Heat Release, Flammability, Smoke and Toxic Hazard of Various Aircraft Insulated Wires

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ABSTRACT

There has been considerable recent interest in the flammability hazards of aircraft wire and cable. This study evaluates the fire hazards associated with of eight commercial electrical wires used in the aerospace industry. Heat release, flammability, smoke, current overload, and toxicity are evaluated using standard and modified procedures. The results are compared to current regulations (1998) as well as other critical requirements. Two populations of wires are revealed in the study, one with low heat release, flammability susceptibility, smoke and toxic gas generation, and the other with values at or near their respective specification limit.

INTRODUCTION

Electrical wiring used in the aerospace industry has to meet rigorous standards covering the categories of fire hazards, chemical resistance, mechanical toughness and durability, electrical performance, and handleability. Flammability properties are important because wires must show ignition resistance, low flame spread, low heat release, and low production of smoke and toxic gases in accordance with standard test procedures. The wire must be evaluated both as installed and after a variety of environmental exposures such as cold, heat, aging, fluids and mechanical abuse. Satisfactory reaction to abnormal electrical conditions such as current overload, arcing and arc-tracking are crucial because they represent a potential fire ignition scenario. (Cahill, 1995; Eddy, 1998). Finally, the wire size, weight, and manufacturing quality are critical to the long term performance in the aircraft.

In this paper we report results of standard fire test methods. Some modifications and innovations in procedures were necessary, however, to characterize the wire specimens. We explored heat release rate measurements by two methods, the Ohio State University calorimeter (OSU) and the Cone Calorimeter (ASTM E1354). Flammability resistance was determined via the 60 degree burn test (FAR.25.853) and a vertical burn test (BSS7230). Smoke production was measured by four methods: two static smoke box methods, ASTM F814-84 and, ISO 5659, the Cone Calorimeter (ASTM E1354), and current overload using a modified smoke chamber. Toxicants were measured using the ASTM F814 smoke box in accordance with BSS7239. The test results were analyzed in terms of a potential fire hazard .

EXPERIMENTAL

A. Wire Samples

Eight different 20 AWG wire constructions have been evaluated. All represent wire types currently installed on commercial transport or military aircraft worldwide. These are listed in Table 1 and micrographs of the cross sections are shown in Figure 1.

Wires 1 2, and 5 are composite insulations comprising an aromatic polyimide tape wrap covered with a polytetrafluoroethylene (PTFE) or fluorinated ethylene propylene (FEP) tape wrap. The constructions vary by location, thickness and composition of the tapes. Wire 4 is a PTFE single layer insulation. Wires 3, 6 and 8 are dual insulation layer products comprising 2 layers of crosslinked ethylene-tetrafluoroethylene (ETFE), crosslinked polyethylene (XLPE)/crosslinked polyvinylidene fluoride (XLPVDF), and FEP/nylon (polyamide) 6, 10 respectively. Wire 7 is a 3 layer product with polyvinyl chloride (PVC)/glass braid/nylon 6. All wires were commercially obtained.

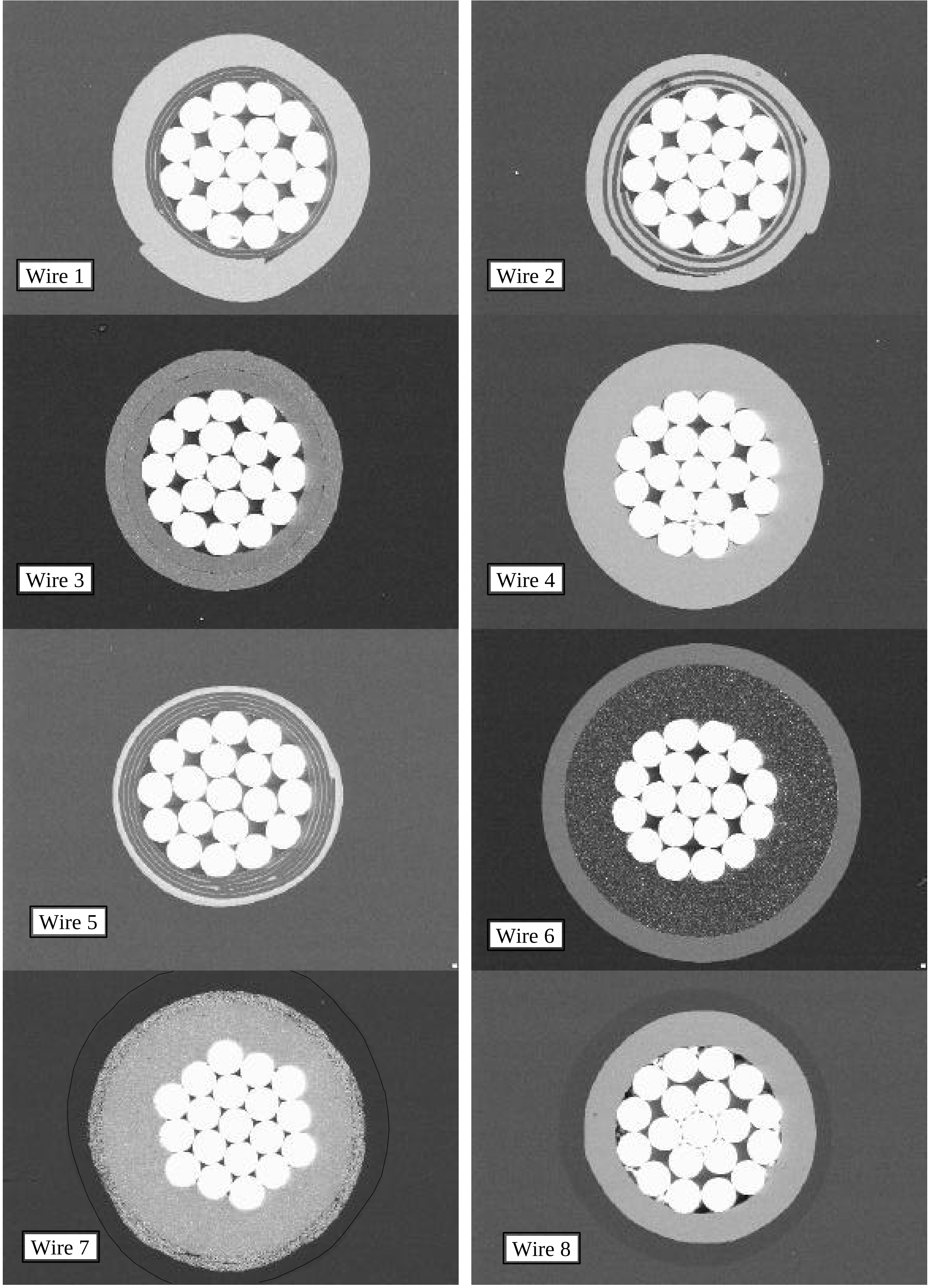
Table 1 - Wires Tested

Reference	**Insulation**
1	Polyimide tape / PTFE tape
2	Polyimide tape / PTFE tape
3	Dual wall, cross-linked, ETFE
4	PTFE
5	Polyimide tape / FEP tape
6	Dual wall, cross-linked, Polyethylene/PVDF
7	PVC/Glass Braid/Nylon6
8	Nylon 6,10/FEP

Table 2 - Wire Dimensions and Mass

Ref	Mass per unit length (g/m)			OD		Wall thickness	
	Conductor	Insulation	Total	inch	mm	inch	mm
1	5.42	1.99	7.41	0.059	1.50	0.0098	0.250
2	5.18	1.51	6.69	0.054	1.36	0.0081	0.205
3	5.22	1.32	6.54	0.055	1.39	0.0084	0.213
4	5.29	2.26	7.55	0.060	1.52	0.0114	0.290
5	5.35	0.97	6.32	0.052	1.33	0.0065	0.165
6	5.24	2.61	7.85	0.074	1.87	0.0177	0.450
7	4.97	2.80	7.77	0.072	1.82	0.0164	0.418
8	5.16	2.00	7.16	0.062	1.58	0.0120	0.305

Figure 1 - Wire cross-sections



B. Aircraft Panels

Aircraft panels, comprised of resin impregnated fiber glass, were supplied by the Boeing Corporation. These precut 152 mm (6 in) x 152 mm (6 in) samples were designated as 5524 and 5565. The former was described by Boeing as being at or near the FAA-OSU specification 65/65 limit and the latter as distinctly below these limits. These panels were used as a comparison base line in the OSU heat release test.

C Test Methods

1 Heat Release

a. Ohio State University (OSU) Calorimeter, (FAR25.853)

This is a standard test method for aircraft cabin materials. Heat release tests were performed on a FAA-certified OSU chamber located at United States Testing Company, Los Angeles, CA, USA. Aircraft panels were tested to the protocol. The procedure was modified to accommodate testing of insulated wires. The specimen wire was wrapped around a block of calcium silicate board, which previously had been encased in aluminum foil. This produced a specimen configuration similar to that used for wire tested in the smoke chamber (see below), and also to the configuration devised for testing wires in the cone calorimeter (also see below) The wire and the calcium silicate board specimen was placed in the standard OSU specimen holder. The wires at the back of the board were cut away, leaving thirty-five lengths of wire spanning the 150 mm of the specimen frame.

b. Cone Calorimeter, ASTM E1354

Cone calorimeter tests were conducted both at Raychem Ltd., Swindon, UK, and at Omega Point Laboratories, Inc., Elmendorf, Texas, USA. Tests were conducted in accordance with ASTM E1354, except that the wire specimens were mounted according to a previously developed protocol (Elliot and Whiteley, 1997). The tests at Raychem were performed at radiant heat flux levels of 50 kW/m^2, 75 kW/m^2 and 100 kW/m^2, while the tests at Omega Point were performed only at 75 kW/m^2 for comparison to the Raychem results. Each test specimen used 3.5 m of wire product cut into 35 equal pieces. These test pieces were spaced equally and parallel across a specially-constructed steel supporting frame. The wires were clamped in the frame and the entire assembly was placed inside the retainer frame (or “edge” frame) on a standard cone calorimeter sample holder.

2. Flammability

a. 60 Degree Burn Test

The standard FAA protocol for testing electrical wire and cable was carried out according to FAR25.853 and Boeing Specification Support Standard (BSS)7324 at Raychem Corporation, Redwood City, CA. The two specifications are identical in procedure but have different pass/fail requirements. The wire was mounted at 60 degrees to the horizontal and a flame applied perpendicular to the wire as specified.

b. Vertical burn test

This procedure was conducted according to BSS7230 which is normally applied to aircraft interior parts. The tests were conducted at Raychem Corporation, Redwood City, CA. Wire was mounted vertically and the flame applied at the bottom of the specimen.

3. Smoke Tests

Four different techniques were employed in this study for comparison of the smoke evolution properties of the wire products. Certain advantages and disadvantages of each of the four test methods are noted below.

a. ASTM F814-84

The FAA smoke test chamber method was used. (FAA Aircraft Materials Fire Test Handbook). This method and BSS7238 are specified for regulation and qualification of products for aircraft use, and are based on ASTM F814-84. The test chamber, however has many limitations for hazard analysis. The apparatus is limited to a relatively low heat flux of 25 kW/m^2 , lower than the exposure in the OSU calorimeter, and the data cannot be easily normalized to specimen mass burned. The smoke is physically collected within the 0.51 m^3 volume. This is helpful for simplified data analysis of the total smoke developed; however, deposition of smoke particles can affect the results.

The tests were carried out in a Stanton Redcroft smoke box at Raychem Ltd., Swindon, UK in the flaming and non-flaming modes. Wires, 3 m (10 ft) in length, were wound around a metal support frame and placed inside a sample holder.

b. ISO 5659

ISO 5659-2 uses the same chamber as the FAA, except the heater element and specimen mounting are different. In the ISO smoke chamber, the cone heater element is capable of exposing specimens at heat fluxes up to 50 kW/m^2, comparable to the cone calorimeter. The smoke is collected and measured in the same manner as in the FAA smoke chamber test. Tests were carried out using the guidelines of ISO 5659-2. The cone heater was set at 50 kW/m^2 and all the tests were carried out in the flaming mode. Wire samples consisted of 24 lengths of wire, each 75 mm long. These wires were placed into the sample holder and backed with an aluminum foil wrapped insulating block. An edge frame was used. The total length of exposed wire was 1.56 m.

c. The Cone Calorimeter (ASTM E1354)

Smoke evolution from the cone calorimeter is measured continuously in a flow-through system, at the same time as mass loss and heat release rates are measured. By suitable calculation techniques, the smoke measurement results are obtainable in a form readily suited to further analysis or extrapolation to different chambers or fire scenarios. For example, the smoke release rate, analogous to heat release rate, may be calculated. Such data are a great benefit for hazard analysis. Exposure of the specimens to heat flux levels as high as 100 kW/m^2 ensures that smoke evolution is measured under conditions that truly represent the potential full scale fire threat. Testing was performed as described under the heat release section, C.1.b.

d. Current Overload Testing

Unless there is a fire in the vicinity of the wiring in an aircraft, current overload is the most obvious cause for smoke evolution from wire coverings. Therefore a test was designed to subject lengths of wire, positioned inside the smoke chamber, to a current overload. The resultant smoke evolution was measured as in both the FAA and ISO smoke test methods. Lengths of wire were tested inside the smoke chamber. Typically one meter length of wire was tested, but to obtain conductor melt conditions, it was necessary to use a 0.5 m length. The chamber was modified by installing electrical connections through the top of the chamber so that the test sample could be connected to a power supply. The power supply used was a 2 kVA single phase current transformer manufactured by Foster Transformers of London capable of supplying 5 amps at 40 volts to 500 amps at 4 volts. Samples were exposed to increasing levels of current.

4. Toxicant Measurements

Toxicant measurements were performed according to BSS 7239 (ASTM F814 smoke chamber) at Omega Point Laboratories, Elmendorf, TX. Gases were measured with Draeger gas detector tubes and the results compared to requirements. Prior to testing fluoropolymer containing products, the chamber was conditioned by burning Tedlar (PVF) films.

A more extensive analysis of the gas effluents resulting from burning wires at high flux levels was not conducted. Additionally, no studies exposing animals to these thermal off-gassing products were performed. The results of animal studies are typically reported in terms of LC_{50} - the concentration necessary to cause death in 50% of air animal population.

RESULTS

A Heat Release Rate Tests

The FAA/OSU requirement for passenger cabin furnishing materials is 65 kW/m^2 and 65 $kWmin/m^2$. Reported are the Peak Heat Release Rates (PHRR) and heat release (HR) over the first two minutes of the test respectively. Table 3 contains OSU heat release results for the specimen wires. The PHRR and HR values are normalized to the surface area of the sample holder. Six of the eight wires have PHRR and HR values of less than 65 kW/m2; only wires 6 and 7 exceed this limit. One aircraft panel, 5524, is near the limit for the HR value

Table 3 - OSU Heat Release Data
(PHRR and HR normalized to the surface area of the holder)

Reference	Description	OSU* PHRR (kW/m^2)	OSU 2 min HR ($kWmin/m^2$)
1	Polyimide composite	*<10*	*0*
2	Polyimide composite	*<10*	*0*
3	dual wall XLETFE	36	28
4	PTFE	*<10*	*0*
5	Polyimide composite	*<10*	*0*
6	XLPE/XLPVDF	190	153
7	PVC/Glass/Nylon 6	124	108
8	FEP/Nylon 6,10	50	35
5524	Panel	43	63
5565	Panel	37	39

* < 10 kW/m^2 used because the actual peak values are not significant below this value

Table 4 - OSU and Cone Calorimeter Peak Heat Release Rate Data

Reference	OSU(35) PHRR * (kW/m^2)	CC(50) PHRR * (kW/m^2)	CC(75) PHRR * (kW/m^2)	CC(100) PHRR * (kW/m^2)
1	<10	0	19	36
2	<10	0	24	40
3	38	44	67	73
4	<10	0	24	35
5	<10	0	13	15
6	148	180	264	282
7	99	131	170	201
8	46	50	61	81

*PHRR and HR values are normalized to the surface area of the wires

Figure 2 -Correlation Between OSU and Cone Calorimeter PHRR

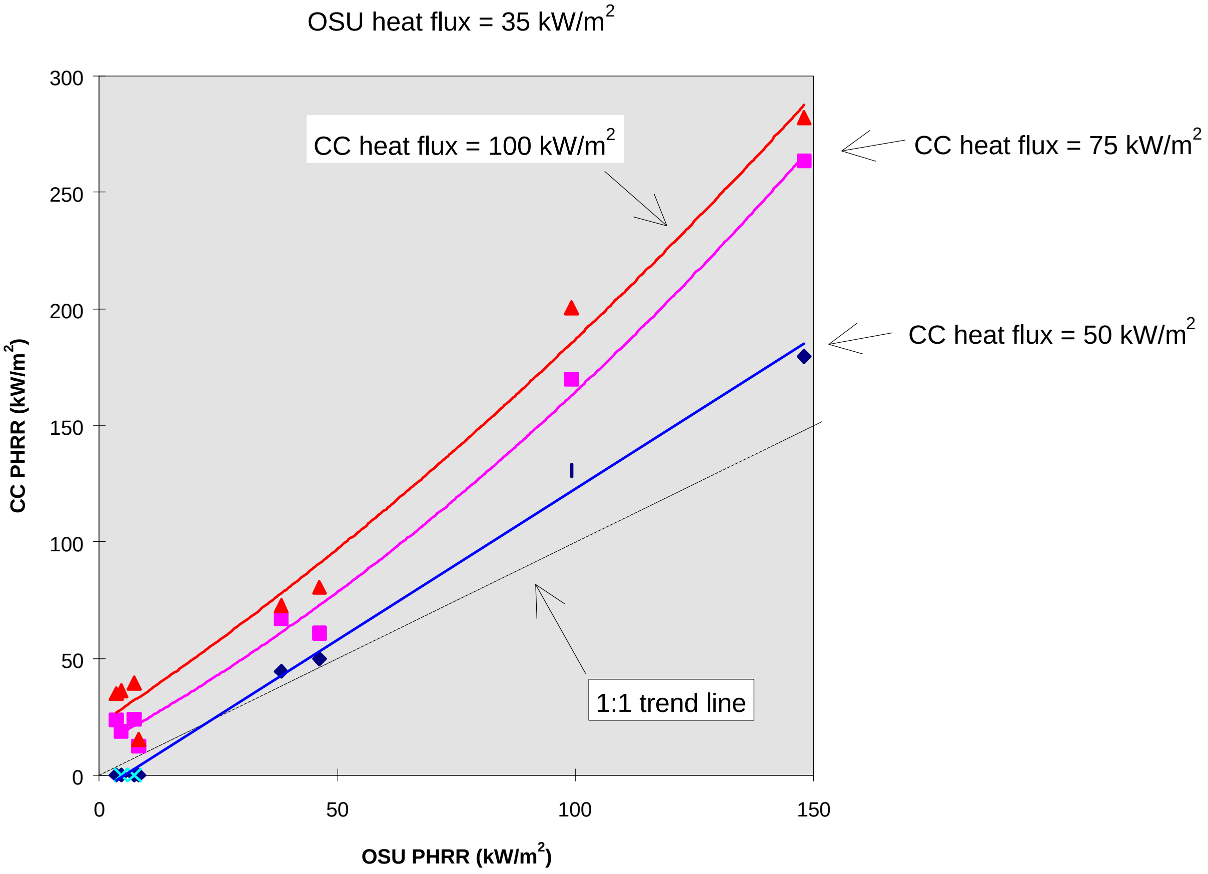


Table 4 contains OSU and cone calorimeter (CC) test data. The peak heat release rate values have been normalized to the surface areas of the exposed wire in order to make the two sets of data directly comparable. PHRR values, shown in Figure 2, are obtained from the cone calorimeter at imposed heat fluxes of 50 kW/m^2, 75 kW/m^2 and 100 kW/m^2, and plotted against PHRR values obtained from the OSU at an imposed heat flux of 35 kW/m^2.

The values obtained at 50 kW/m^2 in the cone calorimeter showed a linear correlation with those obtained in the OSU; the cone calorimeter data being, on average, about 25% higher than the OSU data. At the higher heat fluxes in the cone calorimeter, the PHRR values were significantly higher than those measured in the OSU, which is what one might expect since at higher imposed heat fluxes combustion is likely to be more complete.

Figures 3 and 4 indicate the peak and total heat release values of the various wires at different heat flux levels. The results show two classes of materials, those with high heat release, (wires 6, and 7), and those with relatively low heat release (wires 1, 2, 3, 4, 5, and 8).

Figure 3 - Cone Calorimeter Peak Heat Release Data

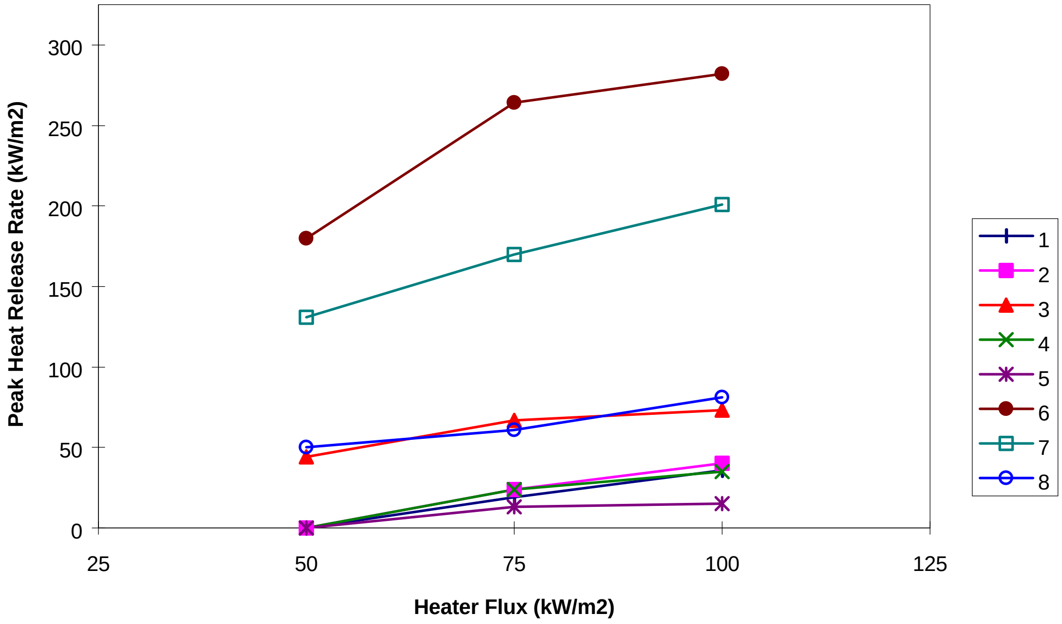
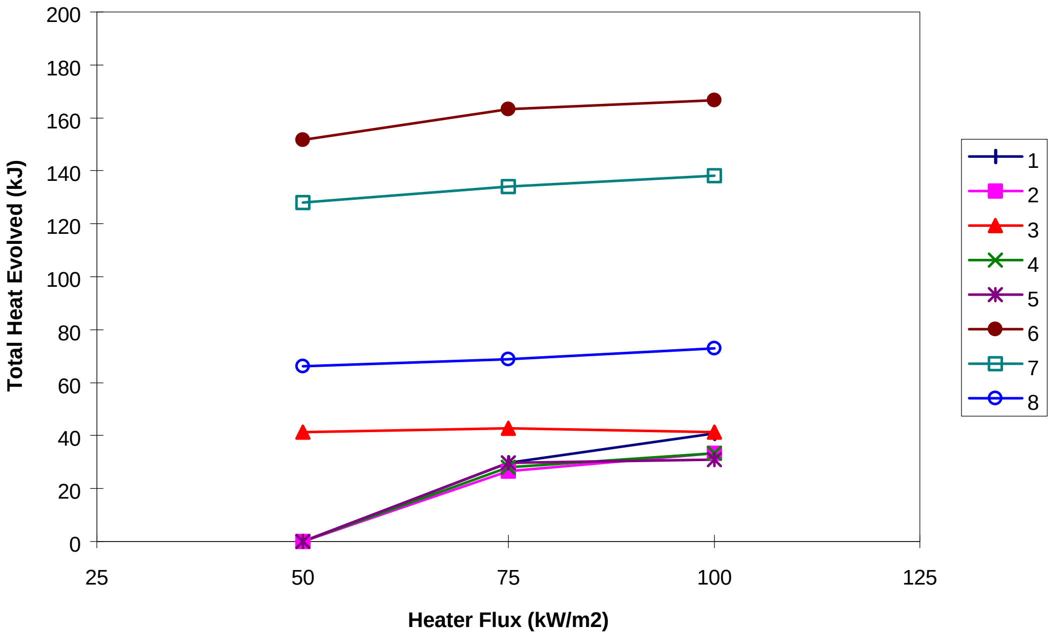


Figure 4 - Cone Calorimeter Total Heat Release Data



B. Flammability

Table 5 contains the results of the 60 degree and vertical flammability tests. Wires 6, 7, and 8 failed while the other wires pass. All the wires that passed appear to be equivalent in flammability.

Table 5 - BSS 7330 Vertical and FAR25.853 60° Flammability Tests

Minimum Flammability requirements: Flame Travel = 3.00 " max; Flame Extinguished 5 sec in BSS: 30 sec in FAR

Reference	**60° Flammability**			**Vertical Flammability**	
	Flame Travel (Inches)	Flame Extinguish (Seconds)	Burned Tissue	Flame Travel (Inches)	Flame Extinguish (Seconds)
1	7/8	0	Passed	2 1/8	0
	1 3/16	0	Passed	2 1/4	0
	15/16	0	Passed	2 1/8	0
2	1	0	Passed	1 3/4	0
	3/4	0	Passed	1 15/16	0
	11/16	0	Passed	1 11/16	0
3	1	0	Passed	2 1/16	0
	7/8	0	Passed	1 7/8	0
	13/16	0	Passed	2 3/16	0
4	5/8	0	Passed	2 1/4	0
	13/16	0	Passed	2	1
	1	0	Passed	1 13/16	0
5	3/4	0	Passed	1 1/2	0
	13/16	0	Passed	1 5/16	0
	13/16	0	Passed	1 3/4	0
6	2 5/6	18	Passed	6	21
	2 3/8	16	Passed	5 1/4	15
	2 7/16	18	Passed	*	*
7	10 1/4	104	Passed	4 5/8	4
	**	16	Passed	**	110
	**	125	Passed	**	92
8	7/8	0	Failed	3 1/2	0
	15/16	0	Passed	2 5/6	0
	2 3/16	0	Failed	2 7/8	1

* Flame reached top of sample and had to be blown out. Sample time at end of test was 2 minutes. Sample travel was 12".

** Flame reached top of sample and had to be blown out. Sample travel was 12".

C. Smoke Measurements (not from current overload)

Table 6 contains a summary of the ASTM F814, ISO 5659 and cone calorimeter (ASTM E1354) smoke measurements. Data have been converted to *S** values. *S** (m) is a measure of the extinction area of smoke per unit length of wire tested. See Discussion, Section B. This was done for ease of comparison and for evaluation and analysis. Figures 5 and 6 illustrate the relative values of *S**.

Table 6 - Smoke Data

	Wire reference number							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
ASTM F814 non-flaming								
D_s,4	0	0	0	0	0	1.2	10.0	1.7
D_{max}	0	0	1.7	0	0	21.3	235.3	20.4
S^*,4 (m)	0	0	0	0	0	0	0.03	0
S^*max (m)	0	0	0.01	0	0	0.07	0.75	0.07
ASTM F814 flaming								
D_s,4	1.45	0.80	37	1.2	3.0	98	457	68
D_{max}	53.3	20.2	246	8.6	63	510	643	458
S^*,4 (m)	0	0	0.12	0	0.01	0.31	1.46	0.22
S^*max (m)	0.17	0.06	0.79	0.03	0.20	1.63	2.05	1.46
ISO 5659 flaming								
D_s,4	0.80	0	44.3	1.3	0	162.9	309.2	140.0
D_{max}	47.8	44.5	102.6	29.0	7.0	211.1	309.2	140.0
S^*,4 (m)	0	0	0.28	0.01	0	1.02	1.93	0.87
S^*max (m)	0.30	0.28	0.64	0.18	0.04	1.32	1.93	0.87
Cone calorimeter								
S^*,4 (m) [50 kW/m^2]	0	0	0.33	0	0	1.41	1.39	0.45
S^*,4 (m) [75 kW/m^2]	0.09	0.11	0.38	0.02	0.08	1.24	1.50	0.43
S^*,4 (m) [100 kW/m^2]	0.10	0.09	0.44	0.06	0.02	1.39	1.52	0.58
S^*max (m) [50 kW/m^2]	0	0	0.33	0	0	1.43	1.39	0.51
S^*max (m) [75 kW/m^2]	0.09	0.11	0.38	0.03	0.09	1.24	1.50	0.43
S^*max (m) [100 kW/m^2]	0.10	0.09	0.44	0.06	0.02	1.39	1.52	0.58

Figure 5 - S* at 4 min (m)

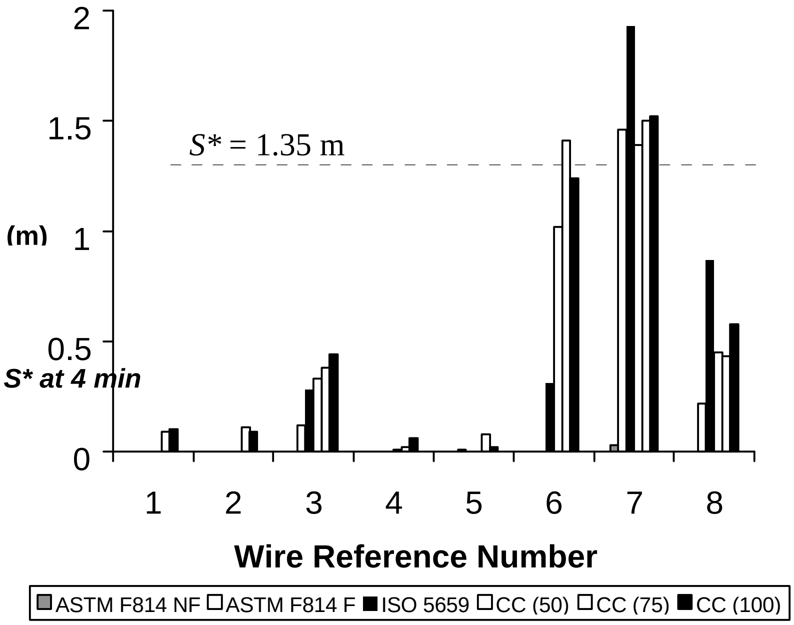
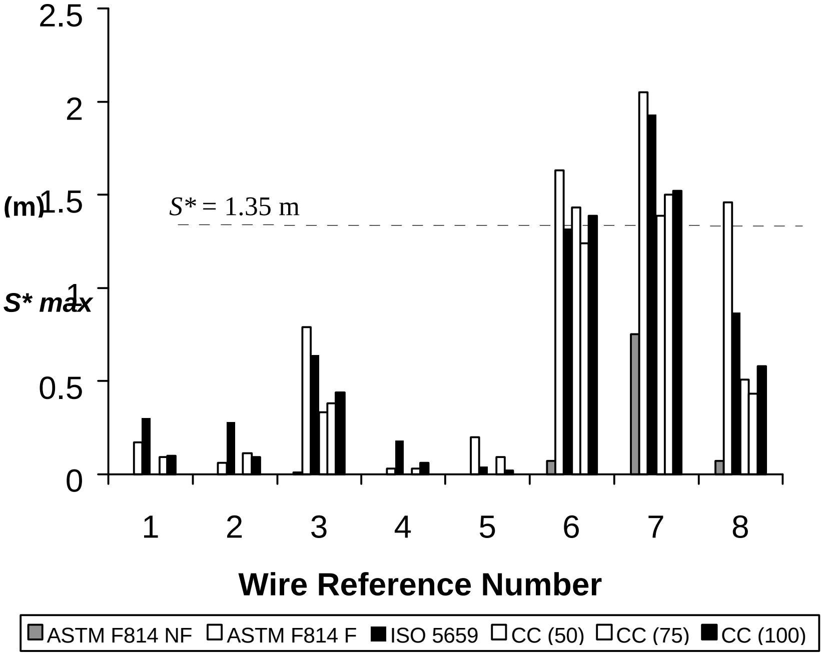


Figure 6 - S* max (m)

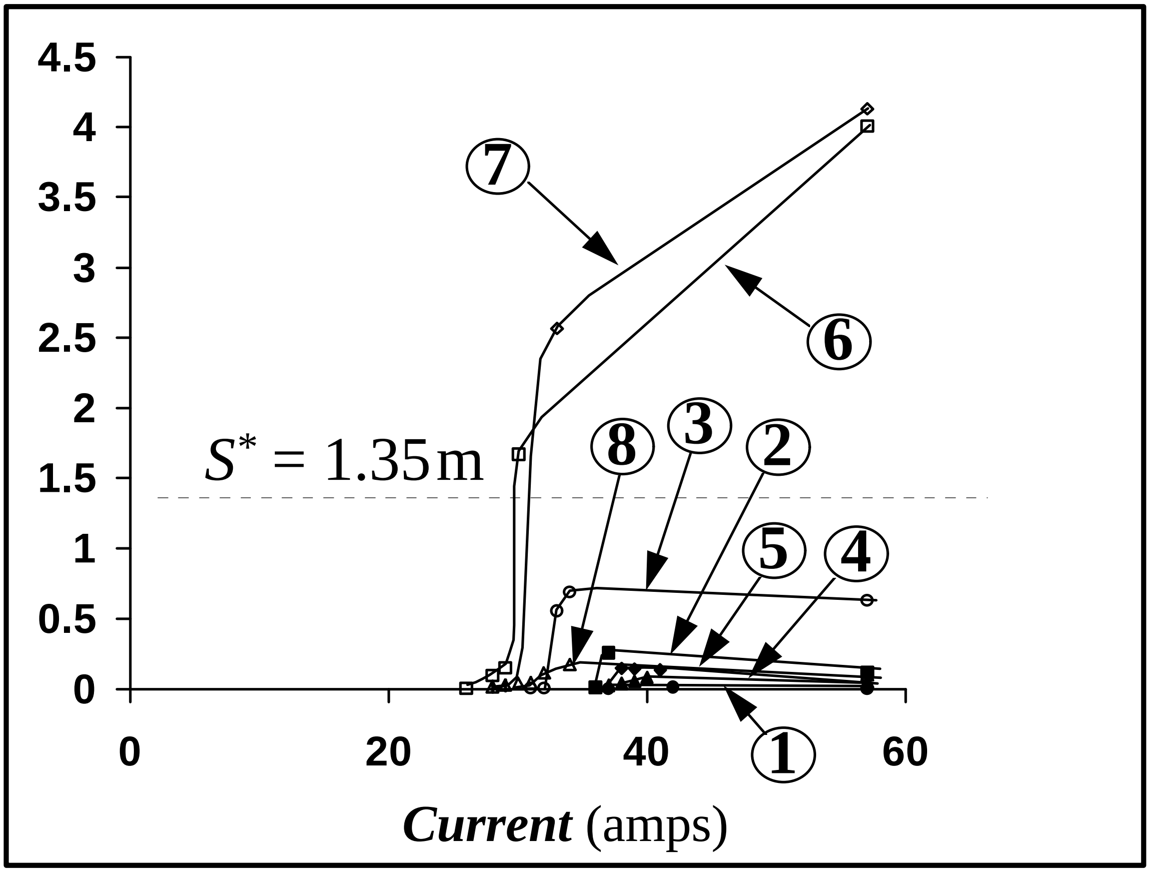


D. Smoke from Current Overload

Conventional "smoke from current overload" tests use current to maintain a constant conductor temperature, usually >200^{o}C, and are used to see if visible smoke is produced e.g. BSG230, 1982). These tests are only qualitative in nature and do not evaluate the potential smoke hazard that could be caused by an electrical fault condition. For this reason, we tested wires over a range of currents up to those that would melt the conductor and cause circuit failure (approximately 57 amps, about ten times the rated current). We have also made quantitative measurements of the smoke produced in order to determine the potential hazard created under these conditions.

Figure 7 shows S* (4 minute) values as a function of the current overload. A plot of S* (maximum) values is nearly identical to the 4 minute result in Figure 7 and is not shown. No wire produced any smoke below 26 A only wires 6 and 7 produced significant smoke above 26A. Once smoke initiated in the wires, it terminated at conductor melting.

Figure 7 - S* (4 minutes) Versus Current



E. Toxicant Results

The results from toxicant tests are summarized in Table 7. Generally, the wire specimens did not ignite and burn under the exposure conditions of the smoke chamber. Only samples 6 and 7 exhibited any significant periods of flaming using this test protocol. Although no sample failed the BSS7239 protocol, wire 7 fails the similar Airbus specification (ABD0031) for excess HCl. Although not test here toxicant results at higher flux levels can be different. See Discussion, Section B.

Table 7. Test Results of Wires to BSS 7230 Procedures (concentrations in ppm)

Specimen	**HF**	**HCl**	**NO_x**	**SO_2**	**HCN**	**CO**
1	6	2	0.5	0	trace	45
2	6	2	0.25	0	0	60
3	3.5	3.5	0.75	0	trace	80
4	7	2	0.25	0	2	30
5	1.5	1	0.25	0	0	50
6	6	2.5	0.5	0	trace	88
7	15	300	8	0	9.5	275
8	27.5	<1	7.5	0	2	70
BSS7239 Spec	200	500	100	100	150	3500
ABD0031 Spec	100	150	100	100	150	3500

DISCUSSION

A. Heat Release and Flammability

We were able to establish a relationship between the cone calorimeter and OSU data as shown in Figure 2. There was good agreement with the cone heater set at 50 kW/m^2 flux. The results of the flammability and heat release tests also show good correlation indicating two populations of materials: those with passing 60 degree/vertical burn and low peak heat values and those that fail one or both of these tests. Wires 6 and 7 do not have sufficient flame retardancy to pass the tests, while wire 8, despite showing passing OSU values, failed the flammability tests because of dripping. This is a characteristic of non-crosslinked systems. This dripping was also noted in the OSU but is not a cause for rejection.

All three wires (6, 7 and 8) represent older technology whereby the flame retardancy of one layer used to overcome limited flame retardancy of a second layer. Flame retardant technology has improved since the commercialization of these wires. In the case of wires 1, 2, 3, 4, and 5, representing the passing population, all components are flame retarded, primarily by the chemical nature of the polymers used and the addition of chemical additives. These formulations are either thermoset, electron beam crosslinked or take advantage of high molecular weight polymers that are resistant to dripping under high flux.

We used panels as a benchmark for our OSU study. The results fall in the same range as for the eight wires examined. One panel (5524) performs on the high end of the OSU specification limit, and the other panel (5565) performs distinctly lower, particularly in the 2 minute heat release test.

B. Smoke and Toxicity

The use of multiple smoke test methods has allowed us to expand the understanding of wire performance in a variety of static and dynamic smoke scenarios. The obscuration of light by smoke in standard test procedures can only be used to rank materials and cannot, by itself, be used to assess the magnitude of the hazard caused by a reduction in visibility. However, we can calculate the "smoke producing potential" of the wire, S*, in units of m^2 of smoke per meter of wire, in order to give us a measure of smoke hazard.

The principles are best illustrated by a worked example. Let us consider a volume of 9 m^3, about the size of a cockpit of a large commercial transport aircraft. We will assume, as a worst case scenario, the degradation of 20 m of wire (e.g., a 0.5 m section of a 40 wire bundle). Again as a worst case, we will use the constant $\gamma = 3$, which relates human visibility to smoke concentration in accordance with Jin (1978). Finally, we will assume that an occupant of the cockpit must be able to see a minimum distance of one meter. From these assumptions, it is possible to calculate the maximum acceptable value of the smoke producing potential S* for comparison to measured values from our smoke tests.

With slight rearrangement of an equation in the Jin reference, the following relates extinction area (a smoke value obtainable from our tests) to our assumed full-scale scenario:

$$S = \gamma V/\omega_{min} \qquad (1)$$

Where:
S = extinction area (m^2);
γ = a constant relating visibility to smoke intensity (dimensionless), which we assumed to be 3;
V = the volume occupied by the smoke, which we assumed to be 9 m^3.
ω_{min} = the minimum acceptable visibility, which we selected to be one meter.

Inserting the assumed values, we calculate an extinction area, S, of 27 m^2. The smoke producing potential, S*, is determined from the extinction area produced from a length of wire, *l*, as follows:

$$S^* = S/l \qquad (2)$$

The length of wire assumed to be affected in our chosen fire scenario is 20 m; therefore, the smoke producing potential is:

$$S^* = 27\ m^2 / 20\ m = 1.35\ m^2 \text{ per m of wire} \qquad (3)$$

This is the maximum acceptable smoke producing potential of any wire for our assumed scenario. We can now compare this value to that calculated for the wires evaluated in the various smoke tests.

Extinction area is the effective cross-sectional area (m^2) of all the smoke particles in a given amount of smoke. Smoke as "extinction area" is readily obtainable for the cone calorimeter; however, it must be calculated for the smoke chamber methods, ASTM F814 and ISO 5659. D_s (smoke chambers) is related to the extinction area (cone), S,

$$S = 0.00973\ D_S \qquad (4)$$

Thus, we can calculate S values, and hence S* values, from the various smoke tests employed in this study. (A detailed discussion of these smoke parameters and units is given in BS 7904: 1998.) The S* values from this study are presented in Table 6. In the non-flaming mode (smoldering), only wire 7 shows appreciable smoke. In the flaming mode, a comparison of S* at 4 minutes for F814, 5659 and the Cone Calorimeter shows good agreement. S* max values on the other hand show some significant unexplained results among the test methods, and may be a less reliable assessment of hazard.

These data reveal that only wires 6, 7 and 8 develop the smoke production above the 1.35 m^2 per meter of wire threshold, i.e., visibility is obscured at a distance of one meter. Wire 3 which has been previously criticized for producing too much smoke (Berkebile et al, 1995) is significantly below the 1.35 m^2 per meter of wire value in all tests. Wires 1, 2, 4, and 5 have low S* values which is to be expected from the chemical nature of the insulation materials used. In a flame, polyimides form a graphitic char and perfluoropolymers evolve gases with little production of smoke.

The BSS7239 toxicity test method, employing gas sampling, confirms that all specimen wires except wire 7 provide similar results and easily meet the requirements. Only low levels of acid gas are generated at this low heat flux.

Our analysis of hazard has incorporated heat release, flammability, smoke and toxicity. When we take these all into consideration, we find that there are two populations within the specimen wires tested. One population, represented by wires 6, 7 and 8, do not have sufficient flame retardancy, smoke and/or toxic gas suppression to meet the most stringent current heat release, flammability, smoke and toxicant levels now required or proposed for new installations. The other population, represented by wires 1, 2, 3, 4, and 5, meet all of these requirements.

Among the specimen wires of the better performing population (wires 1-5), there are still tradeoffs in fire hazard properties. For example, while wire 3 generates the most smoke of the five wires in this group, the other four wires comprise perfluorinated polymers, PTFE and FEP, which evolve very toxic gases (small perfluoro- and oxygenated perfluoro-gases) at high flux. These molecules, which are not evaluated in the gas sampling measurements of BSS 7239, are two orders of magnitude more toxic (very low LC_{50} values) then gases produced from combustion of the polymer employed in wire 3. (Nuttall et al, 1964, Levin et al, 1982, Kaplan et al, 1984).

One should not attempt to rank order and select individual wires based on the values of heat release, flammability, smoke and toxicant tests alone. The general characteristics of fire hazards must be balanced against the hazards associated with the other important wire categories: chemical resistance, mechanical toughness and durability, electrical performance, and handleability. For example, polyimide, a material contained in wires 1, 2, and 5 (from the better performing population), also evolves little smoke during burning. This type of material degrades into a graphitic char. This conductive degradation, typical of aromatic polyimides, can lead to electrical arc-tracking. Aromatic polyimide wire produced prior to 1990 (not tested in this study) is known for its susceptibility to arc-tracking (Cahill, 1989, Cahill, 1998).

In conclusion, fire hazard represents one of the crucial parameters of wire performance. We have demonstrated that 5 wire constructions meet these requirements. Further study is required to complete the overall analysis of the hazards associated with the other critical parameters of chemical resistance, mechanical toughness and durability, electrical performance and handleability.

REFERENCES

Berkebile, D. H., Cahill, P. L., LaCourt, P. R., 1995, “The Increased Safety Factor with Hybrid Wire Construction,” Aerospace Electrical Interconnect Systems Conference, Colorado Springs, CO.

British Standard, BS7904:1998, “Guide to smoke measurement units - their basis and use in smoke opacity test methods,” London, UK.

Cahill, P. L., 1995,” “Electrical Short Circuit and Current Overload Tests on Aircraft Wiring,” Technical Report DOT/FAA/CT-TN94/95, Atlantic City, NJ.

Cahill, P.L., 1989, “Flammability, Smoke, and Dry Arc Tracking Tests of Aircraft Electrical Wire Insulations,” Technical Report DOT/FAA/CT-89/21, Atlantic City, NJ.

Cahill, P. L., 1998, “Aircraft Fires Caused by Electrical Failure,” International Conference on Fire Safety, Vol. 26, pp. 145-158.

Eddy, P.,1998 “Fire Traps,” Sunday Times 18 October, 1998, London, UK.

Elliot, P. J., and Whiteley, R. H., 1997, “A Cone Calorimeter Test for the Measurement of Flammability Properties of Insulated Wire,” Fire Retardant Chemicals Association Conference, San Francisco, CA.

Jin, T., 1978, “Visibility Through Fire Smoke,” Journal of Fire and Flammability, Vol. 9, pp. 135-157.

Kaplan, H. L., Grand, A. F., Switzer, W. C., and Gad, S. C, 1984, “Accute Inhalation Toxicity of the Smoke Produced by Five Halogenated Polymers, Journal of Fire Science, Vol. 2, pp. 153-172.

Levin, B. C., Fowell, A. J., Birky, M. M., Paabo, M., Stotle, A., and Malek, D., 1982, “Further Development of a Test Method for the Assessment of Acute Inhalation Toxicity of Combustion Products,” Technical Report National Bureau of Standards, NBSIR 82-2532.

Nuttall, J. B., Kelly, R. J., Smith, B. S., and Whiteside, C. K., 1964, “Inflight Toxic Reactions Resulting from Fluorocarbon Resin Pyrolysis,“ Aerospace Medicine, July, 1964, pp. 676-683.