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Water Spray as a Fire Suppression Agent for Aircraft Cargo Compartment Fires

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16. Abstract

This report describes full-scale fire tests conducted by the Federal Aviation Administration (FAA) to investigate the effectiveness of several types of water spray systems against in-flight cargo compartment fires. Currently, commercial transport cargo compartments are protected with Halon 1301 fire suppression systems. Water spray is being considered as an alternative agent for Halon 1301 which is no longer being produced because of its ozone depletion potential. A dual-fluid (air/water) nozzle system, two types of high-pressure, single-fluid design systems, and a second dual-fluid (water/nitrogen) nozzle system were evaluated. The in-flight fire scenarios included simulated bulk-loaded fires, containerized fires, flammable liquid fires, and aerosol can explosions. The majority of tests were conducted inside a wide-body DC-10 cargo compartment; additional tests were conducted in a B727 narrow-body compartment. Several tests utilizing one of the high-pressure, single-fluid design systems were conducted according to the Minimum Performance Standard (MPS) for aircraft cargo compartments which standardizes and specifies the fire test performance for halon replacement agents. Parameters such as activation temperature, spray duration, nozzle configuration, and flow rate were varied during the tests to determine the impact on water usage and suppression. The tests determined that the systems were capable of suppressing class-A and class-B cargo fires for extended periods, using varying amounts of water. Water spray systems require additional development and evaluation to become a viable replacement for Halon 1301 because of the weight (agent) penalty associated with the systems tested. Also, the capability of water spray against cargo fires involving aerosol cans needs further investigation.

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EXECUTIVE SUMMARY

Past Federal Aviation Administration (FAA) research and testing highlighted the protection provided by water spray systems to the aircraft cabin and its occupants against the effects of a postcrash fuel fire. In a postcrash cabin fire environment, water spray is effective by cooling the cabin, wetting materials, and slowing the progress of fire. The combined effect of slowed fire growth resulted in significant delays in the onset of cabin flashover, thereby providing a more survivable cabin atmosphere and additional escape time.

In a cargo compartment, gaseous Halon 1301 is the exclusive agent used in civil transports and was proven to be a very effective agent at suppressing class-A type fires. Although effective, halons are being phased out due to their stratospheric ozone-depleting potential. As a result, newer more environmentally acceptable agents are being evaluated. The International Halon Replacement Working Group was formed to conduct research in four main areas: cargo compartments, engine nacelles, lavatory trash receptacles, and hand-held fire extinguishers. The FAA has undertaken the task of developing Minimum Performance Standards (MPS) in these areas in order to implement testing guidelines by which new agents/systems can be certified.

Because emergency water spray technologies have proven effective in other applications and because water is environmentally friendly, nontoxic and abundant, it is being considered as a halon replacement agent for use in cargo compartments. Tests conducted in both narrow- and wide-body test articles examined the effectiveness of water spray during several simulated in-flight fire test scenarios. A dual-fluid (air/water) nozzle system, a high-pressure single-fluid system, a second high-pressure system, and a dual-fluid (nitrogen/water) nozzle system were evaluated. The in-flight fire scenarios included simulated bulk-loaded fires, LD-3 containerized fires, flammable liquid fires (surface burns), and aerosol can explosions. Some of the most recent water spray tests were conducted according to the guidelines established in the new MPS for aircraft cargo compartment gaseous fire suppression systems. This new test standard allows for a direct comparison between the performance of Halon 1301 and new environmentally friendly replacement agents/systems. Since this standard was only recently developed, many of the tests were not run in accordance with the MPS, but prior to its inception. Parameters such as activation temperature, spray duration, nozzle configuration, and flow rate were varied during the tests to determine the impact on water usage and suppression. The tests determined that the systems were capable of suppressing class-A fires in cargo compartments for extended periods, and extinguishing class-B fires using varying amounts of water. In certain instances the systems adequately met the MPS acceptance criteria, although the weight (agent) penalty exceeded that of Halon 1301. In this regard, additional testing and development of water spray systems is required. Also, the capability of water spray against cargo fires involving aerosol cans is currently being investigated. During these tests, several aerosol cans are placed in shredded paper-filled boxes that are loaded into a 2000 ft^3 test compartment to determine the ability of the water spray at mitigating an explosion.

1. INTRODUCTION.

1.1 PURPOSE.

The purpose of this report is to summarize the effectiveness of water spray systems in full-scale cargo compartment fire tests carried out in both narrow- and wide-body test articles. Two dual-fluid nozzle designs and two high-pressure single fluid designs were evaluated for suppression of simulated cargo compartment fires.

1.2 BACKGROUND.

In the early 1990s the Federal Aviation Administration (FAA) initiated a research program to investigate the performance of water spray systems installed in the passenger cabin in providing protection against a postcrash fuel fire. Early designs were effective at reducing the fire hazards and increasing survivability in the cabin, but required large amounts of water [1 and 2]. Subsequent system optimization tests used a zoning approach proved that applying the water spray near the fire hazard improved visibility in other areas of the cabin and reduced the weight penalty by a factor of 9 [3 and 4]. However, the cost of implementing such a system outweighed the benefits, and further cabin water spray research was suspended. Several years later, the FAA William J. Hughes Technical Center formed the International Halon Replacement Working Group to research various environmentally-acceptable agents/systems, such as water spray, that could be used in aircraft cargo compartments, engine nacelles, hand-held extinguishers, and lavatory trash receptacles. The main purpose of the research is to develop Minimum Performance Standards (MPS) for each of these four target areas, which would be used in the certification of all new agents. To date, the MPS for lavatory trash receptacles has been finalized and implemented. The proposed cargo compartments MPS includes separate test protocols for bulk-loaded fires, containerized fires, flammable liquid fires, and an aerosol can explosion. The acceptance criteria were based on the performance of Halon 1301. In addition to the development of MPS, the Halon Replacement Working Group has expanded its focus to include all systems fire protection, such as fuel tanks and inaccessible areas.

Due to its effectiveness against postcrash cabin fires, the feasibility of using water spray against other types of fire threats was of interest, particularly cargo compartment fires. This interest in cargo water spray performance led to the evaluation of three “proof-of-concept” designs. In addition, after the MPS for Aircraft Cargo Compartments was finalized [5], a series of water spray tests were conducted to determine if the suppressing/extinguishing performance of a dual-fluid (nitrogen/water) system met the acceptance criteria.

1.3 DISCUSSION.

Initial testing of various water spray technologies against typical cargo compartment fire threats was conducted to determine if a water-based system could be as effective as existing halon-based systems. In order to be considered a viable replacement for halon, the water spray system had to be capable of suppressing cargo fires for an extended period of time, typically 90 minutes, at a comparable weight to halon. The 90-minute test duration was chosen to represent a typical diversion period for a transoceanic flight. In actuality, the amount of fire suppression agent required, and hence, the length of protection available would depend on the certification basis for each aircraft. These two parameters, fire suppression capability and system weight, were examined closely. The exact halon quantity to achieve a given concentration can be calculated from the following equation:

$$W = \frac{(V)(A_c)(C)}{(S)(100 - C)}$$

where:

W = weight of Halon 1301 required, (lb.)
C = Halon 1301 concentration, percent by volume
V = Volume of compartment (ft^3)
A_c= altitude correction factor
S = specific vapor volume based on temperature, (ft^3/lb.)
S = 2.2062 + 0.005046T; T = Temperature, °F

This calculation does not take into account the leakage rate of the cargo compartment, which would require additional halon to maintain the agent concentration [6]. Based on this equation, the 2357 cubic foot wide-body compartment used in the initial testing requires 49.62 lbs. of agent to reach 5% concentration. Because the leakage rate follows an exponential decay, approximately 100 lbs., or twice the initial amount of Halon 1301, would be needed for 90 minutes of protection. At approximately 8.33 pounds per gallon, 100 pounds of water would equate to 12 gallons. This estimate was used to compare water quantities utilized during the water spray trials.

2. DC-10 TEST ARTICLE.

The aft cargo compartment of a DC-10 aircraft was used for the evaluation of the initial dual-fluid system designed by GEC Marconi Avionics (GEC). The original cargo liner was removed from the compartment and replaced with sheet steel for fire hardening purposes. The compartment volume measured 2357 cubic foot (figure 1). In order to replicate in-flight ventilation conditions, a large blower ducted air into the rear portion of the aircraft cabin, simulating air from the air conditioning system (figure 2).

The intake air flowed down from the cabin ceiling area and exited through the baseboard return-air grills into the cheek area. A fraction of the air then permeated the cargo compartment, while the remaining air flowed around the compartment directly through the outflow valve mounted in the fuselage belly (figure 3).

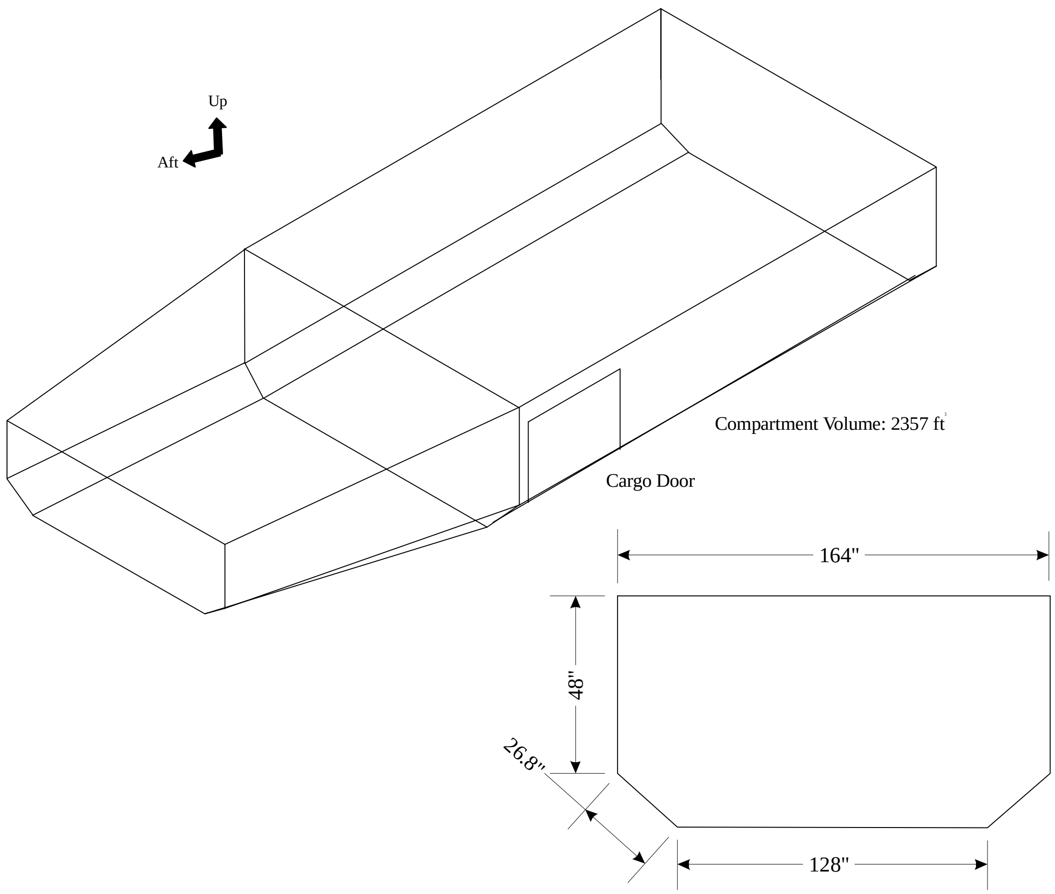


FIGURE 1. SCHEMATIC OF DC-10 CARGO COMPARTMENT

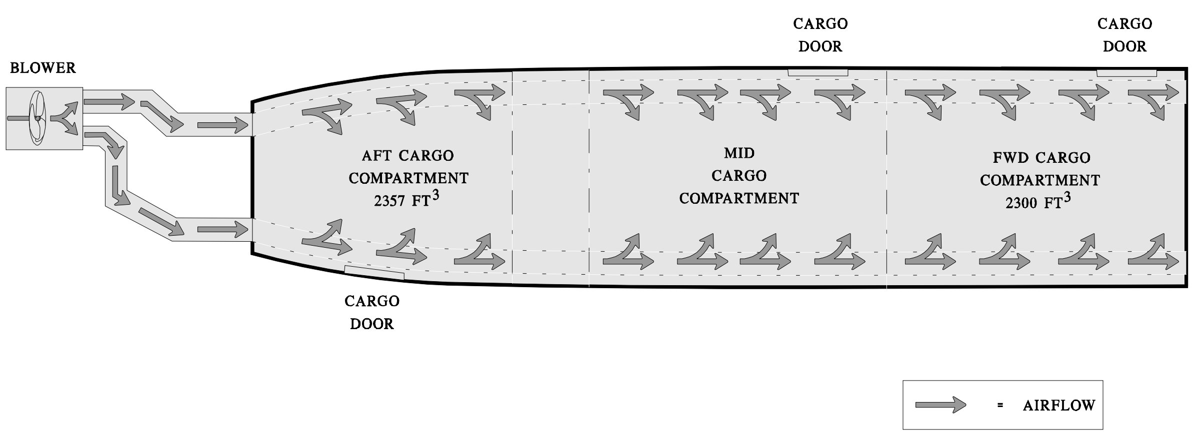


FIGURE 2. DC-10 TEST ARTICLE VENTILATION SCHEMATIC

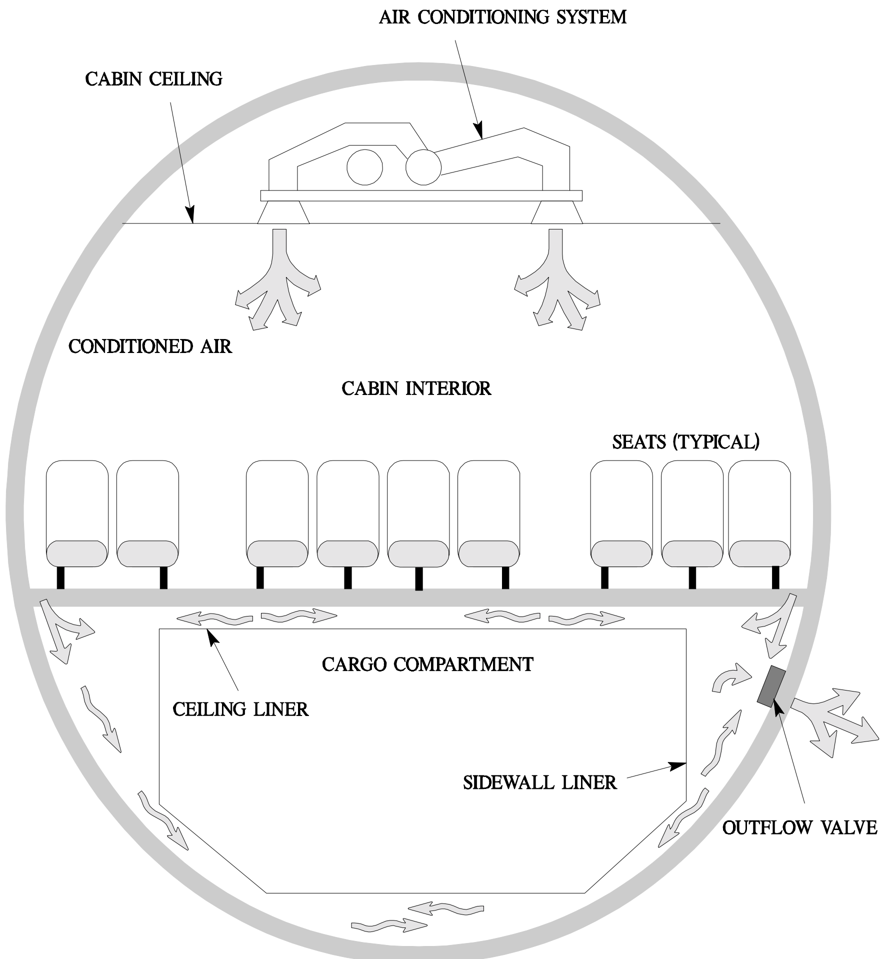


FIGURE 3. TYPICAL AIRCRAFT VENTILATION SYSTEM

2.1 LEAKAGE RATE TESTS IN AFT COMPARTMENT.

In order to determine the compartment leakage rate, several tests were first conducted in which carbon dioxide (CO_2) gas was released into the compartment. With the ventilation system turned on, the decay rate of the CO_2 was recorded, and a calculation was performed to determine the leakage rate. This calculation was based on a model developed for the purpose of determining leakage rates in well-mixed, ventilated compartments [7]. Figure 4 illustrates the method used to calculate the leakage rate. To perform the calculation, an initial concentration C_1 is chosen, along with the corresponding time T_1. Next, a second concentration that is 37% of the initial concentration is chosen, C_2, along with its corresponding time, T_2. The air change for leakage rate is calculated by dividing the compartment volume by the change in time (delta time) required for the concentration to drop 63%.

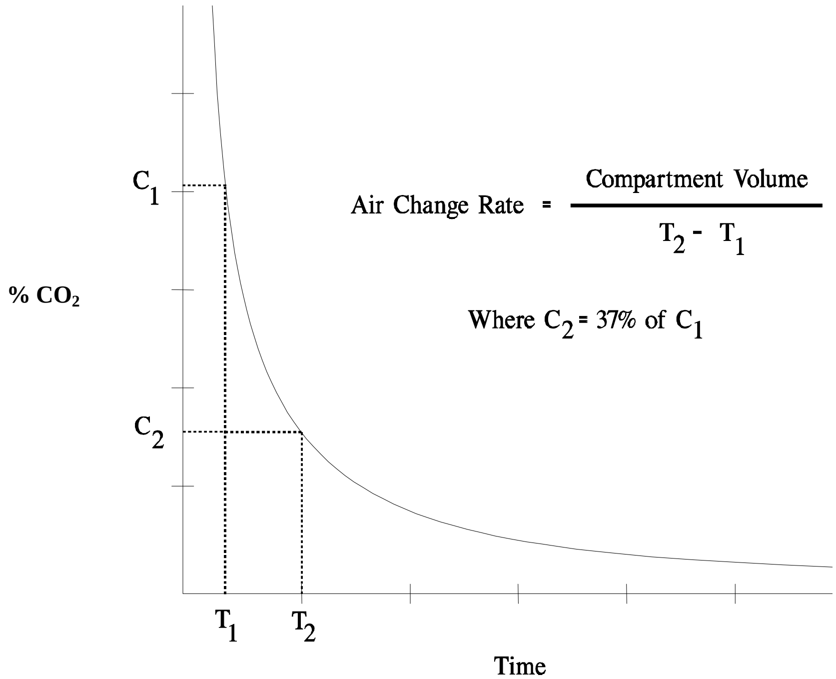


FIGURE 4. LEAKAGE RATE CALCULATION

Figure 5 shows the actual CO_2 concentration versus time profiles used in the calculation. As shown, the concentration was recorded continuously at four heights in the compartment. The leakage rate was calculated for each height and the values were averaged to give a final value.

Leakage rate calculation at a 1 foot height:

Δt (8% to 2.96%) = 83.33 – 30.92 = 52.41
Δt (6% to 2.22%) = 117.0 – 40.58 = 76.42
Δt (avg.) = 64.42

Leakage rate @ 1 foot = 2357 ft^3 ÷ 64.42 min
= 36.59 ft^3/min

Leakage rate calculation at a 2 foot height:

Δt (8% to 2.96%) = 55.42 – 28.04 = 27.38
Δt (6% to 2.22%) = 66.83 – 33.96 = 32.87
Δt (avg.) = 30.13

Leakage rate @ 2 foot = 2357 ft^3 ÷ 30.13 min
= 78.23 ft^3/min

Leakage rate calculation at a 3 foot height:

Δt (8% to 2.96%) = 58.42 – 29.25 = 29.17
Δt (6% to 2.22%) = 69.67 – 35.67 = 34.00
Δt (avg.) = 31.59

Leakage rate @ 3 foot = 2357 ft^3 ÷ 31.59 min
= 74.61 ft^3/min

Leakage rate calculation at a 4 foot height:

Δt (8% to 2.96%) = 57.58 – 28.48 = 29.10
Δt (6% to 2.22%) = 69.00 – 34.67 = 34.33
Δt (avg.) = 31.72

Leakage rate @ 4 foot = 2357 $ft^3 \div$ 31.72 min
= 74.31 ft^3/min

Avg. Leak Rate in Forward Compartment = (L.R.1 + L.R.2 + L.R.3 + L.R.4) ÷ 4 = 65.94 ft^3/min

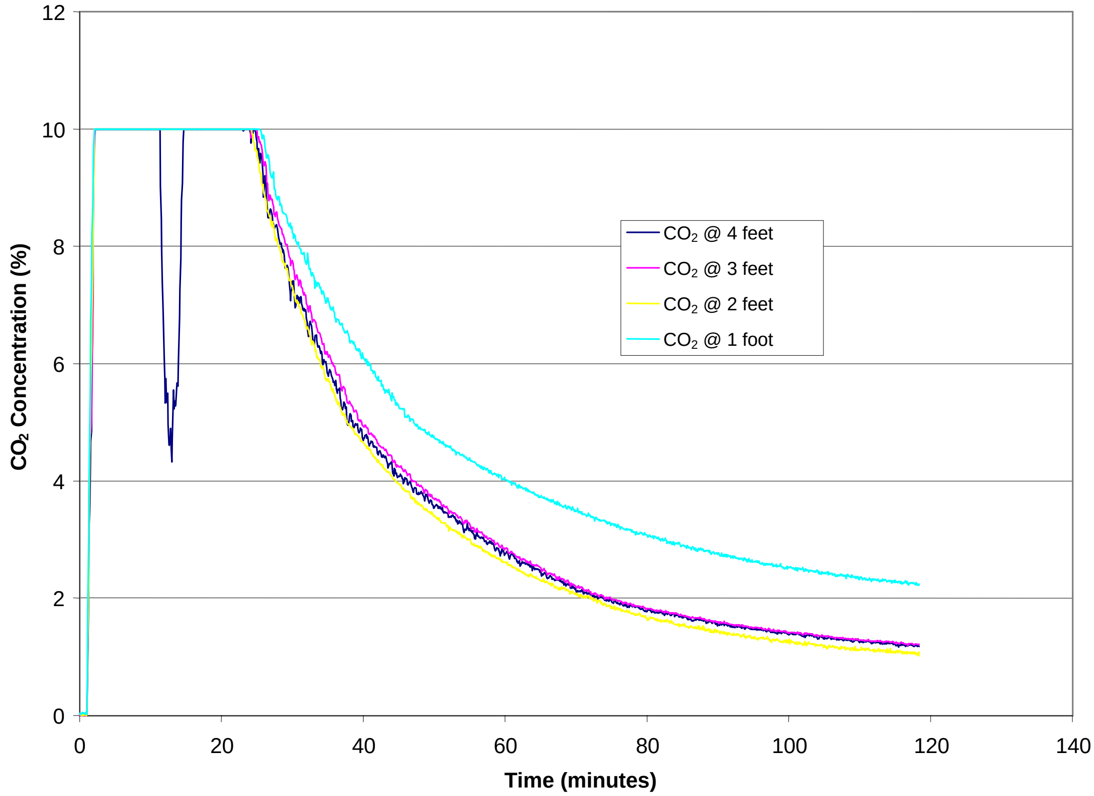


FIGURE 5. CO_2 LEAKAGE RATE TESTS IN DC-10 AFT CARGO COMPARTMENT

2.2 SMOKE DETECTION SYSTEM.

A photoelectric smoke detection system was installed to monitor the conditions inside the cargo compartment. The system used a 47305X series detector manufactured by Walter Kidde Aerospace, Inc., which was set to alarm at a 93% reduction in light transmission. Cargo air was transferred to two parallel-mounted smoke detectors through a series of ports mounted in the ceiling of the compartment. A house vacuum pump was adjusted to provide the proper flow rate. In general, the detection system replicated what is found in service, and provided a realistic response to smoke production, so that the detection time and water spray activation would be representative of actual cargo fire conditions. During the fire tests, the water spray system was activated after a finite period following smoke detection, usually one minute, to factor in the response of the crew.

2.3 WATER SPRAY CONTROL LOGIC.

All of the water spray systems used in this research were divided into individual zones that could be activated independently. Earlier research showed the benefit of restricting the application of water to those areas where the fire threat existed, thereby optimizing water application and reducing the total amount of water required. Once activated, the typical water spray system operates as an "on-demand" type of system, controlled by temperatures monitored within the specific zone or area of the compartment. When a fire develops and the temperature exceeds the preset activation value for a particular zone, the spray is activated; when the temperatures subside, the spray is deactivated. This approach allows the water spray system to maintain control of the fire and not expend an excessive amount of water.

2.4 GEC MARCONI AVIONICS WATER SPRAY SYSTEM.

A water spray system developed by GEC Marconi Avionics was evaluated in the aft cargo compartment of the DC-10 test article. The system used a dual-fluid nozzle in which air at 80-110 lb/in^2 (psi) was used to shear water at 40-60 psi, forming a very fine, mist-like spray. The nozzle produced a horizontal fan-like two-dimensional spray pattern with a resulting droplet size in the area of 100 μm. The GEC system consisted of 18 ceiling nozzles arranged on six pipe runs, resulting in four zones that could be activated independently (figure 6).

An array of zone control thermocouples provided temperature feedback for water discharge (figure 7). The zone control logic was arranged so that if thermocouples 1R and/or 1L reached a preset level, arms 1 and 3 activated. When thermocouples 2R and/or 2L reached a preset level, arms 2 and 3 activated. When thermocouples 3R and/or 3L reached a preset level, arms 2 and 4 activated. Lastly, when any of thermocouples 4RA, 4LA, 4RB, or 4LB reached a preset level, arms 5 and 6 activated. The 10 zone thermocouples were displayed on individual light emitting diode (LED) displays. The zone activation was controlled manually during the tests.

In addition to the zone control thermocouples, 21 thermocouples were installed on the ceiling and 10 more were mounted on the sidewall. A rack of three smoke meters was installed in the compartment at heights of 1 foot, 2 feet, and 3 feet above the floor. The smoke meters consisted of a collimated light source and a photocell separated by a 1-foot distance. As the smoke level increases, the amount of light absorbed by the photocell decreases, and a simple algorithm yields a percentage light transmission. An additional bank of three smoke meters were situated in the passenger cabin above the cargo compartment. A continuous gas sampling port was located in the cargo compartment at a height of 2 feet, and an additional three ports were positioned in the passenger cabin at heights of 1 foot 6 inches, 3 feet 6 inches, and 5 feet 6 inches (figure 8). The sampling ports were run to a nearby gas analysis trailer which housed analyzers that measured carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) concentration.

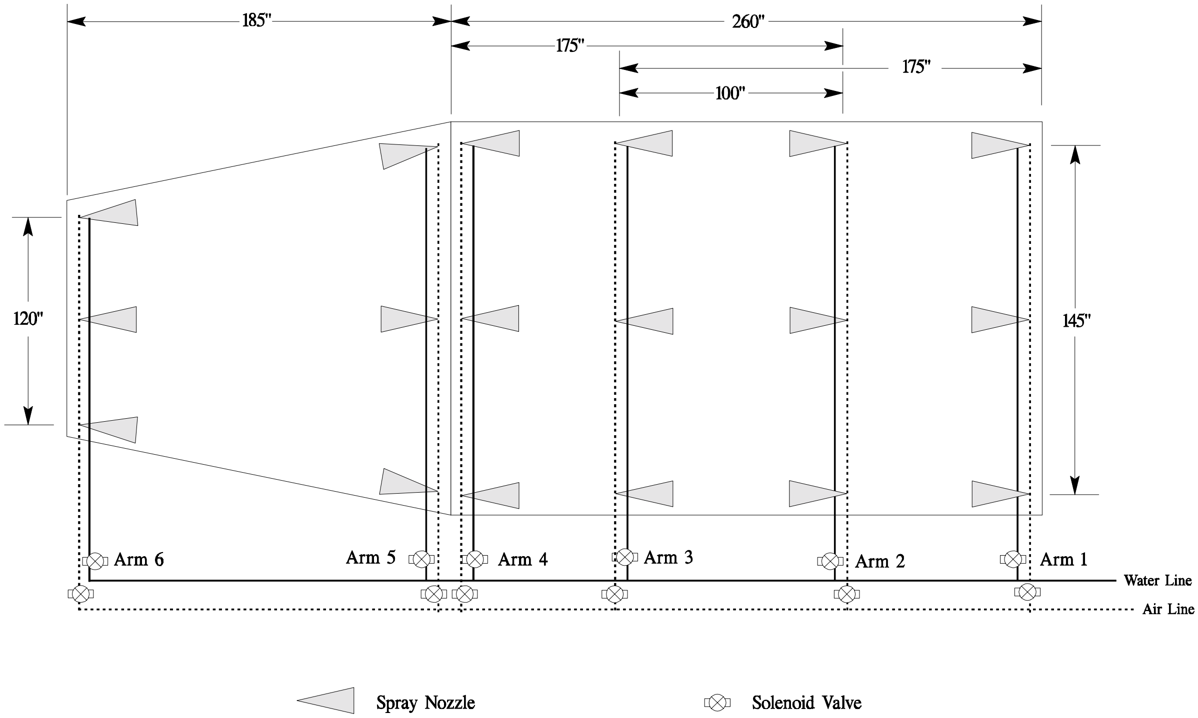


FIGURE 6. SCHEMATIC OF GEC MARCONI AVIONICS WATER SPRAY SYSTEM

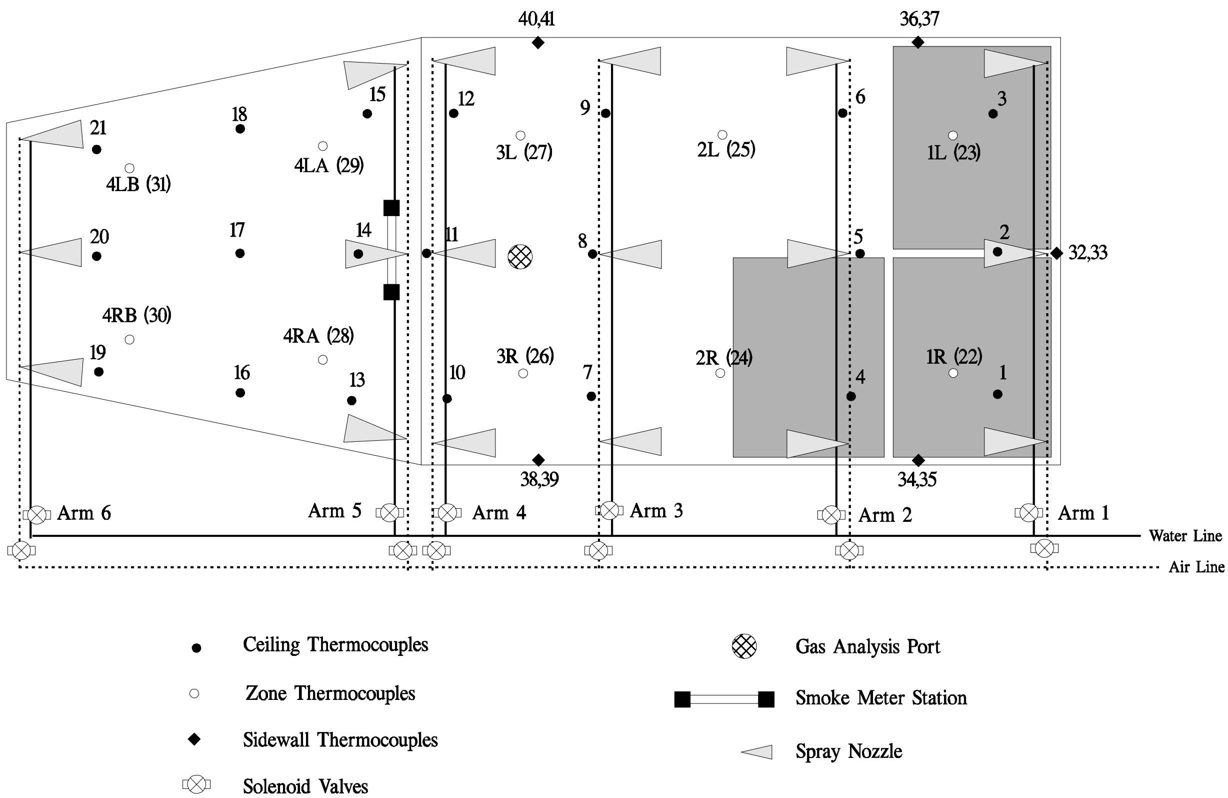


FIGURE 7. SCHEMATIC OF INSTRUMENTATION LOCATION IN DC-10 AFT CARGO

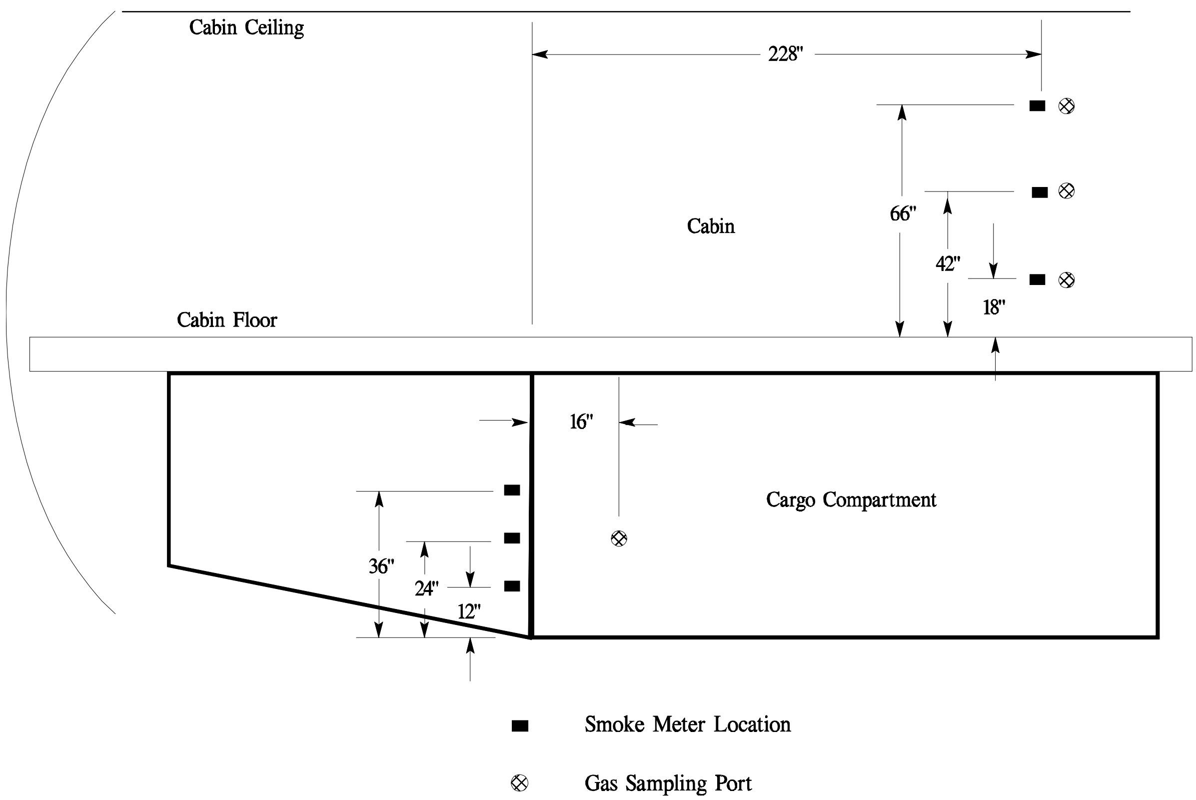


FIGURE 8. GAS SAMPLING STATIONS IN CABIN AND CARGO COMPARTMENT

2.4.1 GEC Marconi Avionics System Test Configuration.

Initially, the system was set at 80 psi air pressure and 60 psi water pressure, which yielded a 2.5 liters per minute (l/min) nozzle flow rate. Nozzle activation and deactivation temperatures were set at 200° and 180°F, respectively. Following the initial test, the deactivation temperature was lowered to 150°F to better control the temperature rise at the ceiling. This resulted in 90 gallons of water being consumed. For the third test the nozzle flow rate was lowered in an effort to reduce the water consumption. The revised configuration did not lower the water consumption, which remained at 90 gallons. The nozzle air pressure was then increased to 110 psi during the fourth test in an effort to produce a different droplet size and spray pattern, but resulted in greater water consumption, 110 gallons. The activation and deactivation temperatures were subsequently raised to 300° and 220°F, respectively, which would allow control of the fire, but at a slightly higher temperature level. This configuration lowered the water consumption to 80 gallons, and did not allow the temperatures in the compartment to escalate to adverse levels. The remaining three tests were conducted using a specified spray duration following initial activation. Once the timed spray period was complete, the nozzles would be reactivated if the temperature was above 300°F or turned off if the temperatures were below 290°F. The three tests were run using 10, 8, and 6 seconds of spray duration, respectively. Table 1 summarizes the spray parameters and water consumption results.

TABLE 1. GEC MARCONI DUAL-FLUID SYSTEM CONFIGURATION AND TEST RESULTS

Test No.	Nozzle Air Pressure (psi)	Nozzle Water Pressure (psi)	Nozzle Flow Rate (l/min)	Nozzle Activation Temperature (°F)	Nozzle Deactivation Temperature (°F)	Test Duration (minutes)	Water Used (gallons)
1	80	60	2.5	200	180	75	undetermined
2	80	60	2.5	250	150	75	90
3	80	40	1.5	250	150	75	90
4	110	60	2.5	250	150	50	110
5	80	60	2.5	300	220	80	80
6	80	60	2.5	300*	290	90	80
7	80	60	2.5	300**	290	90	86.5
8	80	60	2.5	300***	290	90	80

*spray activated for 10 second duration if temperatures exceeded 300°F
**spray activated for 8 second duration if temperatures exceeded 300°F
***spray activated for 6 second duration if temperatures exceeded 300°F

During the initial test, one LD-3 container loaded with shredded-paper-filled cardboard boxes was placed in the forward right corner of the DC-10 aft cargo compartment. An empty LD-3 container was placed behind the test container, and an additional empty LD-3 placed to the side of the loaded container to enclose it (figure 9). The test container utilized transparent Lexan® panels on two sides to allow the fire to burn through in a relatively short time. The loading and construction of the LD-3 container remained standard throughout all the tests. A box located on the floor of the container, adjacent to a Lexan® panel, was ignited using a remotely activated igniter. The igniter consisted of several paper hand towels wrapped with multiple loops of nichrome wire. The energized nichrome wire ignited the paper towels. Temperatures were monitored inside and above the ignited box to ensure ignition. During this initial test, the fire load consisted of 16 large cardboard boxes and 8 small boxes, all filled with shredded paper. All of the water spray arms were activated (18 nozzles) for a period of 1 minute after a 1 minute waiting period to simulate normal crew delay following smoke detection. After this initial spray period, the discharge was terminated, and the normal temperature logic was used to control nozzle activation.

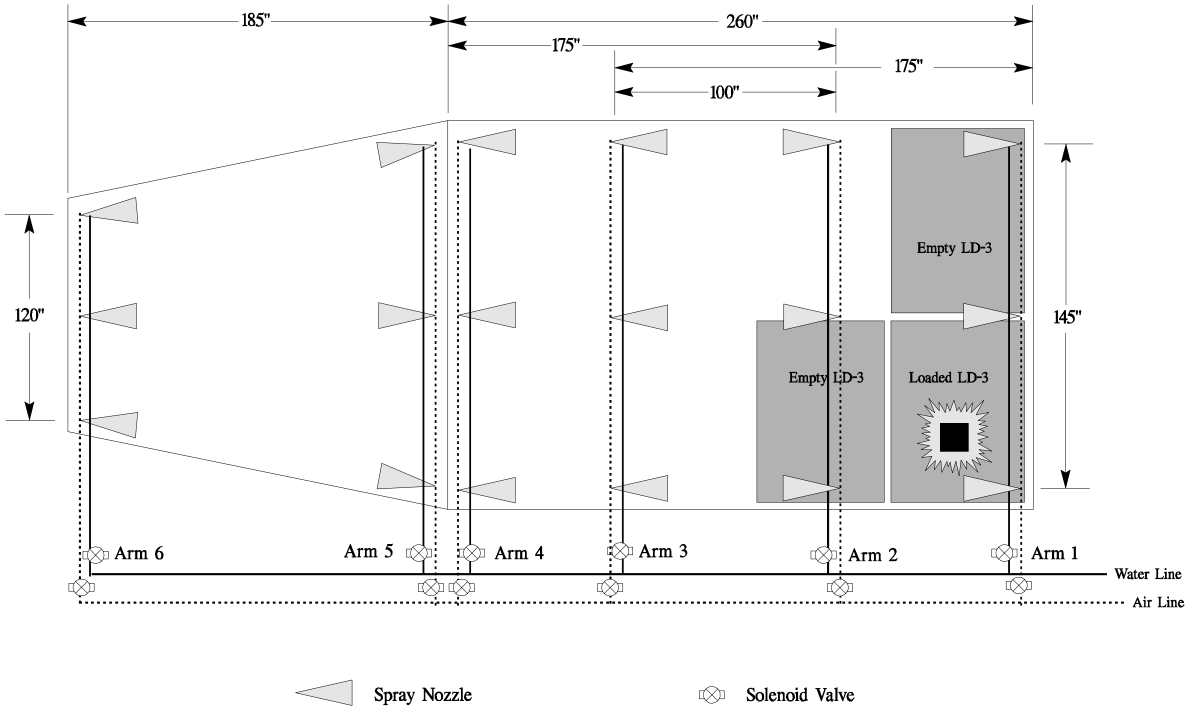


FIGURE 9. LOCATION OF LD-3 CONTAINERS IN AFT CARGO COMPARTMENT

2.4.2 GEC Marconi Containerized Test Results.

For the initial test, zones were activated if either of the two zone thermocouples reached 200°F, and deactivated when the temperature fell below 180°F. This procedure was repeated for the duration of the test. After the initial attempt to ignite the paper-filled box, the temperatures decreased, and there was no apparent fire. After 15 minutes, a decision was made to abort the test, and the compartment door was opened to allow access to the test container in order to relight the boxes. Once the container door was opened, enough air entered to allow the fire to rekindle, and a large fire erupted inside the container. The compartment door was then quickly closed, and the data collection system was initiated shortly thereafter. All of the water spray arms were activated for a period of 1 minute without the prescribed waiting period. After this initial spray period, the discharge was terminated, and the normal temperature logic was used to control nozzle activation. A posttest inspection revealed the Lexan® panels on the test container had completely melted away and the aluminum ceiling of the container was warped, but did not melt through.

During the second test, the identical fire load was ignited on the first attempt. All water spray arms were activated for a period of 30 seconds after smoke detection. Following the initial 30-second spray period, the discharge was terminated and the normal spray logic was used. Individual spray arms were activated if the temperature rose above 250°F and deactivated when the temperature fell below 150°F. Brief periods of elevated ceiling temperatures were experienced at thermocouple 2 above the test container, but these periods were short in duration, typically 1 to 2 minutes. Thermocouple 26 also indicated a slight initial temperature rise to 280°F, which quickly subsided (figure 10).

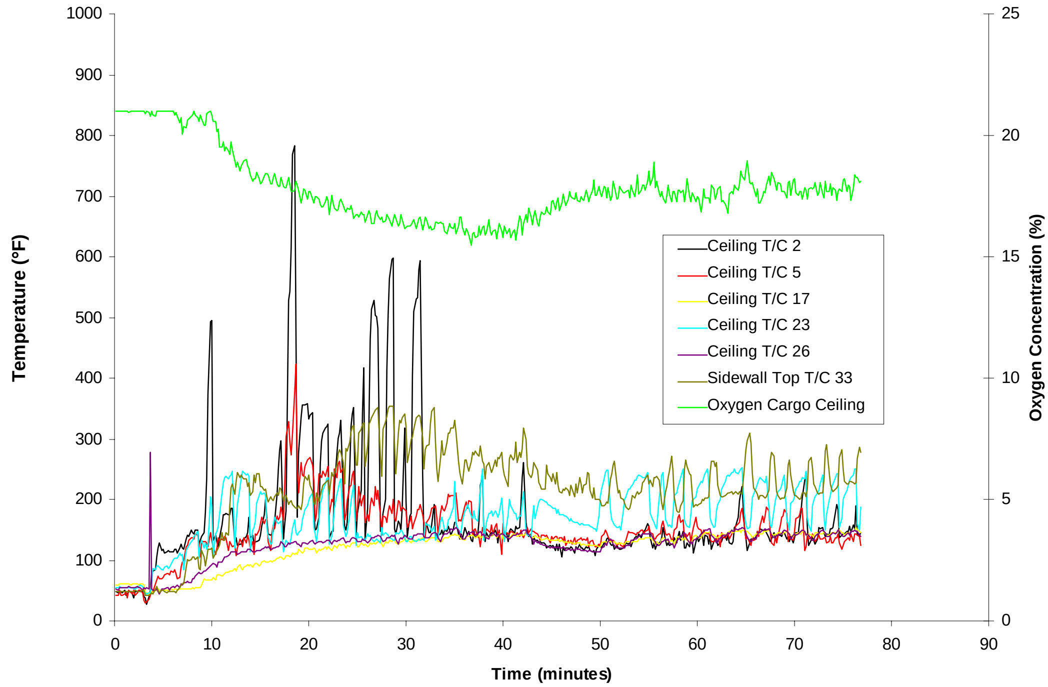


FIGURE 10. GEC MARCONI DUAL-FLUID SYSTEM, TEST 2, TEMPERATURE AND OXYGEN PROFILES

Thermocouple 23 showed the cyclic nature of a water spray-suppressed fire, as the temperature was maintained between 250° and 150°F. The ceiling temperatures in areas more remote to the test container (thermocouple 17) reached a maximum of only 200°F. However, the sidewall temperatures in the test container area (thermocouple 33) reached 350°F, which indicated the fire had penetrated the Lexan® walls of the LD-3 container. Although this was expected, it highlighted the need for additional water mist in the sidewall area. Approximately 90 gallons of water was used during the 75-minute test. A posttest inspection revealed container damage similar to the previous test. During tests 2, 3, and 4, the only difference was the air/water pressure ratio, which affected the droplet size and spray pattern (the flow rate is determined with one zone activated; when additional arms are activated, there is a slight air pressure drop, translating to an increase in water flow of approximately 0.2 liters/min). By increasing the ratio of air pressure to water, the droplet size is reduced. In tests 2 to 4 the temperature, smoke, and gases were nearly identical, indicating the droplet size had little or no impact on controlling the fire.

Similar temperature and gas levels resulted during tests 3, 4, and 5, with the exception of the fourth test in which 110 gallons of water was consumed in only 50 minutes. During this test, the nozzle settings allowed the fire to burn more rapidly, and as a result, the entire spray system was cycled more frequently to keep the temperatures at a minimum. The ceiling temperatures in the forward section of the compartment reached 500°F for brief periods at approximately 30 minutes from the start of the test.

During the fifth test, the nozzle activation and deactivation temperatures were also varied in an attempt to control the fire using less water. In order to accomplish this, the activation temperature was changed from 250° to 300°F, while the deactivation temperature was also raised from 150° to 220°F. With the exception of a brief period between 7 and 12 minutes from the start of the test, the ceiling temperatures did not exceed 400°F, and in most areas of the compartment, the temperatures were kept below 300°F (figure 11). As in the previous tests, the sidewall temperature near the test container (thermocouple 32) experienced a rapid temperature rise as a result of the fire burning out of the test container. As shown, the temperature exceeded 1300°F beginning at 9 minutes into the test, which also coincided with the temperature excursion on thermocouple 2.

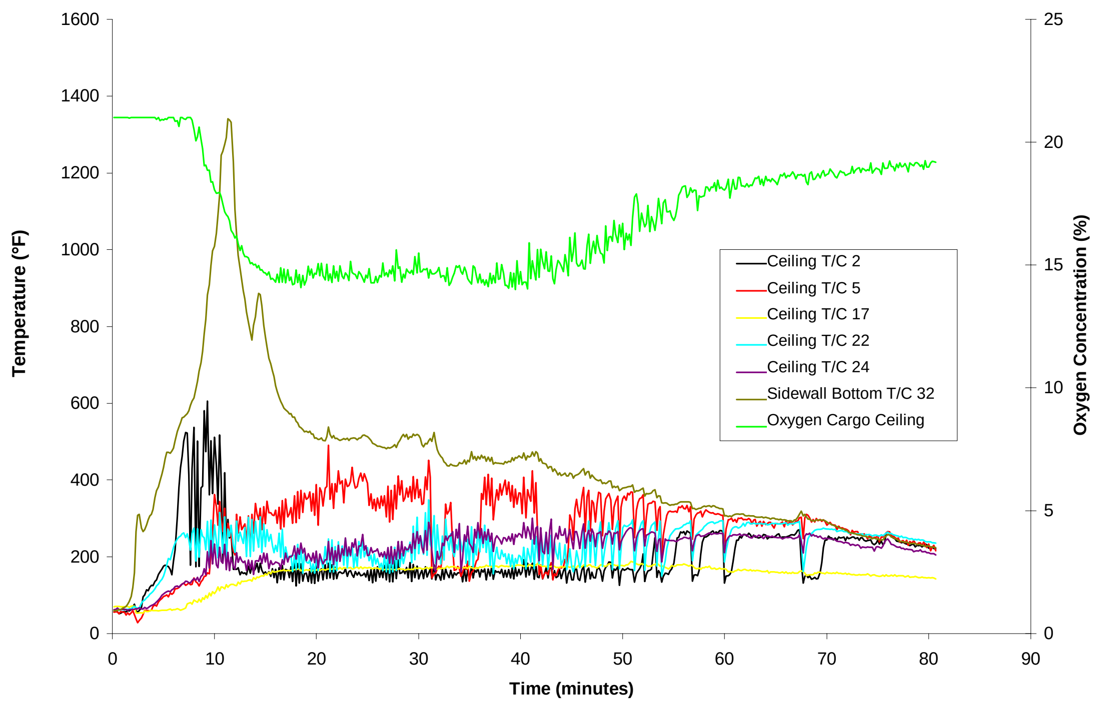


FIGURE 11. GEC MARCONI DUAL-FLUID SYSTEM, TEST 5, TEMPERATURE AND OXYGEN PROFILES

The nozzles were activated for specific time periods of 10, 8, and 6 seconds, during the remaining three tests respectively, following the initial temperature activation (table 1). If, after the initial timed-spray duration the temperatures remained above the deactivation temperature, the nozzles were left activated for an additional time period, and the process was repeated for as long as required. For example, during the sixth test, when the temperature in a zone exceeded 300°F, the water spray was activated for 10 seconds, then switched off if the temperature was below 290°F. If the temperature remained above 290°F, the spray remained on for an additional 10 seconds.

During the sixth test, the spray duration was set at 10 seconds, and at no time did the spray arms require a second activation immediately after the initial 10-second spray. Approximately 80 gallons of water were used during the 90-minute test. The temperatures appeared to be slightly lower during test 6 compared to previous tests, but the level of gases and oxygen depletion was much higher (figure 12). In addition, there was a slight increase in visibility during the timed tests compared to the previous tests.

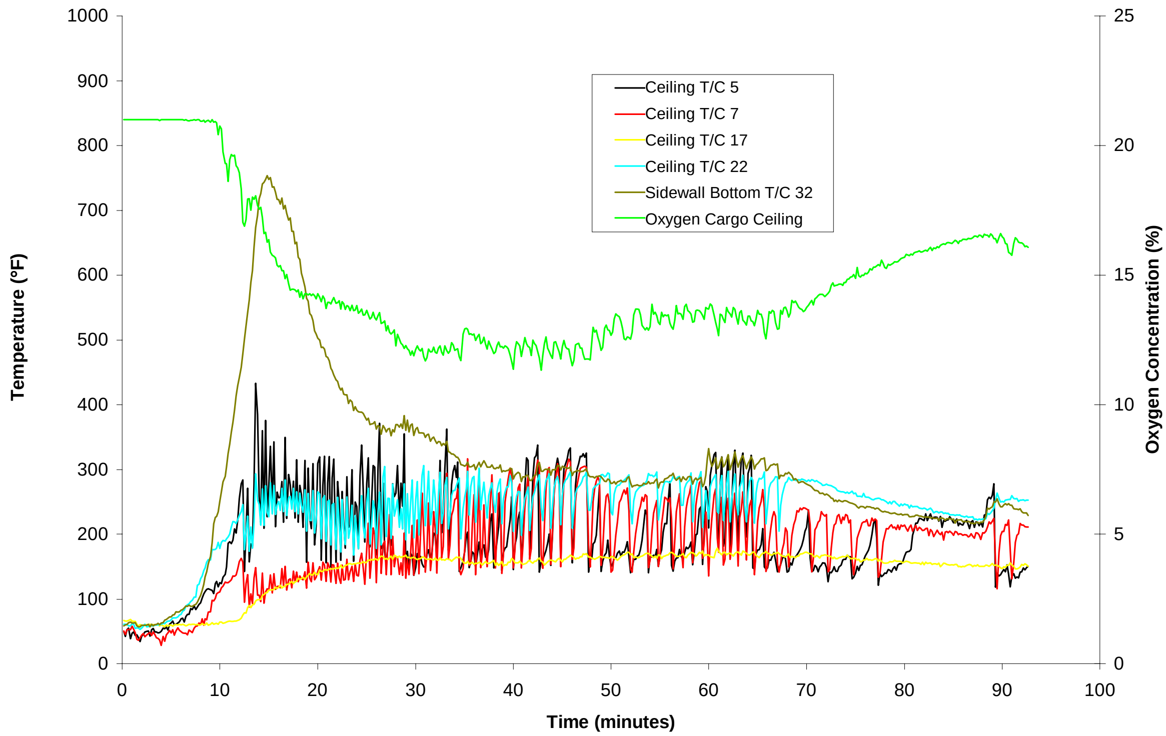


FIGURE 12. GEC MARCONI DUAL-FLUID SYSTEM, TEST 6, TEMPERATURE AND OXYGEN PROFILES

During the seventh test, the spray duration was shortened to 8 seconds. As in the previous test, at no time did the spray arms require a second activation immediately after the initial 8-second spray. Approximately 86.5 gallons of water was consumed during the 90-minute test. During test 8, the spray duration was changed to 6 seconds. This short spray duration required repeated spray applications immediately following the initial spray period. Approximately 80 gallons of water was consumed, and the test duration was 90 minutes (figure 13).

A review of the final three tests using the time duration spray logic produced no obvious differences in gas concentrations, although the ceiling and sidewall temperatures were slightly lower when 8-second spray intervals were used. In general, there seemed to be very little difference in the overall outcome of the tests, as the amount of fire load remaining at the end of the test appeared nearly identical. Approximately 60% to 80% of the fire load was consumed during most tests, which indicated the burning rate of the materials was largely independent of the method of spray application. The results also suggested that the water spray was not suppressing the fire directly, but instead cooling the compartment periphery, thereby protecting adjacent areas.

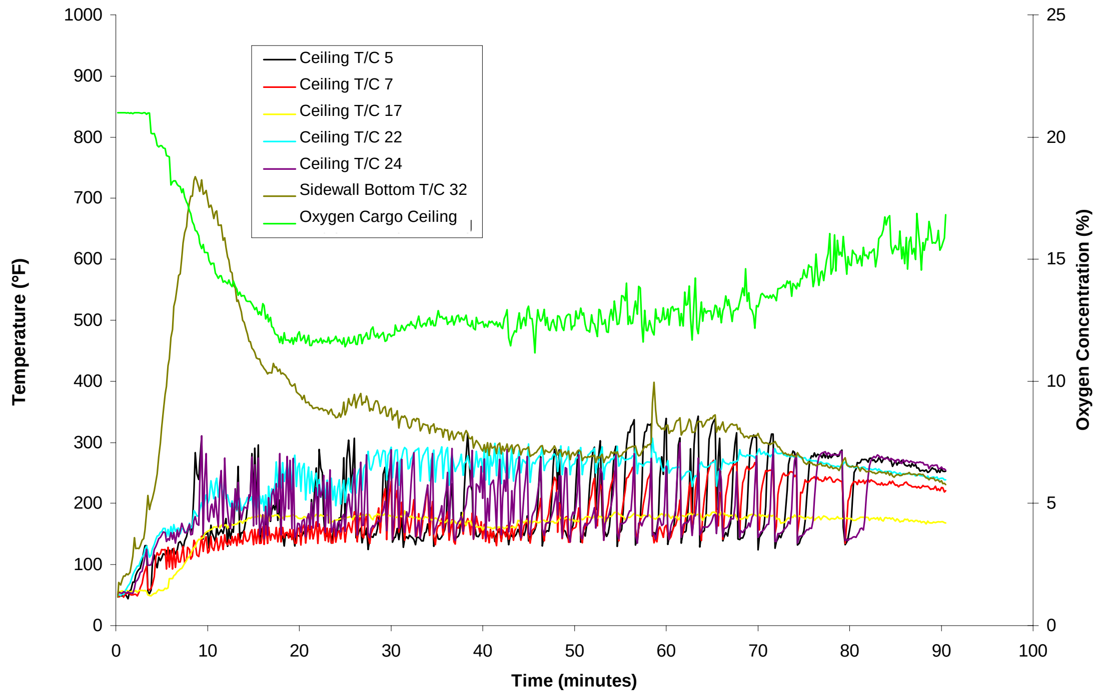


FIGURE 13. GEC MARCONI DUAL-FLUID SYSTEM, TEST 8, TEMPERATURE AND OXYGEN PROFILES

2.5 HUGHES/RELIABLE SYSTEM.

A high-pressure water misting system, co-designed by Hughes Associates Inc. and Reliable Automatic Sprinkler Company, was evaluated in the forward cargo compartment of the DC-10 test article. The system was initially divided into eight identical zones, each containing 14 MX-8™ nozzles that produced a solid cone-shaped spray, as shown in figure 14. The nozzles were oriented horizontally for the purpose of producing mist in the area between the top of the cargo container and the compartment ceiling. Each zone discharged approximately 0.368 gallons per minute (GPM), producing a total flow for the entire system (all zones activated) of approximately 2.94 GPM. The zones were controlled by solenoid valves also shown in figure 14. A thermocouple was installed at the center of each zone near the ceiling to provide control logic data. A smoke detection system identical to the one used in the aft compartment testing was also used. As in the previous tests, after smoke detection, a 1-minute delay period was incorporated to simulate normal crew response, which was followed by the logic-controlled spray zone activation.

Four tests were initially conducted with the Hughes/Reliable system, which were similar to the tests run using the GEC Marconi system. The containerized fire load consisting of 33 shredded, paper-filled boxes was stacked inside a purpose-built LD-3 standardized container. This container was equivalent in shape and size to an actual LD-3 container, with the added feature of being easily refurbished in the event of fire damage to the ceiling and sides. The loaded standard container was positioned between two empty LD-3 containers in the forward cargo compartment.

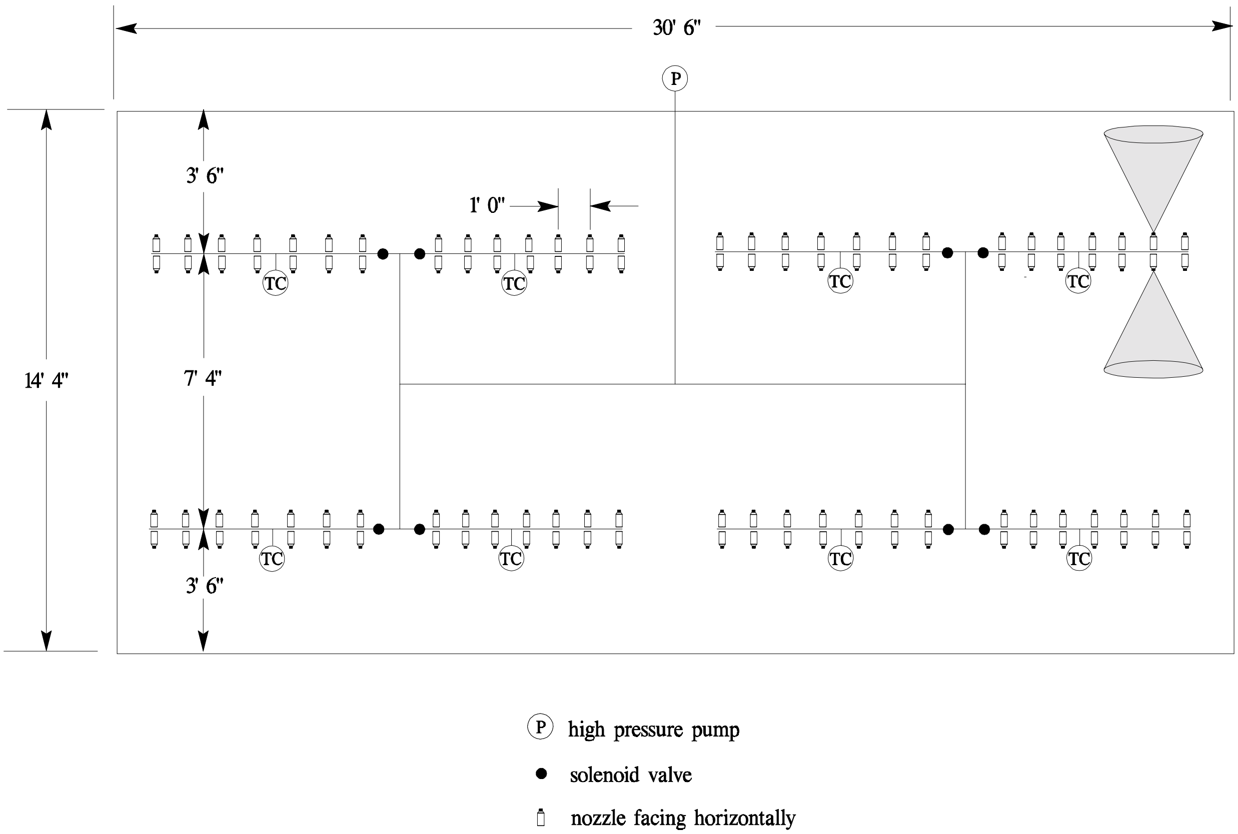
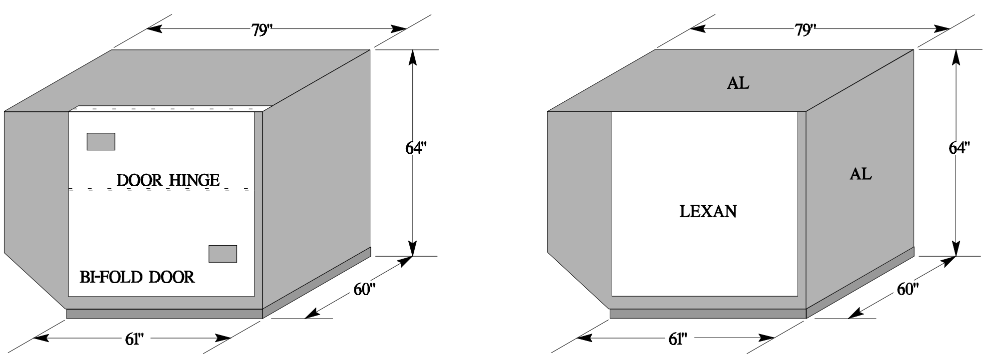


FIGURE 14. ORIGINAL HUGHES/RELIABLE HIGH-PRESSURE SPRAY SYSTEM

The bottom paper-filled box was ignited remotely using a nichrome wire. Figure 15 shows the dimensions of a typical LD-3 container and the standardized LD-3 container, while figure 16 shows the location of the ignition source within the standardized test container. Additional details of the containerized test configuration and materials are shown in table 2. All subsequent tests were initiated in an identical fashion. Thermocouples, smoke meters, and gas sampling stations were installed in the forward compartment as shown in figure 17.



(a) Typical LD-3 Container (b) Standard LD-3 Test Container

FIGURE 15. DIMENSIONS OF TYPICAL LD-3 CONTAINER AND STANDARDIZED TEST CONTAINER

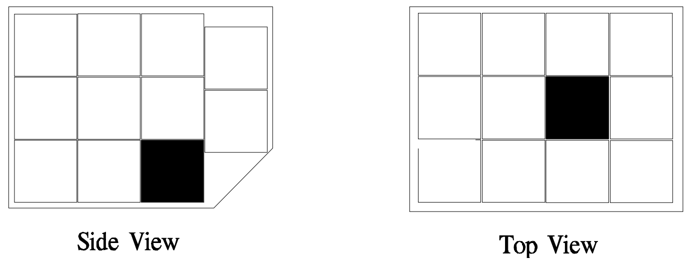


FIGURE 16. PLACEMENT OF BOX CONTAINING IGNITION SOURCE IN LD-3 CONTAINER

TABLE 2. CONTAINERIZED TEST MATERIALS AND DIMENSIONS

Item	Description
Standard LD-3 Container Top and Inner Side Panels	0.0625-inch-thick aluminum
Standard LD-3 Container Front Face	0.084-inch-thick Lexan
Standard LD-3 Container Remaining Panels	0.0625-inch-thick steel
Total Number of Boxes Arranged In LD-3 Container	33
Outer Dimensions of Cardboard Box	18 by 18 by 18 inches
Cardboard Wall Thickness	0.125 inch
Average Weight of Empty Box	2.4 lbs.
Average Weight of Shredded Paper	1.6 lbs.
Ignition Source	7 feet of 18-gauge nichrome wire wrapped 22 times around C-fold paper towels
Outer Dimensions of C-Fold Paper Towels*	3.75 by 10 inches
Ignition Source Location**	Bottom of shredded paper-filled box
Location of Box Containing Ignition Source***	Bottom row, centered, nearest the angled side

*Cardboard boxes folded together, no tape
**All towels are tightly folded lengthwise in half to make a stack 1.875 by 0.50 by 10 inches

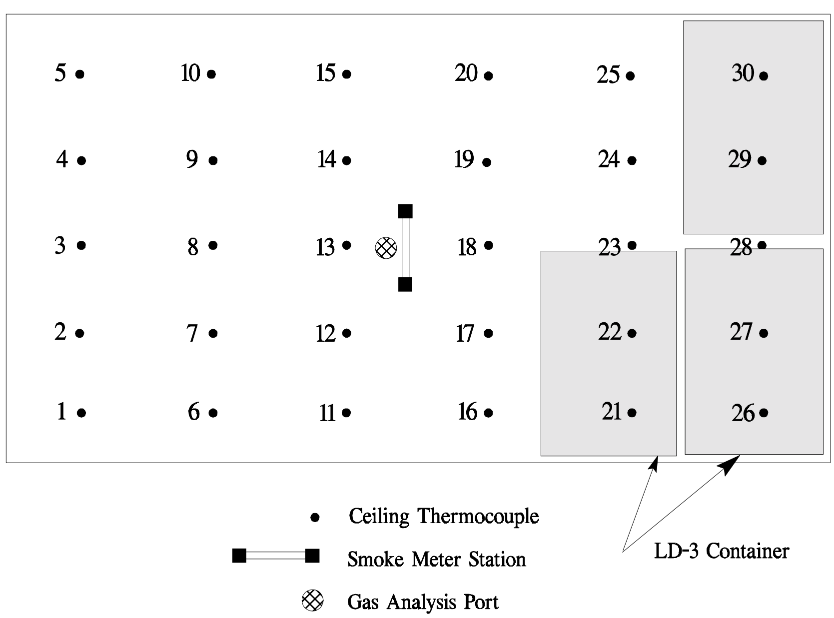


FIGURE 17. INSTRUMENTATION LAYOUT IN DC-10 FORWARD COMPARTMENT

2.5.1 Leakage Rate Testing In DC-10 Forward Cargo Compartment.

Prior to running fire tests, the leakage rate of the forward cargo compartment was determined. As discussed earlier, this was accomplished by flooding the compartment with CO_2 and monitoring the decay rate. A simple formula was again used to calculate the leakage rate from this data. The calculated leakage rate in the forward compartment was 98.43 cubic feet per minute (CFM), which was significantly higher than that of the aft compartment leakage rate, 65 CFM. The difference in leakage rate was attributed to a much tighter aft compartment which was from an actual DC-10 fuselage as opposed to the forward compartment which was constructed in-house from steel framing and corrugated steel, and contained more seams and potential leakage areas. The following calculations were made from the data obtained during the decay monitoring of the CO_2 (figure 18):

Leakage rate calculation at a 1 foot height:

Δt (8% to 2.96%) = 54.42 – 24.58 = 30.84
Δt (6% to 2.22%) = 69.42 – 31.16 = 38.26
Δt (avg.) = 34.55

Leakage rate @ 1 foot = 2298 $ft^3 \div$ 34.55 min
= 66.52 ft^3/min

Leakage rate calculation at a 2 foot height:

Δt (8% to 2.96%) = 43.33 – 23.85 = 19.48
Δt (6% to 2.22%) = 50.42 – 28.75 = 21.67
Δt (avg.) = 20.58

Leakage rate @ 2 foot = 2298 $ft^3 \div$ 20.58 min
= 111.7 ft^3/min

Leakage rate calculation at a 3 foot height:

Δt (8% to 2.96%) = 44.33 – 24.09 = 20.24
Δt (6% to 2.22%) = 50.92 – 29.17 = 21.75
Δt (avg.) = 21.00

Leakage rate @ 3 foot = 2298 $ft^3 \div$ 21.00 min
= 109.4 ft^3/min

Leakage rate calculation at a 4 foot height:

Δt (8% to 2.96%) = 44.83 – 24.08 = 20.75
Δt (6% to 2.22%) = 51.75 – 29.17 = 22.58
Δt (avg.) = 21.67

Leakage rate @ 4 foot = 2298 $ft^3 \div$ 21.67 min
= 106.1 ft^3/min

Avg. Leak Rate in Forward Compartment = (L.R.1 + L.R.2 + L.R.3 + L.R.4) $\div$ 4 = 98.43 ft^3/min

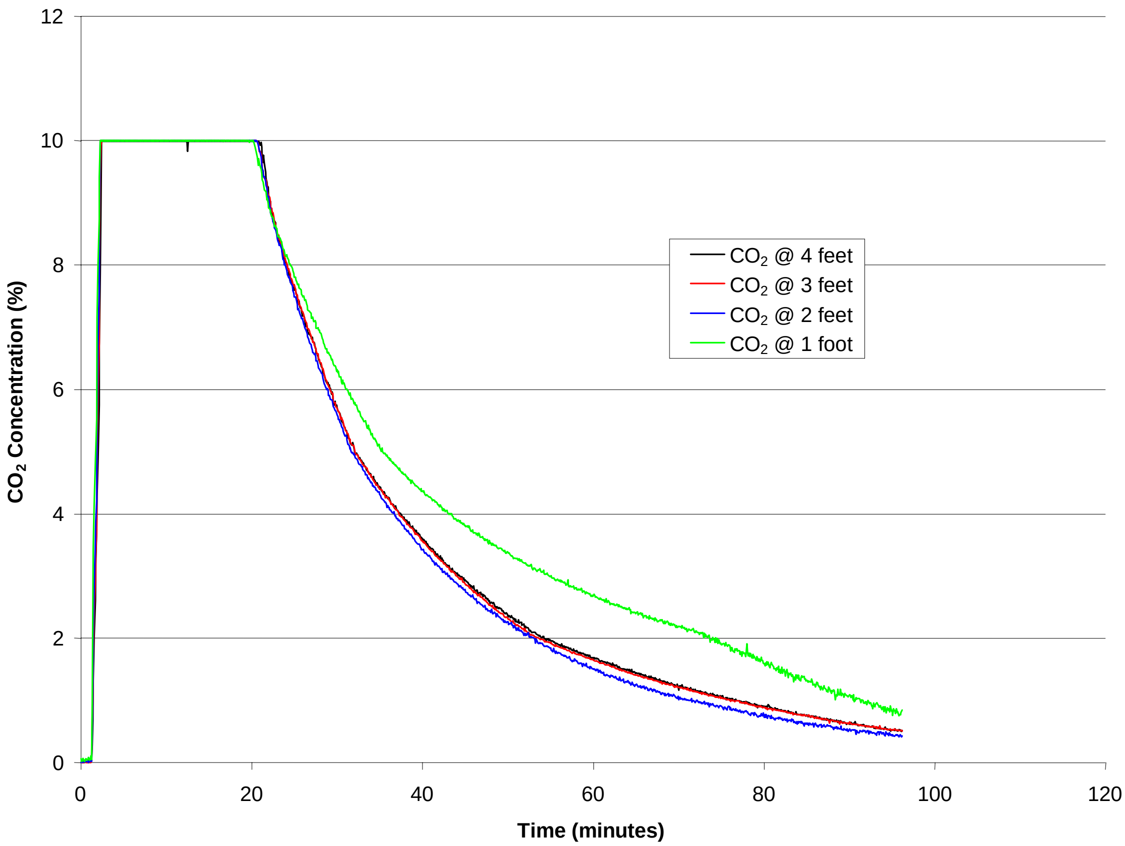


FIGURE 18. CO_2 LEAKAGE RATE TESTS IN DC-10 FORWARD CARGO COMPARTMENT

2.5.2 Hughes/Reliable System Configuration Summary.

The Hughes/Reliable system utilized an electrically driven hydraulic pump to pressurize the water used for spraying. The hydraulic pump was set at 1000 psi for all tests, with individual zone flow rate controlled by the nozzle orifice size. The nozzle activation temperature was initially set at 250°F for the first test, and the controller scanned the zone temperatures every 10 seconds. This configuration resulted in 40 gallons of water consumed for a period of 60 minutes, but with minimal control of the fire. During tests 2, 3, and 4, the zone size was doubled in order to give more complete coverage of the compartment. The nozzle orifice size remained the same for test 2, but was increased 36% to 1.0 GPM in all zones during the third test. The nozzle activation was also lowered to 200°F. This resulted in a substantial increase in water consumption, from 44 gallons to 85 gallons in the third test. During the fourth test, the nozzle activation was changed back to 250°F, and the flow rate was increased to 2.1 GPM in the zone nearest the fire threat. With the exception of a 10-minute period, better control of the fire resulted and the water consumption decreased to 65 gallons (table 3).

TABLE 3. HUGHES/RELIABLE HIGH-PRESSURE SYSTEM CONFIGURATION AND WATER CONSUMPTION

Date	System Configuration	Smoke Detection Time (sec)	System Pressure (psi)	Fire Zone Flow Rate (GPM)	F.Z. Nozzle Flow Rate (GPM)	Nonfire Zone Flow Rate (GPM)	N.F.Z Nozzle Flow Rate (GPM)	Activation Temp (°F)	Scan Rate (sec)	Spray Duration (sec)	Test Duration (minutes)	Water Used (gal)
11/1/94*	initial design	***	1000	0.3675	0.0263	0	0	250	10		60	40
11/2/94*	initial design	***	1000	0.735	0.0263	0.735	0.0263	250	10		90	44
11/3/94*	initial design	***	1000	1	0.036	1	0.036	200	10		90	85
11/4/94*	initial design	***	1000	2.1	0.075	1	0.036	250	5		90	65
3/27/95*	optimized	150	1000	2.1	0.036	1.6	0.114	200	10	20	23	N/A
3/28/95*	optimized	150	1000	2.1	0.036	1.6	0.114	200	10	20	90	64
3/29/95*	optimized	780	1000	1.6	0.028	1.6	0.114	200	10	20	90	34.1
3/29/95*	optimized	120	1000	1.6	0.028	1.6	0.114	200	10	10	90	37.5
3/29/95*	optimized	148	1000	1	0.018	1.6	0.114	200	10	20	90	41.3
3/30/95*	optimized	170	1000	1	0.018	1.6	0.114	200	10	15 on/ 10 off	90	31
3/30/95*	optimized	780	1000	1	0.018	1.6	0.114	150	10		90	34.4
3/31/95*	optimized	140	1000	1	0.018	1.6	0.114	250	10		90	31.6
3/31/95**	3rd design	120	1000	1	0.018	1.6	0.114	250	10		90	42
3/31/95**	3rd design	120	1000	1	0.018	1.6	0.114	150	10		90	24.8

*containerized fire load condition
**bulk loaded fire condition
***not recorded

Following the four initial tests, the spraying configuration was optimized in an attempt to better control the fire with less water, and eight additional tests were conducted. During the first two optimized tests, the flow rate in the nonfire threat areas was increased to 1.6 GPM, but remained at 2.1 GPM in the fire-threat zone. The nozzle activation temperature was decreased to 200°F, resulting in 64 gallons of water consumed during the second test. During the 3rd and 4th optimized tests, the flow rate was dropped to 1.6 GPM in the fire zone, resulting in 34.1 and 37.5 gallons of water consumed, respectively. During the remaining four tests, the flow rate was reduced to 1.0 GPM in the fire zone, in an effort to further reduce water consumption.

<u>2.5.3 Containerized Test Results Using Hughes/Reliable Initial Design System</u>.

During the first test, only half of the zones (those nearest to the fire test container) were active (figure 19). The operating pressure was adjusted to 1000 psi at the nozzles. The activation temperature was set to 250°F for 10 seconds. After the 10-second interval, if the temperature fell below 250°F, the zone was shut off.

The initial test progressed for 60 minutes and used 40 gallons of water. It appeared that the fire was not fully suppressed for a majority of the 60-minute test, with minimal cooling produced by the water mist system. Temperatures on the order of 1000°F were commonplace throughout the compartment. The temperatures along the centerline and down the sides of the compartment were higher than over the center of the cargo container.

In order to better control the fire during the second test, the zone size was doubled, creating four zones of protection for the entire compartment as shown in figure 20. This was accomplished by simultaneously actuating two solenoid valves for each of the four zones. Each zone contained 28 nozzles, while the activation temperature remained at 250°F for 10 seconds, controlled by a single thermocouple centrally mounted in each zone. During the test, temperatures were significantly reduced, reaching a peak of approximately 500°F for a period not exceeding several minutes, but the water usage increased slightly to 44 gallons for the longer test.

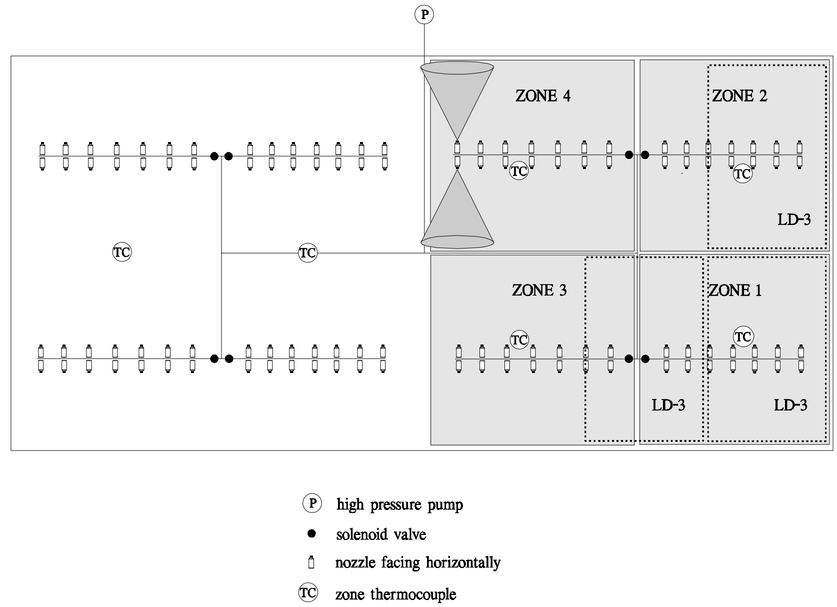


FIGURE 19. HUGHES/RELIABLE HIGH-PRESSURE SPRAY SYSTEM, INITIAL DESIGN, TEST 1

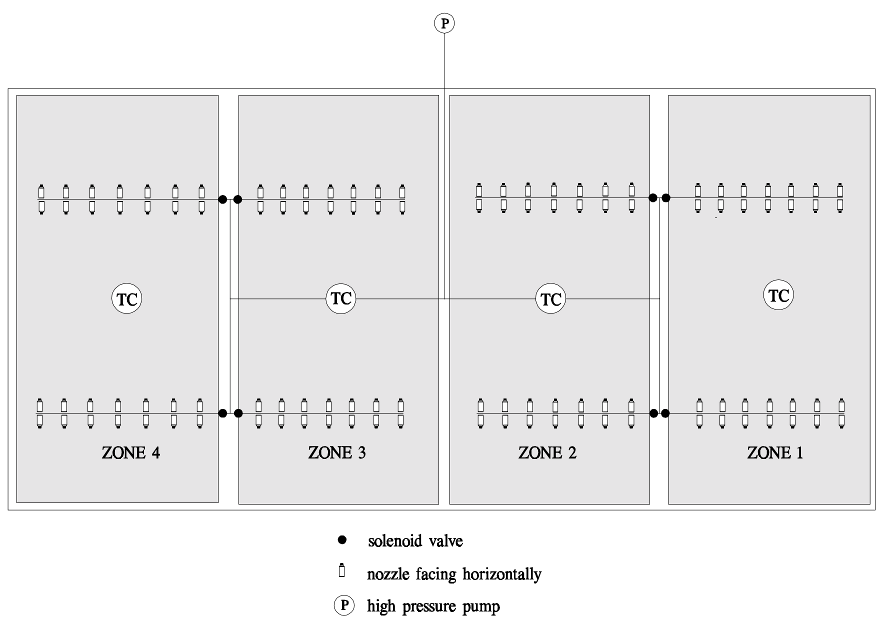


FIGURE 20. HUGHES/RELIABLE HIGH-PRESSURE SPRAY SYSTEM, INITIAL DESIGN, TESTS 2-4

Since additional water was needed in the LD-3 test-container area, the nozzle flow rate was increased by 36% to 1.0 GPM by changing to larger nozzles, and the system activation temperature was decreased to 200°F. During the third test, control of the fire was lost in zone 1 for a period of 25 minutes as temperatures escalated to 1000°F. The temperatures in zones 2 through 4 were much more controlled, reaching a peak of approximately 200°F. The lower activation temperature increased the water usage to 85 gallons, but did not keep the temperatures in zone 1 from rising out of control.

A fourth test was conducted in which higher output nozzles were installed in zone 1, doubling the flow rate in this area to 2.1 GPM. In addition, the scan rate was decreased from 10 seconds to 5 seconds, and the activation temperature was restored to 250°F. During this test, temperatures at several locations in the ceiling escalated beyond 1000°F for a 10-minute period between 12 and 22 minutes from test start. Other than this 10-minute period, the system was able to maintain reasonable control of the fire, and the water usage was reduced to 65 gallons. The temperatures remained between 200° and 300°F during the 90-minute test, with brief excursions of between 400° and 500°F (figure 21).

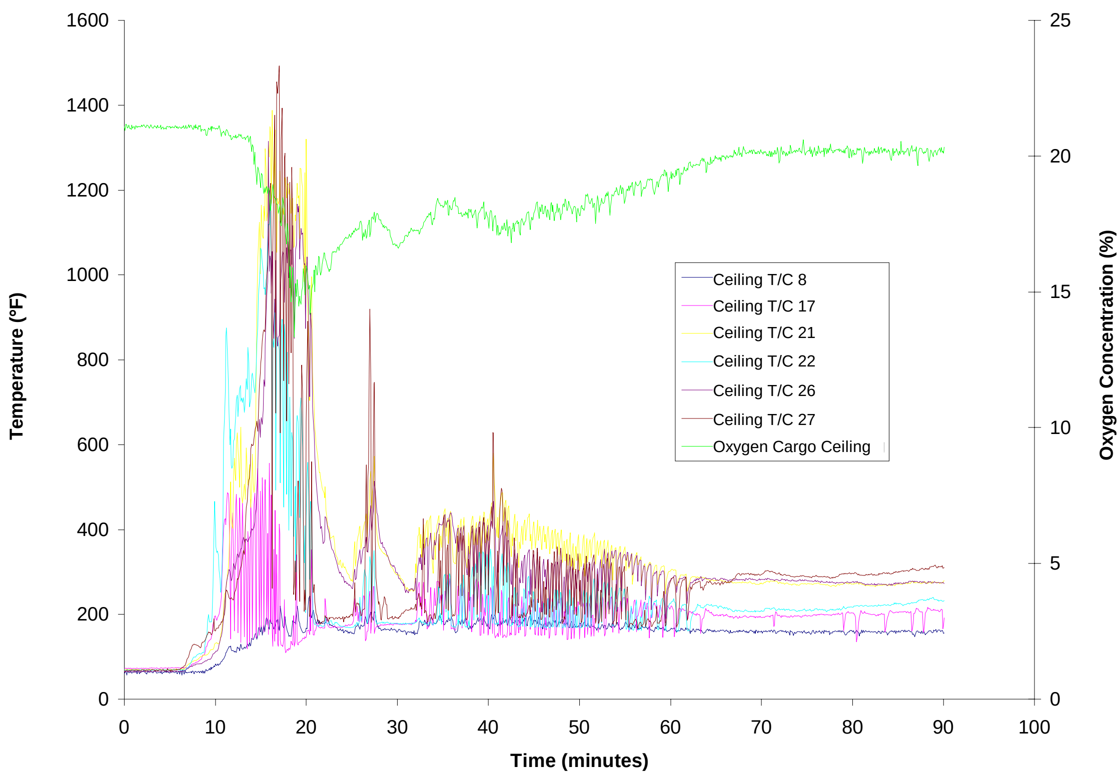


FIGURE 21. HUGHES/RELIABLE INITIAL HIGH-PRESSURE SPRAY, TEST 4, TEMPERATURE AND OXYGEN PROFILES

2.6 HUGHES/RELIABLE OPTIMIZED SYSTEM CONFIGURATION.

An additional eight tests were conducted in which the previous high-pressure system was optimized in an effort to obtain a fire protection system that would be considered a viable replacement for the current Halon 1301 system. The nozzle configuration used during the initial four tests required an excessive amount of water (minimum of 65 gallons to control the fire). In order for a system to be considered as a potential replacement, the water usage would have to fall somewhere in the 10 to 20 gallon range for 90 minutes of protection. To accomplish the task, a new nozzle configuration was conceived, and another series of tests were conducted (figure 22). As shown, the new nozzle arrangement required a heavy concentration of nozzles around the perimeter of the LD-3 container.

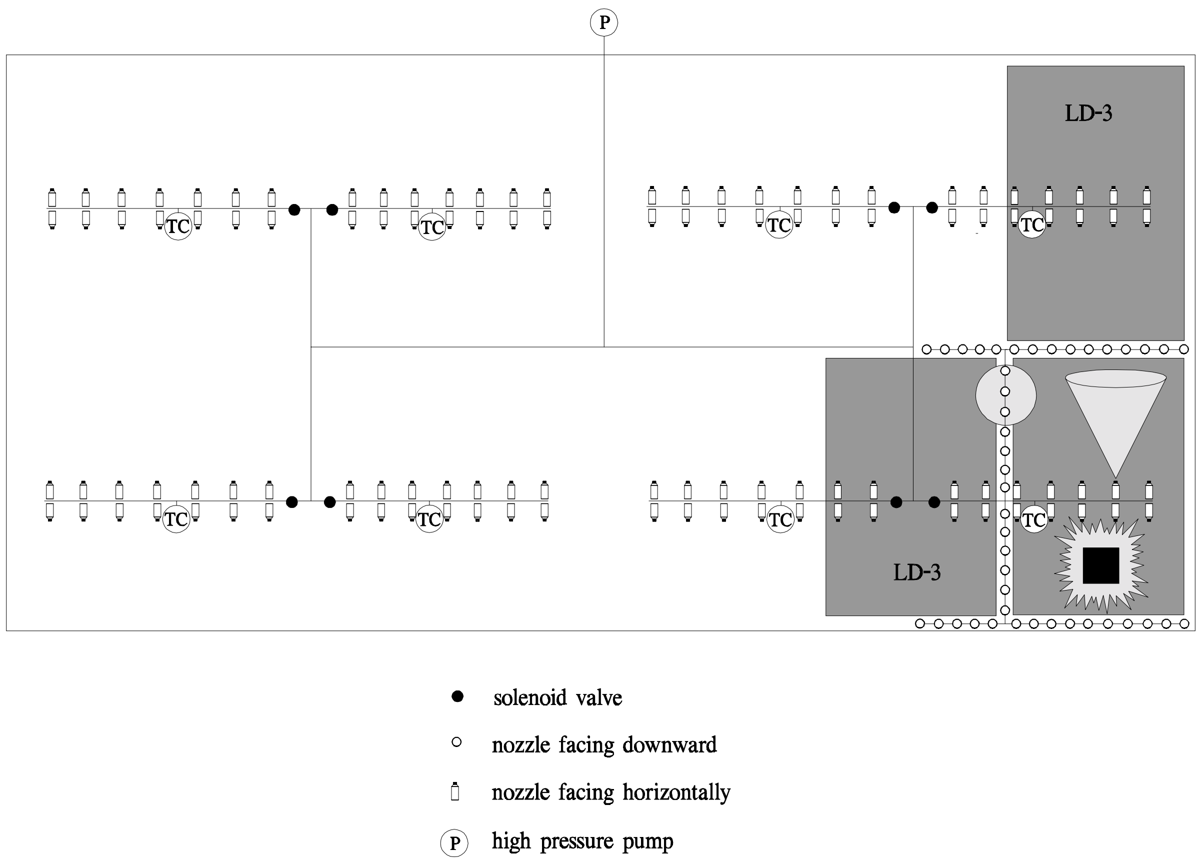


FIGURE 22. HUGHES/RELIABLE OPTIMIZED HIGH-PRESSURE SPRAY SYSTEM

The intent of this spraying configuration was to totally suppress the fire in the fire load area, thereby eliminating the need for activation of the remaining spray zones in the more remote areas. This logic was used in the optimization of the cabin spray system (i.e., applying the water only where the most direct fire threat existed, essentially reducing the amount of water wasted in other nonthreat areas). In the fire zone, a total of 43 MX-8™ nozzles were arranged at the ceiling of the compartment along the perimeter of the LD-3 container, with the discharge directed downward toward the floor of the compartment. Additionally, there were 14 MX-8™ nozzles that discharged horizontally at the ceiling of the compartment to cool the area above the container. This 57-nozzle configuration resulted in a flow rate of 2.1 GPM in the fire zone, or approximately 0.036 GPM per nozzle. The flow rate of the nozzles located in the nonfire zones was increased substantially from 0.036 to 0.114 GPM for a total flow rate of 1.6 GPM.

2.6.1 Containerized Test Results Using Hughes/Reliable Optimized System.

During the initial test using the new configuration, a mechanical failure of the piping occurred and the test was aborted after 23 minutes. A second test was conducted under identical conditions with more favorable results. During this test, the spray was activated manually in the fire zone when the temperature reached 200°F, and left on for 20 seconds. The spray in the nonfire zones was activated automatically when the temperature reached 200°F and left on until the temperature (measured by the computer once every 10 seconds) dropped below 200°F. The system held temperatures in the fire zone below 150°F for the duration of the 90-minute test. The adjacent zone, however, experienced five temperature spikes ranging from 400° to 800°F during the initial stages of the test, but they only lasted on the order of 10 seconds. A total of 64 gallons of water was required to keep the fire suppressed.

Following these initial tests, the fire zone nozzles were replaced with lower flow rate nozzles for the third and fourth tests in an effort to reduce the water consumption. The new nozzles produced 0.028 GPM for a zone flow rate of 1.6 GPM, identical to the nonfire zone flow rate. In test 3, smoke detection occurred at 13 minutes. The spray was activated for a period of 20 seconds when the temperature exceeded 200°F. With the lower flow-rate nozzle, the system was again capable of holding the temperatures in the fire zone below 150°F for the duration of the 90-minute test. The adjacent zone again experienced several brief temperature excursions ranging between 350° and 500°F which lasted on the order of 10 seconds each, comparable to the previous test. Most notably was the relatively low water usage, which was reduced to 34.1 gallons.

A fourth test was conducted in which the spray duration was reduced from 20 seconds to 10 seconds; all other test parameters remained identical to the previous test. The test progressed for 90 minutes, and the spray duration adjustment resulted in no significant temperature differences; however, the water consumption increased slightly to 37.5 gallons.

After successfully suppressing the containerized fire using 34.1 and 37.5 gallons during the 3rd and 4th optimized tests, the nozzle configuration was again altered in an attempt to further reduce water consumption. This was accomplished by simply removing every third nozzle, reducing the flow rate by 1/3 to 1.0 GPM in the fire zone (the nonfire zones were unaltered). During the initial stage of test 5, for a short period (1 to 2 minutes) temperature spikes were observed above 300°F in the fire zone and above 600°F in the adjacent zone (figure 23). As with the previous tests, these spikes were of short duration. For the remainder of the test, the system held temperatures below 300°F, usually around 150°F. The reduced flow rate appeared to allow the fire to grow slightly more intense during the early stages of the test, which resulted in greater overall water consumption. During the 90-minute test, 41.3 gallons were used.

Further refinements were made to the activation temperature and the spray logic to minimize water consumption. During test 6, the spray was activated manually in the fire zone when the temperature reached 200°F. The activated spray was turned on for 15 seconds and then switched off for 10 seconds for the remainder of the test, irrespective of the temperatures. This sequence was maintained for the first 60 minutes of the test, resulting in 28 gallons of water consumed.

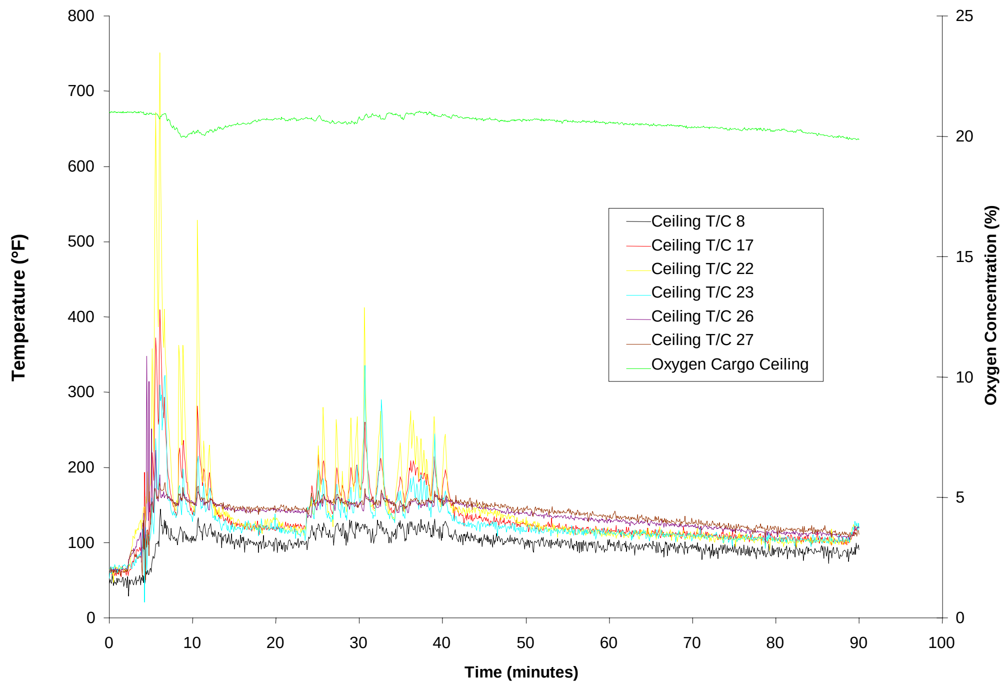


FIGURE 23. HUGHES/RELIABLE OPTIMIZED SYSTEM, TEST 5, TEMPERATURE AND OXYGEN PROFILES

For the remaining 30 minutes, the spray was activated for 5 seconds and then switched off for 30 seconds, again irrespective of zone temperature. A total of three additional gallons of water were used during this period. If the spray sequence used in the first 60 minutes were continued during this latter period, a total of 42 gallons would have been consumed instead of 31, assuming a constant fire hazard. At the end of the test, more heat remained in the container, as if the entire burning sequence was delayed. This spray logic also reduced the temperatures in the adjacent zone, resulting in only two excursions above 200°F (figure 24).

A subsequent test was run in which the activation temperature was reduced from 200° to 150°F (Optimized Test 7). The spray was activated automatically in the fire zone once the temperature reached 150°F. The computer scanned the thermocouples in 10-second intervals, which usually resulted in a 10-second spray interval followed by a 10-second off interval during the periods of greater fire intensity and longer off cycles during less intense periods. This spray logic enabled the system to hold temperatures in and around the fire zone below 150°F for the duration of the 90-minute test, with exception of the area directly above the fire container, which rose to 300°F near the end of the 90-minute test. Temperatures in areas more remote to the fire were also kept at a minimum, in all cases less than 150°F (figure 25).

A total of 34.4 gallons of water was consumed. A review of the temperature data compiled from all the tests indicated the spray configurations used in tests 6 and 7 held the overall temperatures at the lowest level.

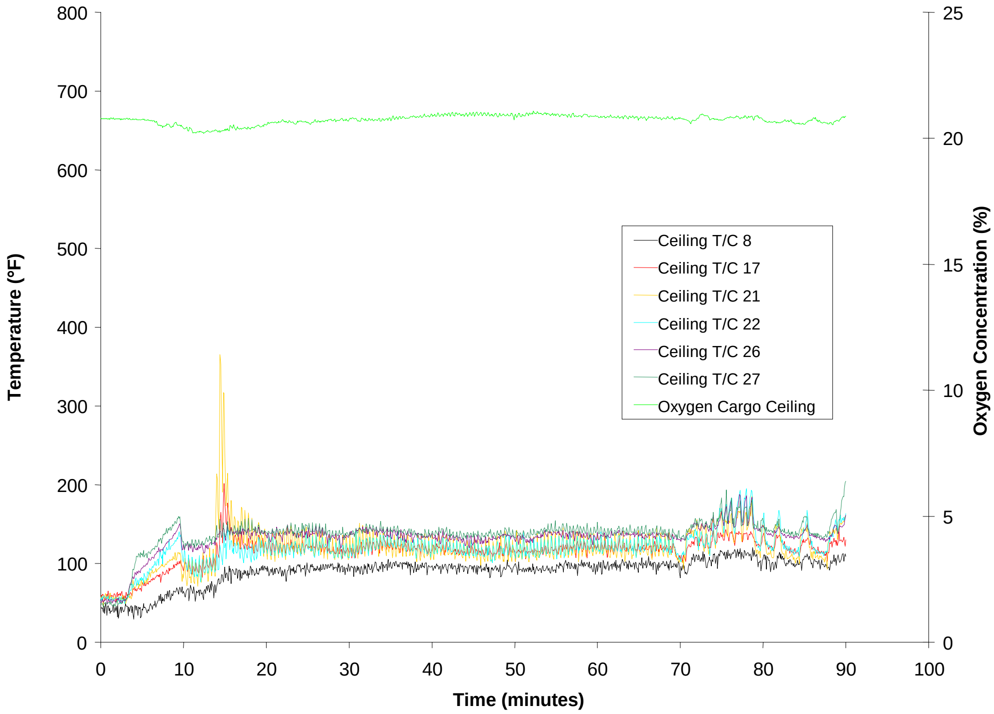


FIGURE 24. HUGHES/RELIABLE OPTIMIZED SYSTEM, TEST 6, TEMPERATURE AND OXYGEN PROFILES

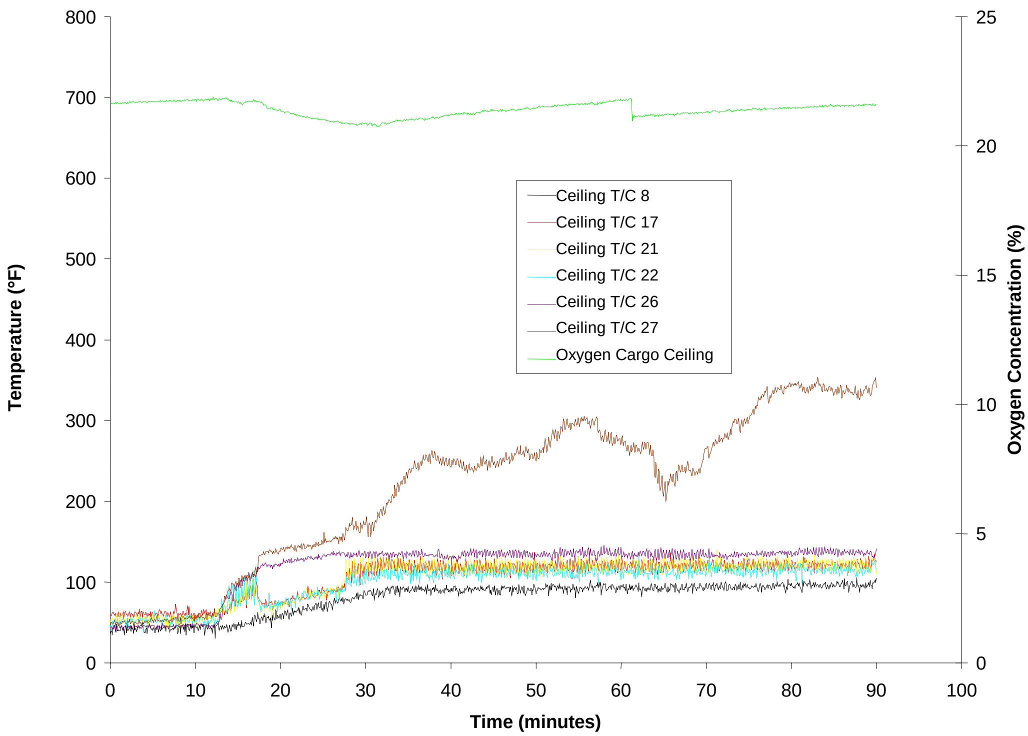


FIGURE 25. HUGHES/RELIABLE OPTIMIZED SYSTEM, TEST 7, TEMPERATURE AND OXYGEN PROFILES

A final test was conducted in which the activation temperature was increased from 150° to 250°F. As in the previous test, spray activation was controlled automatically in the fire zone. During the test, temperature spikes between 300° and 400°F were observed in the fire zone and spikes between 400° and 700°F in the adjacent zone for the duration of the test (figure 26). The O_2 concentration remained close to 21% during the test, although a malfunctioning analyzer indicated a rise above this level. It was concluded that the 250°F activation temperature setting allowed the fire to grow too large for the system to be effective. A total of 31.6 gallons of water were consumed during the 90-minute test.

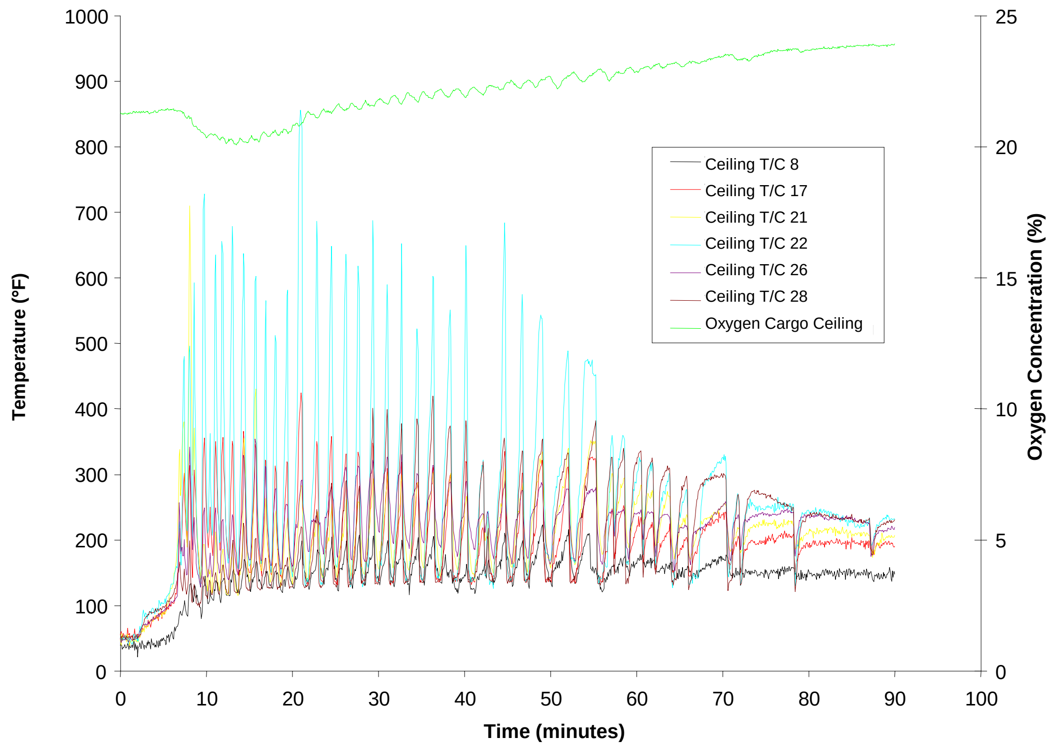


FIGURE 26. HUGHES/RELIABLE OPTIMIZED SYSTEM, TEST 8, TEMPERATURE AND OXYGEN PROFILES

Posttest inspection of the fire load materials revealed results similar to those obtained during the dual-fluid nozzle tests. Approximately 60% to 80% of the materials were consumed, indicating the water spray did not suppress the fire directly, but instead cooled the compartment periphery, thereby protecting adjacent areas.

2.6.2 Improved Hughes/Reliable Optimized System Configuration for Bulk-Loaded Tests.

Two additional tests were conducted with simulated bulk-loaded cargo and employing a third configuration (figure 27). In order to evaluate the effectiveness of the spray system during a simulated bulk-loaded cargo fire, 56 shredded, paper-filled boxes were arranged in two tiers of 7 by 4 boxes. The area of heavily concentrated nozzles was essentially doubled, producing a high protection area twice the size of the area protected during the containerized tests. The flow rate in each of these zones remained at 1.0 GPM (identical to the optimized tests that needed the least amount of water). A thermocouple was installed at the center of each zone near the ceiling to provide control logic data. An identical smoke detection system was also used. As in the previous tests, following smoke detection, a 1-minute delay period was incorporated to simulate normal crew response, followed by the temperature controlled spray zone activation.

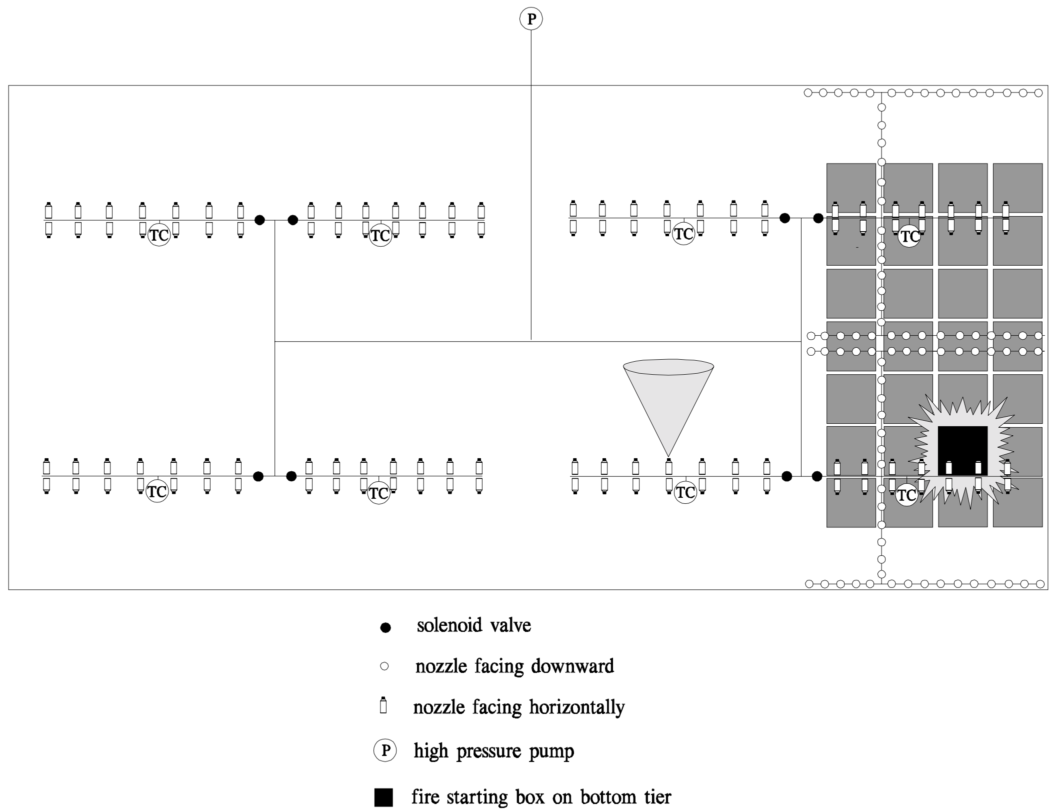


FIGURE 27. IMPROVED HUGHES/RELIABLE OPTIMIZED SYSTEM FOR BULK-LOADED CARGO

2.6.3 Bulk-Loaded Test Results Using Improved Hughes/Reliable Optimized System.

During the first test, the spray was activated when the ceiling temperature reached 250°F, which allowed temperature excursions within the compartment to reach elevated levels (300° to 1000°F) during the initial 10 minutes of the test (figure 28). Because the high activation temperature allowed the fire to grow sizably before allowing the system to gain control, an excessive 42 gallons of water was used for the 90-minute test. It was concluded that the 250°F activation temperature setting allowed the fire to grow too large for the system to be effective. The second and final test in the bulk-loaded configuration used a 150°F activation temperature, which produced noticeably superior results in terms of both the temperatures observed and the amount of water required (24.8 gallons). The system held temperatures both in the fire zone and in the adjacent zone below 150°F with the exception of a few temperature spikes exceeding 400°F (figure 29). These temperature spikes (as with others observed during this test series) lasted for approximately 10 seconds.

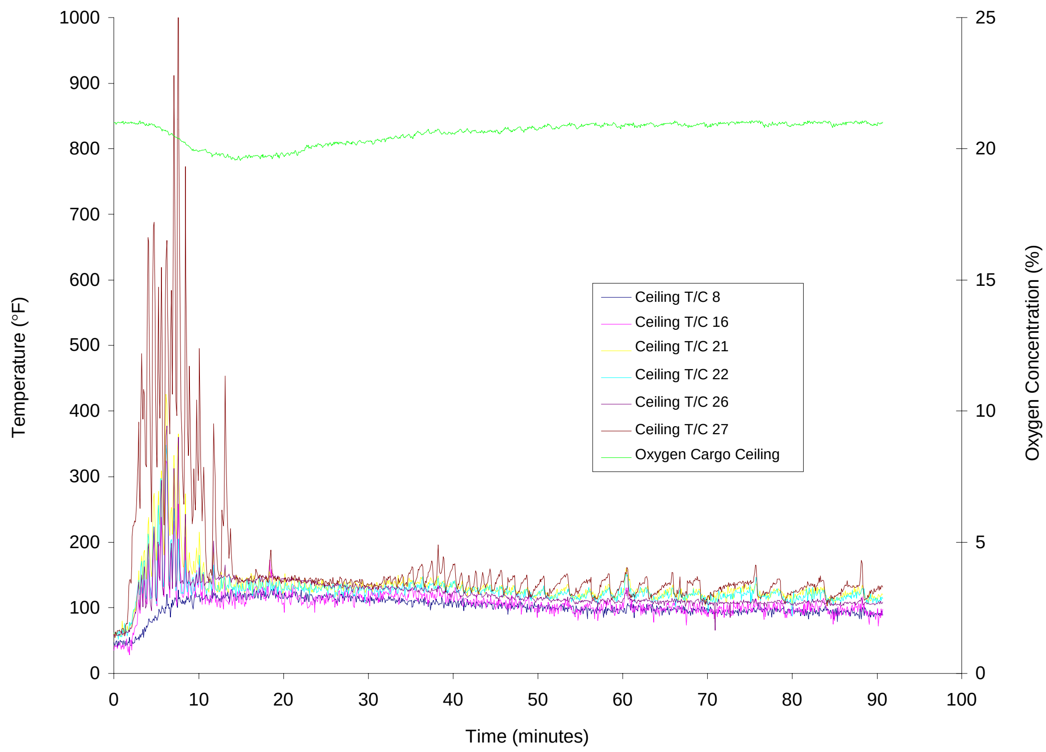


FIGURE 28. IMPROVED HUGHES/RELIABLE OPTIMIZED SYSTEM FOR BULK-LOADED CARGO, TEST 9, TEMPERATURE AND OXYGEN PROFILES

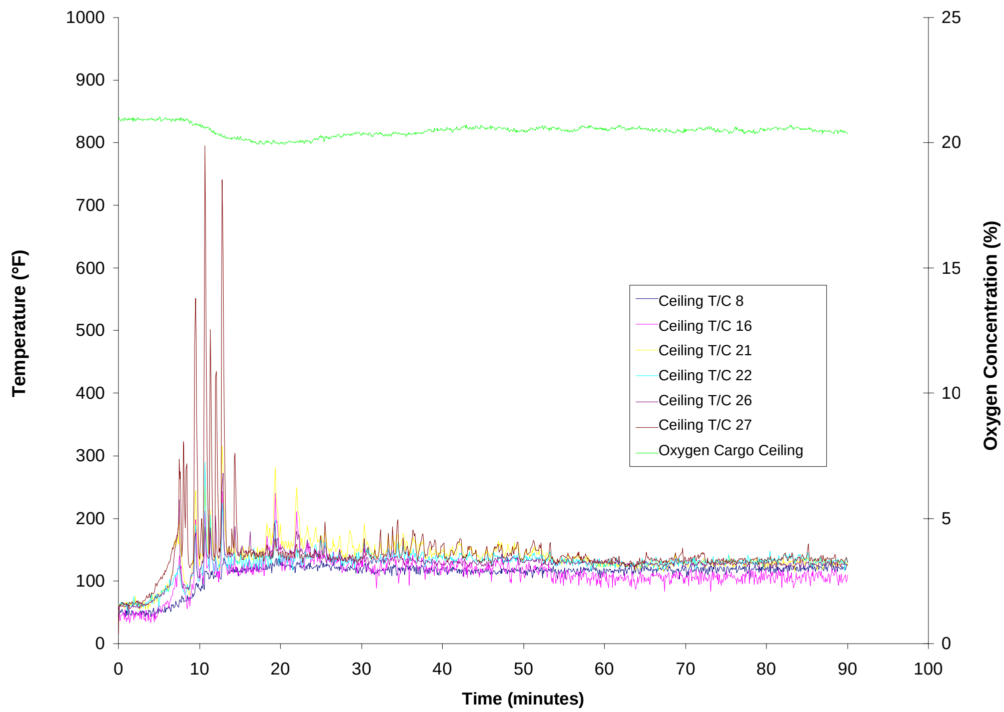


FIGURE 29. IMPROVED HUGHES/RELIABLE OPTIMIZED SYSTEM FOR BULK-LOADED CARGO, TEST 10, TEMPERATURE AND OXYGEN PROFILES

2.7 ENVIRONMENTAL ENGINEERING CONCEPTS SYSTEM.

Additional tests were conducted using a high-pressure water misting system supplied by Environmental Engineering Concepts. The "Enviromist" system was installed in a B727 cargo compartment, and utilized a high-pressure fog between 800-1200 psi, distributed via four thermally activated zones (figure 30). Similar to the previous high-pressure system, the zone activation and deactivation temperatures could be preprogrammed in order to determine optimum settings.

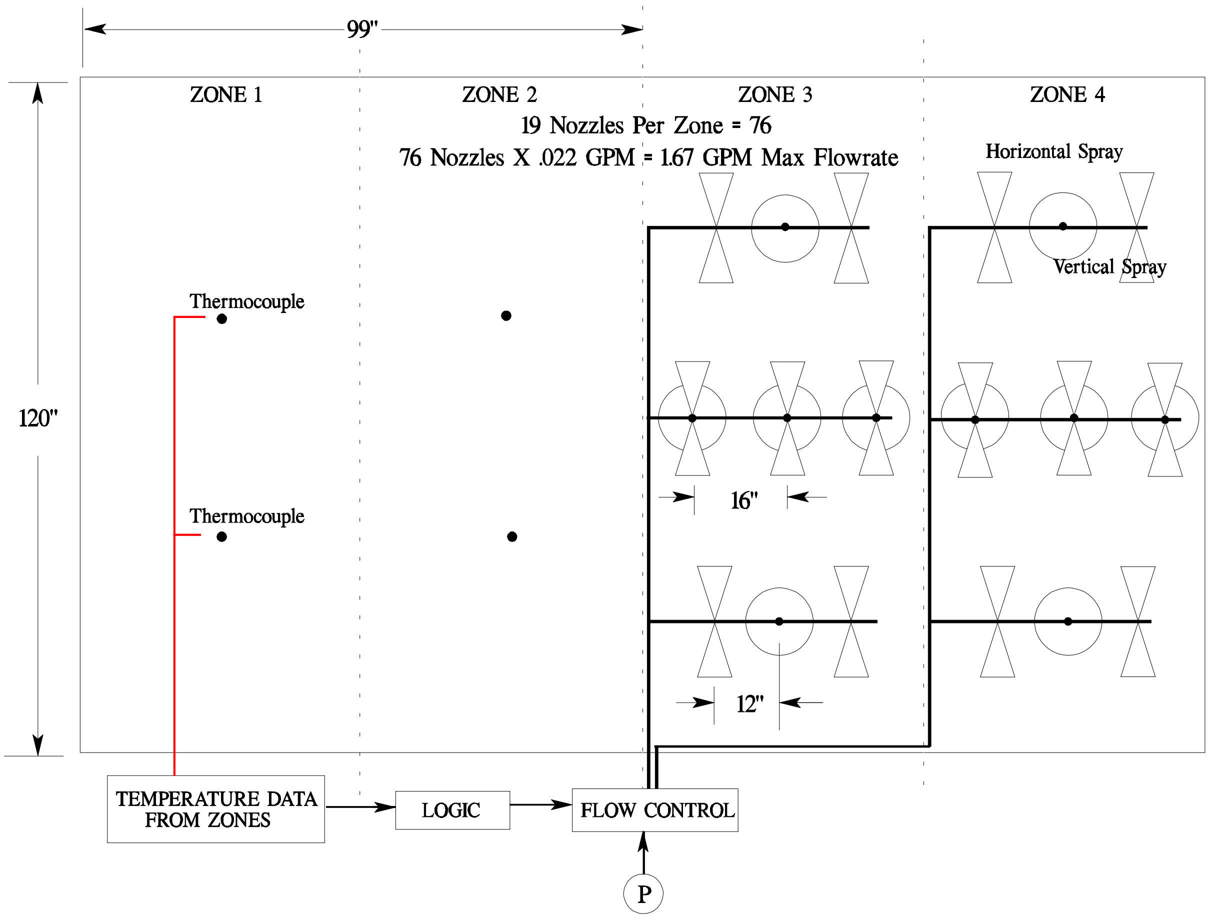


FIGURE 30. ENVIRONMENTAL ENGINEERING CONCEPTS HIGH-PRESSURE WATER MIST SYSTEM SCHEMATIC

Two bulk-loaded tests were conducted, both with favorable results. During these tests, ten shredded, paper-filled boxes were arranged in the compartment, as shown in figure 31. The purpose of the tests was to insure the system was performing normally, and also to determine the capability of suppressing the bulk-load fire. Results indicated the system effectively suppressed the fire for 90 minutes, using approximately 12 gallons of water.

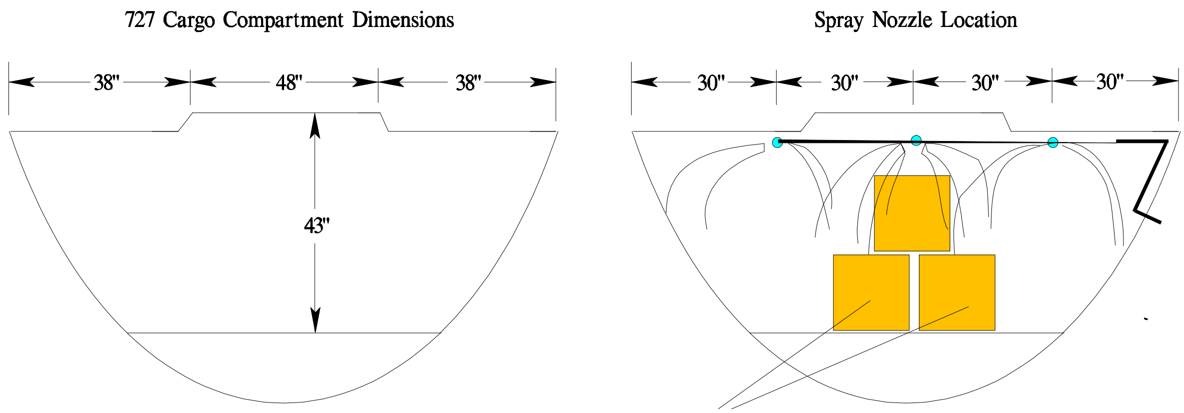


FIGURE 31. ENVIRONMENTAL ENGINEERING CONCEPTS BULK-LOAD FIRE TEST CONFIGURATION

2.8 NEW WORLD TECHNOLOGIES SYSTEM.

Another series of tests were conducted in the aft compartment of the DC-10 test article using a low-pressure dual-fluid nozzle system developed by New World Technologies (NWT). The spray nozzles used nitrogen gas to expel water spray through multiple orifices, producing a fine mist. The system was evaluated in the same cargo compartment used during the GEC Marconi trials, but the compartment volume size and leakage rate were reduced to 2000 ft^3 and 50 CFM, respectively, in order to meet the new Minimum Performance Standard for Aircraft Cargo Compartment Gaseous Fire Suppression Systems [5]. Thirteen tests were conducted using three different system configurations. Due to the proprietary nature of the system, detailed information regarding the system components are not described in this report; therefore, only system performance is reported.

The first system configuration included five nozzles installed equidistant along the centerline of the compartment ceiling (figure 32). The nozzles spray pattern produced a radial mist pattern in the horizontal plane. The initial configuration did not incorporate a control logic to automate the system, which meant that the system had no automatic activation, zoning, or metering capabilities. The initial NWT water mist system activation was controlled manually based on LED temperature displays that were used to monitor the compartment's temperature.

The second system configuration had the same nozzle installation, but incorporated a feedback control system consisting of a proportional controller, solenoids, and thermocouples that were used to activate, zone, and meter the suppression system. Each nozzle was equipped with a solenoid and a thermocouple to automatically control the suppression system. These nozzles were designed to provide a water flow of 0.53 GPM per nozzle when the water and nitrogen pressure in the nozzles were set to 6 psig and 50 psig, respectively. The total water flow rate of the system was 2.65 GPM in both configurations.

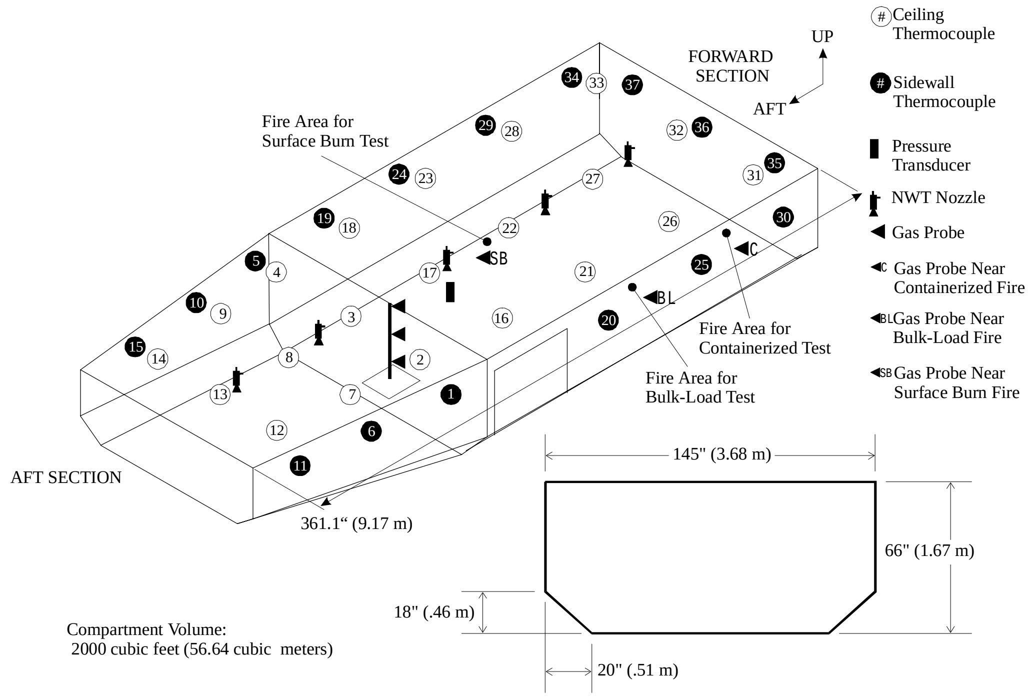


FIGURE 32. NEW WORLD TECHNOLOGIES INSTRUMENTATION LAYOUT IN DC-10 AFT COMPARTMENT FOR FIRST SYSTEM CONFIGURATION

The third system configuration had eight nozzles mounted on the cargo compartment ceiling (see figure 33). The compartment was divided into four zones, with each zone having two nozzles; each nozzle had a solenoid valve and a type K thermocouple (thermocouples A1 through D2). In addition, two other thermocouples were installed 1 inch below the ceiling on the aircraft centerline, in front of thermocouples 22 and 27, to cover the center area near the fire (figure 32). These sensors were used to control the solenoids, but their output was not recorded. The nozzle body had the capability of being fitted with different spray pattern tips such as radial (horizontal) and conical (vertical) patterns. The system contained a proportional controller that monitored the compartment temperatures and activated each nozzle upon demand. The demand depended on the compartment temperature; if the temperature exceeded 200°F at the ceiling, the system activated, followed by a programmed sequence logic (table 4). The total water flow capacity of this configuration was 4.24 GPM (0.53 GPM per nozzle).

The NWT system was challenged against four different types of fire scenarios: three test scenarios followed the MPS protocols and the fourth one used an experimental protocol. The three MPS test protocols included the bulk-load test, the containerized test, and the surface burn (flammable liquids) test [7]. The fourth test (experimental) used the MPS bulk-load test protocol, but with the addition of three aerosol spray cans.

The bulk-load and containerized fire tests were deep-seated, class-A, fires composed of loosely packed shredded paper in cardboard boxes and placed inside the aircraft cargo compartment. The difference between these two tests was that in the bulk-load fire test, 178 cardboard boxes were placed directly into the compartment, while in the containerized fire test, only 33 boxes

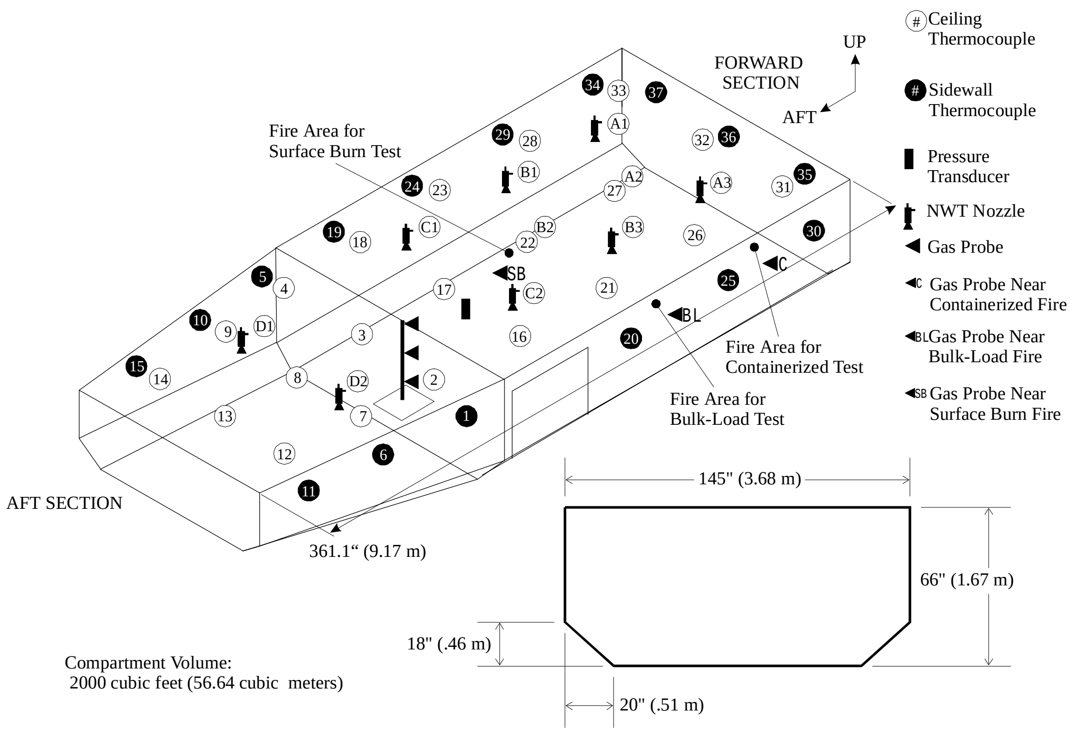


FIGURE 33. NEW WORLD TECHNOLOGIES INSTRUMENTATION LAYOUT IN DC-10 AFT COMPARTMENT FOR THIRD SYSTEM CONFIGURATION

TABLE 4. NEW WORLD TECHNOLOGIES SYSTEM CONFIGURATION

Test Number	Fire Test Scenario	Test ID	Nitrogen Pressure for 1 Nozzle (psig)	Water Pressure for 1 Nozzle (psig)	Water Flow Rate for 1 Nozzle (GPM)	Total Nozzles Used	Control Logic
1	Containerized	110598T1	50	6	0.53	5	Not Used
2	Bulk Load	110598T2	50	6	0.53	5	Not Used
3	Bulk Load	110698T1	50	6	0.53	5	Not Used
4	Surface Burn	080699T1	50	6	0.53	5	Not Provided by OEM
5	Containerized	080999T1	50	6	0.53	5	Not Provided by OEM
6	Surface Burn	080999T2	50	6	0.53	5	Not Provided by OEM
7	Containerized	042400T1	50	6	0.53	8	3 minutes on, 10 seconds check, 3 minutes on after reaching T = > 200°F
8	Containerized	042500T1	50	6	0.53	8	3 minutes on, 10 seconds check, 3 minutes on after reaching T = > 200°F
9	Containerized	042600T1	50	6	0.53	8	3 minutes on, 10 seconds check, 3 minutes on after reaching T = > 200°F
10	Containerized	042700T1	50	6	0.53	8	3 minutes on, 10 seconds check, 3 minutes on after reaching T = > 200°F
11	Bulk Load with Aerosol Cans	042700T2	50	6	0.53	8	3 minutes on, 10 seconds check, 1 minutes on after reaching T = > 200°F
12	Bulk Load with Aerosol Cans	050200T1	50	6	0.53	8	3 minutes on (initially), 2 seconds check, 1 minute on after reaching T = > 200°F. 8 nozzles.
13	Bulk Load with Aerosol Cans	050300T1	50	6	0.53	8	3 minutes on (initially), 2 seconds check, 1 minute on after reaching T = > 200°F. All nozzles on for 3 minutes if T = > 400°F.

were stacked inside an LD-3 container and then placed in the compartment as a unit (figures 34 and 35). Two other empty containers were inserted in the compartment to complete the containerized fire test setup. In both test scenarios, an igniter was placed inside one of the boxes (a box with ten 1-inch holes). The igniter consisted of several paper hand towels wrapped with multiple loops of nichrome wire. The nichrome wire ignited the paper towels when 115 Vac was applied. Temperatures were monitored inside and above the ignited box to determine the ignition status. The duration of the MPS tests was 30 minutes after activating the suppression system.

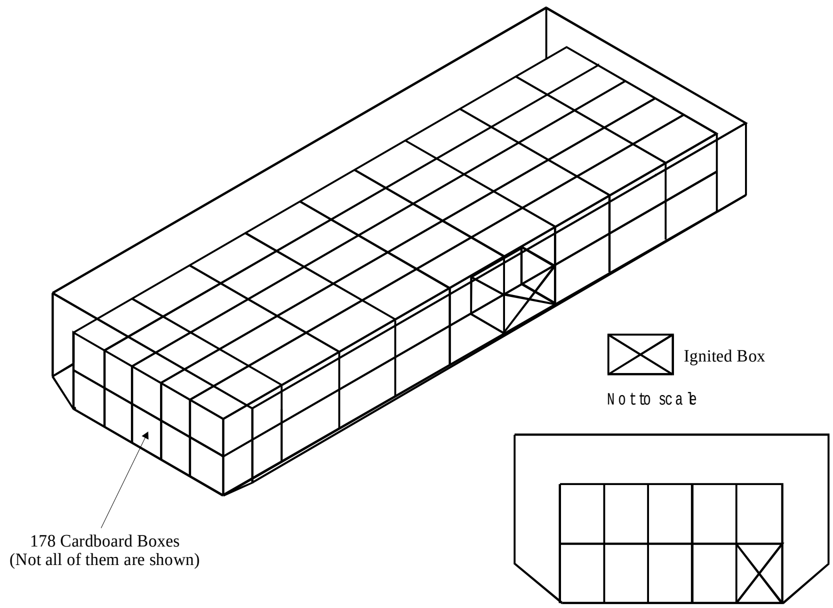


FIGURE 34. MINIMUM PERFORMANCE STANDARDS BULK-LOAD FIRE TEST SETUP

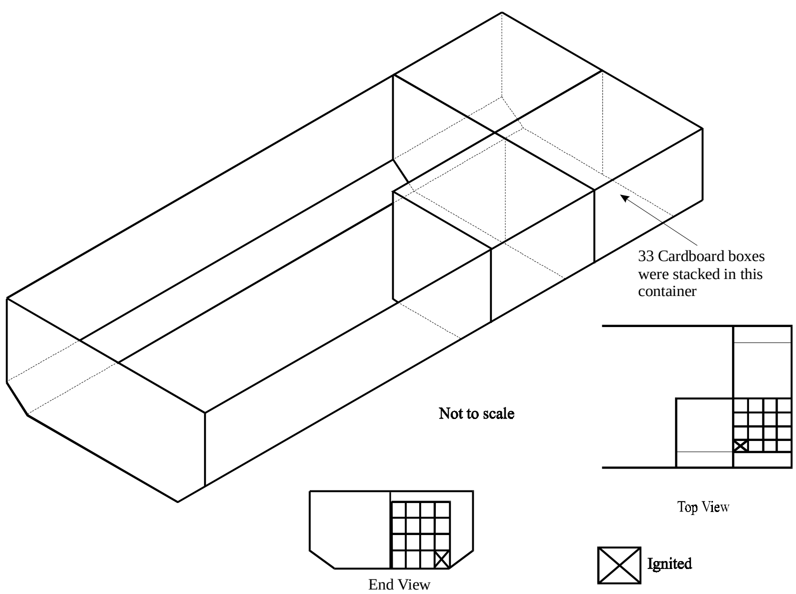


FIGURE 35. MINIMUM PERFORMANCE STANDARDS CONTAINERIZED FIRE TEST SETUP

The third MPS test was the surface burn test, which was basically a flammable liquid fire. One-half gallon of Jet-A fuel was placed in a 2-foot-square pan and ignited with two arcing electrodes. The pan was placed inside the empty DC-10 compartment at a location away from the nozzle discharge (figure 36). The test duration for this scenario was 5 minutes after activating the suppression system.

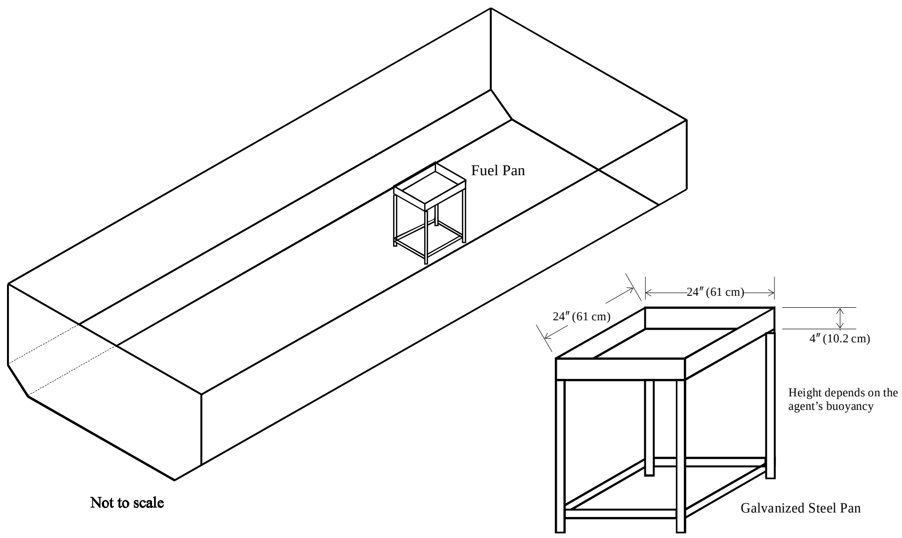


FIGURE 36. MINIMUM PERFORMANCE STANDARDS SURFACE BURN TEST SETUP

The fourth scenario (experimental protocol) was basically the same fire scenario as the bulk-load test, with the exception of three boxes, adjacent to the igniter box, contained aerosol cans. The aerosol cans were individually placed in boxes to the right, in front and to the left of the ignition box as illustrated in figure 37. Identical brand name and size cans were tested beforehand to ensure that the cans would explode if the suppression agent/system was not effective. During all of these tests, the suppression system was activated 1 minute after one or more of the ceiling and/or sidewall thermocouples reached 200°F, as specified in the MPS.

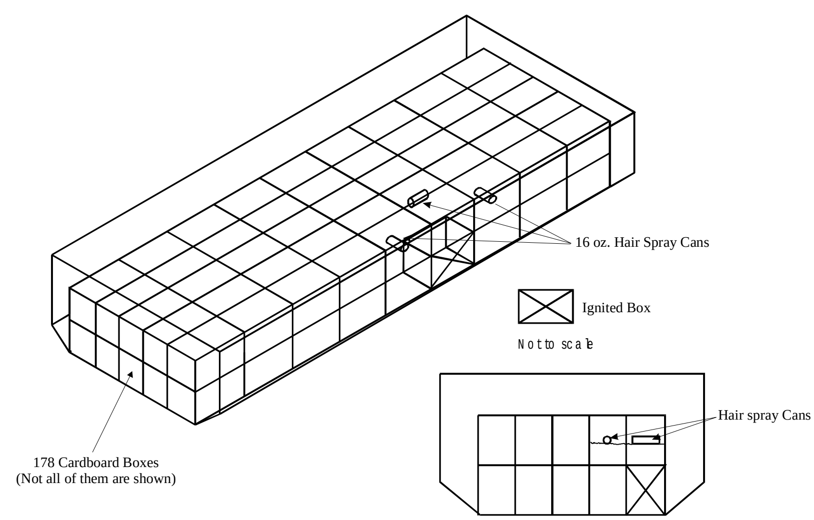


FIGURE 37. BULK LOAD WITH AEROSOL CAN TEST SETUP

The DC-10 aft compartment was equipped with thermocouples and gas analyzer probes. In addition to the suppression system thermocouples, 39 other thermocouples were available in the compartment ceiling (21), sidewall (16), and ignition box (2). There were four gas analyzer probes that continuously sampled the oxygen concentrations in the cargo compartment at three different levels: 16.5″, 33″, and 49.5″ above floor level; a fourth probe was situated near the fire. The exact location of the probe near the fire varied according to the test scenario. During the bulk-load fire and aerosol can explosion tests, this probe was positioned about 6″ in front of the ignition box (starboard side of the aircraft) and 9″ above the floor. The same probe distances were used in the containerized tests, but the fourth probe was placed inside the LD-3 container. For the surface burn test, this fourth probe was installed 12″ below the ceiling and 12″ away from the pan (figures 31 and 32).

A total of 13 tests were conducted with the NWT fire suppression system, although two of these were aborted (tests 10 and 12). Tests with the first suppression system configuration included one containerized test and 2 bulk-load tests; the second system configuration was challenged to two surface burns and one containerized test; and, the third configuration faced four containerized and three aerosol can explosion tests. Table 5 presents a summary of the test results.

TABLE 5. TEST RESULTS

Test Number	Fire Test Scenario	Test ID	Maximum Ceiling Temperature (°F)	Maximum Sidewall Temperature (°F)	Ceiling Max. Time-Temperature Area (°F-min)	Sidewall Max. Time-Temperature Area (°F-min)	Maximum Cargo Compartment Pressure (psig)	Test Duration (min)	Nitrogen Used (ft^3)	Water Used (Gal.)	MPS Acceptance Criteria
1	Containerized	110598T1	468	140	8807	3624	-	30	N/A	79.6	Pass
2	Bulk Load	110598T2	141	285	3391	3238	-	30	N/A	79.6	Pass
3	Bulk Load	110698T1	1039	325	6148	5118	-	30	N/A	11.2 (Est.)	Failed
4	Surface Burn	080699T1	1140	165	-	-	-	5	N/A	N/A	Pass
5	Containerized	080999T1	1051	764	5902	6793	-	30	N/A	49	Failed
6	Surface Burn	080999T2	364	201	928	627	-	5	N/A	N/A	Pass
7	Containerized	042400T1	342	376	8165	7662	-	30	1376.1	12.9	Pass
8	Containerized	042500T1	581	259	9497	6027	-	30	N/A	30.1	Pass
9	Containerized	042600T1	555	345	7474	8482	-	30	1784.3	24.1	Pass
10	Containerized	042700T1	Test Aborted	-	-	-	-	-	-	-	-
11	Bulk Load with Aerosol Cans	042700T2	875	328	13578	7614	N/A	30	1812.6	30.6	Failed
12	Bulk Load with Aerosol Cans	050200T1	Test Aborted								
13	Bulk Load with Aerosol Cans	050300T1	990	434	8269	5869	N/A	30	1869.3	24.5	Failed

The first three trials (tests 110598T1, 110598T2, and 110698T1) were conducted with the nozzles installed using the first nozzle configuration (i.e., five nozzles along the centerline of the aircraft and no automatic system controller). The first trial, test 110598T1, was a standardized containerized test. After igniting the box inside the LD-3 container, the cargo compartment ceiling temperatures were monitored. One minute after the ceiling temperature reached 200°F the suppression system was activated. The system was left on for the duration of the test, suppressing the fire, and consuming a total of 79.6 gallons of water. Following the test, the fire was extinguished with a hand line. This particular scenario cannot be extinguished with water or Halon 1301 because it is a deep-seated fire. The maximum ceiling and sidewall temperatures were 468° and 140°F, respectively (see figure 38). The maximum time-temperature areas for the ceiling was 8807°F-minutes and for the sidewall was 3624°F-minutes. Compared to the standard acceptance criteria, the recorded temperatures and calculated areas were below the maximum allowable temperature and time-temperature area, 670° and 15,400°F-minutes, respectively. Although effective in suppressing the fire, this system design required 660 pounds of water (79.6 gallons), plus 12 nitrogen A-1 cylinders to achieve this performance. Halon 1301 passed this test with approximately 80 pounds of agent.

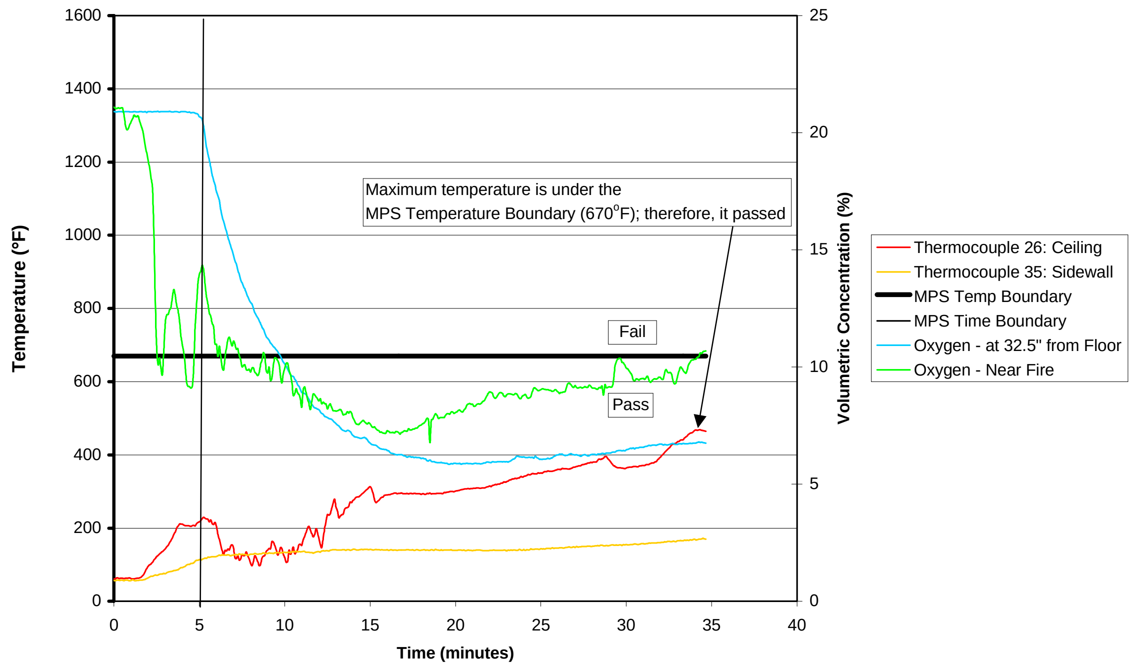


FIGURE 38. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: CONTAINERIZED TEST 1 (110598T1), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

The second and third tests, 110598T2 and 110698T1, were MPS bulk-loaded fire tests. During each test, the cargo compartment thermocouples were monitored to determine the activation time. Following the 1-minute waiting period, after reaching 200°F, the suppression system was activated. Because each of these trials was exploratory, two different manual activation sequences were used to suppress the fires. Test 2 was activated after the 1-minute waiting period and left on for the duration of the 30-minutes test. Test 3, on the other hand, was activated after the 1-minute waiting period and was manually metered as follows: the system was activated after the ceiling temperatures exceeded 250°F and deactivated after temperatures reached 175°F. This sequence was repeated for the duration of the test. Results indicated that test 2 met the acceptance criteria, while test 3 failed. As seen in figure 39, Test 2, recorded maximum ceiling and sidewall temperatures of 141° and 285°F, respectively, which was well below the 730°F threshold. But, once again, 660 pounds of water were used to suppress the fire. Test 3 recorded a peak ceiling temperature of 1039°F and a peak sidewall temperature of 325°F (see figure 40).

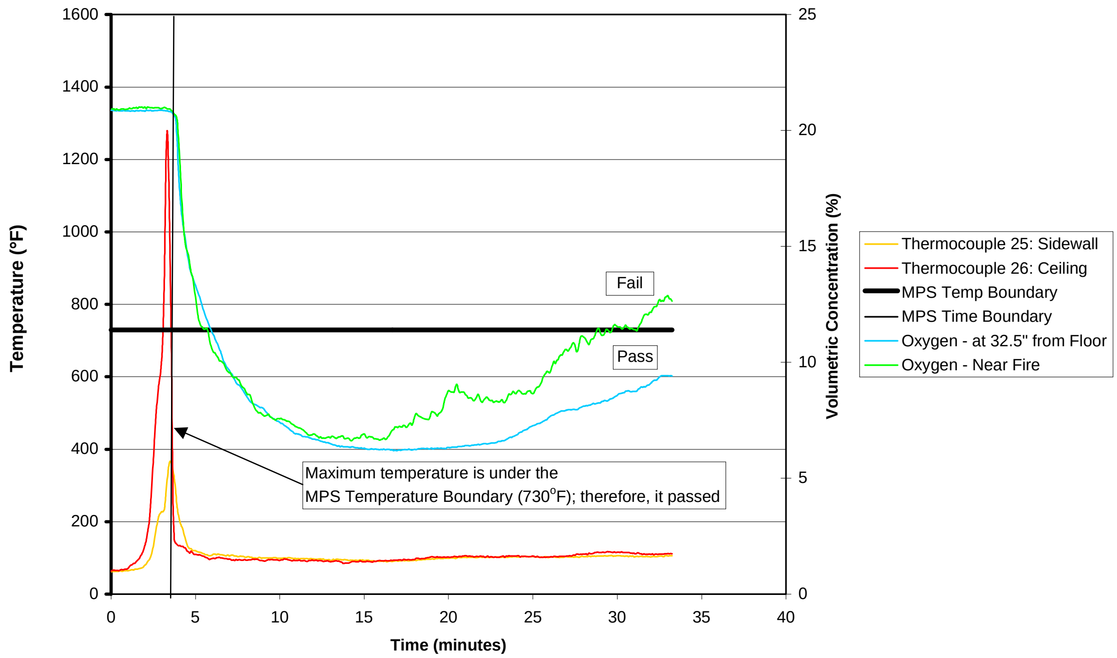


FIGURE 39. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: BULK-LOAD TEST 2 (110598T2), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

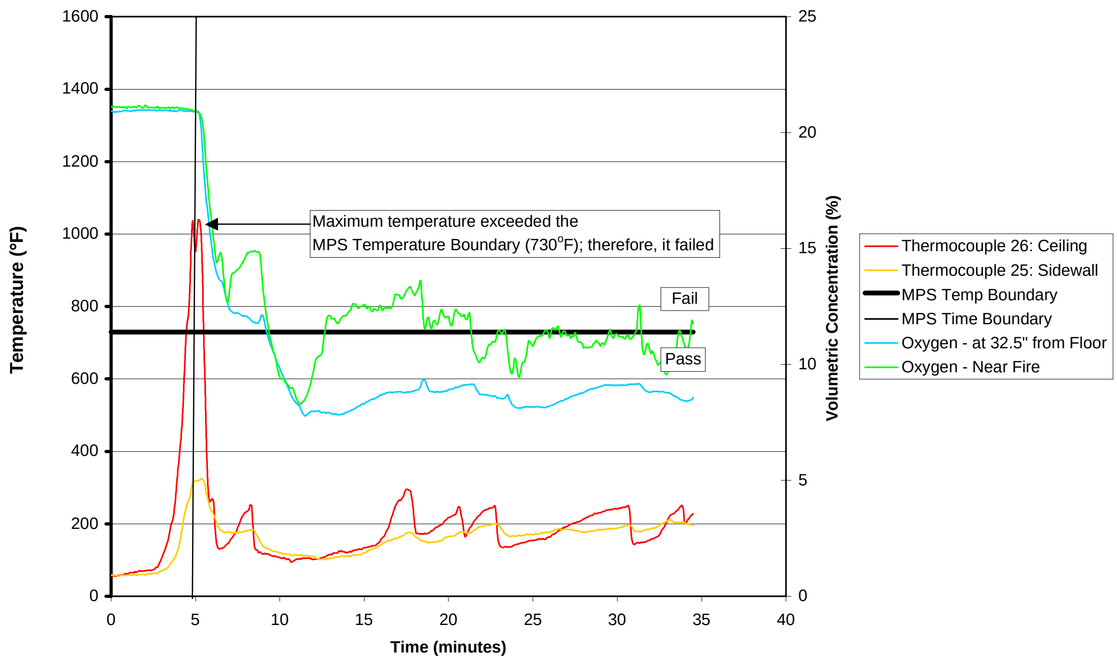


FIGURE 40. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: BULK-LOAD TEST 3 (110698T1), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

The peak ceiling temperature exceeded the 730°F maximum temperature allowed in the standard for this particular fire scenario, but the system was able to reduce the temperature to the acceptable level 20 seconds later. The calculated water consumption for test 3 was approximately 11.2 gallons (93 pounds), based on the time the system was activated and the nozzles flow rate. No instrumentation was available at the time to record this parameter. By metering the system, only 93 pounds of water were used to suppress the fire. In both tests, the calculated areas, under their time-temperature curve were well below the 11,900°F-minute MPS criteria; test 2 area was computed to be 3391°F-minute and test 3 area to be 6148°F. As in the containerized scenario, these deep-seated fires were extinguished with a hand line.

Tests 4, 5, and 6 (figures 41, 42, and 43) used the second system configuration, which included five nozzles with solenoids, thermocouples, and a proportional controller to automate the system. NWT did not provide the proportional controller sequence logic for these tests. Tests 4 and 6, tests 080699T1 and 080999T2, were conducted using the MPS surface burn protocols, while test 5, test 080999T1, was performed using the MPS containerized test protocol. The MPS surface burn standard test requires that after igniting the flammable liquid, the water mist system is activated 1 minute after any of the compartment thermocouples reaches 200°F. During test 4 it was noted that the system was activated much later than required, 1 minute-15 seconds later, due to the type of thermocouples that NWT was using and their placement; NWT used insulated thermocouples while the FAA was using noninsulated ones (exposed). Test 6 activation was achieved on time due to some changes made on the system. Results show that the Jet-A fire was extinguished in both tests. As expected, the maximum temperature in test 4, 1140°F, (figure 41) was higher than test 6, 364°F (figure 43). Both temperatures were below the maximum value allowed, 1250°F, by the standard. The area under the time-temperature curve was computed for test 6 only, since there was not sufficient data to compute the area for test 4 because of the activation delay. Test 6 time-temperature area was to be 928°F-minute, which is well below the maximum value, 3270°F-minute, allowed in the standard. The water consumption of the system was not recorded during these tests. As mentioned before, test 5 was a containerized fire test. This test had the same time delay problem as test 4. This situation resulted in higher compartment temperatures. Figure 42 shows that the maximum ceiling temperature was 1051°F and the area under the time-temperature curve was computed to be 5902°F-minute. In this test, the sidewall computed area, 6793°F-minute, was larger than the ceiling area. This phenomenon can be attributed to the collection of water on top of the LD-3 container that acted as an insulator. Only one maximum value did not meet the standard; the maximum ceiling temperature, 1051°F, exceeded the 670°F threshold. According to NWT, the system consumed 49 gallons of water, more than expected, due to a nozzle problem; the nozzle was stuck open apparently due to foreign objects in the water line.

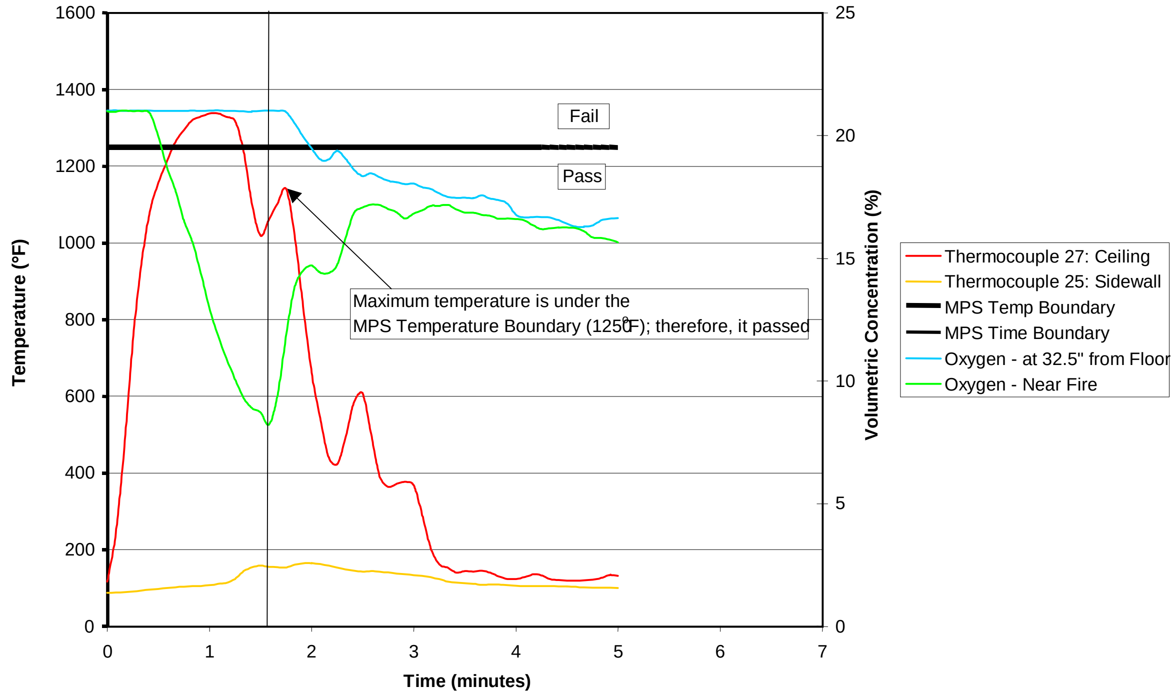


FIGURE 41. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: SURFACE BURN TEST 4 (080699T1), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

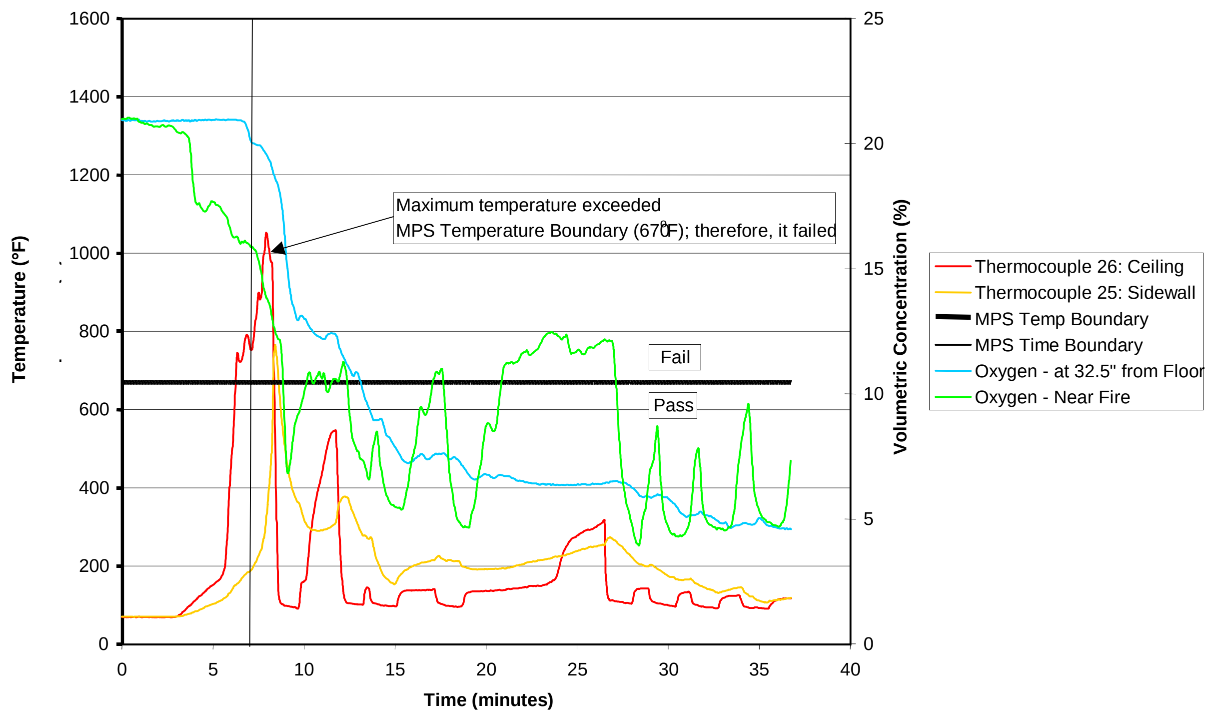


FIGURE 42. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: CONTAINERIZED TEST 5 (080999T1), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

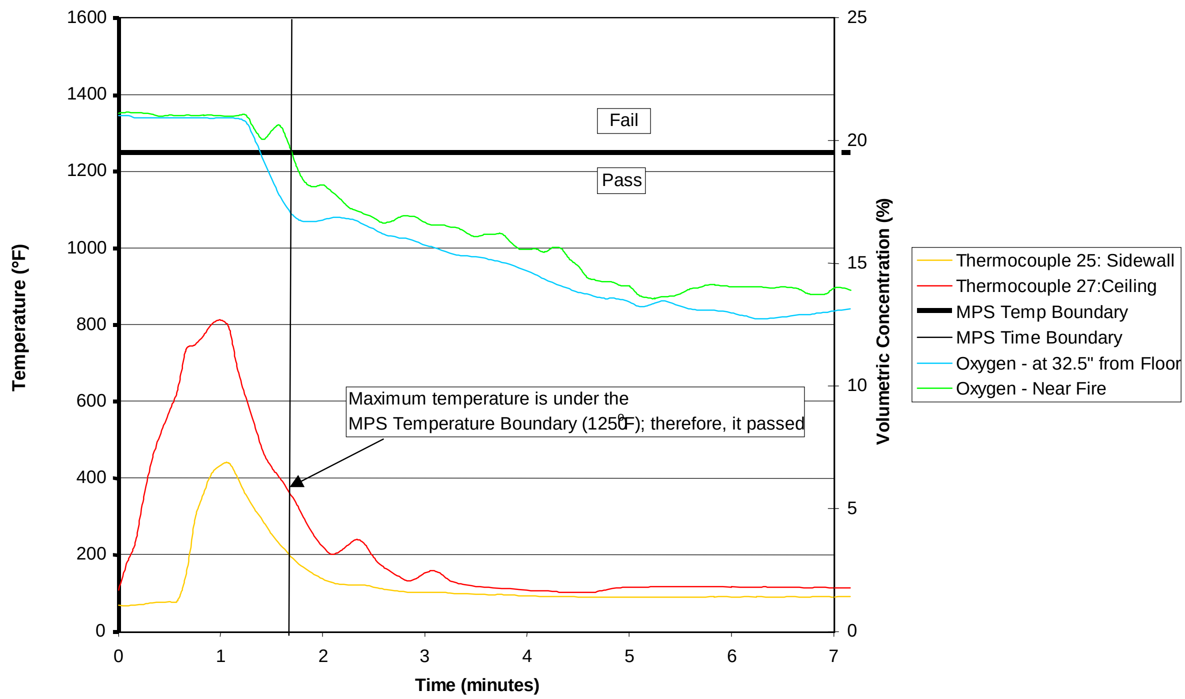


FIGURE 43. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: SURFACE BURN TEST 6 (080999T2), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

Tests 7 through 13 were conducted using the third configuration design; i.e., eight nozzles connected to an automatic closed loop system (with different type K thermocouples). Tests 7 through 10 were MPS containerized tests, while tests 11 through 13 were bulk-loaded fires, each containing three 16-ounces hairspray cans. Tests 10 and 12 were aborted due to system problems. The controller activation sequence logic used during the MPS containerized tests was as follows: the system was run for 3 minutes initially, followed by a 10 second check, and turned back on for 3 minutes if the temperature exceeded 200°F. Containerized test results showed that the system was capable of suppressing this type of fire, with maximum compartment temperatures below 670°F. The maximum temperatures were 376°F during test 7, 581°F during test 8, and 555°F during test 9 (see figures 44, 45, and 46). Their maximum time-temperature areas were also below the standard (15,400°F-minute); 8156°F-minute for test 7, 9497°F-minute for test 8, and 8482°F-minute for test 9. To achieve these results, test 7 consumed 12.9 gallons of water and 1376 ft^3 of nitrogen, test 8 consumed 30.1 gallons of water (nitrogen consumption not reported), and test 9 consumed 24.1 gallons of water and 1784 ft^3 of nitrogen. It seems that the compartment temperatures, during test 7, were cooler than tests 8 and 9 which probably contributed to the lower water consumption value.

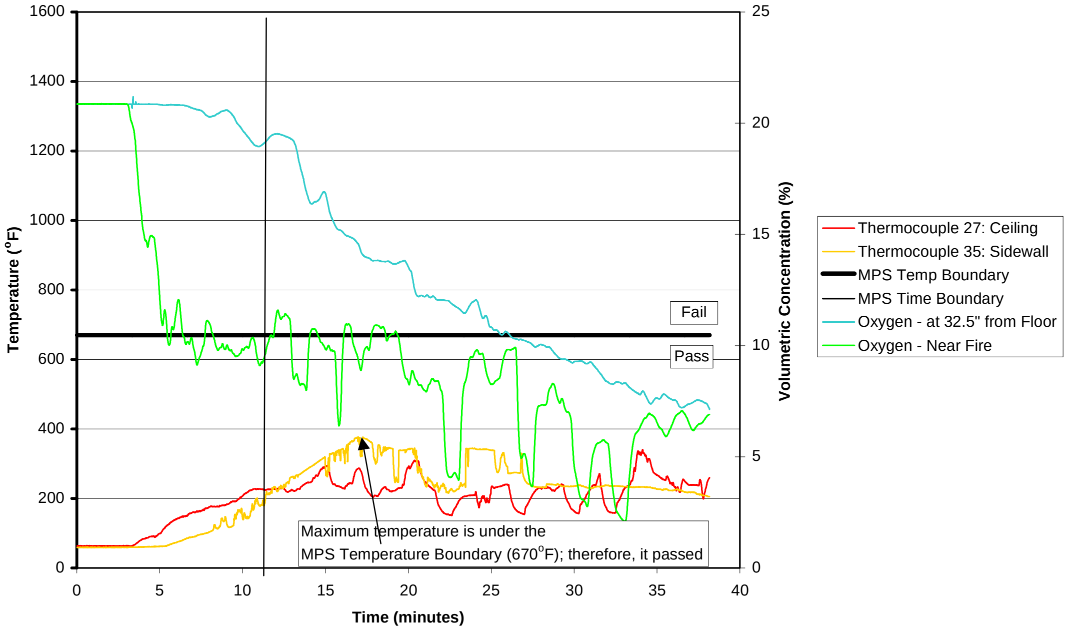


FIGURE 44. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: CONTAINERIZED TEST 7 (042400T1), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

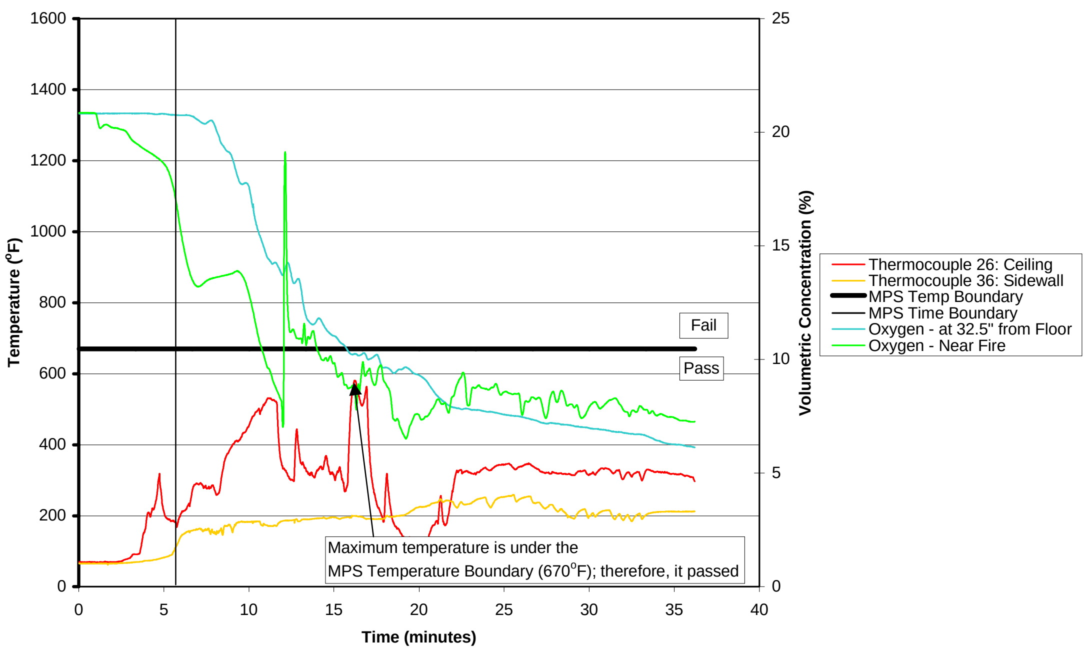


FIGURE 45. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: CONTAINERIZED TEST 8 (042500T1), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

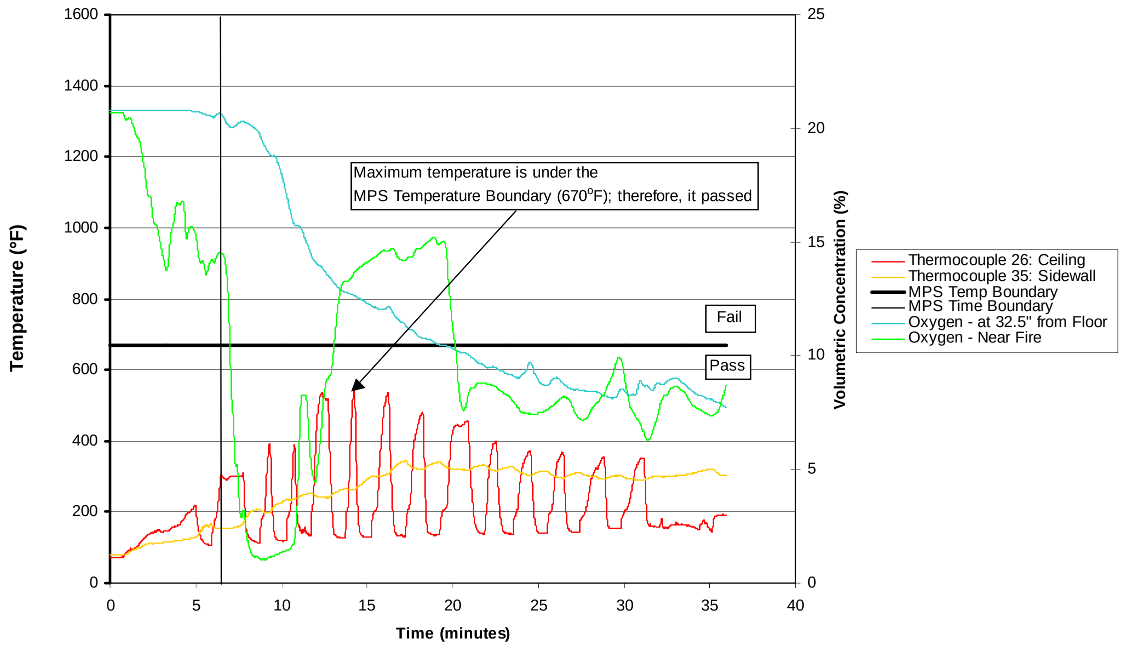


FIGURE 46. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: CONTAINERIZED TEST 9 (042600T1), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

Tests 11 and 13 were not standardized tests; as explained before the protocol used was experimental. These tests were bulk-load tests, just as specified in the MPS standard, with three aerosol cans added individually to three boxes adjacent to the ignition box. The fires experienced in these tests were more severe than in the standard test due to the introduction of flammable liquid and gases. The hairspray cans contained a mixture of alcohol, isobutane, propane, resin, etc, which had the potential for higher heat release and explosions. The activation logic used in test 11 was the same as in tests 7 through 9. The NWT system did not control the fires in this scenario with this sequence logic; temperatures were constantly in the 800°F range and open flames were present (refer to figure 47). Peak temperatures reached 875°F and the maximum area calculated was 13578°F-minute. These values exceeded the MPS acceptance criteria values; that is, a maximum compartment temperature of 730°F and a time-temperature area equal or less than 11,900°F-minutes. The values obtained with Halon 1301 under the same test scenario met the acceptance criteria. A total of 30.6 gallons of water and 1812.6 ft^3 of nitrogen were consumed in test 11. A posttest examination of the cargo revealed that one of the cans (forward can) ruptured; the can dome separated from the can body (cylinder) releasing the hydrocarbon mixture. The can was propelled since it had some signs of impact damage; the sidewall near the door had traces of the hairspray can paint. But the overpressure was not sufficient to open the blowout panel. The reduction of oxygen concentration, due to the injection of nitrogen in the compartment, may have mitigated the explosion. The other two cans did not explode; one was in really good condition and the other one had a melted valve. The can with the melted valve released its content.

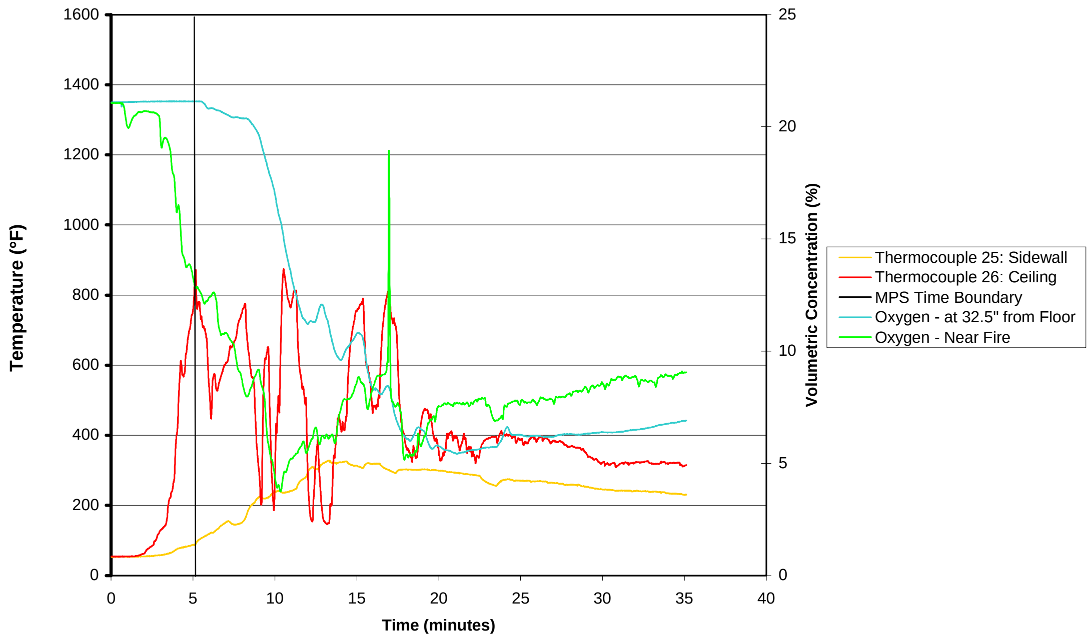


FIGURE 47. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: BULK LOAD WITH AEROSOL CANS TEST 11 (042700T2), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

Test 13 was employed the same aerosol can fire scenario, but the system activation logic was changed to improve its suppression. The sequence logic was designed to run as follows:

- Initially activate water for 3 minutes.
- Conduct a 2-second check to determine if the temperature has dropped to 200°F or below.
- If above 200°F, activate for 1 minute.
- Activate all nozzles for 3 minutes if the temperature is greater than 400°F.

With this sequence, the performance of the NWT system improved. The system suppressed the fire immediately after the initial ignition flames. The peak temperature was 990°F, but decreased after a couple of minutes to below 400°F and stayed at that level for the remainder of the test (see figure 48). The calculated area under the time-temperature curve was 8269°F-minute. The system used a total of 24.5 gallons of water and 1869.3 ft^3 of nitrogen to achieve these results. No explosion occurred during or after the test. The damage patterns found in the cans look similar to the ones from the previous test, but no sign of impact were presents in the cans or walls.

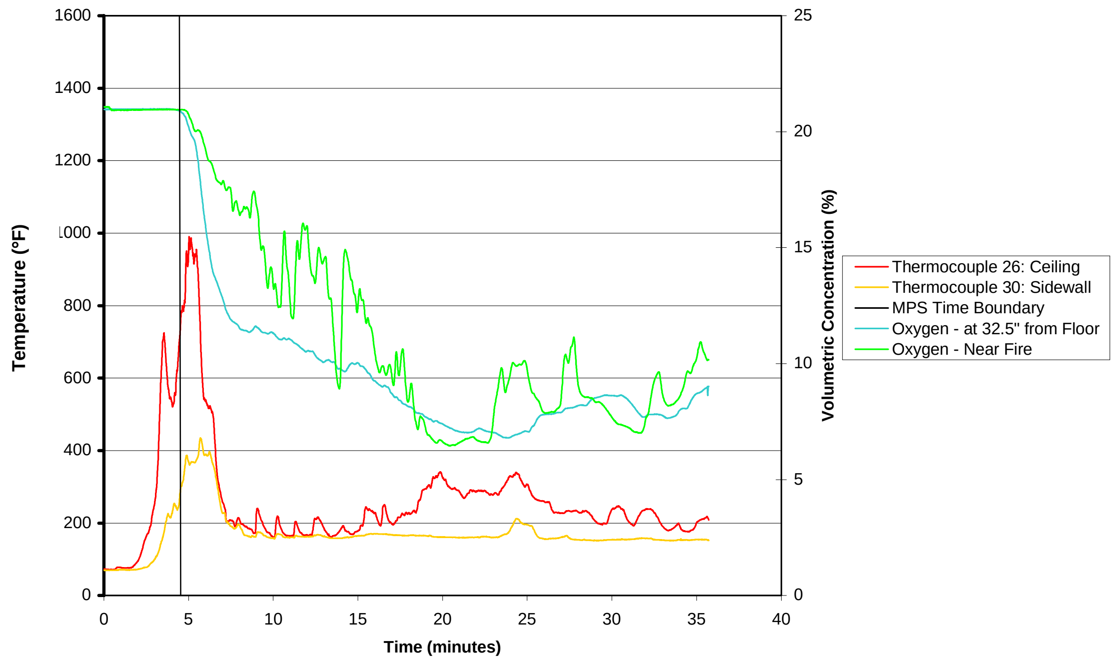


FIGURE 48. NEW WORLD TECHNOLOGIES DUAL-FLUID SYSTEM: BULK LOAD WITH AEROSOL CANS TEST 13 (050300T1), MAXIMUM TEMPERATURE AND OXYGEN PROFILES

3. CONCLUSIONS.

A review of the test data obtained with the first three water mist systems revealed that both the dual-fluid design and high-pressure single fluid systems were effective at suppressing two types of class-A cargo compartment fires: bulk loaded and containerized. Results from the fourth system, the NWT system, showed that it has the potential of passing the MPS since it suppressed some of the bulk-load, containerized, and surface burn fires. Additional testing is required in order to find the optimal relationship between water consumption, activation logic, and fire suppression for all of the systems.

In contrast to a gaseous agent such as Halon 1301, against a deep-seated fire the water spray works by cooling the compartment and wetting the cargo, rather than inerting the compartment. During all successful water spray tests, the fire load materials continued to burn, but under controlled conditions that did not produce high temperatures or hazards to other areas adjacent to the cargo compartment.

Although effective, the quantity of water used to protect the compartment was still at least a factor of 2-3 greater than halon. The best results were obtained using the high-pressure spray during a bulk-load condition in the wide-body configuration, in which 24.8 gallons of water (206 pounds) were required. By comparison, roughly 100 pounds of Halon 1301 would be required for a 90-minute duration under these conditions.

Initially, the containerized fire load was thought to be the most severe test of a water spray system. As discussed, the gaseous agents primarily inert the compartment, preventing a deep-seated fire from erupting into open flaming, but also have some ability to permeate the seams and holes of a container, transferring agent to the fire load. In contrast, water spray cannot penetrate to the fire threat area as readily, reducing its suppression capability during deep-seated containerized fires. Nevertheless, test results indicated the water spray system was effective, primarily by keeping the compartment periphery cool. In the case of the NWT system, the nitrogen supplied to the compartment helped to mitigate the combustion process by reducing the oxygen level in the LD-3 container. The contribution of nitrogen in the suppression of a deep-seated cargo fire by a dual-fluid system, such as the NWT system, needs to be better understood through additional testing.

Perhaps the most difficult test for a water spray system involves the suppression of cargo fires involving a ruptured/exploding aerosol can. Halon 1301 has proven effective against this particular threat, which is standardized in the cargo MPS for gaseous agents. Since a water spray system typically operates under cyclic conditions, it is possible that the system will not be actively spraying water during the exact moment that an aerosol can ruptures. Thus, it was necessary to challenge the NWT system to a nonstandardized bulk-load fire scenario containing aerosol cans. Test 11 results indicated that no explosion resulted after one of the three cans involved in the cargo fire ruptured; the can dome separated from the can body (cylinder) releasing the hydrocarbon mixture. However, the release of the hydrocarbon contents created higher temperatures in the compartment, which the NWT system could not maintain below the MPS acceptance criteria values with the control logic settings used. In test 13 the control logic settings were changed and the suppression performance was improved even though it did not pass the MPS criteria. Additional testing must be conducted in order to determine the optimal control logic sequence that will suppress a cargo fire, involving aerosol cans, and pass the MPS requirements with a minimal quantity of water and nitrogen.

4. REFERENCES.

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