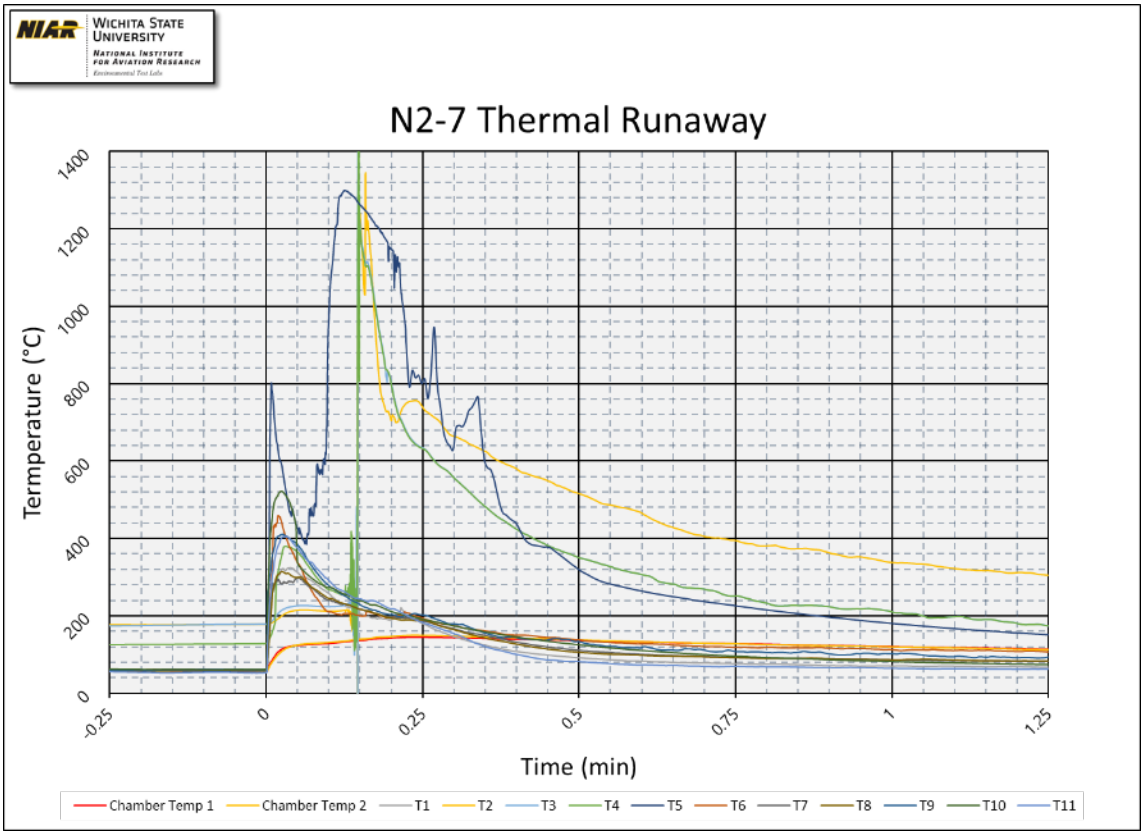

Figure 64: N2-7 Temperature Graph 1

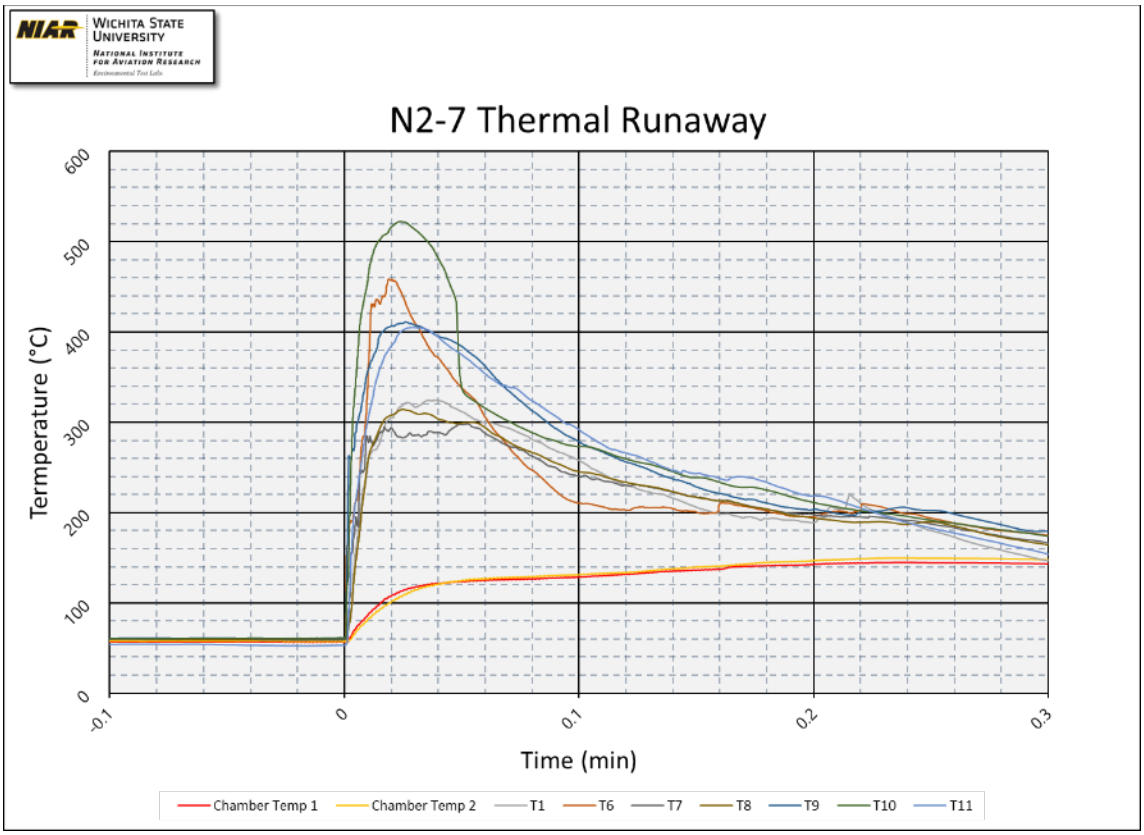

Figure 65: N2-7 Temperature Graph 2

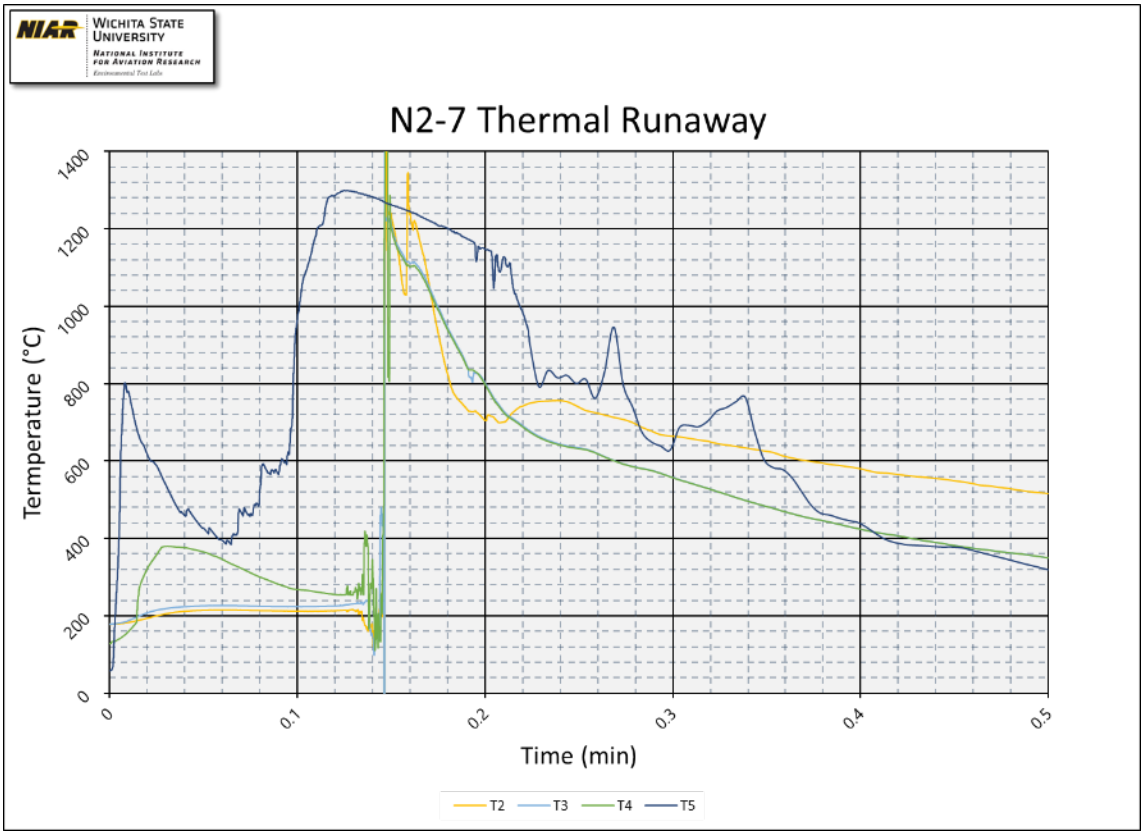

Figure 66: N2-7 Temperature Graph 3

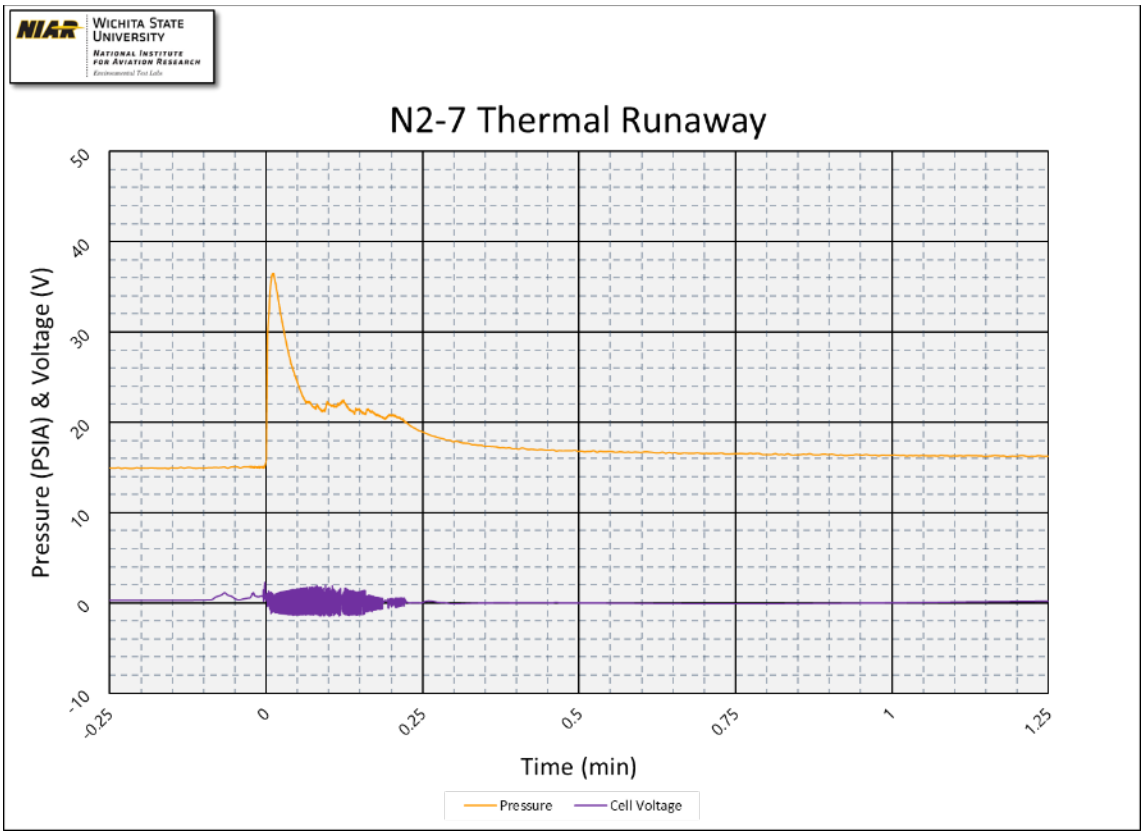

Figure 67: N2-7 Pressure and Voltage Graph

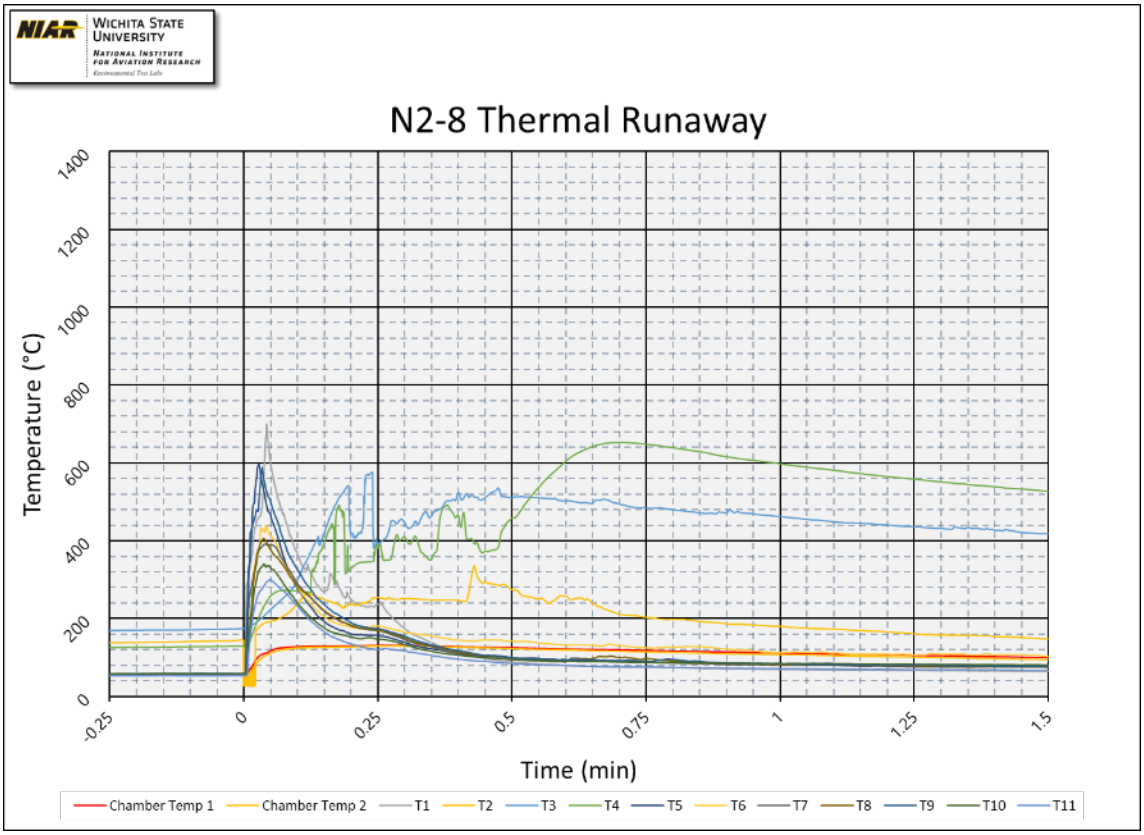

Figure 68: N2-8 Temperature Graph 1

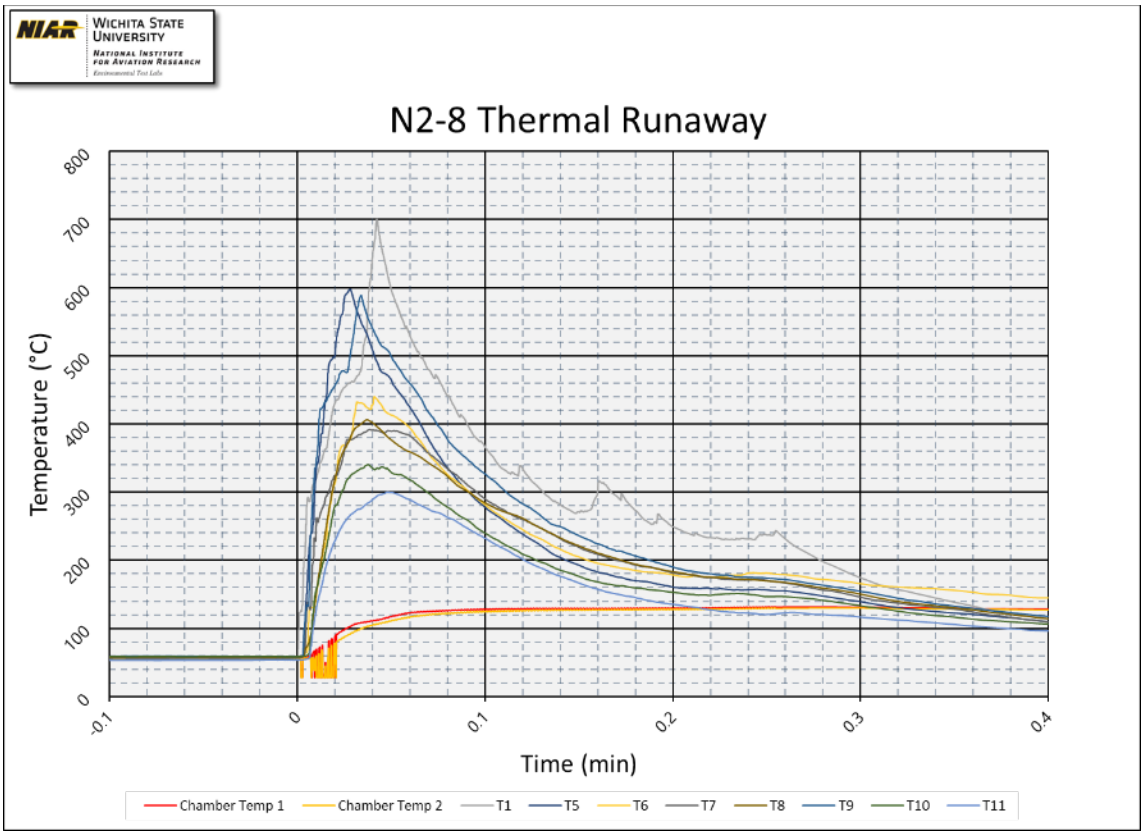

Figure 69: N2-8 Temperature Graph 2

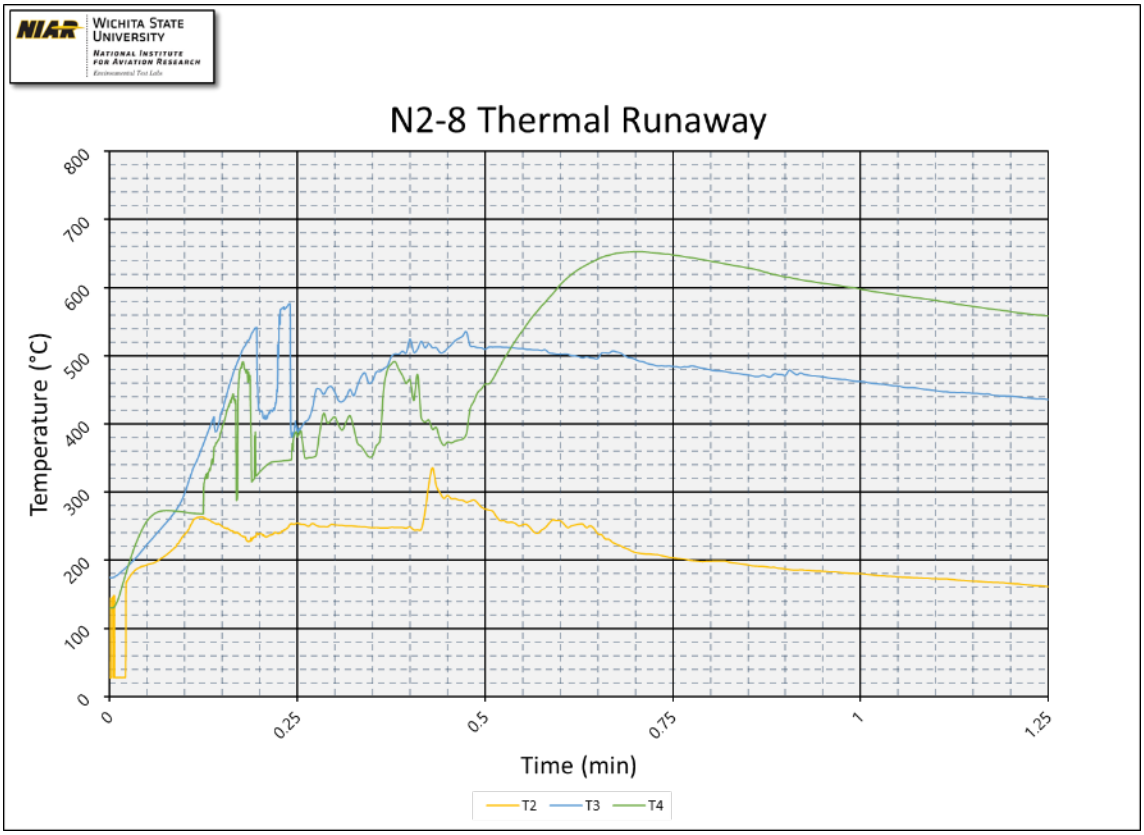

Figure 70: N2-8 Temperature Graph 3

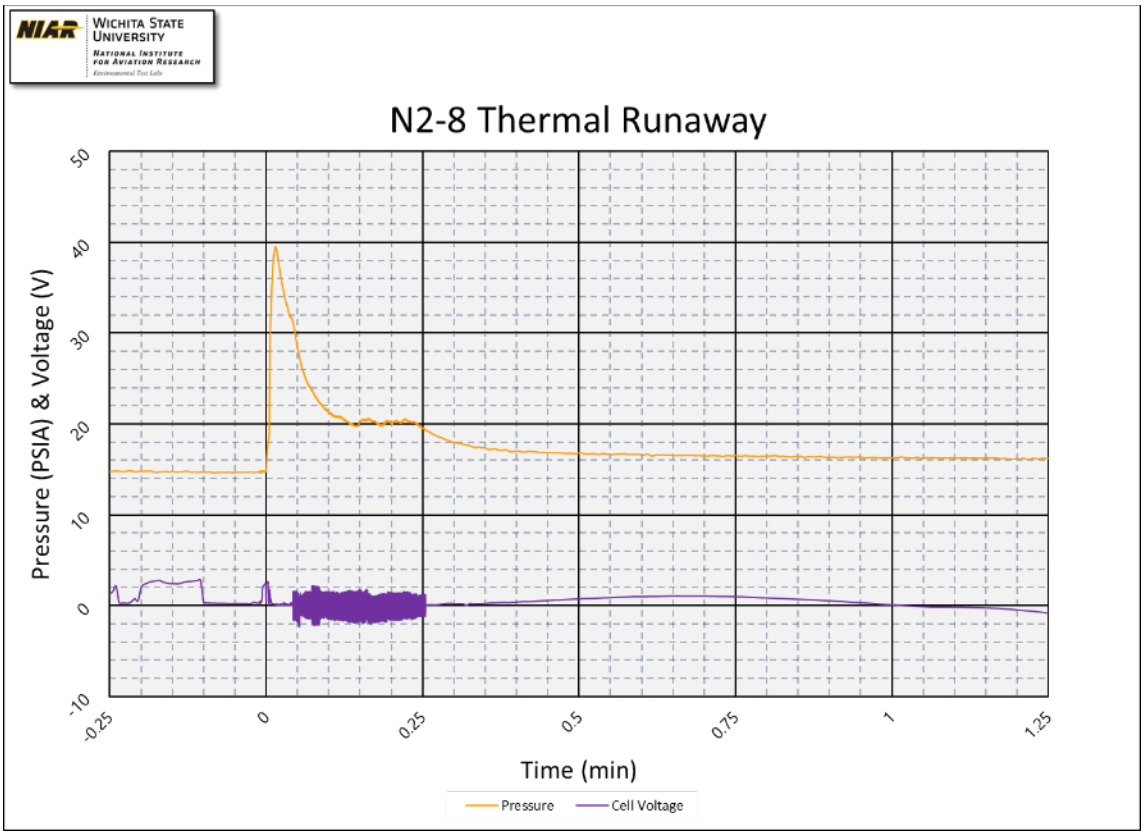

Figure 71: N2-8 Pressure and Voltage Graph

2.2.3 R3-X (Lithium Werks™ ANR26650M1B)

The R3-X cells were the least consistent cells in terms of peak temperatures and gases released. The reactions achieved an average cell peak temperature of 348.5°C and an average chamber peak temperature of 361.4°C. The standard deviation in chamber peak temperatures was almost as high as the peak temperature itself at 335.9°C. The R3 cells also had the largest variation in onset temperatures of the reaction. All five of the valid trials resulted in carbon monoxide, carbon dioxide, ethylene, hydrogen cyanide, and sulfur dioxide being detected, although the amount of each gas varied greatly. The cells lost an average of 14.920g of mass, which translates to a 20% loss in initial mass.

Table 13: R3-X Mass Change Summary

Cell	Pre-Test Mass (g)	Post-Test Mass (g)
R3-3	75.722	61.364
R3-4	75.370	60.575
R3-5	75.668	60.674
R3-11	75.330	60.169
R3-12	75.376	60.084

Table 14: R3-X Detected Gases

Gas Species	Detector Tube Error Range	Moles of Gas Detected R3-3	Moles of Gas Detected R3-4	Moles of Gas Detected R3-5	Moles of gas Detected R3-11	Moles of gas Detected R3-12
CO	±10 - 15%	0.013	2.4E-3	3.6E-3	2.8E-3	3.3E-3
CO_2	±10%	0.44	4.1E-3	0.022	5.6E-3	0.024
C_2H_4	varied	1.1E-4 ± 10%	0.010 ± 20 - 30%	0.011 ± 20 - 30%	0.011 ± 20 - 30%	0.015 ± 20 - 30%
H_2	±15 - 20%	0	0.016	0.022	0.022	0.027
H_2S	±25%	0	0	0	0	0
H_2SO_4	±10%	0	0	0	8.4E-05	1.3E-4
HCl	±15%	0	0	0	0	0
HCN	±10 - 15%	5.5E-06	8.1E-05	8.8E-05	1.7E-4	2.2E-4
HF	±10%	0	0	0	0	0
HNO_3	±15%	0	0	0	0	0
NO	±10%	7.8E-05	0	0	0	0
NO_2	±10 - 15%	1.1E-05	0	0	0	0
SO_2	±10 - 15%	4.4E-06	9.8E-06	5.5E-06	1.7E-05	1.1E-05

Table 15: R3-X Failure Modes

Cell	Leak	Vent	Fire	Rupture
R3-3	Y	Y	Y	Y
R3-4	Y	Y		Y
R3-5	Y	Y		
R3-11	Y	Y		
R3-12	Y	Y		Y

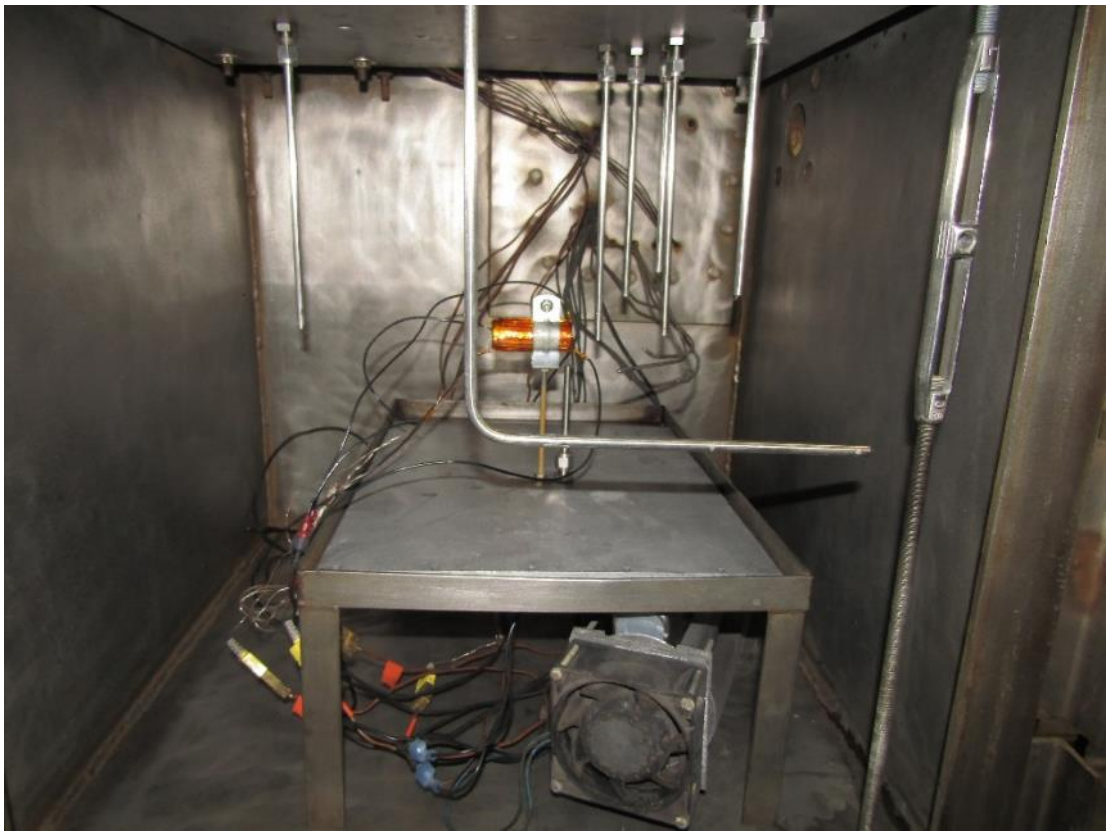

Figure 72: R3-3 Pre-Test

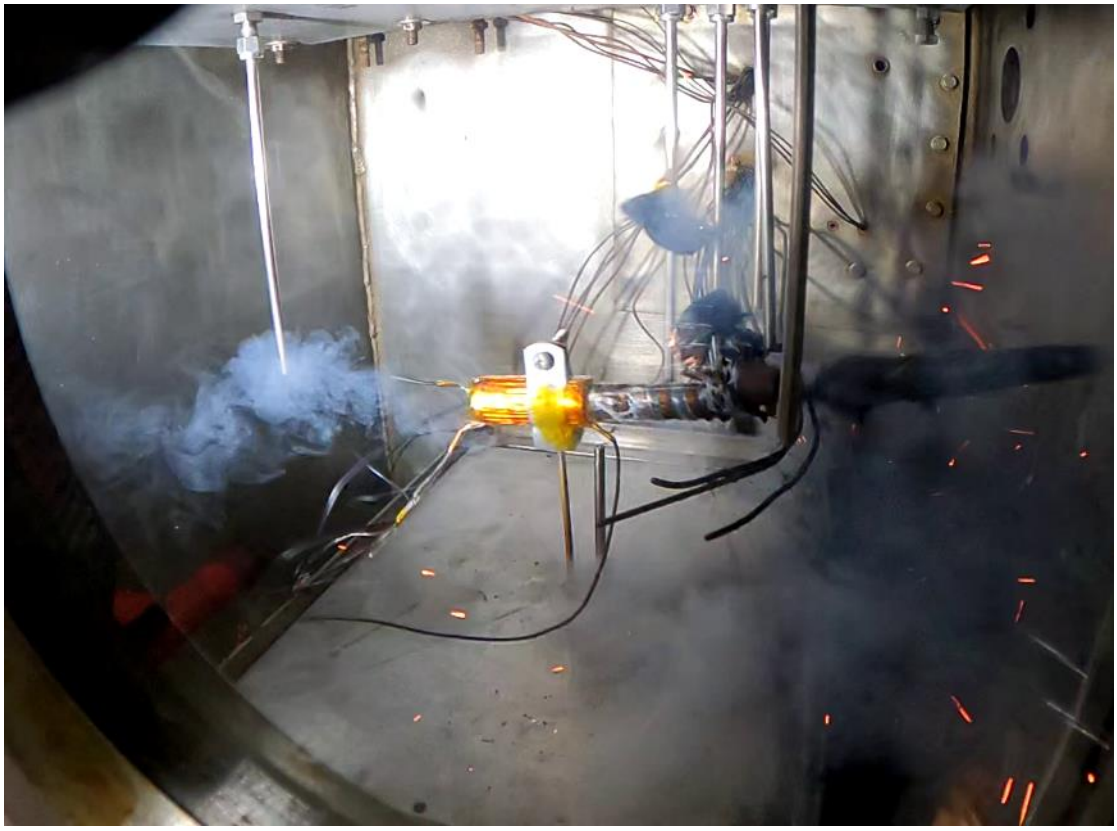

Figure 73: R3-3 Venting and Rupture

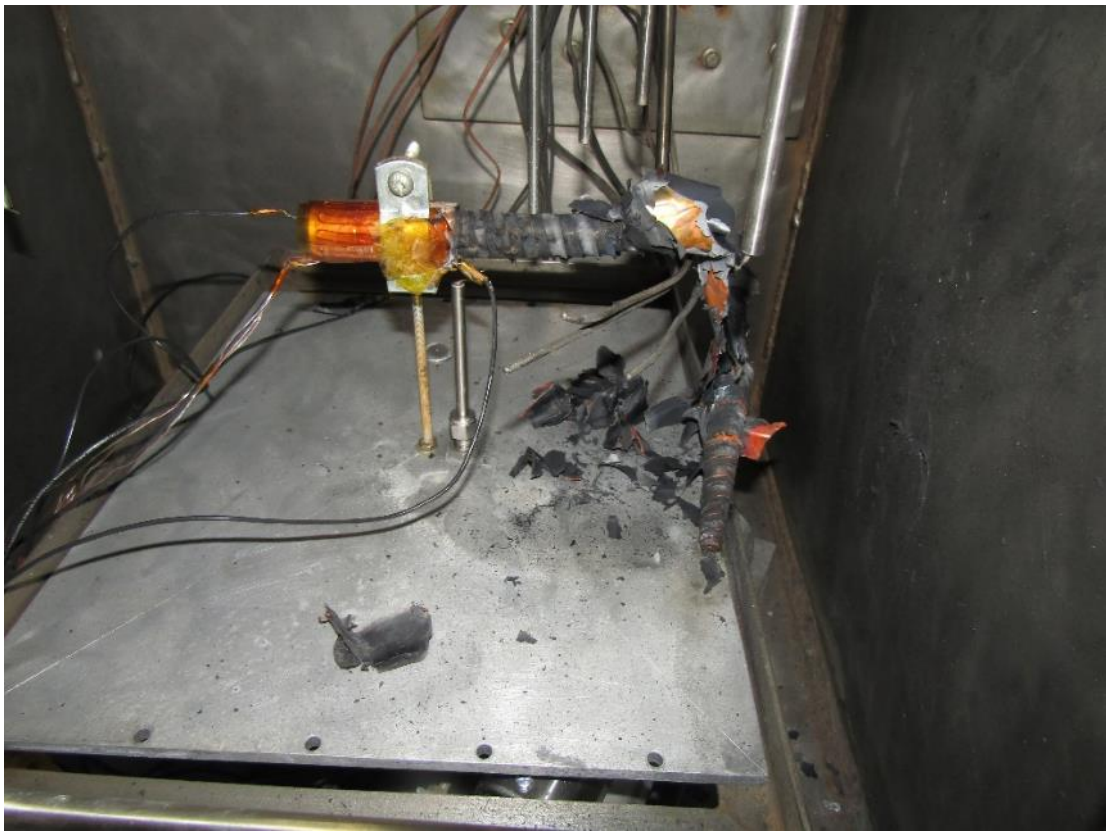

Figure 74: R3-3 Post Test 1

Figure 75: R3-3 Post-Test 2

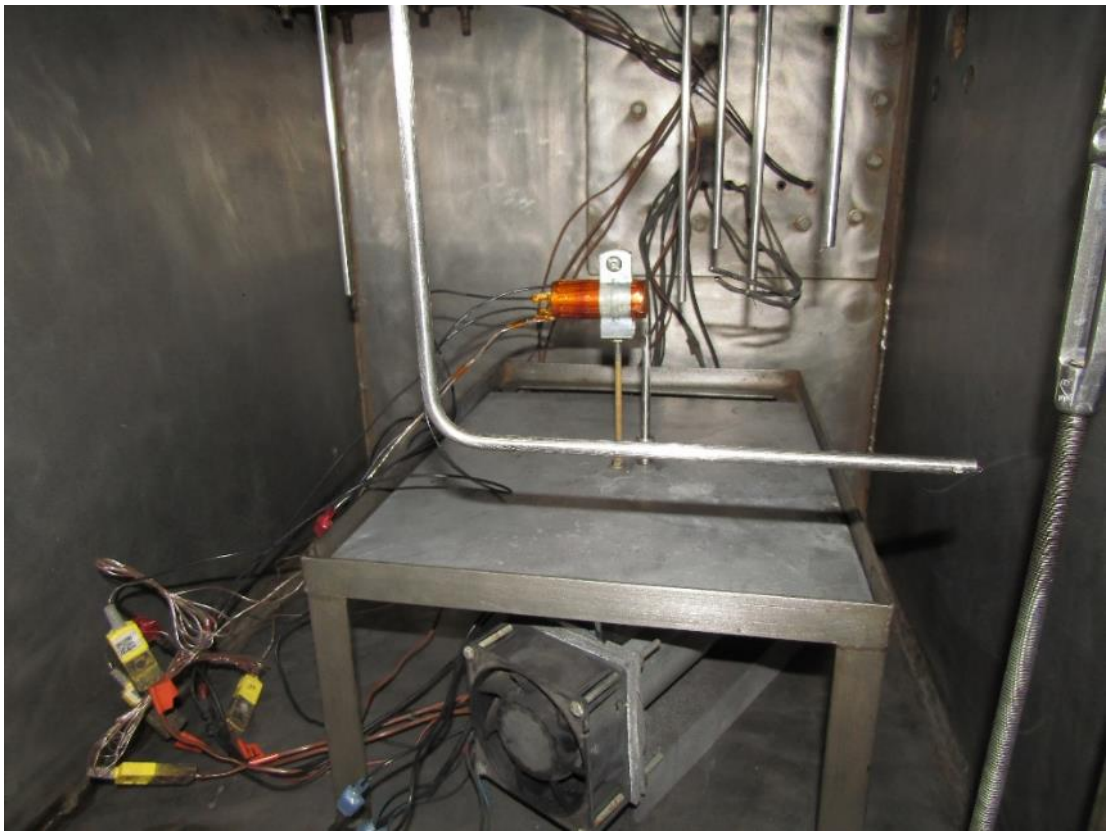

Figure 76: R3-4 Pre-Test

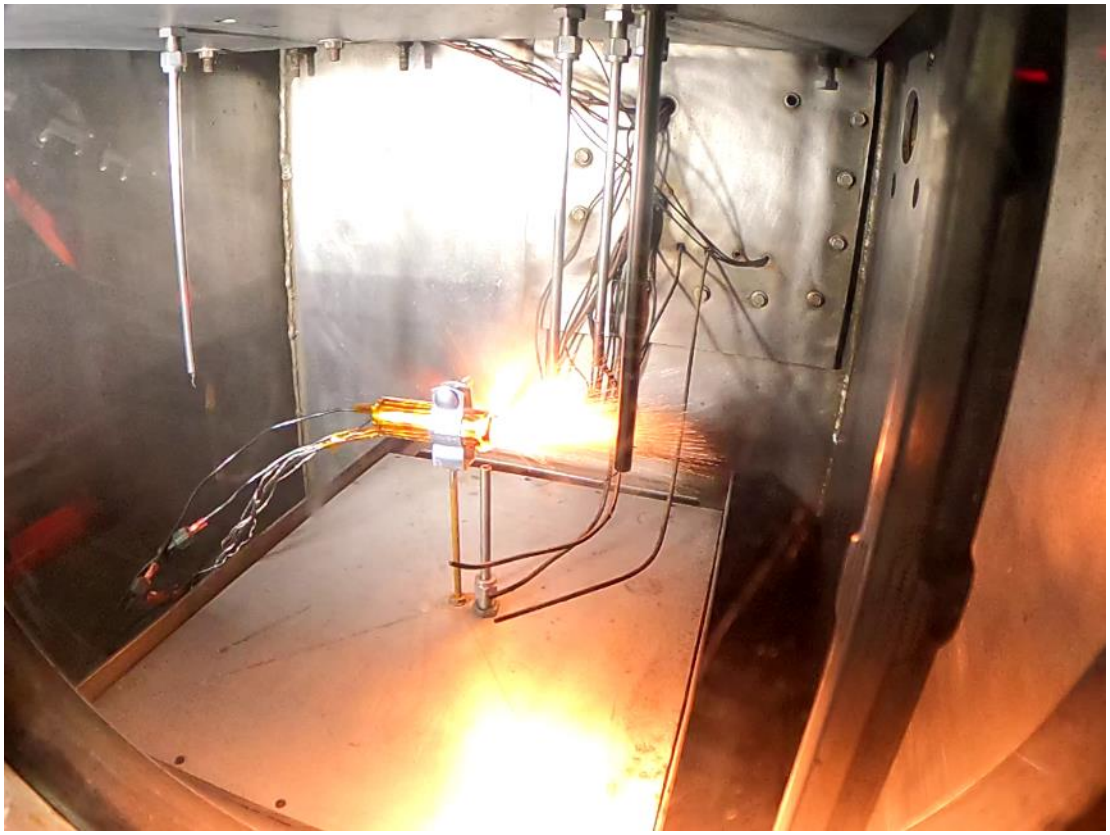

Figure 77: R3-4 Venting and Fire

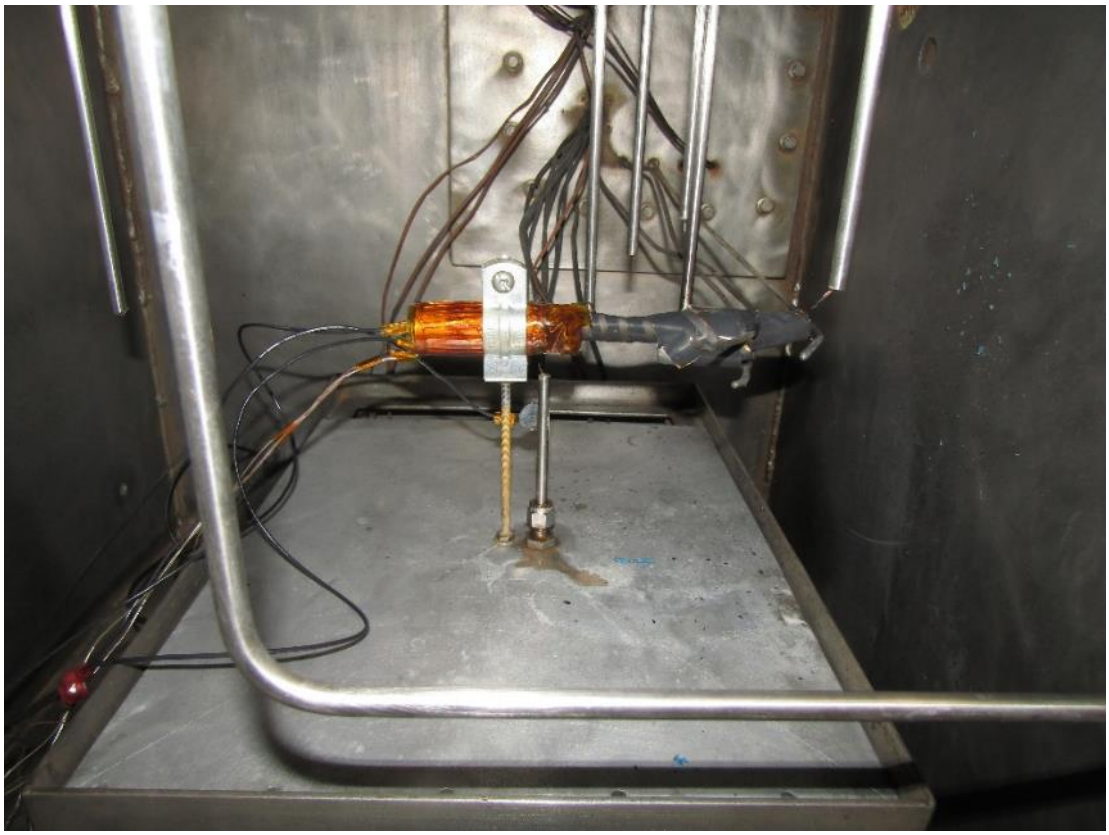

Figure 78: R3-4 Post-Test 1

Figure 79: R3-4 Post-Test 2

Figure 80: R3-5 Pre-Test

Figure 81: R3-5 Venting

Figure 82: R3-5 Post-Test 1

Figure 83: R3-5 Post-Test 2

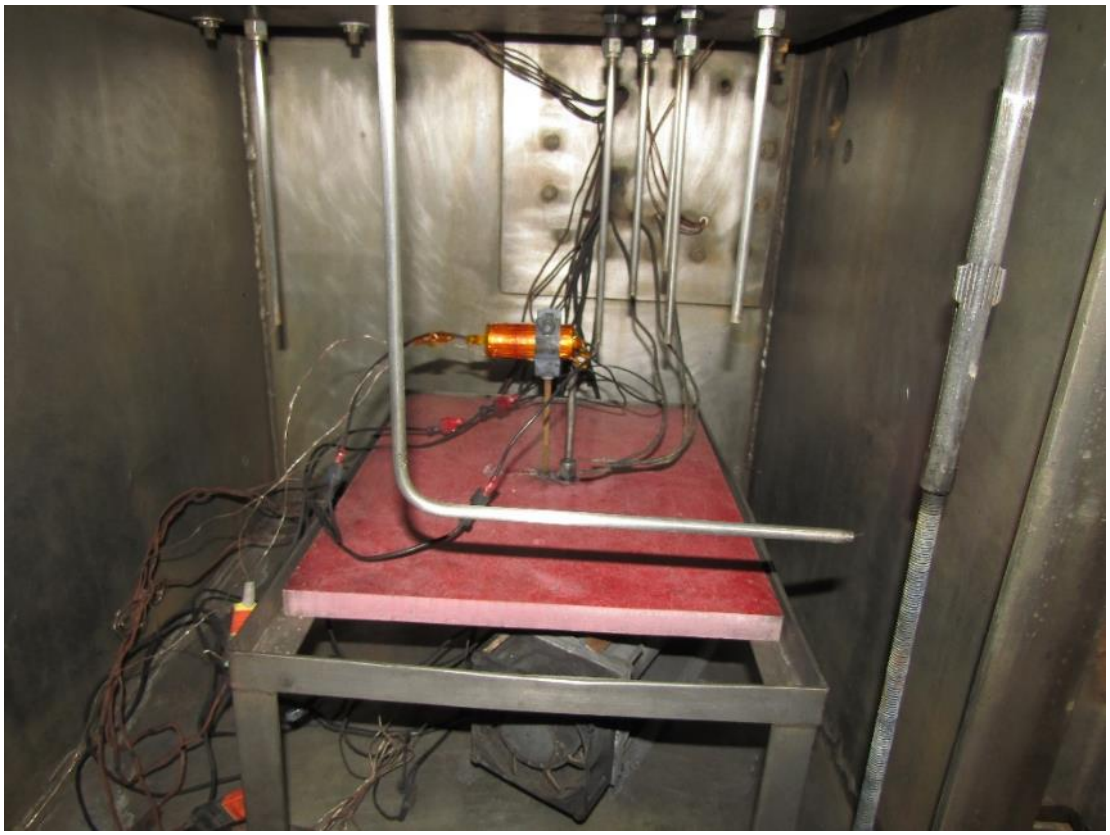

Figure 84: R3-11 Pre-Test

Figure 85: R3-11 Venting

Figure 86: R3-11 Post-Test 1

Figure 87: R3-12 Pre-Test

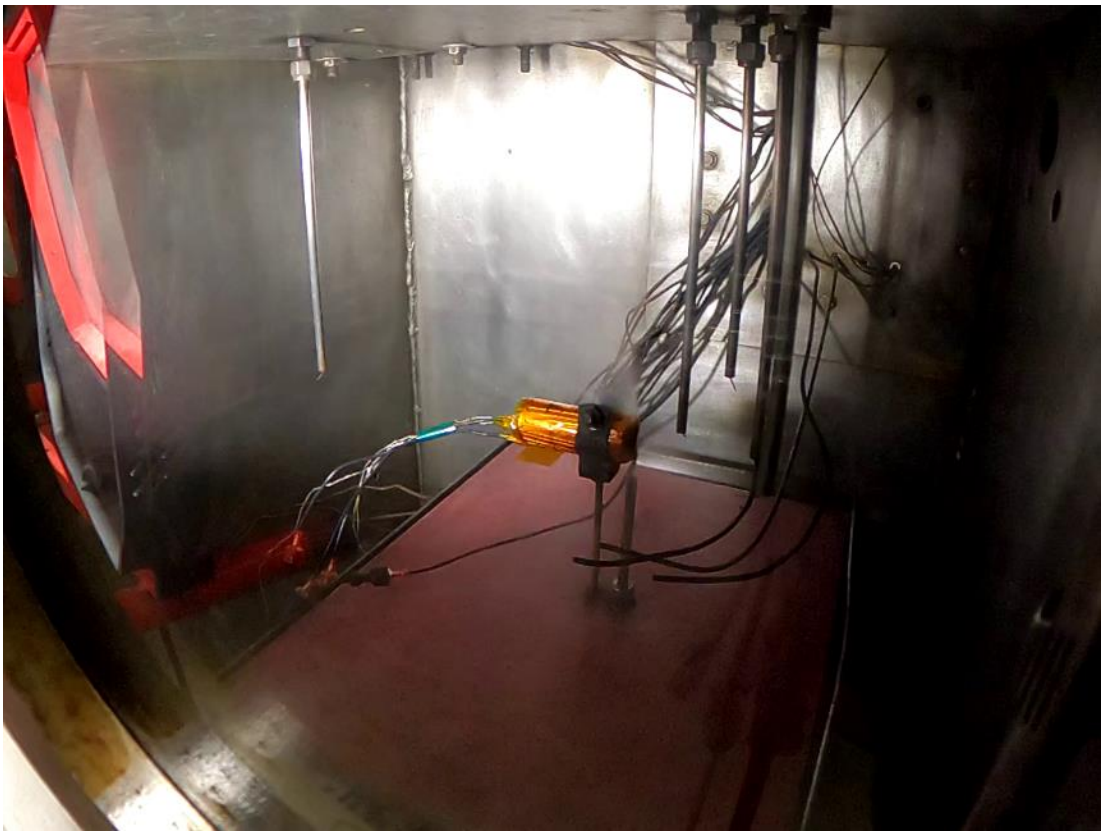

Figure 88: R3-12 Venting

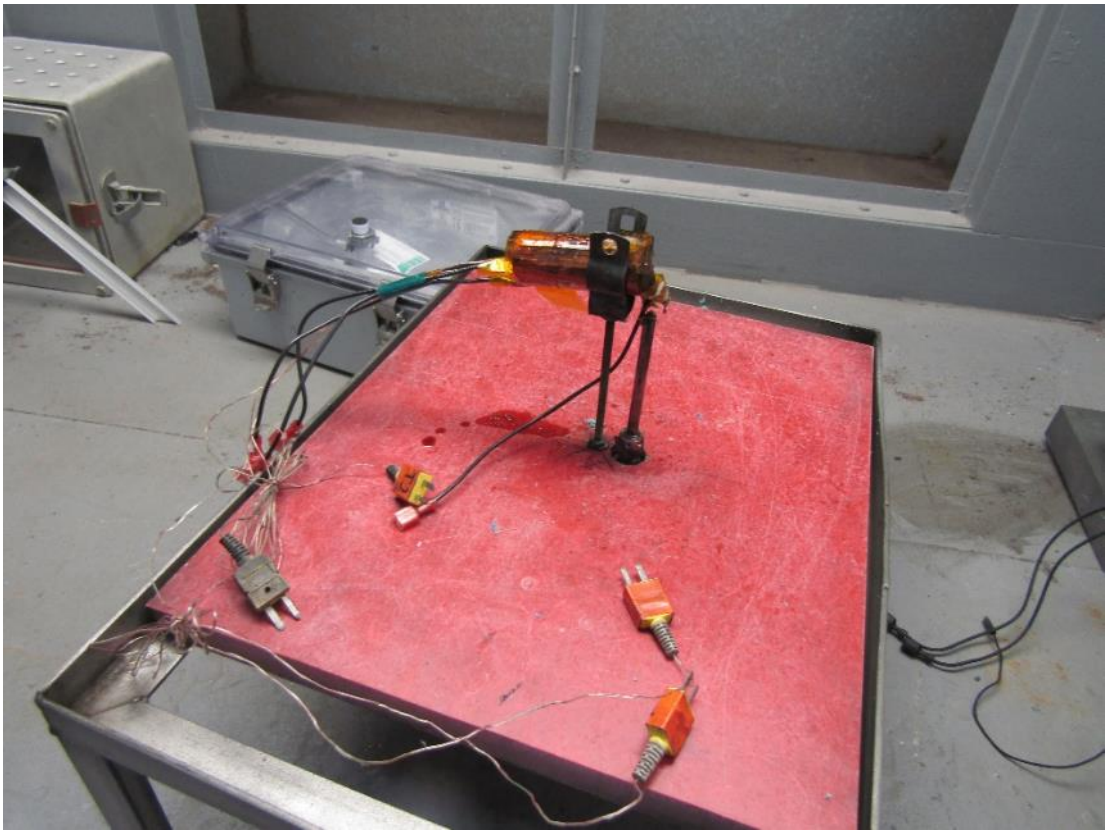

Figure 89: R3-12 Post-Test 1

Figure 90: R3-12 Post-Test 2

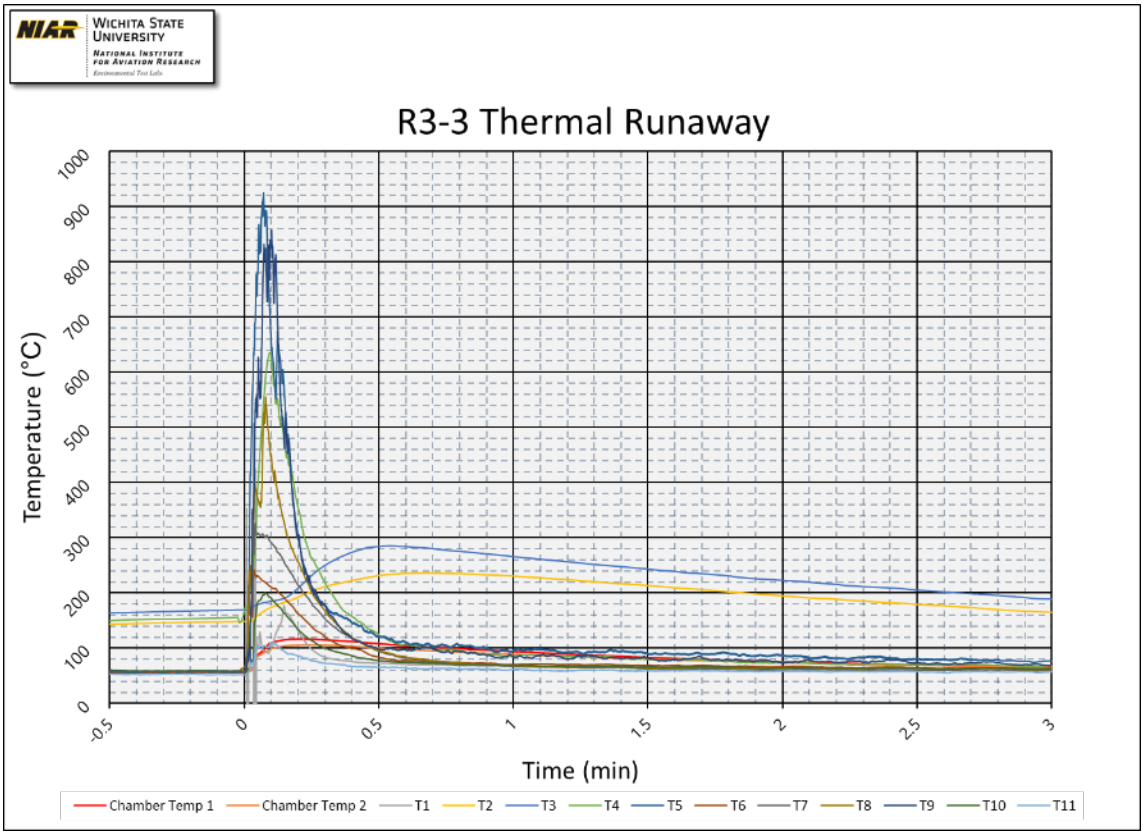

Figure 91: R3-3 Temperature Graph 1

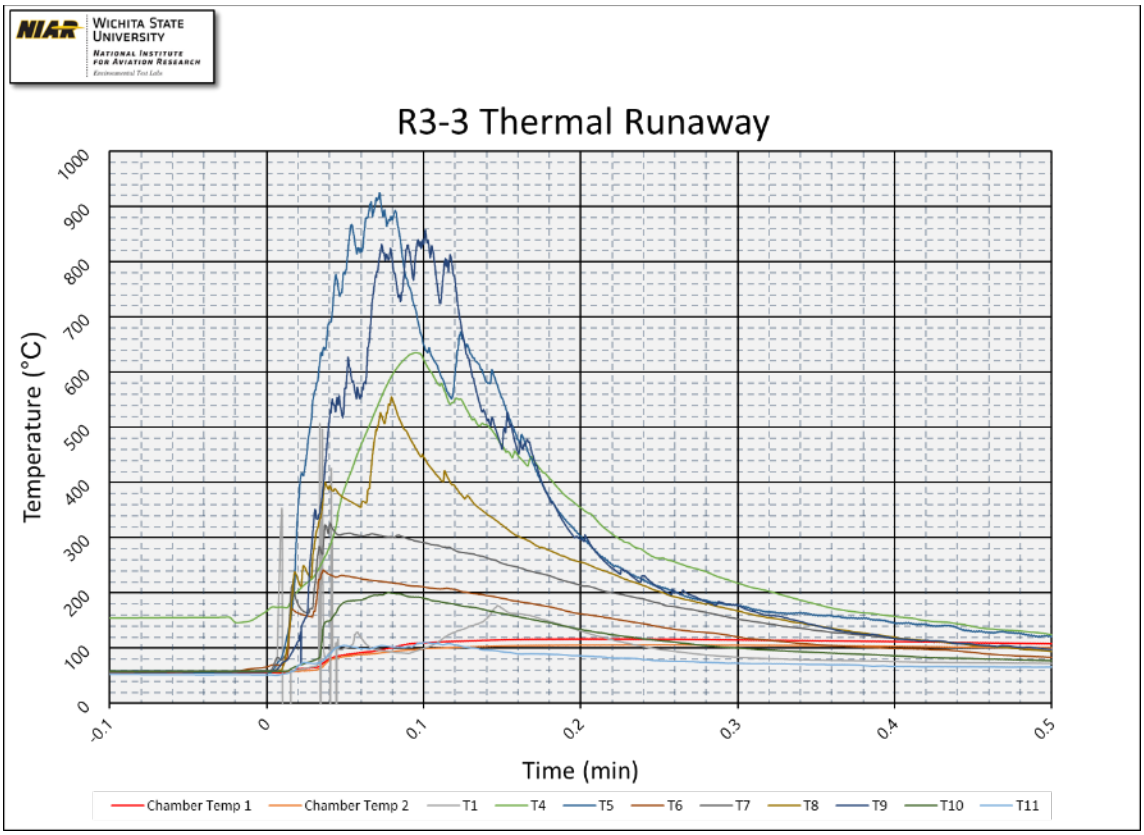

Figure 92: R3-3 Temperature Graph 2

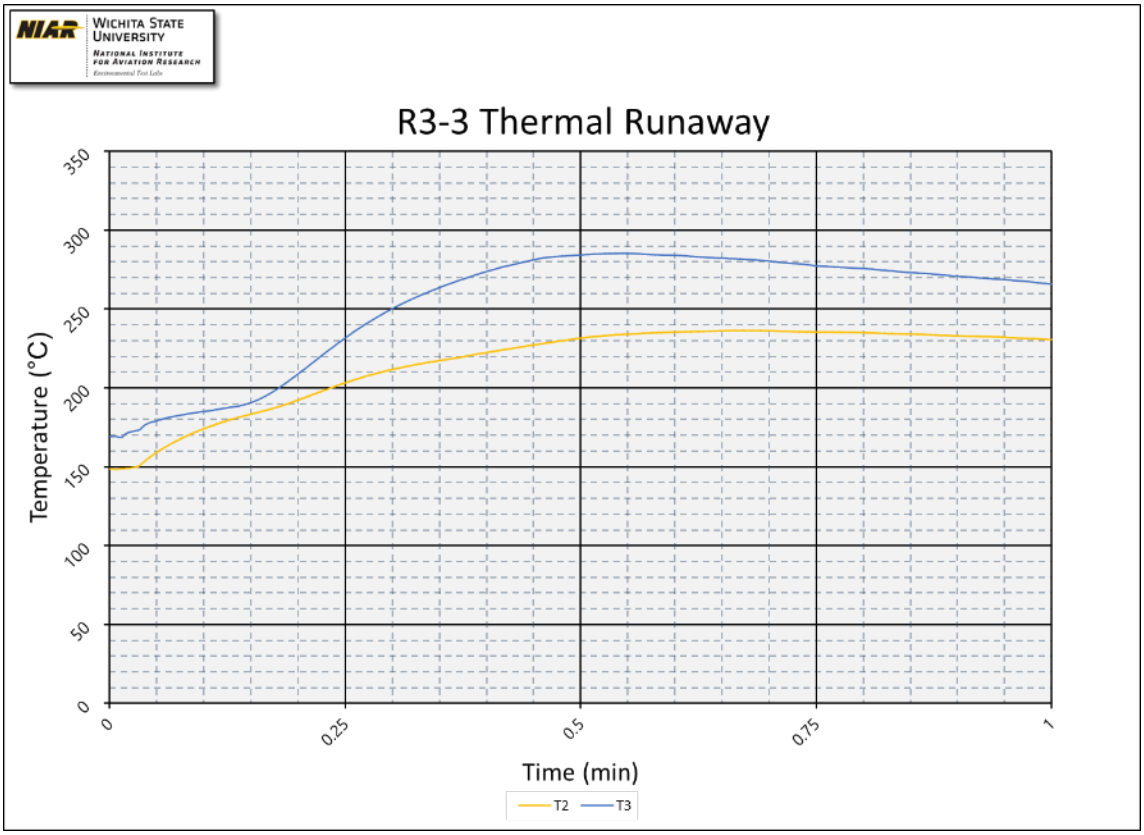

Figure 93: R3-3 Temperature Graph 3

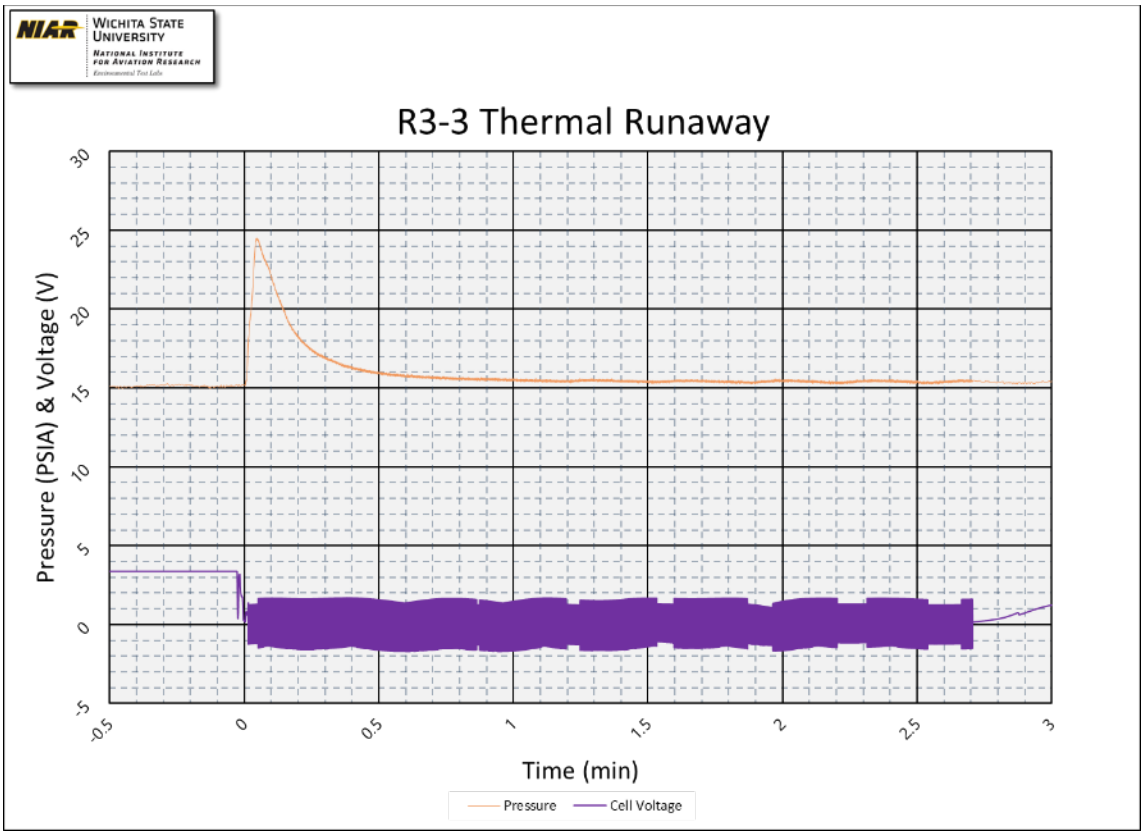

Figure 94: R3-3 Pressure & Voltage Graph

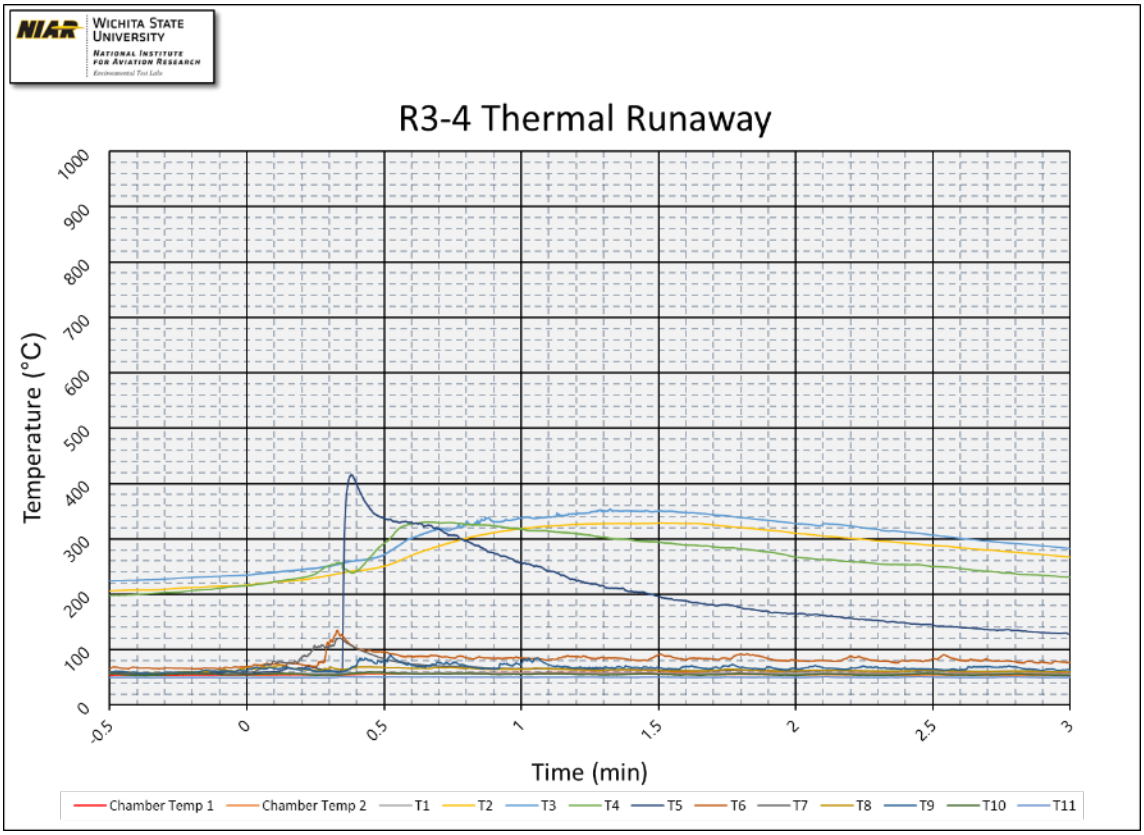

Figure 95: R3-4 Temperature Graph 1

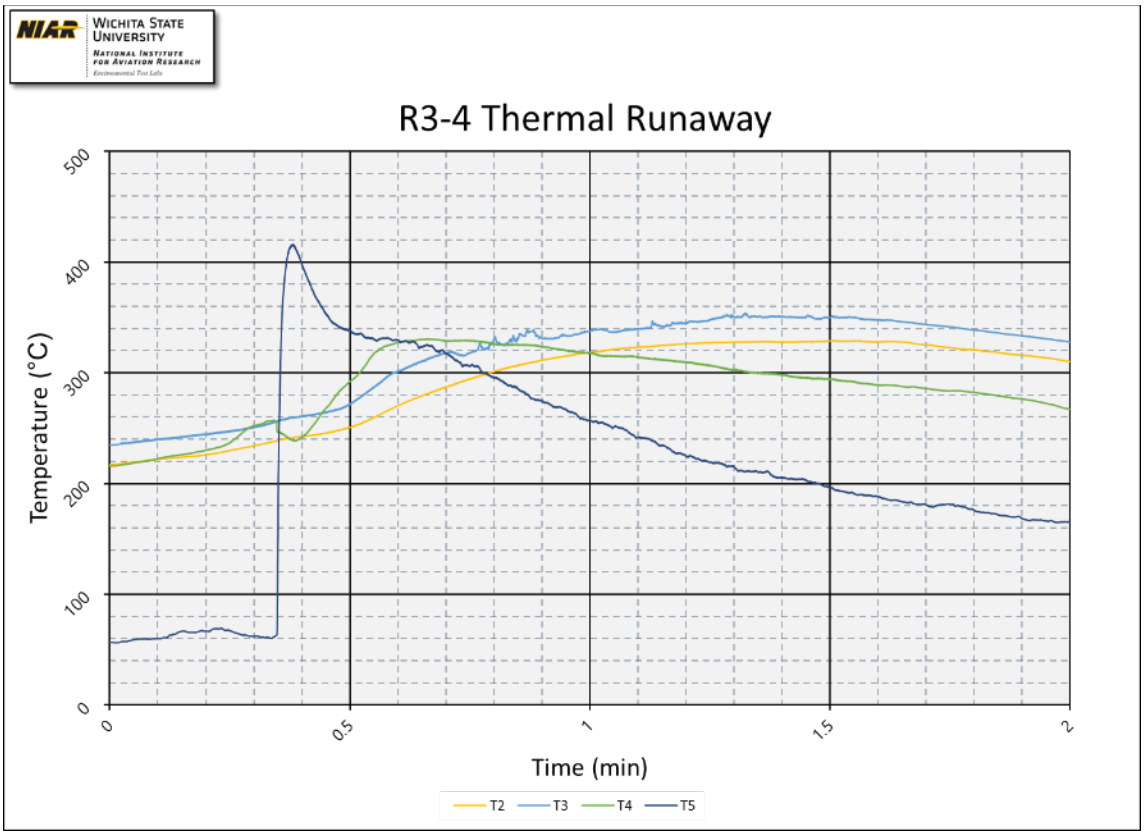

Figure 96: R3-4 Temperature Graph 2

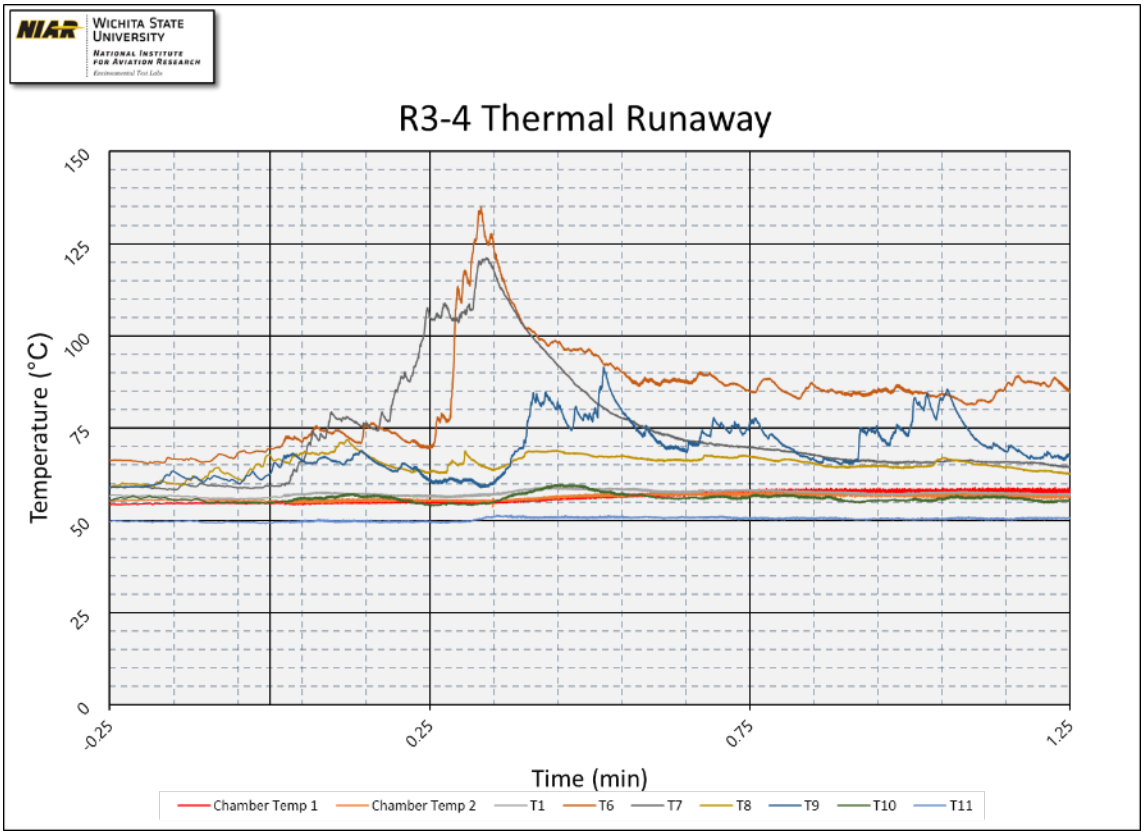

Figure 97: R3-4 Temperature Graph 3

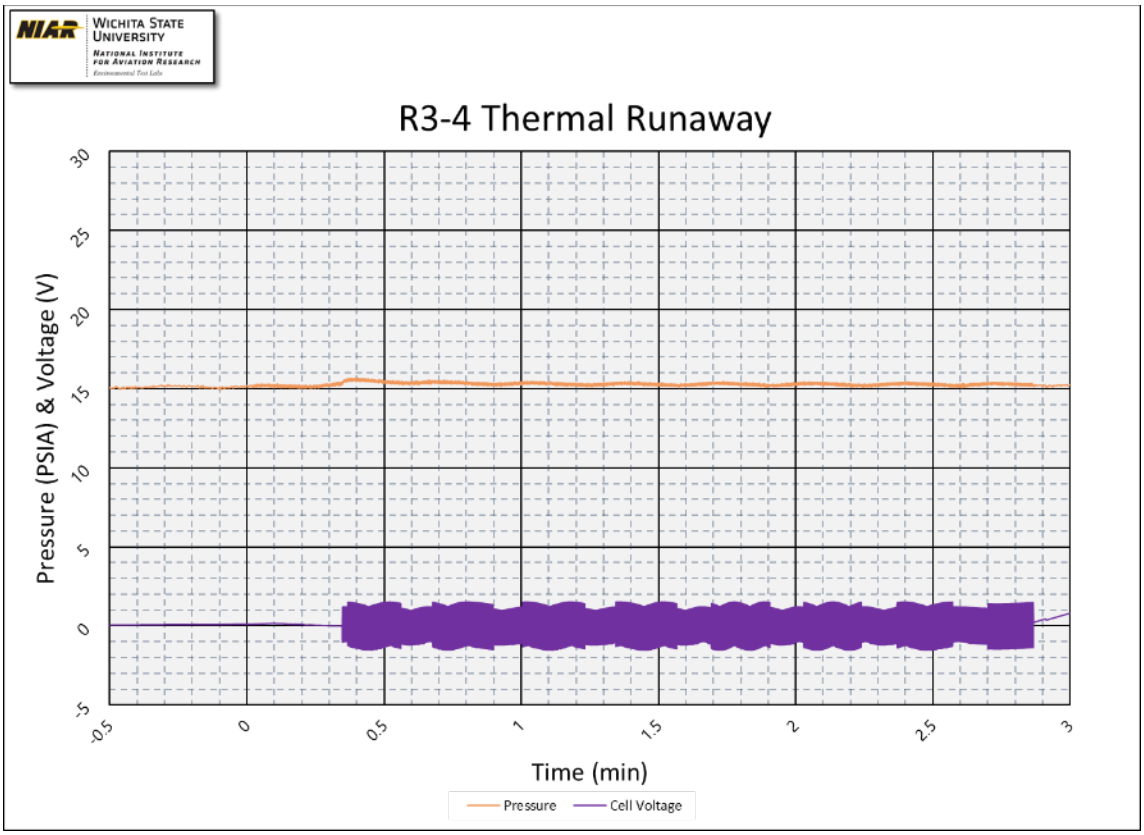

Figure 98: R3-4 Pressure & Voltage Graph

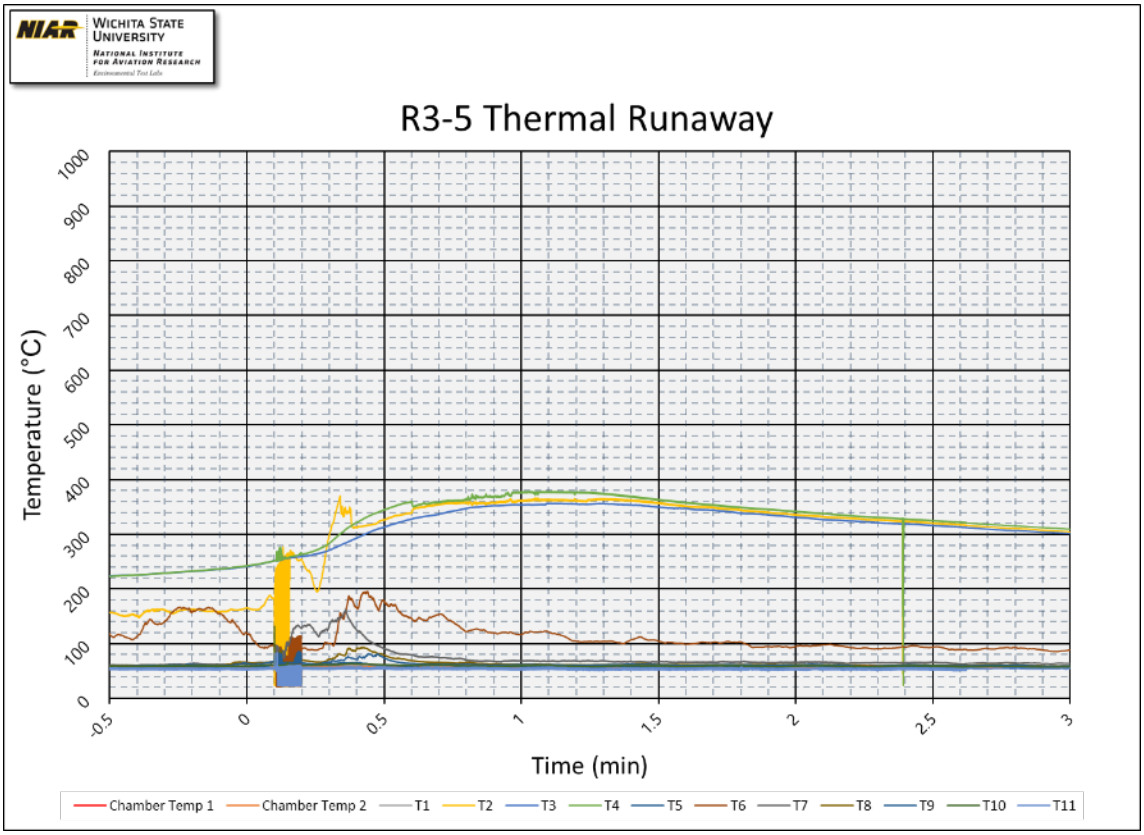

Figure 99: R3-5 Temperature Graph 1

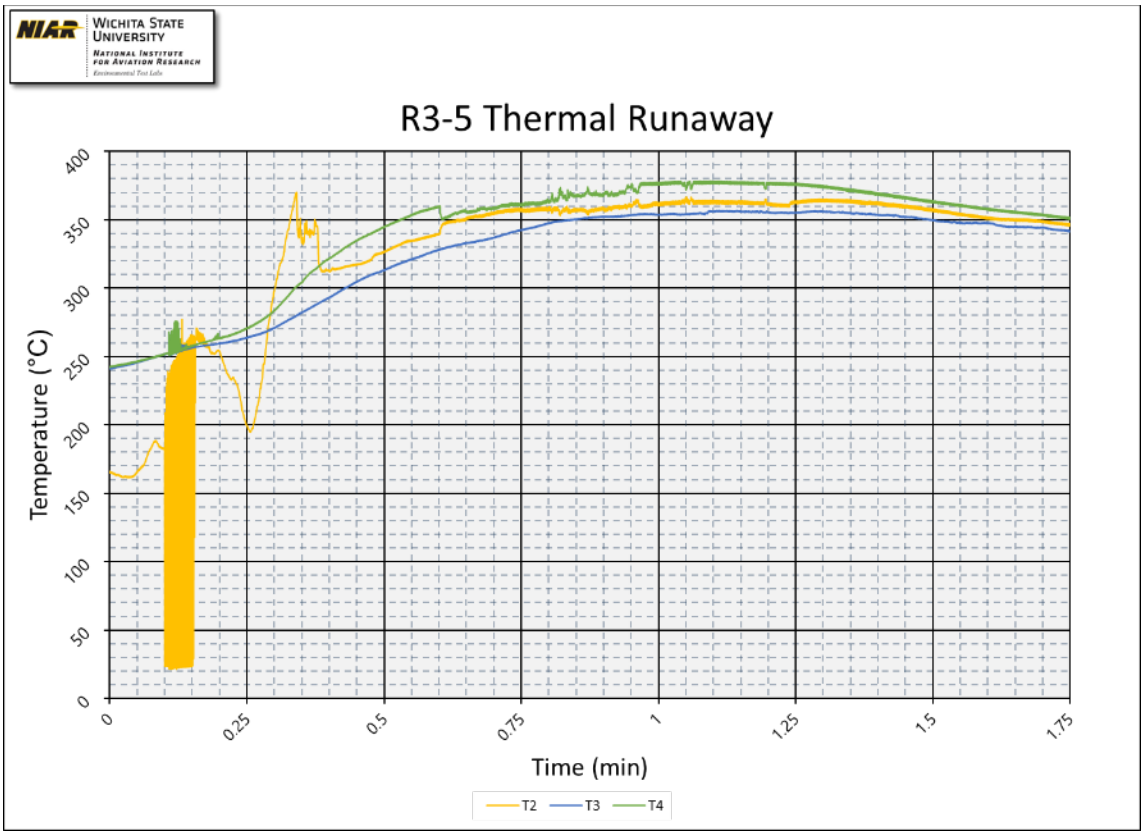

Figure 100: R3-5 Temperature Graph 2

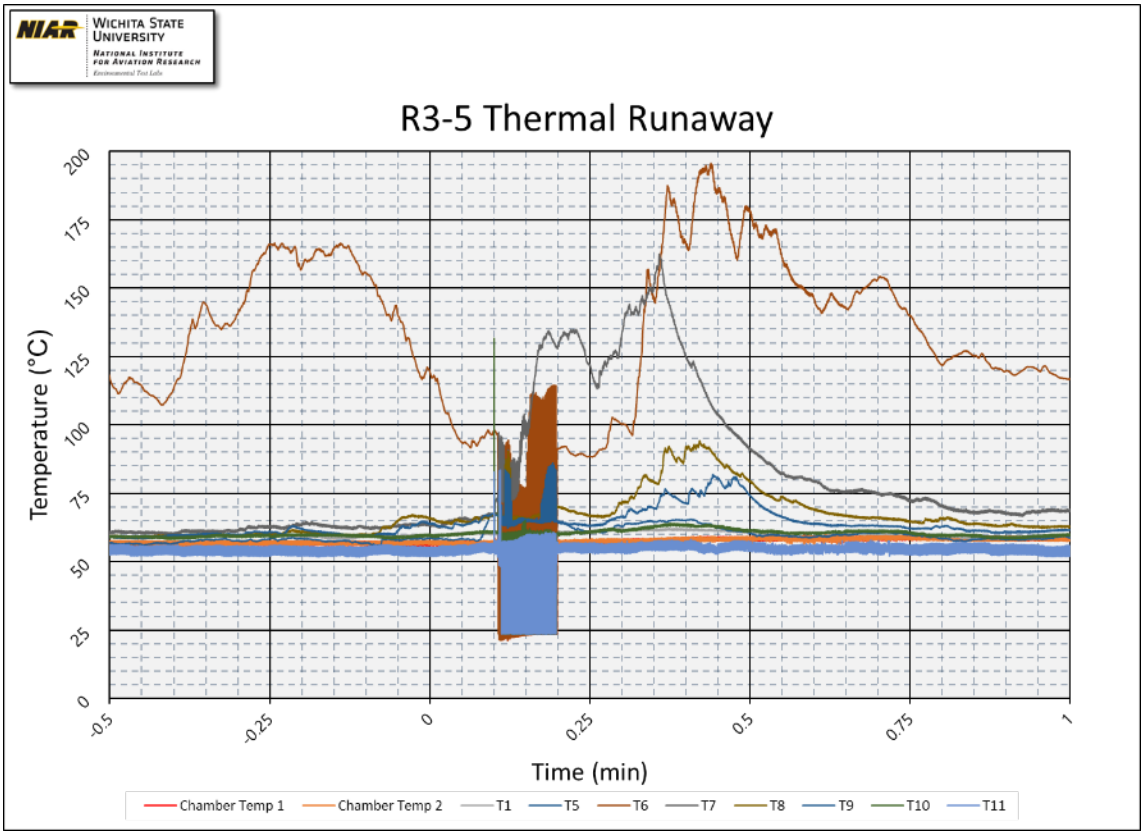

Figure 101: R3-5 Temperature Graph 3

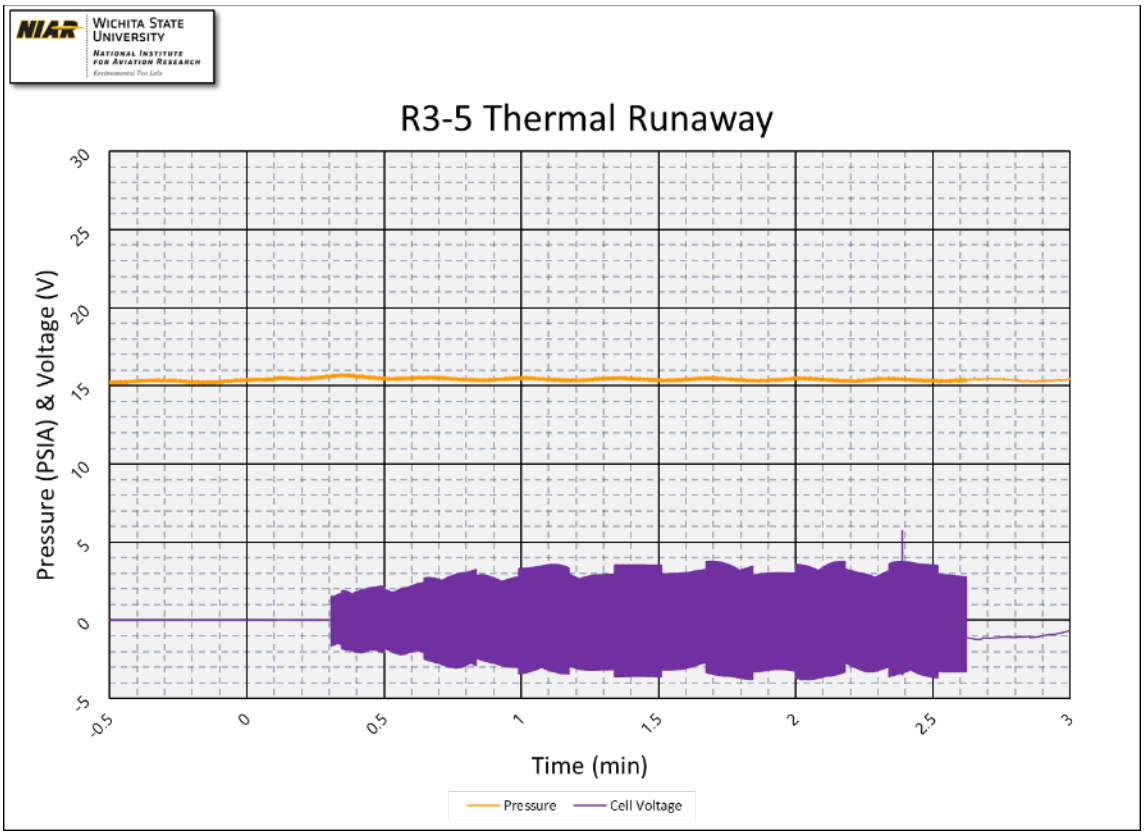

Figure 102: R3-5 Pressure & Voltage Graph

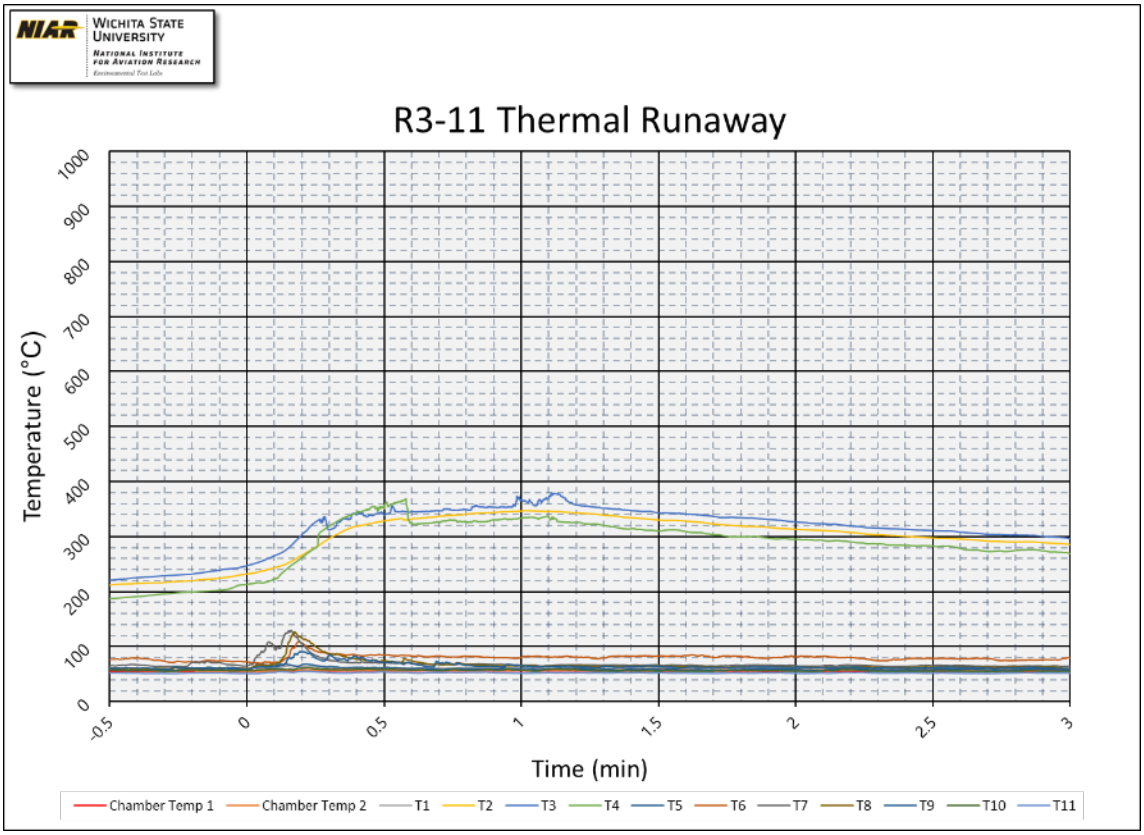

Figure 103: R3-11 Temperature Graph 1

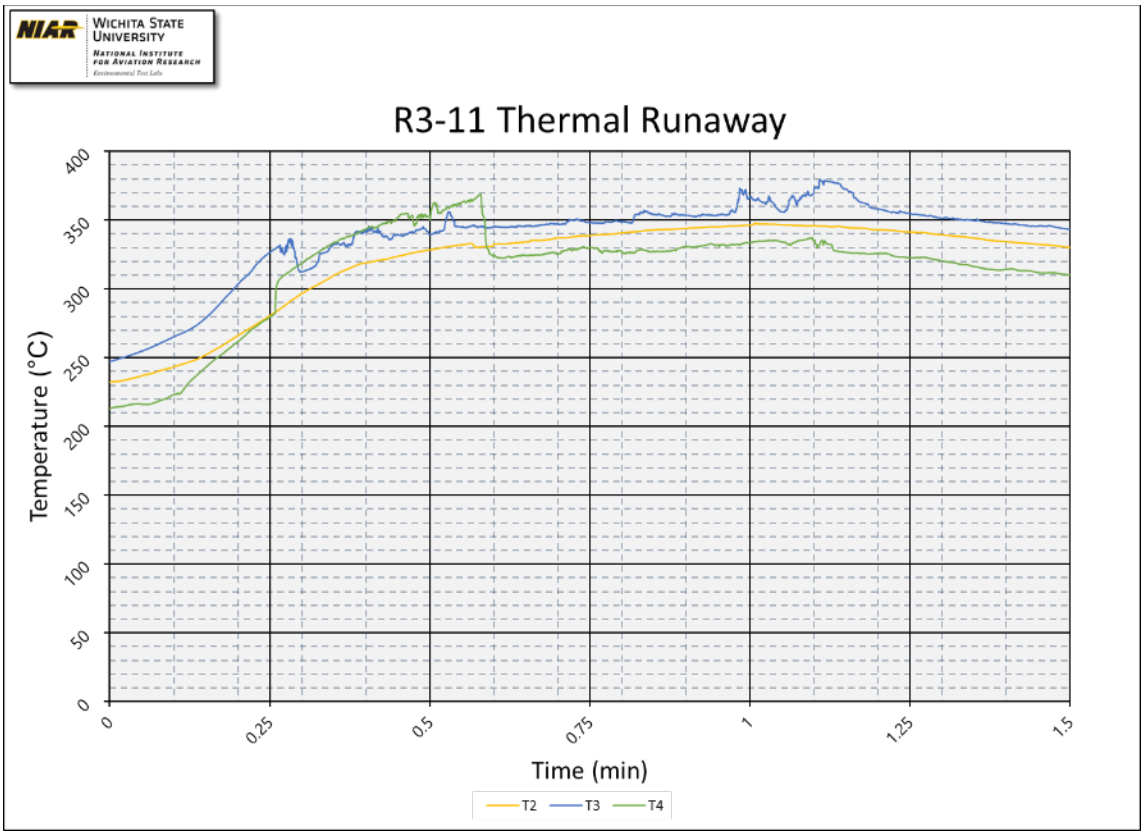

Figure 104: R3-11 Temperature Graph 2

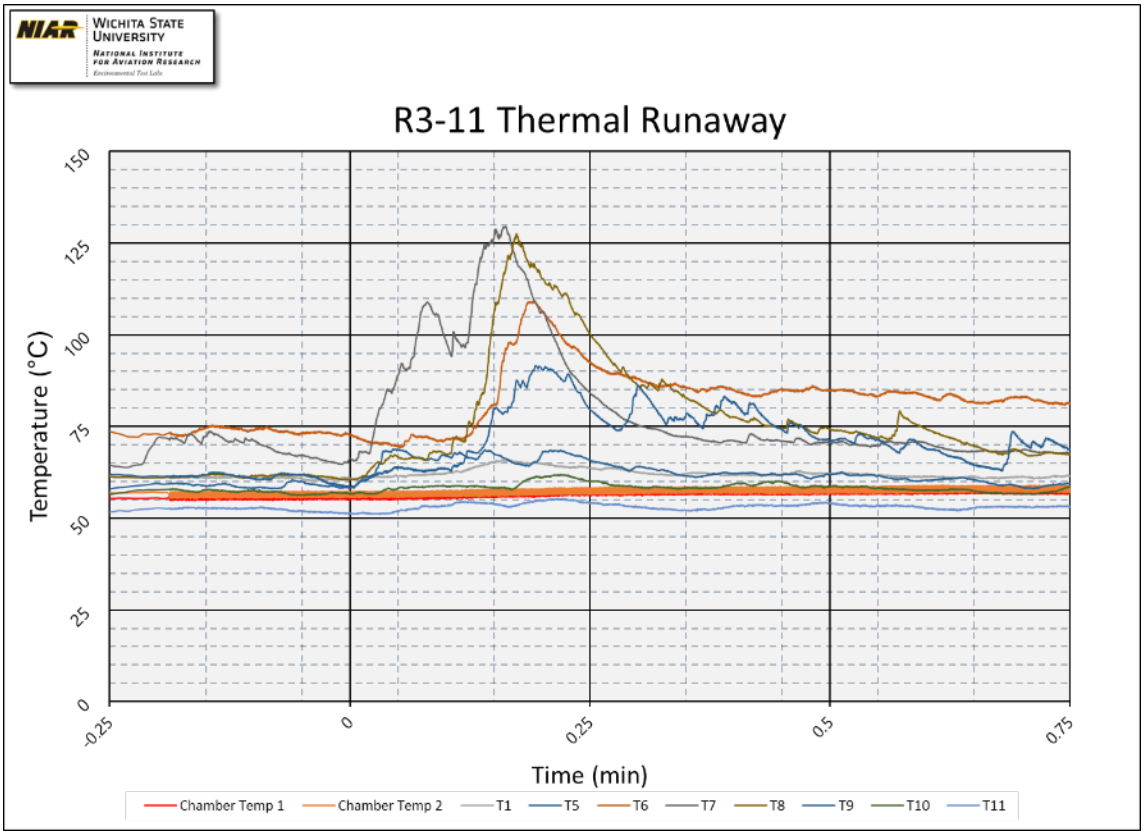

Figure 105: R5-11 Temperature Graph 3

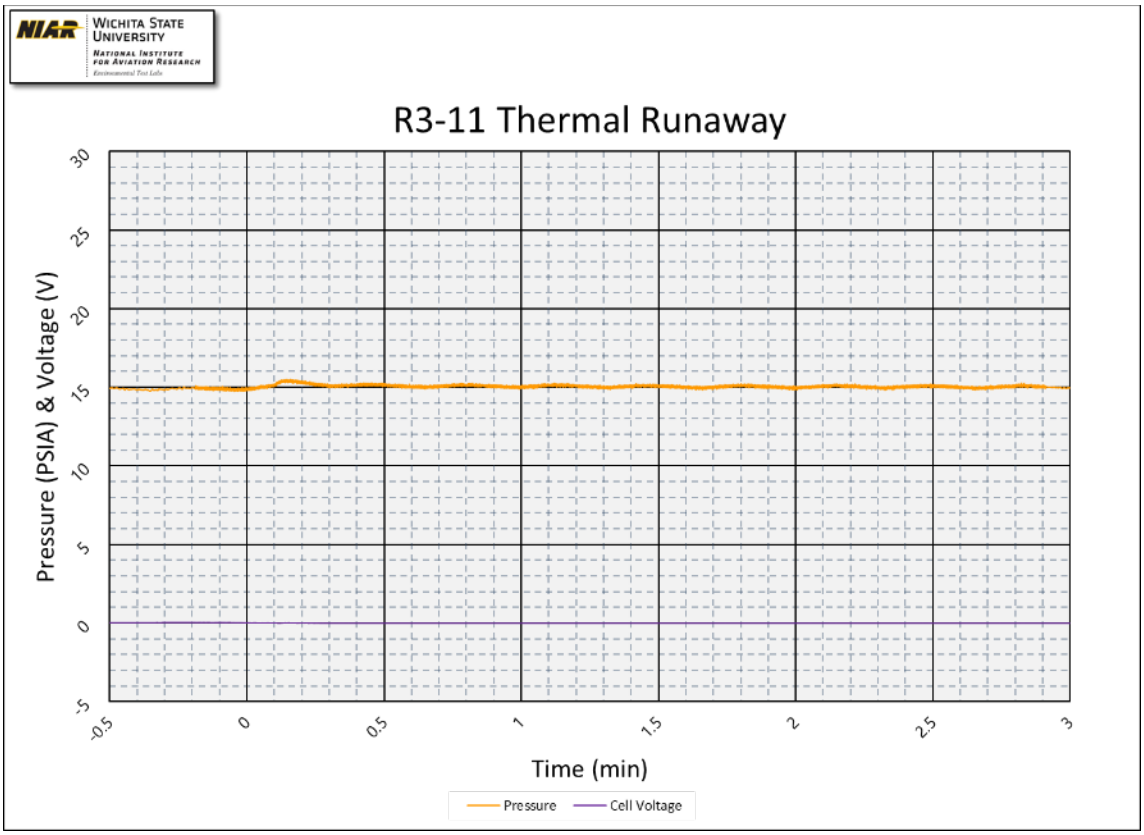

Figure 106: R3-11 Pressure & Voltage Graph

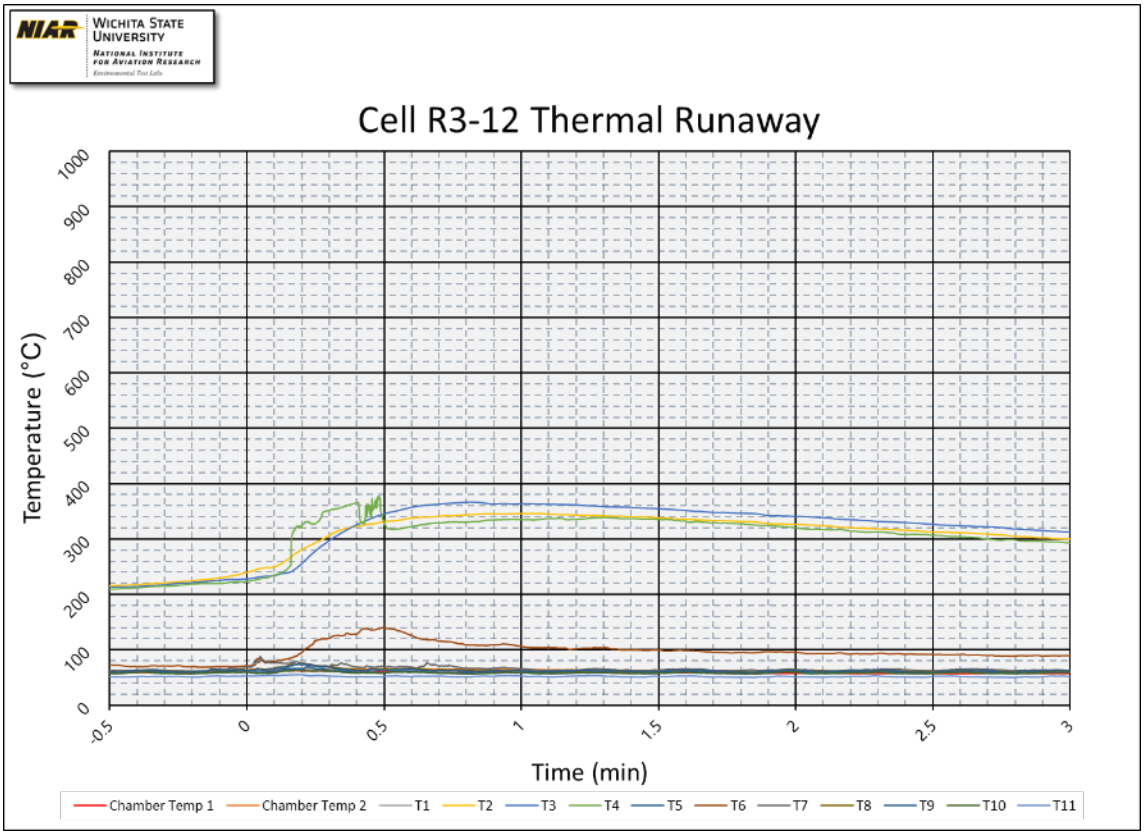

Figure 107: R3-12 Temperature Graph 1

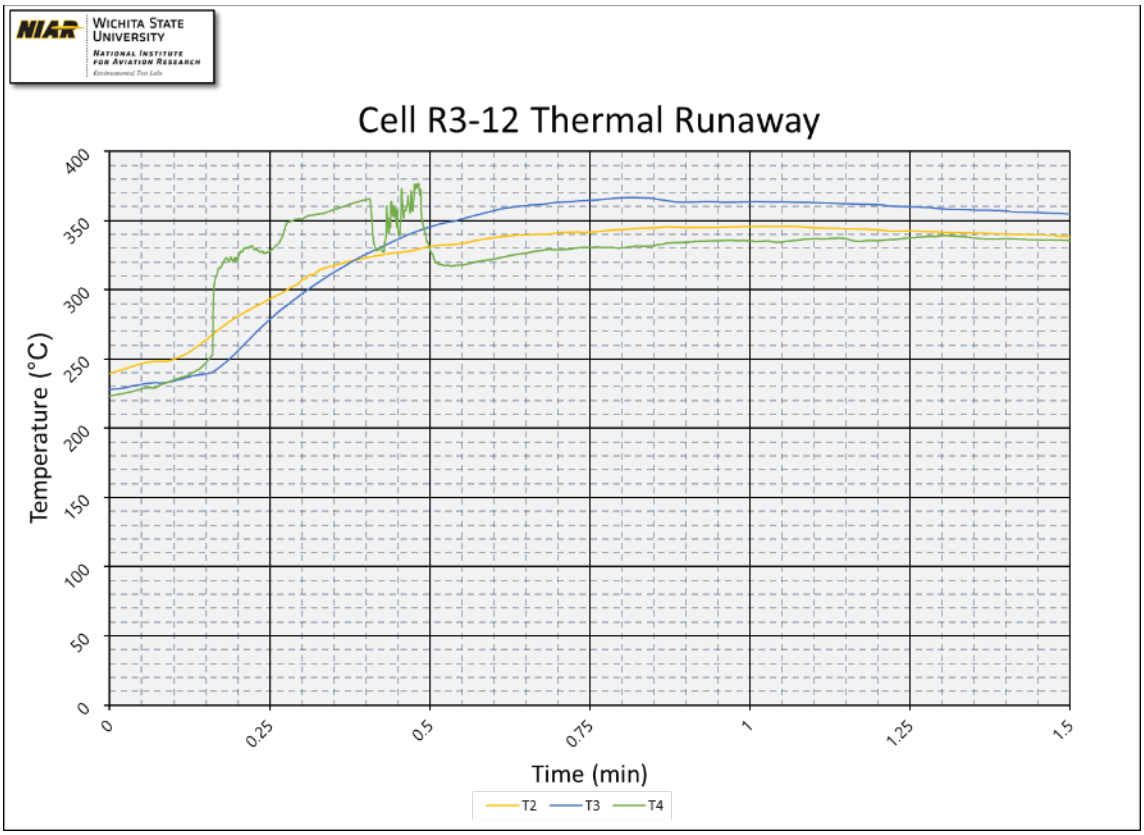

Figure 108: R3-12 Temperature Graph 2

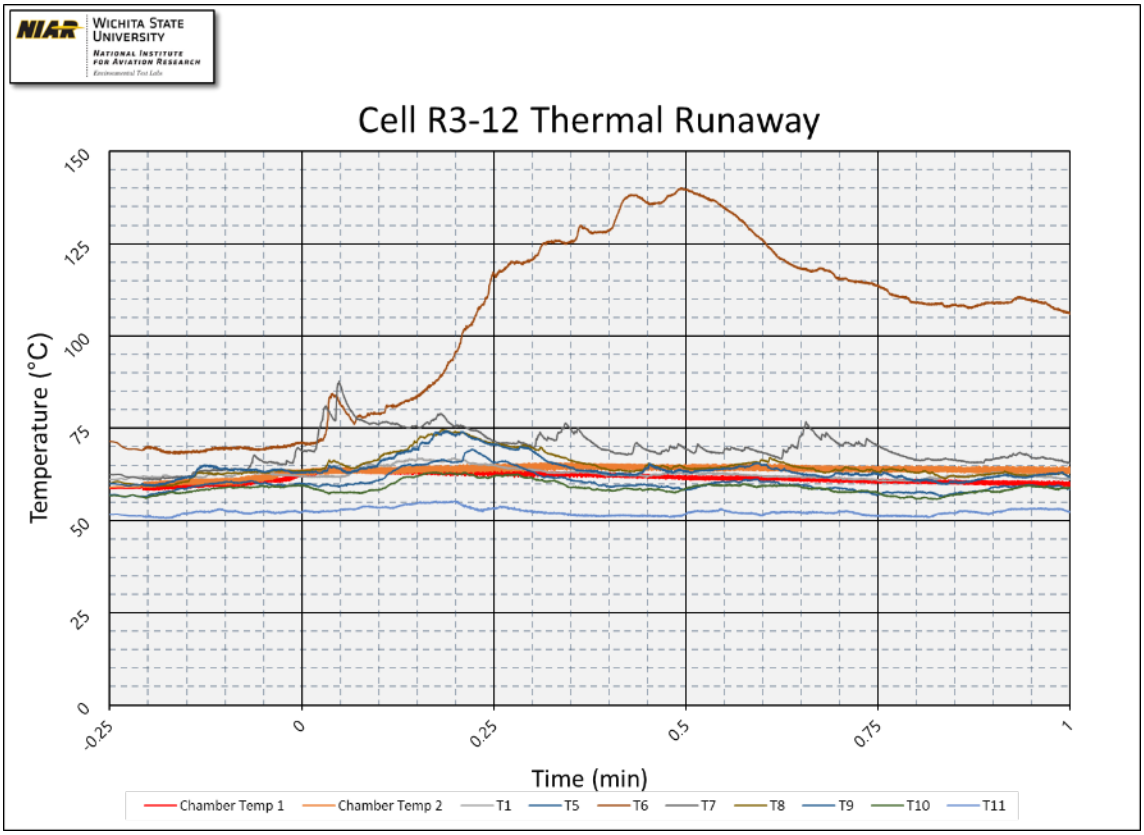

Figure 109: R3-12 Temperature Graph 3

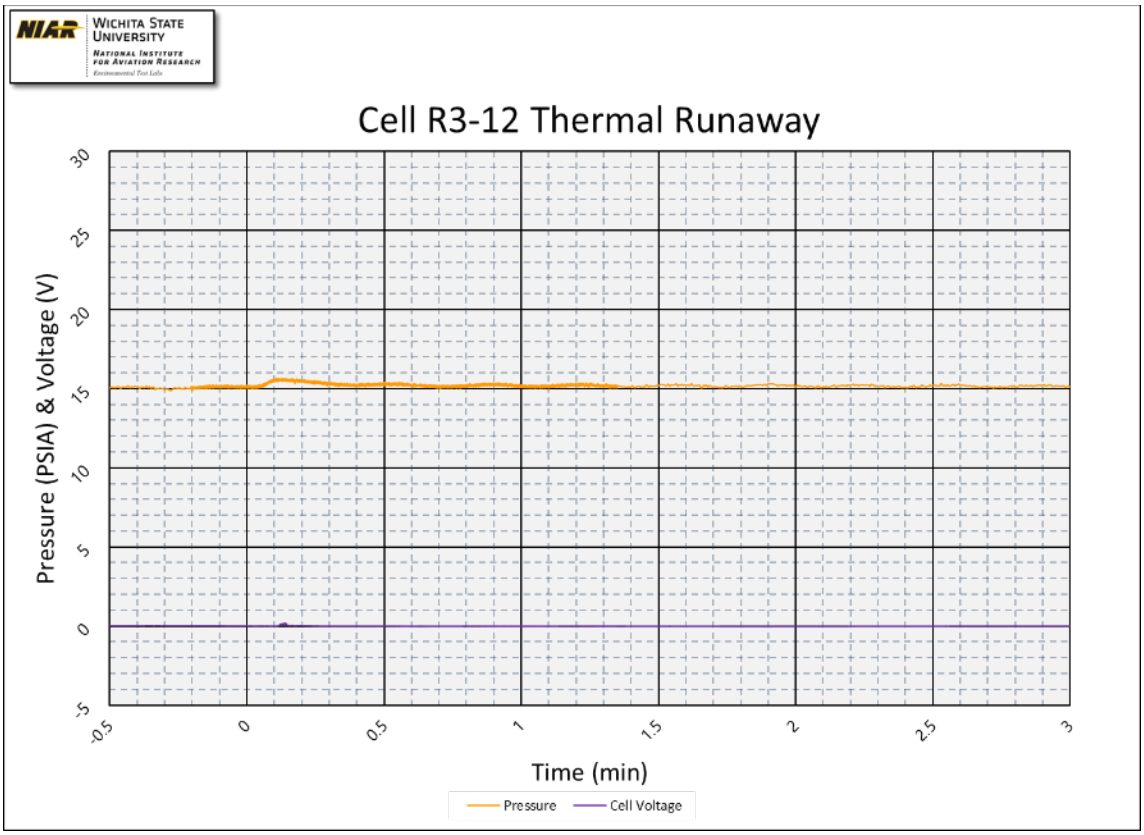

Figure 110: R3-12 Pressure & Voltage Graph

2.2.4 R4-X (Samsung INR21700-50S)

The R4-X cells were the most consistent of all the cell types in terms of gases released although the average temperatures were quite consistent as well. The reactions resulted in an average cell peak temperature of 348.4°C and an average chamber peak temperature of 391.4°C. The R4 cells had the most consistent thermal runaway onset temperature of all the cells, with a standard deviation of only 4.6°C. As stated above, the R4 cells had the most repeatable gas detection results. All 5 cells released similar amounts of carbon monoxide, carbon dioxide, ethylene, sulfuric acid, hydrogen cyanide, nitric oxide, and nitrogen dioxide. The cells lost an average of 34.351g of mass, which translates to a 48% loss in overall cell mass.

Table 16: R4-X Mass Change Summary

Cell	Pre-Test Mass (g)	Post-Test Mass (g)
R4-1	70.843	40.207
R4-2	70.835	32.073
R4-3	70.758	35.364
R4-4	70.961	39.305
R4-5	70.806	35.499

Table 17: R4-X Detected Gases

Gas Species	Detector Tube Error Range	Moles of Gas Detected R4-1	Moles of Gas Detected R4-2	Moles of Gas Detected R4-3	Moles of Gas Detected R4-4	Moles of Gas Detected R4-5
CO	±10%	0.11	0.11	0.083	0.11	0.083
CO_2	±10%	0.34	0.38	0.25	0.33	0.33
C_2H_4	±20 - 30%	4.2E-3	6.2E-3	2.2E-3	3.3E-3	3.3E-3
H_2	±15 - 20%	0	0	0	0	0
H_2S	±25%	0	0	0	0	0
H_2SO_4	±10%	8.0E-06	8.9E-06	2.8E-06	5.4E-06	2.0E-06
HCl	±15%	0	0	0	0	0
HCN	±10 - 15%	5.5E-06	6.2E-06	1.1E-05	6.6E-06	2.8E-06
HF	±10%	0	0	0	0	0
HNO_3	±15%	0	0	0	0	0
NO	±10 - 15%	2.1E-4	4.3E-4	1.5E-4	1.3E-4	1.5E-4
NO_2	±10 - 15%	1.7E-05	6.2E-06	1.4E-05	1.5E-05	1.7E-05
SO_2	±10%	0	0	0	0	0

Table 18: R4-X Failure Modes

Failure Mode	Leak	Vent	Fire	Rupture
R4-1		Y	Y	Y
R4-2		Y	Y	Y
R4-3		Y	Y	Y
R4-4		Y	Y	Y
R4-5		Y	Y	Y

Figure 111: R4-1 Pre-Test

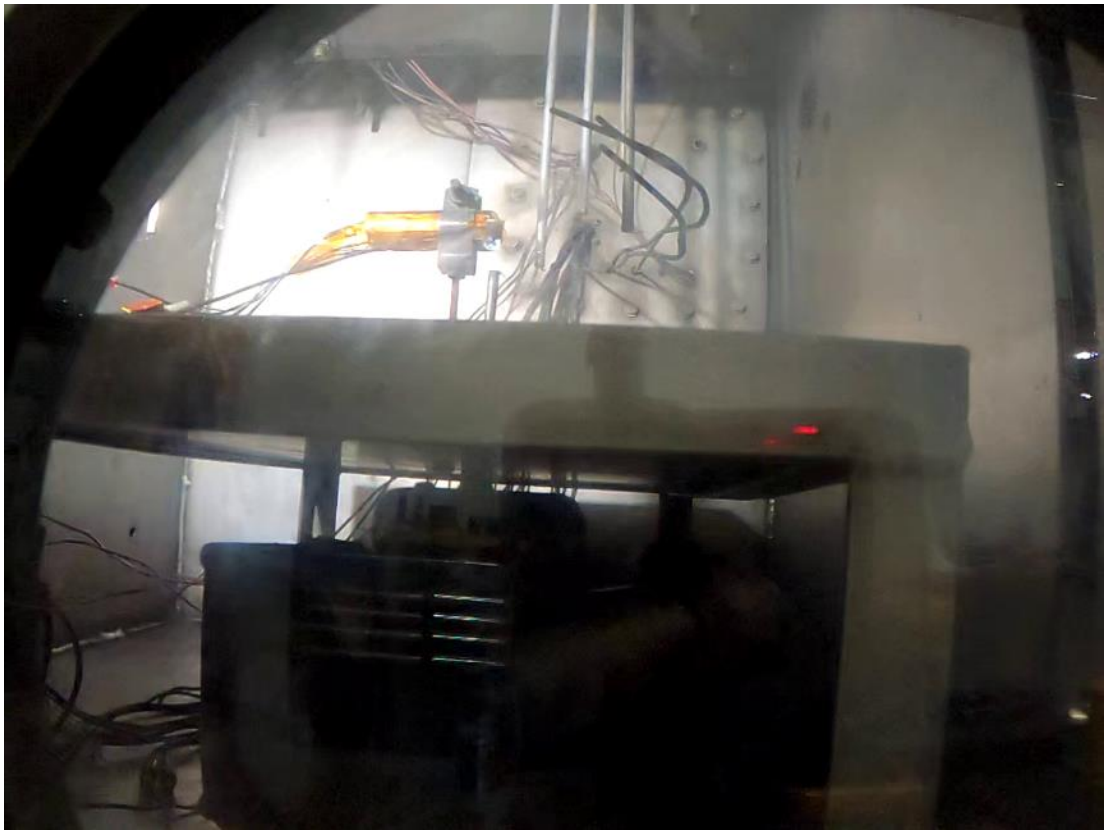

Figure 112: R4-1 Venting

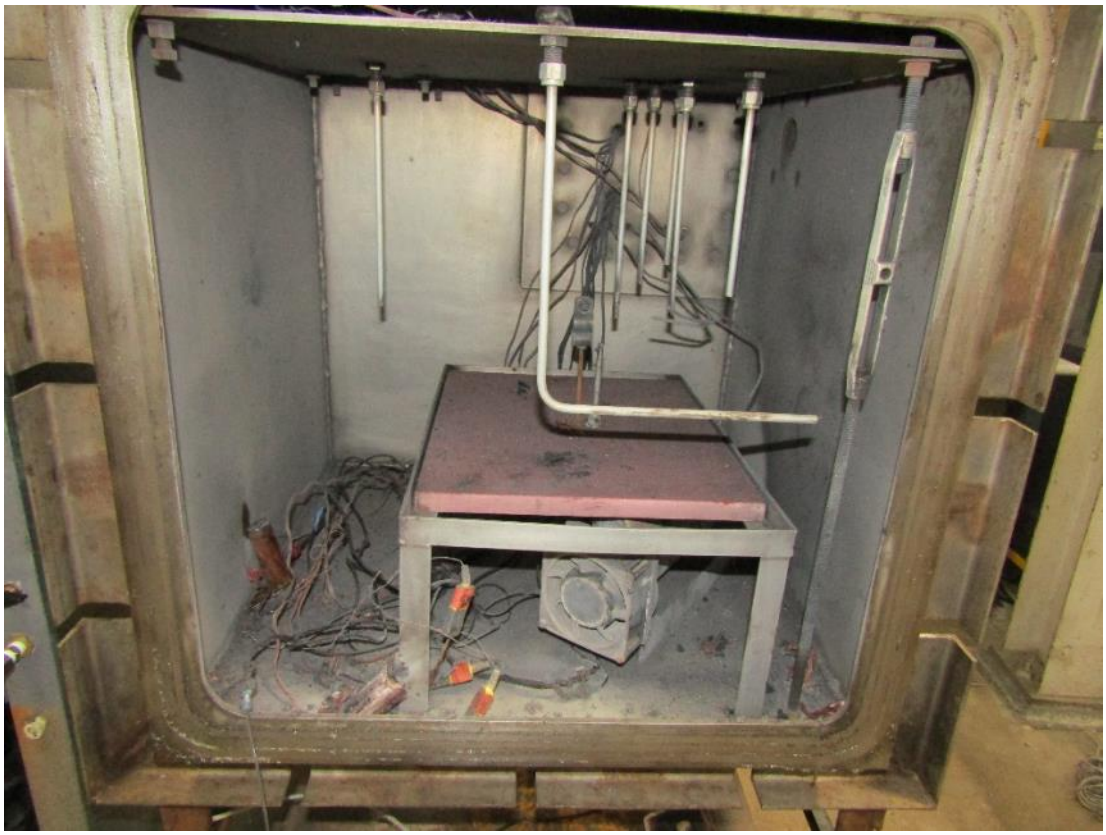

Figure 113: R4-1 Post-Test 1

Figure 114: R4-1 Post-Test 2

Figure 115: R4-2 Pre-Test

Figure 116: R4-2 Venting

Figure 117: R4-2 Post-Test 1

Figure 118: R4-2 Post-Test 2

Figure 119: R4-3 Pre-Test

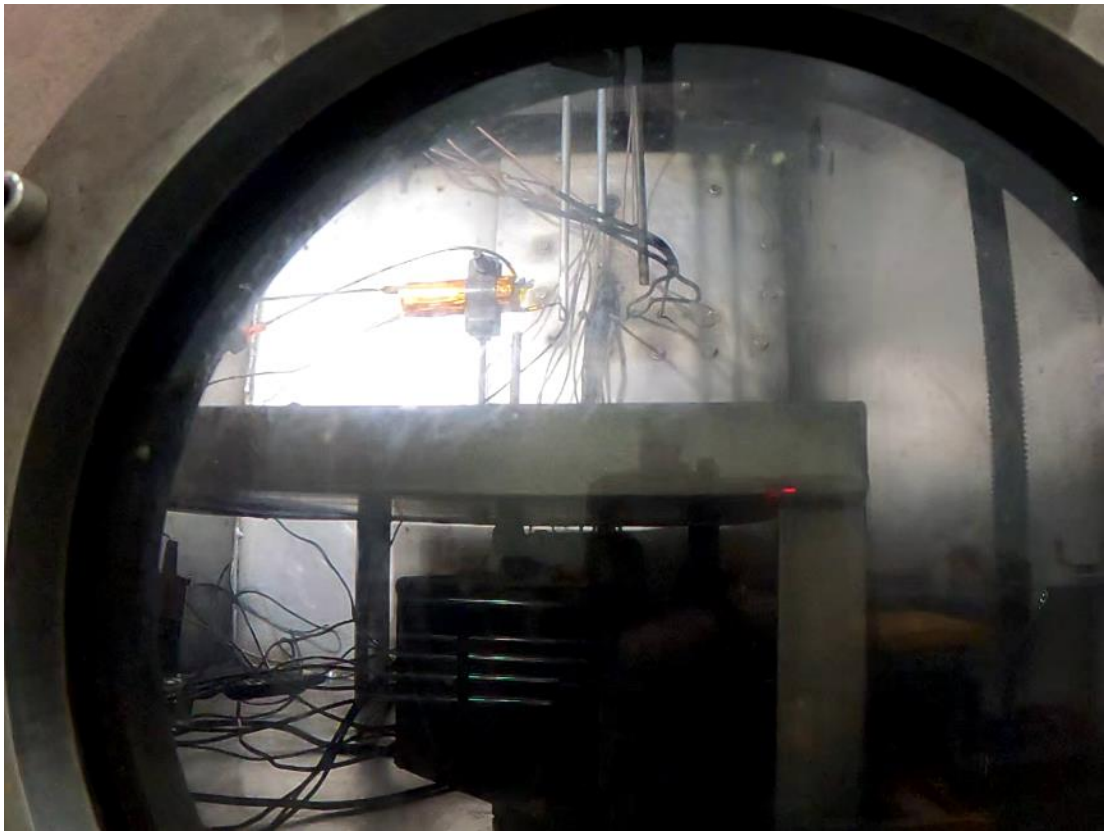

Figure 120: R4-3 Venting

Figure 121: R4-3 Post-Test 1

Figure 122: R4-3 Post Test 2

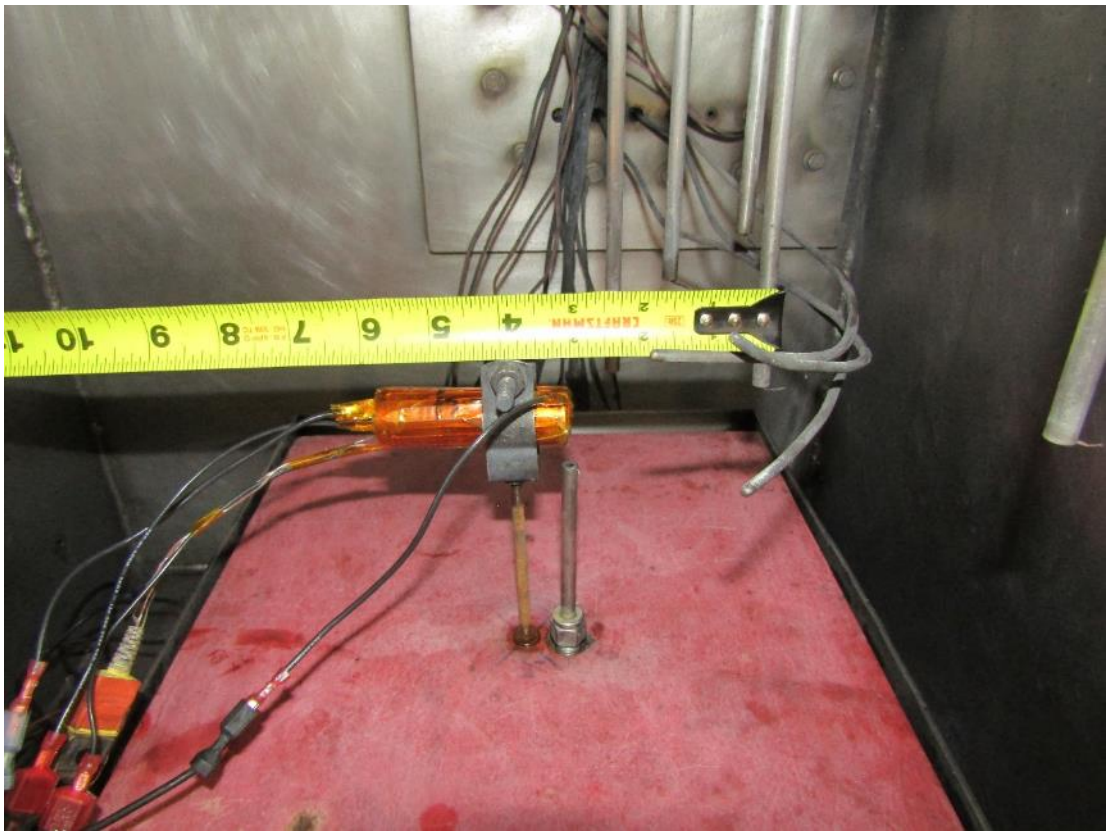

Figure 123: R4-4 Pre-Test

Figure 124: R4-4 Venting and Fire

Figure 125: R4-4 Post-Test 1

Figure 126: R4-4 Post-Test 2

Figure 127: R4-5 Pre-Test

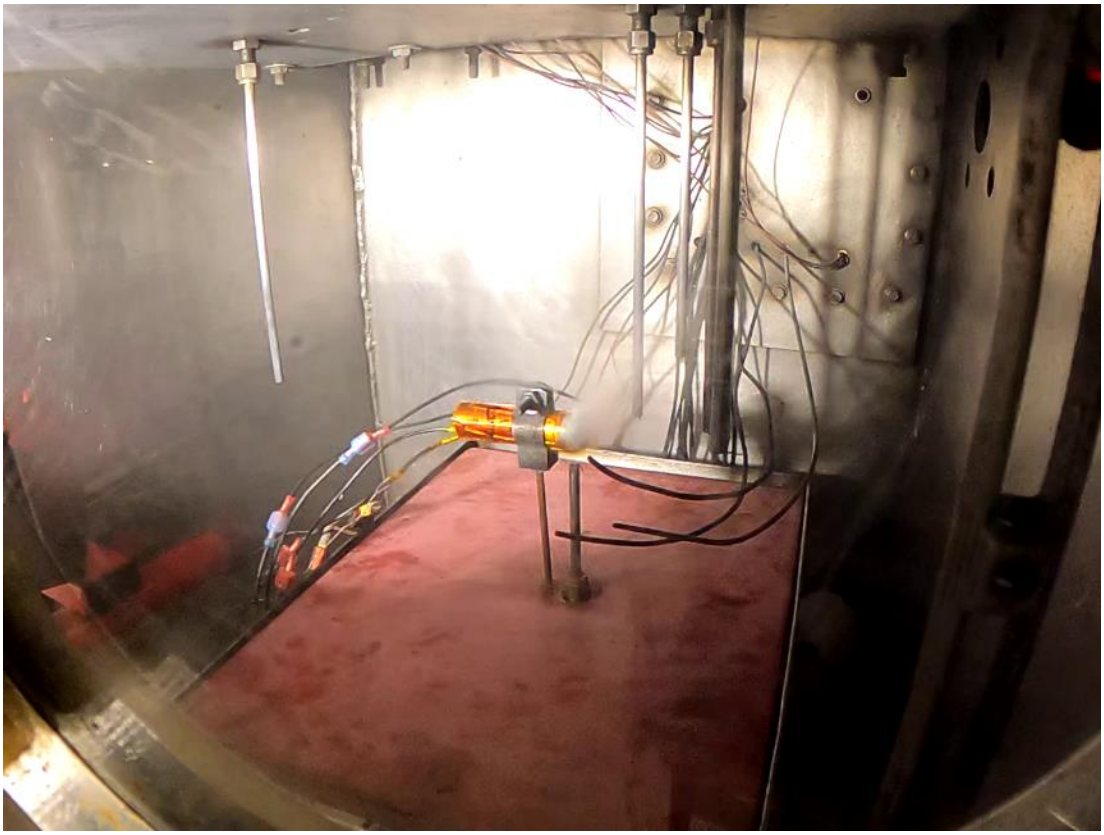

Figure 128: R4-5 Venting and Rupture

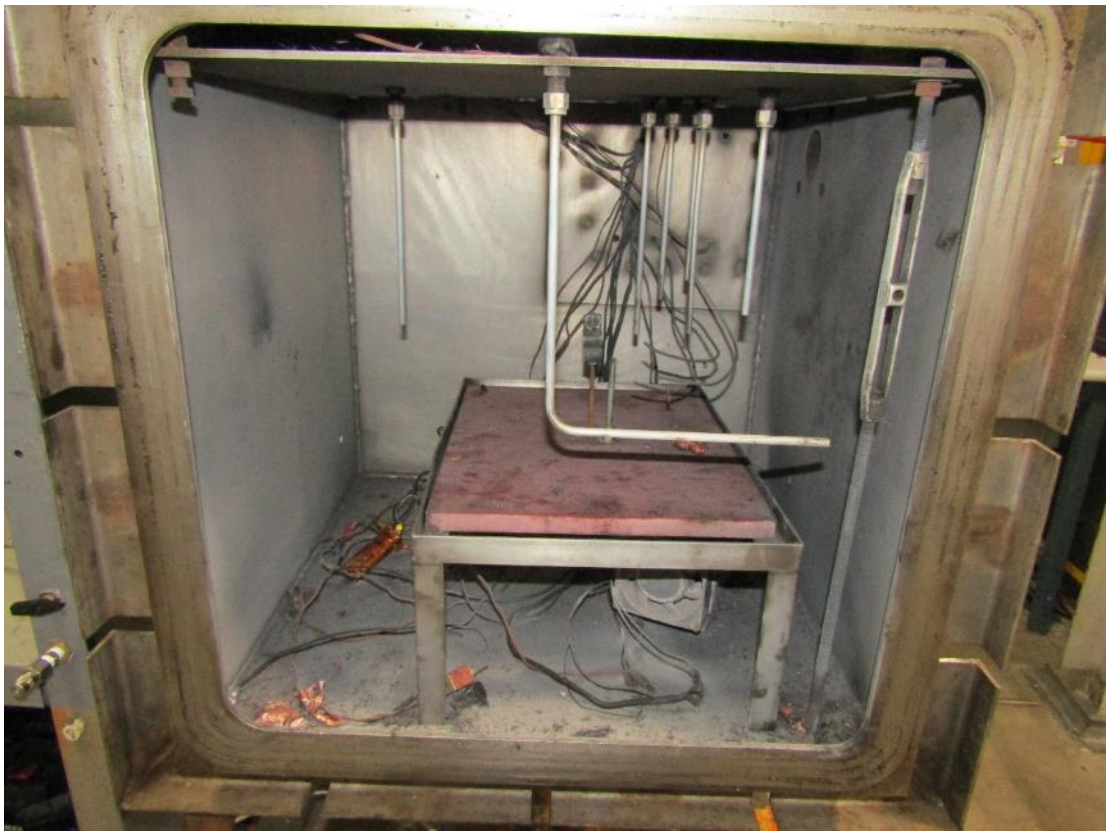

Figure 129: R4-5 Post-Test 1

Figure 130: R4-5 Post-Test 2

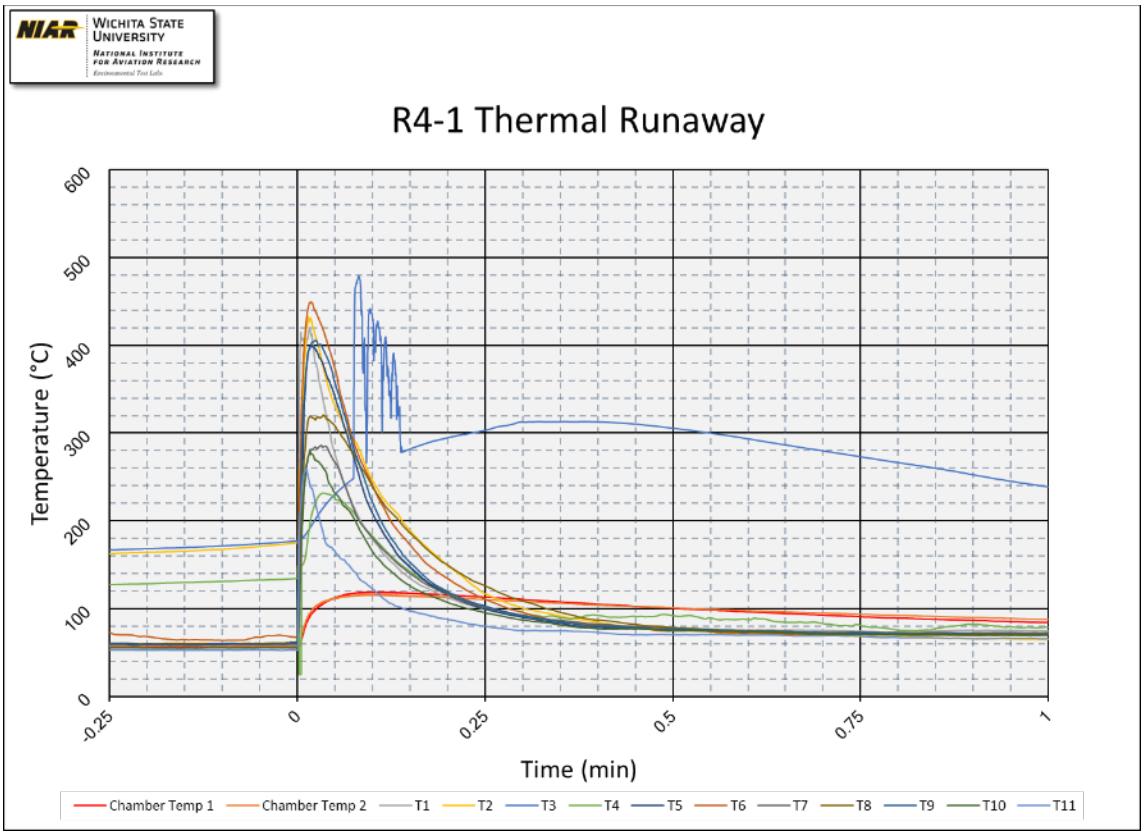

Figure 131: R4-1 Temperature Graph 1

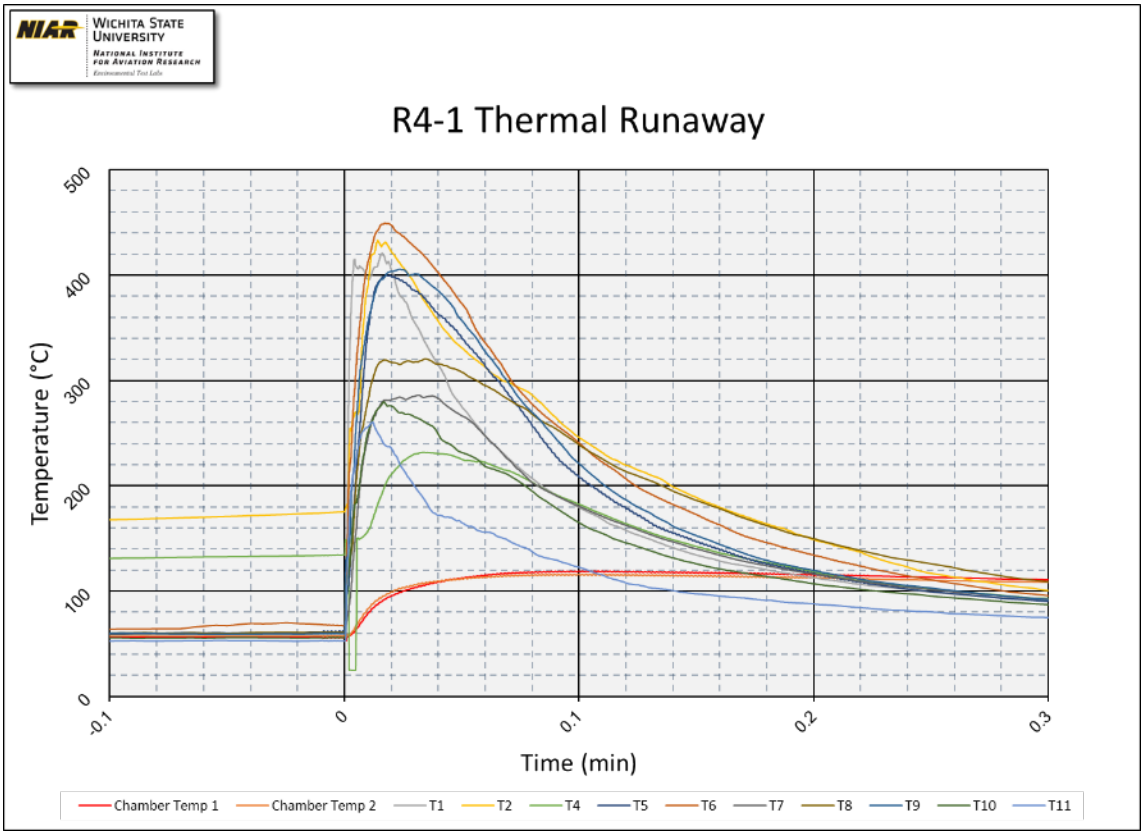

Figure 132: R4-1 Temperature Graph 2

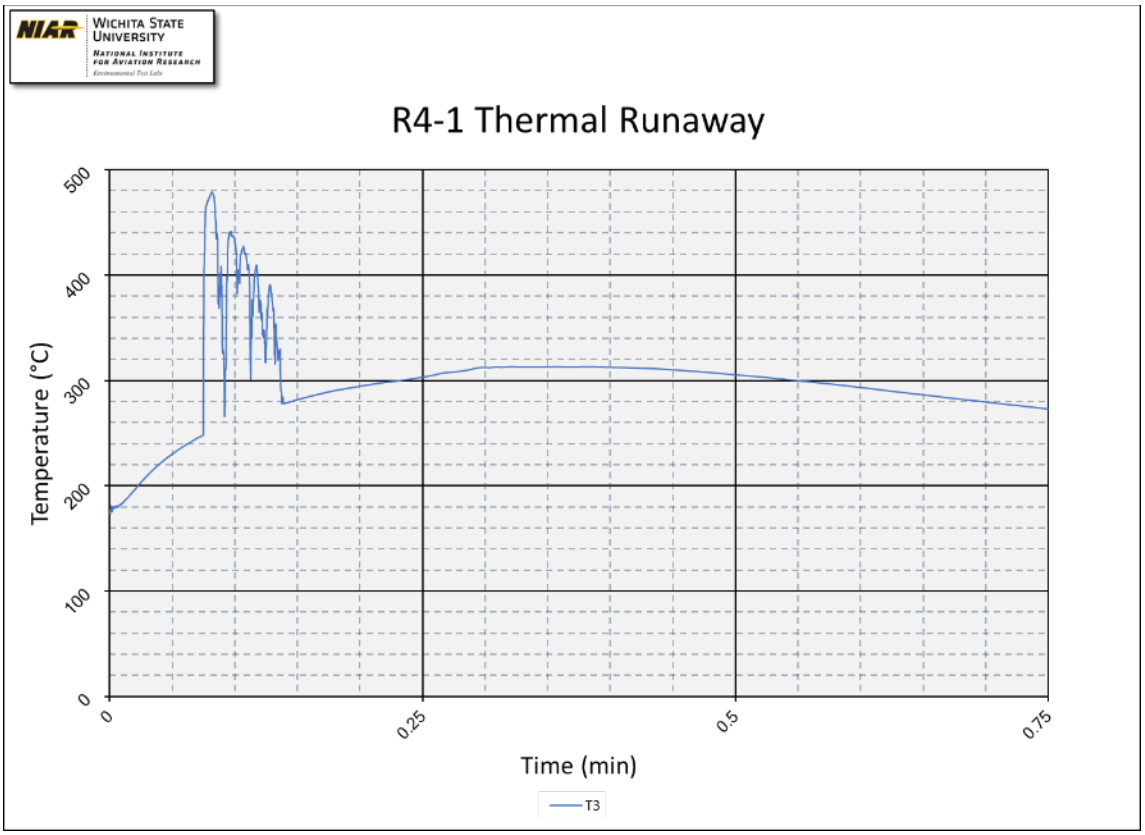

Figure 133: R4-1 Temperature Graph 3

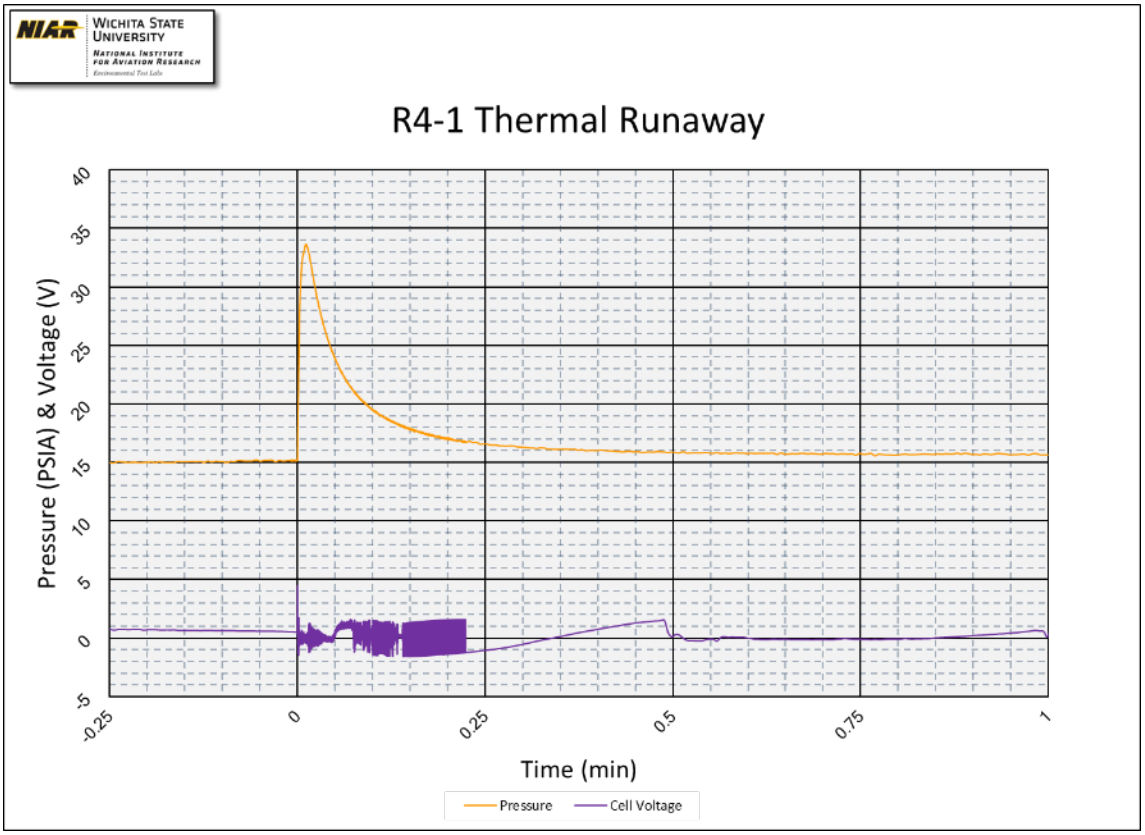

Figure 134: R4-1 Pressure and Voltage Graph

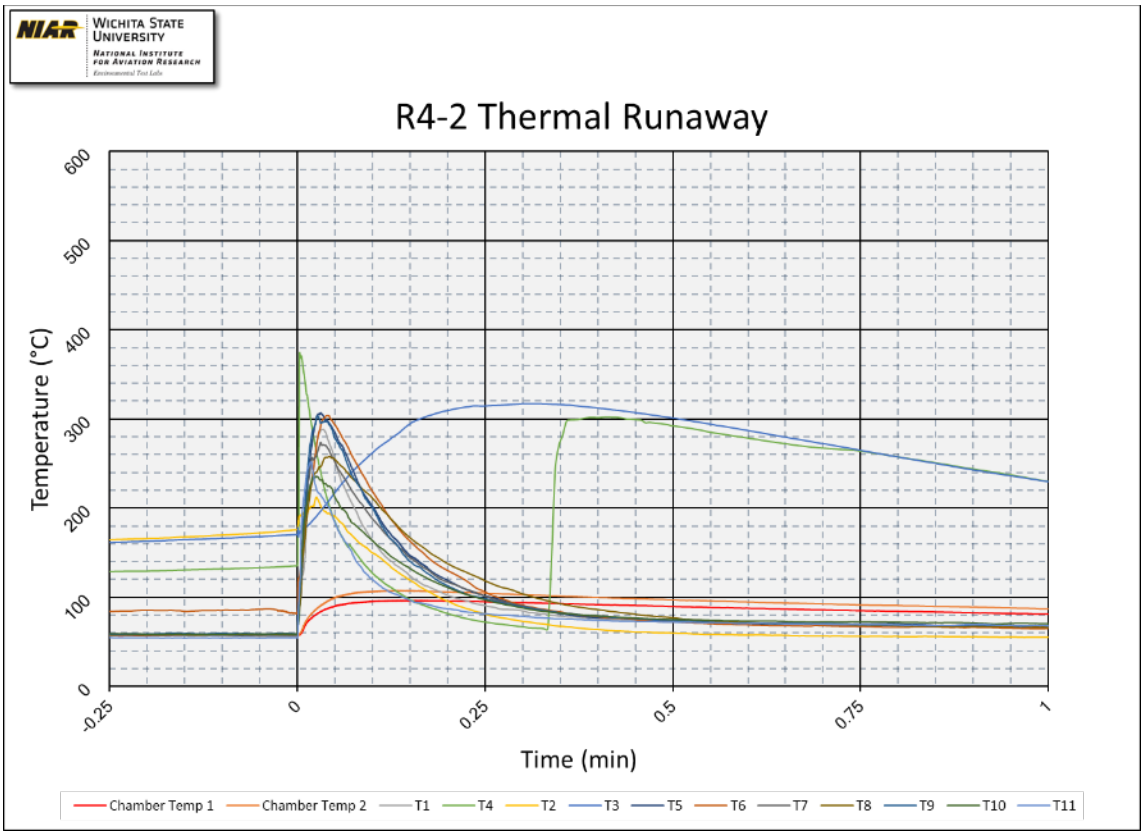

Figure 135: R4-2 Temperature Graph

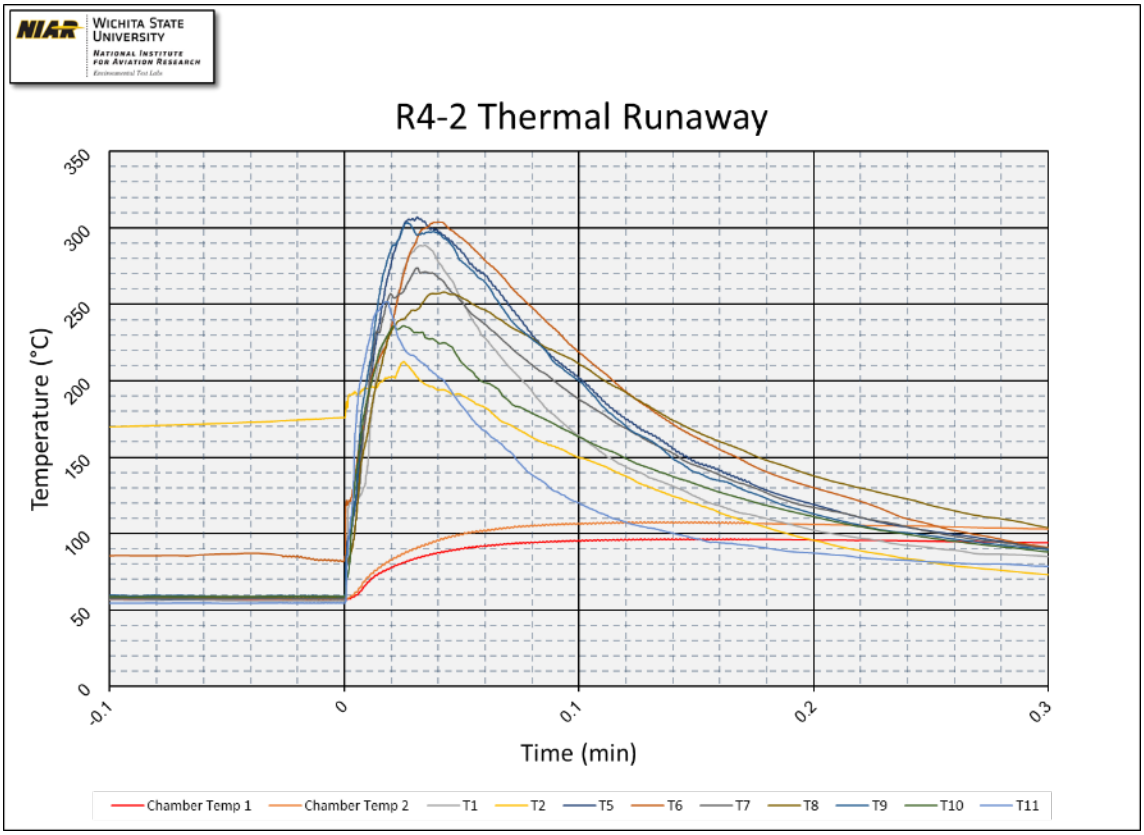

Figure 136: R4-2 Temperature Graph 2

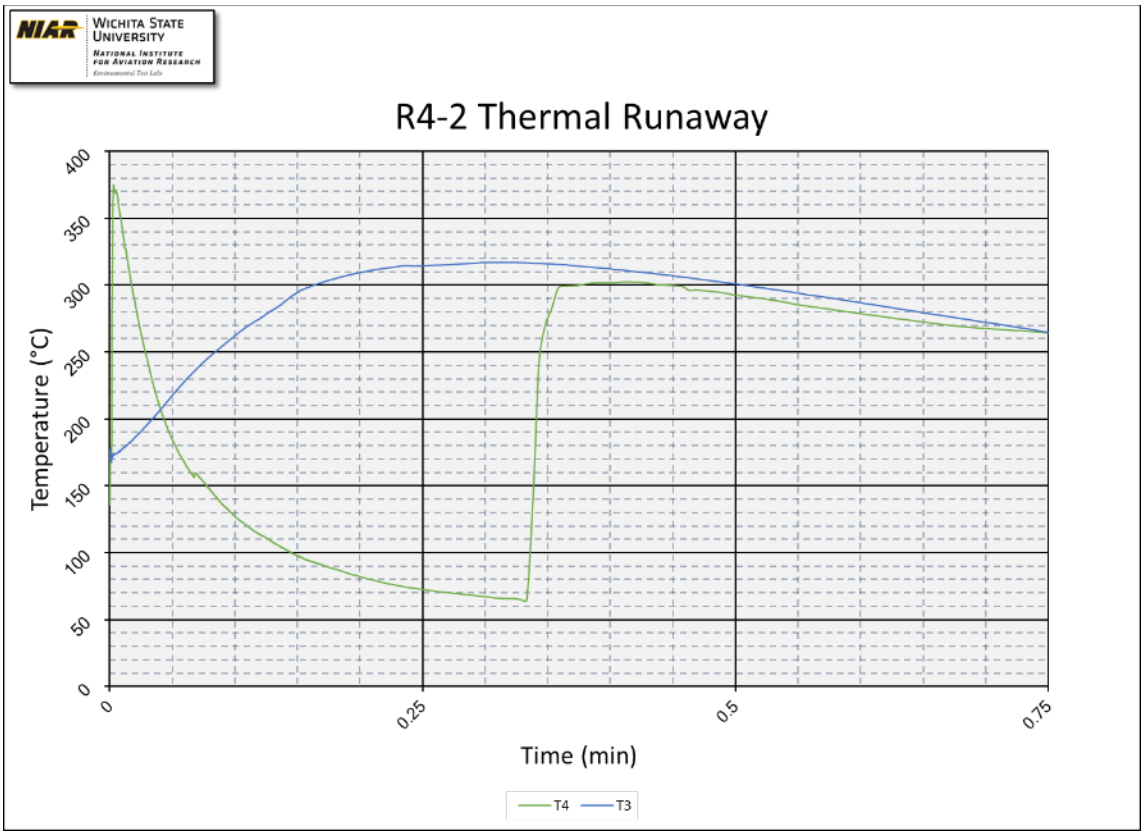

Figure 137: R4-2 Temperature Graph 3

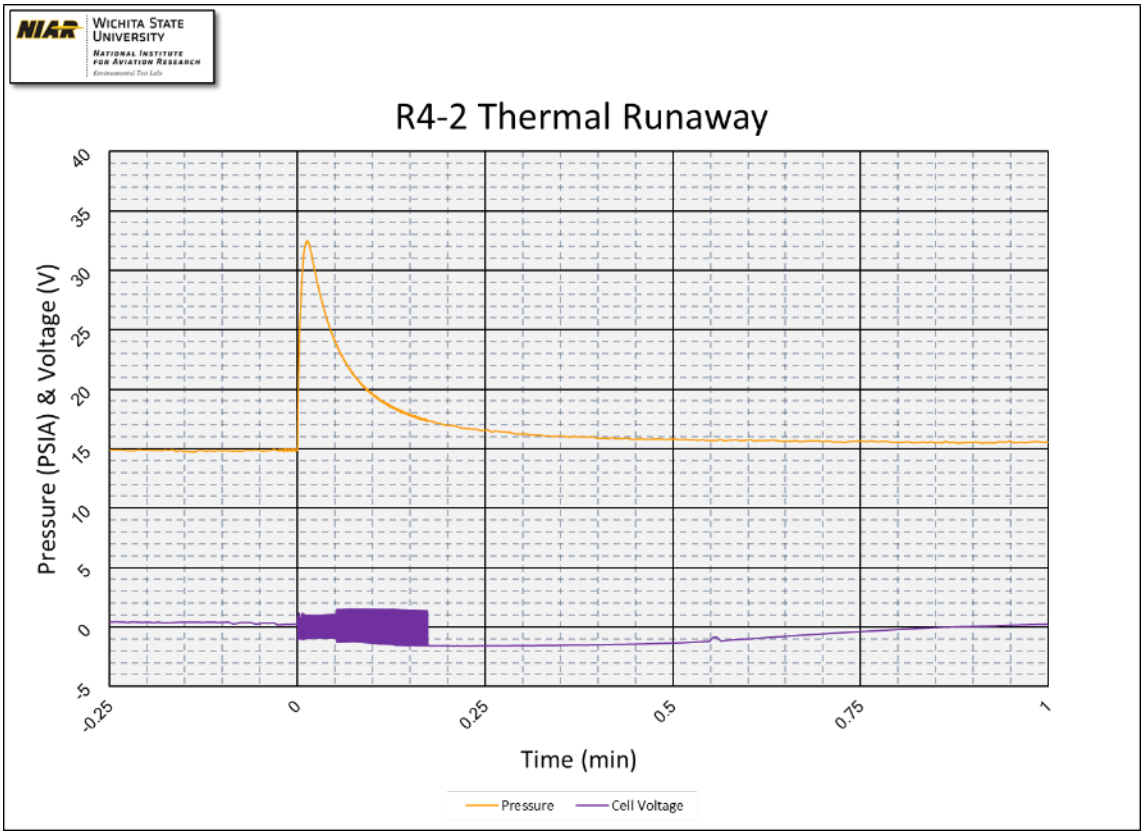

Figure 138: R4-2 Pressure and Voltage Graph

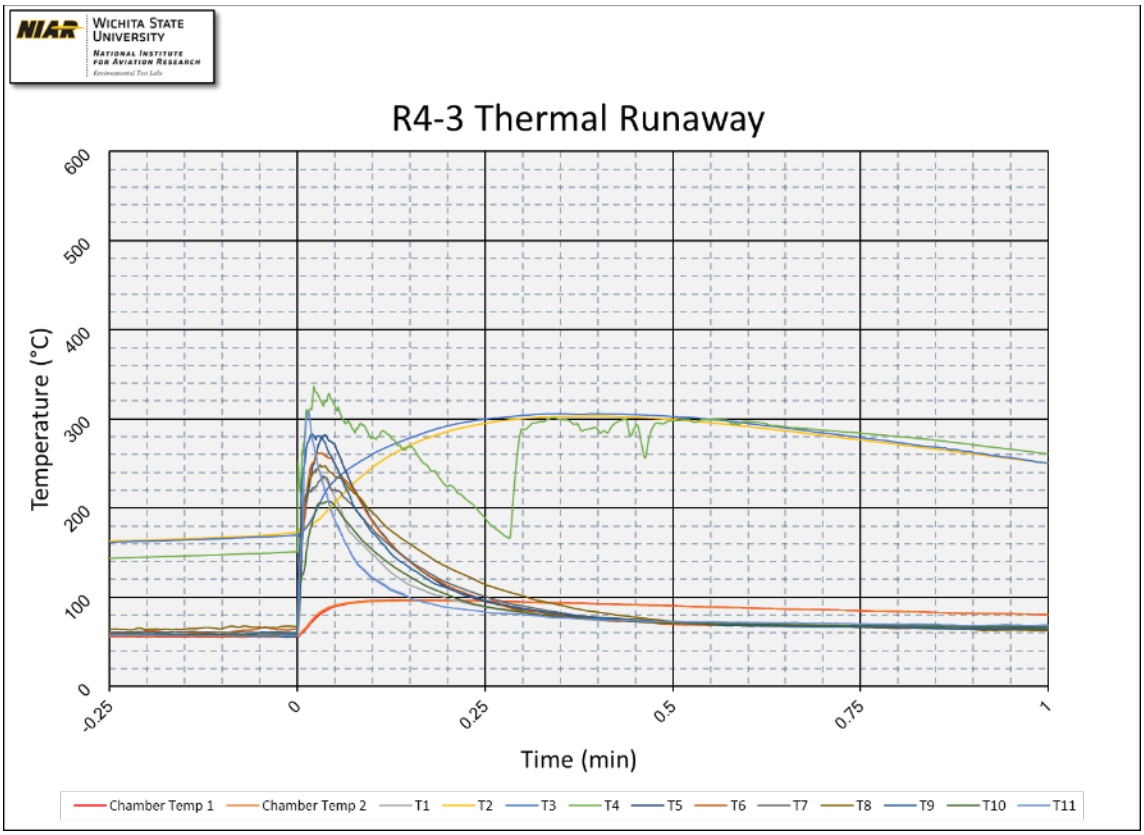

Figure 139: R4-3 Temperature Graph 1

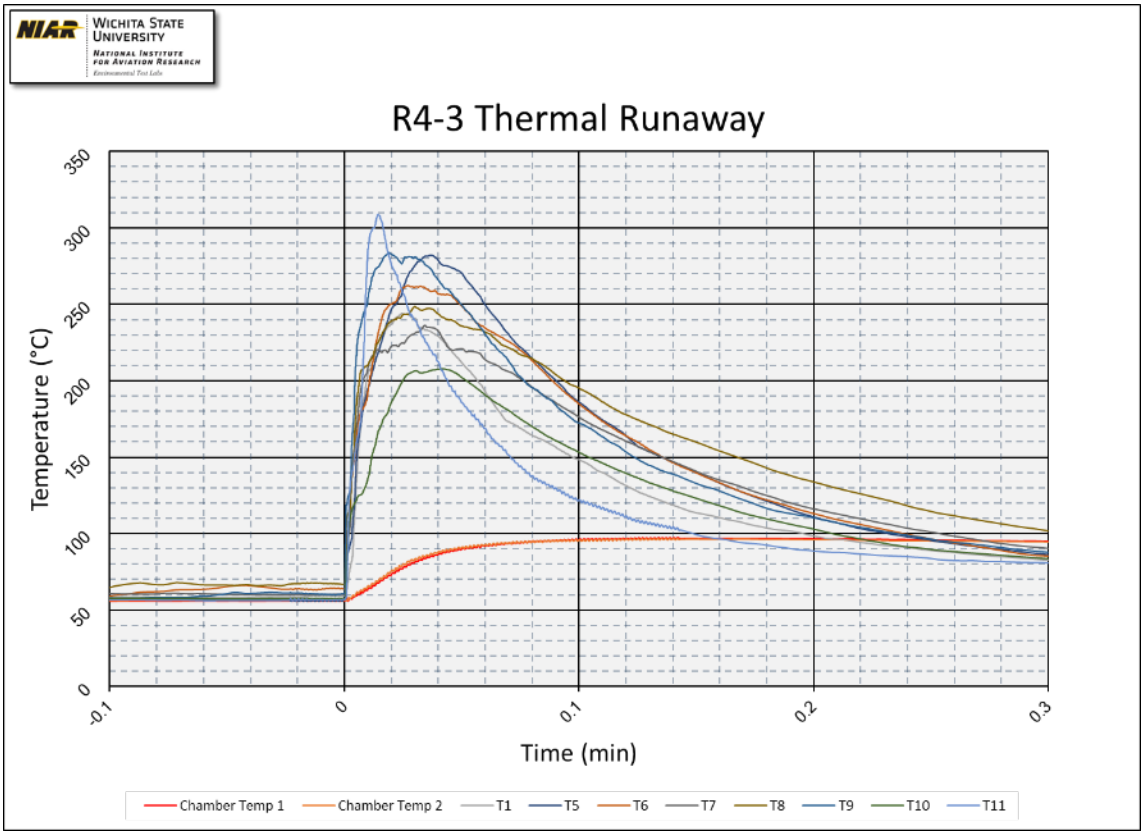

Figure 140: R4-3 Temperature Graph 2

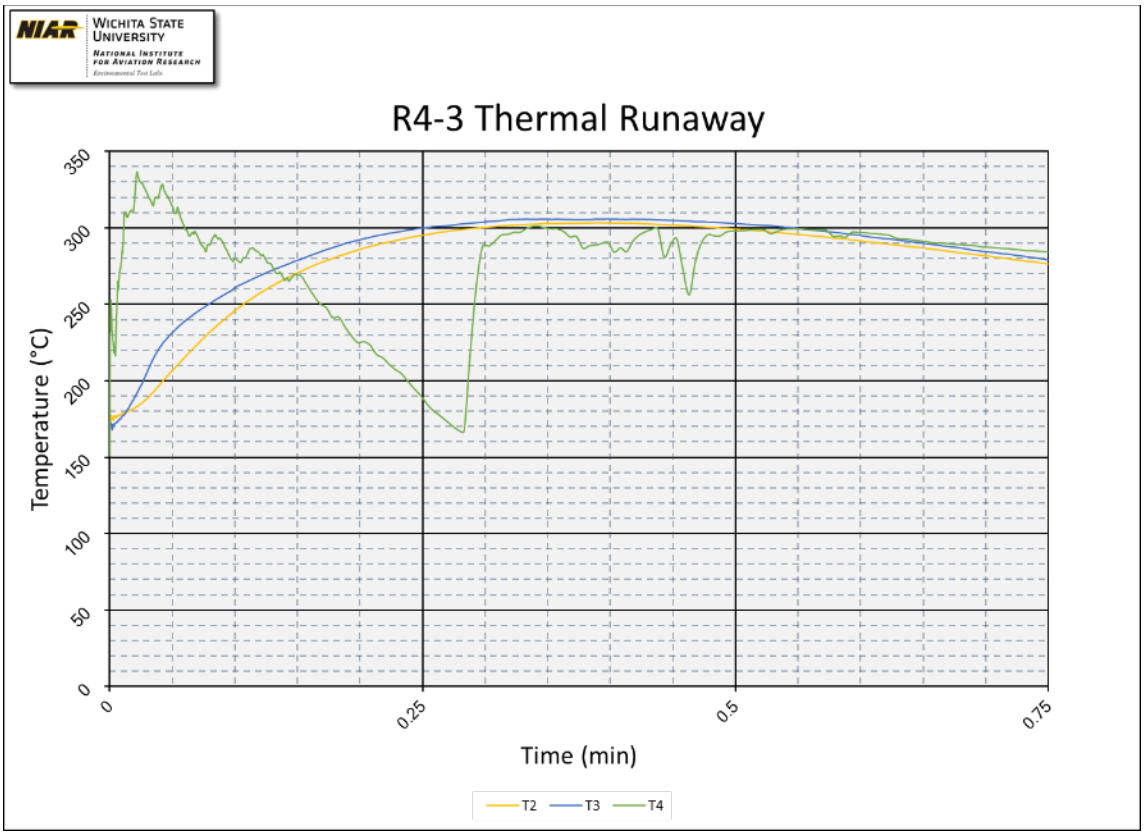

Figure 141: R4-3 Temperature Graph 3

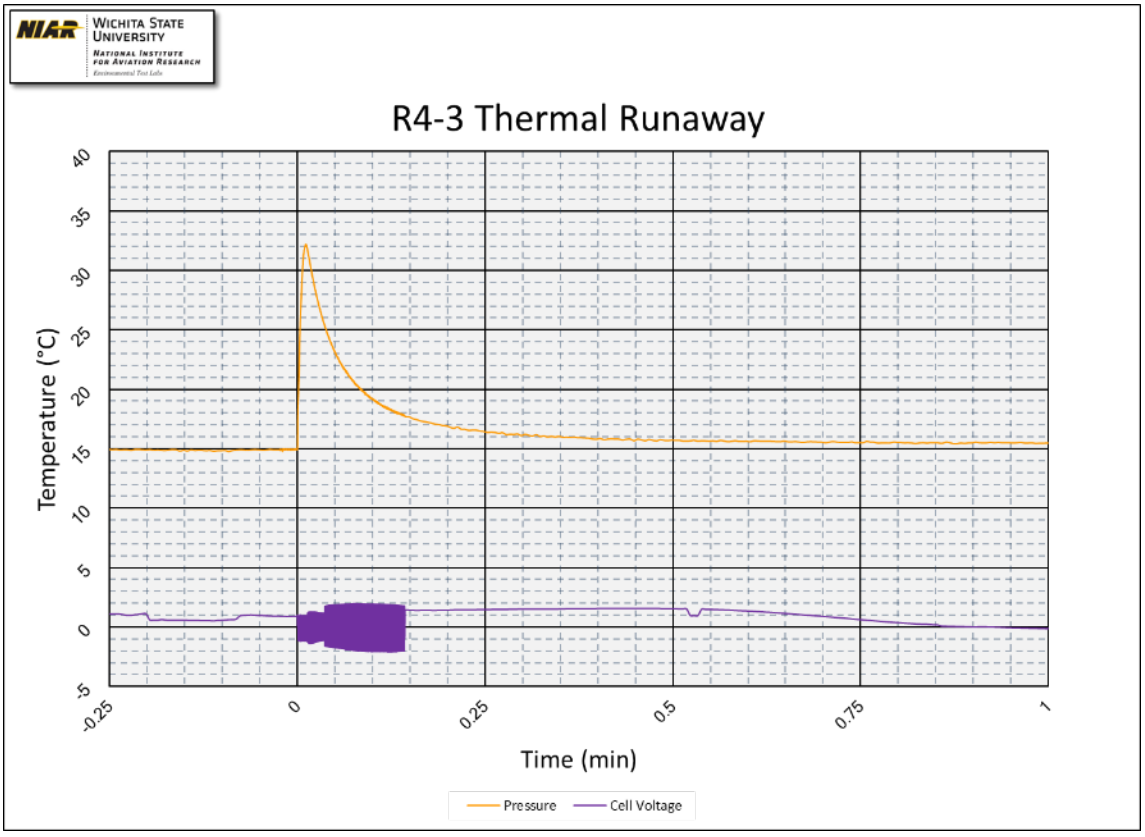

Figure 142: R4-3 Pressure and Voltage Graph

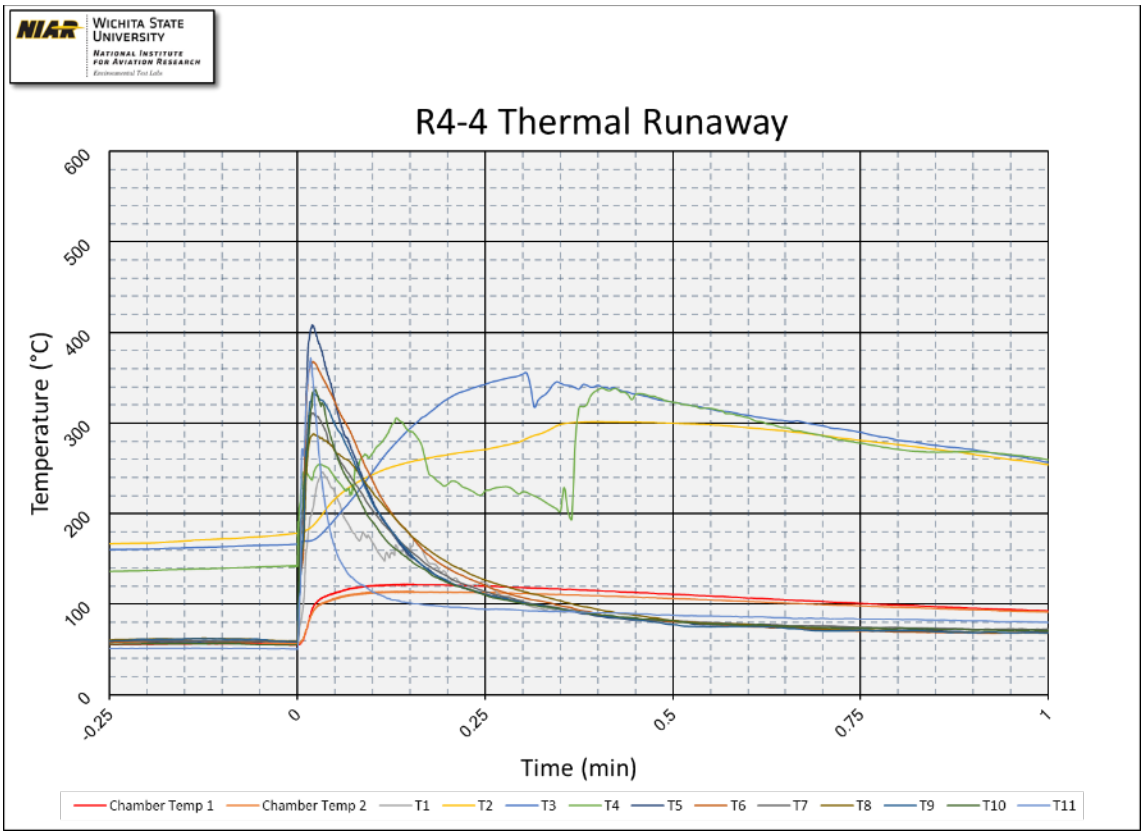

Figure 143: R4-4 Temperature Graph 1

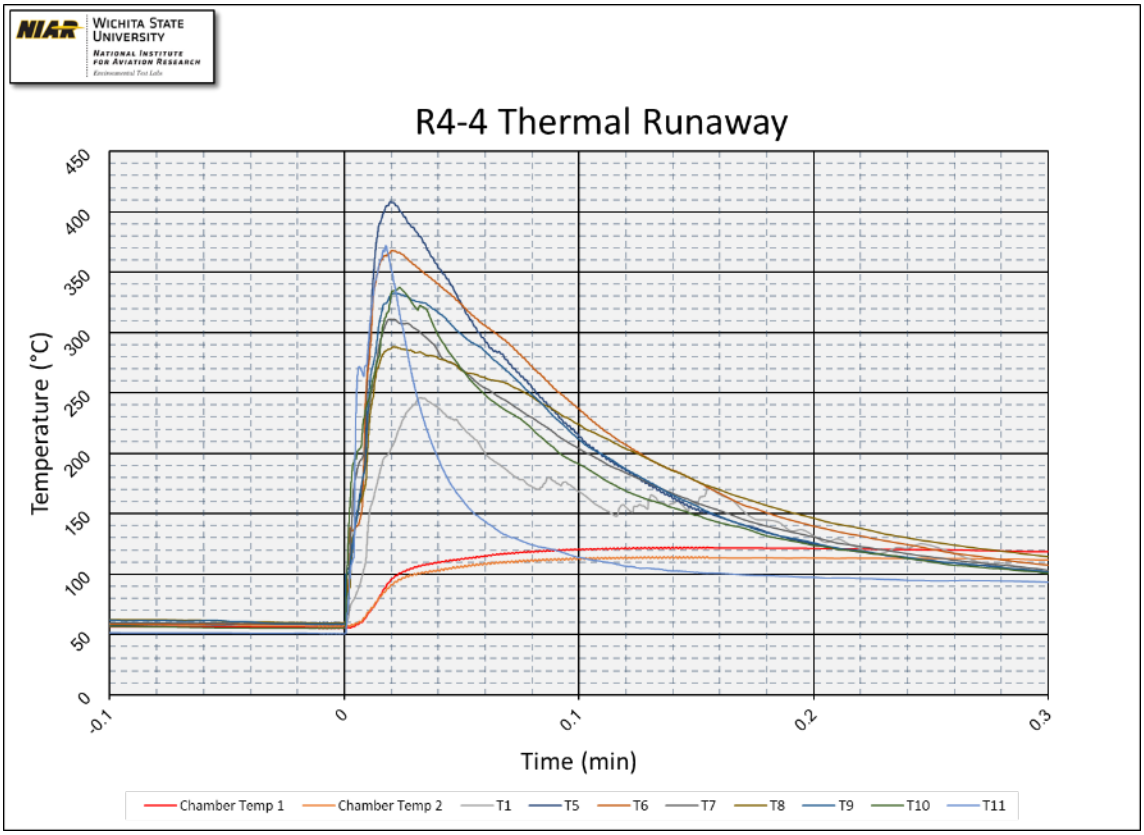

Figure 144: R4-4 Temperature Graph 2

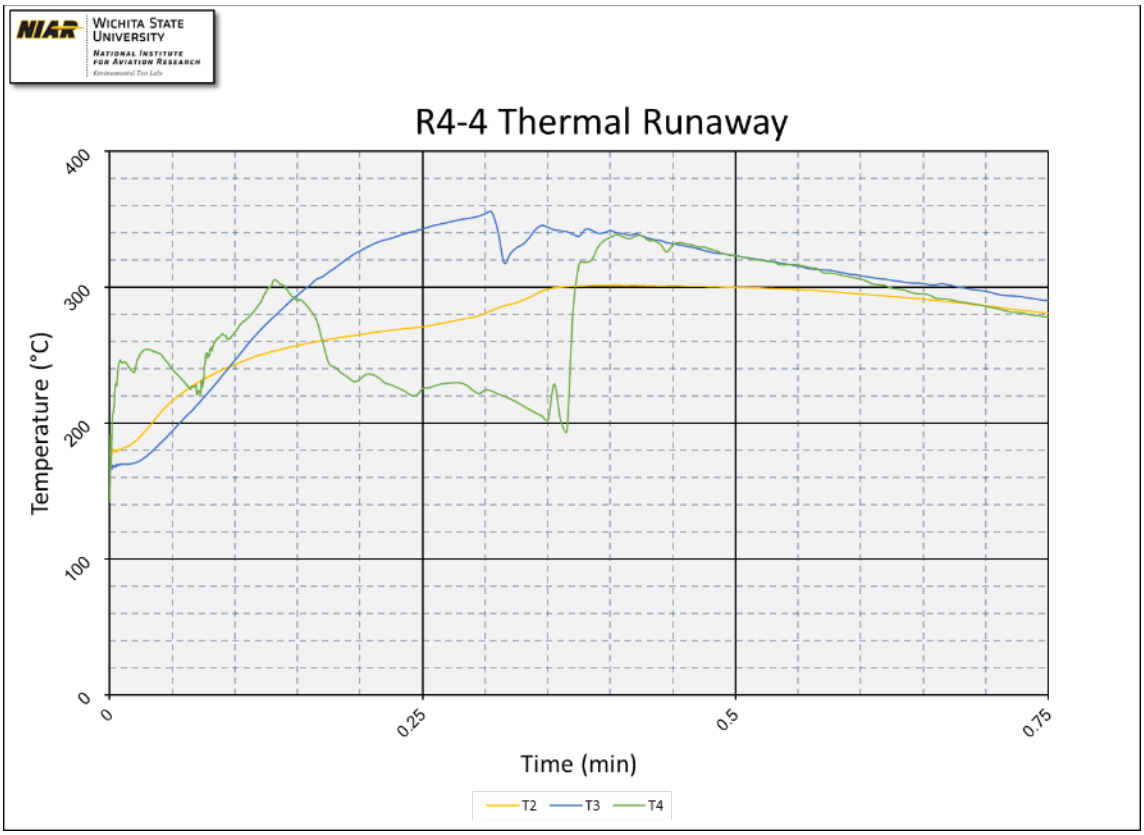

Figure 145: R4-4 Temperature Graph 3

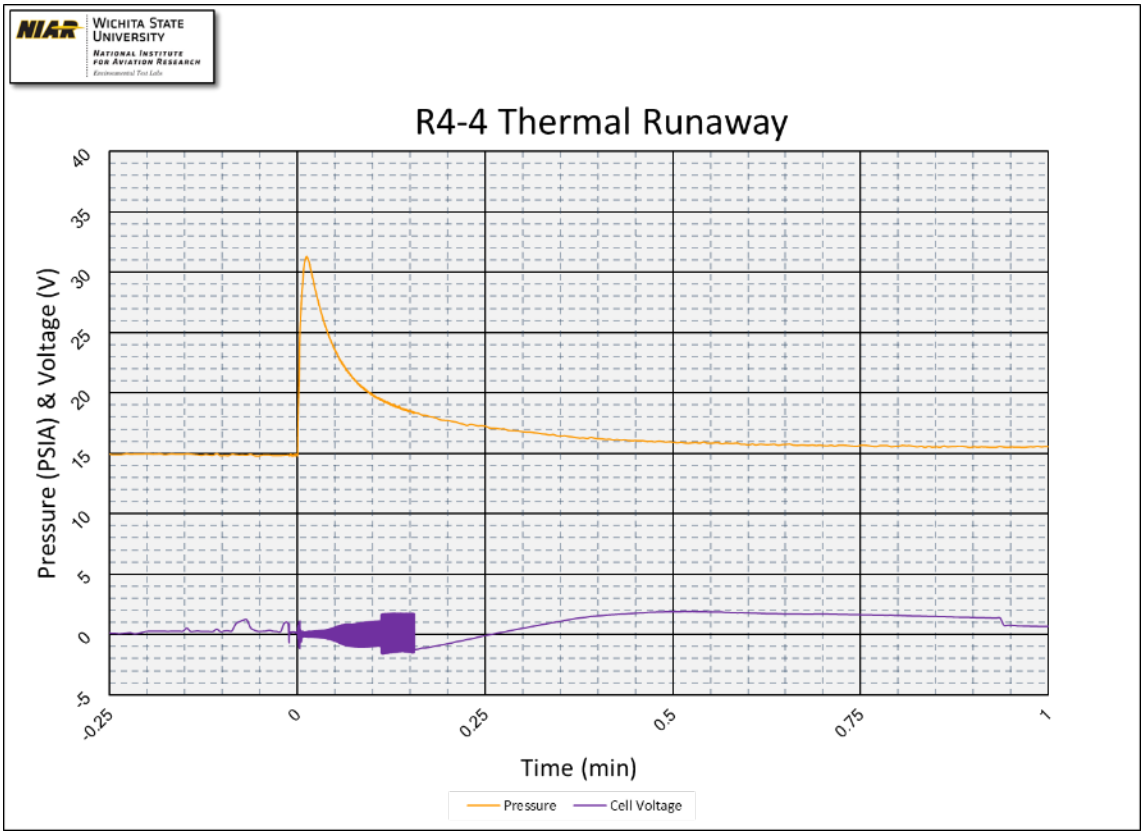

Figure 146: R4-4 Pressure and Voltage Graph

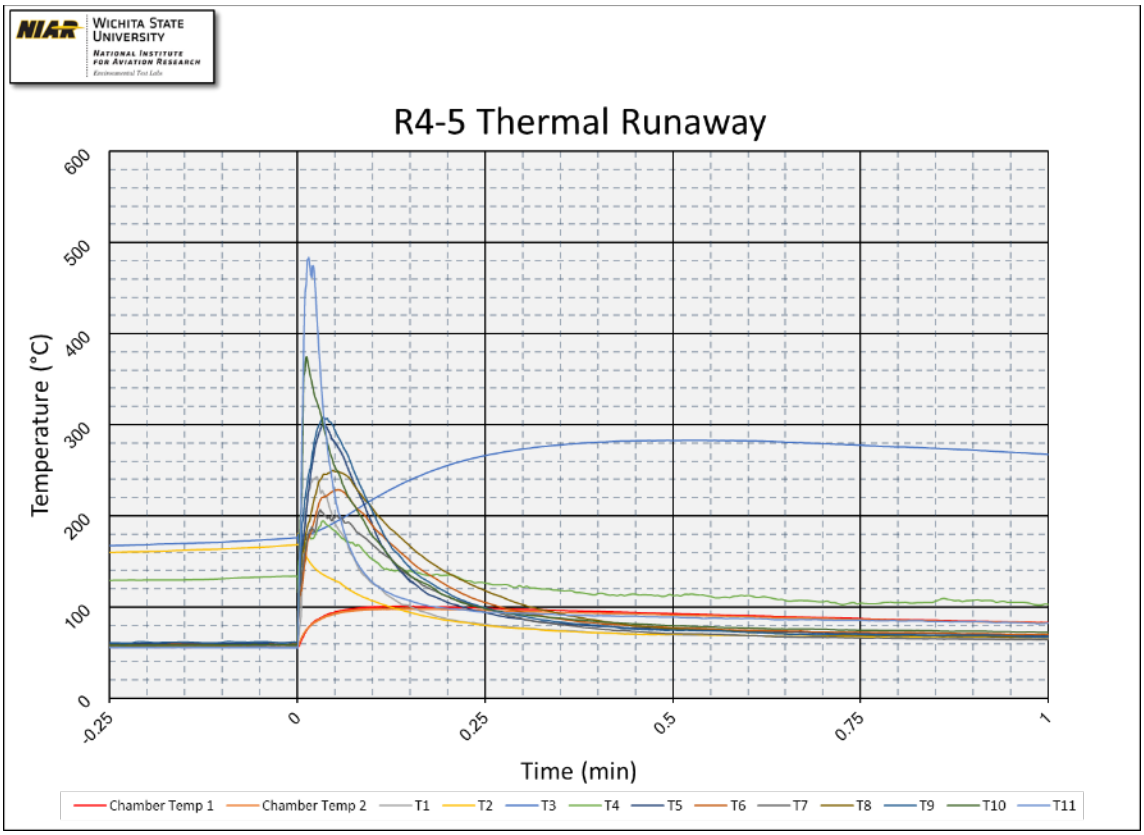

Figure 147: R4-5 Temperature Graph 1

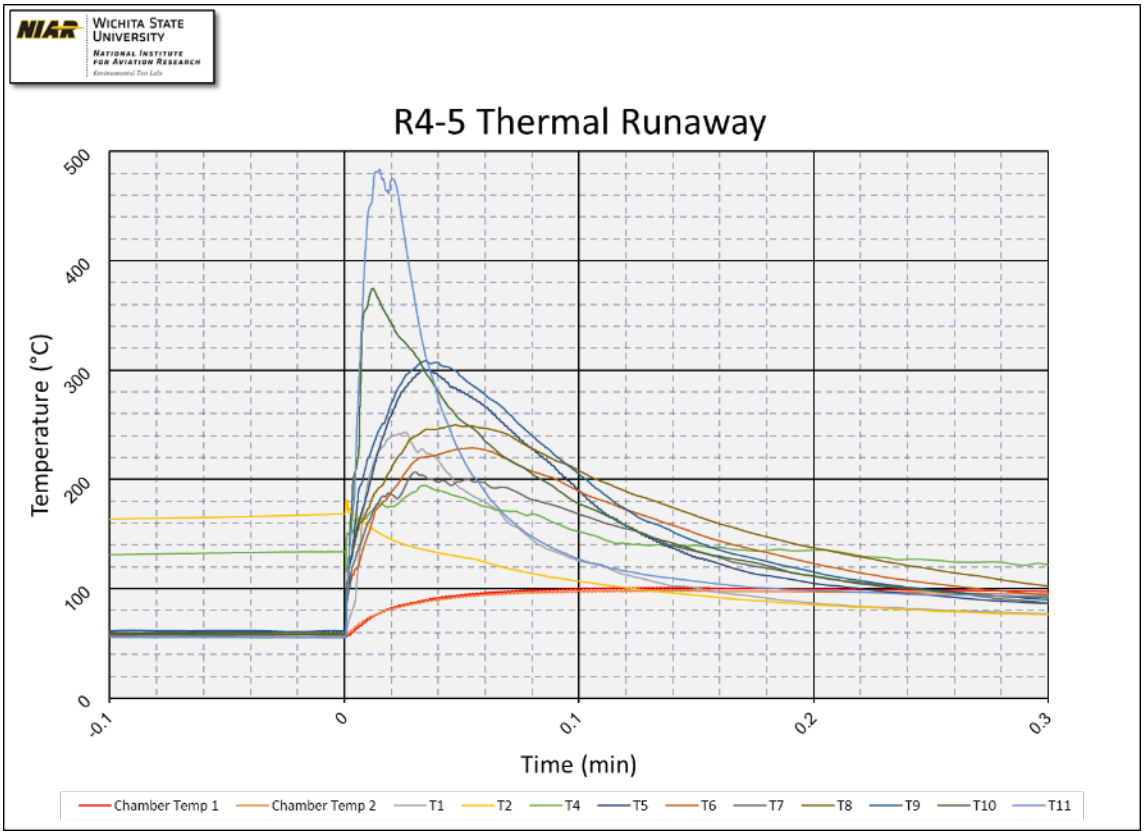

Figure 148: R4-5 Temperature Graph 2

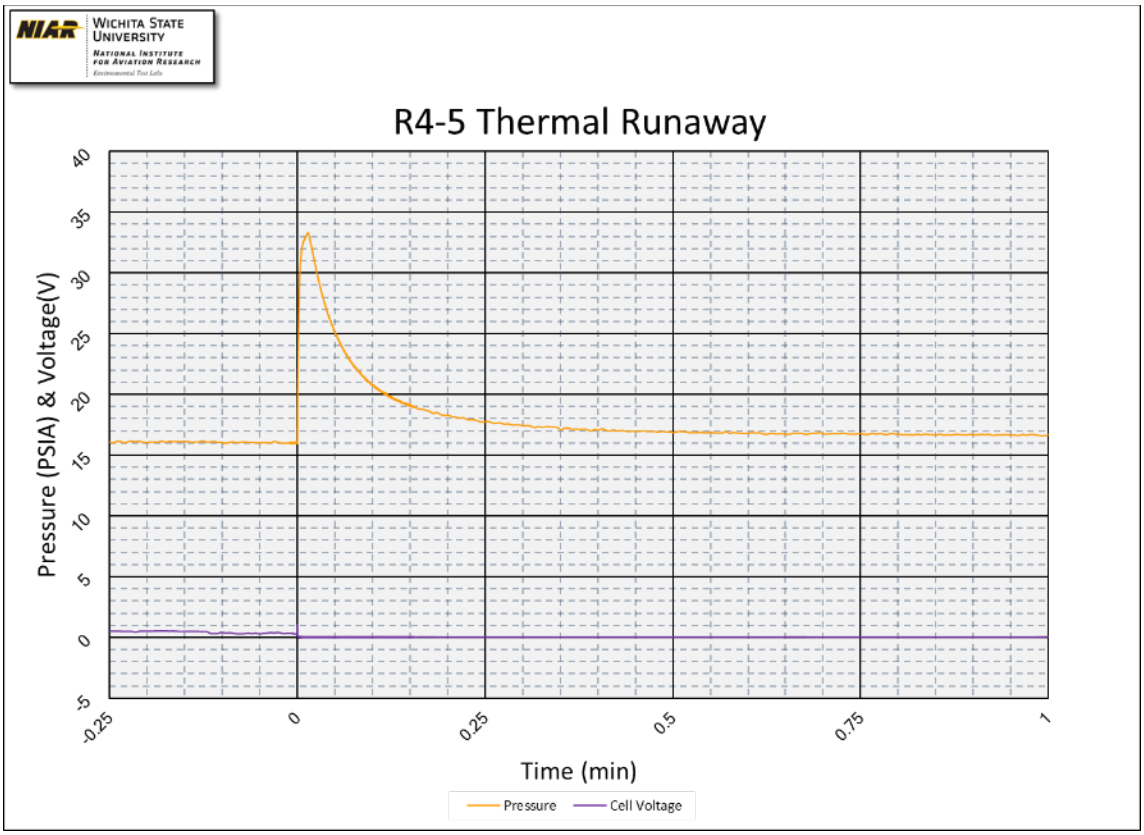

Figure 149: R4-5 Pressure and Voltage Graph

2.2.5 R5-X (Molicel® 20700B)

The R5-X cells were also quite consistent. The reactions resulted in an average cell peak temperature of 365.7°C and an average chamber peak temperature of 712.9°C. The gases detected from the reaction were similar to the R4 cells. All 5 of the valid trials produced similar amounts of carbon monoxide, carbon dioxide, ethylene, sulfuric acid, hydrogen cyanide, nitric oxide, and nitrogen dioxide. The cells lost an average of 34.863g of mass, which translates to a 52% loss in initial mass.

Table 19: R5-X Mass Change Summary

Cell	Pre-Test Mass (g)	Post-Test Mass (g)
R5-2	67.422	39.848
R5-4	67.883	27.039
R5-5	67.742	35.560
R5-6	67.613	43.695
R5-7	67.712	17.917

Table 20: R5-X Detected Gases

Gas Species	Detector Tube Error Range	Moles of Gas Detected R5-2	Moles of Gas Detected R5-4	Moles of Gas Detected R5-5	Moles of Gas Detected R5-6	Moles of Gas Detected R5-7
CO	±10%	2.3E-3	2.0E-3	0.087	0.022	0.022
CO_2	±10%	0.35	5.5E-3	0.44	0.23	5.6E-3
C_2H_4	±20 - 30%	1.2E-3	3.3E-3	1.1E-3	5.5E-4	5.6E-4
H_2	±15 - 20%	0	0	0	0	0
H_2S	±25%	0	0	0	0	0
H_2SO_4	±10%	1.2E-05	1.4E-06	9.7E-06	8.4E-06	8.6E-06
HCl	±15%	0	0	0	0	0
HCN	±10 - 15%	8.7E-06	8.2E-06	8.2E-06	5.5E-06	5.6E-06
HF	±10%	0	0	0	0	0
HNO_3	±15%	0	0	0	0	0
NO	±10 - 15%	5.2E-05	3.4E-4	2.7E-4	1.9E-4	1.7E-4
NO_2	±10 - 15%	2.9E-05	4.4E-05	5.5E-05	3.3E-05	5.3E-05
SO_2	±10%	0	0	0	0	0

Table 21: R5-X Failure Modes

Failure Mode	Leak	Vent	Fire	Rupture
R5-2		Y	Y	Y
R5-4		Y	Y	Y
R5-5		Y	Y	Y
R5-6		Y	Y	Y
R5-7		Y	Y	Y

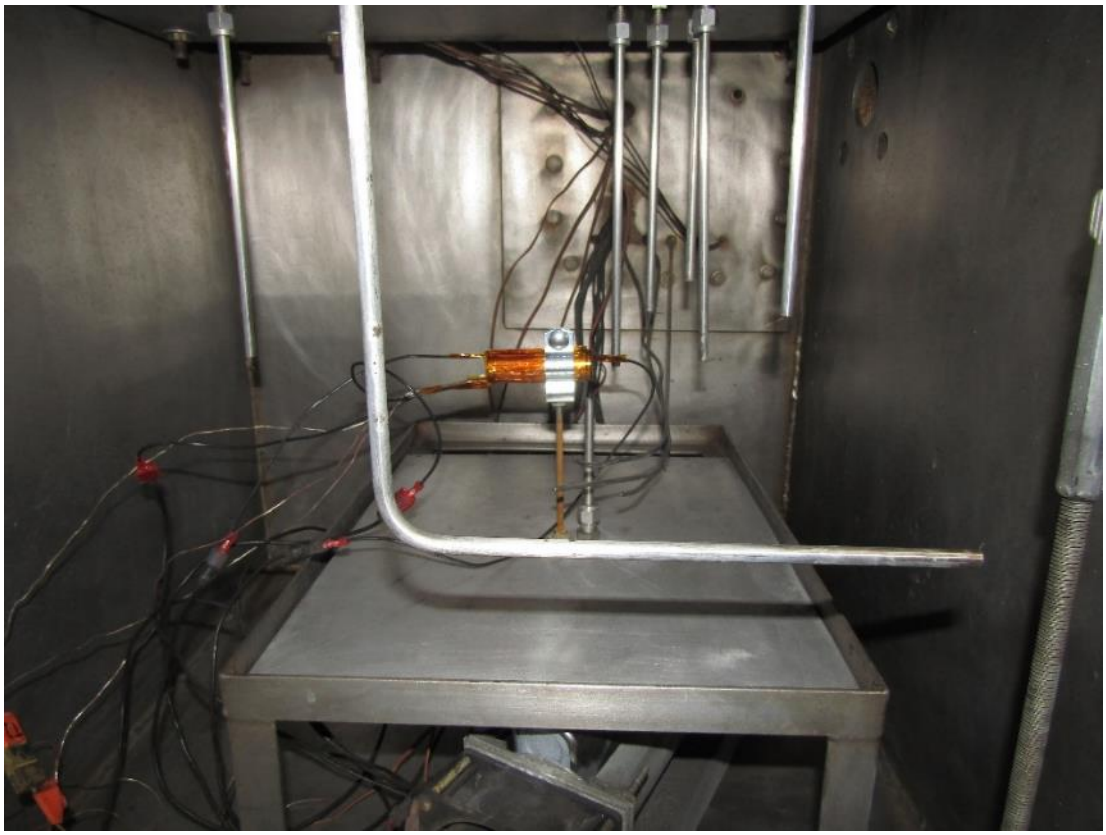

Figure 150: R5-2 Pre-Test

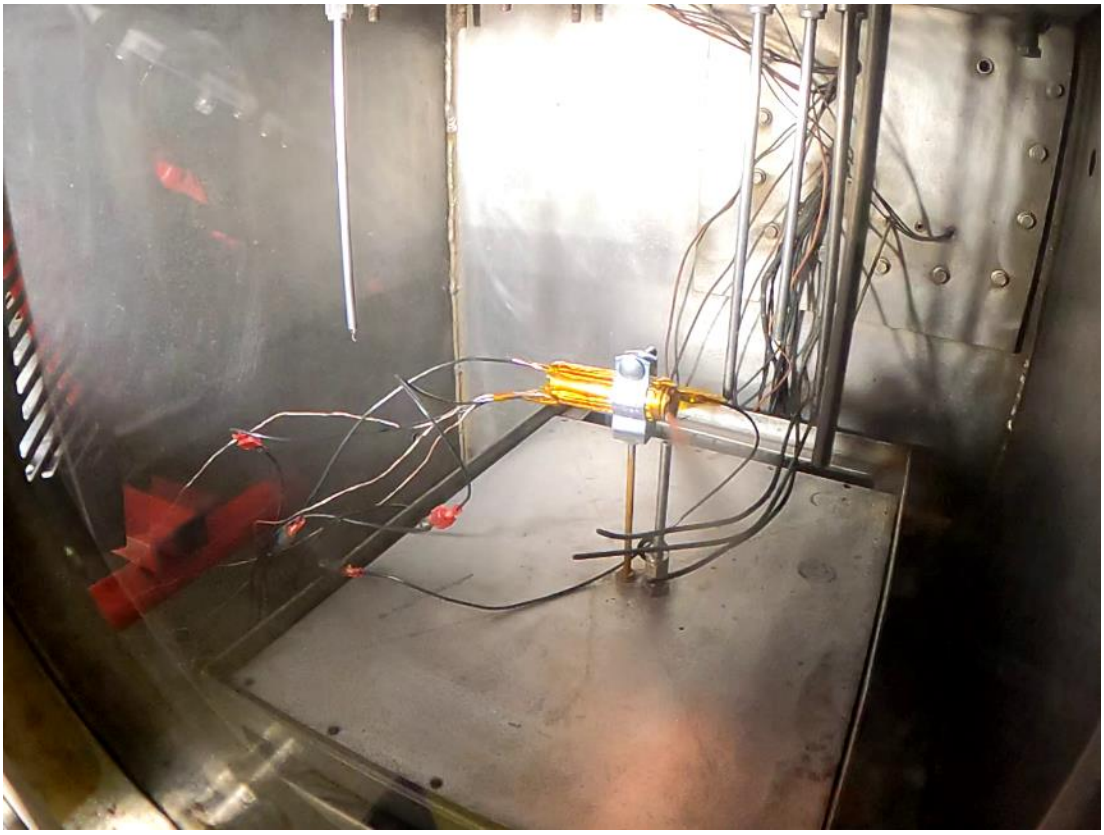

Figure 151: R5-2 Venting

Figure 152: R5-2 Post-Test 1

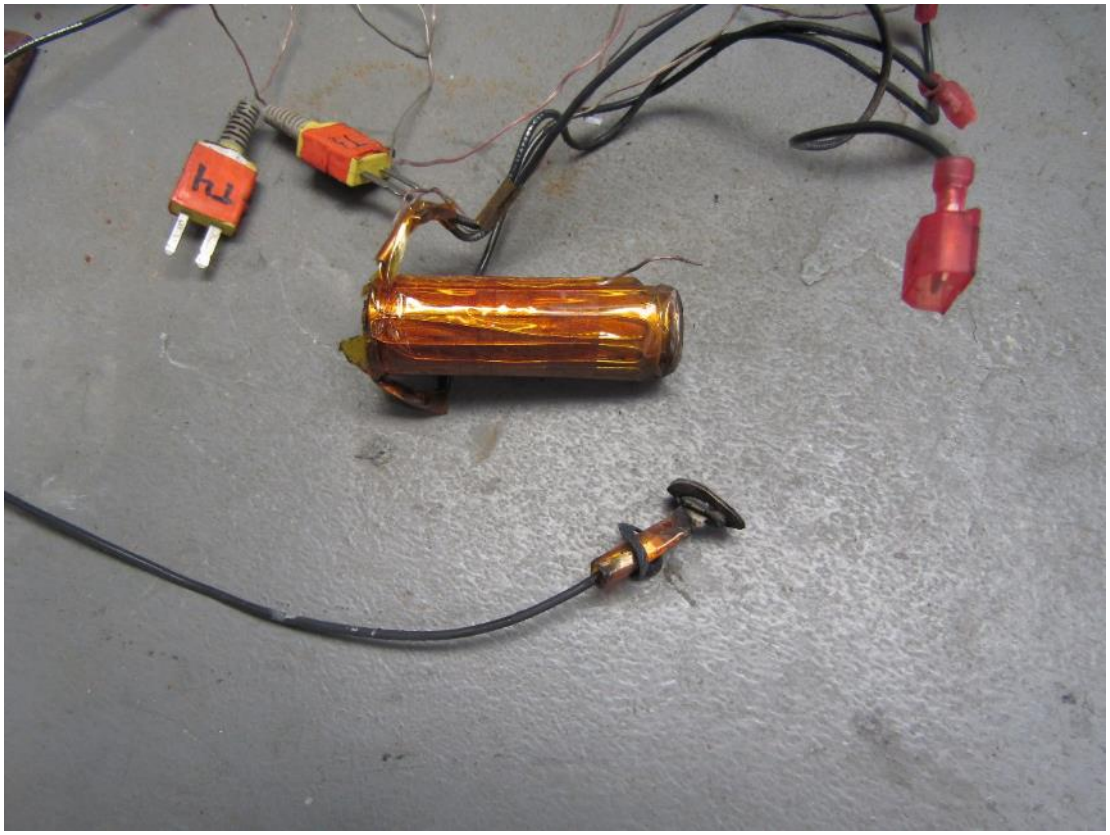

Figure 153: R5-2 Post-Test 2

Figure 154: R5-4 Pre-Test

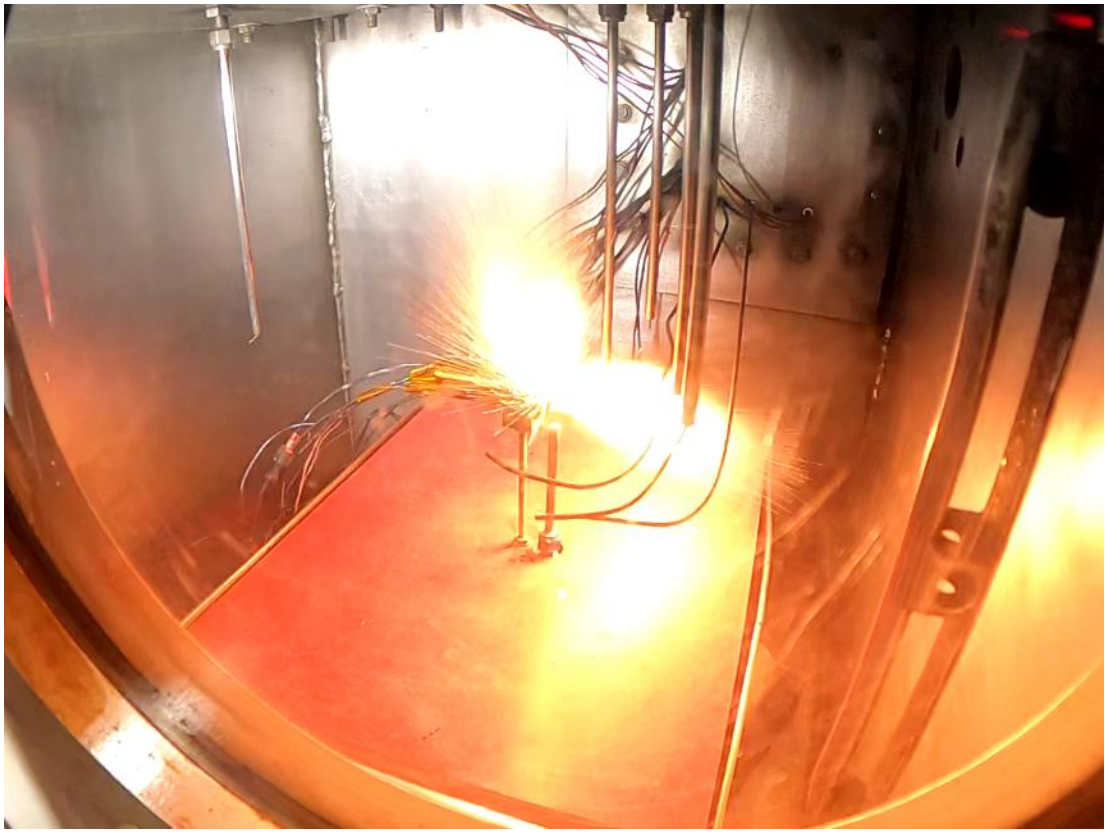

Figure 155: R5-4 Venting and Fire

Figure 156: R5-4 Post-Test 1

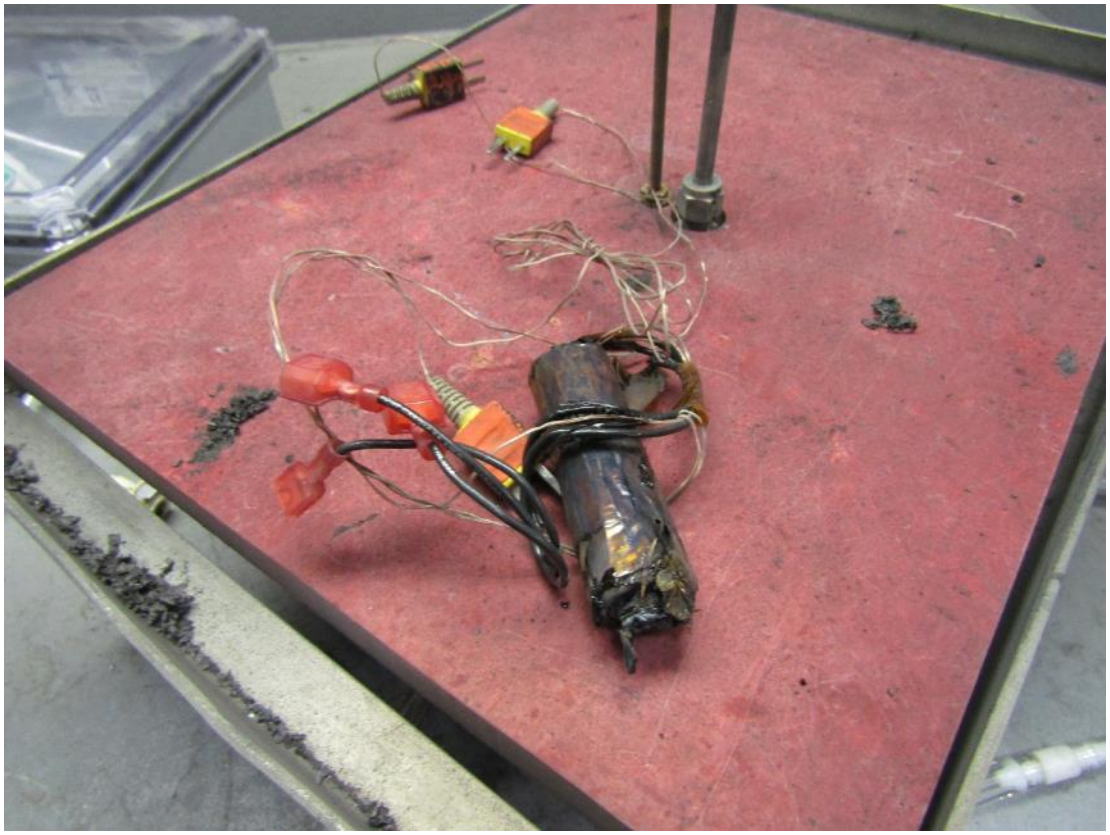

Figure 157: R5-4 Post-Test 2

Figure 158: R5-5 Pre-Test

Figure 159: R5-5 Venting and Fire

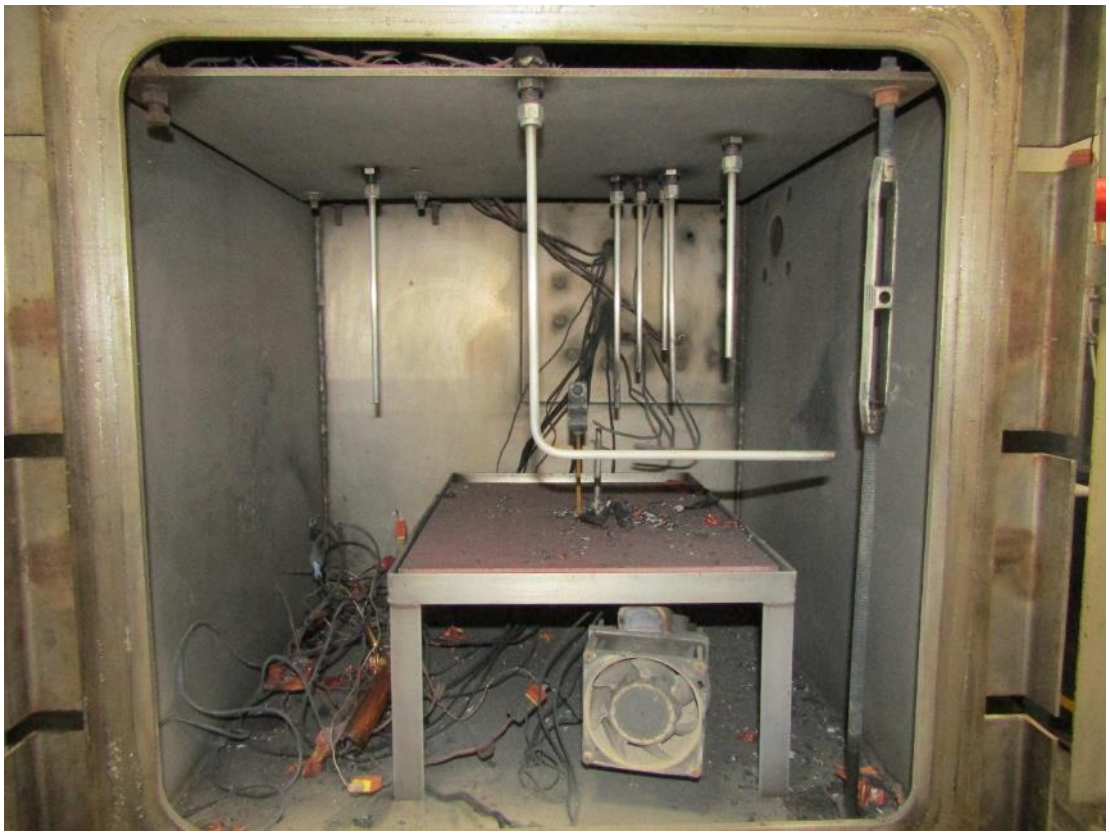

Figure 160: R5-5 Post-Test 1

Figure 161: R5-5 Post-Test 2

Figure 162: R5-6 Pre-Test

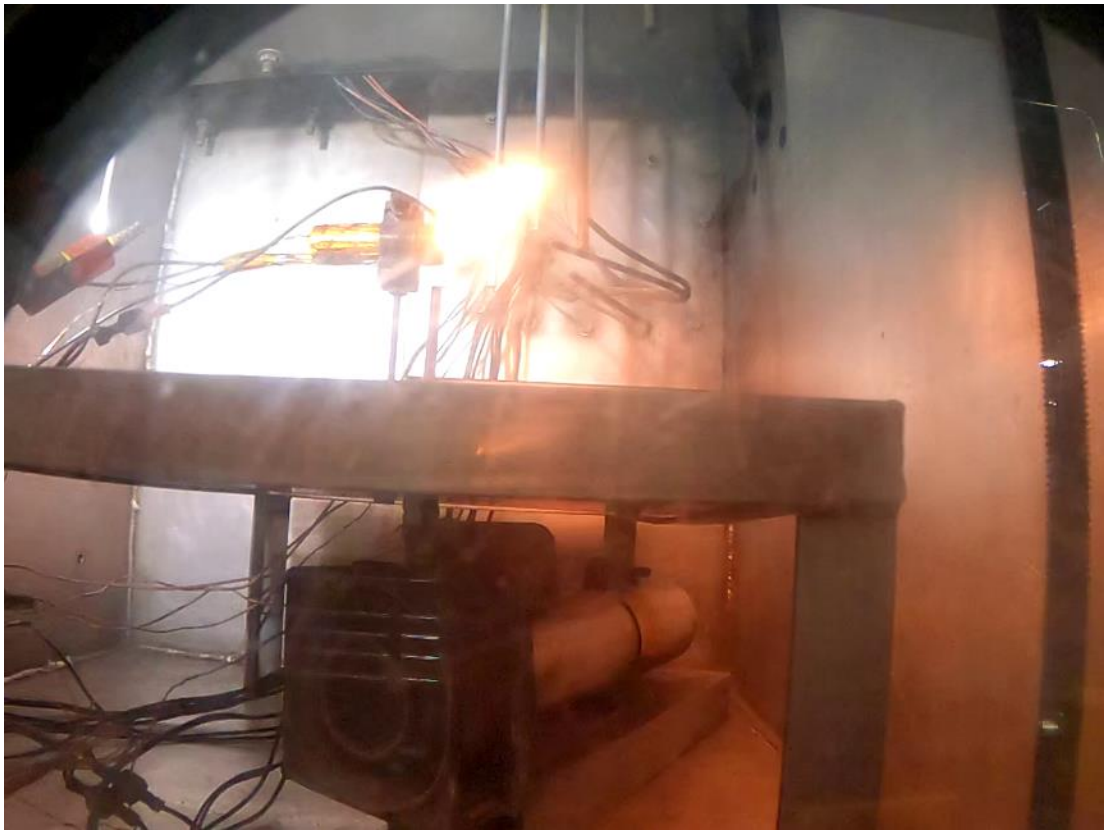

Figure 163: R5-6 Venting and Fire

Figure 164: R5-6 Post-Test 1

Figure 165: R5-6 Post-Test 2

Figure 166: R5-7 Pre-Test

Figure 167: R5-7 Venting and Fire

Figure 168: R5-7 Post-Test 1

Figure 169: R5-7 Post-Test 2

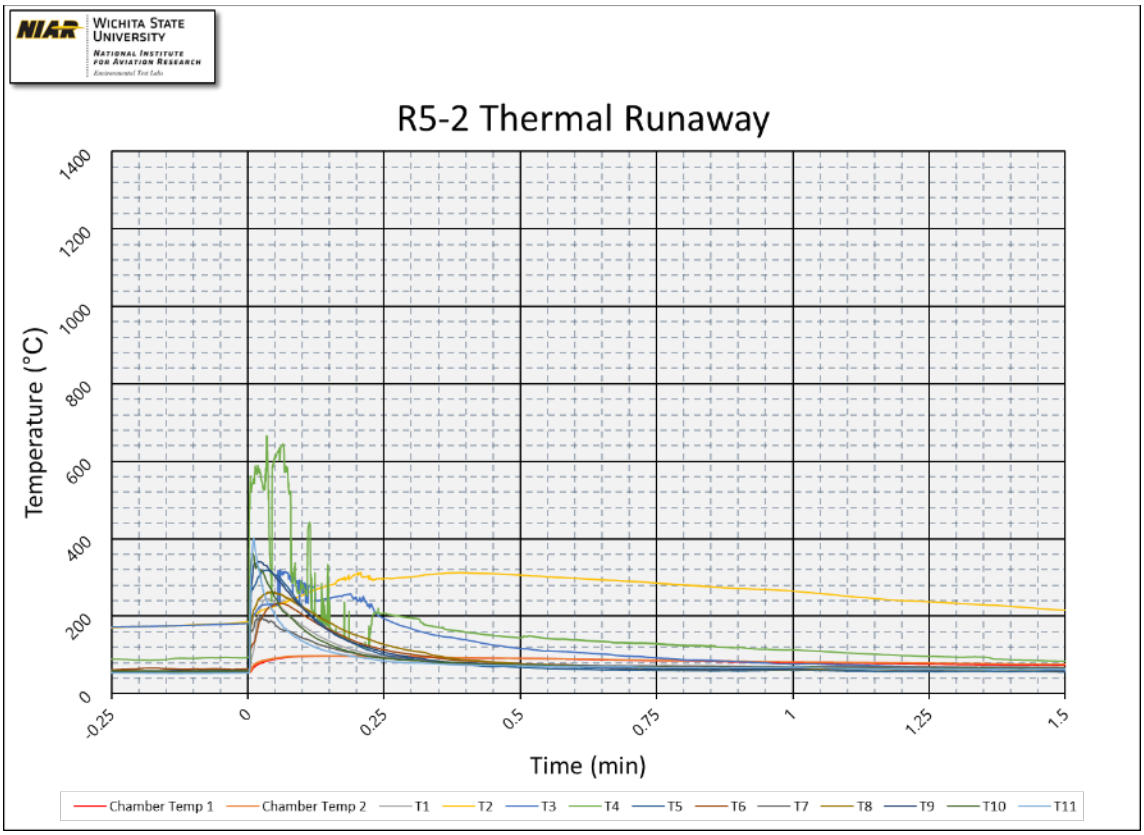

Figure 170: R5-2 Temperature Graph 1

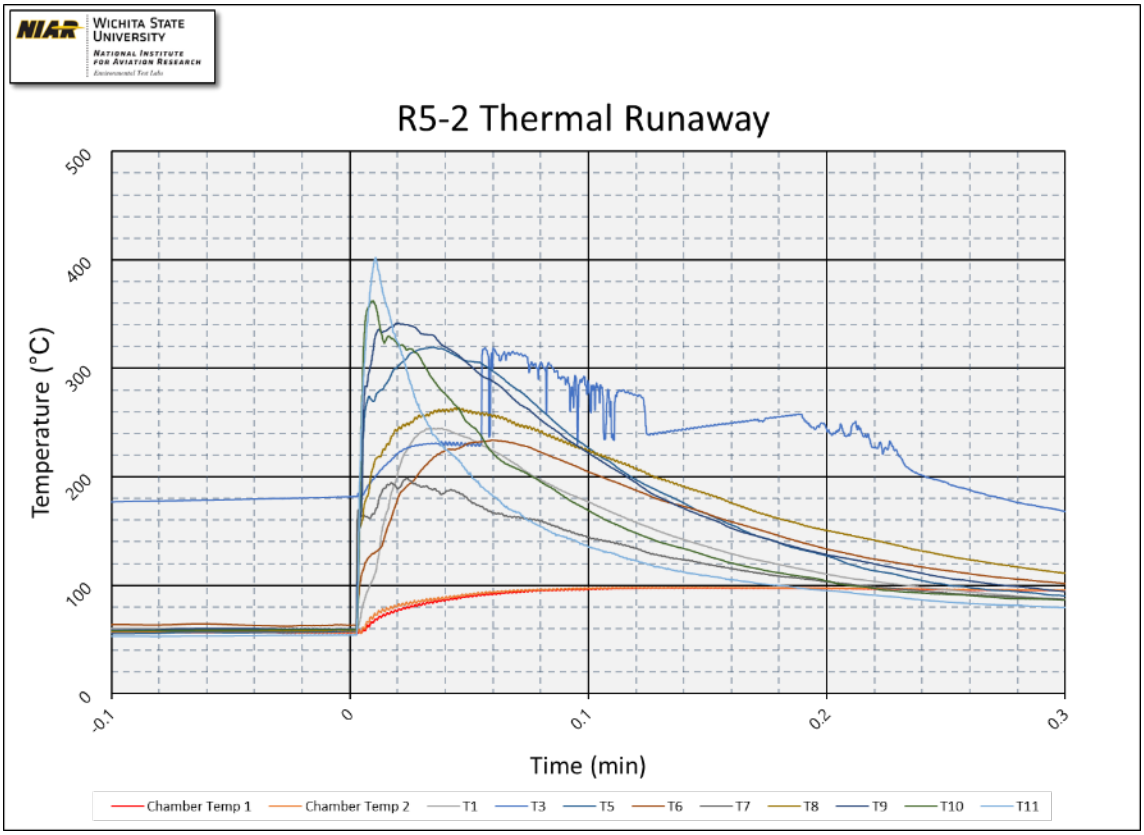

Figure 171: R5-2 Temperature Graph 2

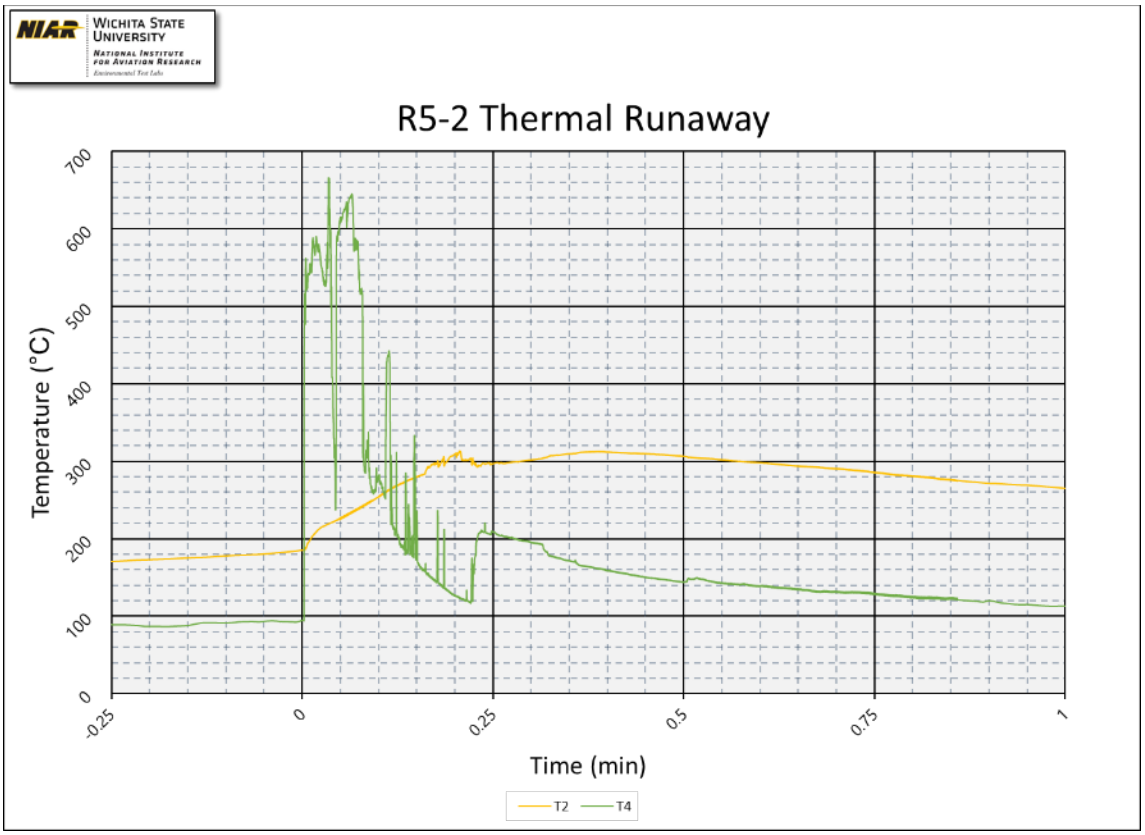

Figure 172: R5-2 Temperature Graph 3

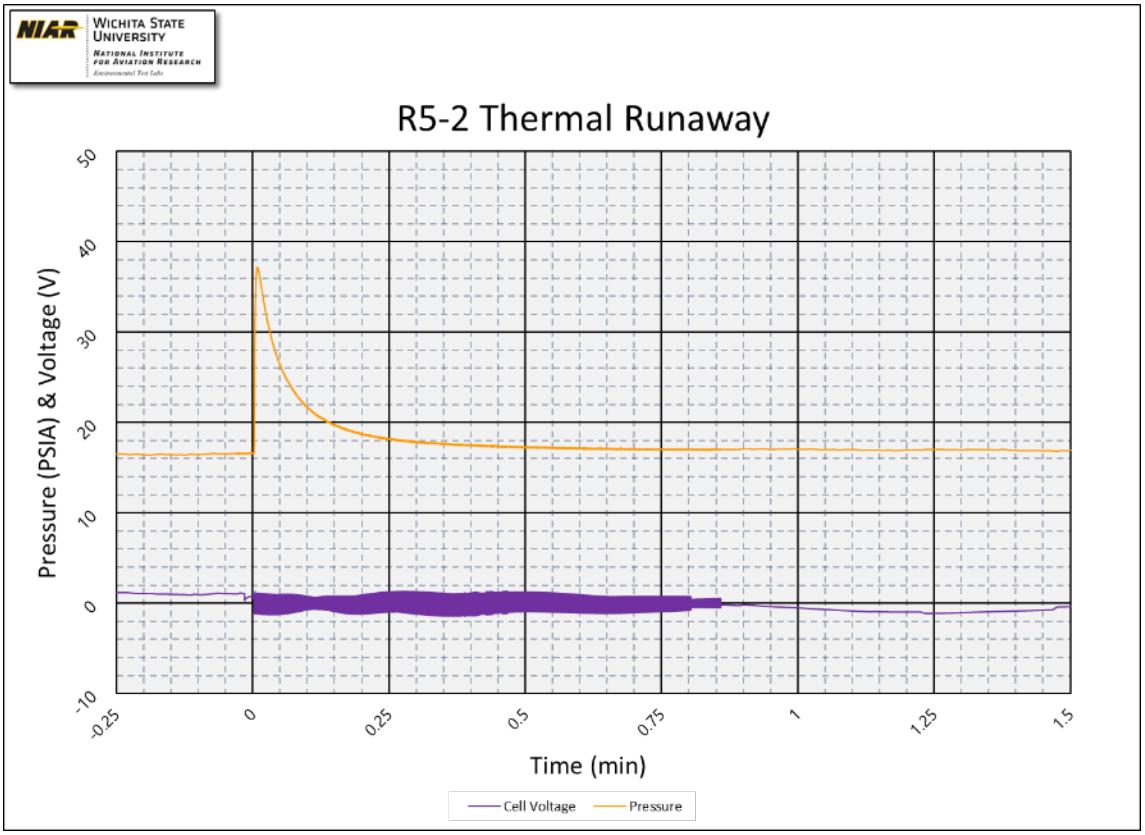

Figure 173: R5-2 Pressure and Voltage Graph

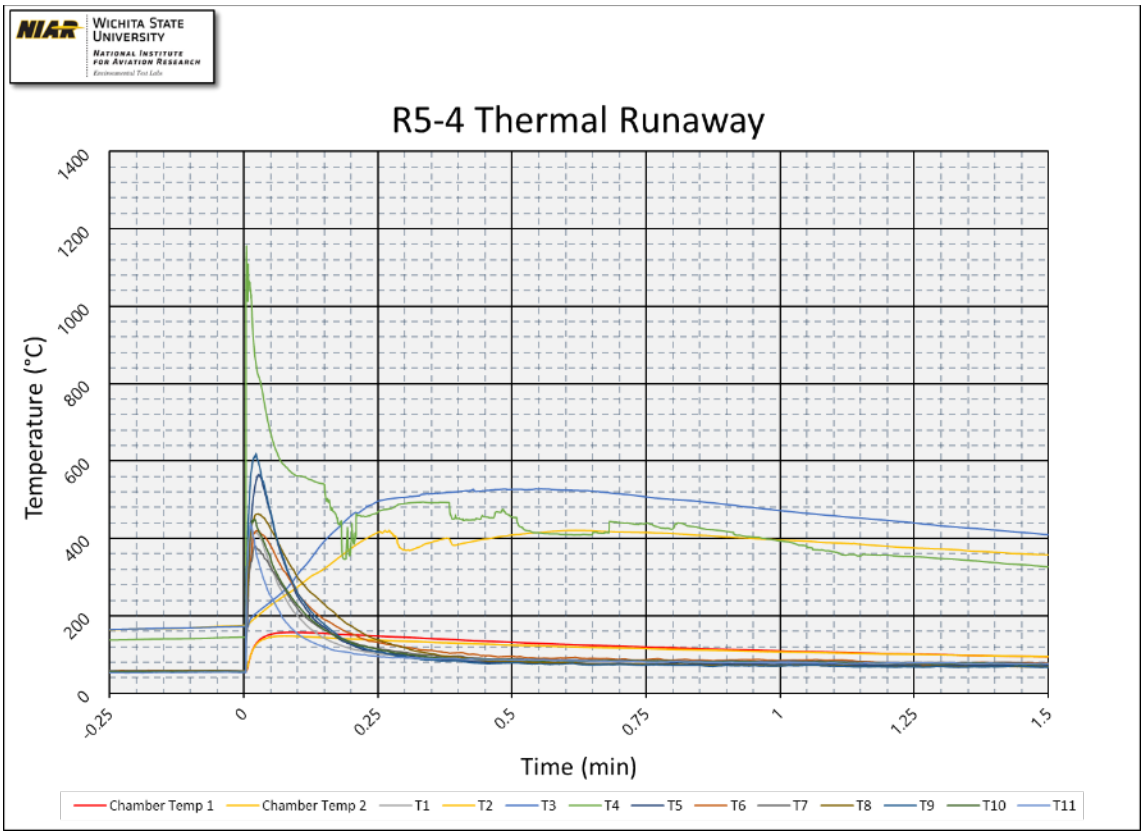

Figure 174: R5-4 Temperature Graph 1

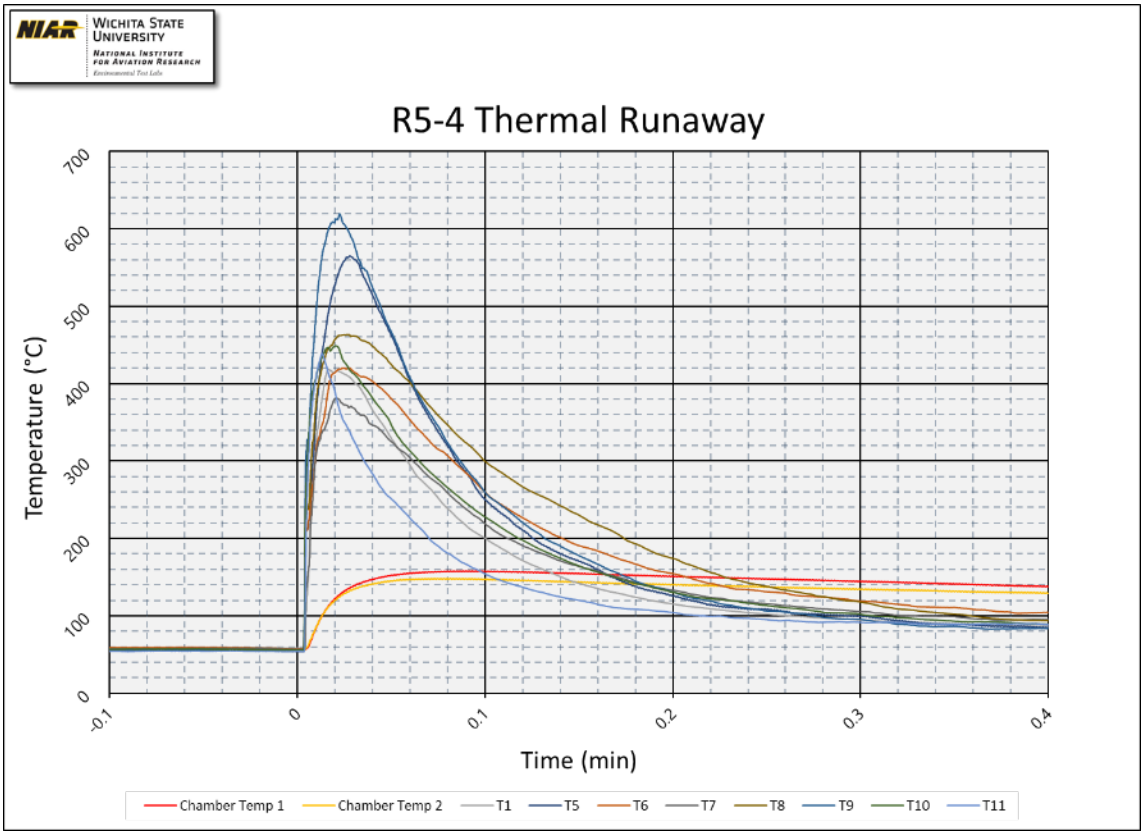

Figure 175: R5-4 Temperature Graph 2

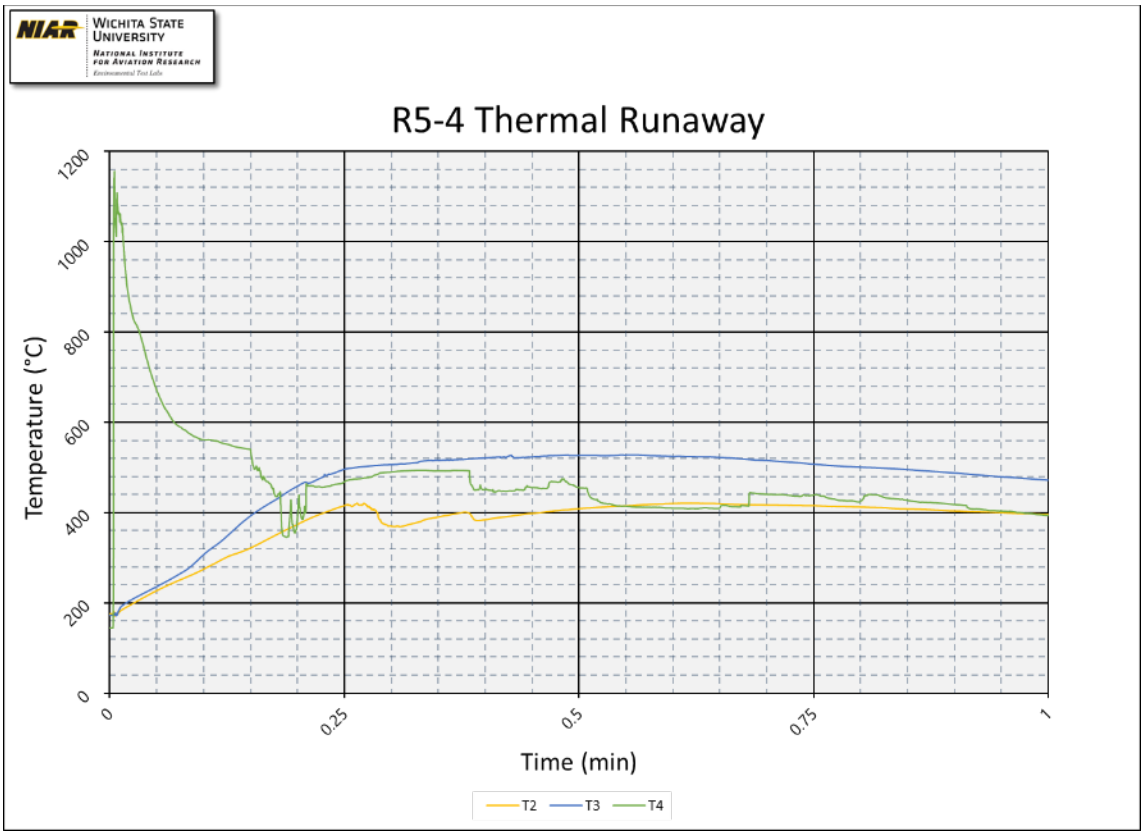

Figure 176: R5-4 Temperature Graph

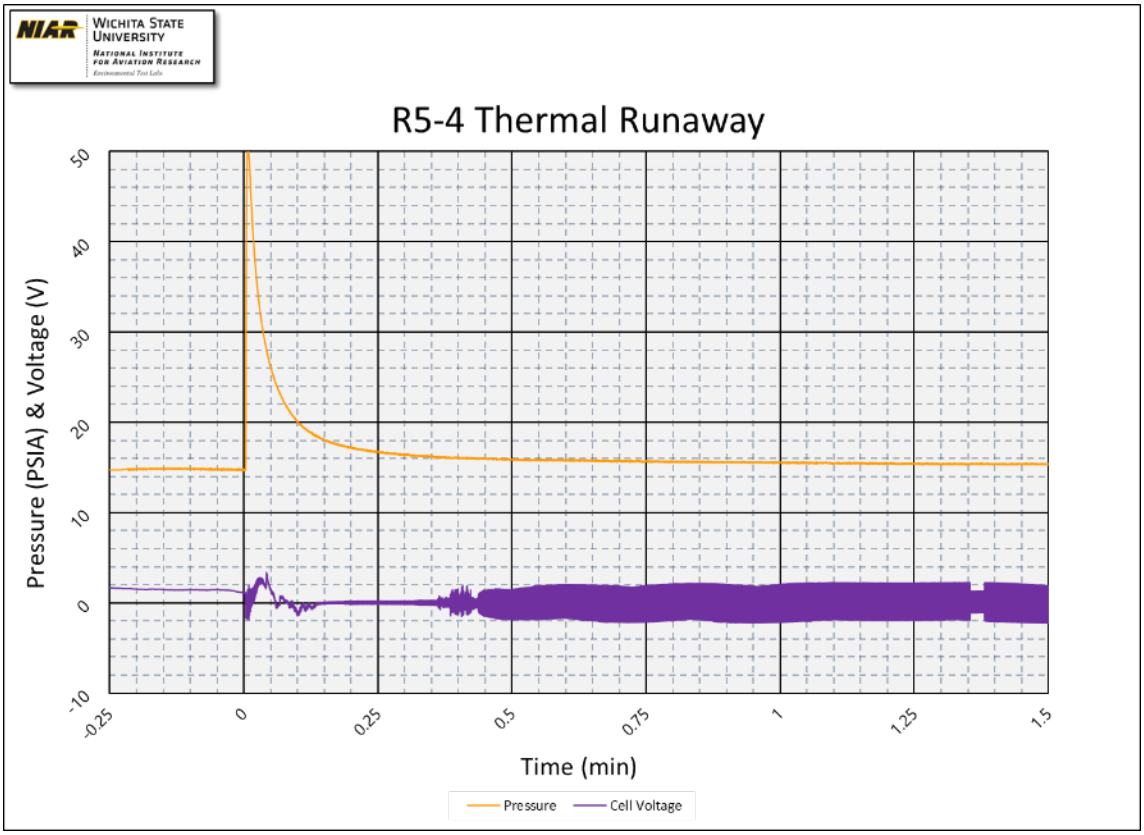

Figure 177: R5-4 Pressure and Voltage Graph

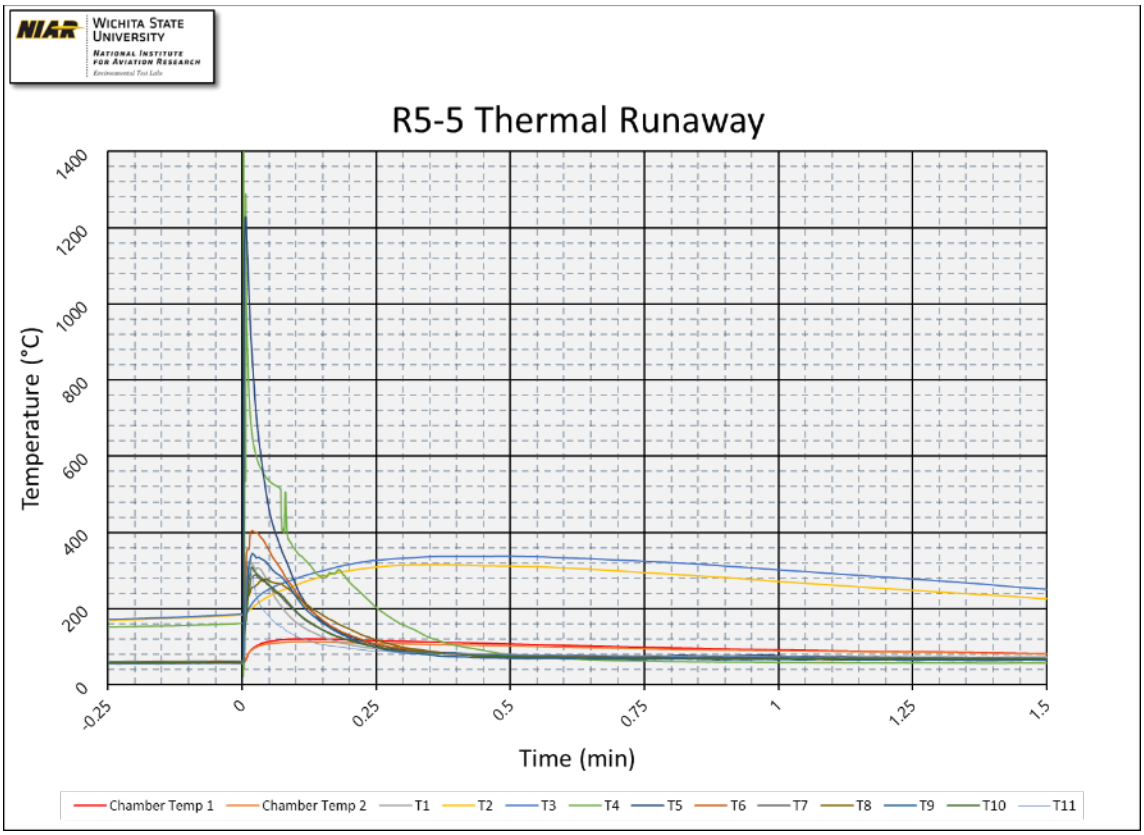

Figure 178: R5-5 Temperature Graph 1

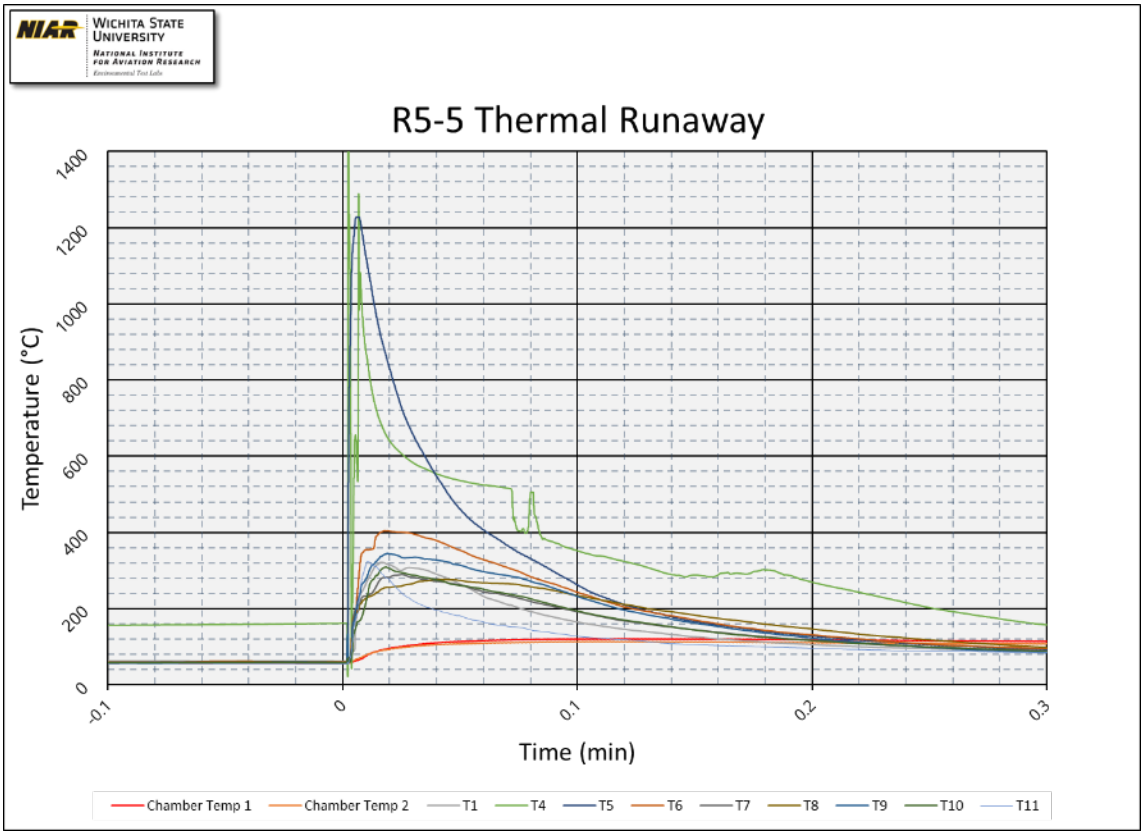

Figure 179: R5-5 Temperature Graph 2

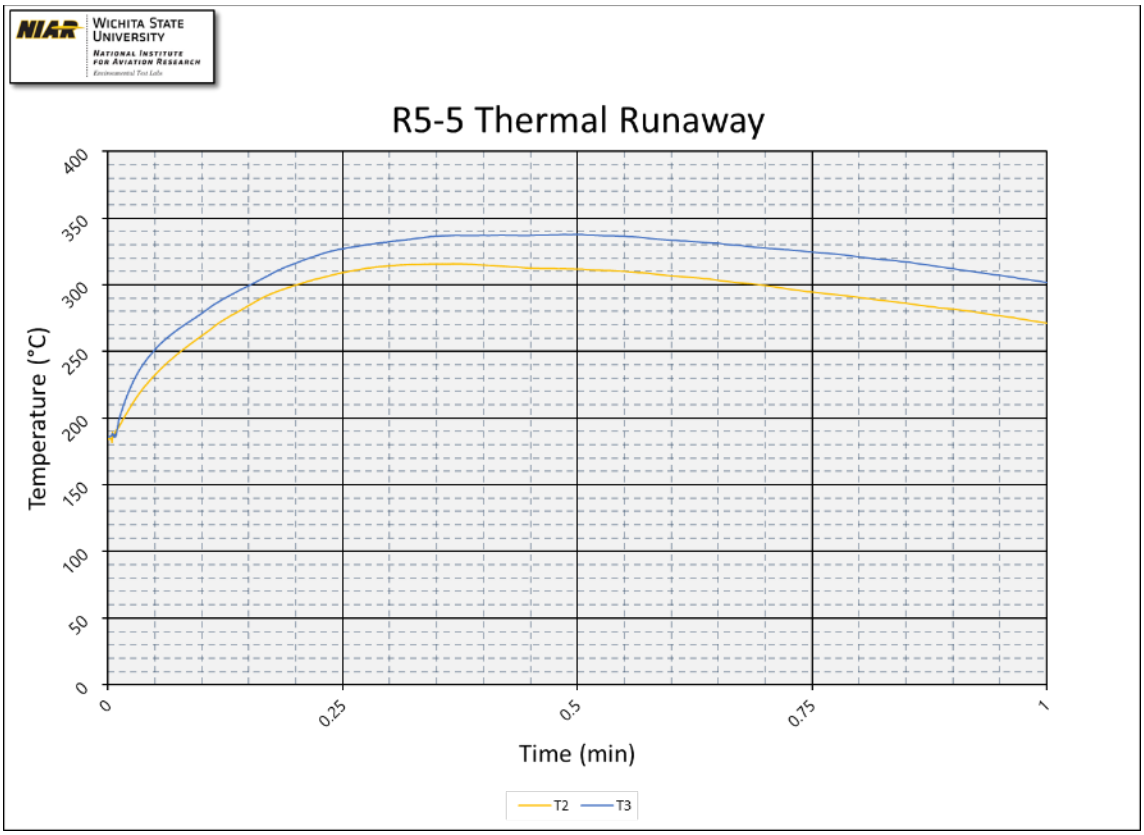

Figure 180: R5-5 Temperature Graph 3

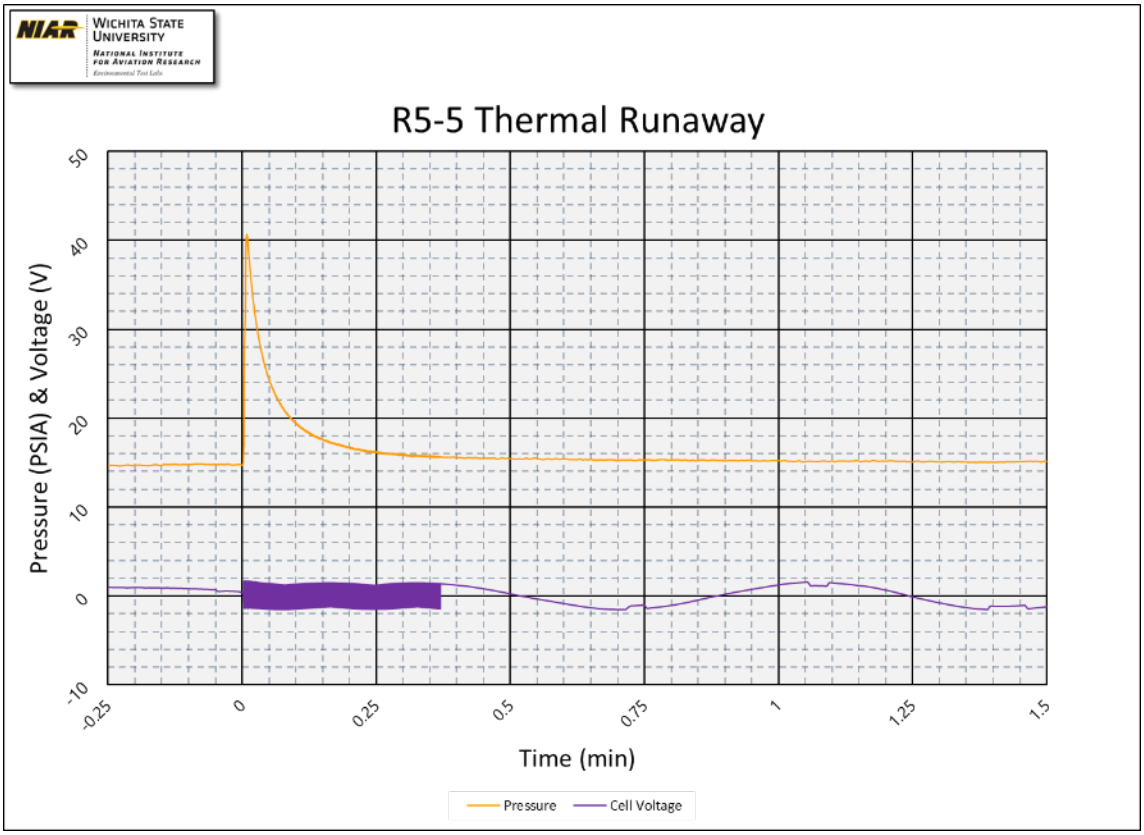

Figure 181: R5-5 Pressure and Voltage Graph

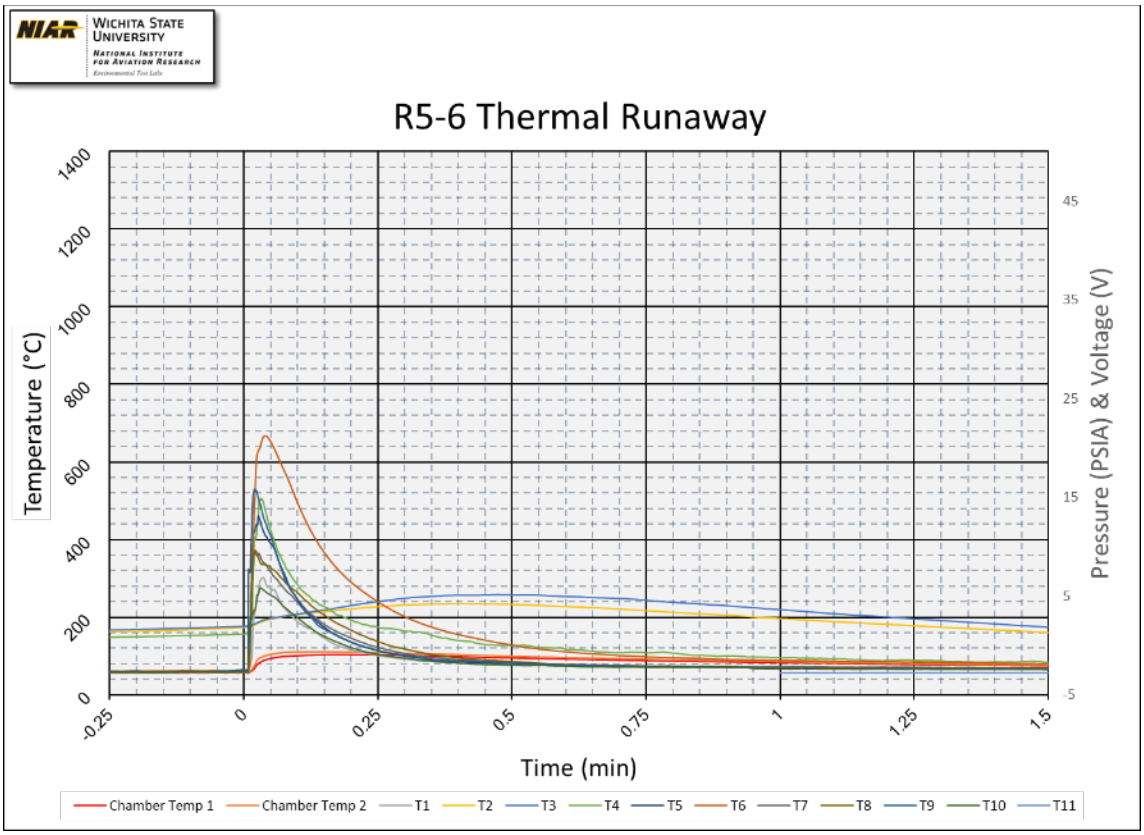

Figure 182: R5-6 Temperature Graph 1

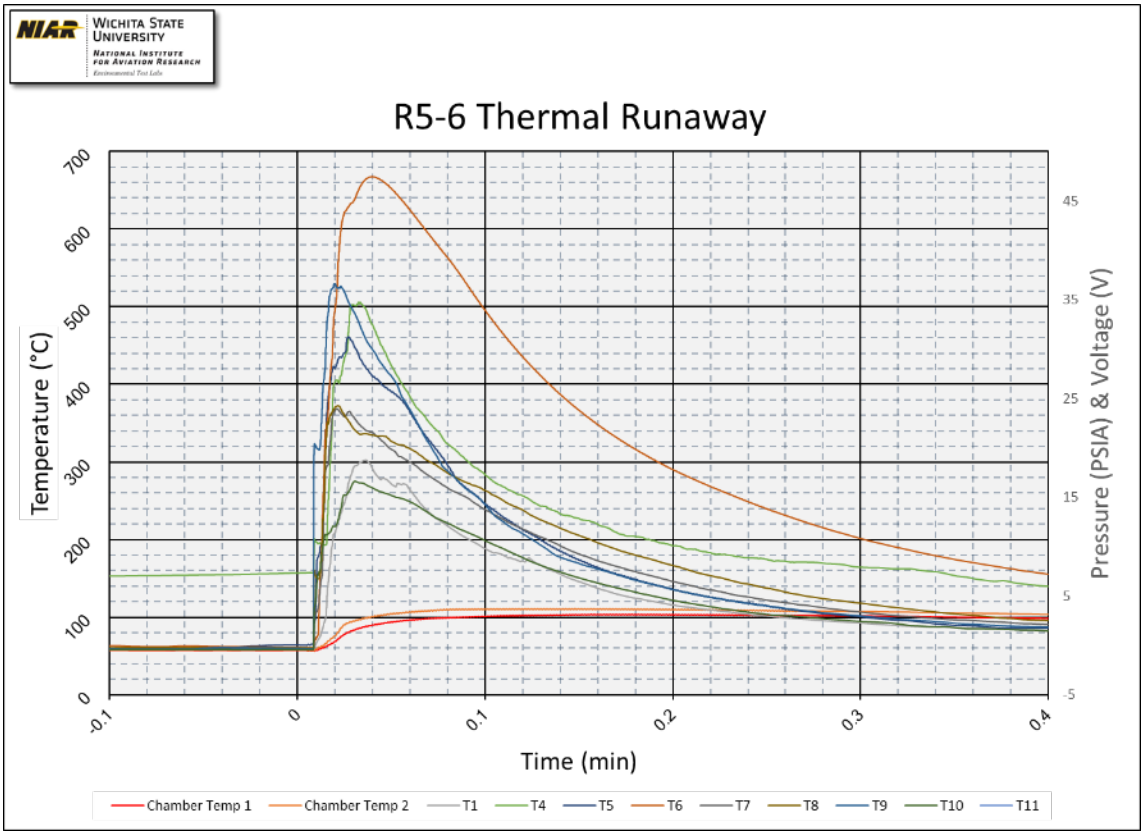

Figure 183: R5-6 Temperature Graph 2

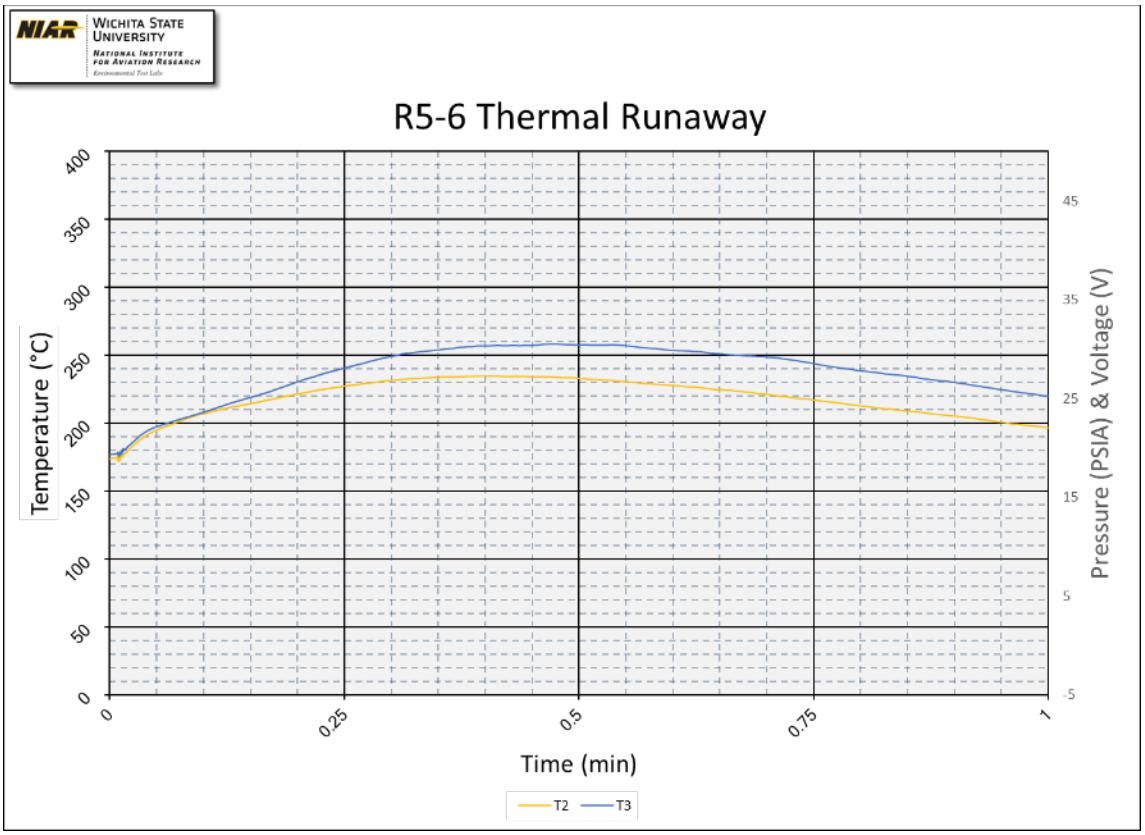

Figure 184: R5-6 Temperature Graph 3

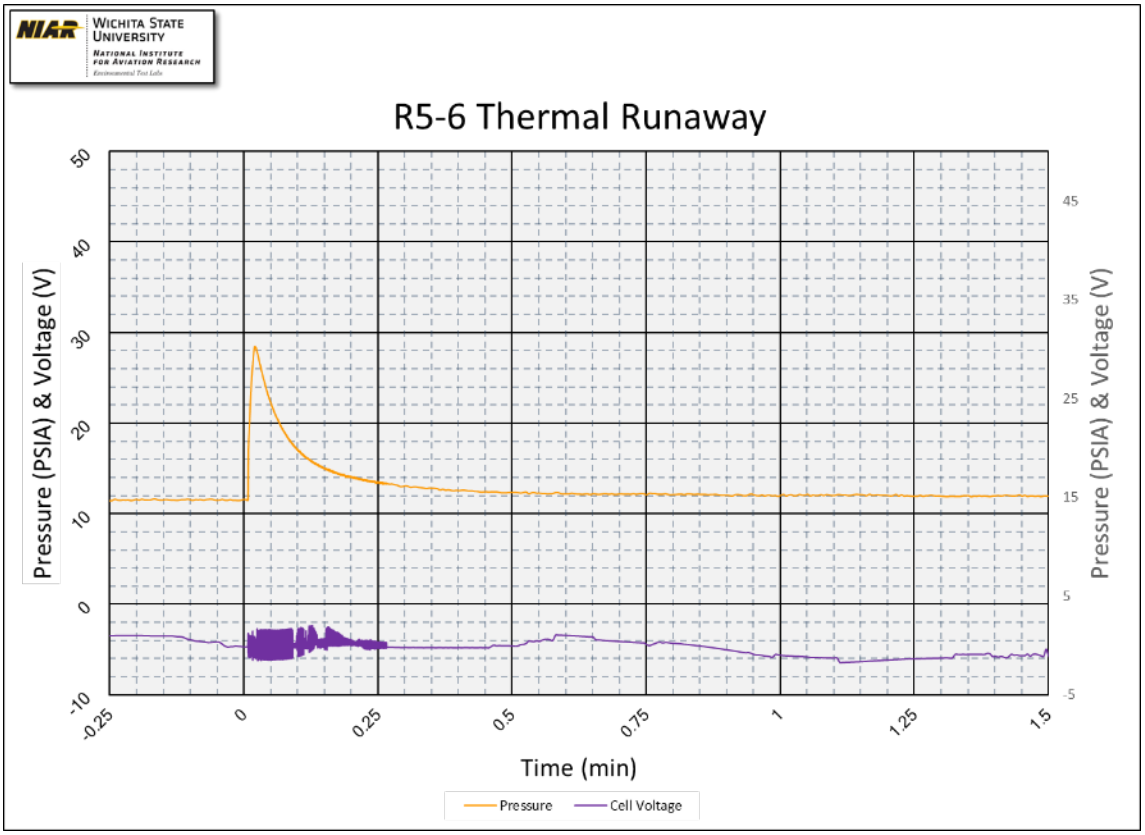

Figure 185: R5-6 Pressure and Voltage Graph

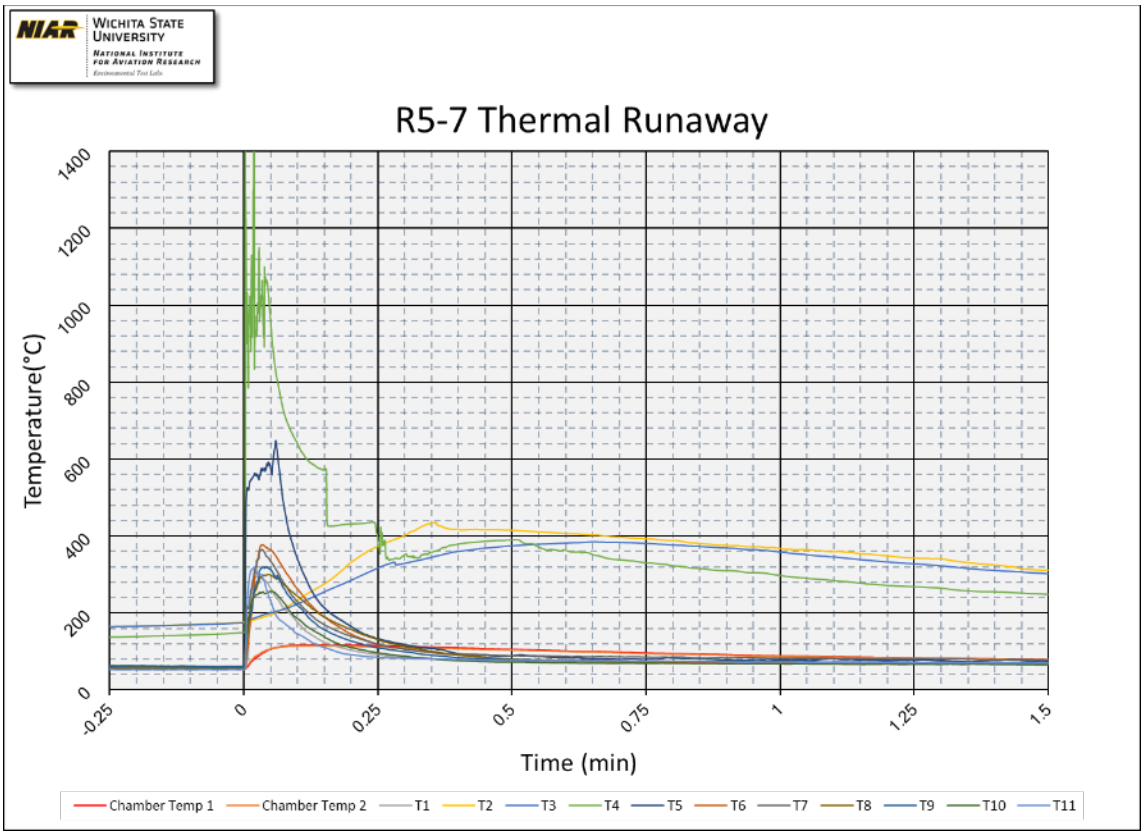

Figure 186: R5-7 Temperature Graph 1

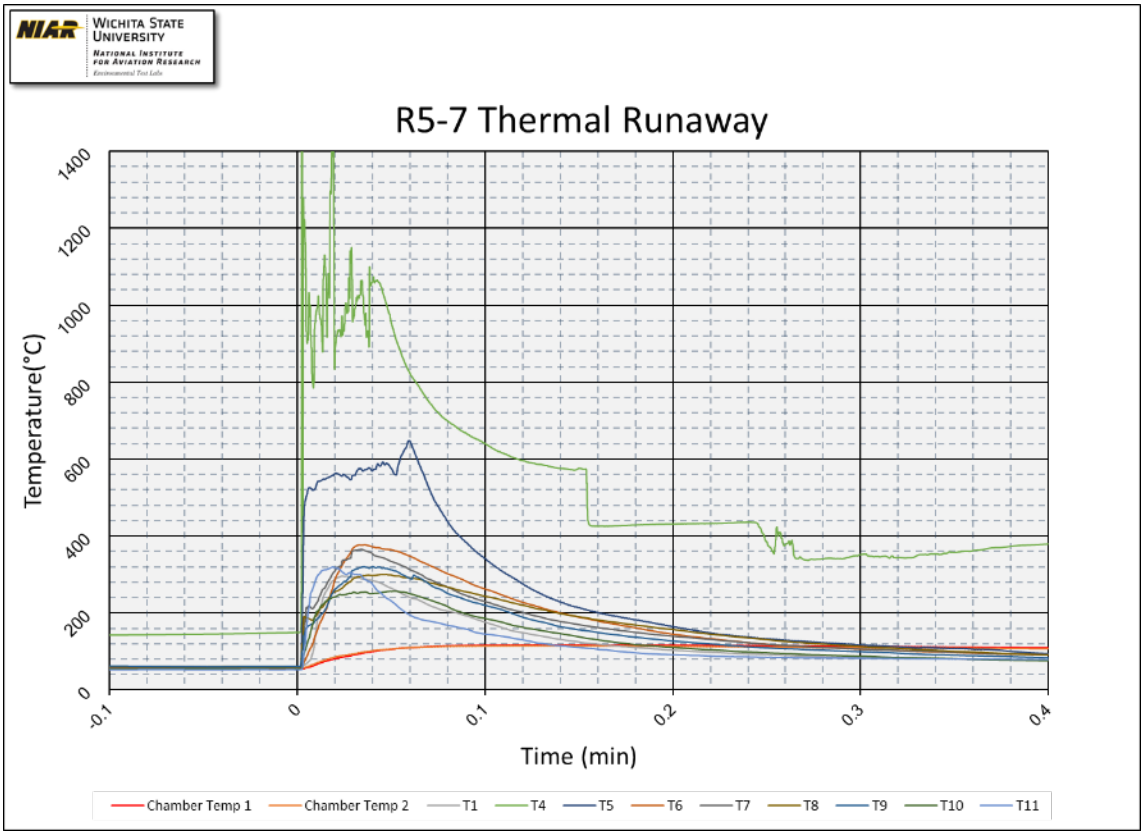

Figure 187: R5-7 Temperature Graph 2

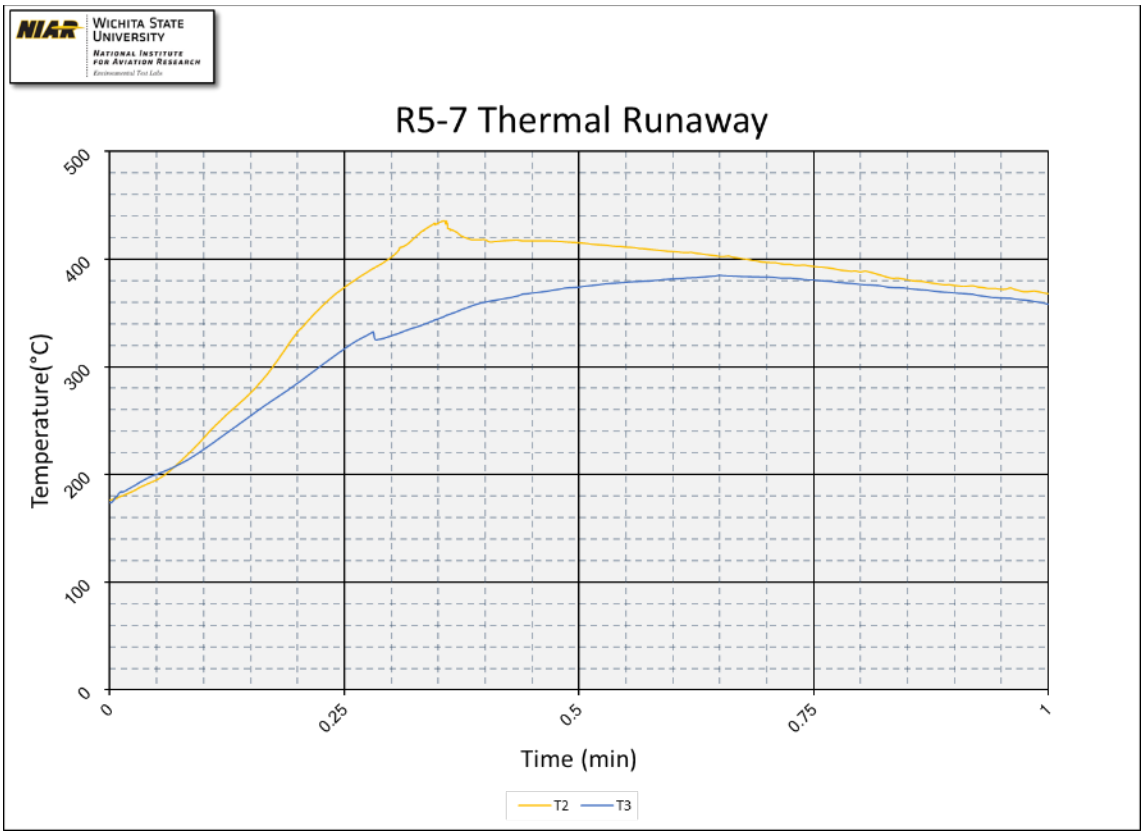

Figure 188: R5-7 Temperature Graph 3

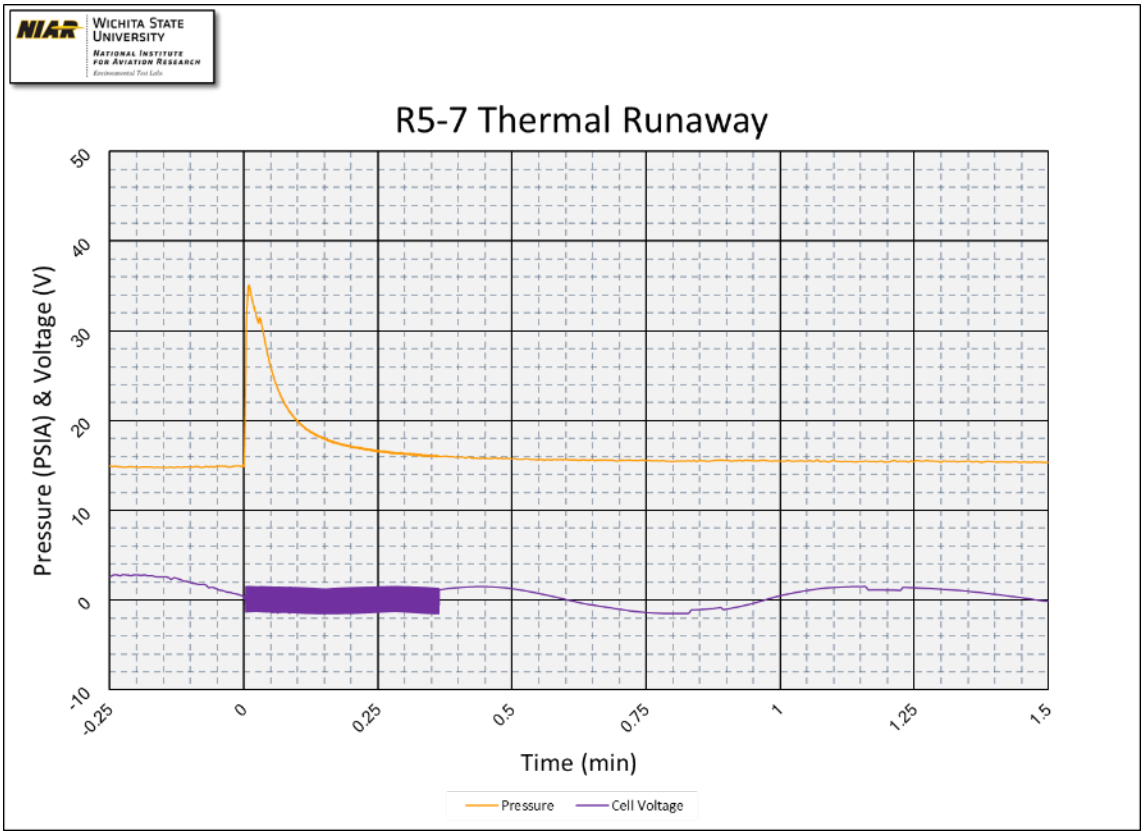

Figure 189: R5-7 Pressure and Voltage Graph

2.2.6 R6-X (Sanyo 20700B)

The R6-X cells were consistent in terms of the temperatures they reached. The reactions resulted in an average cell peak temperature of 458.5°C and an average chamber peak temperature of 778.0°C. The cells were consistent in the types of gas released, with all 5 trials releasing carbon monoxide, carbon dioxide, ethylene, sulfuric acid, hydrogen cyanide, nitric oxide, and nitrogen dioxide. However, the amounts of carbon monoxide and ethylene varied by a large amount between each trial.

Table 22: R6-X Mass Change Summary

Cell	Pre-Test Mass (g)	Post-Test Mass (g)
R6-1	62.023	14.764
R6-2	61.974	19.944
R6-3	61.981	33.743
R6-4	61.947	16.148
R6-5	61.802	31.845

Table 23: R6-X Detected Gases

Gas Species	Detector Tube Error Range	Moles of Gas Detected R6-1	Moles of Gas Detected R6-2	Moles of Gas Detected R6-3	Moles of Gas Detected R6-4	Moles of Gas Detected R6-5
CO	varied	0.082 ± 10%	0.076 ± 10%	5.0E-3 ± 10 - 15%	0.022 ± 10 - 15%	0.056 ± 10%
CO_2	±10%	0.24	0.22	0.39	0.16	0.20
C_2H_4	±20 - 30%	1.1E-3	5.5E-4	0.017	1.6E-3	4.5E-3
H_2	±15 - 20%	0	0	0	0	0
H_2S	±25%	0	0	0	0	0
H_2SO_4	±10%	7.1E-6	5.6E-6	8.4E-6	5.7E-6	3.4E-6
HCl	±15%	0	0	0	0	0
HCN	±10 - 15%	1.1E-5	5.5E-6	5.5E-6	8.2E-6	8.4E-6
HF	±10%	0	0	0	0	0
HNO_3	±15%	0	0	0	0	0
NO	±10 - 15%	1.5E-4	1.9E-4	2.1E-4	4.3E-4	1.5E-4
NO_2	varied	1.1E-5 ± 10 - 15%	3.3E-5 ± 10 - 15%	1.1E-5 ± 10%	1.1E-5 ± 10%	9.0E-6 ± 10%
SO_2	±10%	0	0	0	0	0

Table 24 R6-X Failure Modes

Failure Mode	Leak	Vent	Fire	Rupture
R6-1	Y	Y	Y	Y
R6-2	Y	Y	Y	Y
R6-3	Y	Y	Y	
R6-4	Y	Y	Y	Y
R6-5		Y	Y	Y

Figure 190: R6-1 Pre-Test

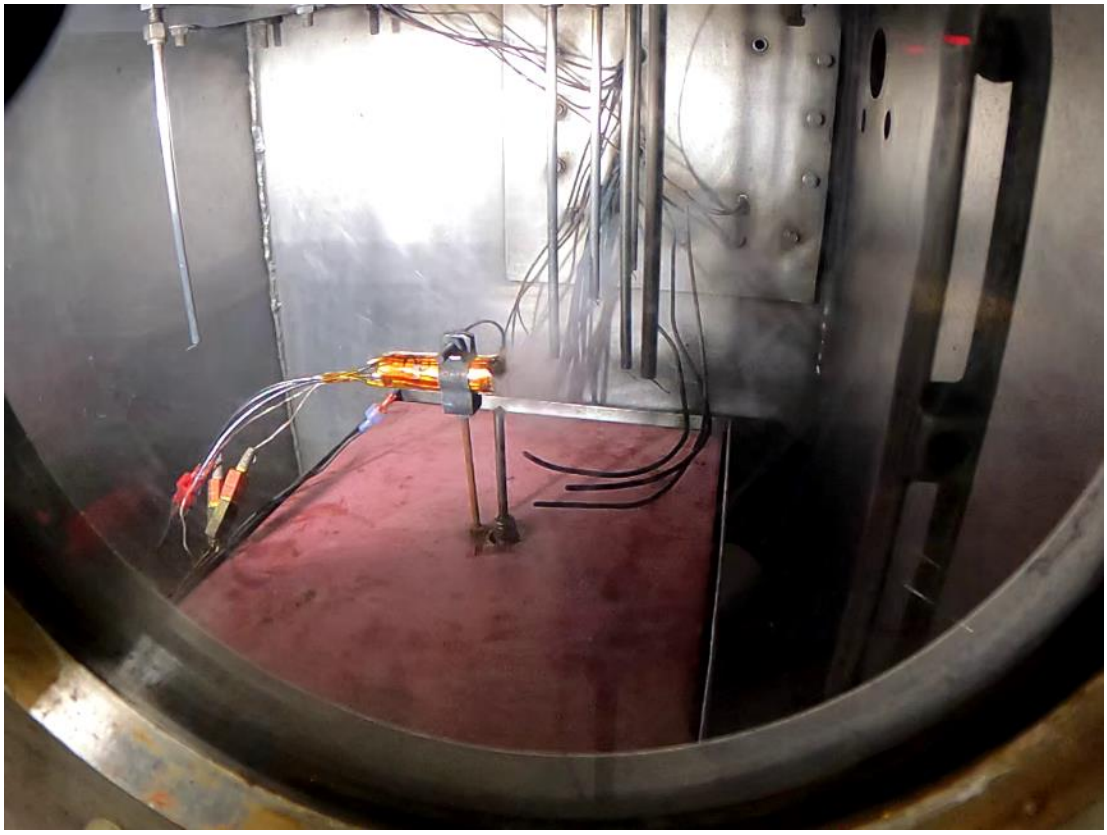

Figure 191: R6-1 Venting

Figure 192: R6-1 Post-Test 1

Figure 193: R6-1 Post-Test 2

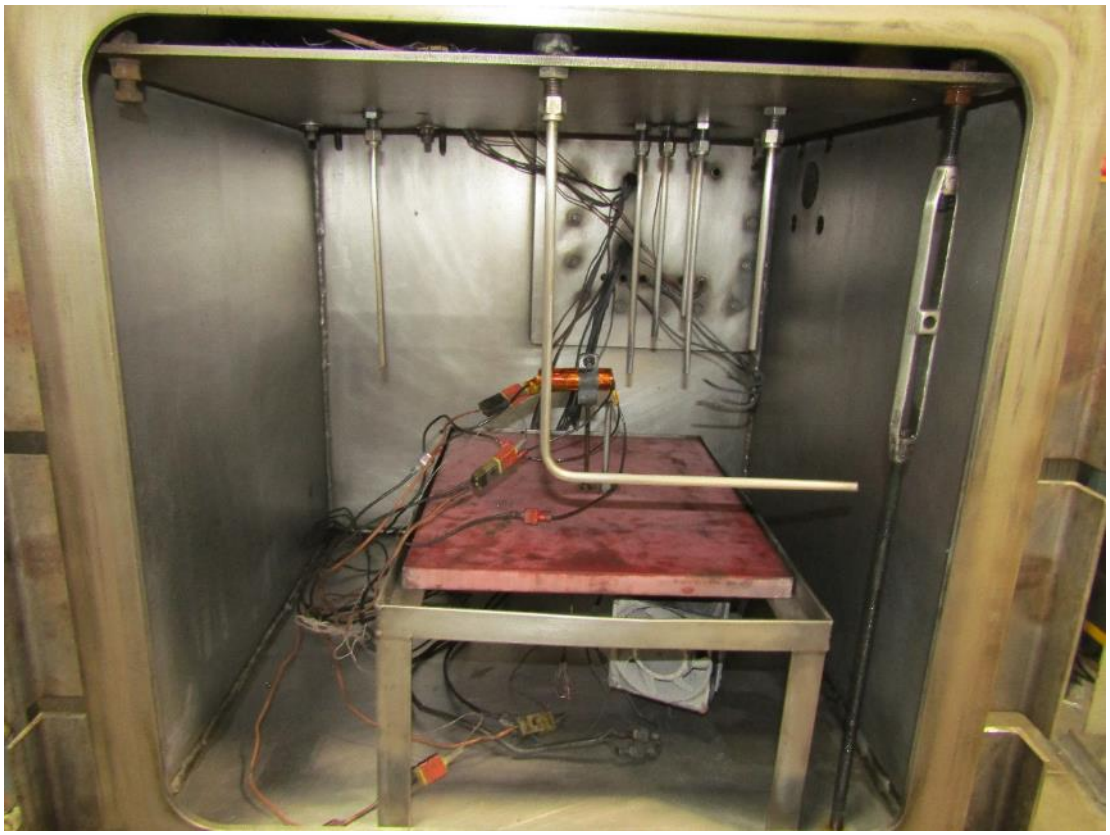

Figure 194: R6-2 Pre-Test

Figure 195: R6-2 Venting

Figure 196: R6-2 Post-Test 1

Figure 197: R6-2 Post-Test 2

Figure 198: R6-3 Pre-Test

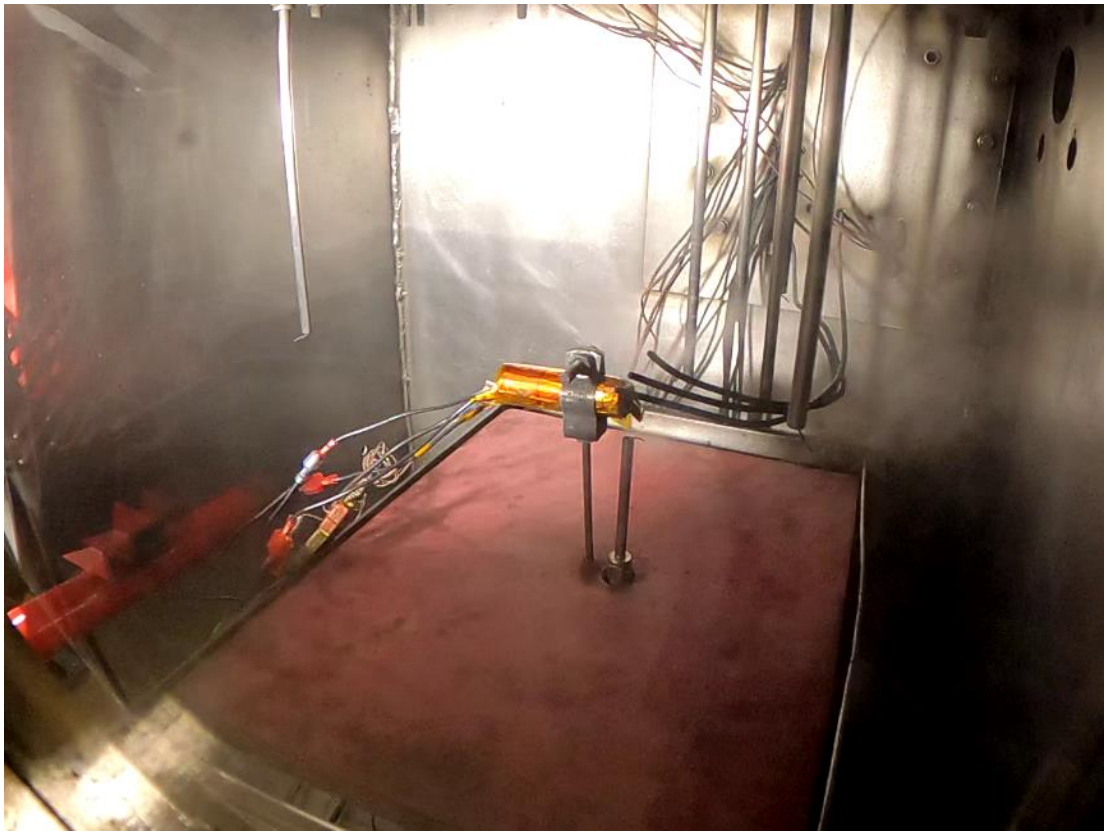

Figure 199: R6-3 Venting

Figure 200: R6-3 Post-Test 1

Figure 201: R6-3 Post-Test 2

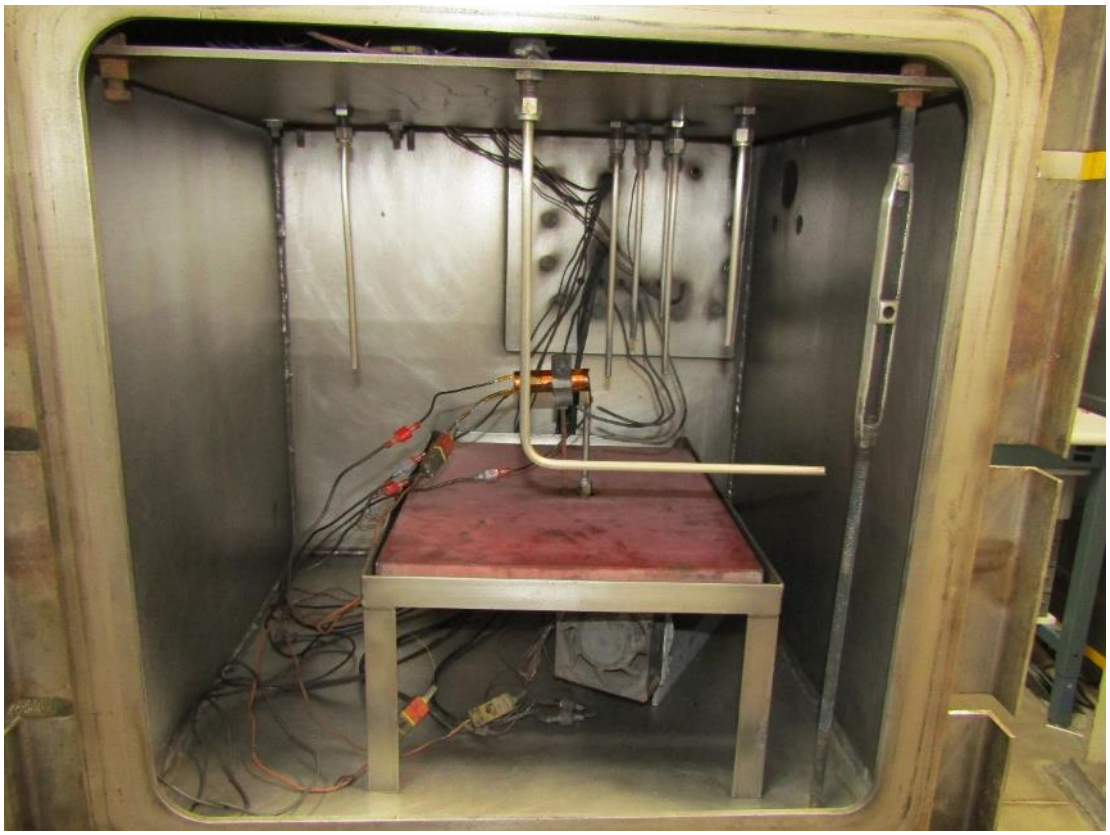

Figure 202: R6-4 Pre-Test

Figure 203: R6-4 Post-Test 1

Figure 204**: R6-4 Post-Test 2**

Figure 205: R6-5 Pre-Test

Figure 206: R6-5 Venting

Figure 207: R6-5 Post-Test 1

Figure 208: R6-5 Post-Test 2

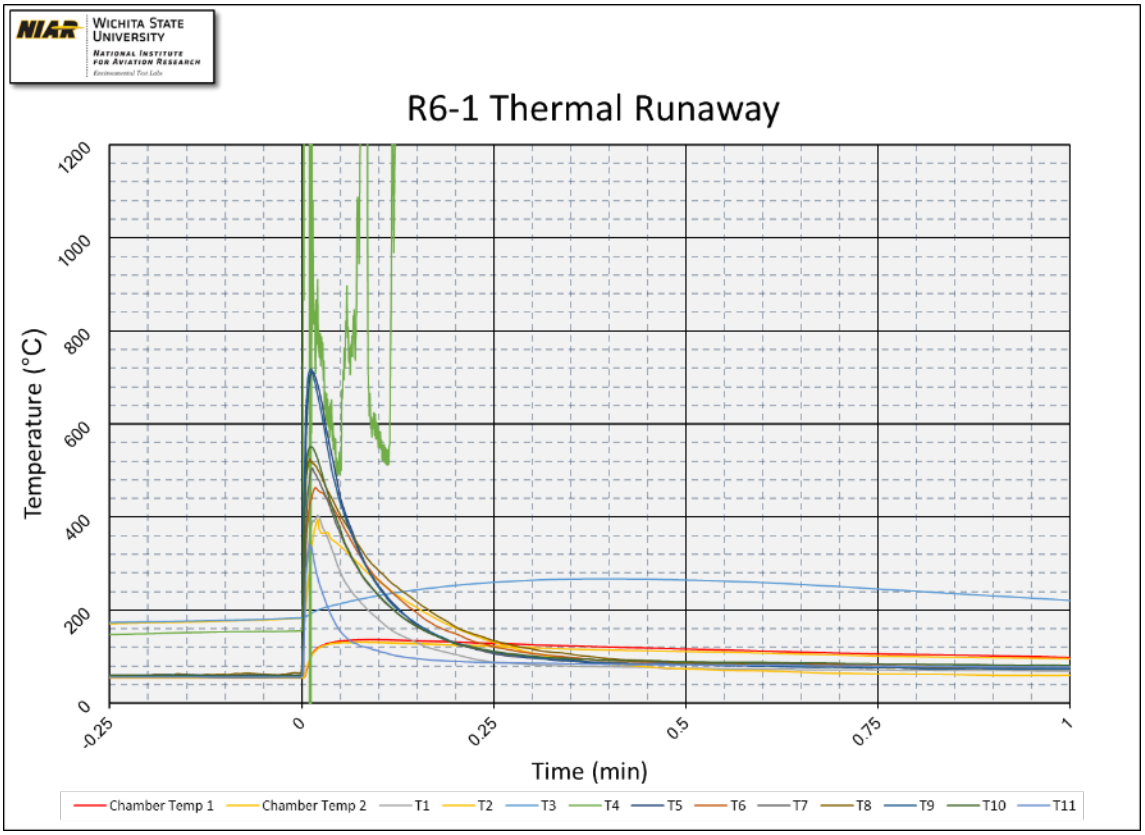

Figure 209: R6-1 Temperature Graph 1

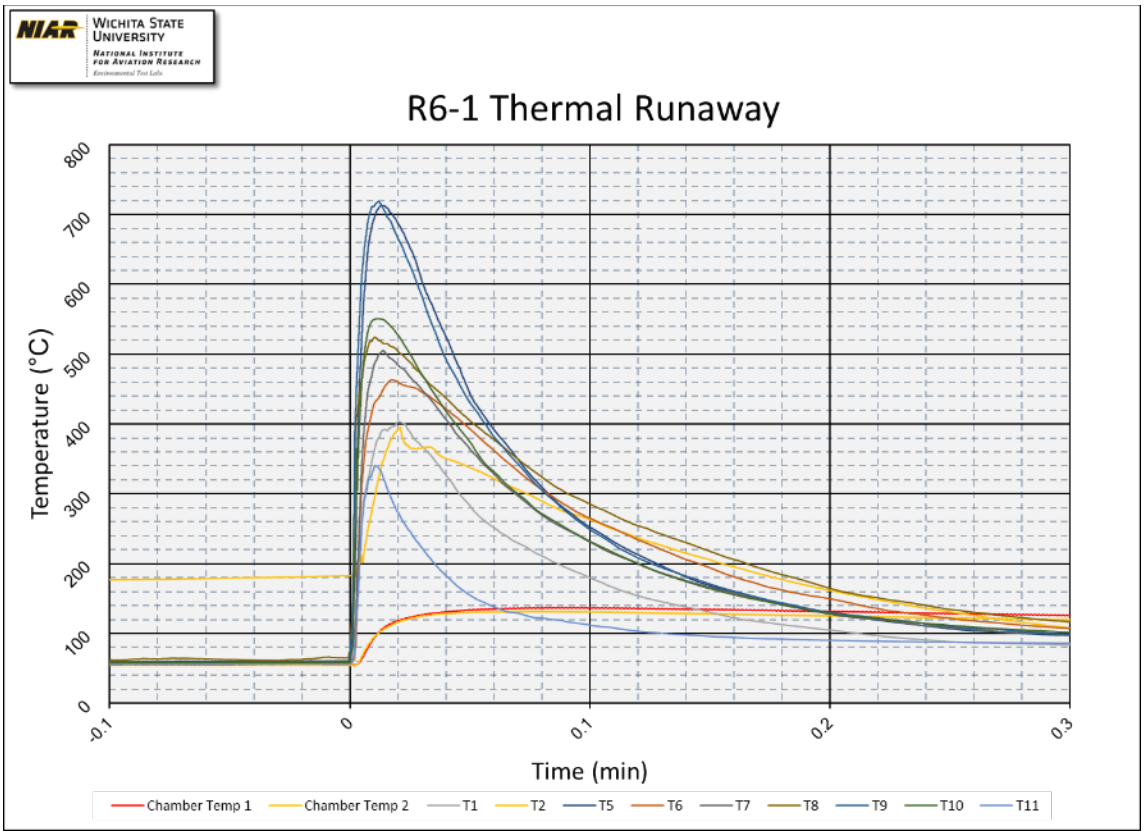

Figure 210: R6-1 Temperature Graph 2

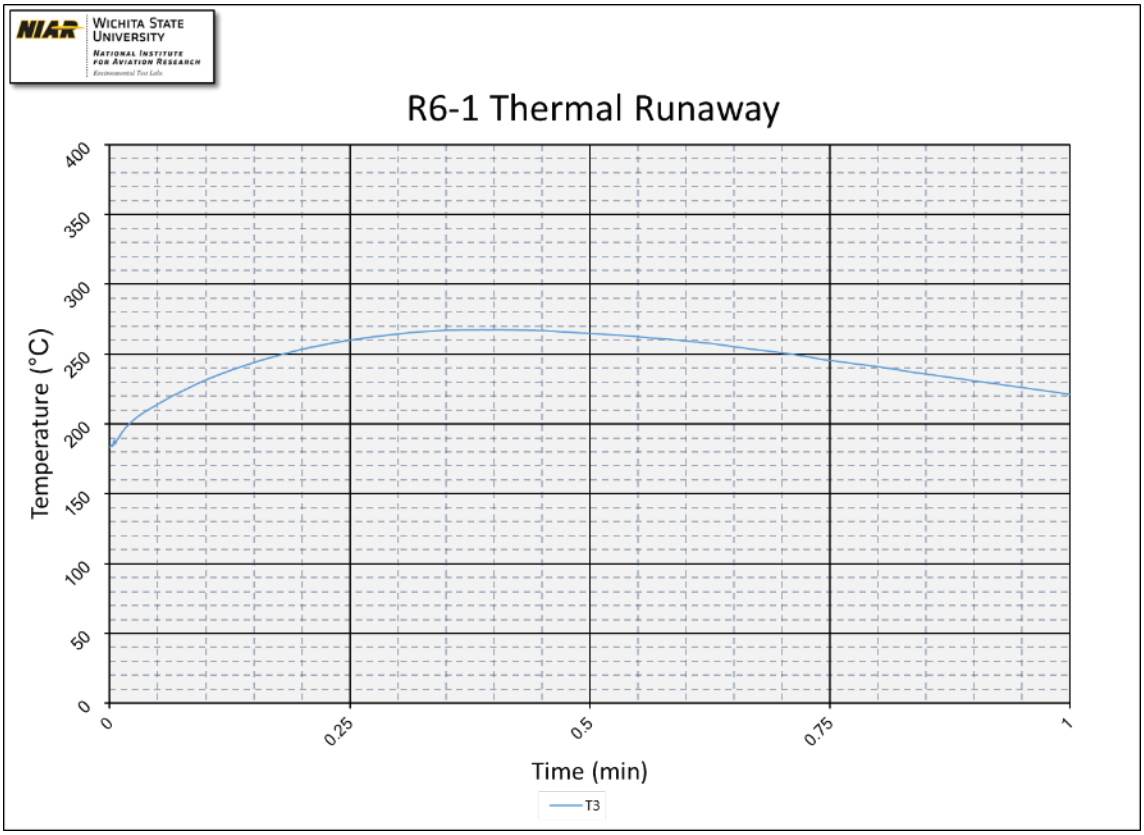

Figure 211: R6-1 Temperature Graph 3

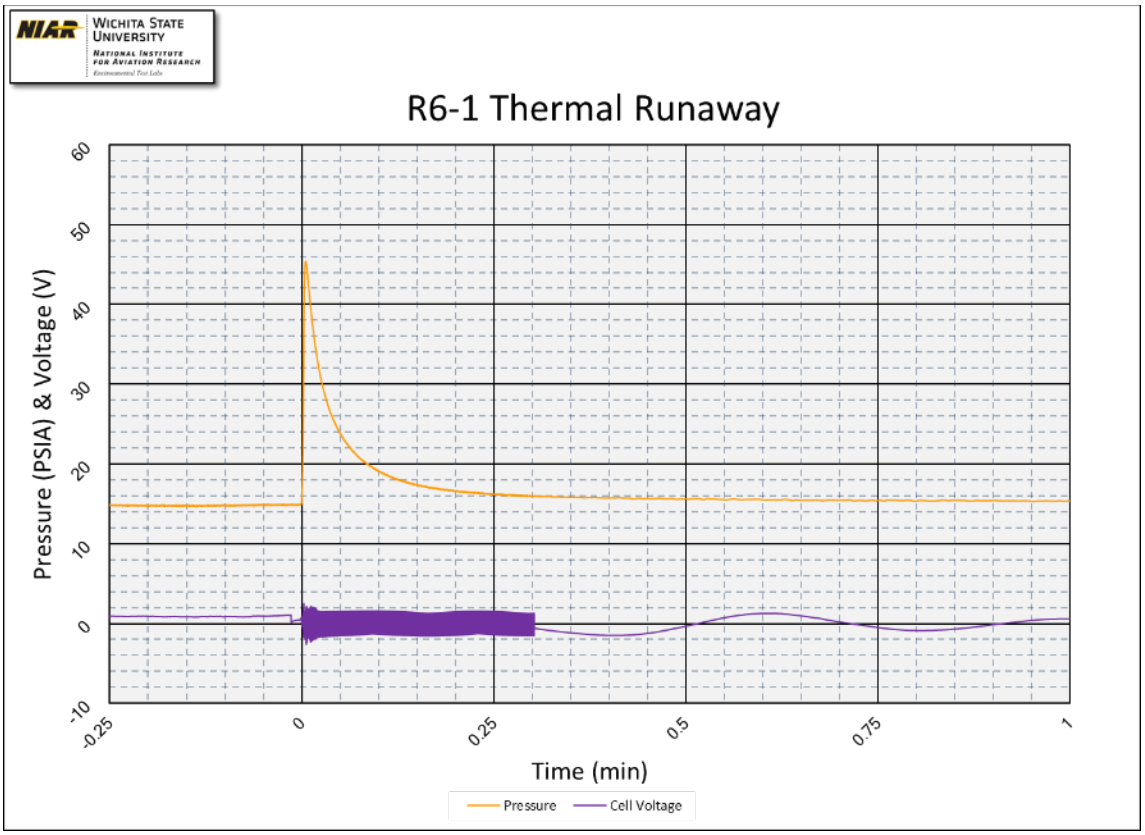

Figure 212: R6-1 Pressure and Voltage Graph

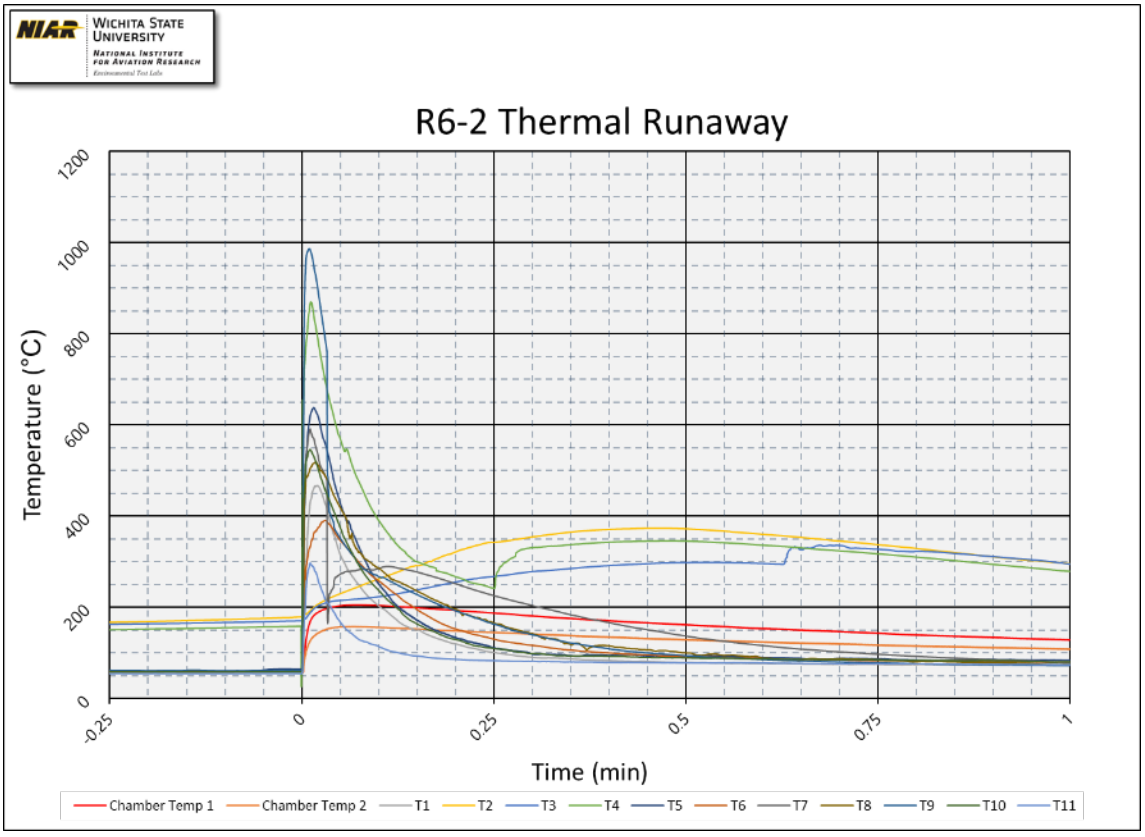

Figure 213: R6-2 Temperature Graph 1

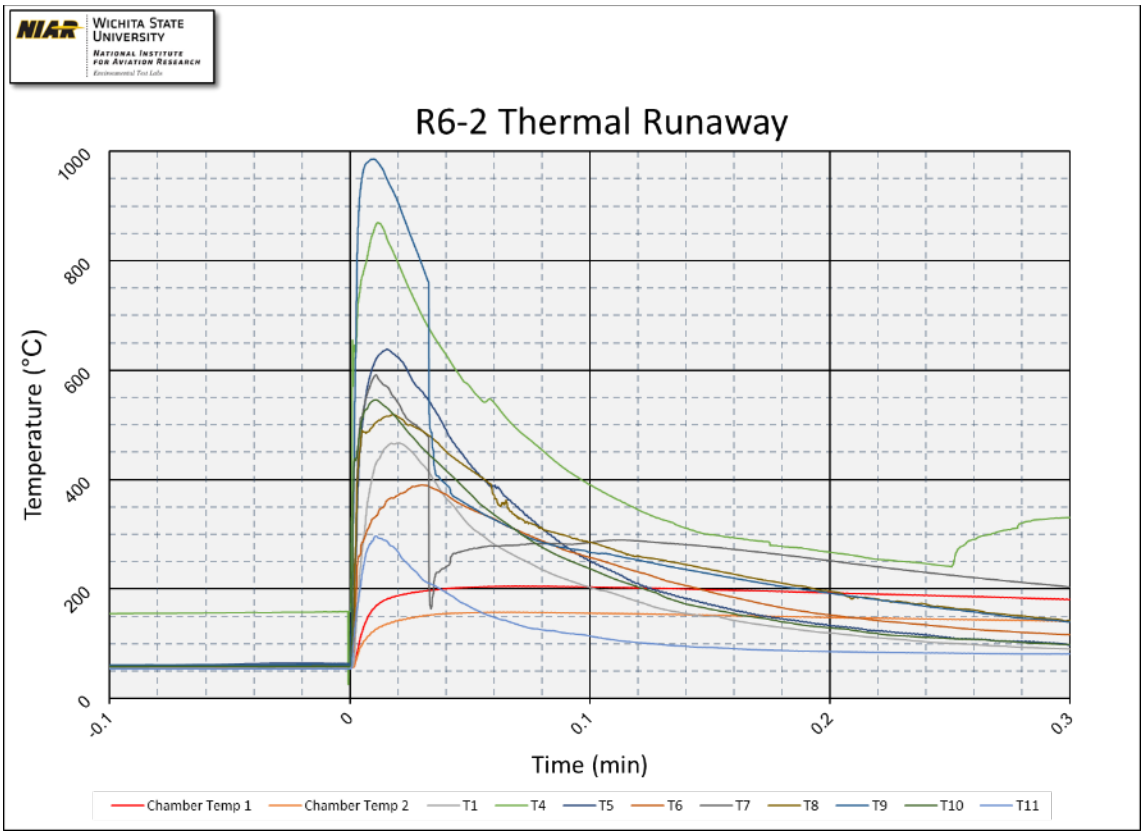

Figure 214: R6-2 Temperature Graph 2

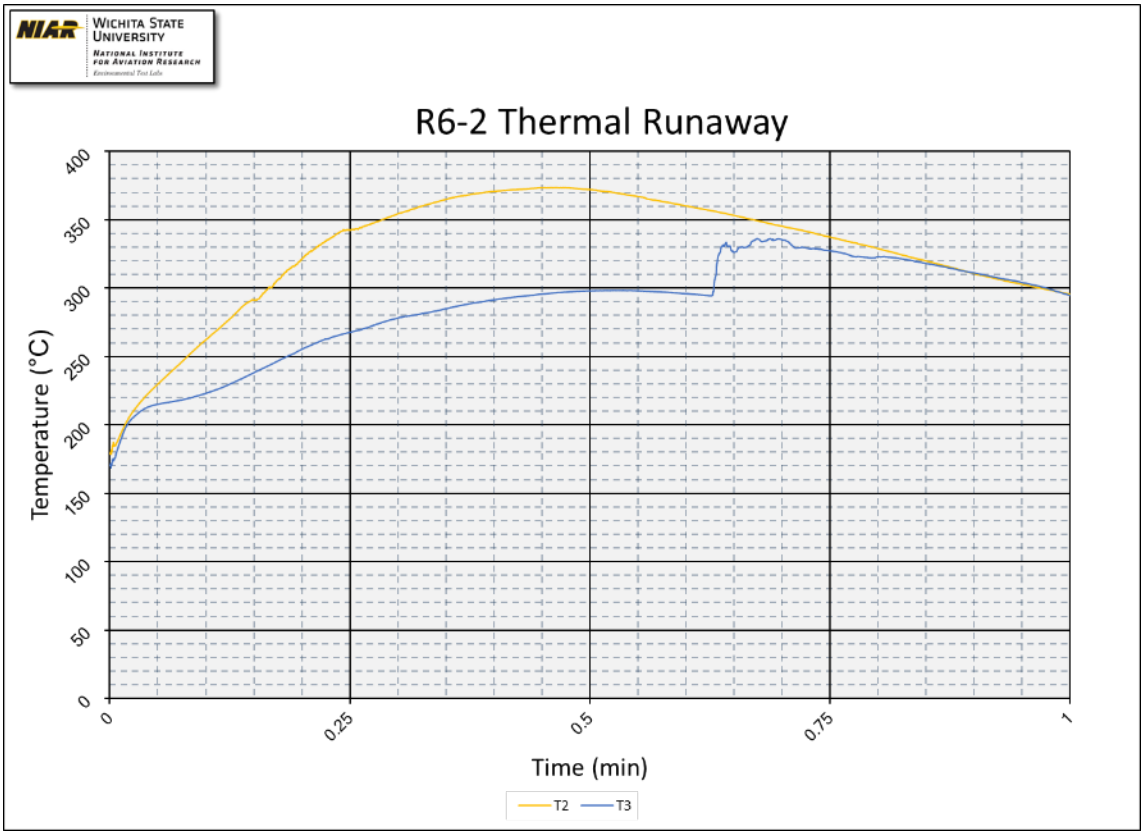

Figure 215: R6-2 Temperature Graph 3

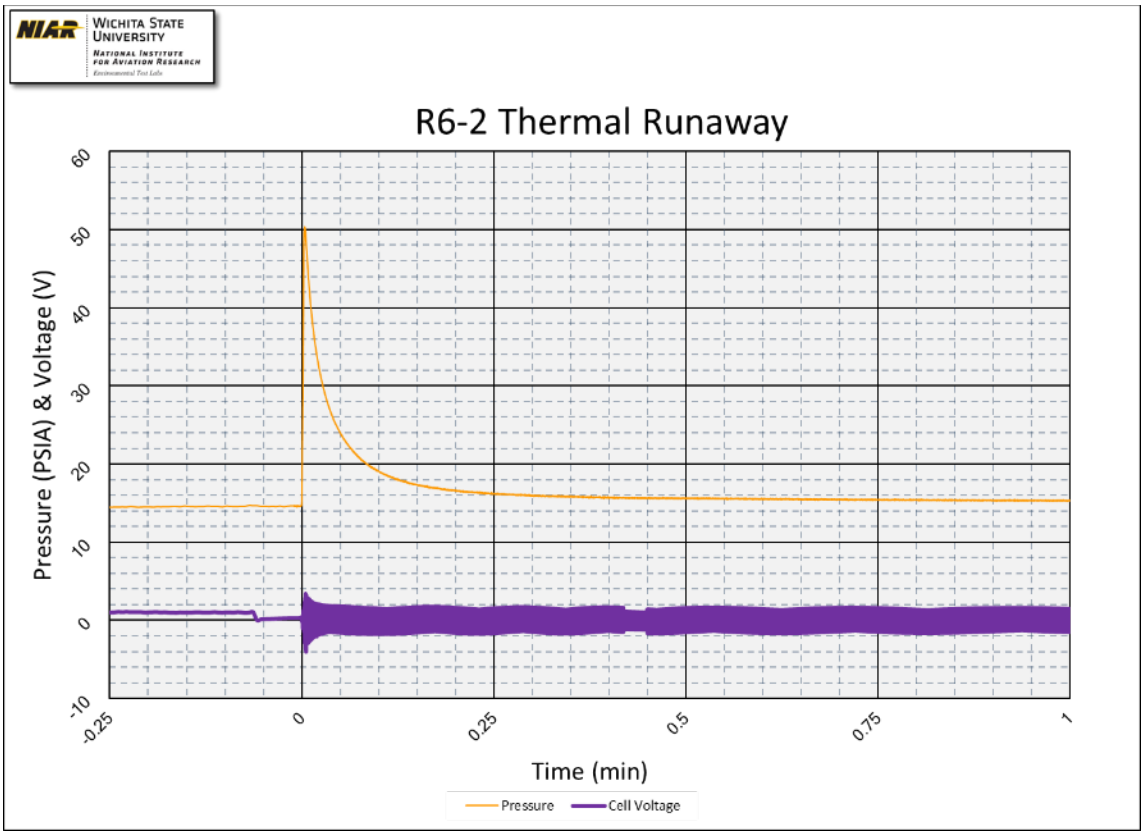

Figure 216: R6-2 Pressure and Voltage Graph

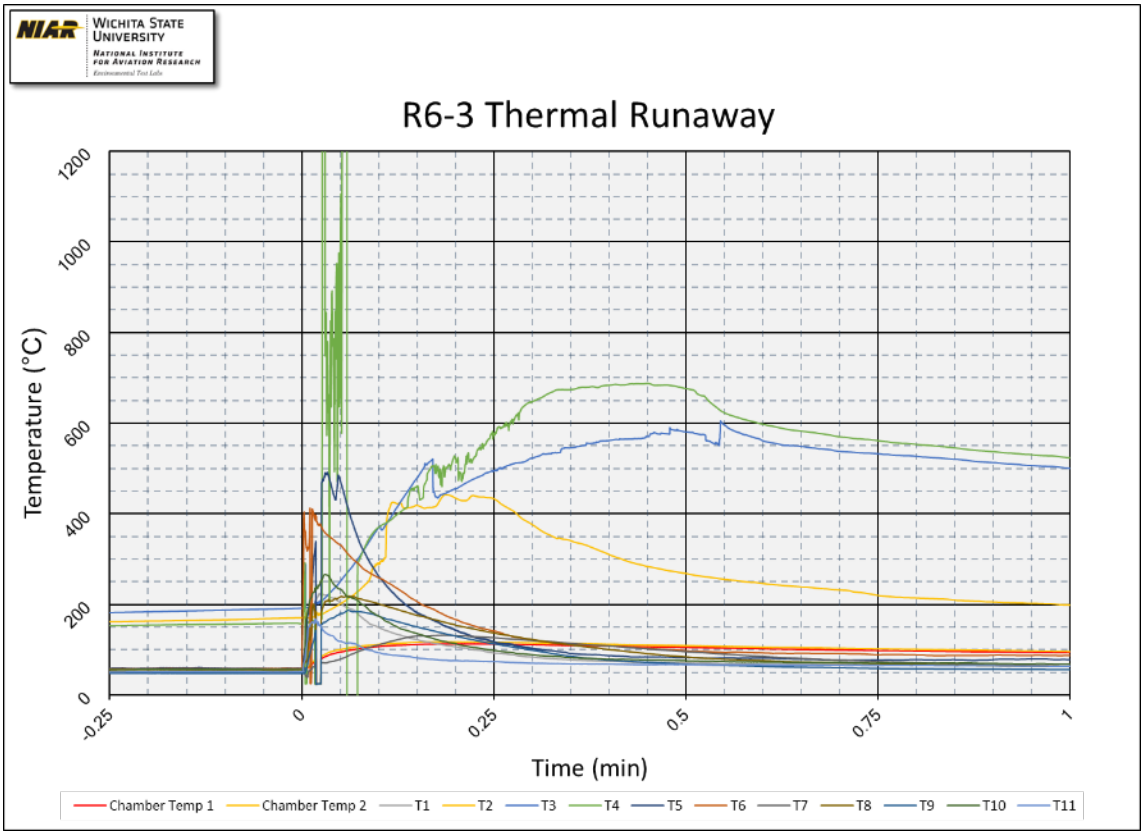

Figure 217: R6-3 Temperature Graph 1

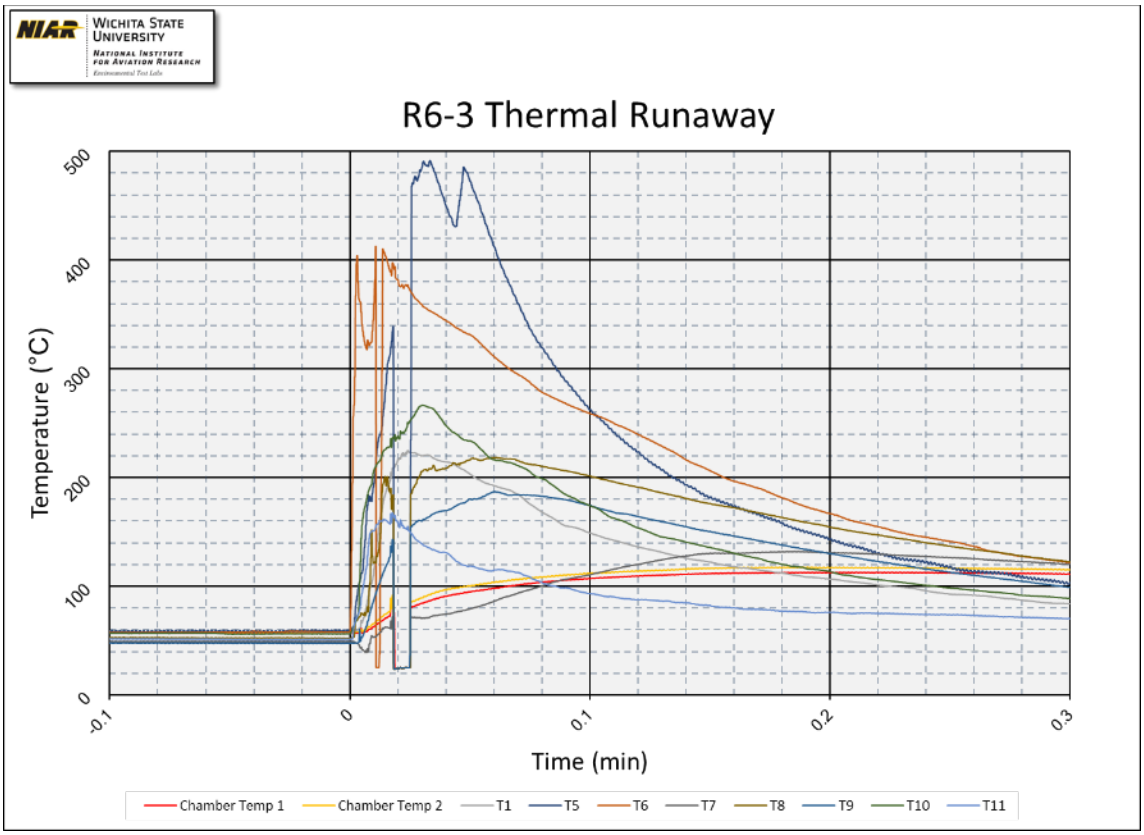

Figure 218:R6-3 Temperature Graph 2

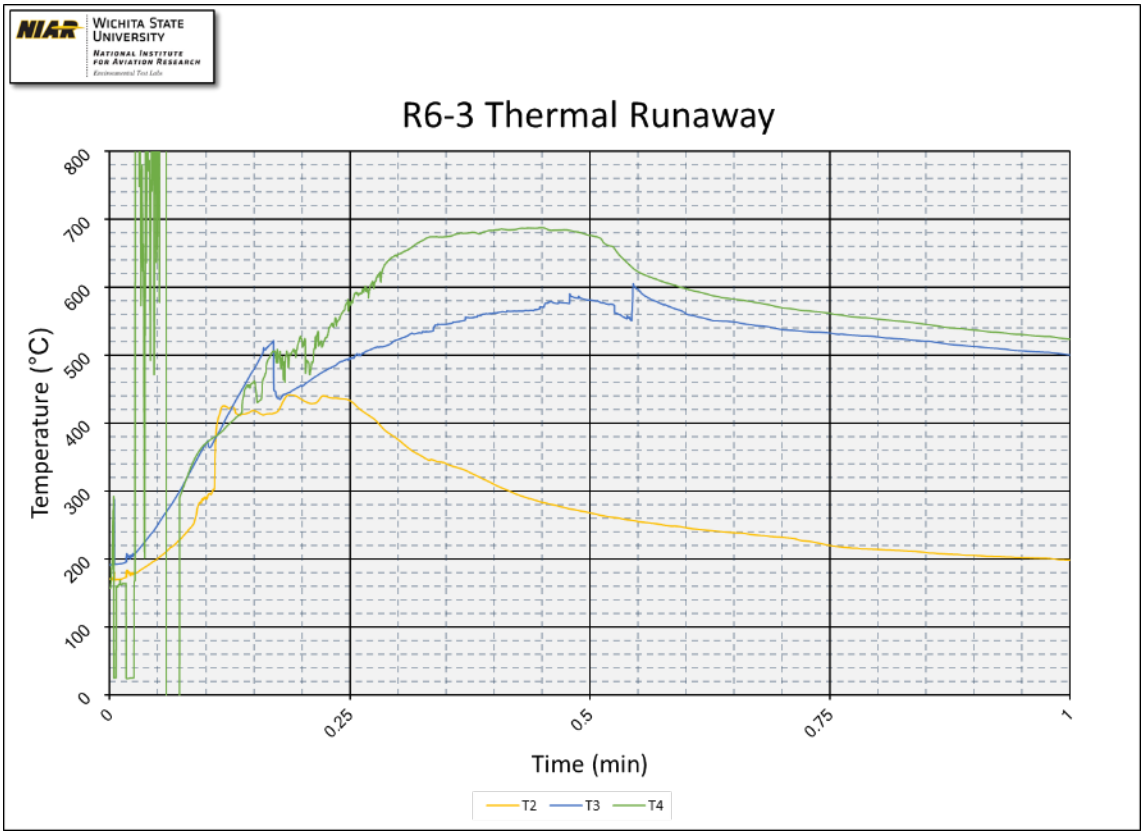

Figure 219: R6-3 Temperature Graph 3

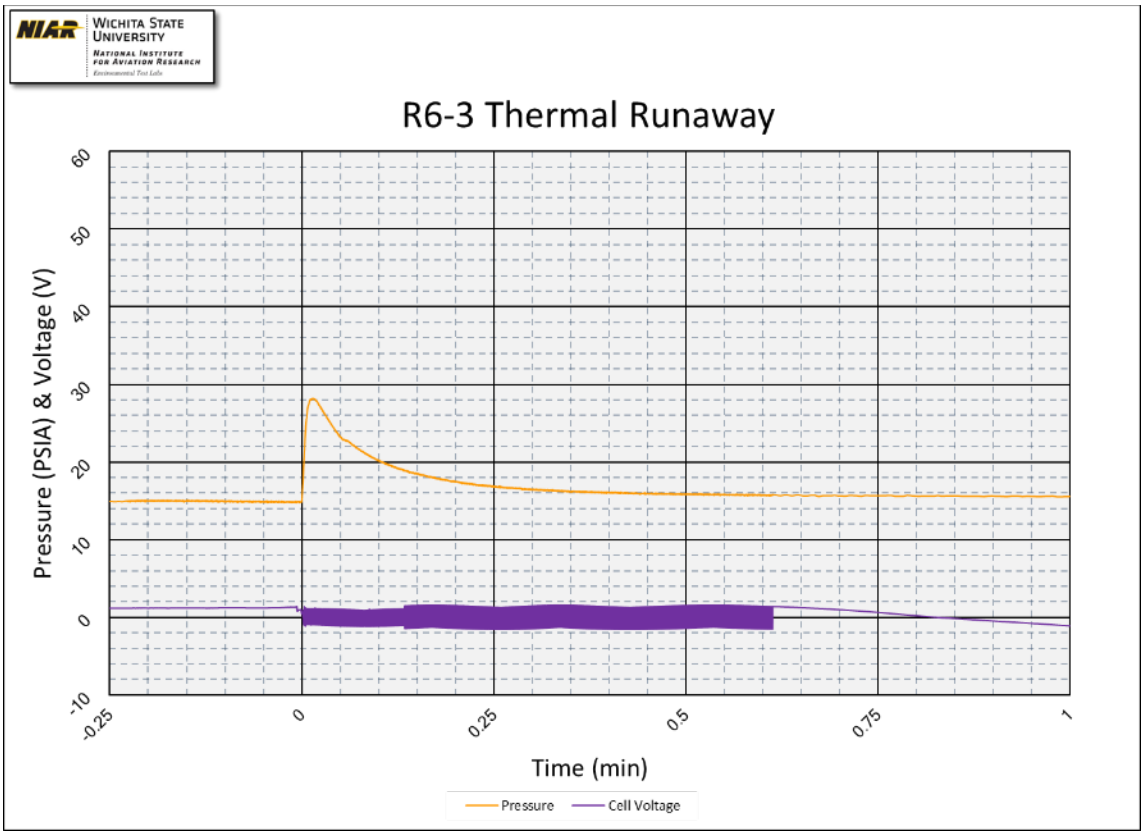

Figure 220: R6-3 Pressure and Voltage Graph

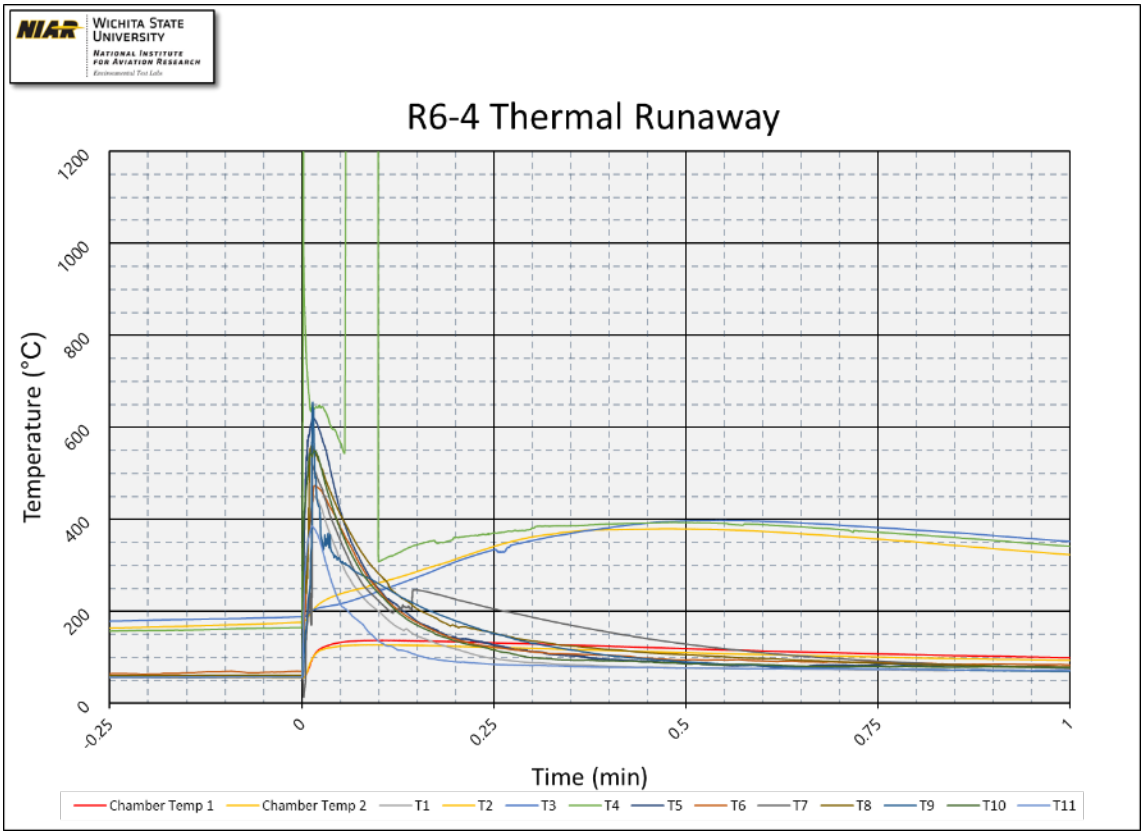

Figure 221: R6-4 Temperature Graph 1

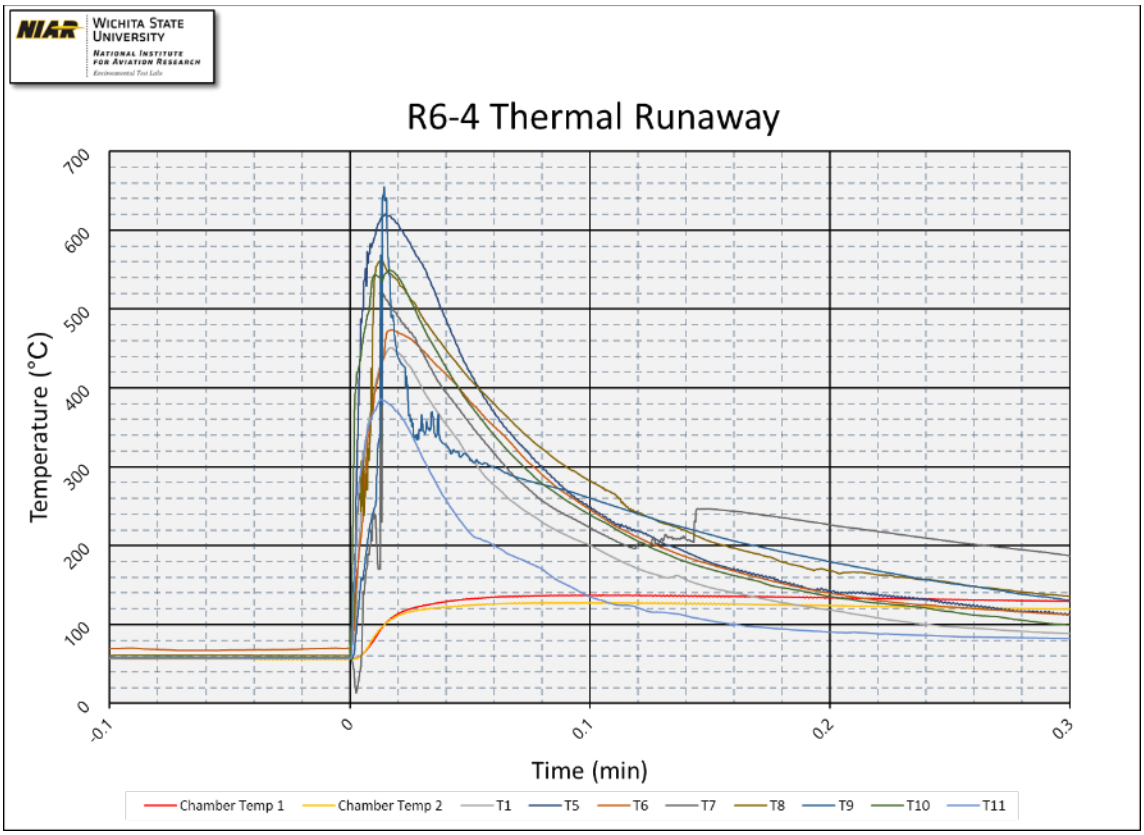

Figure 222: R6-4 Temperature Graph 2

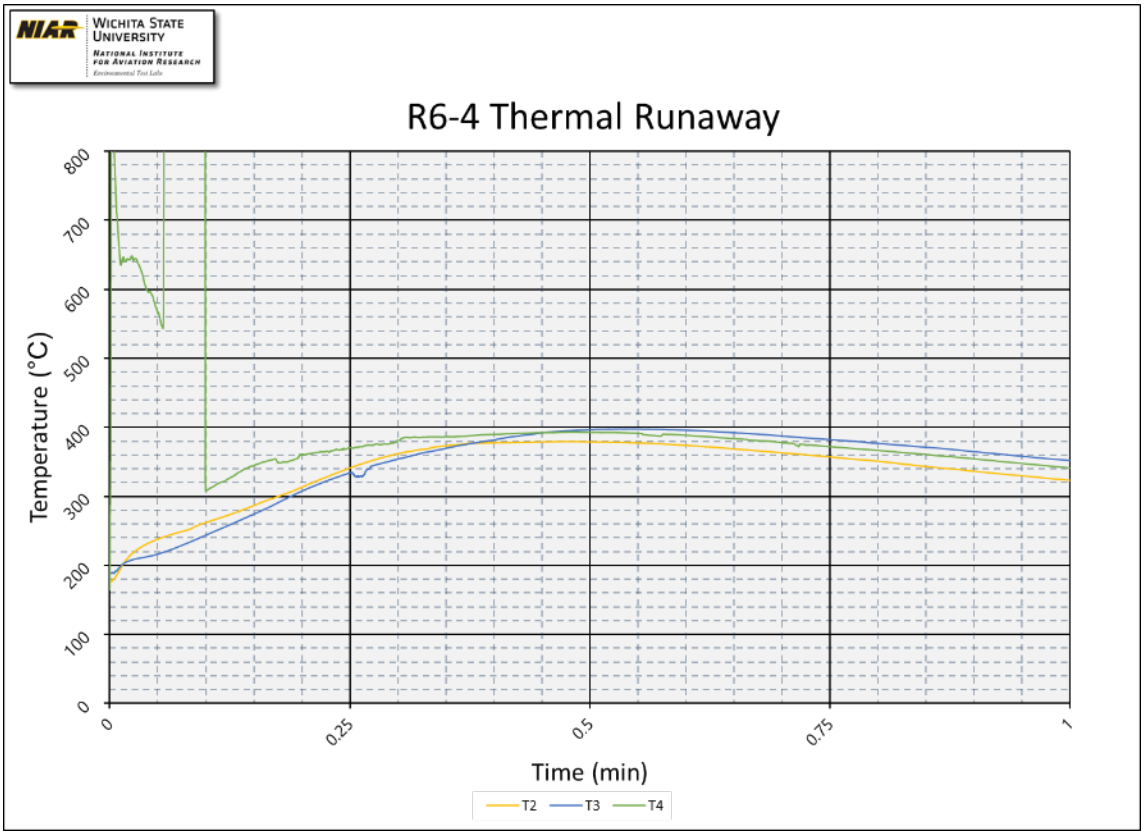

Figure 223: R6-4 Temperature Graph 3

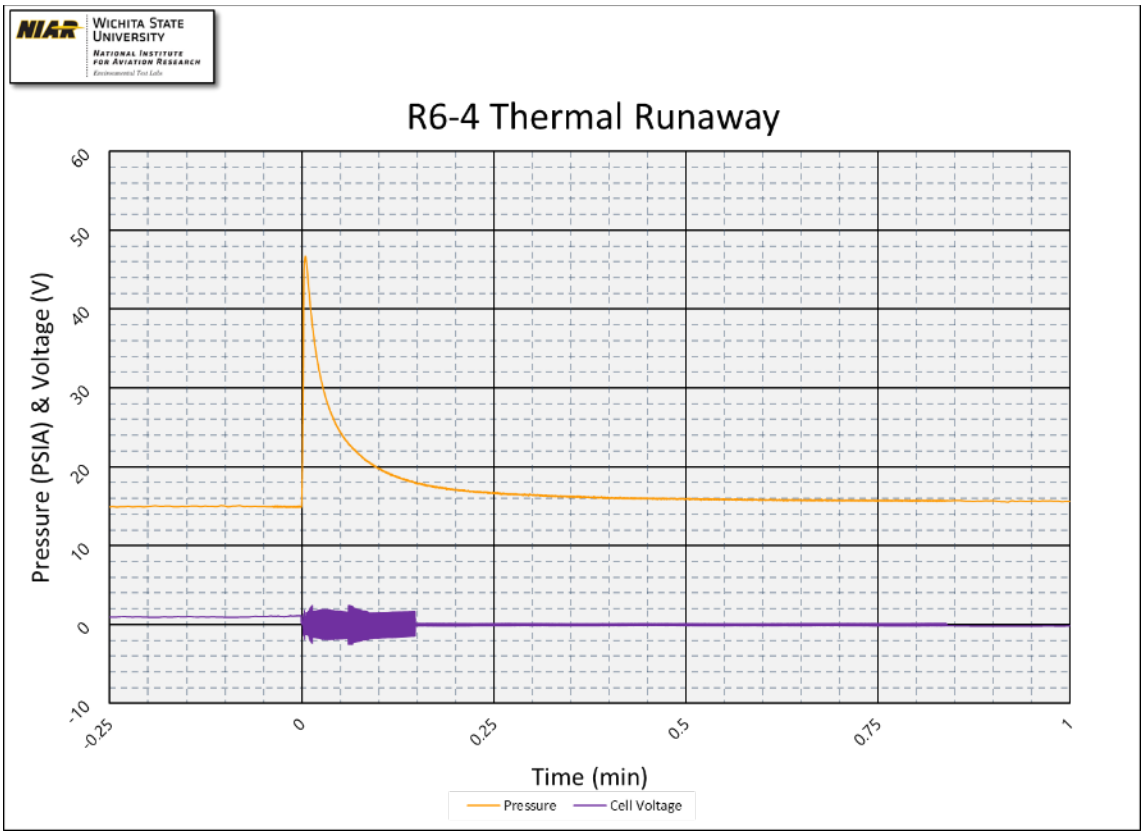

Figure 224: R6-4 Pressure and Voltage Graph

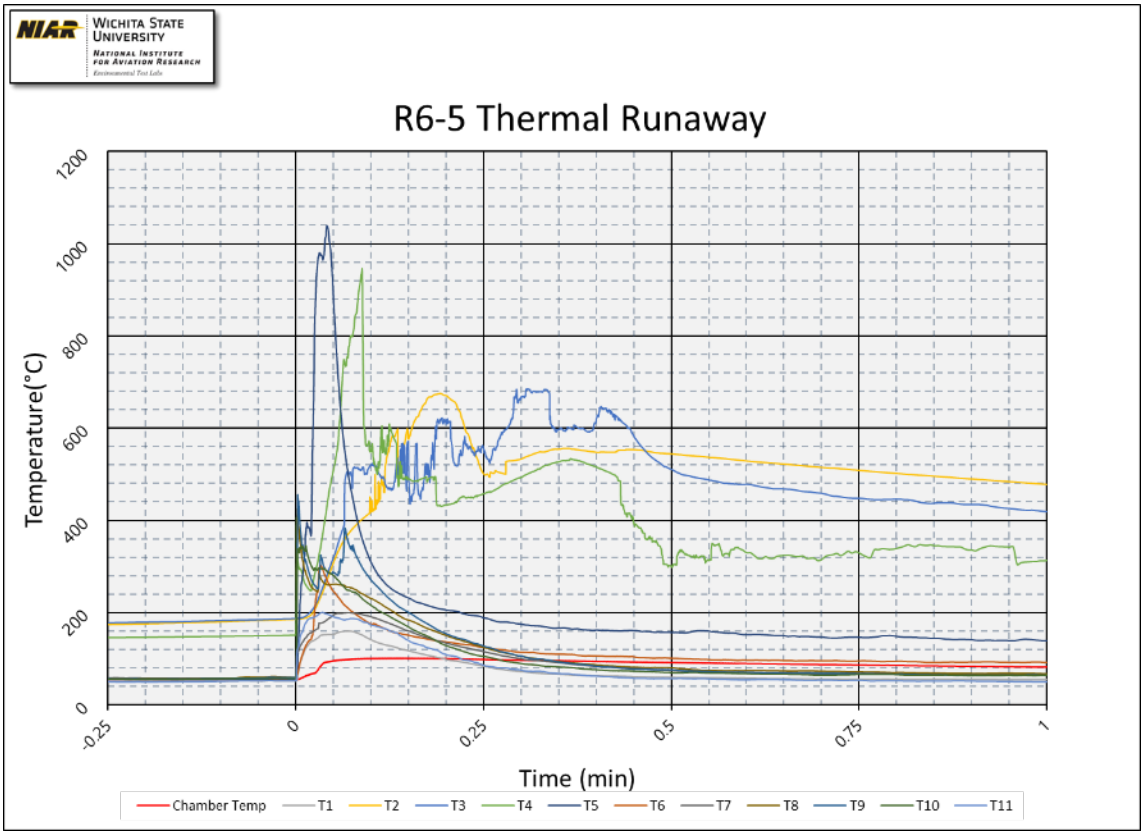

Figure 225: R6-5 Temperature Graph 1

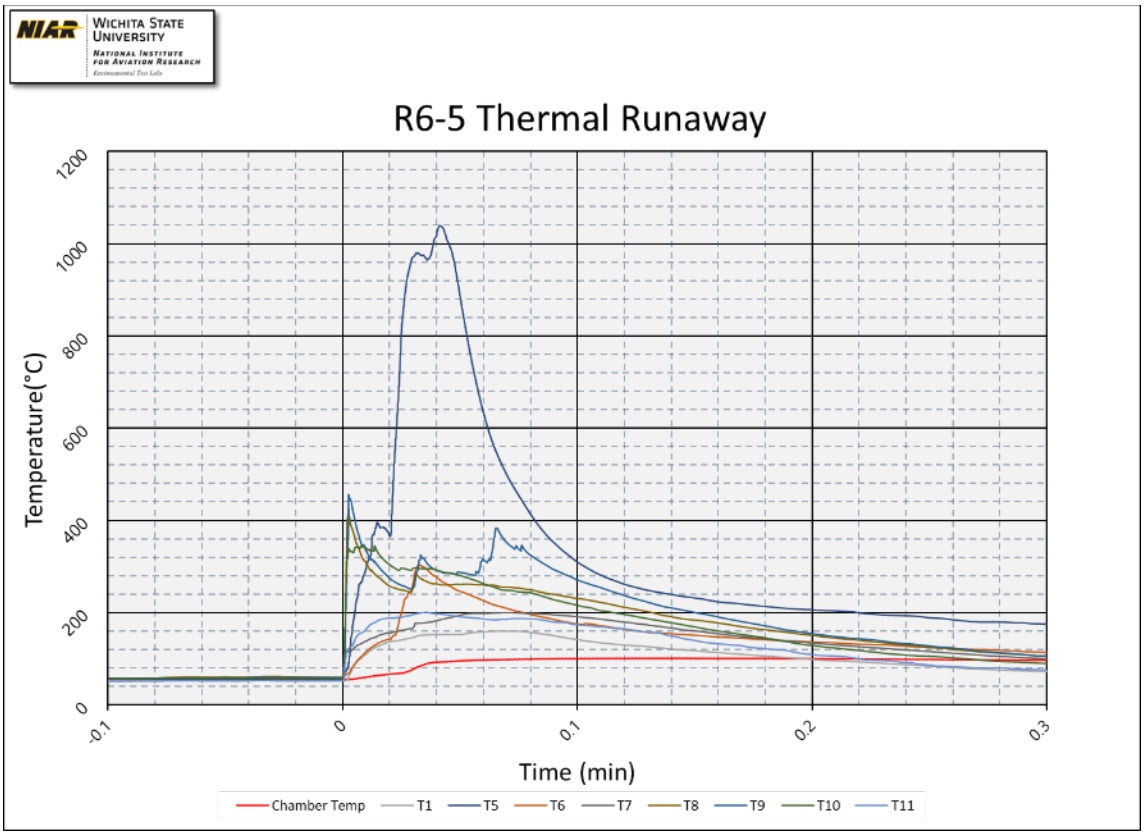

Figure 226: R6-5 Temperature Graph 2

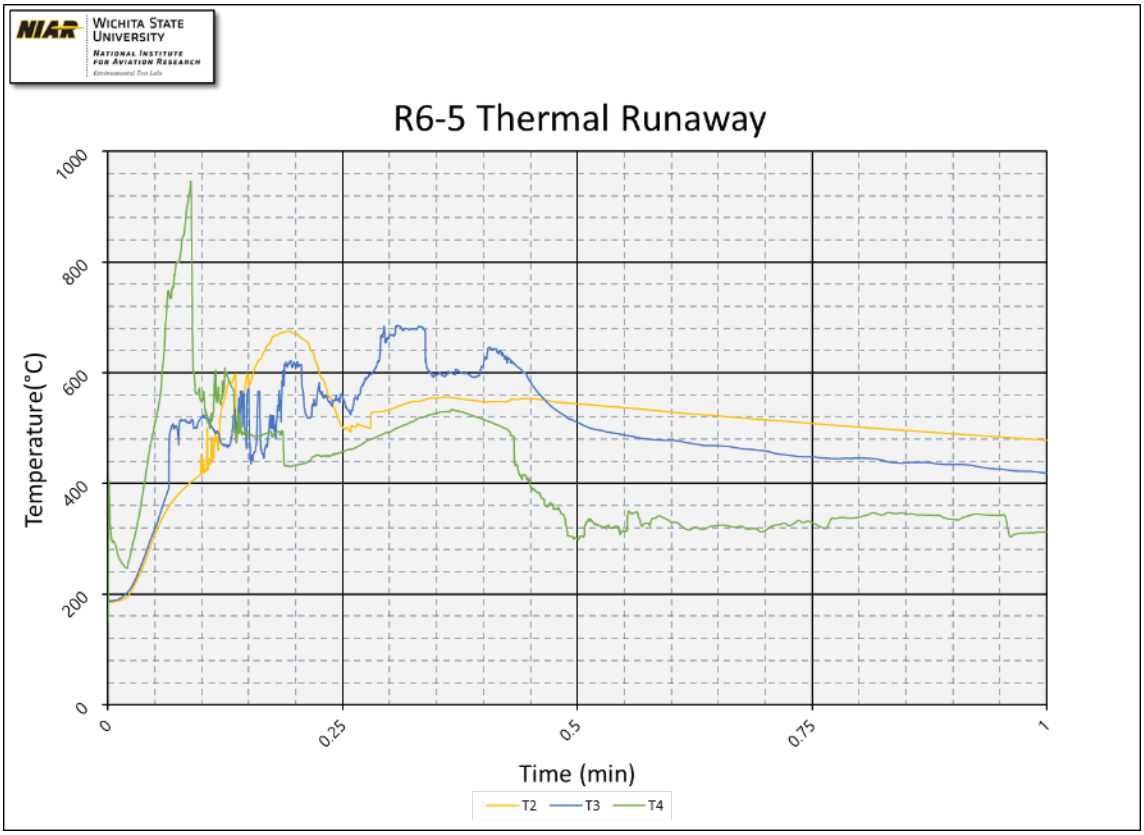

Figure 227: R6-5 Temperature Graph 3

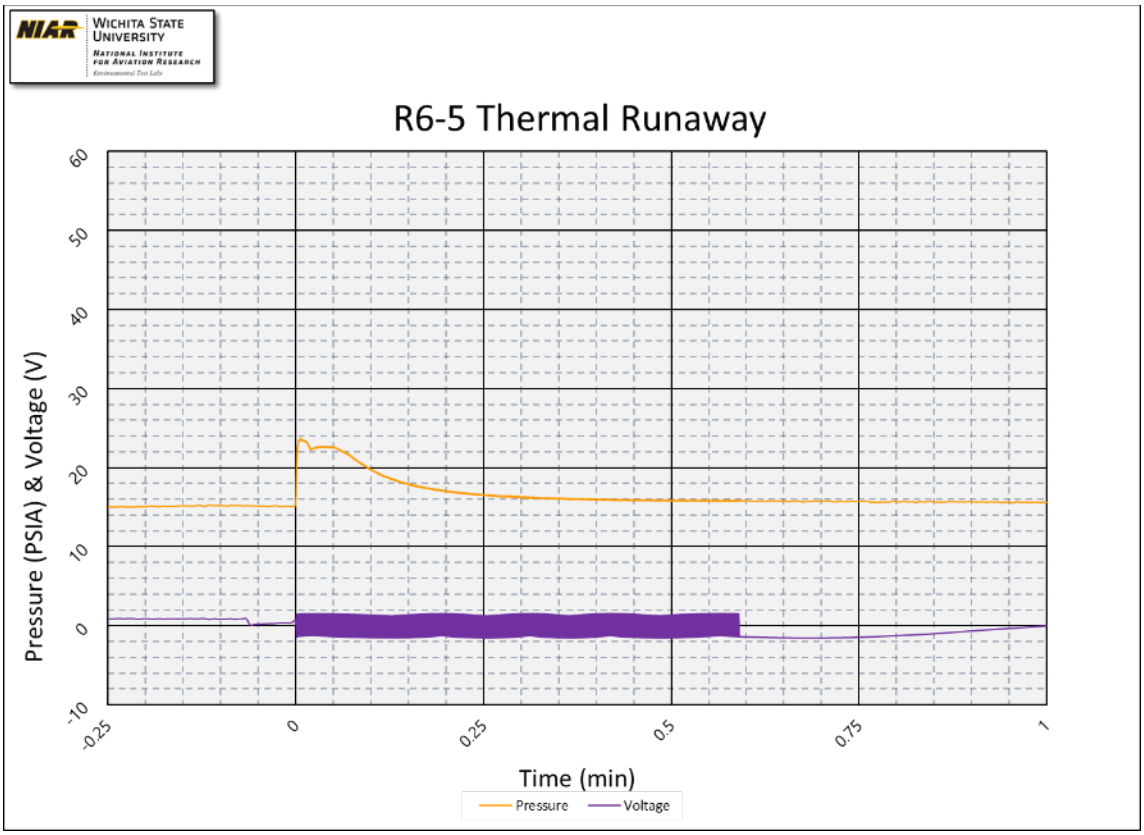

Figure 228: R6-5 Pressure and Voltage

2.3 Safety & Chemical Hazards

Many gas species can be present during a battery thermal runaway event depending on the chemical composition of the electrolyte. 13 gases were selected for detection based on the gases listed in DO-227A. Gases detected during this effort can be extremely chemically reactive or can pose health risks. A summary of the risks and hazards associated with each gas can be found in Table 25. Information listed in the table below is for healthy adults and is not an exhaustive list of every possible risk. A description of each of the physical and chemical hazards mentioned is shown in Table 26.

Table 25: Gas Safety & Chemical Hazards

Gas Species	Chemical Name	Health Symptoms	Health Notes	Chemical and Physical Hazards
CO	Carbon Monoxide	Headache, dizziness, weakness, chest pain, confusion, death. [1]	83 ppm: Irreversible health effects within 1 hour 1700 ppm: Death can occur within 10 minutes [2]	Category 1 Flammable Gas Category 3 Acute Toxicity (inhalation) [3]
CO_2	Carbon Dioxide	Headache, dizziness, paresthesia, increased heart rate, asphyxia, coma, death [4]	10,000 ppm: Onset of nondisabling health effects 50,000 ppm: Becomes toxic due to oxygen deprivation.	N/A [6]

Gas Species	Chemical Name	Health Symptoms	Health Notes	Chemical and Physical Hazards
			100,000 ppm: Death can occur within minutes [5]	
C_2H_4	Ethylene	Generally considered to be non-toxic. May displace oxygen at high concentrations, causing dizziness, drowsiness, or suffocation. [7]	N/A	Category 1 Flammable Gas Category 3 Specific Target Organ Toxicity [7]
H_2	Hydrogen	Considered to be non-toxic.	N/A	Category 1 Flammable Gas [8].
H_2S	Hydrogen Sulfide	Eye irritation, sore throat, dizziness, headache, stomach pain weakness, coma, death [9]	0.75 ppm: Onset of nondisabling health effects 27 ppm: Irreversible health effects within 1 hour 76 ppm: Death can occur within 10 minutes [2]	Category 1 Flammable Gas Category 2 Acute Toxicity (inhalation) Category 3 Specific Target Organ Toxicity [10]
H_2SO_4	Sulfuric Acid	Eye irritation, skin irritation, burns, shortness of breath, pulmonary edema, death [11]	0.2 mg/m^3: Onset of nondisabling health effects 8.7 mg/m^3: Irreversible health effects within 1 hour 270 mg/m^3: Death can occur within 10 minutes [2]	Category 1 Corrosive to Metals Category 1 Skin Corrosion Category 1 Serious Eye Damage Category 3 Specific Target Organ Toxicity [12]
HCl	Hydrogen Chloride	Eye irritation, skin irritation, burns, sore throat, coughing, blistering, stomach pain, death [13]	1.8 ppm: Onset of nondisabling health effects 22 ppm: Irreversible health effects within 1 hour 620 ppm: Death can occur within 10 minutes [2]	Category 3 Acute Toxicity (inhalation) Category 1 Skin Corrosion Category 1 Serious Eye Damage Category 3 Specific Target Organ Toxicity [13]
HCN	Hydrogen Cyanide	Irritation of skin and eyes, headache, nausea, vomiting, shortness of breath [14]	2.5 ppm: Onset of nondisabling health effects 7.1 ppm: Irreversible health effects within 1 hour 27 ppm: Death can occur within 10 minutes. [2]	Category 1 Flammable Gas Category 1 Acute Toxicity(Oral, Inhalation, Dermal) Category 1 Specific Target Organ Toxicity [15]
HF	Hydrogen Fluoride	Serious skin and eye damage, blistering, burns, pulmonary edema, bronchitis, death [16]	1 ppm: Onset of nondisabling health effects 24 ppm: Irreversible health effects within 1 hour 170 ppm: Death can occur within 10 minutes [2]	Category 3 Acute Toxicity (inhalation) Category 1 Skin Corrosion Category 1 Serious Eye Damage Category 1 Specific Target Organ Toxicity [17]

Gas Species	Chemical Name	Health Symptoms	Health Notes	Chemical and Physical Hazards
HNO_3	Nitric Acid	Cough, dizziness, nausea, vomiting, hemorrhagic edema, death. Possible relapse in symptoms is also possible several weeks after exposure. [18]	0.16 ppm: Onset of nondisabling health effects 24 ppm: Irreversible health effects within 1 hour 170 ppm: Death can occur within 10 minutes [2]	Category 3 Oxidizing Liquid Category 1 Corrosive to metals Category 3 Acute Toxicity (inhalation) Category 1 Skin Corrosion Category 1 Serious Eye Damage [19]
NO	Nitric Oxide	Although Nitric Oxide itself is not toxic to humans, it rapidly reacts with oxygen in the air to produce nitrogen dioxide, which is toxic. For this reason nitric oxide is considered to have the same health effects as nitrogen dioxide. [20]	0.5 ppm: Onset of nondisabling health effects 12 ppm: Irreversible health effects within 1 hour 34 ppm: Death can occur within 10 minutes [2]	Category 1 Oxidizing Gas Category 1 Acute Toxicity (inhalation) Category 1 Skin Corrosion Category 1 Serious Eye Damage [21]
NO_2	Nitrogen Dioxide	Skin and eye irritation, redness, blistering, stomach pain, death [22]	0.5 ppm: onset of nondisabling health effects 12 ppm: irreversible health effects within 1 hour 34 ppm: death can occur within 10 minutes [2]	Category 1 Oxidizing Gas Category 1 Acute Toxicity (inhalation) Category 1 Skin Corrosion Category 1 Serious Eye Damage [22]
SO_2	Sulfur Dioxide	Skin and eye irritation, redness, blistering, stomach pain, death [23]	0.2 ppm: Onset of nondisabling health effects 0.75 ppm: Irreversible health effects within 1 hour 30 ppm: Death can occur within 10 minutes. [2]	Category 3 Acute Toxicity (inhalation) Category 1 Skin Corrosion Category 1 Serious Eye Damage [23]

Table 26: Chemical and Physical Hazards Key

Hazard Class	Category	Description
Skin Corrosion	1	Causes irreversible skin damage
Skin Irritation	2	Causes skin irritation
Serious Eye Damage	1	Causes irreversible eye damage
Eye Irritation	2	Causes serious eye irritation
Acute Toxicity (Inhalation)	1	Toxic at concentrations below 100ppm
	2	Toxic at concentrations between 100 and 500ppm
	3	Toxic at concentrations between 500 and 2500ppm
Acute Toxicity (Oral)	1	Toxic when under 5mg/kg bodyweight is consumed
	2	Toxic when 5 to 50mg/kg bodyweight is consumed
	3	Toxic when 50 to 300mg/kg bodyweight is consumed
Acute Toxicity (Dermal)	1	Toxic when under 50 mg/kg bodyweight is applied
	2	Toxic when 50 to 200 mg/kg bodyweight is applied
	3	Toxic when 200 to 1000mg/kg bodyweight is applied
Specific Target Organ Toxicity	1	Known to cause specific non-lethal organ toxicity

Hazard Class	Category	Description
	2	Presumed to cause specific non-lethal organ toxicity
Specific Target Organ Toxicity	3	Causes respiratory irritation, drowsiness, or dizziness
Flammable Gas	1	Flammable compressed gas
Corrosive to Metals	1	May be corrosive to metals
Oxidizing Gas	1	Not combustible, but may cause or intensify fires in other materials
Oxidizing Liquid	1	Not combustible, but may cause or intensify fires in other materials. May cause other materials to spontaneously ignite.
	2	Not combustible, but may cause or intensify fires in other materials.
	3	Not combustible, but may cause or intensify fires in other materials.

3.0 References

[1] Committee on Acute Exposure Guideline Levels, "Acute Exposure Guideline Levels for Selected Airborne Chemicals: Volume 8," 2010. [Online]. Available: https://www.epa.gov/sites/default/files/2014-11/documents/carbon_monoxide_final_volume8_2010.pdf. [Accessed 27 June 2024].

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[10] Airgas USA, "Safety Data Sheet - Hydrogen Sulfide," 3 March 2022. [Online]. Available: https://apps.spheracloud.net/msds/viewfetch.aspx?materialID=3051766&facilityID=8133&msdsVersion=1&companyid=bUv387RyuroA&userid=%2f7uinXkWSN8A. [Accessed 21 June 2024].

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3] Available: https://www.airgas.com/msds/001047.pdf. [Accessed 24 June 2024].