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Final Report on Fire Performance of Shipboard Electronic Space Materials

John B. Hoover
Clarence L. Whitehurst
Eric B. Chang
Frederick W. Williams

Navy Technology Center for Safety and Survivability
Chemistry Division

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14. ABSTRACT

Compartment-scale tests were conducted to evaluate the fire performance of typical cables, false deck panels, and thermal/acoustic insulation panels found in electronic spaces (such as CIC) on DDG-51 class destroyers. Cable fires were ignited by combinations of simulated short circuits and external spray fires, and the progress of the fires was monitored. It was found that modern electronic space materials are remarkably resistant to ignition and tend to be self-extinguishing. Compartment temperatures were found to be survivable, but the atmosphere was seriously degraded due to production of smoke and toxic gases and to oxygen depletion.

15. SUBJECT TERMS

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Electronic Space	Nomex	

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FINAL REPORT ON THE FIRE PERFORMANCE OF SHIPBOARD ELECTRONIC SPACE MATERIALS

1.0 BACKGROUND

Historically, performance parameters for most Navy materials have been defined in various military specifications and standards. For example, MIL-C-24643 lists requirements for low smoke cables and MIL-PRF-32161 describes thermal and acoustic insulation. Most of these specifications mandate that the values of selected material parameters meet some threshold, as determined by given laboratory-scale tests. While useful, this approach is not easily extrapolated to permit prediction of full-scale performance of mixed materials under conditions of actual use. To better estimate the behavior which may be expected in actual shipboard spaces, it is necessary to conduct tests at larger scales and to use realistic mixtures of materials for the fuel load. These data sets will add to our knowledge of materials fire performance and will be useful inputs for improved computer fire modeling.

To address these concerns, the Naval Research Laboratory (NRL) proposed a program to investigate the fire performance of real materials in typical shipboard compartments [1]. This proposal was accepted by the Department of Defense Joint Live Fire Test and Evaluation Office (JLFT&E) and initial funding was provided for FY 2005. During that year, phase one tests [2] were conducted to investigate issues related to shipboard electronic spaces; phase two testing of storage spaces has been funded for FY 2006 [3] and it is anticipated that subsequent phases in later years will include machinery spaces.

We expect that the results from the this program will help to characterize the fire behavior of materials used in current shipboard spaces and will prove useful for improving the design of spaces in future ships. The data will also provide useful benchmarks for numerical simulations using computer fire models.

2.0 OBJECTIVES

The objectives of this test series were to characterize the ignitability and fire growth behavior of various combinations of materials used in shipboard electronics spaces. Specific materials tested included MIL-C-24643 (low smoke) and MIL-C-17 (coaxial) cables, Nomex honeycomb false deck panels and MIL-PRF-32161 high temperature thermal and acoustic insulation.

3.0 APPROACH

A mockup of a generic, shipboard electronic space, shown in Figure 1, was constructed at the NRL Chesapeake Bay Detachment (CBD). The mockup design was based on the configuration used in the Combat Systems Equipment Rooms (CSERs), Tomahawk Equipment Room and Combat Information Center (CIC) spaces on the *USS Arleigh Burke* (DDG-51) class ships. This class was chosen because it is representative of current US Navy surface ship electronic spaces. It is expected that lessons learned from tests of this configuration will be applicable to future combatant designs, including the DD(X) destroyer and the Littoral Combat Ship (LCS).

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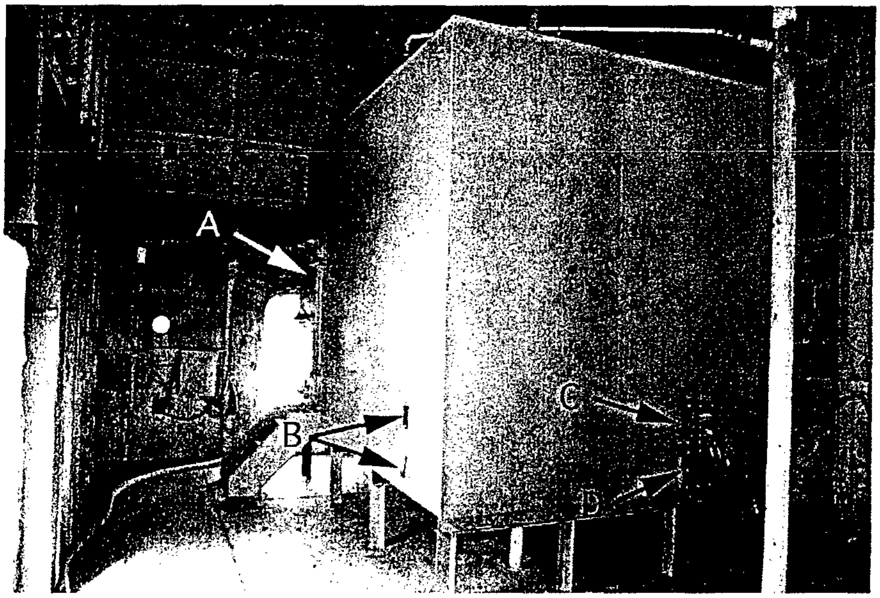

Figure 1. Exterior View of Electronic Space Mockup

This photograph shows the electronic space mockup as viewed from the forward end of the compartment looking aft. The mockup is elevated to permit installation of a below-deck spray fire system. Access to the mockup is via the watertight door located at the aft, starboard corner (A). Note the makeup air inlets near the forward, starboard corner (B) and the MCT near the forward, port corner (C). An unused port, below the MCT, has been blanked off with a steel plate (D).

The mockup was outfitted with low smoke and coaxial cables, Nomex false deck panels and polyimide thermal and acoustic insulation. Shakedown tests were carried out to verify the operation of the instruments and to validate the test procedures. The initial materials tests were conducted with cables only. Subsequently, Nomex deck panels were added and, finally, tests were carried out with cables, deck panels and polyimide insulation. In all cases, the cables were installed on trays representative of actual, below-deck cable configurations.

Tests were run in two different fire environments. In the first, tubular electric heaters were inserted into the cable bundle to heat the cables from within, simulating a short circuit condition. In the second environment, an external heptane spray fire was added to the electric heaters in order to investigate the effects of a fire in a lower compartment. For each environment, fire conditions were characterized on the basis of air temperatures, smoke obscuration and concentrations of carbon monoxide, carbon dioxide and oxygen. A baseline spray fire test was run without the cables, deck panels or insulation in order to measure the effects of the external fire alone.

A preliminary report [4] compared the results of two selected experiments, one using the tubular heaters and the other using both heaters and a spray fire for ignition. Both of those tests involved a full fire load (cables, decking and insulation). The current work expands on the earlier report and documents all of the tests in the electronic space test series.

4.0 EXPERIMENTAL

4.1 Mockup Description

The test compartment was built of 0.64 cm (0.25 in.) thick mild steel plate. To permit access below the compartment, it was supported on 10 cm (4 in.) horizontal "T" beams so that the deck was elevated 46 cm (18 in.) above the floor of the test building. As seen in Figures 2A and 2B, "T" beams were also used as vertical and horizontal stiffeners inside the the test space. A grid of steel angle iron, having a nominal 61 cm x 122 cm (24 in. x 48 in.) spacing, was installed at an elevation of approximately 30.5 cm (12 in.) above the deck, supported by posts and baffles. In actual electronic spaces, false deck panels are installed on the grid and the baffles provide additional strength for support of consoles. Both support posts and baffles are visible below the grid in Figure 2B.

In shipboard electronic spaces, ventilation is provided by balanced supply and exhaust terminals located in the overhead. This configuration is not appropriate for an experimental environment because much of the supply air could flow directly to a nearby exhaust, without mixing into the compartment, leading to premature extinguishment. This is especially problematic in the case of fires located near or below the false deck. In order to reduce the chances that low-lying fires will be oxygen limited, we used a modified ventilation configuration in which the exhaust was located in the overhead and the supply was provided through passive vents located in the sub-floor area and immediately above the false deck level in the main part of the space.

A 30.5 cm (12 in.) diameter port, seen at the top center in Figure 2A and top right in Figure 2B, provided exhaust from the compartment. Makeup air was admitted through four vents, located in pairs at diagonally opposite corners of the space, as discussed below.

Four pairs of ports, approximately 12.1 cm x 15.9 cm (4.75 in. x 6.25 in.), were provided near the lower corners of the mockup. To permit easy access to all areas within the test compartment, the port locations were selected so that the upper four were above the false deck level and the others were below. The dimensions of each port were designed to fit a standard MIL-P-24705 multi-cable transit (MCT); depending on the requirements of the test, ports could be used as cable/piping transits (with an MCT installed), a ventilation inlet or could be blanked off with a steel plate. For the tests discussed here, MCTs (Nelson Firestop Products model RGM4X1) were installed on one forward and one aft port (above and below the false deck level, respectively) and were used for instrumentation feed-throughs. Blanks were installed on the other forward and aft ports; the remaining four ports were used as makeup air inlets. In Figure 1, a pair of ventilation ports are visible near the forward, starboard corner of the mockup; an MCT is installed in the upper opening in the forward, port corner and the opening in the lower, port corner has been blanked off.

4.2 Fuel Load

As mentioned previously, the test items included MIL-SPEC cables, deck panels and acoustic/thermal insulation panels. The pan and spray fires were produced using commercial heptane as

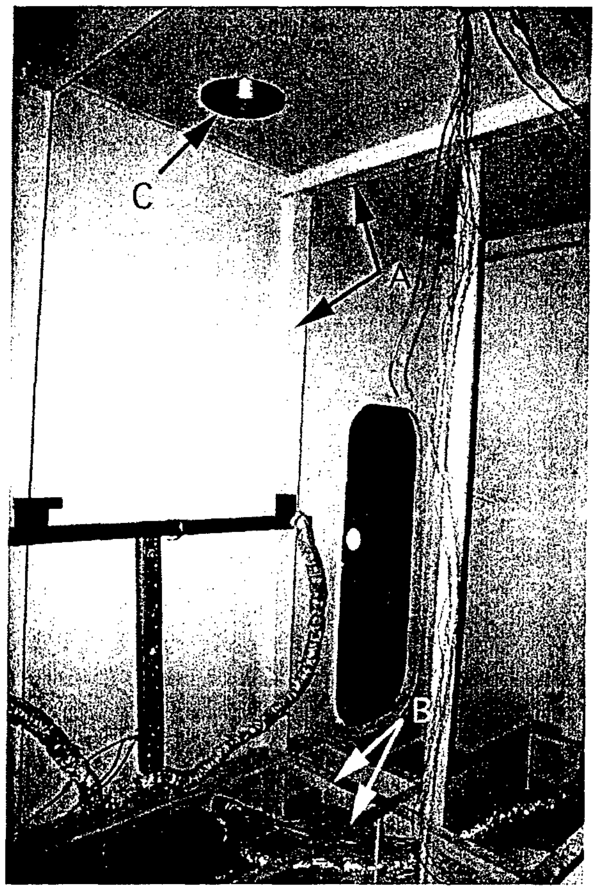

Figure 2A. Interior View of Electronic Space Mockup

This photograph shows the interior of the electronic space mockup, as viewed from the forward, port corner looking toward the watertight door. The vertical and horizontal stiffeners (A) are 10 cm (4 in.) "T" beams; the grids near the bottom of the picture (B) support the false deck panels (not installed). The exhaust ventilation is the circular port visible at the the top (C).

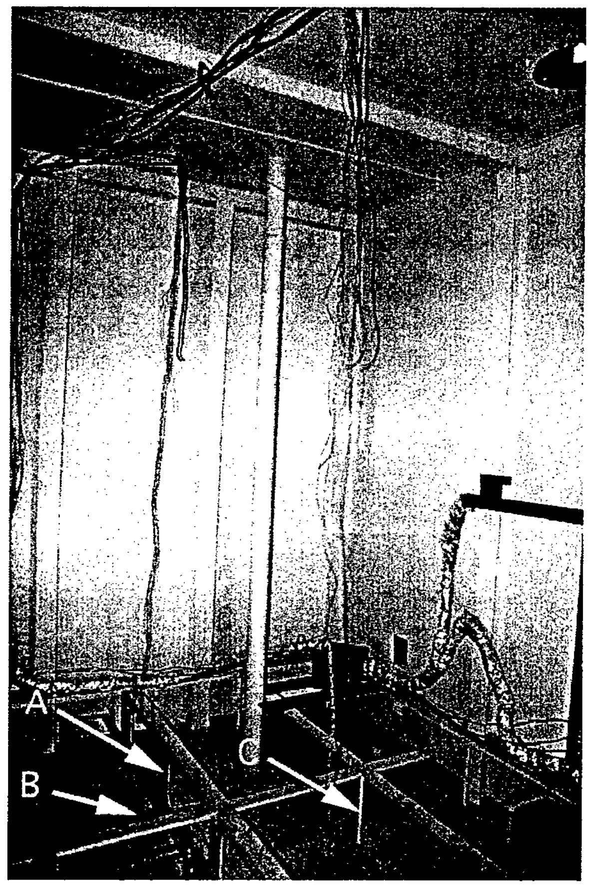

Figure 2B. Interior View of Electronic Space Mockup

This photograph shows the interior of the electronic space mockup, as viewed from the aft, port corner looking toward the forward, starboard corner. Note the vertical baffle (A), the cable tray (B), and the support post for the false deck located at the grid intersection (C).

the fuel. Each of fuel configurations is discussed in more detail below. The relative locations of cable bundles, Nomex panels and polyimide insulation panels is illustrated in Figure 3, where each cable bundle, Nomex deck panel and polyimide insulation panel is numbered for reference.

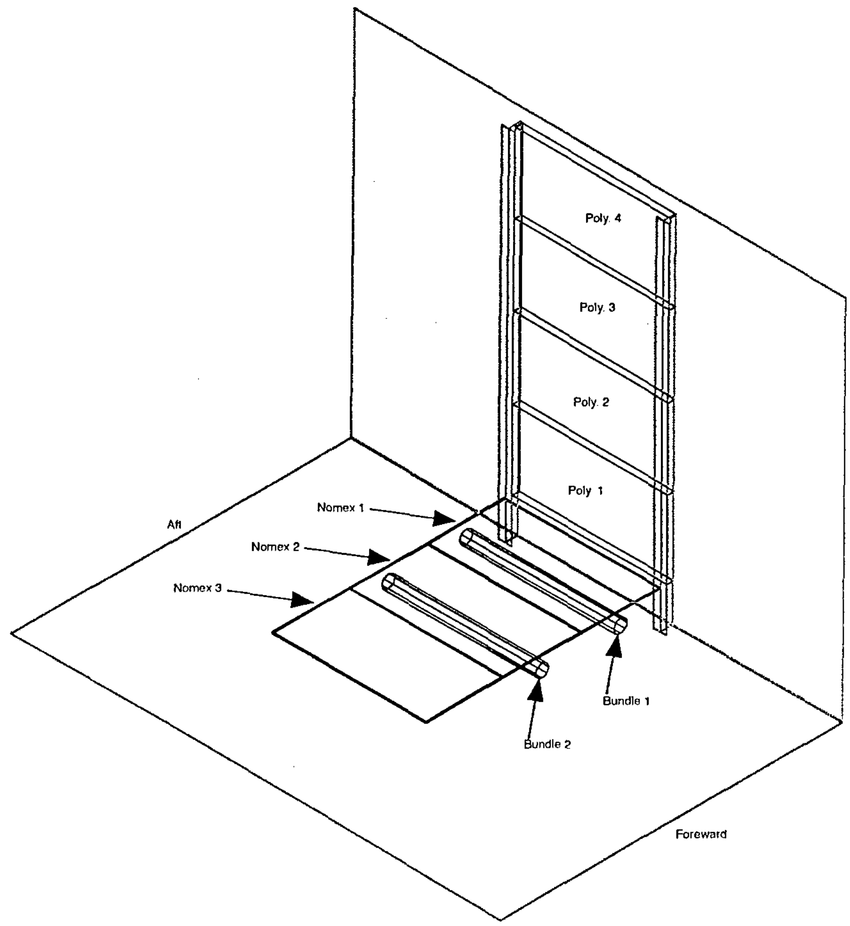

Figure 3. Layout of Fuel Load

The locations and identification numbers for the cable bundles, deck panels and insulation panels are shown. Structural components (deck, port bulkhead and cable trays) are in gray.

The spray nozzle array, shown in Figure 4, consisted of five nozzle stations and was located in the crawl space under the test compartment, directly below the Bundle 1 location. Nozzle stations were closed off with pipe plugs when not in use.

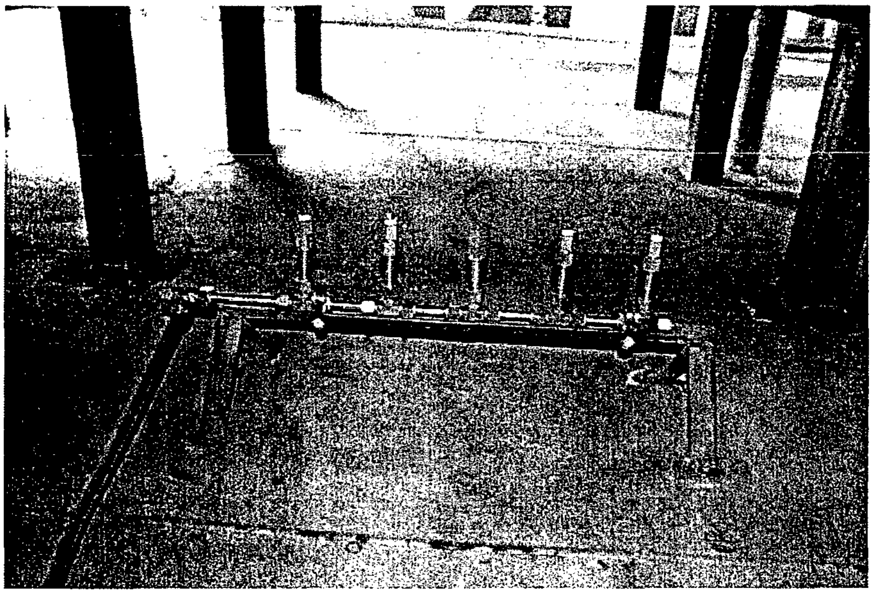

Figure 4. Spray Fire Nozzle Array

The nozzle array consisted of five stations for spray nozzles. In this photo, four of the stations have been plugged and no nozzle has yet been installed at the center station.

4.2.1 Pan fires

Two shakedown tests were conducted using mixed heptanes (Tilley Chemical Company, Inc., Baltimore MD) as the fuel. For the first test, one liter (0.26 gal) was placed in a 19 cm (7.5 in.) square pan; the second used two liters (0.52 gal) in a 36 cm (14 in.) square pan. In both cases, ignition was accomplished using a "Levenberry device" — a paper-covered twist tie bent so as to provide a free-standing wick approximately 4 cm (1.6 in.) tall. The device was placed in the pan, weighted to remain upright, and adjusted so that the top of the wick was between the two L-shaped spark igniter electrodes. The electrodes were connected to a high voltage (approximately 15 KVAC) transformer that produced an arc with enough energy to ignite the fuel. The transformer was remotely activated from the test control room.

4.2.2 Spray fires

As explained above, the nozzle array provided stations for up to five Bete P24 fog nozzles (Bete Fog Nozzle, Inc., Greenfield MA) and was positioned so that it heated the electronic space deck directly below the Bundle 1 location. Heptane was pumped directly from the drum, through one cm (0.5 in.) diameter tubing, to the nozzle array. Fuel flow was controlled by the pumping pressure and the nozzle k-factor. Spray fire ignition was accomplished using the spark igniter, described above, with the electrodes placed within the spray pattern of one of the nozzles. Both the fuel pump and the electric arc were remotely controlled.

The most important characteristics of the P24 nozzle, as provided by the manufacturer [5], are presented in Table 1. The heat release rate per nozzle, Q_r, was estimated from the nozzle k-factor, the operating pressure, P and the heat of combustion of the fuel

$$Q_r = k\,P^{0.5}\,H_c \text{ kW} \qquad \text{Eq. 1}$$

where k is the nozzle k-factor (0.0228 liter/min-kPa$^{-0.5}$), P is the nozzle operating pressure (in kPa) and H_c, the heat of combustion of heptane, is 32.8 MJ/liter (118 x 10^3 Btu/gal). Nozzle operating pressures were measured and found to be approximately 200 kPa (30 psi), as shown for a typical case in Figure 5. This pressure gives a flow rate of about 0.33 liter/min (0.09 gpm) and an estimated heat release rate of 226 kW (171 Btu/s) for each nozzle.

Parameter	**Value**
Nozzle Type	Impingement
Spray Pattern	Solid Cone
Spray Angle	90°
k Factor	0.0228 liter- min^{-1}-kPa$^{-0.5}$ (0.0158 gpm-psi$^{-0.5}$)

Table 1. Parameters of the Bete P24 Nozzle

These nozzle parameters were taken from the Bete product catalog [5].

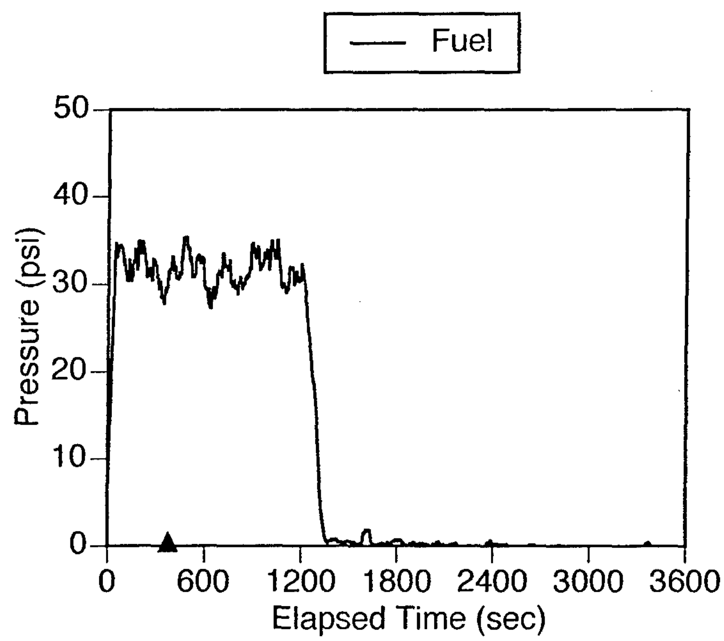

Figure 5. Fuel Pressure

A typical fuel nozzle operating pressure curve is shown. The information was used to estimate the fuel flow rates and heat release rates, as explained in the text.

4.2.3 Cables

Many different types of cables are used on ships, depending on the application. They range from high voltage power cables to low voltage, multi-conductor data cables to radio frequency (RF) coaxial (coax) cables. For these tests, five different types were selected to provide a representative cross section of the available types. The cables chosen included power, communication and RF. Both armored and unarmored versions of the power and communications cables were used.

All cables were obtained from Murray Benjamin Electric Co., Stamford CT and all met the appropriate MIL-SPEC (MIL-C-24643 low smoke production standard for power and communications cables; MIL-C-17 for RF cable). The MIL-SPECs, part numbers and brief description of each type are listed in Table 2.

Cables were cut to a nominal length of 1.2 meters (four feet) and five of each type (for a total of 25 cables) were bundled together, using short lengths of bailing wire as cable ties. Figure 6 is an end view of a cable bundle in which the various types of cables may be seen. Each bundle was weighed prior to and after use and the weights were recorded. For each test, a bundle was placed on a 1.2 m x 23 cm (48 in. x 9 in.) cable tray, elevated approximately 15 cm (6 in.) above the test compartment deck, and the bundle was wired in place with a bailing wire tie at each end.

Category	Mil-Spec Part (Size)	Description
Power and lighting cable	MIL-C-24643/16 02-UN (LSTSGU-4)	3 conductor; 14 AWG
Armored power and lighting cable	MIL-C-24643/16 02-AN (LSTSGA-4)	3 conductor; 14 AWG; armored
Control and communications cable	MIL-C-24643/18 01-UN (LSMSCU-7)	4 shielded pairs; 20 AWG
Armored control and communications cable	MIL-C-24643/18 01-AN (LSMSCA -7)	4 shielded pairs; 20 AWG; armored
RF coaxial cable	MIL-C-17/6 (RG11)	75 ohm coax

Table 2. Description of Cables used in Bundles

Each standard cable bundle used in these tests was made up of five lengths, each approximately 1.2 meter (four feet) long, of each of the five standard Navy cable types listed.

Two cable bundles were used in each of these tests, designated as Bundle 1 and Bundle 2. Bundle 1 was placed on a tray directly above the location of the spray fire nozzle array while Bundle 2 was located on a second tray approximately 0.5 m (20 in.) starboard of the first (see Figure 3). Two Chromalox 925 watt tubular heaters (model STRI-3648, 120 VAC) were inserted axially into the first bundle, as illustrated in Figure 6. A typical bundle, installed on a cable tray, is shown in Figure 7. The power cables for the tubular heaters were wrapped in Fiberfax and aluminum foil insulation and extended from the aft end of the bundle.

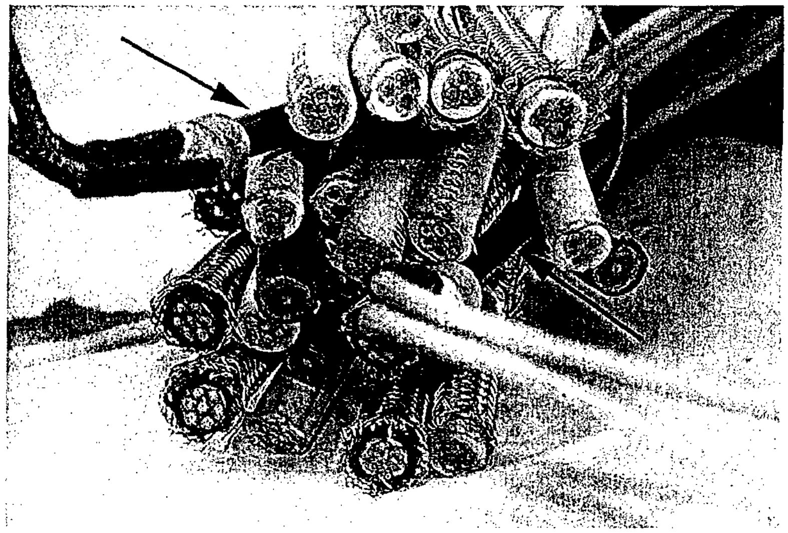

Figure 6. Cable Bundle

An end view of a cable bundle, showing the various types of cables. Electric heaters (arrows) have already been inserted into this bundle.

4.2.4 Nomex deck panels

For the false deck material tests, Nomex panels were added to the cable bundles described above. The Nomex deck panels were obtained from Whiting Custom Laminated Panels, Akron NY and are the same as those provided to Bath Iron Works (BIW) and Northrop Grumman Ship Systems (NGSS) for use on current construction DDG-51 class destroyers.

The panels consist of a Nomex honeycomb core with a GRP (glass reinforced plastic) sheath on both sides and have a maximum flame spread index of 25 (ASTM-E-162 test) and a maximum optical density rating of 150 (ASTM-E-662 test). They were delivered as 1.22 m x 2.44 m 1.4 cm (4 ft x 8 ft x 0.536 in.) sheets and were cut to nominal dimensions of 0.61 m x 1.22 m (2 ft x 4 ft) as illustrated in Figure 8. In accordance with standard shipyard procedures for installation of Nomex deck panels, the Nomex core was routed out to a depth of approximately 0.64 cm (0.25 in.) on all edges and the gap was filled with Bondo lightweight polyester resin filler (Bondo Corp., Atlanta GA). Figure 9 shows two panels, one prior to and one after treatment.

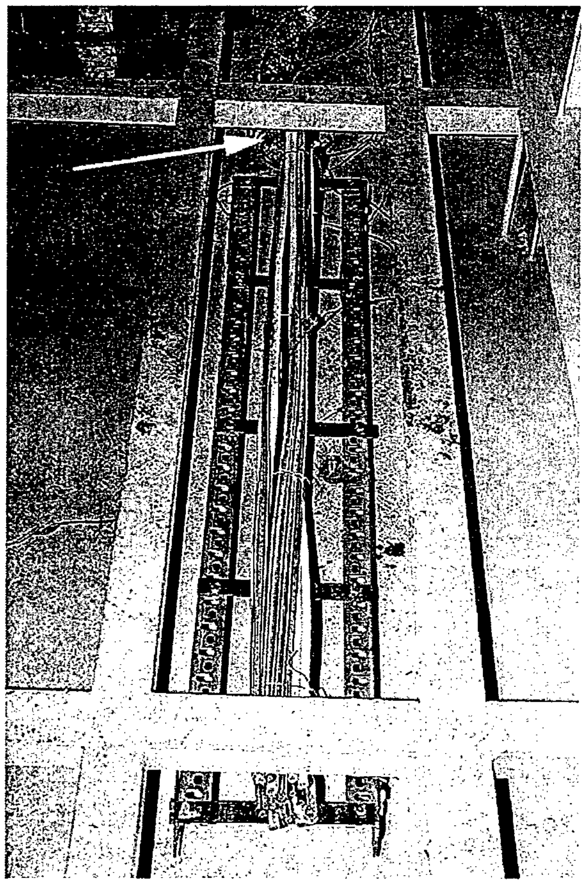

Figure 7. Cable Tray

A typical cable bundle, consisting of five lengths of each of five cable types, is shown installed on a cable tray. The arrow points to the insulated power cables for the tubular heaters.

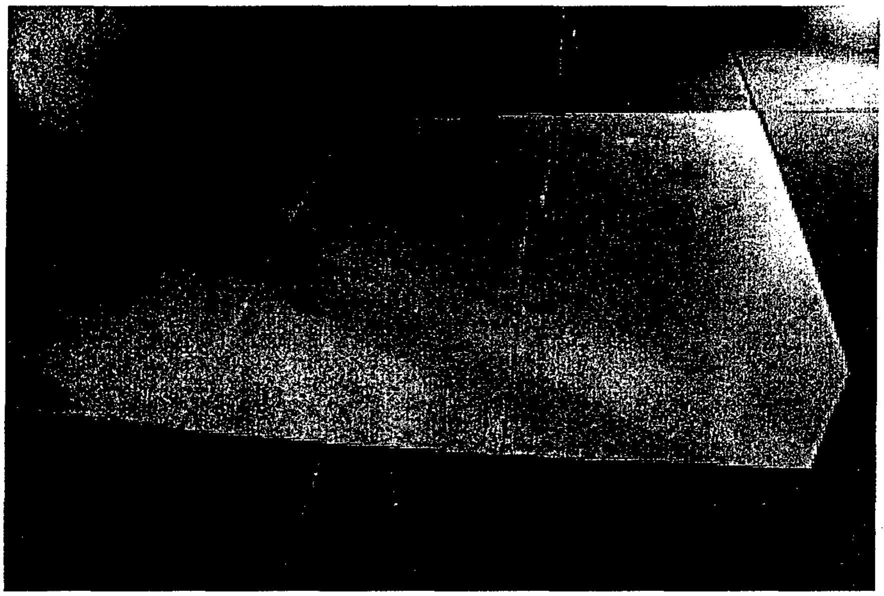

Figure 8. Nomex Panels

The three light colored panels are Nomex false deck material, as installed for a test. The dark panels surrounding the Nomex, composed of a non-flammable, cement-based flooring material, were used to simulate the remainder of the false deck.

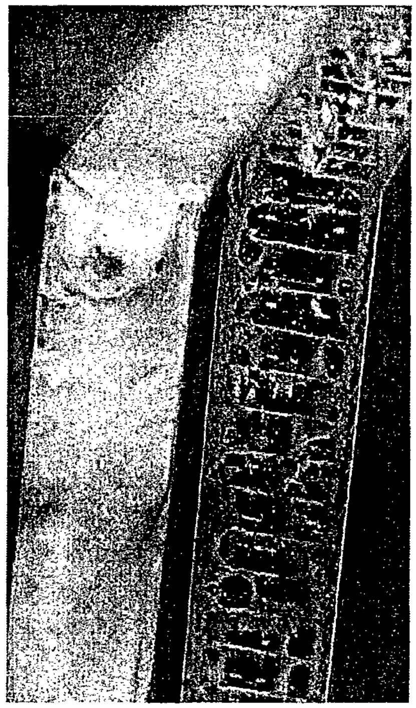

Figure 9. Nomex Panel Edge Preparation

The core of the Nomex panel on the right was routed out as described in the text. The panel on the left has been filled with Bondo lightweight polyester resin.

Each test used three Nomex panels which were installed above the cable bundles, in the position of maximum exposure to flames. Panels were identified as Nomex 1 through Nomex 3, as shown in Figure 3. The first panel was directly above the center of the fire; the second was adjacent to the starboard edge of first and the third was adjacent to the second.

The remainder of the false deck was simulated with sheets of one cm (0.5 in.) Durock Cement Board (US Gypsum Co., Chicago IL), which is a cement-based construction material normally used as a rigid underlay for ceramic tile floors. As an inexpensive, non-flammable substitute for Nomex, it was used to restrict the below-deck air circulation to mimic that which occurs in real electronic spaces.

4.2.5 Polyimide insulation panels

For the insulation tests, thermal and acoustic bulkhead insulation panels were added to the fire load used for the deck panel tests. A variety of insulation materials are used in actual shipboard electronic spaces, depending on the need for thermal or acoustic protection. Individual panels range in thickness from 2.5 — 5.0 cm (1 — 2 in.), may be made of polyimide or fiberglass and may have any of several different facing materials. For these tests, we selected 5.0 cm (2 in.) polyimide with perforated facing. This type of material is heavily used in actual electronic spaces and, from the standpoint of fire safety, provides a more severe threat than do fiberglass or thinner layers of polyimide.

Insulation was purchased from M & A Supply LLC, Wallingford CT. As in the case of the deck panels, this company supplies both the BIW and NGSS shipyards for DDG-51 class construction. The material was supplied as 0.61 m x 1.22 m (2 ft x 4 ft) pre-cut panels and was installed on the bulkhead using standard Navy studs and mushroom caps.

These studs (Figure 10) look somewhat like blunt nails, the heads of which are welded to the bulkhead in a square pattern, about 30.5 cm (12 in.) on centers. As the name suggests, the caps resemble mushrooms and have hollow stems that are hammered onto the studs. Approximately one centimeter (0.5 in.) of the protruding end of the studs has circumferential grooves to provide a tight friction fit with the caps. These grooves make it difficult to remove the caps without damaging the studs.

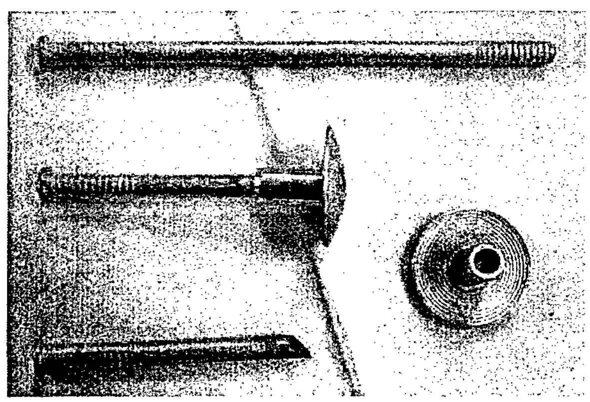

Figure 10. Insulation Installation Studs and Caps

The standard Navy studs (top) were modified by cutting off the grooved section to permit easy removal of the mushroom caps (right) for replacement of the insulation panels. A modified stud is shown at the bottom and a modified stud with the cap installed is in the middle.

Normally, the length of the stud is chosen to match the thickness of the insulation. However, due to the necessity for easy replacement of damaged panels, we used 10 cm (4 in.) studs and cut off the grooved end at an angle of approximately 45°. Without the grooves, caps and insulation panels were easily removed; the bevel cut provided a sharp point, which made it easier to punch through the insulation panels during installation.

The insulation panels (Figure 11) were installed in the frame gap immediately adjacent to the Nomex 1 deck panel (see Figure 3). The lowest insulation panel, Poly. 1, was at the level of the false deck; the other three were numbered in ascending order above that.

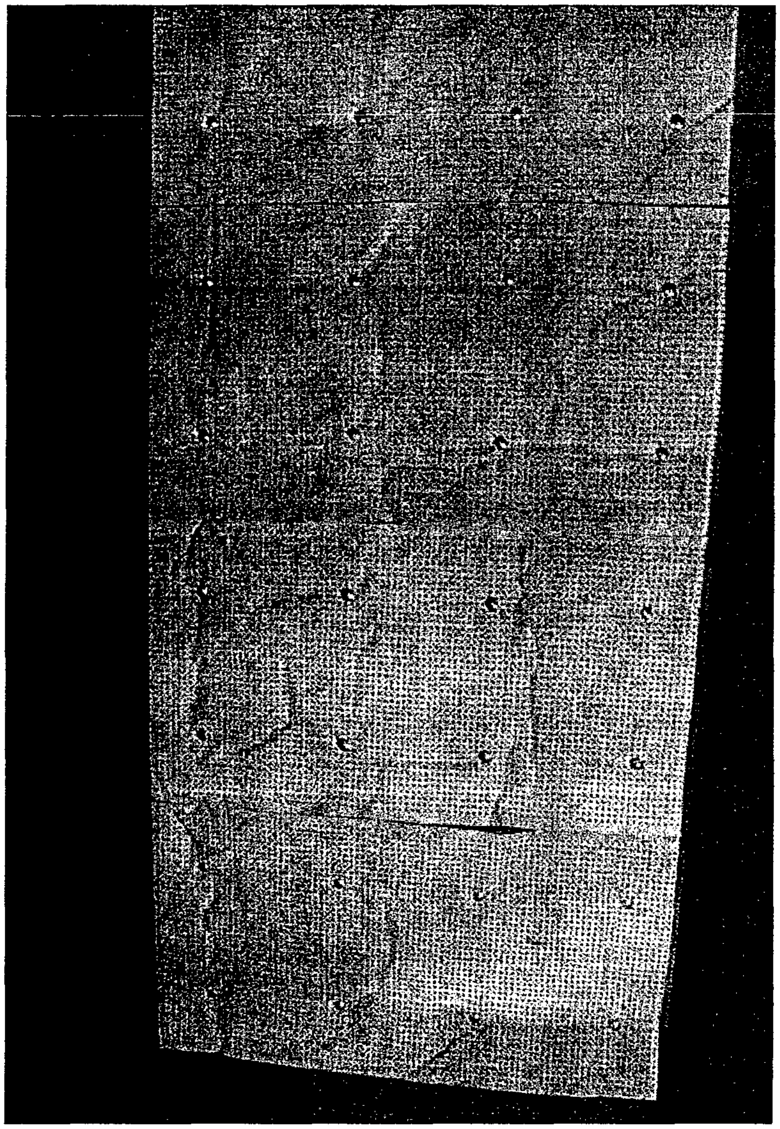

Figure 11. Polyimide Insulation Panel

Polyimide panels were installed, with a horizontal orientation, to span the gap between frames. Four panels were sufficient to cover the bulkhead from the false deck to the overhead. The circles on a square grid are the heads of the mushroom caps used to attach the insulation to the bulkhead.

4.3 Instrumentation

The data system included the transducers and a computerized data acquisition system that converted data from voltage or current signals to engineering units and stored the data for off-line analysis. The key instruments and the data acquisition system are described in more detail below.

Test instrumentation locations are shown in Figure 12; additional details are given in Table 3. Note that instruments located at elevations greater than 31 cm (12 in.) are above the false deck while those at lower elevations are below the false deck. Services (power, data connections and cooling, for example) for the below-deck instruments were provided via the MCT near the aft, starboard corner of the test compartment while those for the above-deck instruments were provided by the forward, port MCT.

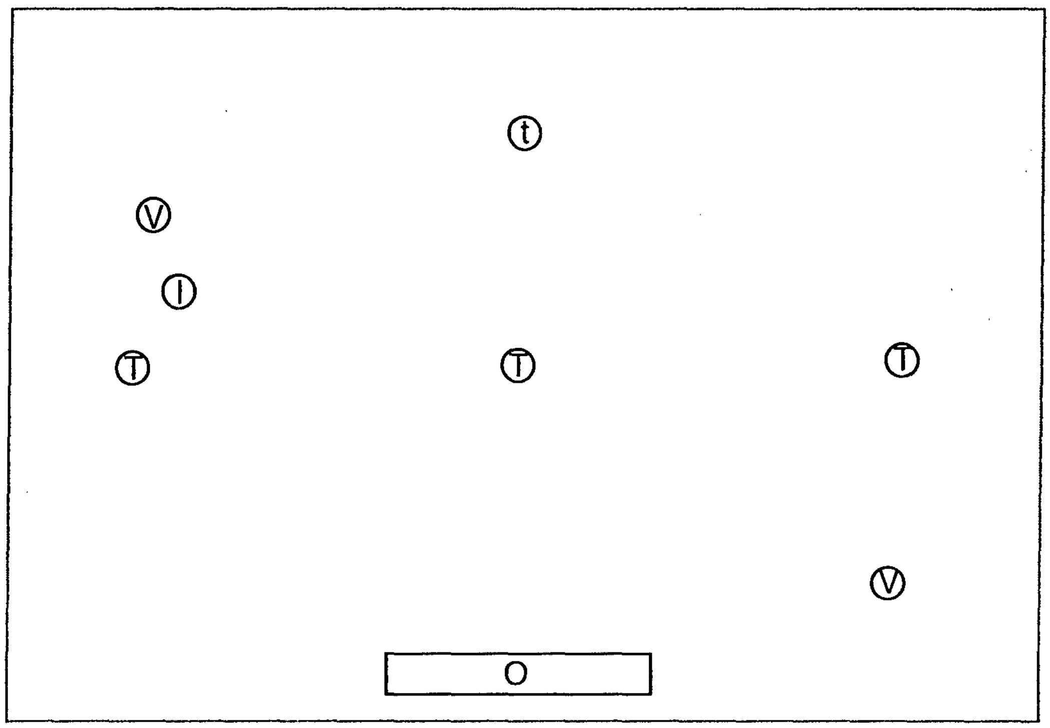

Figure 12. Plan View of Instrument Positions

Instruments were located approximately as shown. Forward is to the right.

Symbols:

T = Instrument tree (thermocouples and gas sample inlet)
t = Individual thermocouple
V = Visible light video camera
I = Infrared video camera
O = Optical density meter (ODM)

Instrument	Description
Instrument trees	On center line @ left, middle & right; five thermocouples + one gas sample per tree: TC 0 @ 0.15 m (6 in.) TC 1 @ 0.46 m (18 in.) TC 2 @ 1.00 m (39 in.) TC 3 @ 1.6 m (61 in.) TC 4 @ 2.1 m (82 in.) TC 5 @ 2.6 m (104 in.) Gas sample @ 1.8 m (71 in.)
Individual thermocouples	Upper center; on electric heat rods Upper center; on cable bundles
Visible light cameras	Lower, right @ 37 cm (14 in.) Upper, left @ 5 cm (2 in.)
Infrared video camera	Upper, left @ 10 cm (4 in.)
Optical density meter	Bottom @ 142 cm (56 in.)

Table 3. Test Instrumentation

Each instrument shown in Figure 12 is described in more detail in this Table. Nominal elevations are given relative to the actual deck, not the false deck; instruments located at elevations less than 31 cm (12 in.) are below the false deck. Location descriptions (upper, lower, left, center and right) are given with respect to Figure 12.

4.3.1 Thermocouples

American National Standards Institute (ANSI) Type K (chromel-alumel) thermocouples (TCs) were used, both as individual instruments and as components of instrument trees. To monitor surface temperatures, individual TCs were attached to each of the two heater rods and to one cable on the outside of each cable bundle. At three locations, shown in Figure 12, chains were hung from the overhead to support six TCs (numbered 0 - 5) as reported in Table 3. For each tree, location zero was in the space below the false deck; locations one through five were in ascending order above the false deck. Each thermocouple was connected to one of the datalogger channels, as discussed below.

4.3.2 Gas sampling

Gas sampling was accomplished using a pump to draw air from the compartment through 0.64 cm (0.25 in.) diameter copper tubes. After passing through filters and a cold trap to remove particulates and condensable vapors, the gas then flowed through analyzers (Rosemount Analytical MLT Analyzer, Model NGA-2000) which monitored the concentrations of oxygen, carbon monoxide and carbon dioxide. The analyzer outputs were digitized and recorded by the datalogger system.

4.3.3 Optical density meters

An optical density meter (ODM) was located along the starboard bulkhead at an elevation of about 1.4 m (56 in.) to measure the optical transmission, which is inversely related to the amount of soot in the air. The ODM used a low power laser to monitor light absorption over a fixed path length of one meter (39 in.).

4.3.4 Video

Three video cameras, one operating in the 10 micron infrared (IR) band and the other two working in the visible light range, were used to monitor the situation inside the test compartment. The IR camera and one of the visible light cameras were place below the false deck, near the aft bulkhead, and oriented to view forward, toward the cable bundle. The second visible light camera was located above the false deck, near the forward, starboard corner of the space, with a view toward the starboard bulkhead. An additional camera was placed outside of the test compartment to monitor the spray fire conditions. Images from all four cameras were displayed in the test control center in real time and were recorded for later review.

4.3.5 Data acquisition system

The data acquisition system consisted of a computer, running custom National Instruments LabVIEW software, connected to a SCXI-1001 chassis (containing a maximum of 12 data acquisition or control modules) configured data rates up to 2 Hz. For these tests, the actual data rate was set, by the software, to 1 Hz.

National Instruments type SCXI 1100 data acquisition modules, with SCXI 1303 terminal blocks, were used for both voltage and millivolt inputs (gas analyzers and thermocouples, for example). These modules digitized the instrument signals and the output of each data channel were logged by the computer and saved onto a hard drive for later analysis. Selected signals were also displayed in real time for the benefit of the test director.

The states of critical control panel switches (for example, those for the heater rods, fuel pump and arc igniter) were monitored by the data acquisition system so that activation and deactivation times were logged.

4.4 Procedures

In this section, we discuss the procedures used during test preparation, actual testing and the subsequent analysis of the test data. Test procedures included pre-test instrument calibrations, installation of the fuel load, setup of the data acquisition system, ignition and monitoring of the progress of the test. Data analysis procedures involved data filtering to remove bad data points, data smoothing to reduce signal noise and plotting of the results. Each of these areas is discussed below; the detailed test procedures are given in Appendix A and the checklist for conducting tests is in Appendix B.

4.4.1 Instrument calibration

The gas analyzers were calibrated each day, using nitrogen, air and a CO/CO_2 mixture as standards. The ODM output was checked prior to the start of each test; the optics were cleaned and the instrument span was adjusted as needed. Thermocouple cold-junction temperatures were measured by a thermistor in the SCXI 1303 terminal block and cold-junction corrections were performed by the acquisition software. Further calibrations were not necessary because thermocouple voltages are an inherent function of the properties of the thermocouple materials.

4.4.2 Test setup and execution

For each test, pre-weighed fuel items were installed at the locations shown in Figure 3. Various combinations of cables, Nomex deck panels and polyimide insulation panels were used, depending on the test requirements, as shown in Table 4. New fuel items were used, except in cases where the item in question had not been damaged during the previous test. These cases are discussed below.

For those tests that used heat rods as the ignition source, two rods, with thermocouples attached to each, were inserted into Cable 1. For all tests, a surface temperature TC was attached to one of the unarmored cables in each bundle to monitor the exterior cable temperatures. The armored cables were not used because, due to the high conductivity of the armor, their surface temperatures were not representative of a typical cable. In the cases in which spray fires were used, the appropriate number of nozzles were installed in the array and, for the pan fire shakedown tests, the pan was charged with fuel and the "Levenberry device" was placed in the pan. For both the spray and the pan fires, the arc igniter electrodes were positioned to ensure that they would ignite the fuel.

The fuel load was photographed to document the pre-burn conditions, the water tight door was secured and the data acquisition system and video recorders were started. After verifying that these systems were operating correctly, there was a delay of approximately two minutes before the actual start of the test[1]. This "pre-burn period" permitted baseline conditions to be recorded for later use during data analysis, as discussed below. For tests using the hot rod ignition source, the rods were switched on at ignition time. For those that used the spray fire ignition source, the electric arc was activated and the fuel pump turned on at ignition time and, after the spray ignited, the electric arc was secured.

In keeping with standard Navy doctrine, which calls for ventilation to be secured when a fire is detected, the test compartment exhaust was turned off when smoke was seen in the above-deck space. The tests were continued, through the flaming combustion phase of the cable fire, until the cable fire burned out. For the spray fire tests, the fuel was secured after approximately 20 minutes and the cable fire was monitored to determine whether the fire was self-sustaining. Finally, at the end of each test, the data were saved as a tab-delimited text file to be analyzed off-line.

[1] Note that the test start time was the time at which the ignition source(s) was (were) activated. Data acquisition began earlier and the ignition of the cable bundle occurred much later.

Test	Fuel Load			Ignition Source(s)	
	Cable Bundles	Deck Panels	Insul. Panels	Heat Rods (0.925 kW ea.)	Nozzles (226 kW ea.)
Cable 1	1	0	0	2	0
Cable 2	1	0	0	0	1
Cable 3	1	0	0	0	5
Deck 1	2	3	0	2	0
Deck 2	2	3	0	2	0
Deck 3	2	3	0	2	0
Deck 4	2	3	0	2	0
Insulation 1	2	3	4	2	0
Insulation 2	2*	3	4	2	0
Insulation 3	2	3	4	2	2
Insulation 4	2	3	4	2	2
Spray Baseline	0	0	0	2	2

Table 4. Test Descriptions

The planned fuel loads (number of bundles, deck panels and insulation panels) and ignition sources (number of heat rods and spray nozzles) are given for all tests. The four shakedown tests, used for instrument checkout and procedure validation, are not included.

* This test used a non-standard cable bundle ("T" bundle), as described in the text.

During the test, key event times were logged manually on the test checklist (Appendix B) to supplement the automated data acquisition system record. Times noted in the checklist included the observed cable bundle ignition time, first appearance of smoke above the false deck and the time that the fire burned out.

4.5 Data Analysis

The test data file used a tab-separated value spreadsheet format in which each instrument was represented by a column and data for each time was recorded in a row. The system was configured to write data rows at one second intervals. Since the output times were controlled by the data acquisition hardware, there was no need for the time to be included in the file.

After loading the data file into a plotting program, a time column, in seconds, was added starting at one second and incrementing by one for each row. This column was then shifted so that zero corresponded with the nominal start time for the test (*i.e.*, the time at which the ignition sources were activated).

The background temperatures and gas concentrations within the test compartment differed from one test to another and, consequently, direct comparison of test data would yield misleading results. To compensate for this, temperature and gas offsets were adjusted by subtracting the mean pre-test background value (calculated by averaging the values for all negative times, *i.e.*, for times prior to the activation of the ignition sources) and adding a nominal value (given in Table 5) to each datum. This procedure had the effect of adjusting the pre-test values to a standard ambient condition and made it possible to compare results from different experiments.

Parameter	Nominal Value
Temperature	25 C
CO concentration	0 %
CO_2 concentration	3.3%
O_2 concentration	20.9%
Optical transmission	100%

Table 5. Nominal Values for Ambient Corrections

After subtracting the mean pre-burn values for each instrument, the nominal values from this Table were added to correct for differences in ambient conditions among the tests.

As an example, assume that the mean ambient temperature for one day was 15 °C (59 °F) while that for another day was 30 °C (86 °F). By applying the above correction, the temperatures for the first day would be raised by 10 degrees C (18 degrees F) while those for the second day would be reduced by 5 degrees C (9 degrees F); as a result, both are adjusted to a nominal pre-test ambient temperature of 25 C (77 °F) so that direct comparisons between the tests are meaningful.

In the case of optical density data, the instrument span varied slightly for each test. To adjust this data, each point was multiplied by a correction factor, calculated as 100% divided by the mean transmission for the pre-test period, so that the ODM outputs were properly scaled. Finally, after applying the above adjustments, the resulting data were smoothed, using a sliding average, to reduce signal noise. For most data, the sliding average used a 10-point window but, due to relatively high noise levels, a 50 point average was used for nozzle pressure data.

For air temperatures and gas concentrations, where there were multiple instruments in the test space, mean values were calculated for each elevation to reduce the localized variability in the data. In a few cases (which are discussed in the following sections), data from specific instruments were rejected due to malfunctions or excessive noise even after the smoothing process. In those cases, the rejected data were not included in the elevation mean values. It was found that, for all above-deck elevations, the temperatures were very similar. Accordingly, in the final analysis, all of the above-deck data were combined to obtain an average temperature for the entire space.

Additional processing was necessary for the gas data due to the time required to pump the gas through the sample lines. As a result of this transit time, gas analysis data were delayed relative to the other data. Because of the differences in the pumping speeds and the lengths of the lines, the delay differed for each of the sample systems.

To obtain correction factors, gas transit times for each sampling system were measured, prior to the start of the testing, by monitoring oxygen concentration while first drawing normal air, then sampling from a gas bag filled with nitrogen and, finally, switching back to normal air. The time between the start of sampling and the first response of the analyzer was measured for both falling and rising oxygen concentrations. The test was repeated three times and the data for each gas sampling system were offset by the mean delay time for that system, presented in Table 6.

Tree	1A	1B	2A	2B	3A	3B	Mean	SD
#1	16.22	18.30	18.17	12.94	18.43	19.49	17.26	2.37
#2	18.49	29.69	21.03	26.48	19.43	23.44	23.09	4.34
#3	21.55	25.09	21.95	21.23	21.66	21.45	22.16	1.46
Exhaust	19.74	22.74	22.84	22.84	22.65	23.26	22.34	1.29

Table 6. Transit Delay Corrections for Gas Sampling

Gas transit times, in seconds, were measured, as described in the text, and the mean values calculated for each sampling system. The measurements were repeated three times and each measurement included both falling and rising oxygen levels ("A" and "B" measurements, respectively).

Lastly, it was found that the operation of the fuel pump caused significant spikes in the temperature data and that the normal smoothing process was not sufficient to remove them. Therefore, in the spray fire case, the data were filtered to remove outliers prior to performing the offset correction. This greatly improved the quality of the data plots.

5.0 RESULTS & DISCUSSION

In this section, we first provide brief descriptions of the individual tests, emphasizing the purpose of the test and the relationships among the tests. We will then present results of the tests, including temperature, visibility and habitability data.

5.1 Test Descriptions

The general test descriptions, including fuel loads and ignition sources, were given in Table 4. To better illustrate the relationships among the various tests, this information has been reorganized into a matrix, as presented in Table 7. Note that the tests within a cell are similar, in terms of the fuel loads and ignition sources, but may differ in the number of nozzles or other details.

		Fuel Load			
		None	**Cable**	**Cable + Nomex**	**Cable + Nomex + Polyimide**
Ignition Source	**Spray Fire**	NA	Cable 2 (1) Cable 3 (5)	NA	NA
	Heat Rods	NA	Cable 1	Deck 1 Deck 2* Deck 3 Deck 4	Insulation 1 Insulation 2**
	Spray Fire + Heat Rods	Baseline (2)	NA	NA	Insulation 3 (2) Insulation 4(2)

Table 7. Test Matrix

This test matrix emphasizes the relationship among the test configurations. The numbers in parentheses are the number of nozzles used for the spray ignition tests.

* The cables did not ignite during this test.
** This test used a non-standard cable bundle ("T" bundle), as described in the text.

5.1.1 Shakedown tests

As mentioned previously, the main purposes of the four shakedown tests were to check the performance of the instruments and data system and to verify the planned test procedures. Two of those tests included attempts to ignite a cable bundle using electric heater rods. In the first of these, we found that it was impossible to ignite the bundle using only a single hot rod (approximately 925 W); in the second, we verified that two rods (1850 W) were sufficient. As a result, the plans were modified to require two rods in all tests that involved the ignition by electric heaters.

It was believed that the burning cables might produce dangerous levels of hydrogen cyanide, which is not detected by the standard gas analyzers used in our tests. Accordingly, we tested for the presence of this gas before reentry into the test space using a hand-operated Draeger Accuro Bellows Pump (model ARFM-F002) with hydrogen cyanide-sensitive diffusion tubes (model CH25701 batch UM-1401). Because this test required a human presence in the test compartment, it cold only be performed after a post-test cool down period and did not permit determination of hydrogen cyanide during or immediately after a test. During the shakedown tests, it was determined that a 30-minute post-test ventilation period was sufficient to render the space safe for reentry and this time became the standard for all further tests. Hydrogen cyanide testing was not part of the procedure for subsequent tests.

5.1.2 Cable 1

The Cable 1 test used a single cable bundle, ignited by two heater rods. Figure 13 shows before and after photographs of the cables. In the enlarged view (Figure 14), it is evident that the insulation on the unarmored cables is badly charred in places.

5.1.3 Cable 2

The second cable test, Cable 2, was similar to the first except that the ignition source was a single nozzle (approximately 226 kW), as seen in Figure 15. Figure 16 shows that the paint was burned off of the deck above the nozzle but the cables, which were only 15 cm (6 in.) above the deck, never ignited and, if fact, suffered no apparent damage other than slight discoloration from smoke.

5.1.4 Cable 3

The Cable 3 test was a repeat of Cable 2, except that the ignition source consisted of a five-nozzle array (about 1.13 MW), as illustrated in Figure 17. The same cable bundle, which suffered no damage in the previous test, was recycled for this test. In this test, the cables did ignite and the bundle was heavily damaged (see Figure 18). In addition, the flames rose up the exterior of the starboard bulkhead, burning the paint off and damaging some of the instrumentation. As a result of this damage, the remaining spray fire tests were restricted to two nozzles.

5.1.5 Deck 1

Starting with the Deck 1 test, two cable bundles were used, with heater rods installed in the Cable 1 bundle, to investigate the possibility that a fire could spread from on bundle to another. Figure 19 shows the relative placement of the two sets of cables and Figure 20 illustrates the placement of Nomex panels above the cables. Prior to starting this test, a third Nomex panel was installed at the bottom, center of the photograph and the area on the left was covered with Durock Cement Board to complete the false deck, as described previously.

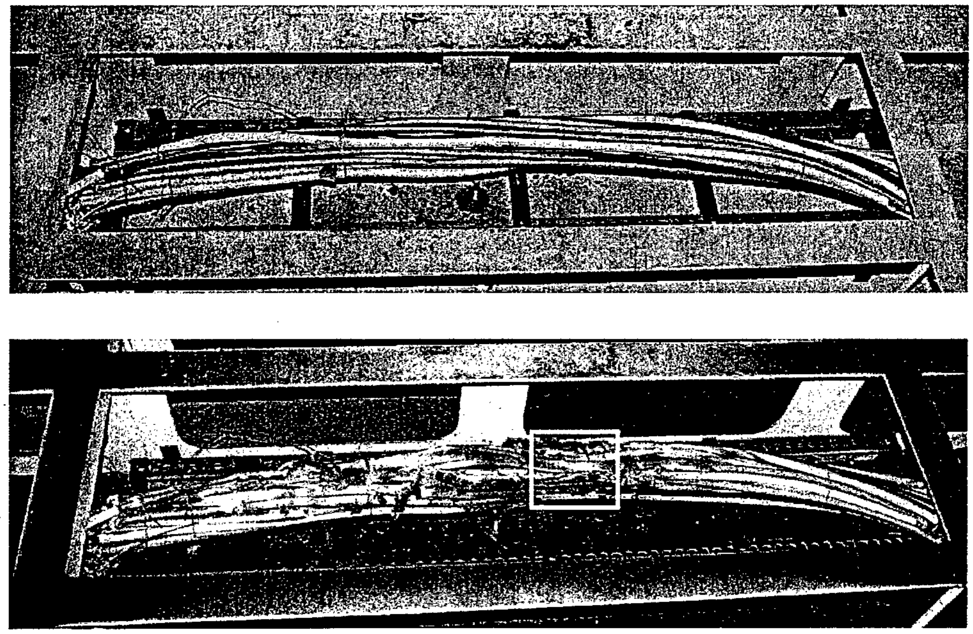

Figure 13. Pre- and Post-Test Views of Bundle 1 (Cable 1 Test)

Photographs of Bundle 1 before (upper) and after (lower) the Cable 1 test. The area inside the white rectangle in the lower photo is enlarged in the next figure.

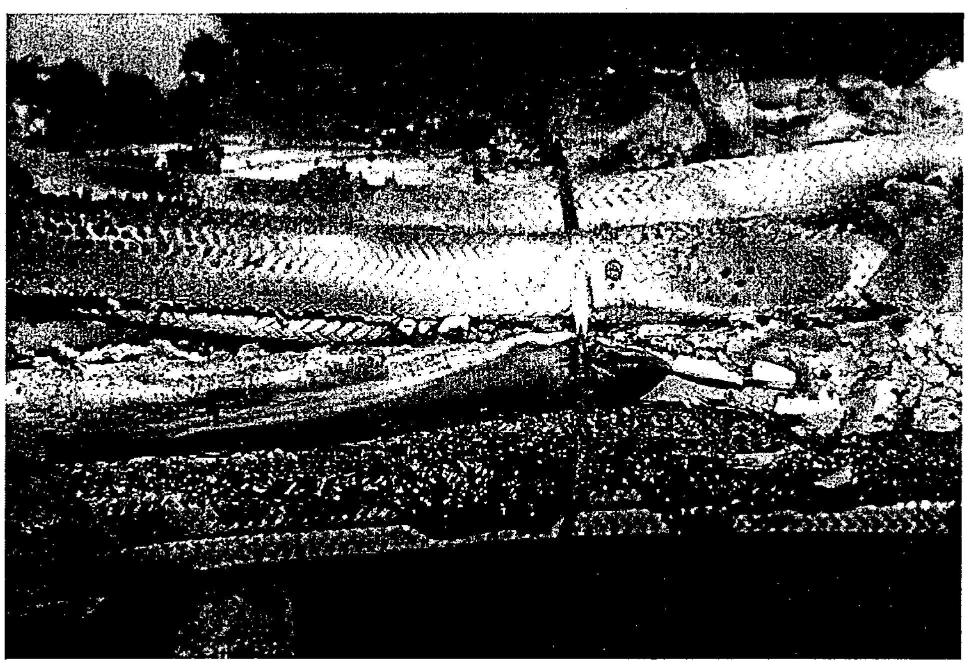

Figure 14. Enlargement of Bundle 1 (Cable 1 Test)

This enlargement of one of the most severely damaged portions of Bundle 1 after the Cable 1 test.

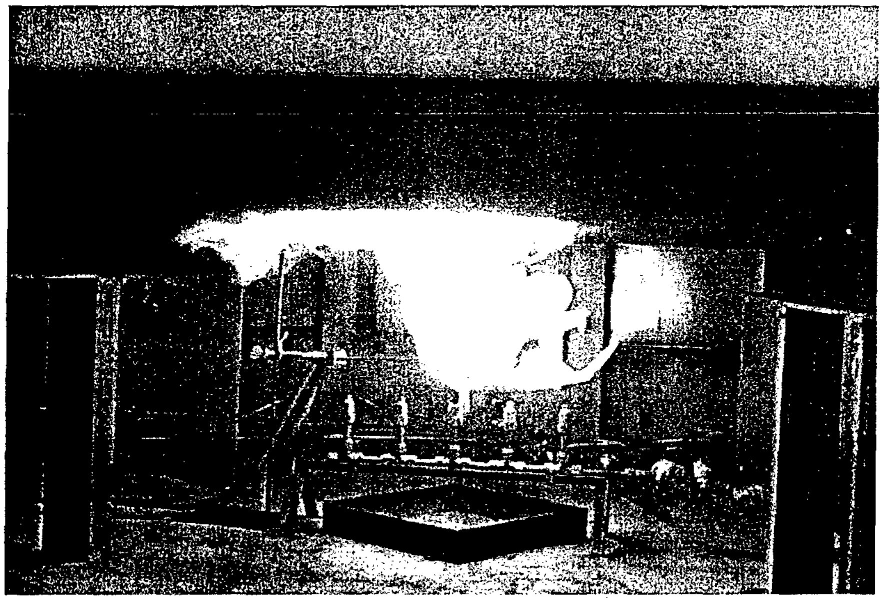

Figure 15. Single Nozzle Spray Fire (Cable 2 Test)

A single spray nozzle, producing an fire of approximately 226 kW, was the ignition source for the Cable 2 test.

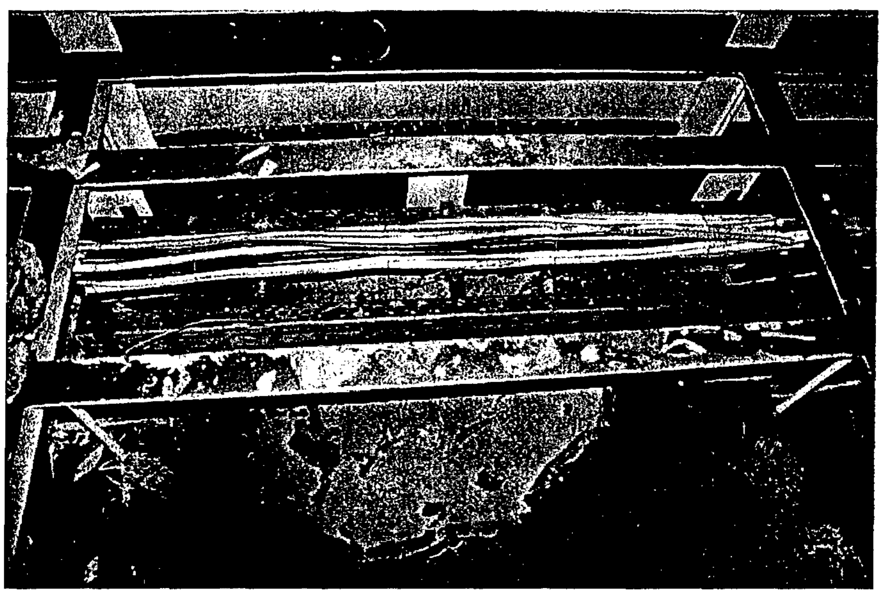

Figure 16. Results of Single Nozzle Spray Fire (Cable 2 Test)

The 226 kW spray fire burned the paint off the deck but did no noticeable damage to Bundle 1, which was only 15 cm (6 in.) above the deck.

Figure 17. Five-Nozzle Spray Fire (Cable 3 Test)

The array of five spray nozzles produced a fire of approximately 1.13 MW for the Cable 3 test.

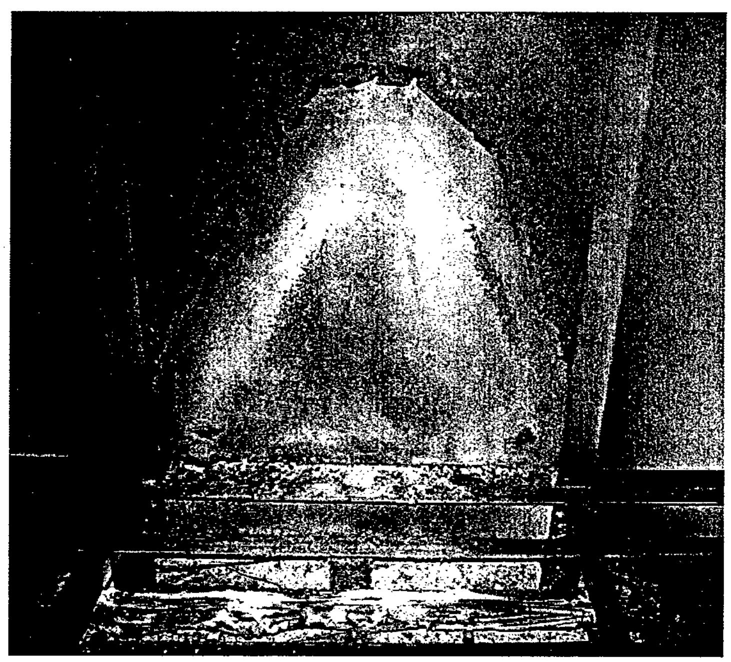

Figure 18. Results of Five-Nozzle Spray Fire (Cable 3 Test)

The 1.13 MW spray fire destroyed most of the cables in Bundle 1 and burned the paint off of a large section of the starboard bulkhead.

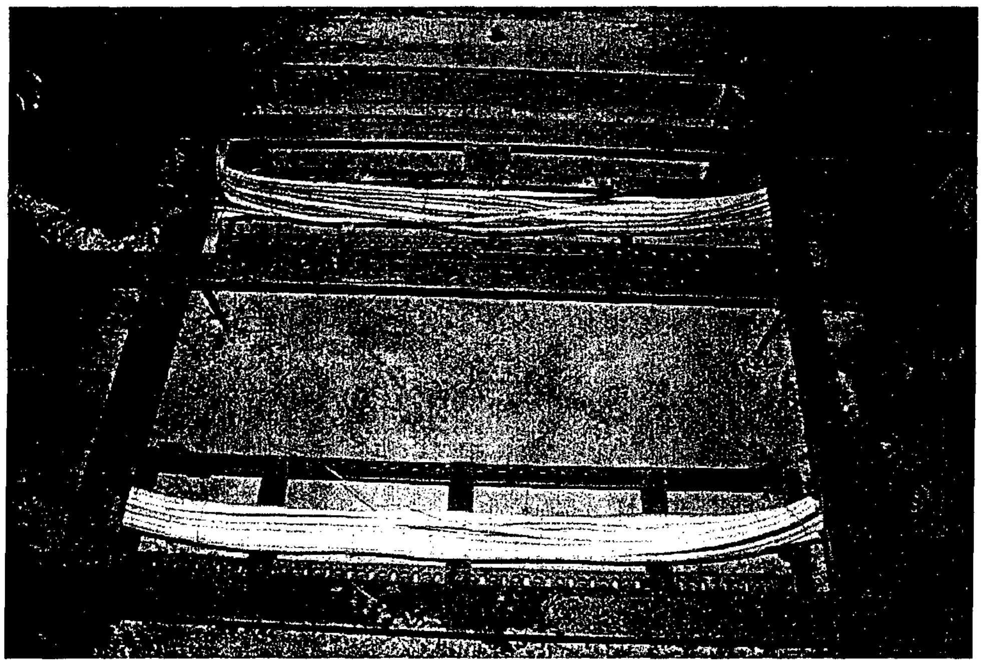

Figure 19. Two-Bundle Cable Placement (Deck 1 Test)

In addition to the standard Cable 1 placement, at the top of the picture, a second bundle (Bundle 2) was added, starting with this test. Only Bundle 1 had electric heaters installed as ignition sources. Note the igniter power cables, covered with aluminum foil for insulation, in the upper left.

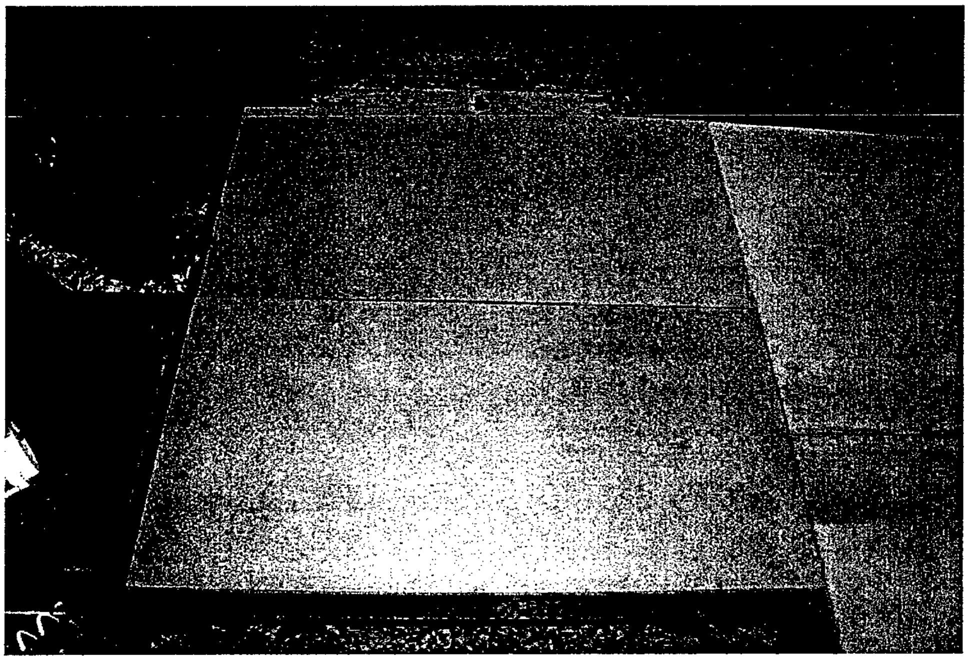

Figure 20. Installation of Nomex Panels (Deck 1 Test)

The placement of two of the three Nomex panels (Nomex 1 and 2) prior to the test is shown in this picture. Nomex 3 occupied the space at the bottom center of the picture; Durock Cement Boards, similar to those on the right, were also used on the left.

At the end of the test, we found that panel Nomex 1, directly above Bundle 1, was blistered and warped, Nomex 2 was slightly burned along the edge adjoining Nomex 1 and third panel (Nomex 3) was heavily sooted but not damaged (see Figure 21). Upon lifting the two damaged panels (Figure 22), large flakes of material were seen to be peeling off the bottom of Nomex 1 and additional material was found on the cables and deck below. The large blister seen on the top surface was due to delamination of the upper GRP layer from the Nomex core. The fire destroyed Bundle 1, as shown in Figure 22, but Bundle 2 was intact.

5.1.6 Deck 2 — Deck 4

Tests Deck 2 through Deck 4 were intended to be replicates of the Deck 1 test. In the case of Deck 2, the cables never ignited and, therefore, data from this test is not included in the analysis presented below. For the other two tests in this set, the cables did ignite and the damage to the cables and to the deck panels were similar to those discussed above.

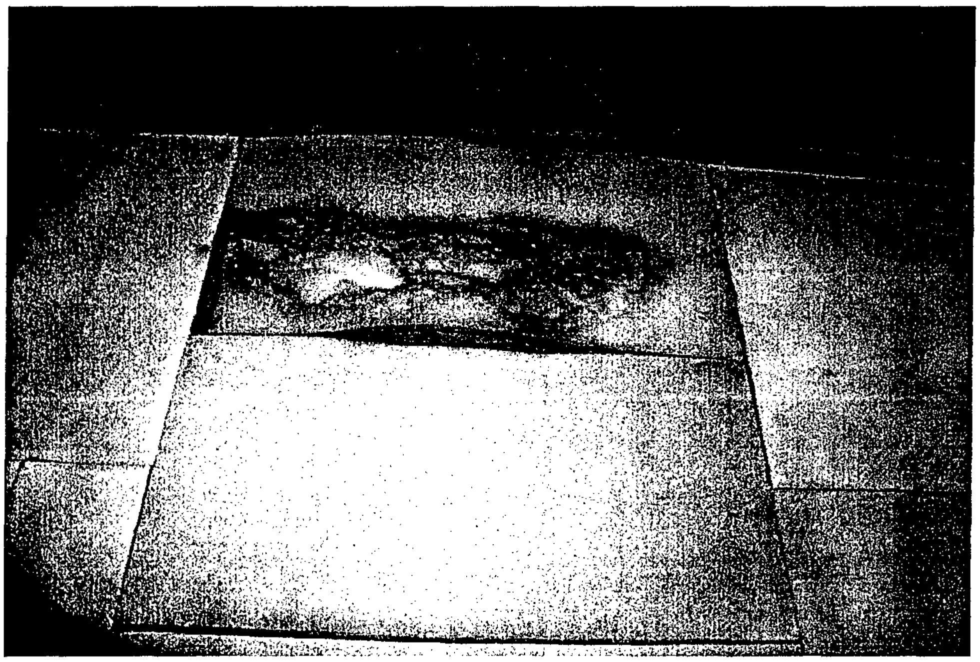

Figure 21. Post-Test Damage to Nomex Panels (Deck 1 Test)

After the test, the Nomex 1 panel was found to have been blistered and discolored on the top and Nomex 2 was slightly damaged. The Nomex 3 panel was covered in soot, but undamaged.

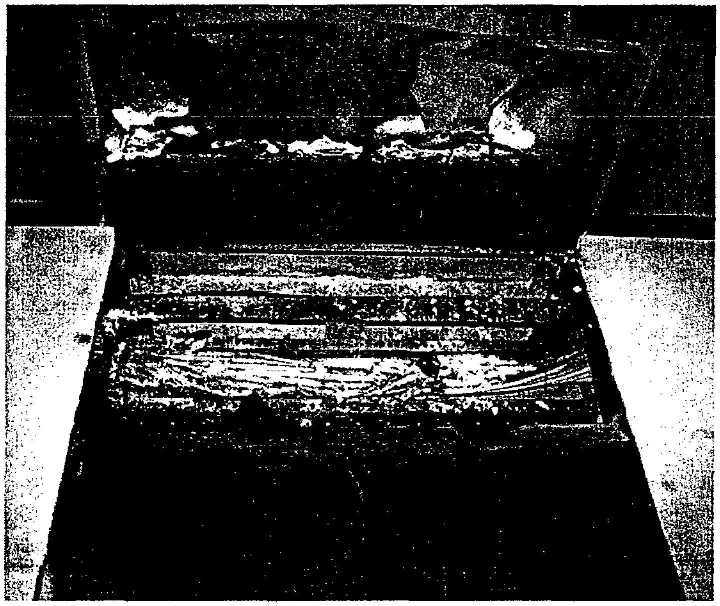

Figure 22. Post-Test Damage to Nomex 1 and Cable 1 (Deck 1 Test)

Nomex 1 has been lifted, and Nomex 2 turned upside down, to show the damage to the bottom of each panel. Note the warping along the upper edge of Nomex 1 and the large pieces of material that have peeled off from the bottom surface. Nomex 2 is scorched on one edge but is otherwise intact and Bundle 1 was destroyed.

5.1.7 Insulation 1

Beginning with this test, the polyimide insulation panels shown in Figure 11 were added to the fuel load. The ignition source for this test was the same as in the cases of the deck panel tests — two electric heater rods inserted into the Bundle 1 bundle.

Damage to the deck panels and to the cable bundles was similar to that reported above. The lowest insulation panel (Poly 1) was slightly discolored, especially at the lower corners, but was not otherwise harmed.

5.1.8 Insulation 2

This test was a replicate of Insulation 1, except that a modified cable bundle was used. To make this, one standard bundle was disassembled and two sets of 10 cables (two of each type) were removed. These sets were added to a second bundle so that, at each end of the intact bundle, the ends of the 35 cables were aligned. The 20 added cables were then bent at right angles and bundled together to form a perpendicular branch. The bundle was installed in the Cable 1 position with the branch oriented vertically, protruding through a hole in the Nomex 1 panel.

The goal of this was to determine whether cables extending though holes in the false deck could act as wicks that might expedite ignition of nearby insulation panels. This construction mimics actual shipboard practice, where cables penetrate the false deck to reach connectors located on the rear of the electronic consoles.

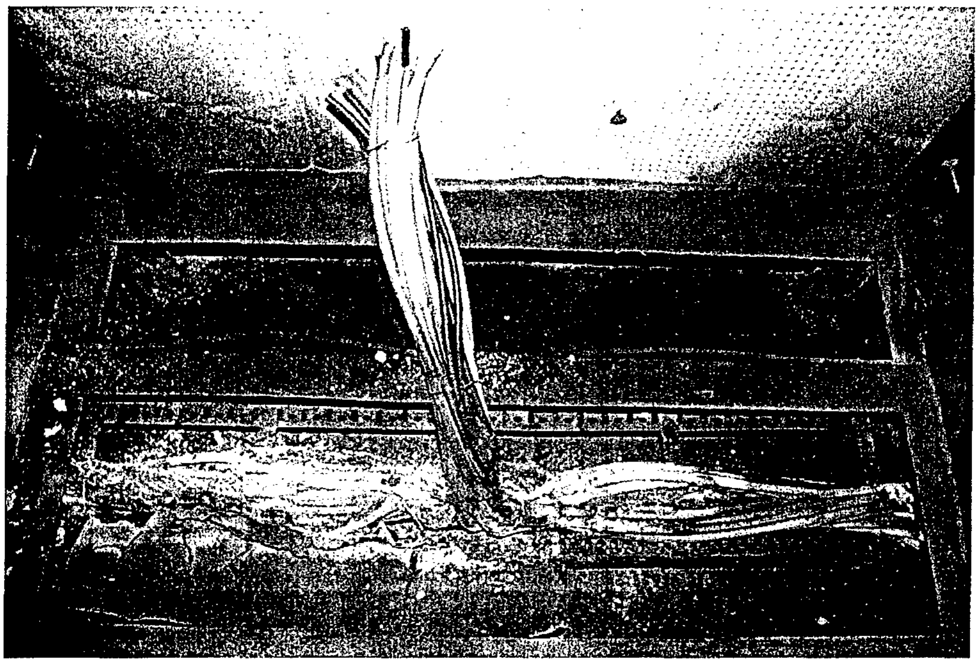

Figure 23. Special "T" Cable Bundle (Insulation 2 Test)

In this test, a special, T-shaped cable bundle was used, with the upper branch extending through a hole in the Nomex 1 deck panel, in the Bundle 1 position.

The results of this test are shown in Figure 23. Note that the below deck portion of the "T" bundle was burned out but the part that was above the false deck was relatively undamaged. Also, the Poly 1 panel was only slightly scorched at the lower corners. Figure 24 shows the Nomex 1 panel, removed from the test compartment after the test. The hole for the vertical branch of the "T" bundle is near the center of the panel.

5.1.9 Insulation 3 and Insulation 4

The last two insulation tests were replicates that used both two-nozzles (approximately 452 kW total) spray fires and two electric heaters for ignition. Similar levels of damage to the deck panels and to the cables were seen in both tests and, as before, the insulation was not seriously damaged.

Figure 24. Nomex 1 Panel (Insulation 2 Test)

The underside of the Nomex 1 panel is shown after removal from the test compartment. The vertical branch of the cable bundle protruded through the hole near the center of the panel. Note the warping of the panel, especially visible at the bottom edge.

As seen in Figure 25, both the top and bottom GRP facings delaminated from the Nomex honeycomb core of the Nomex 1 panel, which was located directly above both Cable 1 and the spray fire. The Nomex 2 panel was severely warped and burned along the starboard edge, where it abutted Nomex 1. In Figure 26, the deck panels have been removed to show Cable 1. Note the many pieces of GRP that peeled off of the Nomex 1 panel. A close-up of a portion of the Cable 1 bundle is shown in Figure 27, where the outer electrical insulation has been completely burned away in places and has split open in other places.

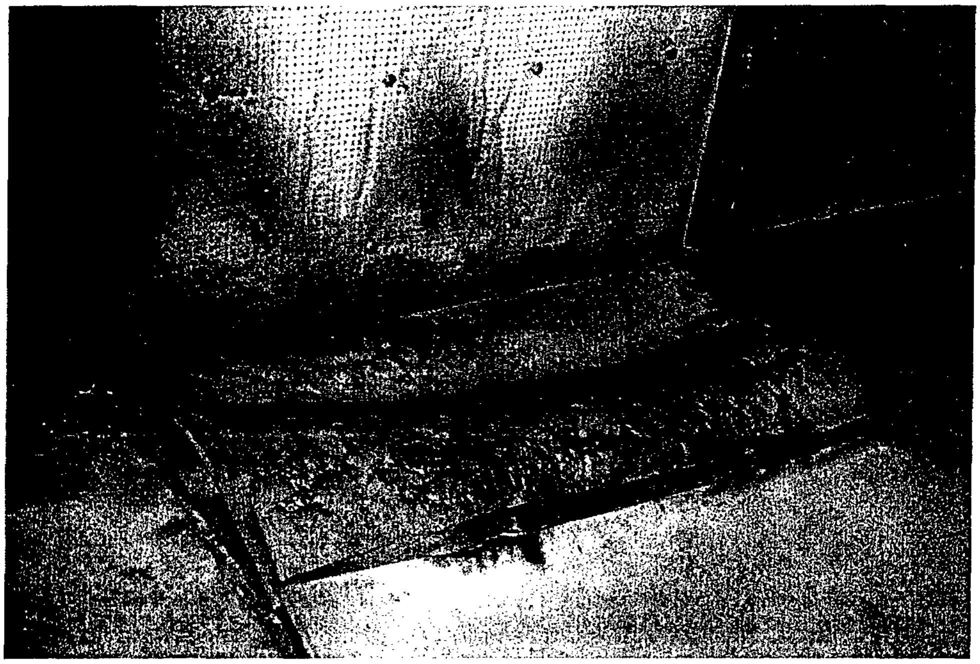

Figure 25. Post-Test Damage to Nomex 1, Nomex 2 and Poly 1 (Insulation 3 Test)

Nomex 1 has been reduced to a brittle shell (note the layers of GRP facing and the Nomex core visible on the left edge). Nomex 2 was damaged where it adjoined Nomex 1 and was severely warped. The Poly 1 insulation panel was scarcely damaged.

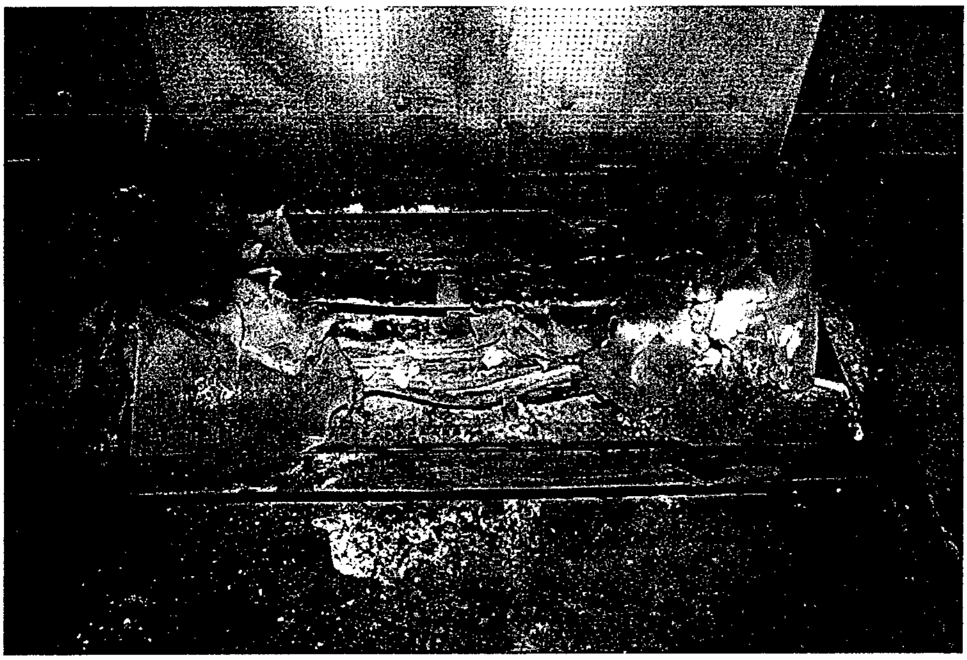

Figure 26. Post-Test Damage to Bundle 1 (Insulation 3 Test)

In addition to the burned out cables, large flakes of charred GRP facing material from the Nomex 1 panel are visible.

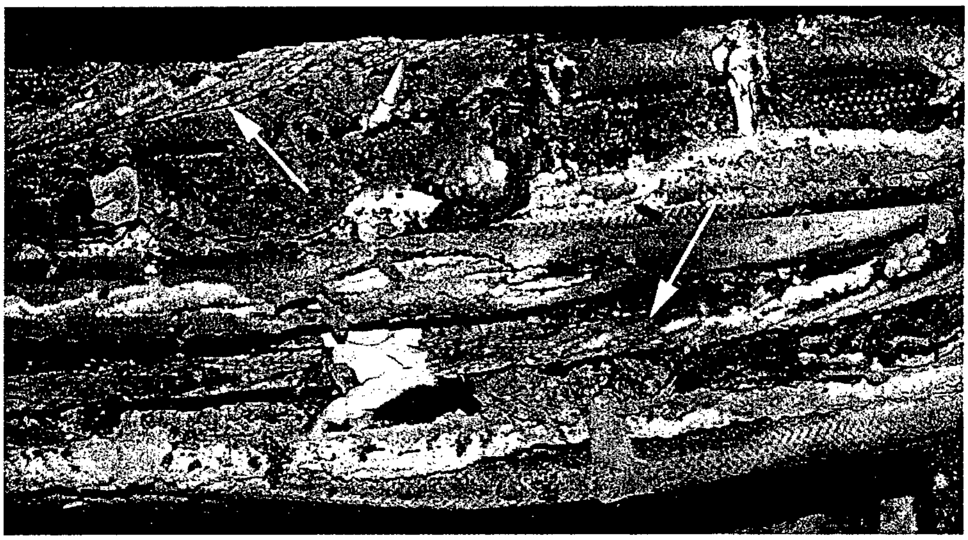

Figure 27. Close-up of Damage to Bundle 1 (Insulation 4 Test)

This close-up view of a portion of Bundle 1 shows that the insulation has been completely burned off in places (arrows), exposing the conductors.

5.1.10 Spray Baseline

The purpose of the Spray Baseline test was to measure the effects of the ignition sources, especially the spray fire, on the environmental conditions within the test compartment. In this test, two spray nozzles and two heater rods were used, just as in the previous two cases, but there were no combustible materials (cables, deck panels or insulation) in the test compartment. The pre-test arrangement is shown in Figure 28.

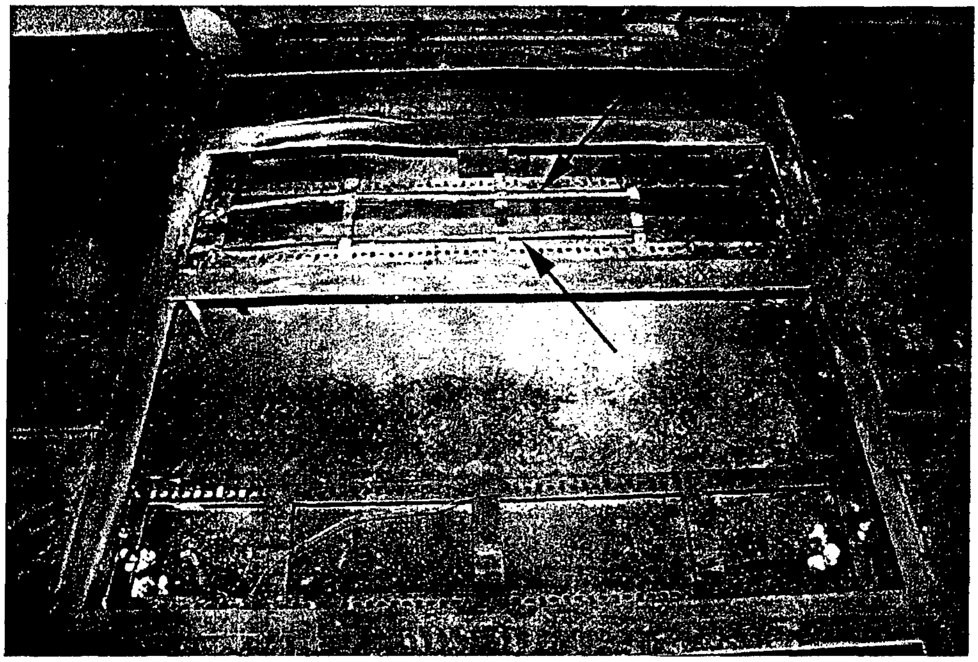

Figure 28. Heater Rod Placement (Spray Baseline Test)

The electric heater rods (arrows) were installed in the position normally occupied by Bundle 1.

5.2 Test Results

In this section, we first place the tests into groups having common characteristics so that we may estimate the reproducibility of the the tests. Comparison among these groups then permits us to estimate the effects of various variables, including such factors as different fuel loads and ignition mechanisms.

5.2.1 Test groups

Based on the matrix presented in Table 7, there were two groups of replicate tests. Group 1, tests Deck 1 — Deck 4, had a fuel load of two cable bundles and three Nomex panels and used electric heaters for ignition. Group 2, consisting of tests Insulation 3 and 4, added four polyimide insulation panels to the previous fuel load and used both electric heaters and a two-nozzle spray fire as the ignition source.

In addition to these replicates, the matrix reveals that there were several sets of tests that differed in one significant parameter and which can be compared to elucidate the contribution of that parameter. In particular, Insulation 2 was the essentially the same as Insulation 1, except that the cable bundle was changed so that it penetrated the false deck. Finally, the Spray Baseline test replicated the ignition conditions of Insulation 3 and 4, but without the fuel load.

5.2.2 Ignition and combustion

Table 8 shows the times at which critical events occurred for each test. For our purposes, the critical events were: (1) the time of fire detection in the above-deck region; (2) the ignition time for Bundle 1; (3) the times at which the ignition sources were secured; and (4) the time at which the fire burned out. Fire detection was visual, based on the observation of smoke above the false deck on the video monitors in the test control room. This was also the time at which the compartment ventilation system was secured. Burnout time was determined by observation of the below-deck region using both a thermal imager and a visible light video camera.

Test	**Fire Detection (s)**	**Bundle 1 Ignition (s)**	**Heaters Secured (s)**	**Spray Secured (s)**	**Burnout (s)**
Cable 1	238	478	3658	NA	3898
Cable 2	540	NA	NA	3540	NA
Cable 3	420	1380	NA	2730	NA
Deck 1	390	530	5670	NA	4860
Deck 2	300	NA	NA	NA	NA
Deck 3	266	1376	3486	NA	3596
Deck 4	210	3480	3615	NA	4960
Insulation 1	440	1210	3930	NA	4320
Insulation 2	450	2505	3630	NA	3960
Insulation 3	240	330	1800	1250	2940
Insulation 4	360	495	600	1305	3480
Spray Baseline	360	NA	600	1330	NA

Table 8. Fire Event Times

The times (in seconds after activation of ignition sources) at which critical events occurred are given for each test. The ventilation was secured at the time that the fire was visually detected in the above-deck region of the test compartment. Fire burnout was not observed in test Cable 3 due to obscuration caused by heavy smoke.

The mean cable ignition times for the replicate tests are given in Table 9, where we compare the results from the Group 1 and Group 2 tests. We note that, because the ignition time for the Deck 2 test was infinite (it never ignited), that test was omitted from the calculation of the mean and standard deviation for Group 1. In addition, we have included the results from the first two insulation tests because, although they were not strictly replicates (the cable masses differed and the hole in the deck in Insulation 2 changed the air flow pattern), we do not expect that the differences would have had a major effect on the time to ignition.

Group	Tests	Ignition Time (s)	SD (s)	Rel. SD
1	Deck 1 Deck 3 Deck 4	1795	1519	0.85
2	Insulation 3 Insulation 4	412	117	0.28
3*	Insulation 1 Insulation 2	1858	916	0.49

Table 9. Mean Cable Ignition Times

For the replicate tests described in the text, the mean times to cable ignition, and the standard deviation of those mean times, are given.

* Technically, these are not replicates because the cable fuel loads were different. However, this is not expected to have had a major impact on ignition time.

There was considerable variation in the cable ignition time, even within replicate tests, as shown by the large standard deviations. It is likely that this was primarily due to small differences in the configurations of the cable bundles, particularly the locations of the heater rods relative to the various cables. Due to the higher heat conduction of the armor braid, as compared to the elastomer covering of the unarmored cables, armored cables could have caused a significant reduction in the surface temperatures of the heater rods if there was direct contact between the cable and the rod. The fact that the relative standard deviation is much smaller in the case of spray fire ignition (Group 2) lends credence to that idea. Considering that the tests in Group 3 were not true replicates, the agreement between them is surprisingly good.

Table 10 presents pre- and post-test mass and calculated mass losses of Bundle 1 for each of the tests. Note that, during the Cable 2 test, the bundle was not burned (as indicated by the zero mass loss) and, therefore, the same bundle was recycled for the Cable 3. Since Bundle 2 never burned during any test, the same cables were reused for all tests; we have not included mass data for that bundle in the table.

Table 11 gives the means and standard deviations for the Bundle 1 mass losses. We see that there is high variability for the Group 1 tests but mass losses within the other two groups were very similar.

	Bundle 1 Mass [kg (lb.)]		
Test	**Pre-Test**	**Post-Test**	**Loss**
Cable 1	6.02 (13.25)	5.22 (11.50)	0.80 (1.75)
Cable 2	6.02 (13.25)	6.02 (13.25)	0.00 (0.00)
Cable 3	6.02 (13.25)	4.60 (10.12)	1.42 (3.13)
Deck 1	6.02 (13.25)	4.20 (9.25)	1.82 (4.00)
Deck 2	6.02 (13.25)	5.57 (12.25)	0.45 (1.00)
Deck 3	5.96 (13.12)	4.12 (9.06)	1.84 (4.06)
Deck 4	6.02 (13.25)	4.91 (10.81)	1.11 (2.44)
Insulation 1	6.02 (13.25)	4.18 (9.19)	1.84 (4.06)
Insulation 2 *	8.30 (18.25)	6.45 (14.19)	1.85 (4.06)
Insulation 3	5.96 (13.12)	4.04 (8.88)	1.92 (4.24)
Insulation 4	6.02 (13.25)	3.86 (8.50)	2.16 (4.75)

Table 10. Mass Loss of Bundle 1

Pre- and post-test weights and weight changes for Bundle 1 are given for each test that included cables. The units are kilograms (pounds).

* This test used a non-standard cable bundle ("T" bundle), as described in the text.

Group	Tests	Mass Loss [kg (lb.)]	SD [kg (lb.)]	Rel. SD
1	Deck 1 Deck 3 Deck 4	1.59 (3.50)	0.42 (0.92)	0.26 (0.26)
2	Insulation 3 Insulation 4	2.04 (4.50)	0.17 (0.36)	0.08 (0.08)
3	Insulation 1 Insulation 2	1.84 (4.06)	0.01 (0.00)	0.004 (0.00)

Table 11. Mean Mass Loss of Bundle 1

For the replicate tests described in the text, the mean mass loss for Bundle 1, and the standard deviation of those values, are given. The units are kilograms (pounds).

Mass loss data for the Nomex 1 and Nomex 2 deck panels, which were replaced after each test, are presented in Table 12. Nomex 3 was reused for all deck and insulation tests and, because it was never burned, is not included in the table. We should note that it was very difficult to obtain accurate post-test masses for the Nomex panels due to their disintegration during the test. An effort was made to collect and include the debris when weighing the panels, but some of the material, in the form of flakes and ashes, was inevitably lost. Accordingly, the post-test masses must be considered to be lower limits and, therefore, the mass losses, given in Table 13, have most likely been overestimated.

The insulation panels, Poly. 1 — 4, were virtually undamaged, except for scorch marks on the lowest panel. Accordingly, these panels were reused for all of the insulation tests and weight loss data for them has not been reported.

5.2.3 Environment

The environmental data were processed as described previously. However, in some cases, it was found that the results were very poor, either because of sensor malfunctions or because of extreme noise pickup. In order to address these issues, special processing procedures (listed in the tables included in Appendix C) were applied to selected data channels. Appendix D shows plots of the air temperatures, cable surface temperatures, gas concentrations and optical densities for all of the tests.

Typically, we found that the oxygen, carbon monoxide and carbon dioxide concentrations did not change much until the cable bundle ignited. As we have seen, there were wide variations in the cable ignition times and, as a result, test-to-test comparisons at specific test elapsed times are not meaningful. Instead, we time shifted the data displays to align data from corresponding times after the start of flaming combustion. After this correction, it became feasible to calculate

	Nomex 1 Mass [kg (lb.)]			Nomex 2 Mass [kg (lb.)]		
Test	**Pre-Test**	**Post-Test**	**Loss**	**Pre-Test**	**Post-Test**	**Loss**
Deck 1 *	5.51 (12.12)	4.32 (9.50)	1.19 (2.62)	5.51 (12.12)	5.11 (11.25)	0.40 (0.87)
Deck 2	5.77 (12.69)	5.45 (12.00)	0.32 (0.69)	5.80 (12.75)	5.80 (12.75)	0.00 (0.00)
Deck 3	5.85 (12.88)	4.55 (10.00)	1.30 (2.88)	5.80 (12.75)	5.80 (12.75)	0.00 (0.00)
Deck 4	5.85 (12.88)	5.37 (11.81)	0.48 (1.07)	5.77 (12.69)	5.82 (12.81)	-0.05 (-0.12)
Insulation 1	5.80 (12.75)	4.83 (10.62)	0.97 (2.13)	5.80 (12.75)	5.80 (12.75)	0.00 (0.00)
Insulation 2	5.82 (12.81)	4.91 (10.81)	0.91 (2.00)	5.82 (12.81)	5.82 (12.81)	0.00 (0.00)
Insulation 3	5.82 (12.81)	3.69 (8.12)	2.13 (4.69)	6.31 (13.88)	5.88 (12.94)	0.43 (0.94)
Insulation 4	6.31 (13.88)	4.12 (9.06)	2.19 (4.82)	6.34 (13.94)	4.95 (10.88)	1.39 (3.06)

Table 12. Mass Loss of Panels Nomex 1 and Nomex 2

Pre- and post-test weights and weight changes for the Nomex 1 and Nomex 2 panels are given for each of the tests that included a false deck. The units are kilograms (pounds).

* For this test, the mean sample weight, rather than actual weights, were used for the pre-test value.

		Nomex 1			Nomex 2		
Group	**Tests**	**Mass Loss [kg (lb.)]**	**SD [kg (lb.)]**	**Rel. SD**	**Mass Loss [kg (lb.)]**	**SD [kg (lb.)]**	**Rel. SD**
1	Deck 1 Deck 3 Deck 4	0.99 (2.19)	0.45 (0.98)	0.45 (0.45)	0.12 (0.25)	0.25 (0.54)	2.11 (2.16)
2	Insulation 3 Insulation 4	2.16 (4.76)	0.04 (0.09)	0.02 (0.02)	0.91 (2.00)	0.68 (1.50)	0.75 (0.75)
3*	Insulation 1 Insulation 2	0.94 (2.06)	0.04 (0.09)	0.05 (0.05)	0.00 (0.00)	0.00 (00.0)	--

Table 13. Mean Mass Loss of Nomex 1 and Nomex 2

For the replicate tests described in the text, the mean mass loss for Nomex 1 and Nomex 2 are given, along with the standard deviations of those values. The units are kilograms (pounds).

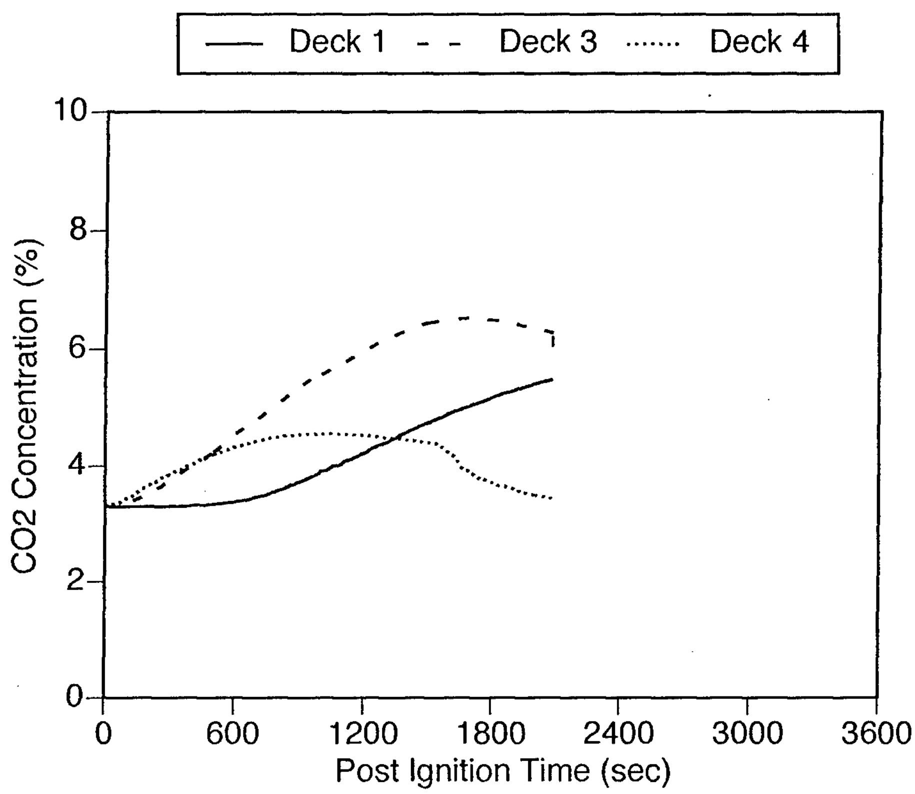

Figure 29. Comparison of CO_2 Concentrations for Group 1 Tests

After alignment of the cable ignition times at time zero, as discussed in the text, the carbon dioxide concentrations for the three Group 1 tests could be directly compared.

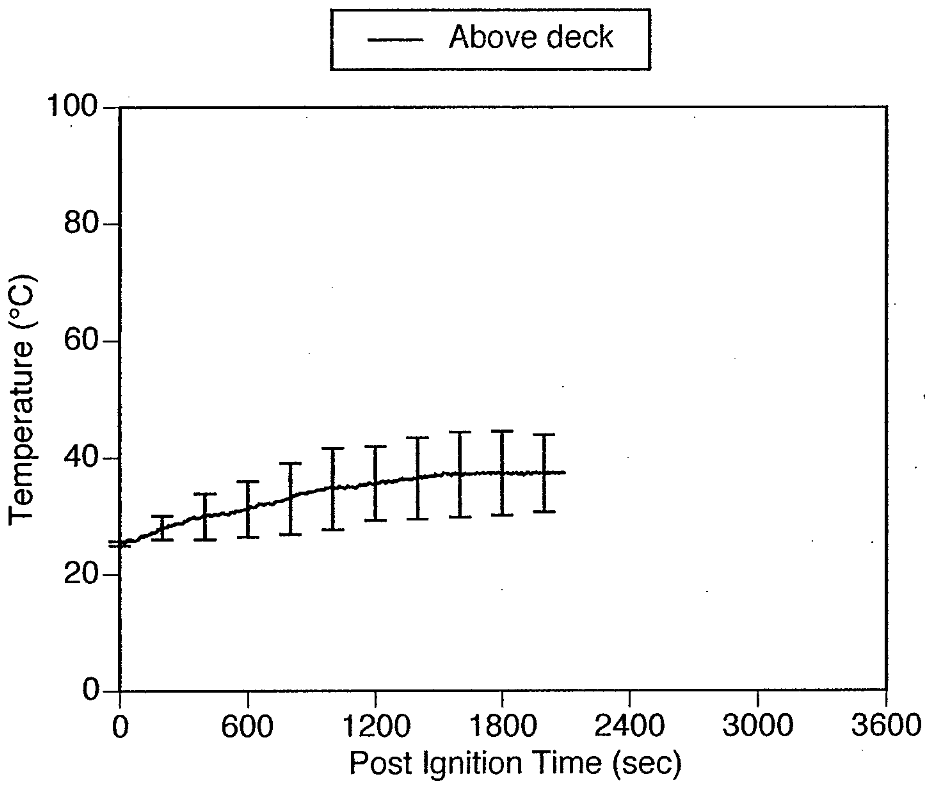

Figure 30. Mean CO2 Concentrations for Group 1 Tests

The mean carbon dioxide concentrations for the Group 1 tests, calculated from the data shown in the previous figure, are shown. The error bars represent one standard deviation.

meaningful average values for tests within each group. As an example, the individual Group 1 carbon dioxide concentrations, after alignment of the cable ignition times, are compared in Figure 29 and the resulting mean concentrations are shown in Figure 30.

In those cases in which the cables ignited, this time shifting procedure proved to be effective for analyzing air temperatures but not for optical transmission. Due to prolonged smoldering combustion, visibility was often seriously affected well before cable ignition and, as a result, the test start time proved to be a more meaningful reference. Of course, for those tests in which there were no cables (Spray Baseline test) or the cables never ignited (tests Cable 2 and Deck 2), time shifting of the data was neither necessary nor possible. Note that, in the figures, the horizontal axis is labeled "Post Ignition Time" for the time-shifted cases and "Elapsed Time" for the others.

5.3 Discussion

5.3.1 Cable 1, Group 1 and Group 3 tests

The Cable 1, Group 1 and Group 3 tests differed in fuel load, with Cable 1 having only cables, Group 1 having cables plus Nomex deck panels and Group 3 adding polyimide insulation to the mix. As seen from Figure 31, the air temperature error bars overlap for Group 1 and Group 3. Because the Cable 1 test was not replicated, it was not possible to calculate errors but, as seen in Figure 32, Cable 1 was also within the Group 3 error bars for most of the test (Group 1 data were left out of the figure for clarity).

Similar data for gas concentrations and optical transmission are shown in Figures 33 — 36. Again, the Group 1 and Group 3 tests have overlapping error bars and, except for carbon monoxide and transmission, the Cable 1 results are also within the error limits.

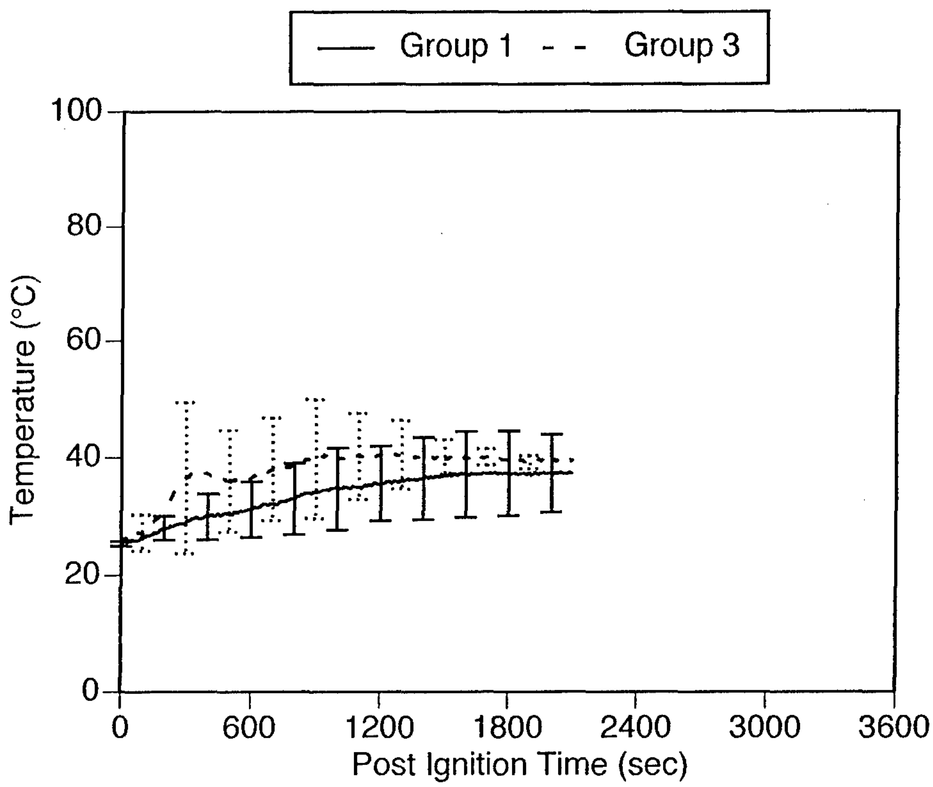

Figure 31. Above Deck Group 1 and Group 3 Air Temperatures

The mean above deck air temperatures from the Group 1 and Group 3 tests are shown. The error bars represent one standard deviation (solid bars correspond to Group 1; dotted bars to Group 3).

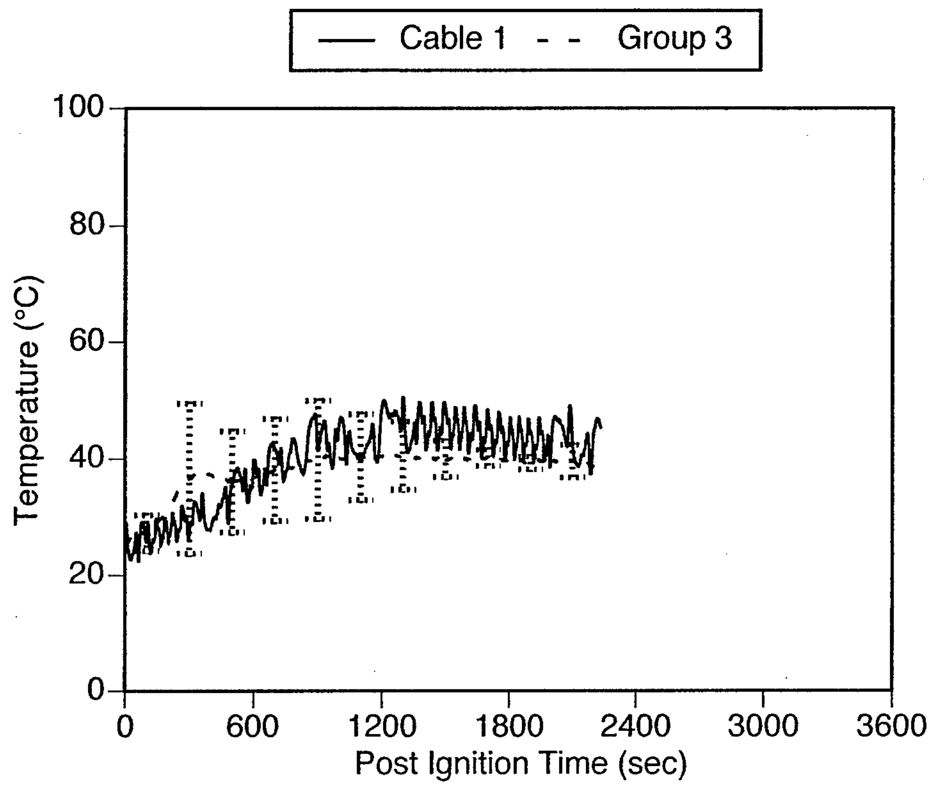

Figure 32. Above Deck Cable 1 and Group 3 Air Temperatures

The above deck air temperatures from the Cable 1 test are compared with those from the Group 3 tests. The dotted error bars represent one standard deviation for the Group 3 results; Cable 1 was a single test and, therefore, no errors could be calculated.

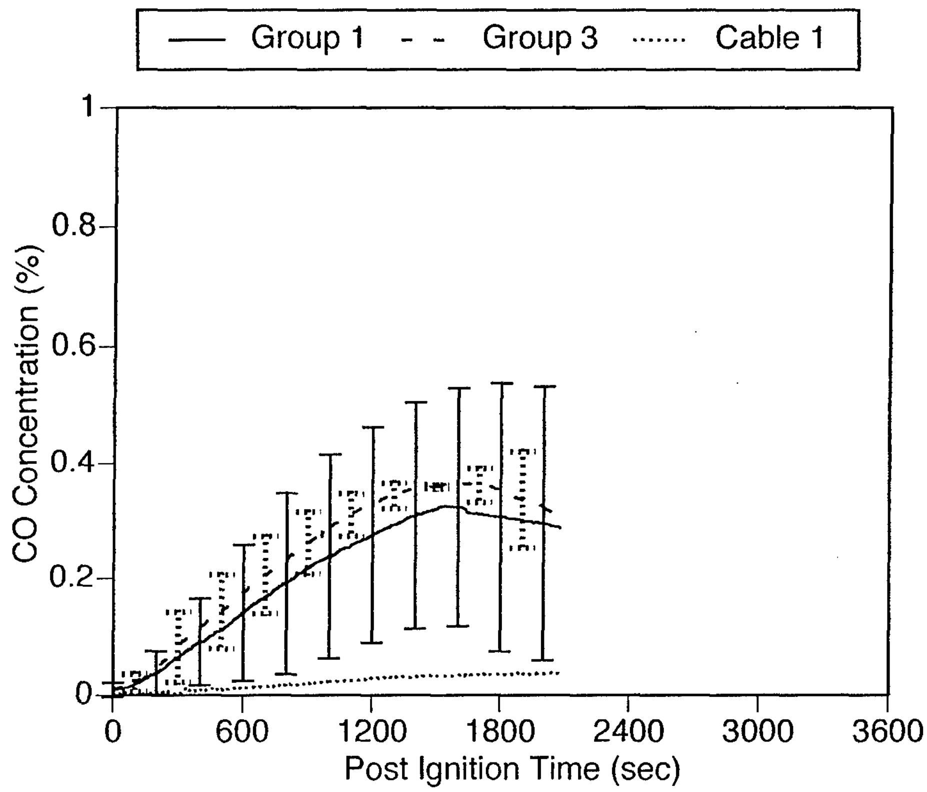

Figure 33. CO Concentrations for Group 1, Group 3 and Cable 1 Tests

Group 1 and Group 3 carbon monoxide concentrations were virtually indistinguishable, but the values from the Cable 1 test were much lower. The error bars represent one standard deviation (solid bars correspond to Group 1; dotted bars to Group 3).

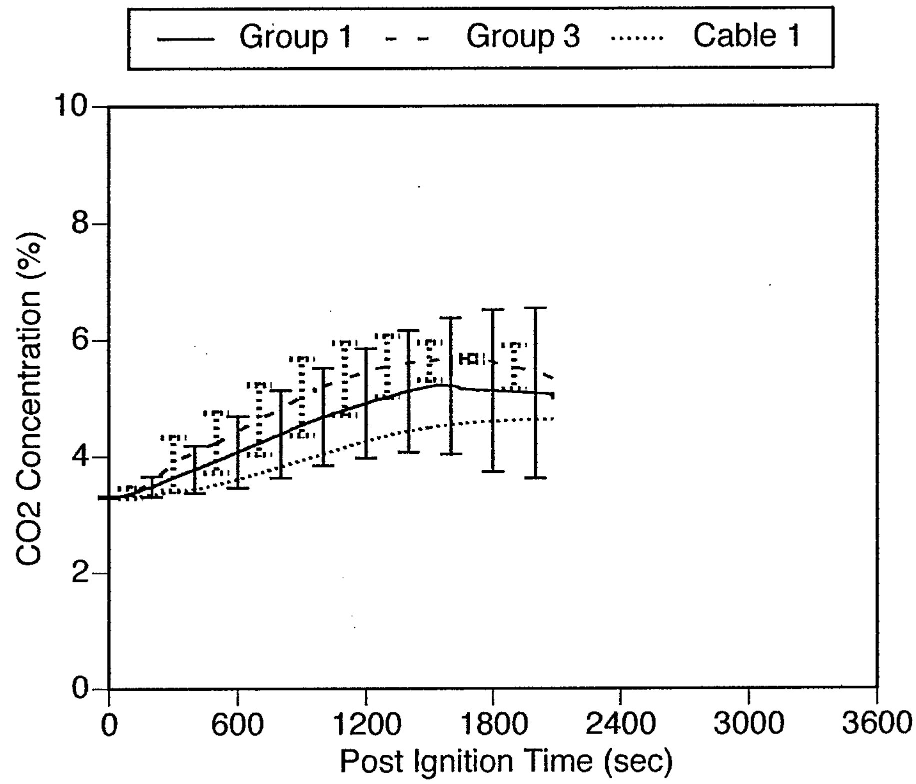

Figure 34. CO_2 Concentrations for Group 1, Group 3 and Cable 1 Tests

Carbon dioxide concentrations were very similar for Cable 1, Group 1 and Group 3. The error bars represent one standard deviation (solid bars correspond to Group 1; dotted bars to Group 3).

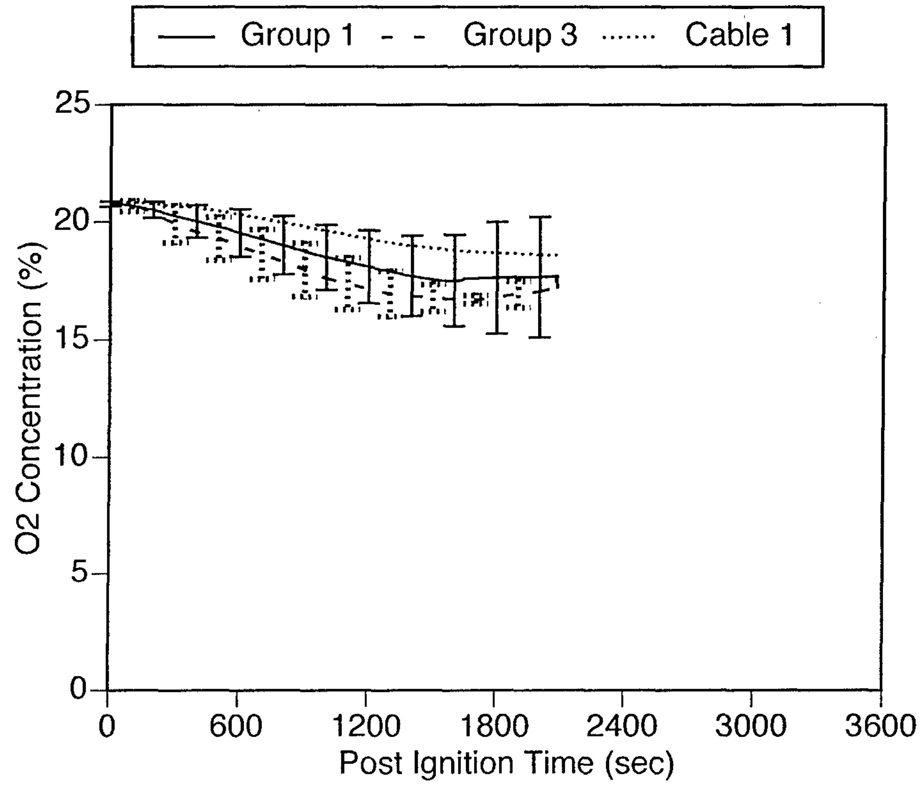

Figure 35. O_2 Concentrations for Group 1, Group 3 and Cable 1 Tests

Oxygen concentrations were also similar for all three sets of tests but Cable 1 was slightly higher than the other two. The error bars represent one standard deviation (solid bars correspond to Group 1; dotted bars to Group 3).

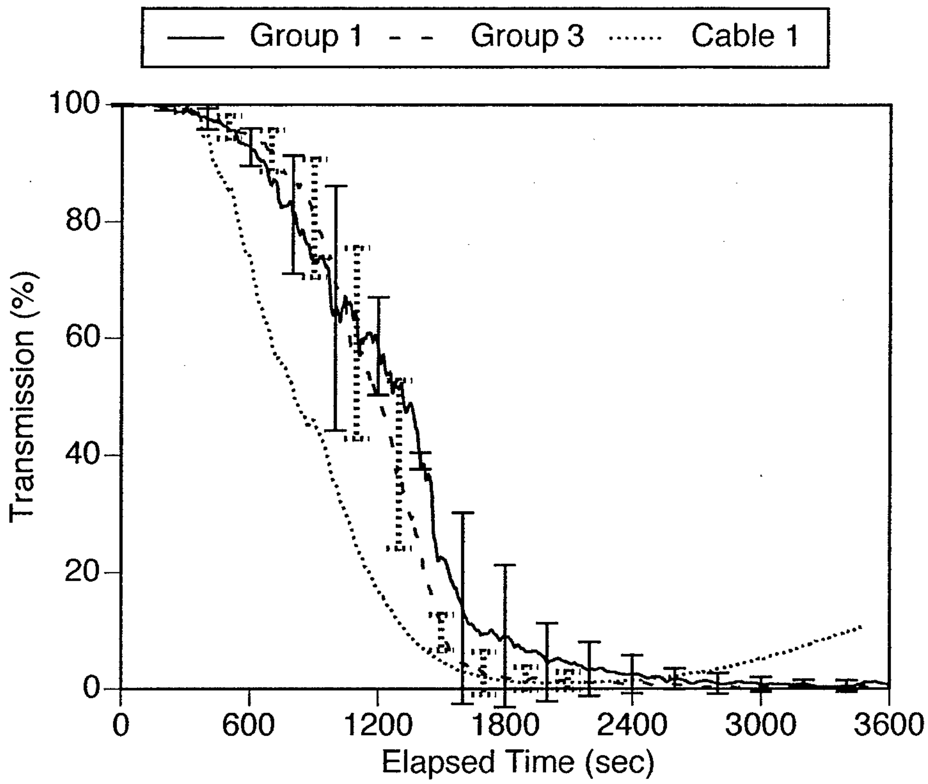

Figure 36. Optical Transmission for Group 1, Group 3 and Cable 1 Tests

Optical transmission was somewhat lower for Cable 1 than for Group 1 or Group 3. The error bars represent one standard deviation (solid bars correspond to Group 1; dotted bars to Group 3).

Based on the above, we conclude that the these tests are not significantly different in temperature effects or production of fire byproducts. It follows that the burning cables were the primary sources of thermal energy, toxic gases and smoke with the deck and insulation panels contributing little additional energy or combustion products. We note that the trends in oxygen consumption and carbon dioxide production are consistent — the Cable 1 test shows the lowest carbon dioxide production and the least oxygen consumption while the Group 3 tests are the opposite and the Group 1 tests are intermediate. However, due to the low significance of the observed differences, this effect may have been fortuitous.

It is not clear why the carbon monoxide concentrations were so much lower in Cable 1 than in the other two data sets, especially given the good inter-test agreement seen for oxygen and carbon dioxide. One possible explanation is that, due to the absence of deck panels in Cable 1, there would have been free circulation within the entire space whereas, for the Group 1 and Group 3 tests, free circulation would have been limited to the region below the false deck. As a result, a reasonable hypothesis is that the combustion efficiency was higher in Cable 1 and, therefore, that much less carbon dioxide was produced. This is supported by the observation that transmission declined more quickly during the Cable 1 test, which is consistent with greater circulation within the entire space.

5.3.2 Group 2 and 3 tests

The tests in Groups 2 and 3 involved the same fuel load but differed in their ignition sources, with the former using both electric heaters and a spray fire and the later using only heat rods. As you would expect, the air temperatures begin to climb at the start of the test in the Group 2 tests, due to the large (approximately 0.45 MW) spray fire whereas they remain essentially constant until the cable bundle ignition for the Group 3 tests. This effect is shown in Figure 37 (below-deck temperatures) and Figure 38 (above-deck temperatures). It is clear that the primary thermal source for the compartment is the external, rather than the internal, fire.

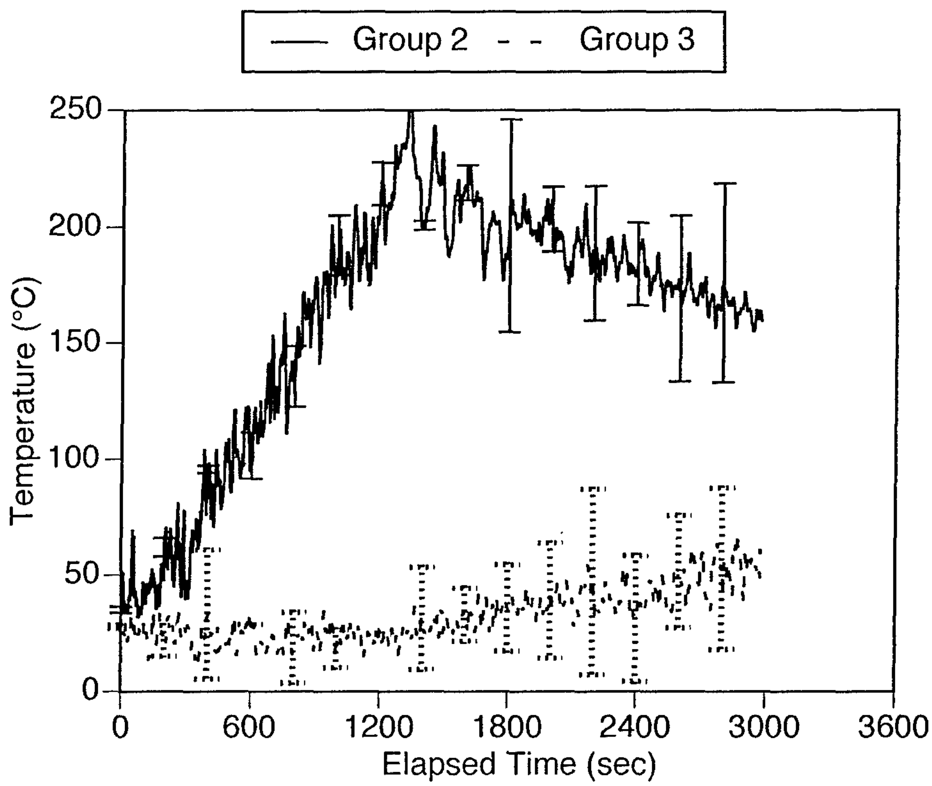

Figure 37. Below-Deck Temperatures for Group 2 and 3 Tests

In the Group 2 tests, temperatures begin to rise immediately after the spray fire is ignited at the start of the tests while, for Group 3 tests, there is little change until the cable bundles ignite. The error bars represent one standard deviation (solid bars correspond to Group 2; dotted bars to Group 3).

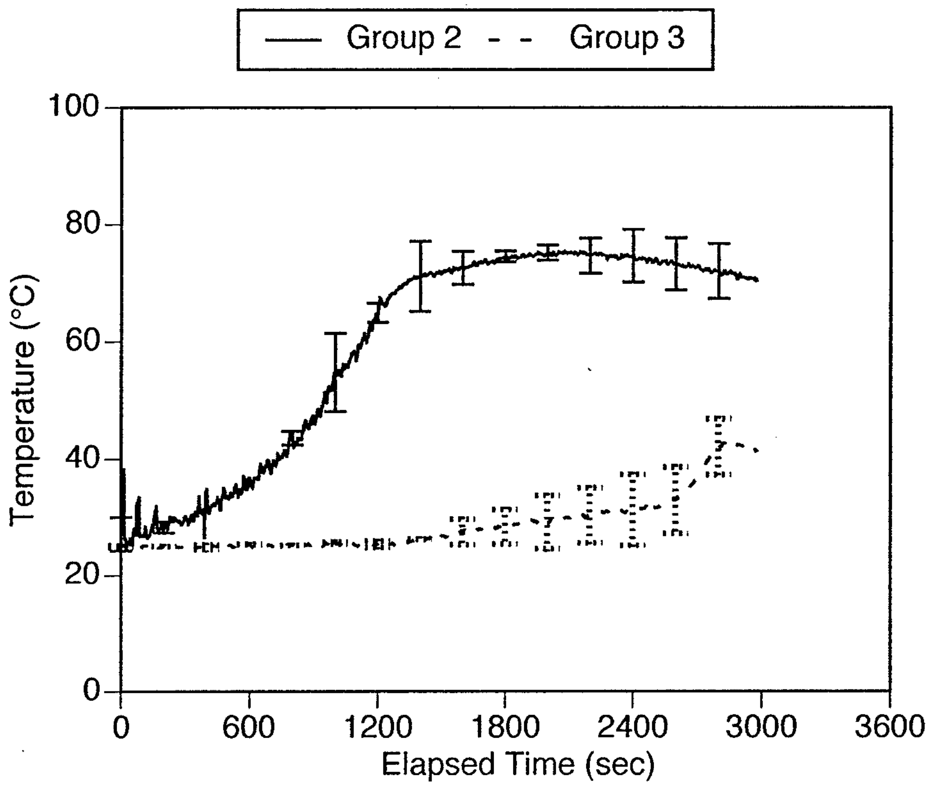

Figure 38. Above-Deck Temperatures for Group 2 and 3 Tests

The above-deck air temperatures behave in the same manner as the below-deck temperatures. The error bars represent one standard deviation (solid bars correspond to Group 2; dotted bars to Group 3).

The gas concentrations are compared in Figures 39 — 41 and we find that the Group 2 tests produced more carbon monoxide and carbon dioxide and consumed more oxygen than the Group 3 tests and, in Figure 42, we see that the optical transmission declined much earlier in the test for Group 2 than for Group 3.

There are two possible (not mutually exclusive) explanations for these effects: the spray fire may have contributed significantly to the production of toxic gases and the consumption of oxygen or the more severe thermal conditions in the below-deck area during spray fires may have magnified the effects of the smoldering cables. Based only on evidence from the Group 2 and 3 tests, we can not distinguish between these hypotheses but data from the Spray Baseline test does permit the question to be resolved, as discussed below.

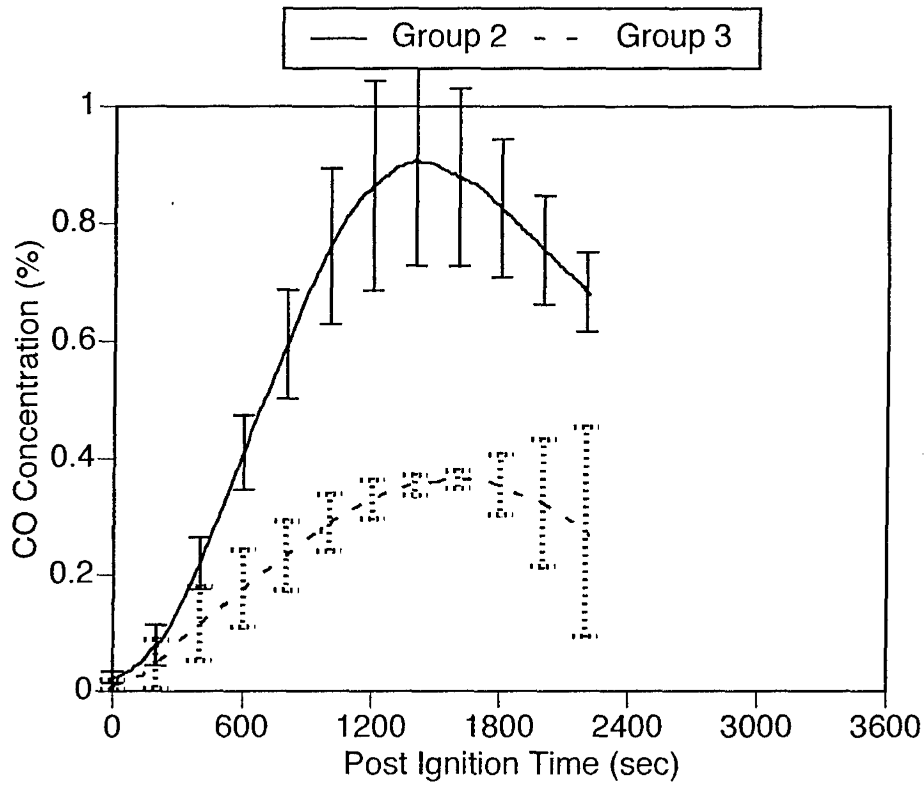

Figure 39. CO Concentrations for Group 2 and 3 Tests

The error bars represent one standard deviation (solid bars correspond to Group 2; dotted bars to Group 3).

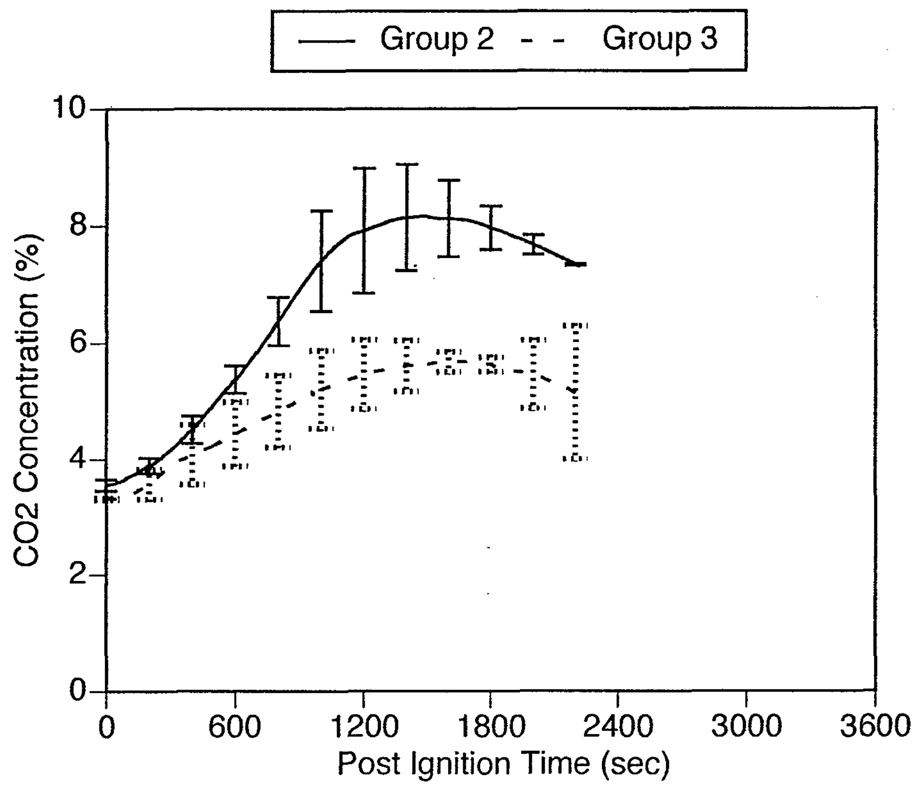

Figure 40. CO_2 Concentrations for Group 2 and 3 Tests

The error bars represent one standard deviation (solid bars correspond to Group 2; dotted bars to Group 3).

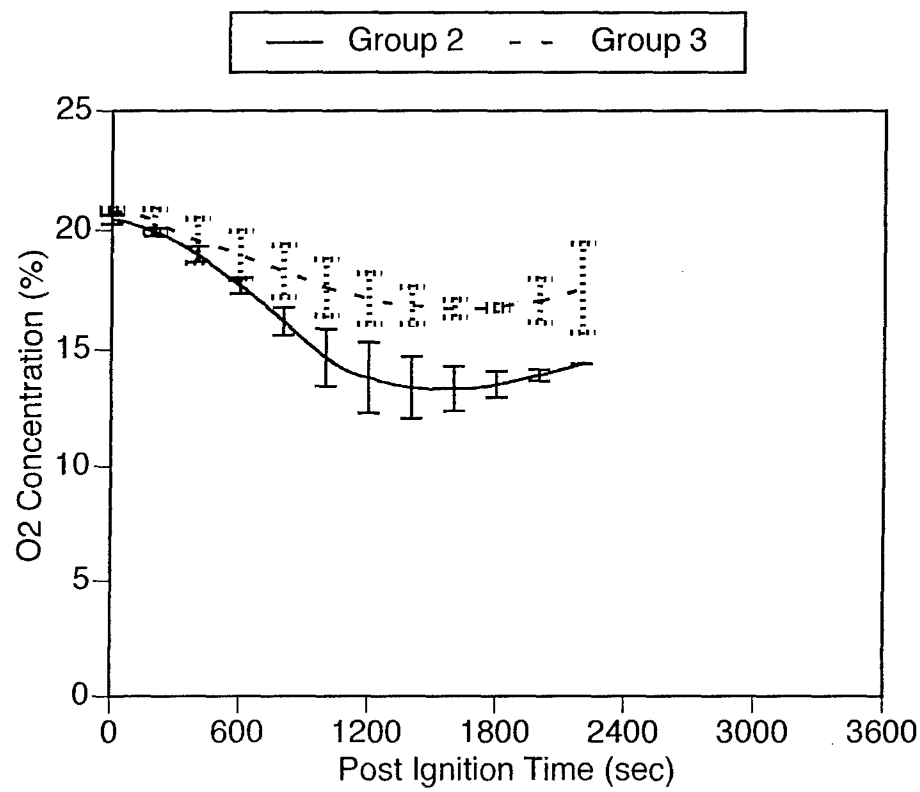

Figure 41. O_2 Concentrations for Group 2 and 3 Tests

The error bars represent one standard deviation (solid bars correspond to Group 2; dotted bars to Group 3).

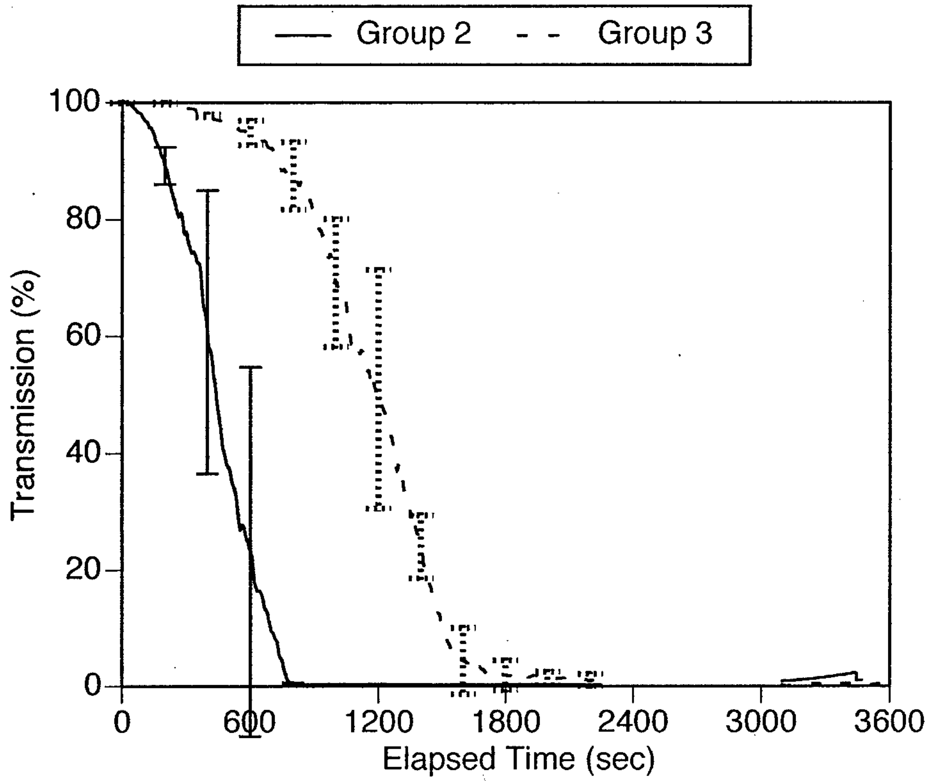

Figure 42. Optical Transmission for Group 2 and 3 Tests

The error bars represent one standard deviation (solid bars correspond to Group 2; dotted bars to Group 3).

5.3.3 Spray Baseline and Group 2 tests

The Spray Baseline test differed from the Group 2 tests in that the there were no combustible materials present in the former. By comparing these data sets, we may estimate the contribution due to the spray fire alone. Because there was no cable ignition in the baseline test, it was not possible to use the time shift procedure described above and, in order to make the data comparable, the Group 2 data was also not shifted.

Figures 43 and 44 compare the Baseline and Group 2 air temperatures (below- and above-deck, respectively). We see that the temperatures track very closely during the early portions of the tests and begin to deviate after the cables ignite, with the Group 2 temperatures greater than those from the Spray Baseline. The differences are noticeable, but not very great (on the order of 25 °C), indicating that the spray fire is the primary driver for the compartment temperatures and that the cable fire provides a relatively small additional contribution.

In contrast to the temperatures, the concentrations of carbon monoxide, carbon dioxide and oxygen in the Spray Baseline test were essentially constant during the spray fire, as seen in Figures 45 — 47. Transmission (Figure 48) behaved similarly, except the spray fire made a greater contribution than it did for the three gases. This indicates that the atmospheric composition was primarily controlled by the cable fire, with relatively little contribution from the spray fire. Because optical transmission is very sensitive to even tiny quantities of particulate matter, a small amount of smoke from the spray fire and circulated through the vents had a disproportionate effect on visibility.

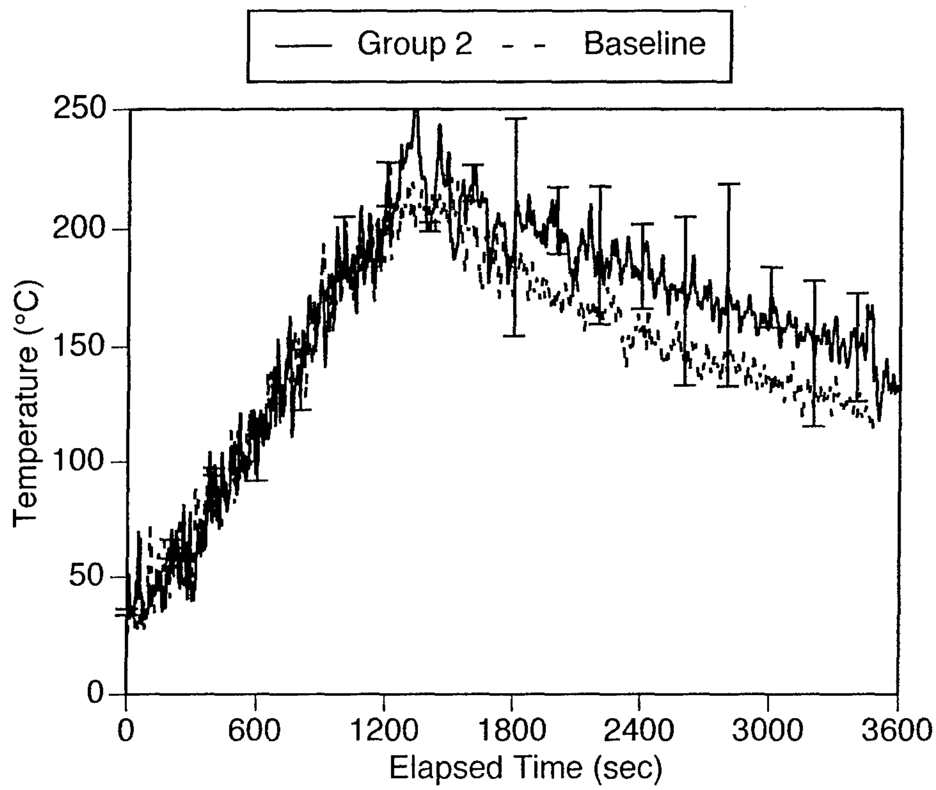

Figure 43. Below-Deck Temperatures for Spray Baseline and Group 2 Tests

For Group 2 and the Baseline tests, the below-deck temperatures were essentially identical up to the time at which the spray fire was secured (approximately 1300 seconds) but cooling was slightly faster for the Baseline case. The error bars represent one standard deviation.

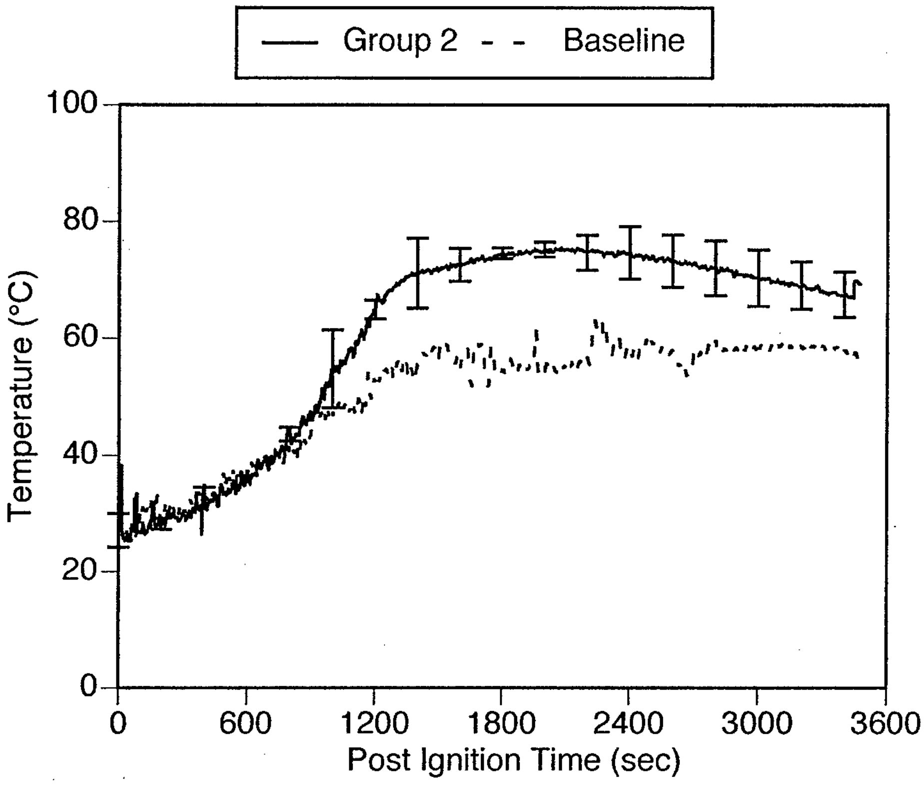

Figure 44. Above-Deck Temperatures for Spray Baseline and Group 2 Tests

The above-deck temperatures for the Group 2 tests began to deviate somewhat from the Baseline case slightly before the spray fire was secured (approximately 1300 seconds). The error bars represent one standard deviation.

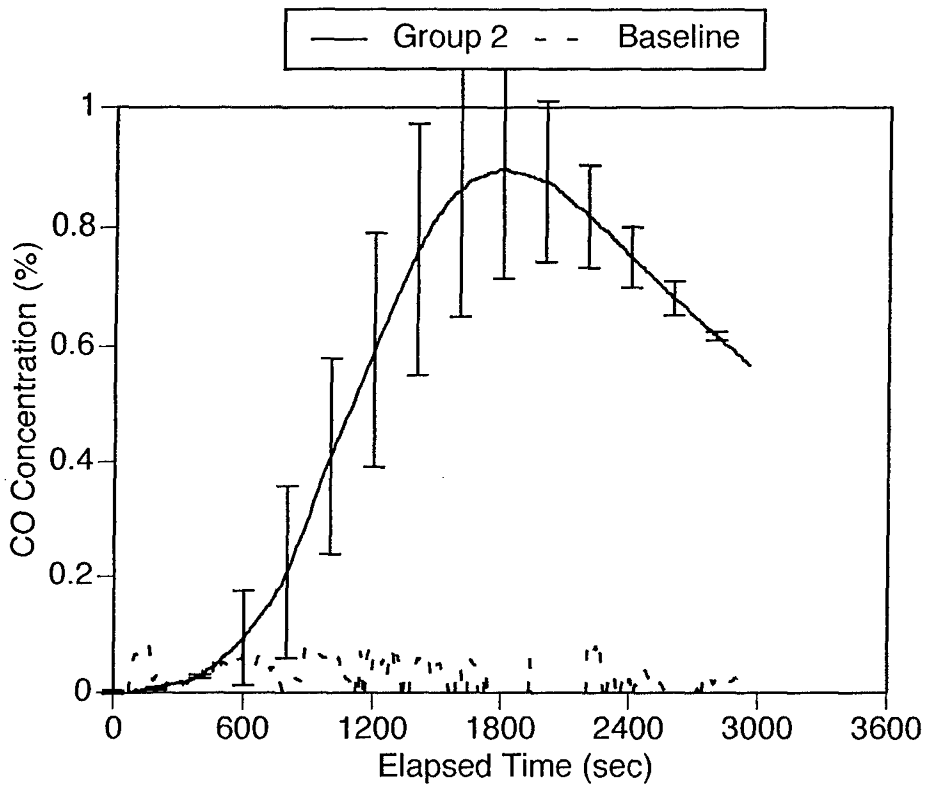

Figure 45. CO Concentrations for Spray Baseline and Group 2 Tests

The error bars represent one standard deviation.

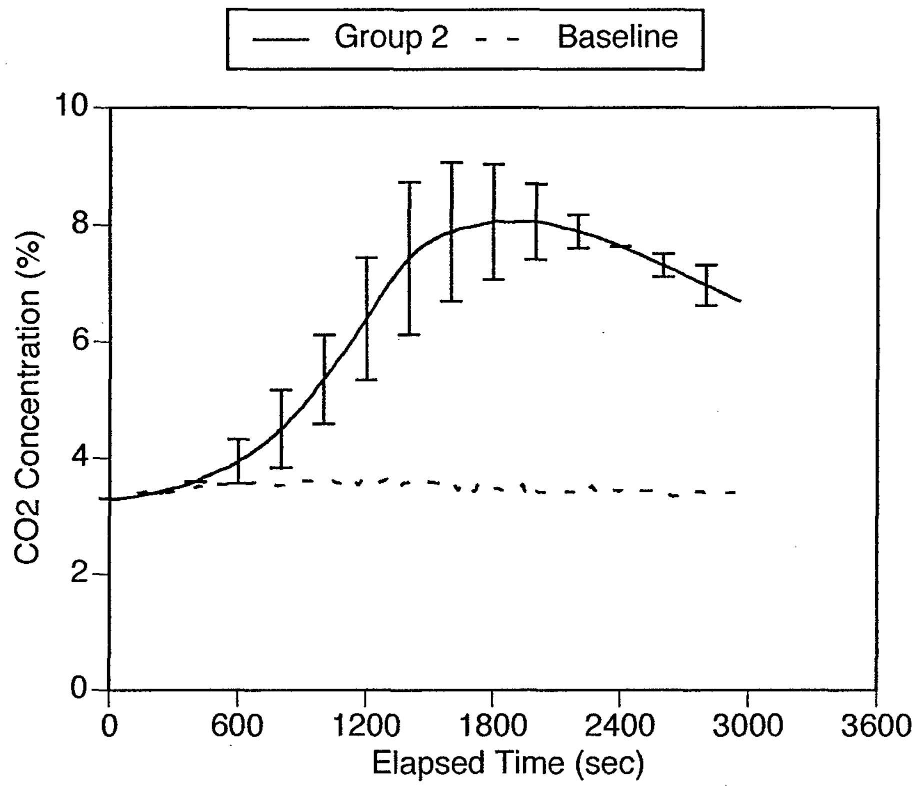

Figure 46. CO_2 Concentrations for Spray Baseline and Group 2 Tests

The error bars represent one standard deviation.

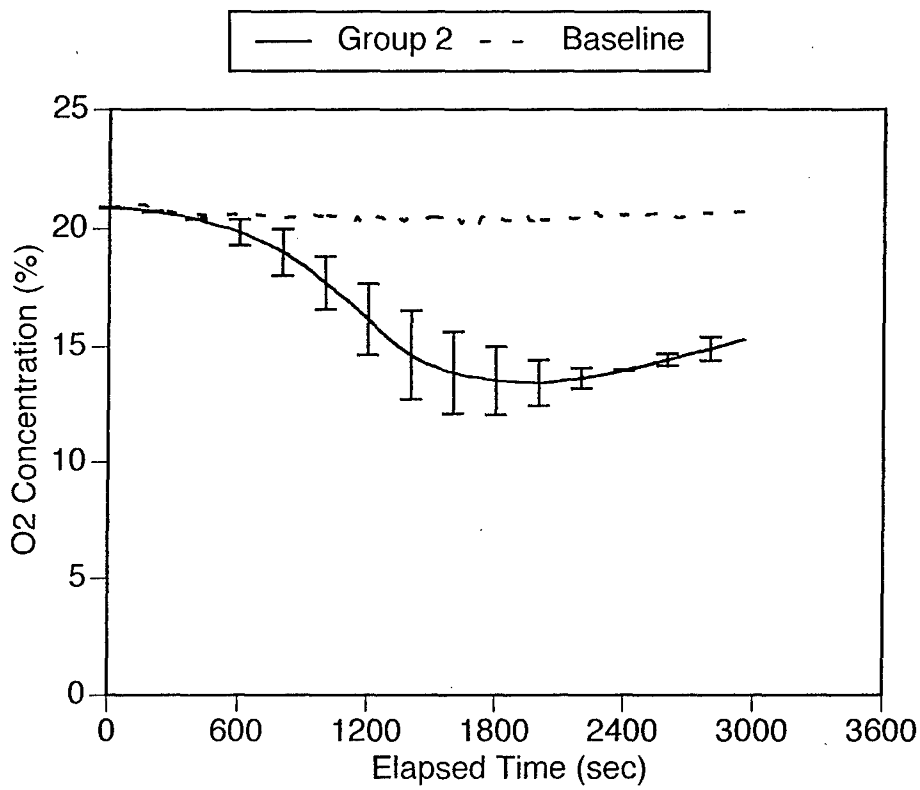

Figure 47. O_2 Concentrations for Spray Baseline and Group 2 Tests

The error bars represent one standard deviation.

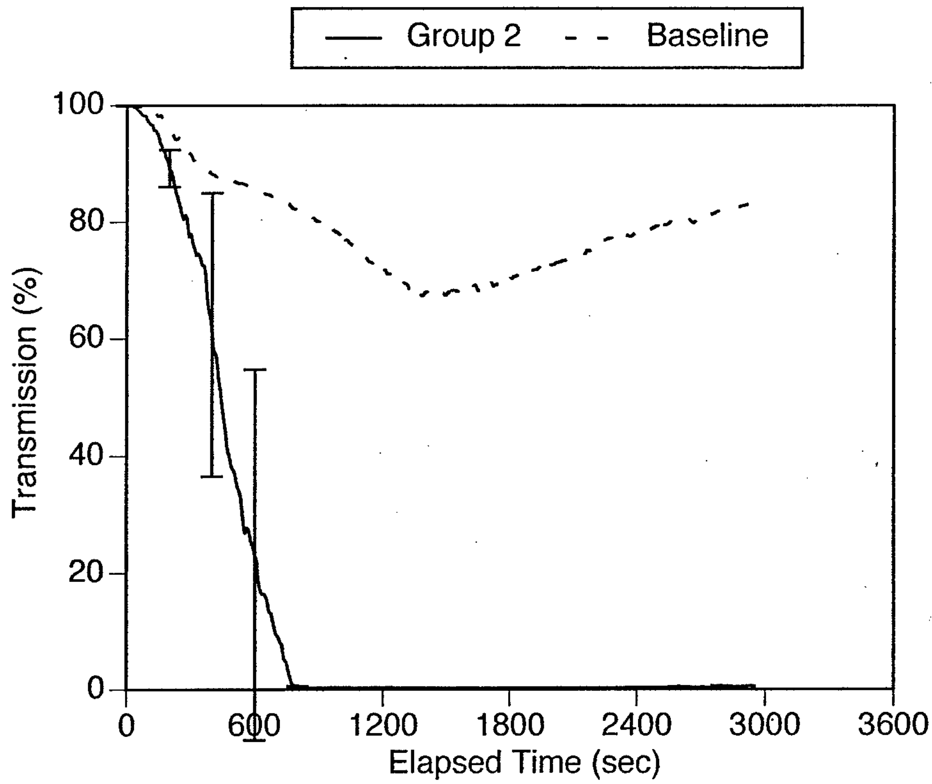

Figure 48. Optical Transmission for Spray Baseline and Group 2 Tests

Transmission was more strongly effected by the spray fire than were the gas concentrations shown in previous figures. The error bars represent one standard deviation.

As mentioned in the discussion of the Group 2 and 3 comparison, that data suggested that either the spray fire made a significant contribution to the production of toxic gases and consumption of oxygen or the higher temperatures in the below-deck area led to greater production of fire products and greater oxygen depletion. Based on the additional information obtained from this comparison of the Spray Baseline with the Group 2 tests, it is clear that the spray fire did not contribute significantly to the production of carbon monoxide and carbon dioxide or to the oxygen depletion while it did have a noticeable, but not controlling, effect on optical transmission. Thus, we can rule out the first hypothesis and conclude that the effects of the spray fire on the compartment atmosphere were primarily due to the higher temperatures to which the cables were exposed. This led to a longer, more severe smoldering period during which the cables produced increased quantities of carbon monoxide, carbon dioxide and smoke and consumed a larger quantity of oxygen.

6.0 CONCLUSIONS

The most important conclusions from these tests are that the current materials used for shipboard cable insulation, false deck panels and thermal/acoustic insulation are remarkably fire resistant.

We were unable to ignite the cables using a single, 0.9 kW electric heater (test Cable 2) and, in test Deck 2, they did not ignite even with two heaters (approximately 1.8 kW) in direct contact with the cable insulation.

In the other tests using only electric heaters, the time to cable ignition was highly variable, ranging from 478 to 3480 seconds. The ignition times were highly dependent on random variables, such as the location and of the heat source and the specific type of cables with which it is in contact, even when the fuel load, fire geometry and ignition conditions were carefully controlled. In addition, the cable fires self-extinguished after the ignition source was secured. For the tests in which the only ignition sources were the electric heaters, the average extinguishment time was slightly over eight minutes while the average for the spray fires was more than three times longer (see Table 8 and compare the burnout times with the times at which ignition was secured). It should be noted that, for much of the time after the ignition was secured, the only visible flames appeared to be due to puddles of melted insulation. The extended extinguishment times for the spray fire cases were most likely due to the larger amount of cable insulation that had melted and accumulated on the deck.

We found that the second cable bundle never ignited, even though is was located about 0.5 m (20 in.) from the first and was exposed to the flames form the first bundle. Also, although a Nomex panels was located directly above Bundle 1, within the flames from the cable fire, this panel warped, charred and delaminated, but did not ignite. The other deck panels were only slightly damaged, primarily at the edge closest to the fire. Similarly, the polyimide insulation was discolored, but not significantly damaged, along the lower edge.

For most tests, the temperatures in the above-deck space were low enough that it would have been survivable. Even in the worst cases (Group 2 spray fire tests), the air temperature only reached about 75°C (167 °F). However, the visibility in the space was significantly degraded, even prior to ignition of the cables, and the atmosphere reached hazardous levels of carbon monoxide, carbon dioxide and oxygen due to the byproducts of the cables. Therefore, even in the absence of extreme temperatures, the space would not have been habitable for unprotected personnel.

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ACKNOWLEDGMENTS

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APPENDIX A Test Procedures

The procedures for the electronic space materials tests are given in this appendix. They have been divided into sections, depending on the when the procedures were carried out.

CONTENTS

I. Site Startup

A. Power and Instrument Sheds

1. Turn on circuit breaker C1 in the power shed.
2. Turn on camera power supply in the instrument shed.

B. Control Trailer

1. Turn on power strip below SCXI chassis.
   a. Verify that SCXI chassis is on (should always be left on).
   b. Verify that 15 volt camera power supply below the splitter box is on (should always be left on).

2. Turn on 12 volt rack-mount power supply below computer.

3. Activate ventilation
   a. Turn on supply and exhaust power on control panel.
   b. Open supply and exhaust dampers and wait for "Open" lights to illuminate.
   c. Turn on supply and exhaust fan power.

4. Turn on computer
   a. Turn on UPS below desk.
   b. Boot up computer.

5. Set radiometer purge pressure
   a. Close needle valve on nitrogen purge gas cylinder.
   b. Open main valve on nitrogen purge gas cylinder.
   c. Verify that there is sufficient pressure (typically, a minimum of several hundred psi).
   d. Adjust second stage pressure on nitrogen purge gas cylinder to ~10 psi.

II. Weekly Setup

A. Pre-calibrate gas analyzers

Note: This procedure sets up the main gas flow rate and needs to be repeated if the main gas rotameter setting is changed!

1. For all loops to be used, set the mode selector values to the "Analyze" position.
2. For all loops to be used, open the green Nupro valves.
3. Close the drain valves on the outside rear wall of the instrument shed.
4. Verify that the cold traps are capped and placed in the coolers.
5. Verify that the drains on the traps mounted on the inside rear wall of the instrument and power sheds are closed.
6. Add ice to the cold trap coolers.
7. Verify that all pump valves are in the pump position (pointed down).
8. Turn on the gas sampling pump circuit breaker (PS1).
9. Adjust the main flow rotameters to ~40 SCFM (some loops will not go over ~30).
10. Turn off the gas sampling pump circuit breaker (PS1).
11. Close the green Nupro valves for all loops.
12. For all loops to be used, set the mode selector valves to the "Calibrate" position.

III. Daily Setup

A. Check cold traps

1. Verify that the cold traps have drain caps in place and place them in the coolers, if not done as part of the weekly setup.
2. Add ice to the cold trap coolers, if not done as part of the weekly setup.

B. Check gas sampling pumps (if not done as part of the weekly setup)

1. Verify that all pump valves are in the pump position (pointed down).
2. Verify that the cold traps are capped and placed in the coolers.
3. Add ice to cold trap coolers.

C. Turn on gas analyzer calibration gases

1. Verify that the calibration gas selector (bottom of gas panel) is set to "Nitrogen"
2. Close the green Nupro valves for all loops.
3. For all loops to be used, set the mode selector valves to the "Calibrate" position.
4. Set the Wilkes rotameters to zero flow.
5. Open main valves on nitrogen, air and CO/CO_2 calibration gas cylinders.
6. Verify that there is sufficient pressure in all calibration gas cylinders (typically, a minimum of several hundred psi).
7. Open needle valves on all calibration gas cylinders.
8. Verify that second stage pressures are set to ~40 psi on all calibration gas regulators.

D. Calibrate gas analyzers

1. Adjust the MLT-1 rotameters to 1 lpm and flow gas for several minutes (until the gas concentration readings are stable).
2. Zero each analyzer
   a. Select the CO single gas display.
   b. Press: Main > Analyzer and I/O > Analyzer Module Controls > Calibration Parameters > Advanced Calibration Methods > Start Zero Calibration for all Channels.
   c. Wait for completion of zero operation and press "Measure" — all Function Control entries ("Function Control", "Maintenance

Requests" and "Failures") should be "No" on the single gas display

Note: May have to wait for Function Control to change from "Yes" to "No"

d. Verify that the analyzer reads approximately zero.

e. Repeat for remaining analyzers.

3. Set the gas selector valve to the "Air" position.

4. Adjust the MLT-1 rotameters to 1 lpm and flow gas for several minutes (until the gas concentration readings are stable).

5. Span each analyzer for oxygen.

   a. Select the O_2 single gas display.

   b. Press: Basic Cal > Start Span Calibration and press "Enter" to start the calibration.

   c. Wait for completion of span operation (procedure status should read "Ready").

   d. Repeat for remaining analyzers.

6. Set the gas selector valve to the "CO/CO_2" position.

7. Adjust the MLT-1 rotameters to 1 lpm and flow gas for several minutes (until the gas concentration readings are stable).

8. Span each analyzer for CO.

   a. Select the CO single gas display.

   b. Press: Basic Cal > Start Span Calibration and press "Enter" to start the calibration.

   c. Wait for completion of span operation (procedure status should read "Ready").

   d. Repeat for remaining analyzers.

9. Span each analyzer for CO_2.

   a. Select the CO_2 single gas display.

   b. Press: Basic Cal > Start Span Calibration and press "Enter" to start the calibration.

   c. Wait for completion of span operation (procedure status should read "Ready").

   d. Repeat for remaining analyzers.

10. Set displays to multiple gas display.

11. Set the gas selector valve to the "Nitrogen" position.

E. Turn off gas analyzer calibration gases.

1. Close main valves on air and CO/CO_2 gas cylinders.

F. Setup Video

1. Turn on VCR and load tapes.
2. Verify VCRs are in "EP" mode.
3. Set date-time generators to current date and time (if necessary).

G. Setup Safety Systems

1. Turn hydrant on.
2. Test hoseline and deploy at side door.
3. Check extinguishers and deploy at double doors.

H. Start LabVIEW software

1. Open Menu.vi and click "Run" button.

IV. Test Setup

A. Replace consumables

1. For cable fires

   a. Install Cable 1 bundle on cable tray

   b. Test and install hot rods in Cable 1 bundle (if needed for test).

   c. Verify thermocouple on hot rods.

   d. Install thermocouple on exterior of Cable 1 bundle.

   e. Replace Cable 2 bundle, if necessary.

   f. Replace thermocouple on exterior of Cable 2 bundle, if necessary.

2. For deck panel fires

   a. Install deck panels in positions 1 and 2.

   b. Replace deck panel in positions 3, if necessary.

3. For insulation fires

   a. Replace insulation panels, if necessary.

4. Replace inert deck panels, as necessary.

5. Photo document the fuel load.

B. Set switches to initial (safe) positions

1. Turn on room light.
2. Turn on room camera.
3. Turn on sub-floor light.
4. Turn on above- and below-deck cameras.
5. Turn off flow instrument power.
6. Turn off ODM instrument power.
7. Turn off fuel pressure transducer.
8. Turn off igniter power.
9. Turn off hot rod 1 power.
10. Turn off hot rod 2 power.
11. Turn off fuel pump power.
12. Turn off fuel pump kill switch.

C. Check Instruments

1. ODM

   a. Turn on ODM power.

   b. Verify ODM output with no obstruction (should be ~ 5 volts).

   c. Clean ODM optics, as necessary.

   d. Verify ODM output with total obstruction (should be ~ 0 volts).

   e. Turn off ODM power.

2. Radiometers

   a. Clean radiometer optics.

D. Check Ignition Systems

1. For pan fires

   a. Verify spark igniter function.

2. for spray fires

   a. Verify spark igniter function.

   b. Turn on fuel pump circuit breaker.

   c. Turn on remote manual fuel pump switch.

   d. Verify fuel pump operation.

E. Setup Instruments

1. Activate gas analyzers

   a. For all loops to be used, set the mode selector valves to the "Analyze" position.

   b. For all loops to be used, open the green Nupro valves.

   c. Turn on the gas sampling pump circuit breaker (PS1).

   d. Adjust MLT-1 rotameters to 1 lpm.

2. Turn on flow, ODM and fuel pressure instrument power.

3. Open radiometer cooling water valve.

4. Open radiometer purge gas needle valve.

5. For pan fires

   a. Pour fuel into pan.

b. Install Levenberry igniter between the arc igniter electrodes[2].

c. Log quantity of fuel used.

6. Secure Water Tight Door

7. Place chains and warning signs on all enclosure doors

F. Setup LabVIEW system

1. Click "Configure Data Acquisition" button.
2. Select folder for test series (which must contain the appropriate ini files).
3. Click on "Run Acquisition" button to continue.
4. Create new folder for the test.
5. Wait for completion of preprocessing ("Continue..." button will become active when ready).
6. Reset stop watch to zero.

G. Check control panel

1. Verify that the room light is on.
2. Verify that the room camera is on.
3. Verify that the sub-floor light is on.
4. Verify that the above- and below-deck cameras are on.
5. Turn on flow instrument power.
6. Turn on ODM instrument power.
7. Turn on fuel pressure transducer.

[2] A Levenberry igniter is a twist tie, bent so that it is self-supporting and acts as a wick.

V. Test Execution

A. Complete the test checklist.

B. Start Data Acquisition

1. Push "Record" buttons on VCRs.
2. Click LabVIEW "Continue..." button and start stop watch.
3. Run background acquisition (normally, two minutes).
4. Log background O_2, CO and CO_2 for reentry.

C. Ignite Fires

1. For pan fires
    a. Turn on spark igniter.
    b. Secure spark igniter immediately upon ignition of pan.
2. For spray fires
    a. Turn on fuel pump power and kill switch.
    b. Turn on spark igniter.
    c. Secure spark igniter immediately upon ignition of spray.
3. For internal ignition cable fires
    a. Turn on power to hot rod(s).
4. Secure exhaust ventilation at fire detection.

D. Secure Ignition Source (per test plan)

1. For spray fires
    a. Turn off fuel pump power.
    b. Turn off fuel pump kill switch.
2. For internal ignition cable fires
    a. Turn off power to hot rod(s)

VI. Post Test

A. Secure Instruments

1. Turn off room camera.
2. Turn off room light.
3. Turn off sub-floor light.
4. Turn off above- and below-deck cameras.
5. Turn off flow instrument power.
6. Turn off ODM instrument power.
7. Turn off fuel pressure transducer.
8. Turn off VCRs.
9. Close radiometer purge gas needle valve.
10. Close radiometer cooling water valve.

B. Ventilate Test Compartment

1. Ventilate for minimum time, as specified in the test plan (typically, 30 min)
2. Verify safe conditions (log measurements on the test data sheet)
   a. Temperature ≤ 35 °C (as measured by thermocouple trees)
   b. oxygen ≥ 19% (as measured by gas analyzers)
   c. carbon monoxide ≤ 0.001% (as measured by gas analyzers)
   d. carbon dioxide ≤ 0.5% (as measured by gas analyzers)
   e. hydrogen cyanide ≤ 5 ppm (as measured by Draeger tubes)
   f. log concentration values

Note: HCN measurement is only required during the initial cable tests to adjust and validate the minimum ventilation time. Subsequent tests will rely on the validated ventilation time.

3. Open Water Tight Door
4. Secure gas analyzers
   a. Turn off the pump circuit breaker (PS1).
5. Photo document post-fire state of test compartment.

VII. Daily Shutdown

A. Stop LabVIEW software

1. Click “Quit” button, then stop Menu.vi and quit LabVIEW.

B. Secure Safety Systems

1. Turn hydrant off.
2. Bleed hoseline and stow outside the enclosure.
3. Stow extinguishers inside the enclosure.
4. Remove chains and warning signs on all enclosure doors.

C. Secure Video

1. Turn off VCR and monitors

D. Turn off gas analyzer calibration gases

1. Verify that the green Nupro valves are closed and that the mode selector valves are set to the “Calibrate” position.
2. Open MLT-1 rotameters to bleed gas lines.
3. Verify that the calibration gas selector (bottom of gas panel) is set to the “Nitrogen” position.
4. Adjust MLT-1 rotameters to set nitrogen flow to trickle.

VIII. Site Shutdown

A. Gas Sample Loops

1. Purge gas analyzer loops

a. With pumps running, open the drain valves at the outside rear of the instrument shed.

Warning: Water and other materials may spray from the valve!

b. Remove cold traps from coolers and open drain plugs.

Warning: Water and other materials may spray from the drains!

c. Turn off the pump circuit breaker (PS1)

2. Blow down gas sampling lines

Note: This may have to be done more often than once per day!

a. Turn on the air compressor circuit breaker (PS2).

b. Turn the pump valves to the blow down position (horizontal).

c. Turn on the compressor (red switch) and allow the pressure to build to ~80 psi.

d. Open the two-way valve at the compressor.

e. Open all two-way valves on the wall-mounted water traps.

f. For each loop, turn the three-way valve to point up and purge for several minutes.

g. Close the two-way valves on the wall-mounted water traps.

h. For each loop, turn the three-way valve to point up, purge for several minutes and then turn the three-way valve to horizontal.

i. Turn off the air compressor (red switch).

j. Open the drain valve on the bottom of the compressor.

k. Close the two-way valve on the compressor and allow the pressure to bleed off.

l. Turn off the air compressor circuit breaker (PS2).

m. Close the drain valve on the bottom of the compressor after the pressure has bled off.

B. Control Trailer

1. Secure Analyzers

a. Close the green Nupro valves.

b. Set the mode selector valves to the "Calibrate" position.

c. From the main menu, press "Select" twice to get to the single gas display.

d. Reduce display intensity (Select > Main > Display Controls > Brightness ~20%; Contrast ~ 20%).

e. Press "Enter" to retain the reduced brightness

f. Select Contrast and use the down arrow key to turn the contrast all the way down

g. Press "Enter" to retain the reduced contrast

h. Press "Display" to return to the main menu

i. Set displays to multiple gas display (Measure).

2. Turn off gas analyzer calibration gases

a. If the site is to be shut down for a long period, close the main valve on the nitrogen cylinder.

b. Set the calibration gas selector (bottom of gas panel) to air and allow the air regulator to bleed down.

c. Set the calibration gas selector (bottom of gas panel) to CO/CO_2 and allow the CO/CO_2 regulator to bleed down.

d. Set the calibration gas selector (bottom of gas panel) to nitrogen.

e. If the site is to be shut down for a long period, allow the nitrogen regulator to bleed down; otherwise, adjust the MLT-1 rotameters to a trickle flow of purge gas.

f. Close the needle valves on the air and CO/CO_2 cylinders.

g. If the site is to be shut down for a long period, close the needle valve on the nitrogen cylinder; otherwise, leave it open to provide a minimal flow of purge gas.

3. Shutoff radiometer purge cylinder

a. Close main valve on nitrogen purge gas cylinder.

b. Allow nitrogen purge gas second stage pressure to bleed off.

c. Close nitrogen purge gas needle valve.

4. Turn off computer

a. Shutdown computer.

b. Turn off UPS below desk.

5. Secure ventilation

a. Turn on supply and exhaust fan power on control panel.

b. Close supply and exhaust dampers and wait for "Close" lights to illuminate.

c. Turn off supply and exhaust power.

6. Turn off 12 volt rack-mount power supply below computer.

7. Turn off power strip below SCXI chassis.

C. Power Sheds

1. Turn off camera power supply in the instrument shed.

2. Turn off circuit breaker C1 in the power shed.

APPENDIX B Test Checklist

The following checklist was completed for each test in order to log pertinent information regarding the setup and progress of the test.

Test #: __________ Test Name: __________________________ Date: ________

Ambient Temp.: ________ Ambient Press.: ________ Ambient Humidity: ________

Fuel Load: __________ Fuel Quant.: __________ Ignition: ________________

Procedures Completed: ___ Weekly ___ Daily ___ Test Setup

Time Event

_______ Start Test

_______ Ignite Fire

_______ Bundle 1 Ignition

_______ Bundle 2 Ignition

_______ Deck Panel Ignition

_______ Insulation Ignition

_______ Burnout

_______ Extinguishment

_______ Secure Test

_______ Start Post-Test Ventilation (Minimum ventilation time: ________)

_______ Secure Post-Test Ventilation

_______ Reentry

Pre/Post Test Ventilation Record

Gas	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Oxygen					
Carbon Dioxide					
Carbon Monoxide					
Hydrogen Cyanide					NA

APPENDIX C Special Data Processing

The standard methods for processing test data are described in the text. However, in some cases, data from certain channels were found to be bad, either due to extreme noise or sensor failure. The special processing methods used in these cases are listed in these tables.

CONTENTS

Instrument	Condition	Special Processing
TC 1-0	Non-responsive	Ignore
TC 2-0	Non-responsive	Ignore
TC 2-2	Spikes	Filter: 0<T<75
TC 3-0	Off-scale	Ignore
TC Deck	Open	Ignore

Table C 1. Cable 1 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-0	Non-responsive	Ignore
TC 1-1	Spikes	Filter: 25<T<100
TC 1-2	Extreme noise	Ignore
TC 1-3	Spikes	Filter: 25<T<100
TC 1-4	Spikes	Filter: 25<T<100
TC 1-5	Spikes	Filter: 25<T<100
TC 2-0	Non-responsive	Ignore
TC 2-1	Spikes	Filter: 25<T<100
TC 2-2	Spikes	Filter: 25<T<100
TC 2-3	Spikes	Filter: 25<T<100
TC 2-4	Spikes	Filter: 25<T<100
TC 2-5	Spikes	Filter: 25<T<100
TC 3-0	Spikes	Filter: 0<T<100
TC 3-1	Spikes	Filter: 25<T<100
TC 3-2	Spikes	Filter: 25<T<100
TC 3-3	Extreme noise	Ignore
TC 3-4	Spikes	Filter: 25<T<100
TC 3-5	Spikes	Filter: 25<T<100
TC Rod 1	Spikes	Filter: 0<T<300
TC Rod 2	Spikes	Filter: 0<T<300
TC Cable 1	Spikes	Filter: 0<T<300
TC Cable 2	Spikes	Filter: 0<T<600
TC Deck	Open	Ignore

Table C 2. Cable 2 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-0	Spikes	Filter: 0<T<400
TC 1-1	Spikes	Filter: 0<T<300
TC 1-2	Spikes	Filter: 0<T<300
TC 1-3	Spikes	Filter: 0<T<300
TC 1-4	Spikes	Filter: 0<T<300
TC 1-5	Spikes	Filter: 0<T<300
TC 2-0	Non-responsive	Ignore
TC 2-1	Spikes	Filter: 0<T<350
TC 2-2	Spikes	Filter: 0<T<350
TC 2-3	Spikes	Filter: 0<T<350
TC 2-4	Spikes	Filter: 0<T<350
TC 2-5	Spikes	Filter: 0<T<350
TC 3-0	Spikes	Filter: 0<T<500
TC 3-1	Spikes	Filter: 0<T<300
TC 3-2	Spikes	Filter: 0<T<300
TC 3-3	Spikes	Filter: 0<T<300
TC 3-4	Spikes	Filter: 0<T<300
TC 3-5	Spikes	Filter: 0<T<300
TC Rod 1	Spikes	Filter: 0<T<700
TC Rod 2	Spikes	Filter: 0<T<700
TC Cable 1	Spikes	Filter: 0<T<600
TC Cable 2	Spikes	Filter: 0<T<800
TC Deck	Open	Ignore
Gas 1	Loop failure	Ignore
Gas 3	Loop failure	Ignore
ODM	Malfunction @ ~ 1950 sec	Truncate

Table C 3. Cable 3 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-2	Intermittent	Ignore
TC 2-0	Non-responsive	Ignore
TC 2-5	Extreme noise	Ignore
TC 3-0	Off-scale	Ignore
TC Deck	Open	Ignore
ODM	Sensor failure	Ignore

Table C 4. Deck 1 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-0	Spikes	Filter: 25<T<100
TC 2-0	Non-responsive	Ignore
TC 2-5	Extreme noise	Ignore
TC 3-0	Off-scale	Ignore
TC Deck	Open	Ignore

Table C 5. Deck 2 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-0	Spikes	Filter: 0<T<75
TC 2-0	Non-responsive	Ignore
TC 2-5	Extreme noise	Ignore
TC Deck	Open	Ignore

Table C 6. Deck 3 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-0	Spikes	Filter: 0<T<75
TC 2-0	Non-responsive	Ignore
TC 2-5	Extreme noise	Ignore
TC Deck	Open	Ignore

Table C 7. Deck 4 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-0	Spikes	Filter: 0<T<75
TC 2-0	Non-responsive	Ignore
TC 2-5	Extreme noise	Ignore
TC Deck	Open	Ignore

Table C 8. Insulation 1 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-0	Spikes	Filter: 0<T<75
TC 2-0	Non-responsive	Ignore
TC 2-5	Extreme noise	Ignore
TC Deck	Open	Ignore

Table C 9. Insulation 2 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-0	Spikes	Filter: 0<T<300
TC 1-1	Spikes	Filter: 0<T<100
TC 1-2	Spikes	Filter: 0<T<100
TC 1-3	Spikes	Filter: 0<T<100
TC 2-0	Non-responsive	Ignore
TC 2-1	Spikes	Filter: 0<T<100
TC 2-2	Spikes	Filter: 0<T<100
TC 2-3	Spikes	Filter: 0<T<100
TC 2-4	Spikes	Filter: 0<T<100
TC 2-5	Extreme noise	Ignore
TC 3-0	Spikes	Filter: 0<T<300
TC 3-1	Spikes	Filter: 0<T<100
TC 3-2	Spikes	Filter: 0<T<100
TC 3-3	Spikes	Filter: 0<T<100
TC 3-4	Spikes	Filter: 0<T<100
TC 3-5	Spikes	Filter: 0<T<100
TC Deck	Open	Ignore
Heater 1	Spikes	Filter: 0<T<1000
Heater 2	Spikes	Filter: 0<T<1000
Cable 1	Spikes	Filter: 0<T<800
Cable 1	Spikes	Filter: 0<T<800
Gas 1	Loop failure	Ignore

Table C 10. Insulation 3 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-0	Spikes	Filter: 0<T<300
TC 1-1	Spikes	Filter: 0<T<100
TC 1-2	Spikes	Filter: 0<T<100
TC 1-3	Spikes	Filter: 0<T<100
TC 1-4	Spikes	Filter: 0<T<100
TC 1-5	Spikes	Filter: 0<T<100
TC 2-0	Non-responsive	Ignore
TC 2-1	Spikes	Filter: 0<T<100
TC 2-2	Spikes	Filter: 0<T<100
TC 2-3	Spikes	Filter: 0<T<100
TC 2-4	Spikes	Filter: 0<T<100
TC 2-5	Extreme noise	Ignore
TC 3-0	Spikes	Filter: 0<T<300
TC 3-1	Spikes	Filter: 0<T<100
TC 3-2	Spikes	Filter: 0<T<100
TC 3-3	Spikes	Filter: 0<T<100
TC 3-4	Spikes	Filter: 0<T<100
TC 3-5	Spikes	Filter: 0<T<100
TC Deck	Open	Ignore
Heater 1	Spikes	Filter: 0<T<700
Heater 2	Spikes	Filter: 0<T<700
Cable 1	Spikes	Filter: 0<T<800
Cable 1	Spikes	Filter: 0<T<800
Gas 1	Loop failure	Ignore

Table C 11. Insulation 4 Test Special Data Processing

Instrument	Condition	Special Processing
TC 1-0	Spikes	Filter: 0<T<300
TC 1-1	Spikes	Filter: 0<T<100
TC 1-2	Spikes	Filter: 0<T<100
TC 1-3	Spikes	Filter: 0<T<100
TC 1-4	Spikes	Filter: 0<T<100
TC 1-5	Spikes	Filter: 0<T<100
TC 2-0	Non-responsive	Ignore
TC 2-1	Spikes	Filter: 0<T<100
TC 2-2	Spikes	Filter: 0<T<100
TC 2-3	Spikes	Filter: 0<T<100
TC 2-4	Spikes	Filter: 0<T<100
TC 2-5	Extreme noise	Ignore
TC 3-0	Spikes	Filter: 0<T<300
TC 3-1	Spikes	Filter: 0<T<100
TC 3-2	Spikes	Filter: 0<T<100
TC 3-3	Spikes	Filter: 0<T<100
TC 3-4	Spikes	Filter: 0<T<100
TC 3-5	Spikes	Filter: 0<T<100
TC Deck	Open	Ignore
Heater 1	Spikes	Filter: 0<T<600
Heater 2	Spikes	Filter: 0<T<600
Cable 1	Spikes	Filter: 0<T<400
Cable 1	Spikes	Filter: 0<T<700

Table C 12. Spray Baseline Test Special Data Processing

APPENDIX D Temperatures, Gas Concentrations and Optical Transmission

Graphs of air temperatures, cable surface temperatures, gas concentrations and optical transmission for the electronic space materials tests are presented in this appendix. The black triangles indicate the times at which the Cable 1 bundle ignited.

Note that tests Deck 4 and Insulation 2 ran longer than the normal one hour test period. As a result, data acquisition had to be restarted during the test, leading to brief gaps in the plots.

CONTENTS

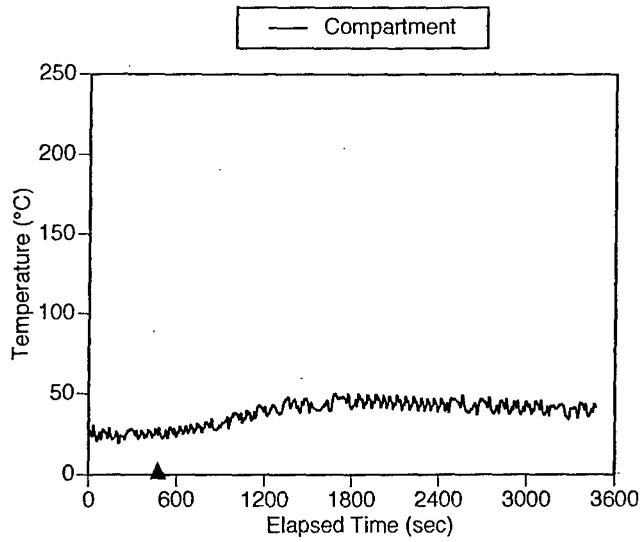

Figure D 1. Cable 1 Test Air Temperatures

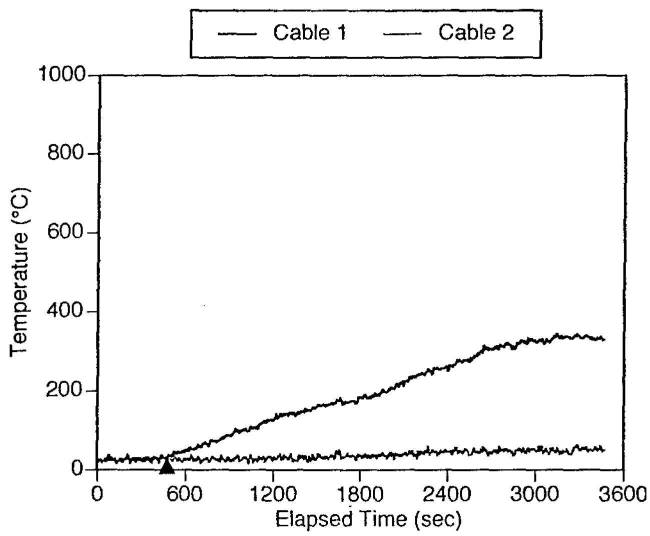

Figure D 2. Cable 1 Test Cable Surface Temperatures

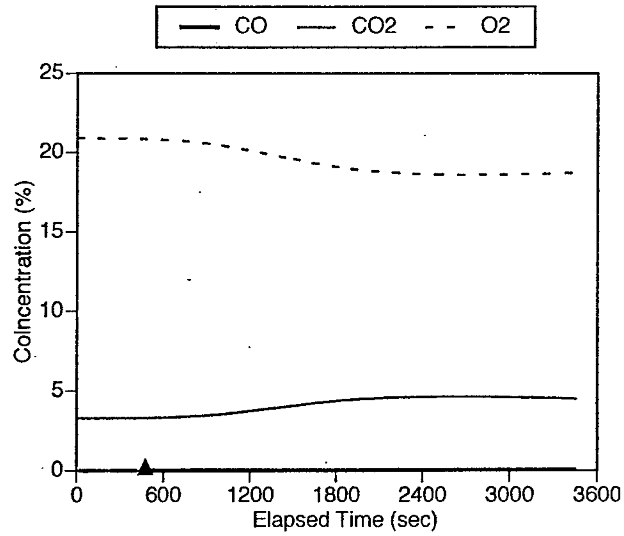

Figure D 3. Cable 1 Test Gas Concentrations

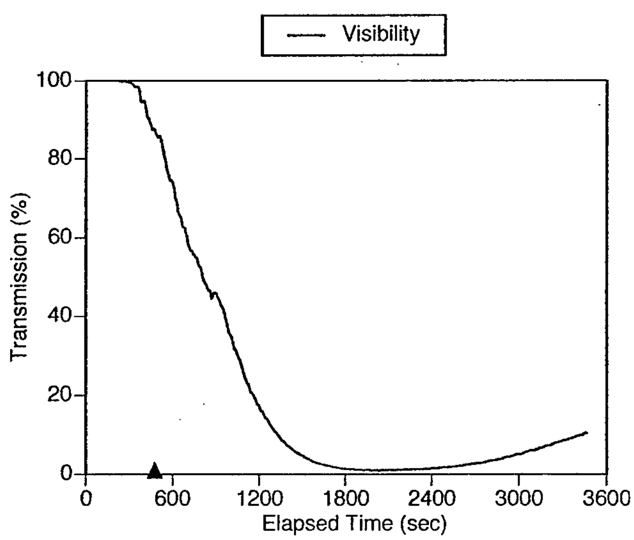

Figure D 4. Cable 1 Test Optical Transmission

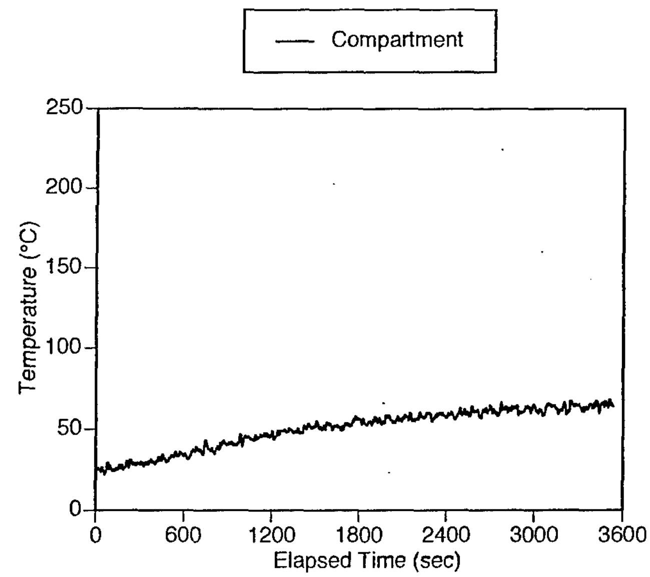

Figure D 5. Cable 2 Test Air Temperatures

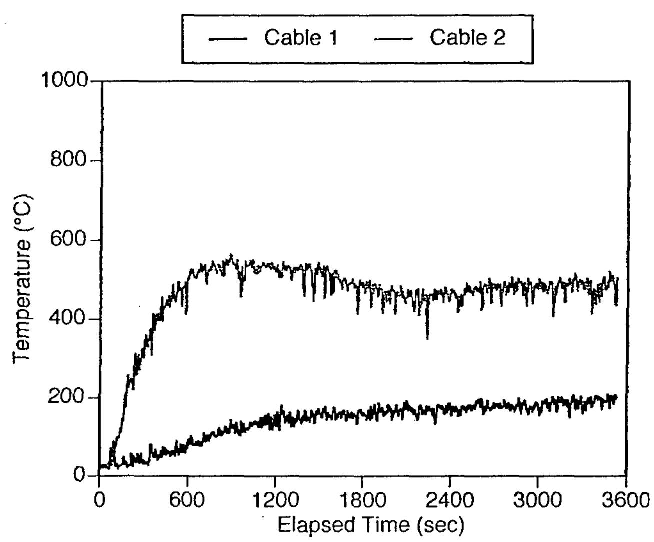

Figure D 6. Cable 2 Test Cable Surface Temperatures

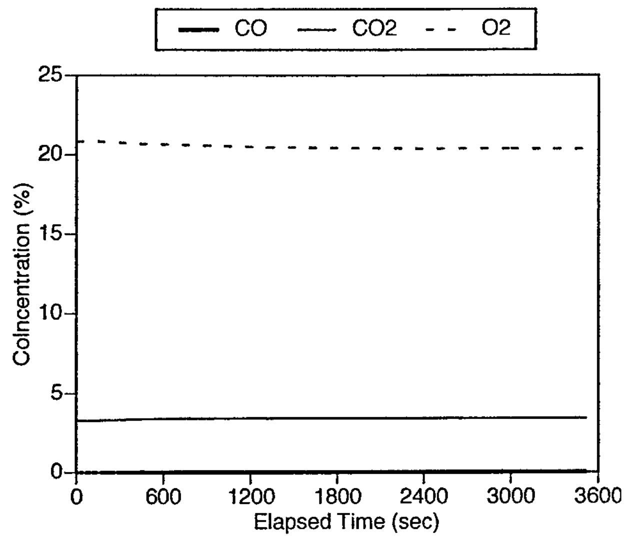

Figure D 7. Cable 2 Test Gas Concentrations

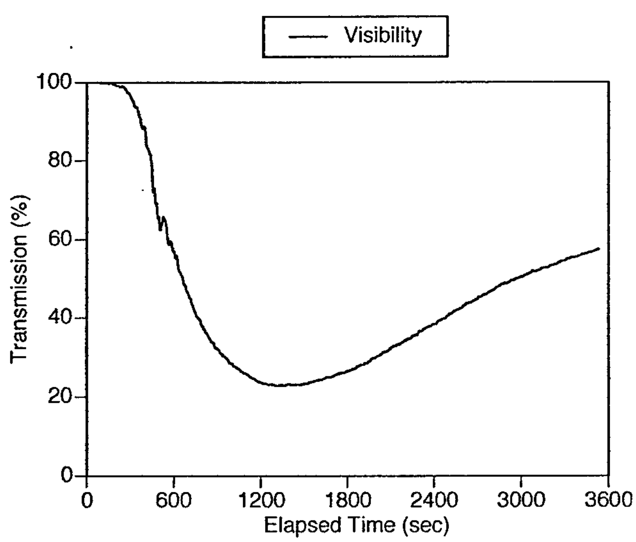

Figure D 8. Cable 2 Test Optical Transmission

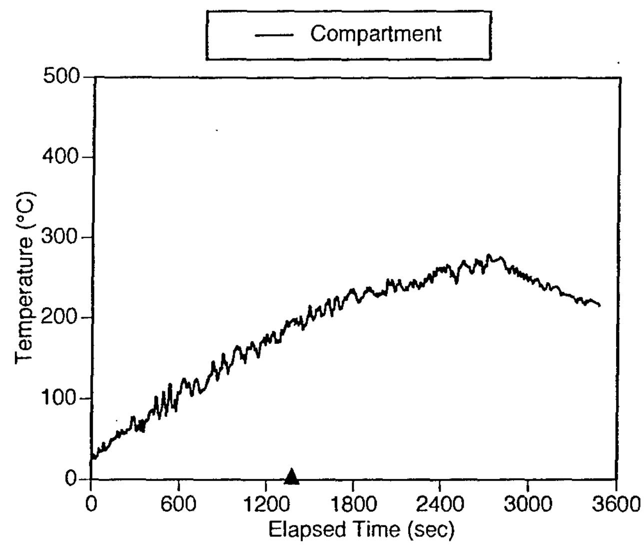

Figure D 9. Cable 3 Test Air Temperatures

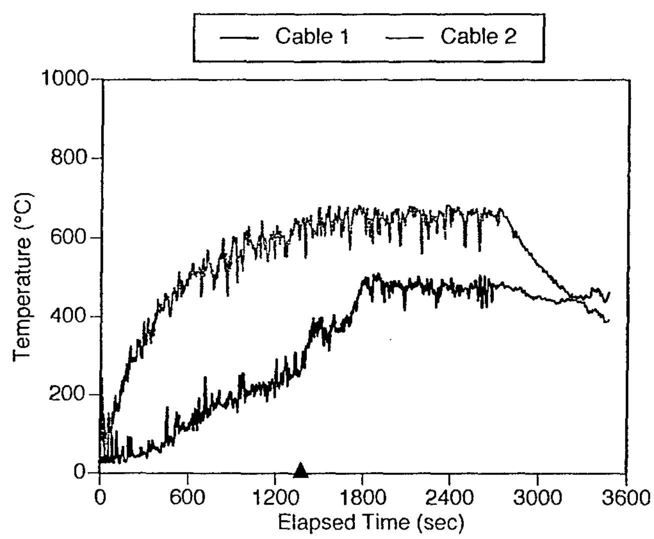

Figure D 10. Cable 3 Test Cable Surface Temperatures

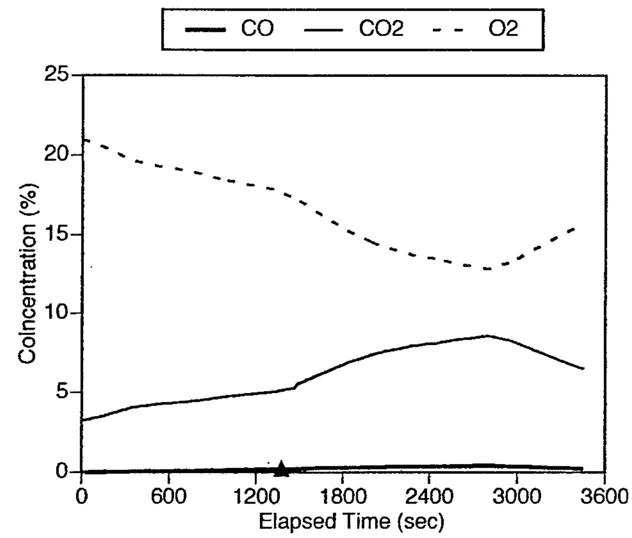

Figure D 11. Cable 3 Test Gas Concentrations

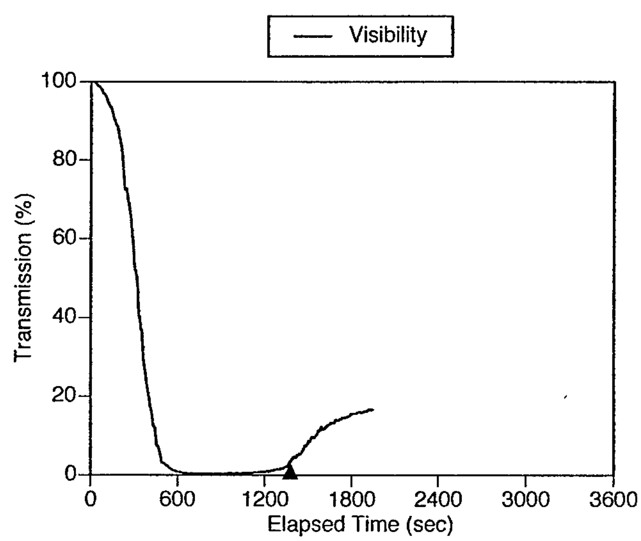

Figure D 12. Cable 3 Test Optical Transmission

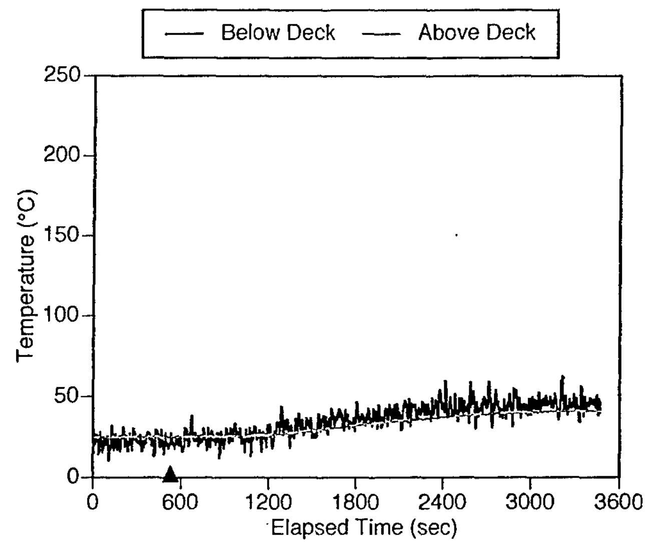

Figure A 13. Deck 1 Test Air Temperatures

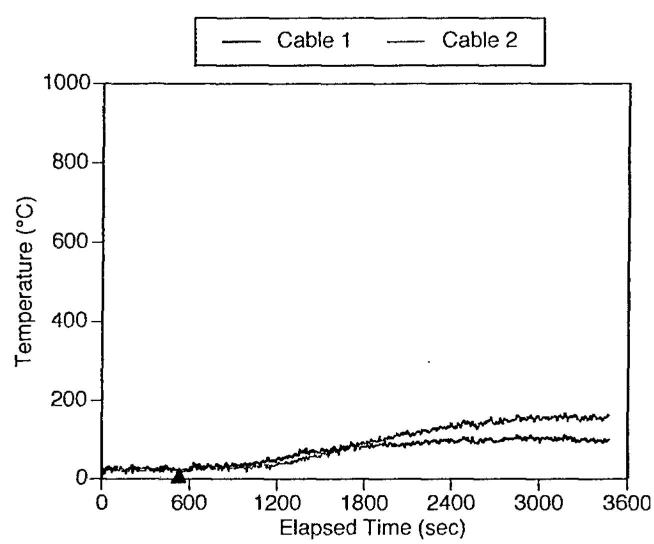

Figure A 14. Deck 1 Test Cable Surface Temperatures

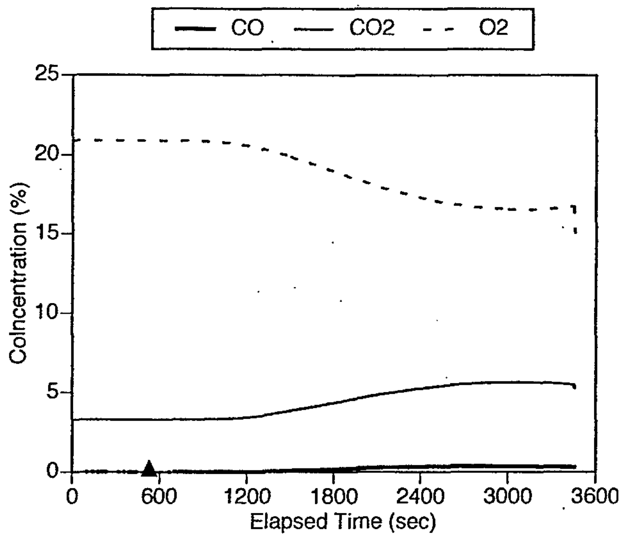

Figure D 15. Deck 1 Test Gas Concentrations

Sensor Failure

Figure D 16. Deck 1 Test Optical Transmission

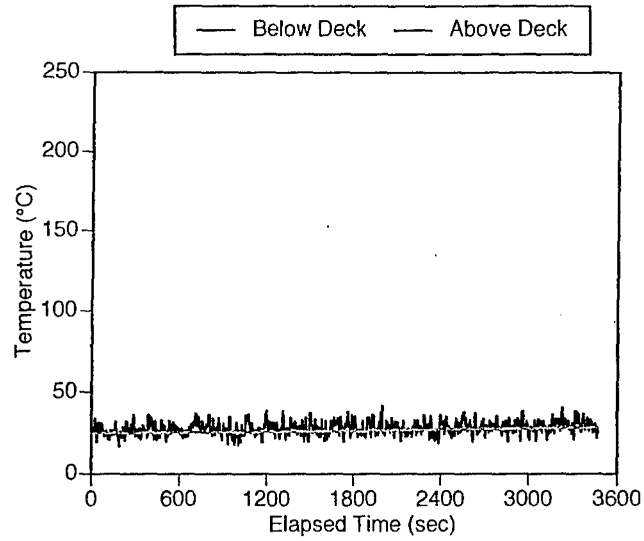

Figure D 17. Deck 2 Test Air Temperatures

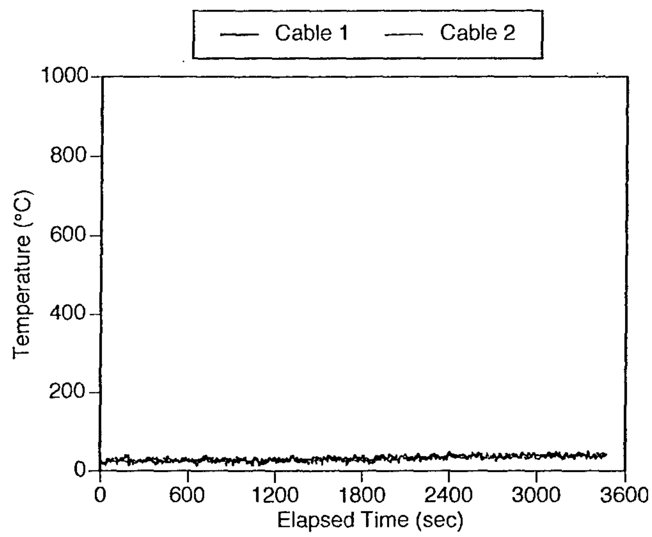

Figure D 18. Deck 2 Test Cable Surface Temperatures

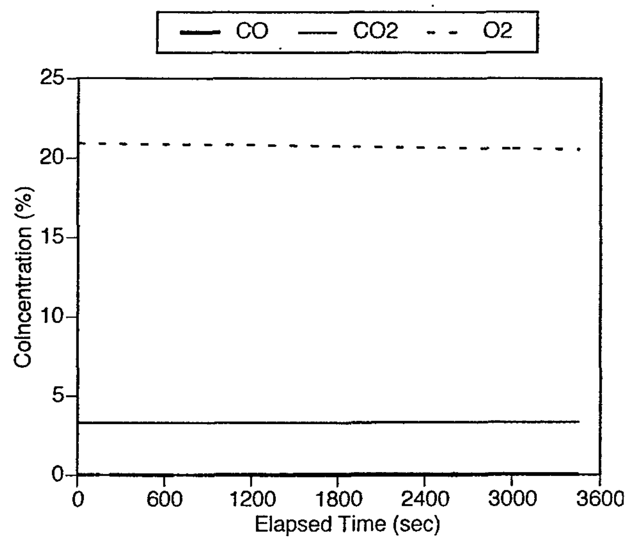

Figure D 19. Deck 2 Test Gas Concentrations

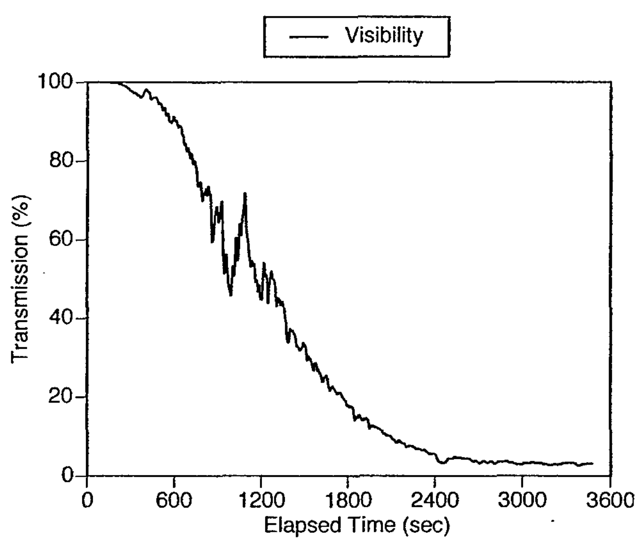

Figure D 20. Deck 2 Test Optical Transmission

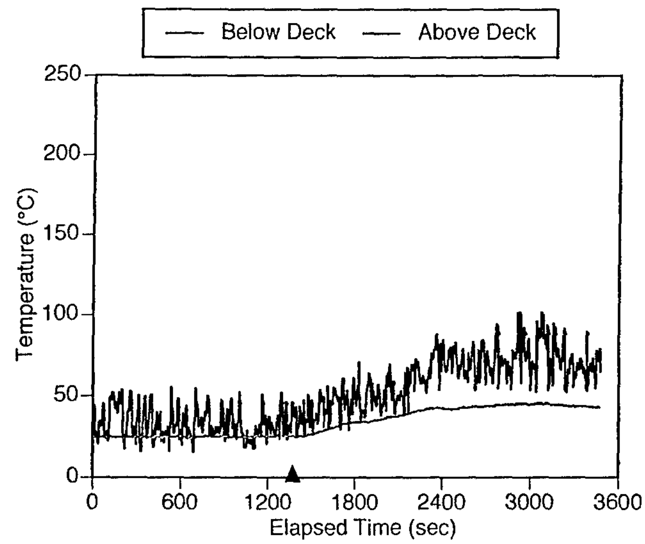

Figure D 21. Deck 3 Test Air Temperatures

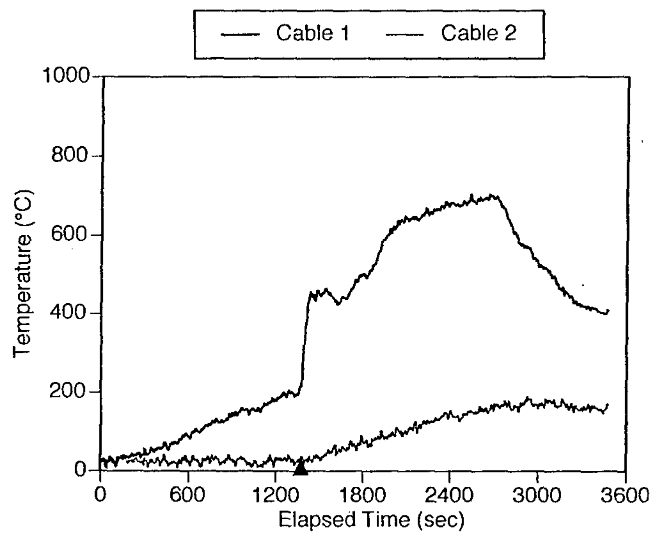

Figure D 22. Deck 3 Test Cable Surface Temperatures

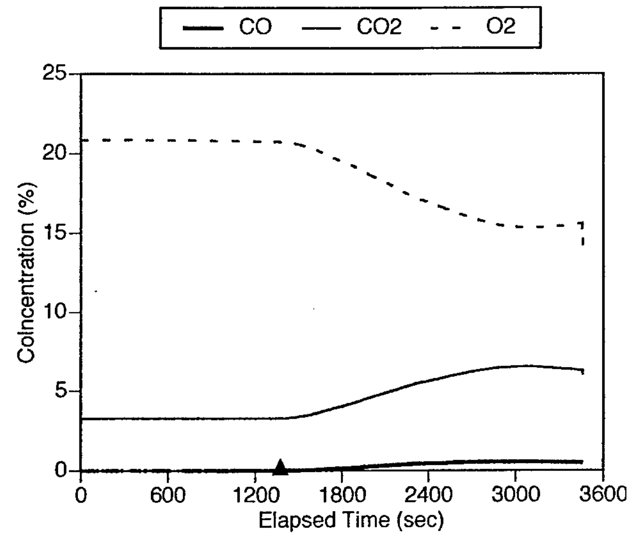

Figure D 23. Deck 3 Test Gas Concentrations

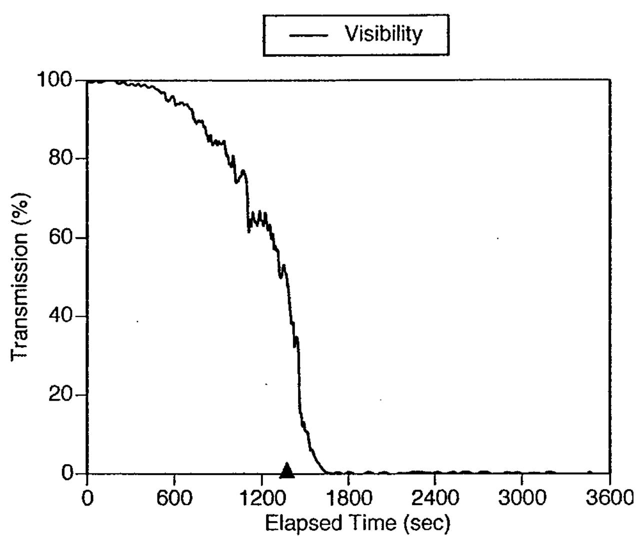

Figure D 24. Deck 3 Test Optical Transmission

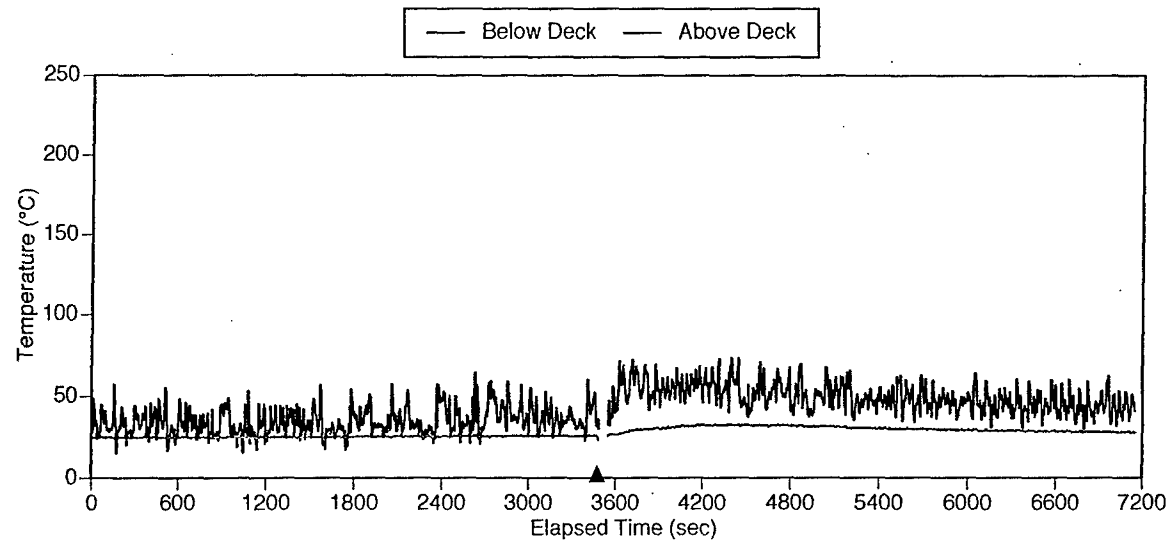

Figure D 25. Deck 4 Test Air Temperatures

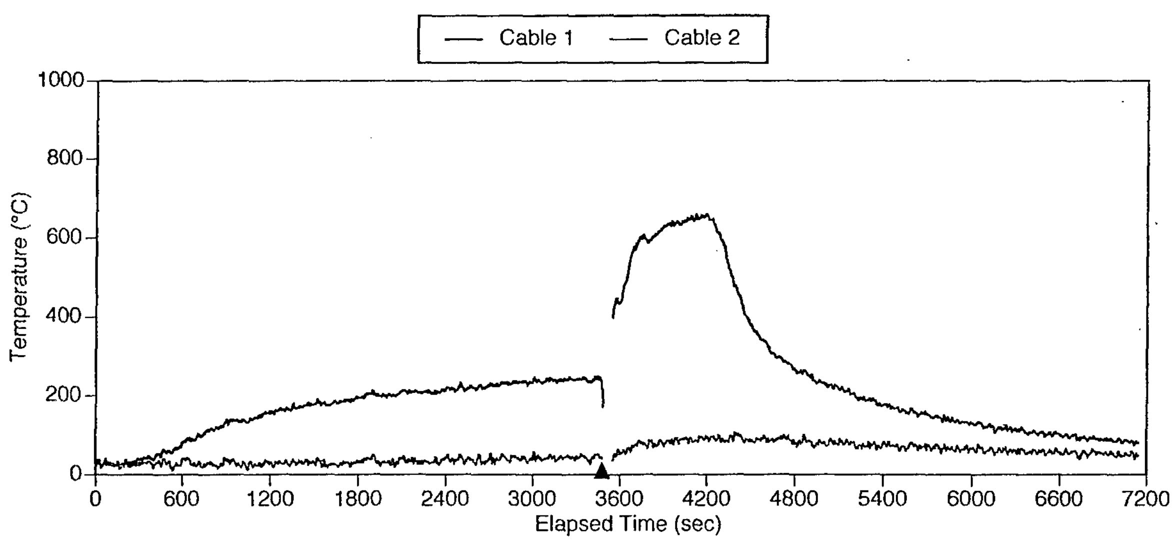

Figure D 26. Deck 4 Test Cable Surface Temperatures

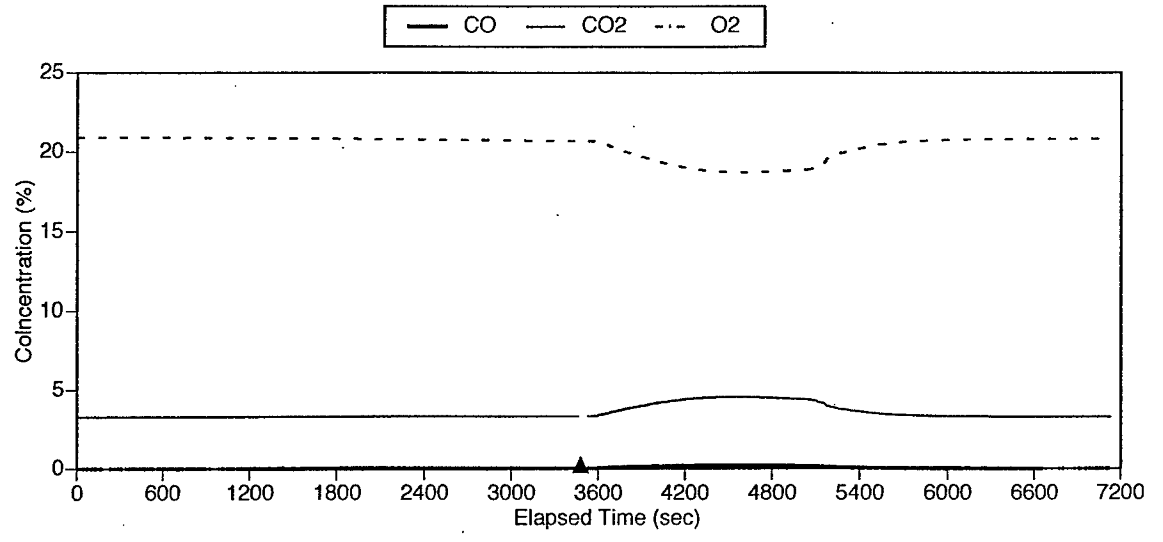

Figure D 27. Deck 4 Test Gas Concentrations

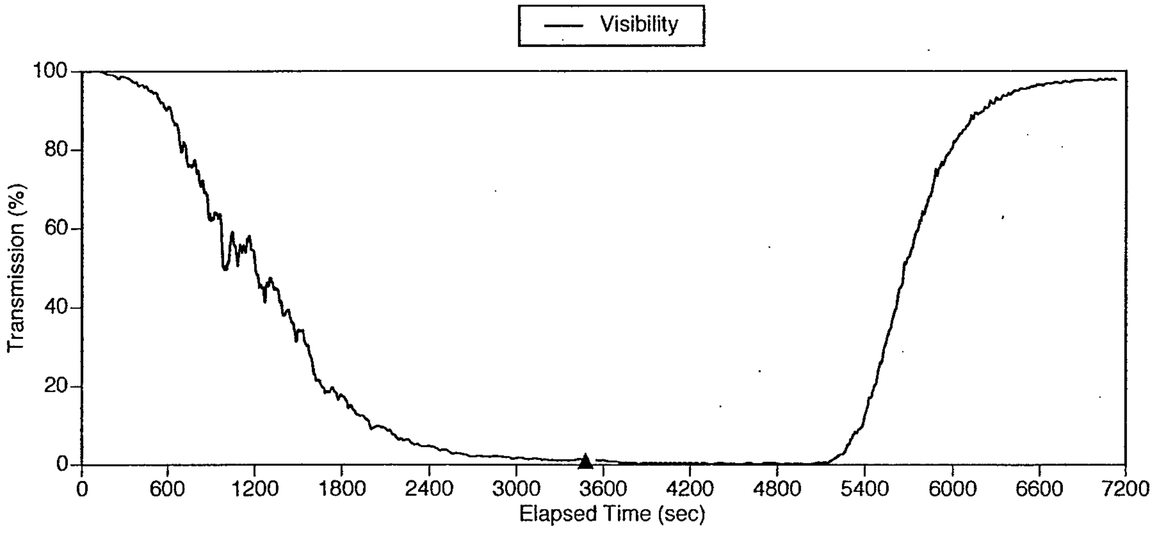

Figure D 28. Deck 4 Test Optical Transmission

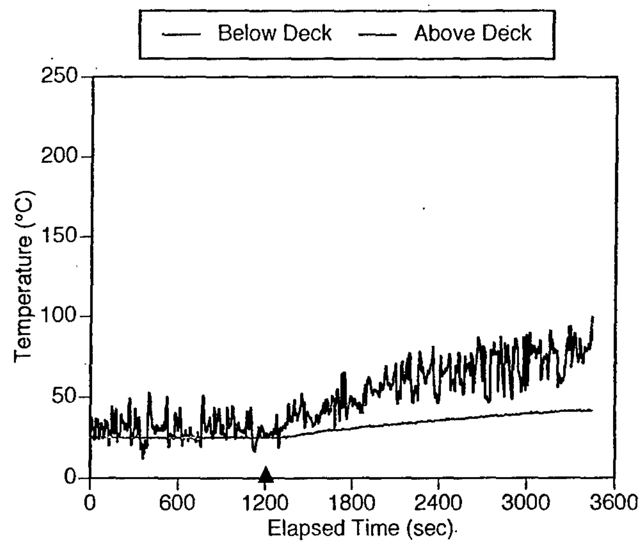

Figure D 29. Insulation 1 Test Air Temperatures

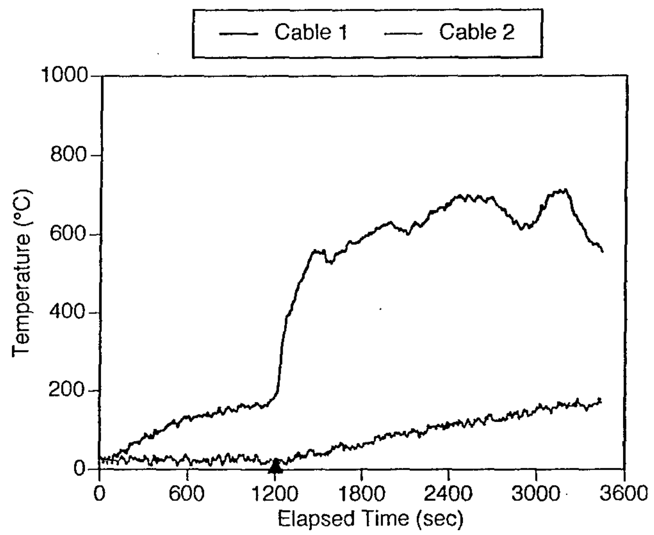

Figure D 30. Insulation 1 Test Cable Surface Temperatures

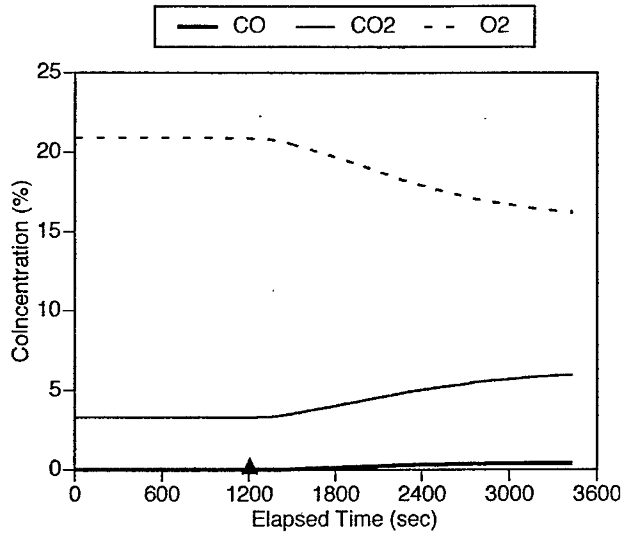

Figure D 31. Insulation 1 Test Gas Concentrations

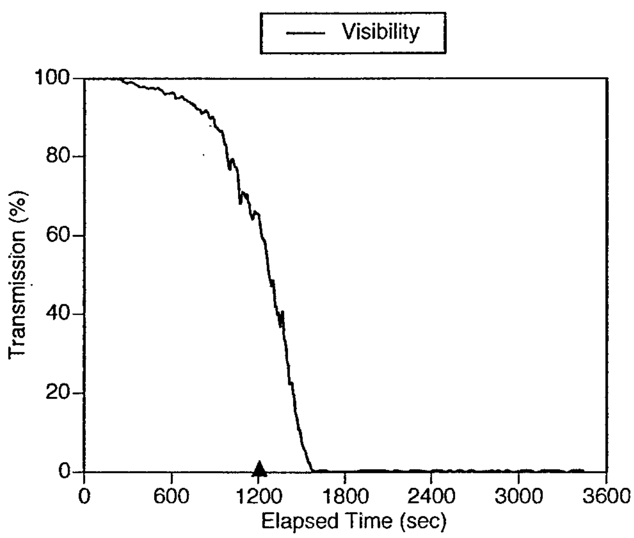

Figure D 32. Insulation 1 Test Optical Transmission

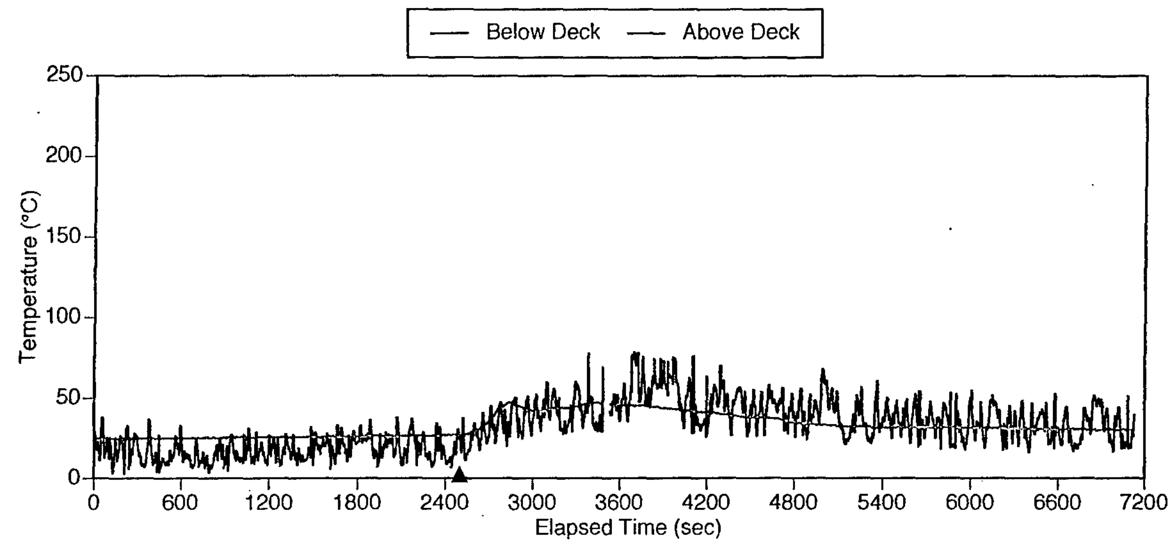

Figure D 33. Insulation 2 Test Air Temperatures

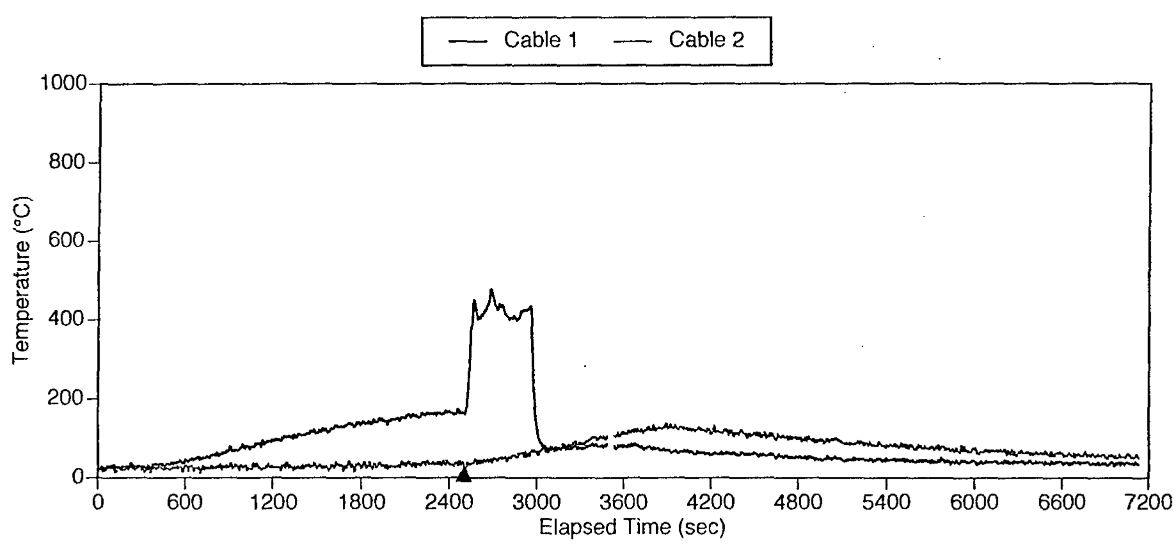

Figure D 34. Insulation 2 Test Cable Surface Temperatures

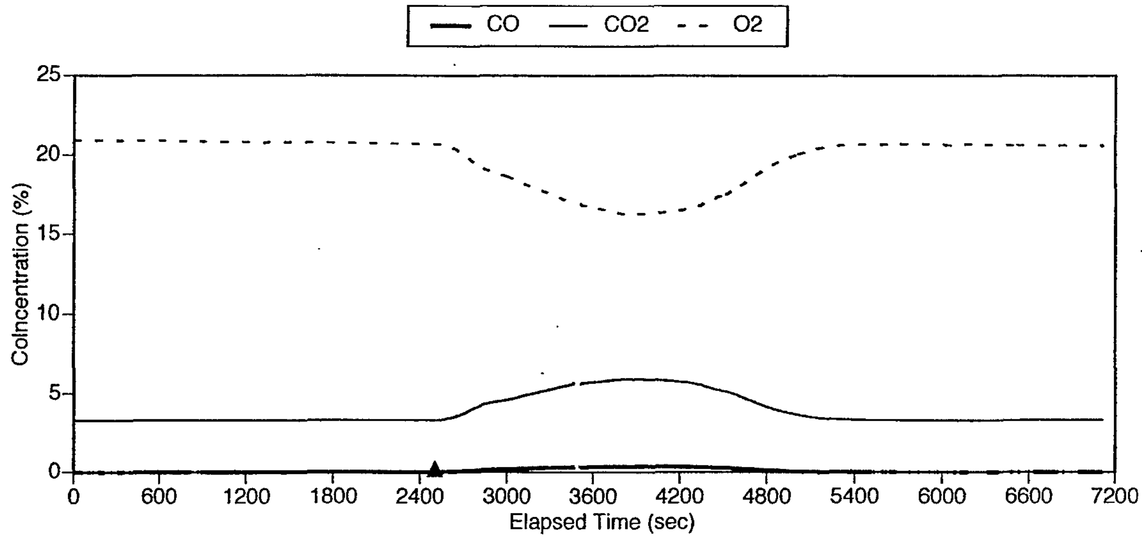

Figure D 35. Insulation 2 Test Gas Concentrations

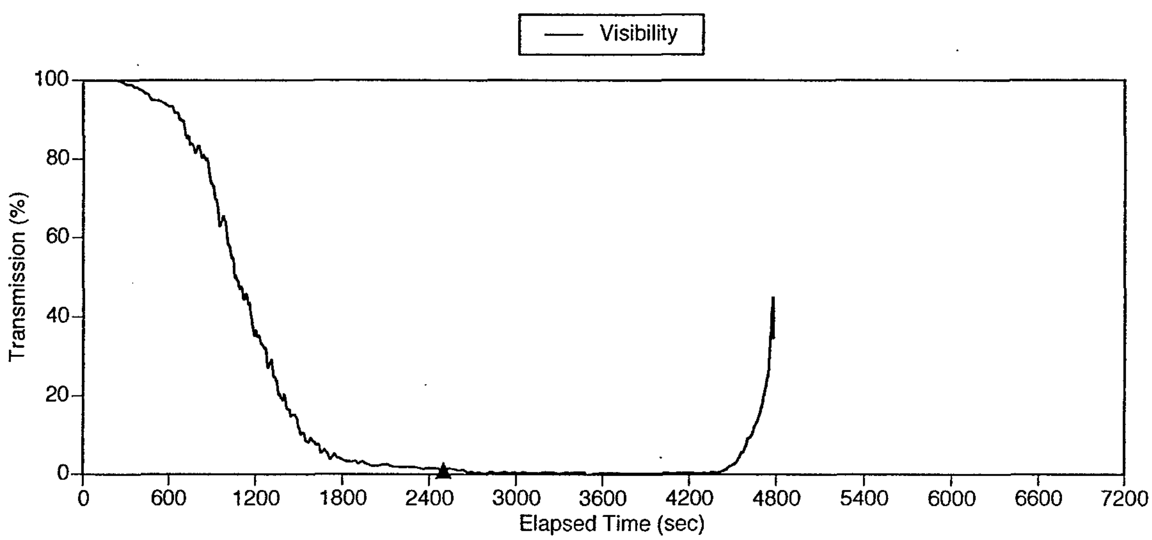

Figure D 36. Insulation 2 Test Optical Transmission

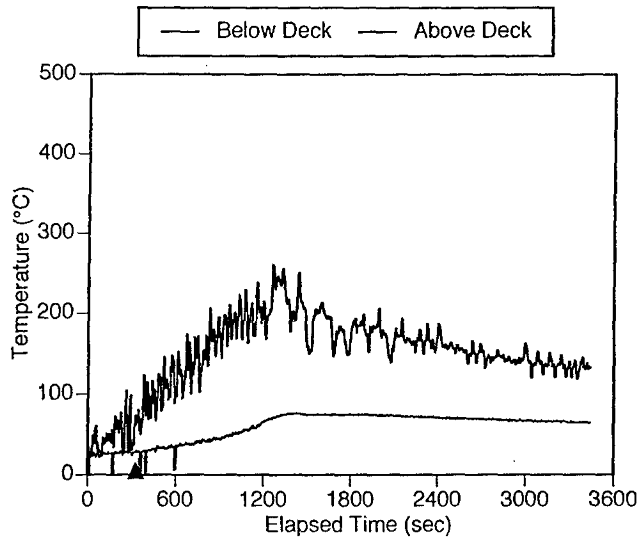

Figure D 37. Insulation 3 Test Air Temperatures

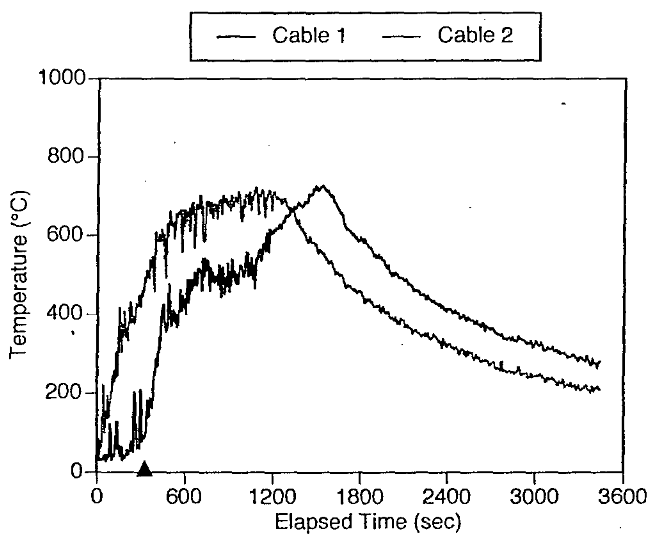

Figure D 38. Insulation 3 Test Cable Surface Temperatures

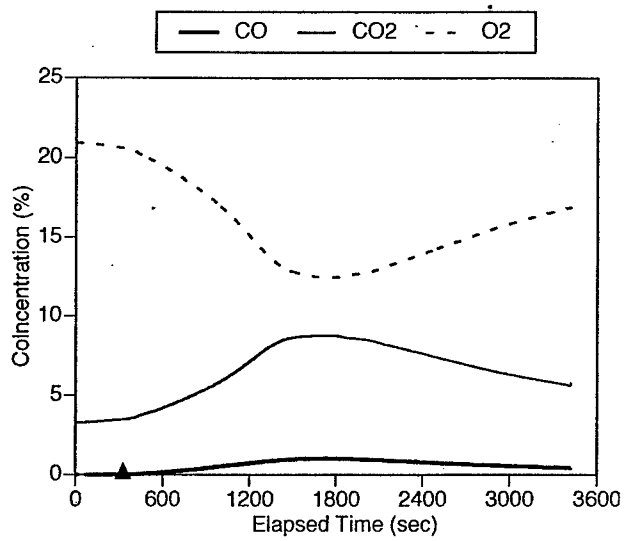

Figure D 39. Insulation 3 Test Gas Concentrations

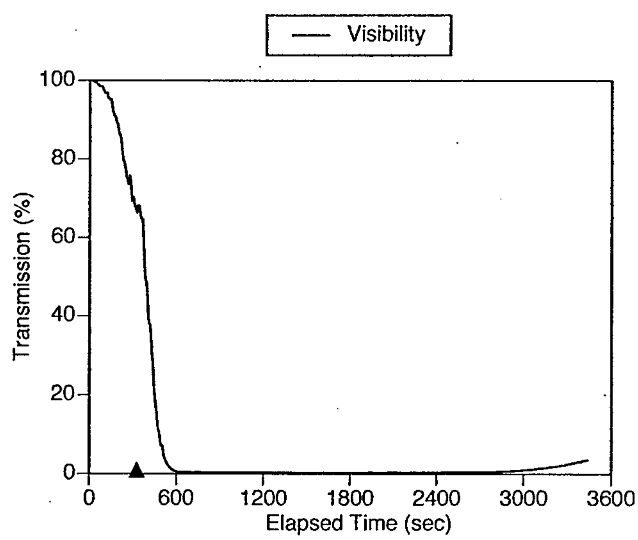

Figure D 40. Insulation 3 Test Optical Transmission

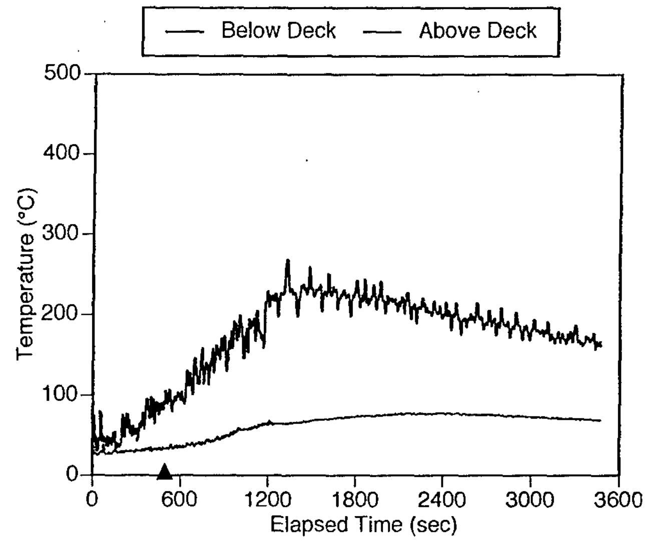

Figure D 41. Insulation 4 Test Air Temperatures

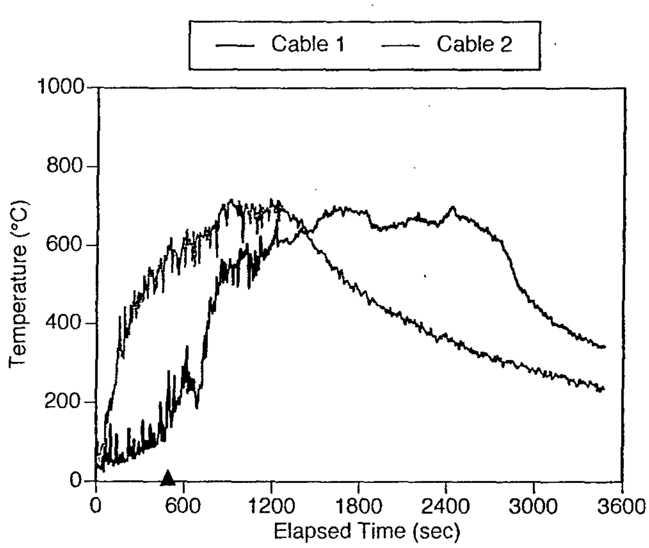

Figure D 42. Insulation 4 Test Cable Surface Temperatures

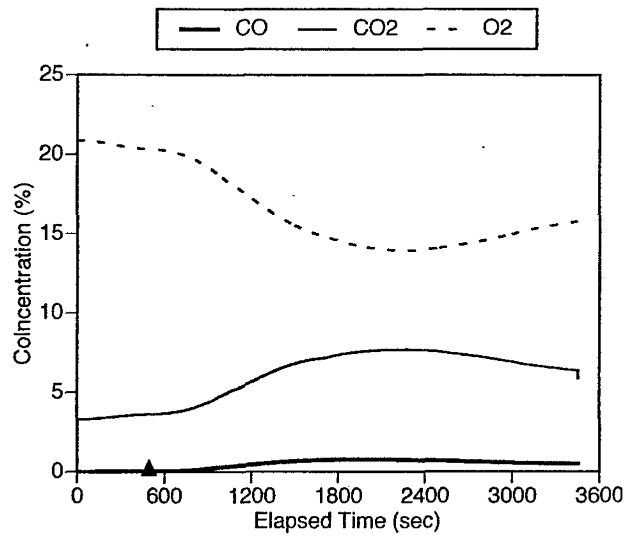

Figure D 43. Insulation 4 Test Gas Concentrations

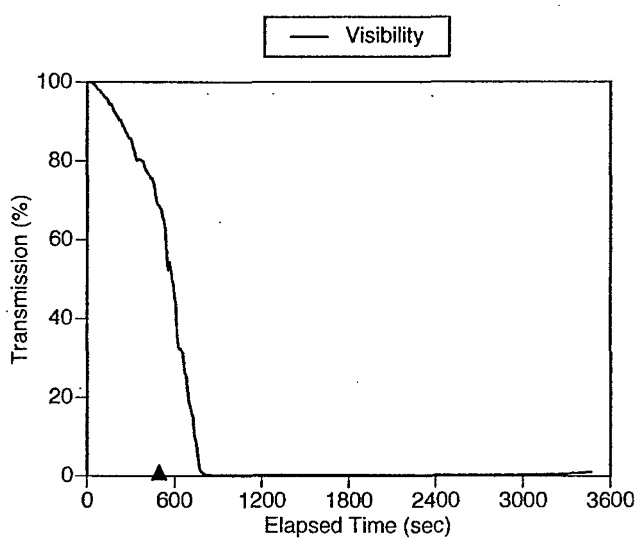

Figure D 44. Insulation 4 Test Optical Transmission

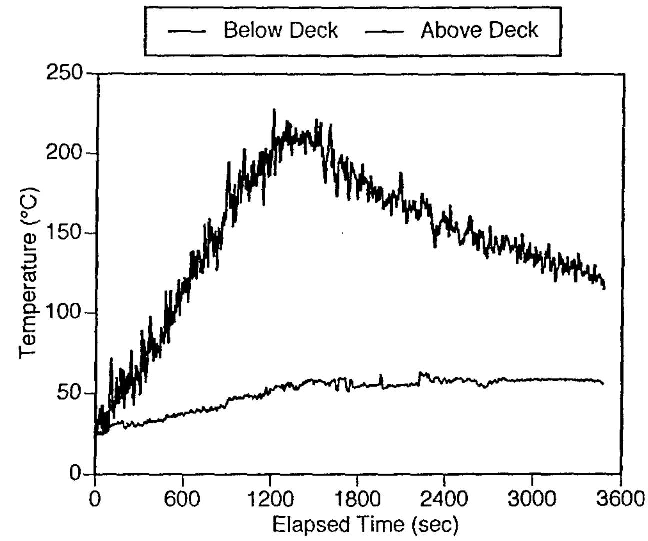

Figure D 45. Spray Baseline Test Air Temperatures

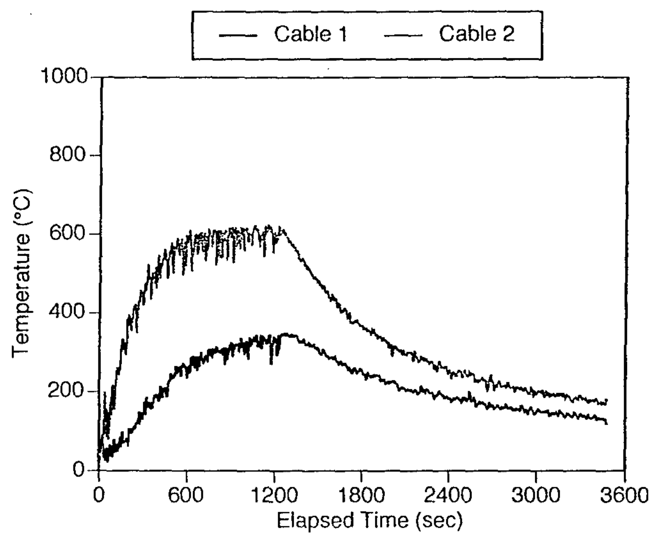

Figure D 46. Spray Baseline Test Cable Surface Temperatures

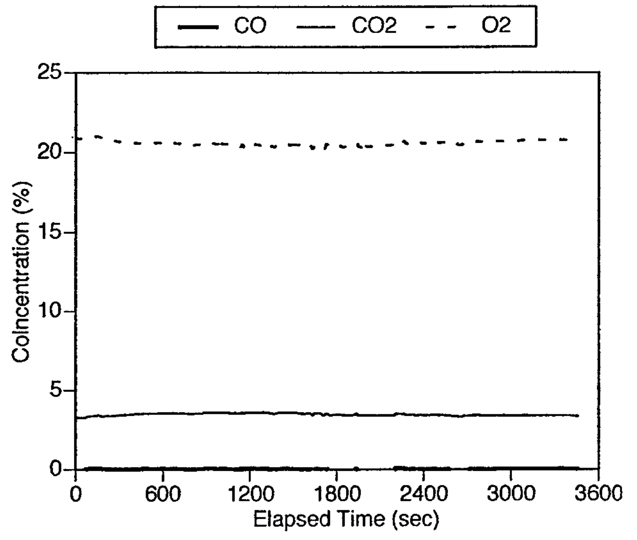

Figure D 47. Spray Baseline Test Gas Concentrations

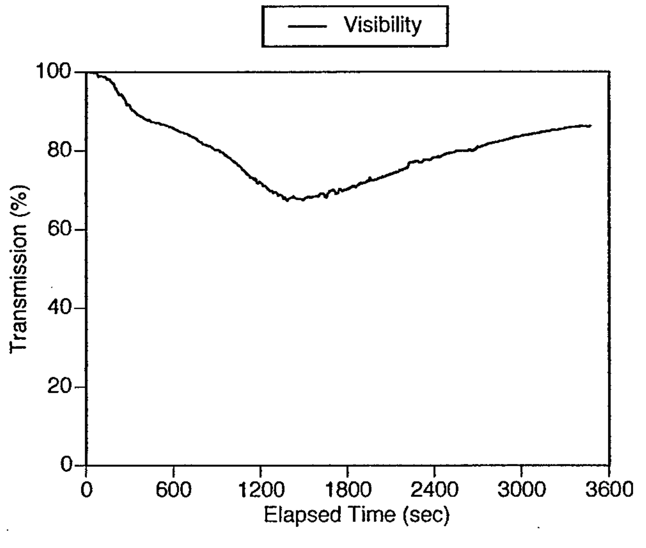

Figure D 48. Spray Baseline Test Optical Transmission