Water Spray as a Fire Suppression Agent for Aircraft Cargo Fires

Abstract. Full-scale fire tests investigated the effectiveness of several types of water spray systems at suppressing and/or controlling in-flight cargo compartment fires. A dual-fluid (air/water) nozzle system was used in the initial testing, followed by 2 types of high-pressure single-fluid designs. The in-flight fire scenarios ranged from simulated bulk-loaded fires to LD-3-containerized fires inside a widebody DC-10 cargo compartment. Additional tests were conducted in a B727 narrowbody compartment. Parameters such as activation temperature, spray duration, nozzle configuration, and flowrate 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 cargo fires for extended periods using varying amounts of water.

## EXECUTIVE SUMMARY

Past FAA research highlighted the effectiveness of water spray systems at protecting an aircraft cabin and its occupants against the effects of a postcrash fuel fire 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 has 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 water spray technologies have proven their effectiveness in previous applications, and the fact that water is environmentally friendly and abundant, it is being considered as a halon replacement agent for use in cargo compartments. Tests conducted in both narrow and widebody test articles examined the effectiveness of water spray during several simulated in-flight fire test scenarios. A dual-fluid (air/water) nozzle system was used in the initial testing, followed by 2 types of high-pressure single-fluid designs. The in-flight fire scenarios ranged from simulated bulk-loaded fires to LD-3-containerized fires inside a widebody DC-10 cargo compartment. Additional tests were conducted in a B727 narrowbody compartment. Parameters such as activation temperature, spray duration, nozzle configuration, and flowrate 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 cargo fires for extended periods using varying amounts of water.

## INTRODUCTION

### PURPOSE.

The purpose of this report is to summarize the findings of full-scale cargo compartment fire tests carried out in both narrow and wide body test articles. A dual-fluid nozzle design and 2 high-pressure single fluid designs were evaluated for suppression of simulated cargo compartment fires.

BACKGROUND.

In the early 1990's, the Federal Aviation Administration (FAA) initiated a research program to investigate the performance of water spray systems installed in the passenger cabin at protecting against postcrash fuel fire hazards. Early designs were effective at reducing these hazards and increasing survivability in the cabin, but required large amounts of water [1, 2]. Subsequent testing aimed at system optimization used a zoning approach and proved that by applying the water spray near the fire hazard not only improved visibility in other areas of the cabin, but reduced the weight penalty by a factor of 9 [3, 4]. However, the cost of implementing such a system outweighed the life saving potential, and further research was suspended. Several years later, the FAA Technical Center formed the International Halon Replacement Working Group in an effort to research various environmentally acceptable agents/systems in aircraft cargo compartments, engine nacelles, hand-held extinguishers, and lavatory trash receptacles. Due to its effectiveness against postcrash cabin fires, interest was generated regarding the feasibility of using water spray against other types of fire threats, including the smoldering, class A type fires typical of cargo compartments.

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 a class A-type fire for an extended period of time, typically 90 minutes, and also use a minimum amount of water. 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
$A_c$= altitude correction factor
S = specific vapor volume based on temperature, ($ft^3$lb)
S = 2.2062 + 0.005046T; T = Temperature, $^oF$

This calculation does not take into account the leakage rate of the cargo compartment, which would require additional halon to provide a similar concentration [5]. Based on this equation, the 2357 cubic foot compartment used in the initial testing would require 49.62 lb. of agent to reach 5% concentration. Because the leakage rate follows an exponential decay, approximately 100 lb. or twice the 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.

DC-10 TEST ARTICLE

The aft cargo compartment of a DC-10 aircraft was used for the evaluation of a dual-fluid system designed by GEC Marconi Avionics. 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 inflight ventilation conditions, a large

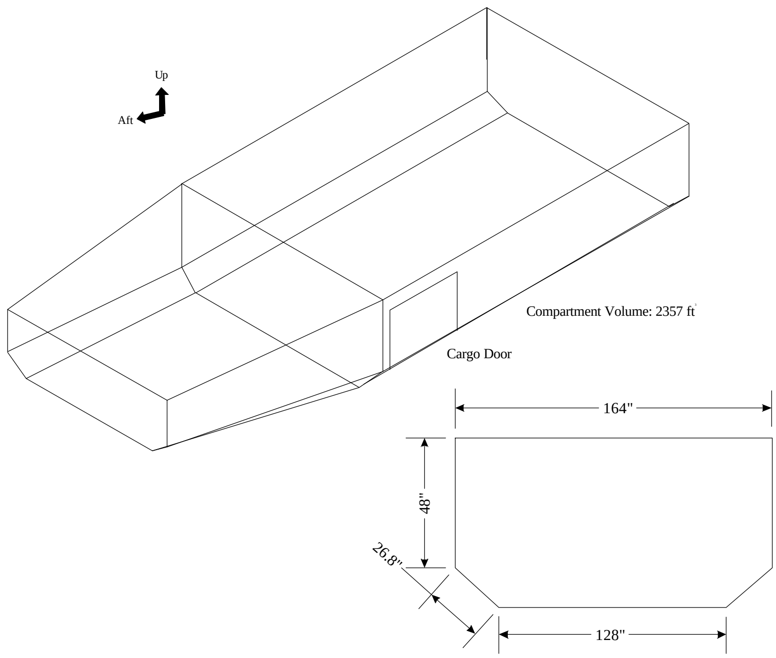



Figure 1. Schematic of DC-10 Cargo Compartment

blower ducted air into the rear portion of the aircraft cabin, simulating air from the air conditioning system (figure 2).

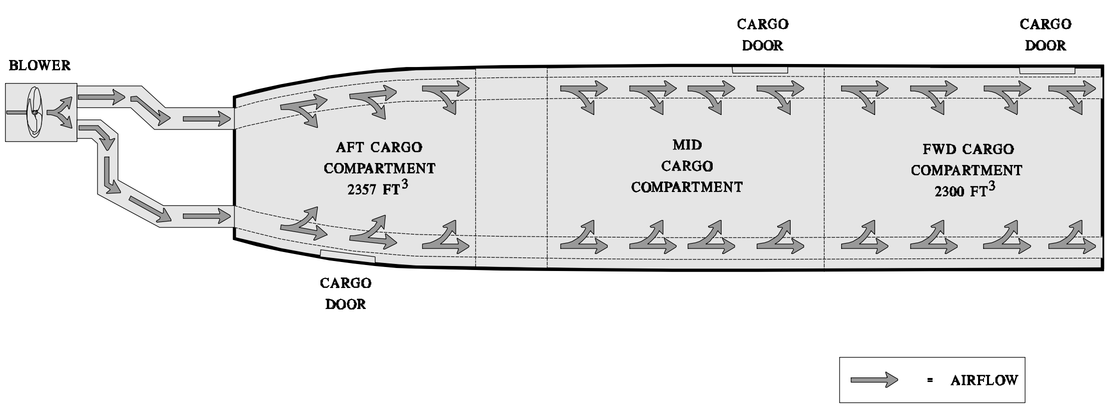



Figure 2. DC-10 Test Article Ventilation Schematic

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).

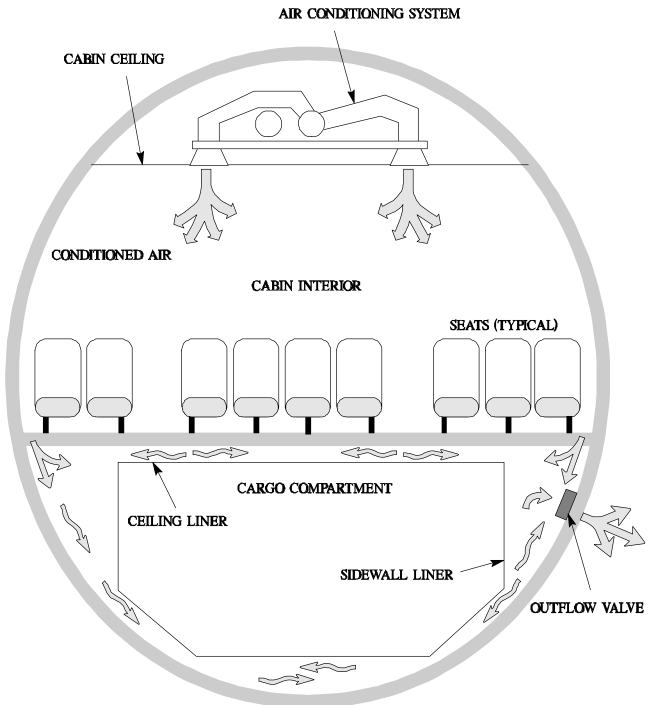



Figure 3. Typical Aircraft Ventilation System

## 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 until the concentration exceeded 10%. 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 [6]. Figure 4 illustrates the method used to calculate the leakage rate. To perform the calculation, an initial concentration is chosen, along with the corresponding time.

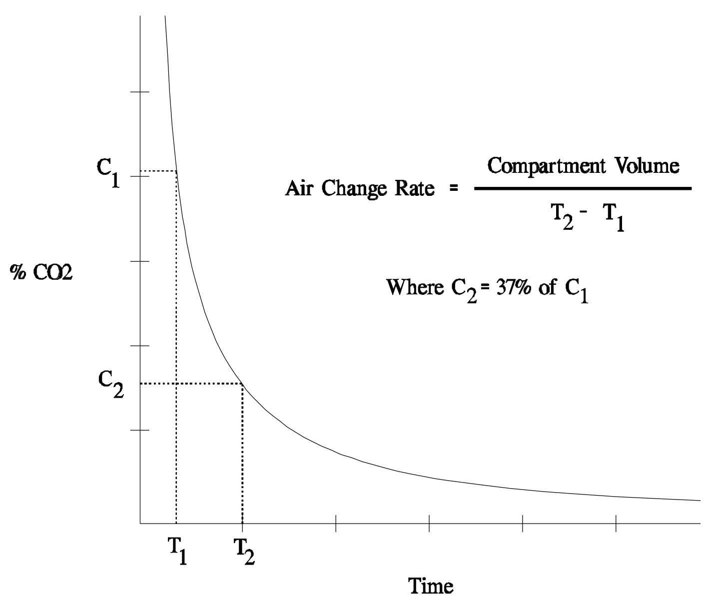



Figure 4. Leakage Rate Calculation

Next, a second concentration that is 37% of the initial concentration is chosen, along with its corresponding time. The air change is calculated by dividing the compartment volume by the change in time (delta time) required for the concentration to drop 63%. Figure 5 shows the actual $CO_2$ concentration versus time profiles used in the calculation. As shown, the concentration was recorded continuously at 4 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 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 (ave) = 64.42

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

Leakage rate calculation at 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 (ave) = 30.13

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

Leakage rate calculation at 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 (ave) = 31.59

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

Leakage rate calculation at 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 (ave) = 31.72

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

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

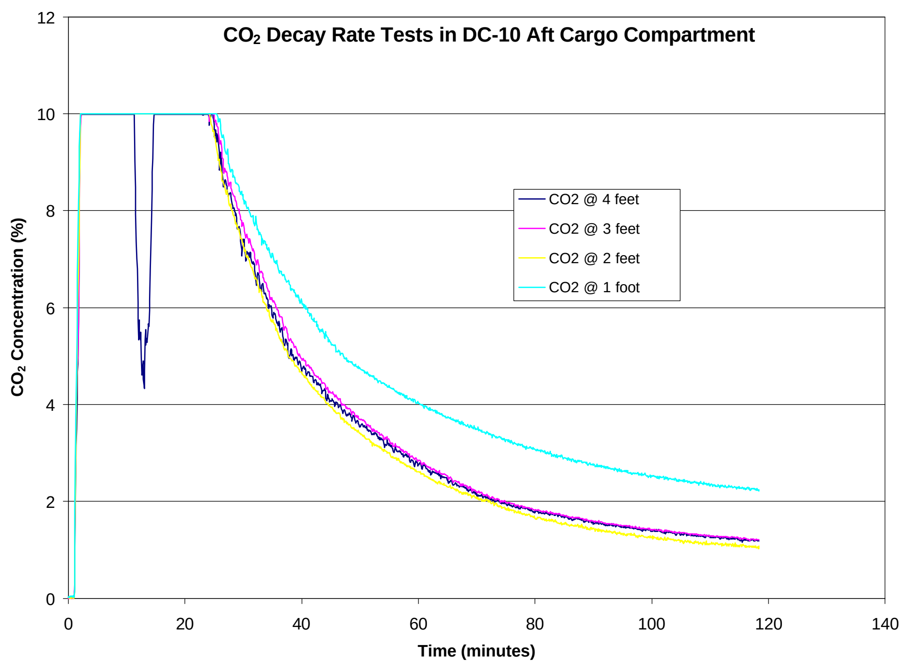



Figure 5. CO2 Leakage Rate Data

## SMOKE DETECTION SYSTEM

A photoelectric smoke detection system was installed to monitor the conditions inside the compartment of the DC-10 test article. 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 flowrate. In general, the system is typical of the types found in service, and provided a realistic response to smoke production, so that fire growth and detection time would be representative of actual 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.

## 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 reducing the amount of water required. Once activated, the typical water mist system operates as an "on-demand" type of system in which one or two zone thermocouples monitor the temperatures within the compartment. When a fire develops and the temperatures exceed the pre-set activation value for a particular zone, the mist is activated. When the temperatures subside, the mist is deactivated. In doing so, the system can maintain control of the fire while at the same time not expend an excessive amount of water.

## GEC MARCONI SYSTEM.

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

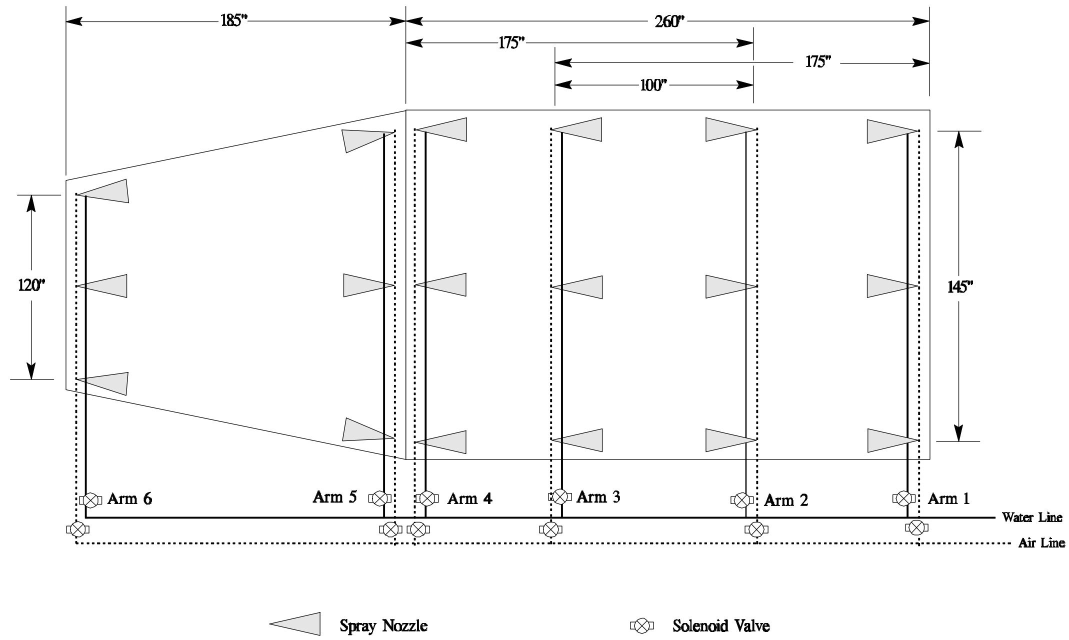



Figure 6. Schematic of GEC Marconi Avionics Water Spray System

An array of zone control thermocouples was installed to provide temperature feedback (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.

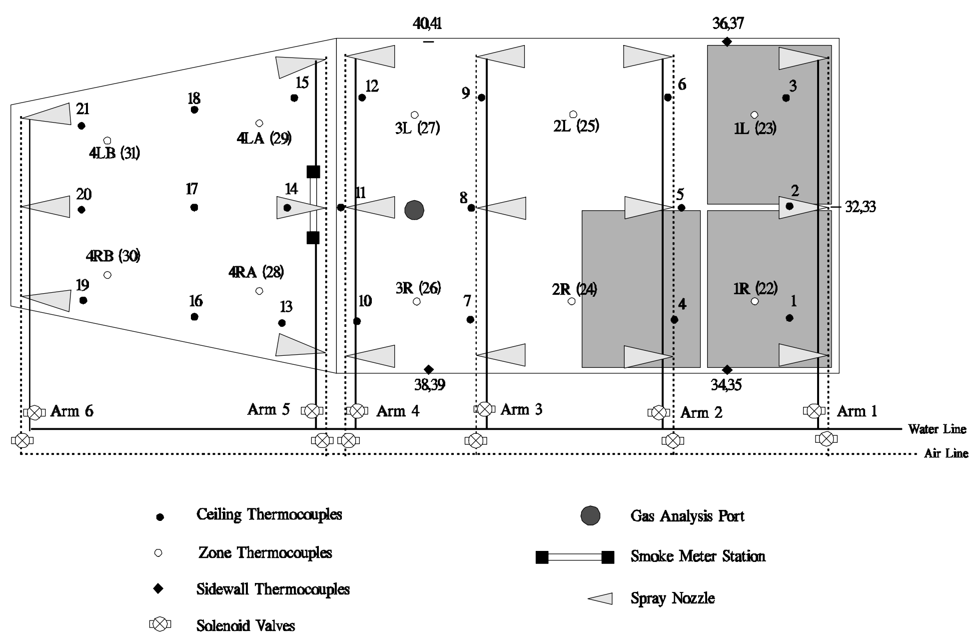



Figure 7. Schematic of Instrumentation Location in DC-10 Aft Cargo Compartment

In addition to the zone control thermocouples, 21 thermocouples were installed in the ceiling and 10 more were mounted in 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 rose, the amount of light absorbed by the photocell decreased, and a simple algorithm yielded a percentage light transmission. An additional bank of three smoke meters were situated in the DC-10 cabin above the cargo fire testing area. 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 cabin area above the test compartment 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 monitored for carbon monoxide (CO), carbon dioxide ($CO_2$), and oxygen ($O_2$).

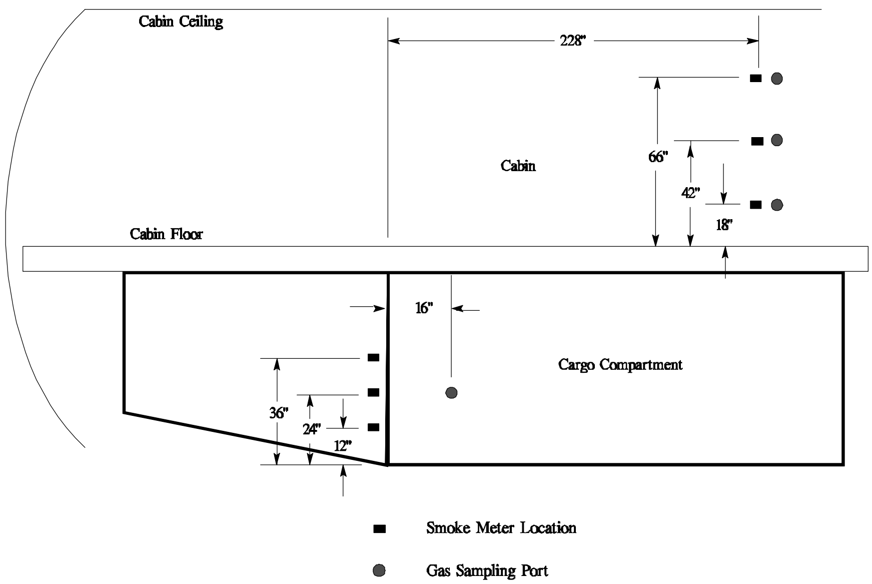



Figure 8. Gas Sampling Stations in Cabin and Cargo Compartment

<u>CONTAINERIZED TEST RESULTS USING GEC MARCONI AVIONICS SYSTEM</u>

Initially, the system was set at 80 psi air pressure and 60 psi water pressure, which yielded a 2.5 l/min nozzle flowrate. Nozzle activation and deactivation temperatures were set at 200°F 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, so the nozzle flowrate was lowered in an effort to reduce the water consumption. This configuration did not lower the water consumption, as it remained at 90 gallons. The nozzle air pressure was then increased to 110 psi during the next test in an effort to produce a different droplet size and spray pattern, but resulted in greater consumption, 110 gallons. Following this, the activation and deactivation temperatures were raised to 300°F and 220°F, respectively, which would allow control of the fire, but at a slightly higher temperature level. This configuration proved to lower 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. See Table 1 for all spray parameters and water consumption results.

| Date | Nozzle Air Pressure (psi) | Nozzle Water Pressure (psi) | Nozzle Flowrate (l/min) | Nozzle Activation Temperature (°F) | Nozzle Deactivation Temperature (°F) | Test Duration (minutes) | Water Used (gallons) |
|---|---|---|---|---|---|---|---|
| 1/18/94 | 80 | 60 | 2.5 | 200 | 180 | 75 | undetermined |
| 1/20/94 | 80 | 60 | 2.5 | 250 | 150 | 75 | 90 |
| 1/24/94 | 80 | 40 | 1.5 | 250 | 150 | 75 | 90 |
| 1/27/94 | 110 | 80 | 2.5 | 250 | 150 | 50 | 110 |
| 2/8/94 | 80 | 60 | 2.5 | 300 | 220 | 80 | 80 |
| 3/14/94 | 80 | 60 | 2.5 | 300* | 290 | 90 | 80 |
| 3/16/94 | 80 | 60 | 2.5 | 300** | 290 | 90 | 86.5 |
| 3/18/94 | 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

Table 1. GEC-Marconi Dual Fluid System Configuration and Test Results

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 at the bottom 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 nichrome wire would ignite the paper towels when 115 Volts A.C. was passed through it. 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 one minute after a one 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. For the initial test, zones were activated if either of the two 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 the technicians 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 one 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 post test inspection revealed the Lexan® panels on the test container had completely melted away and the aluminum ceiling of the container had become warped, but did not melt through.

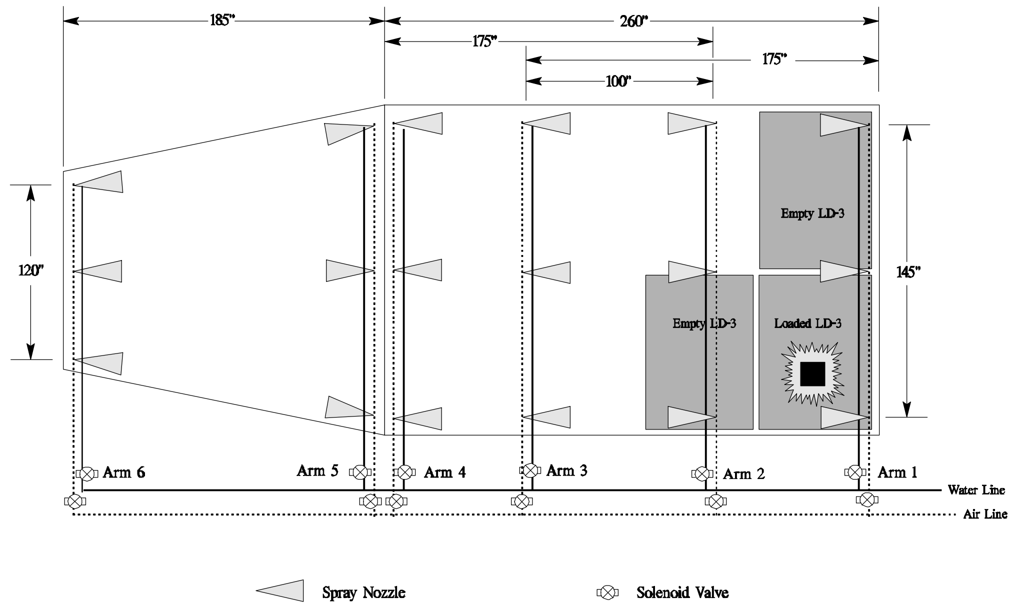



Figure 9. Location of LD-3 Containers in Aft Cargo Compartment

During the second test, the fire load remained identical, and the fire started on the first attempt. All water spray arms were activated for a period of thirty seconds after smoke detection occurred. Following this 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 above the test container, but these periods were short in duration, typically 1-2 minutes (figure 10).

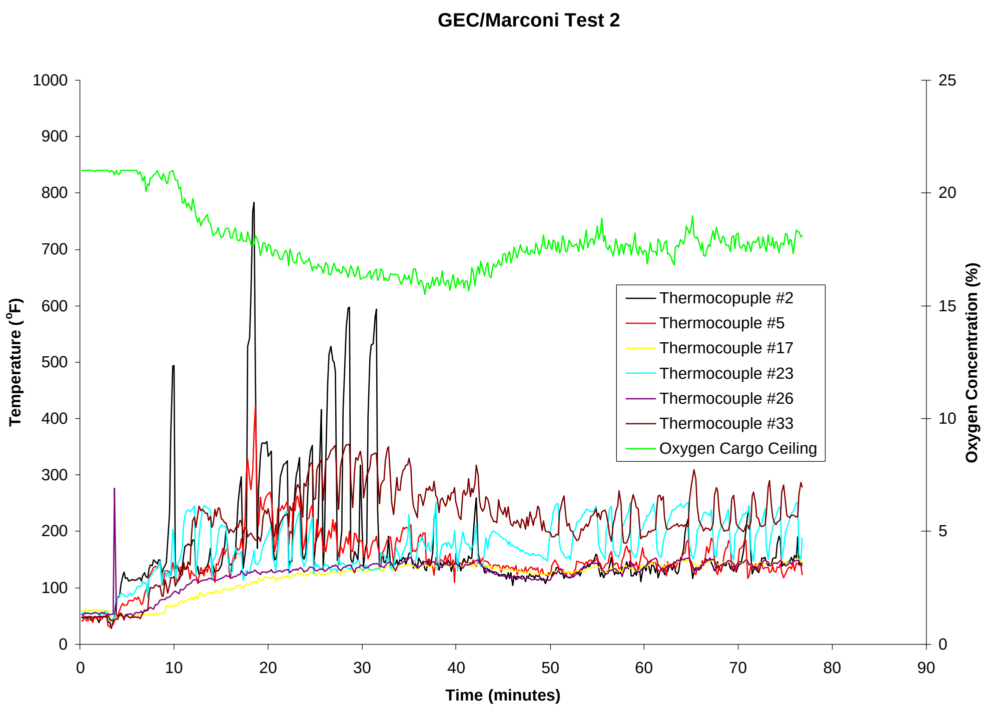



Figure 10. GEC/Marconi Dual Fluid System Test 2 Temperature and Oxygen Profiles

Thermocouples 22 and 23 also show the cyclic nature of a water spray-suppressed fire, as the temperatures were maintained between 250°F and 150°F. The ceiling temperatures in areas more remote to the test container reached a maximum of only 200°F. However, the sidewall temperatures in the test container area 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. A total quantity of approximately 90 gallons of water was used during the 75-minute test. A post test 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 flowrate 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 per nozzle). 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°F to 300°F, while the deactivation temperature was also raised from 150°F to 220°F. With the exception of a brief period between seven and twelve 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

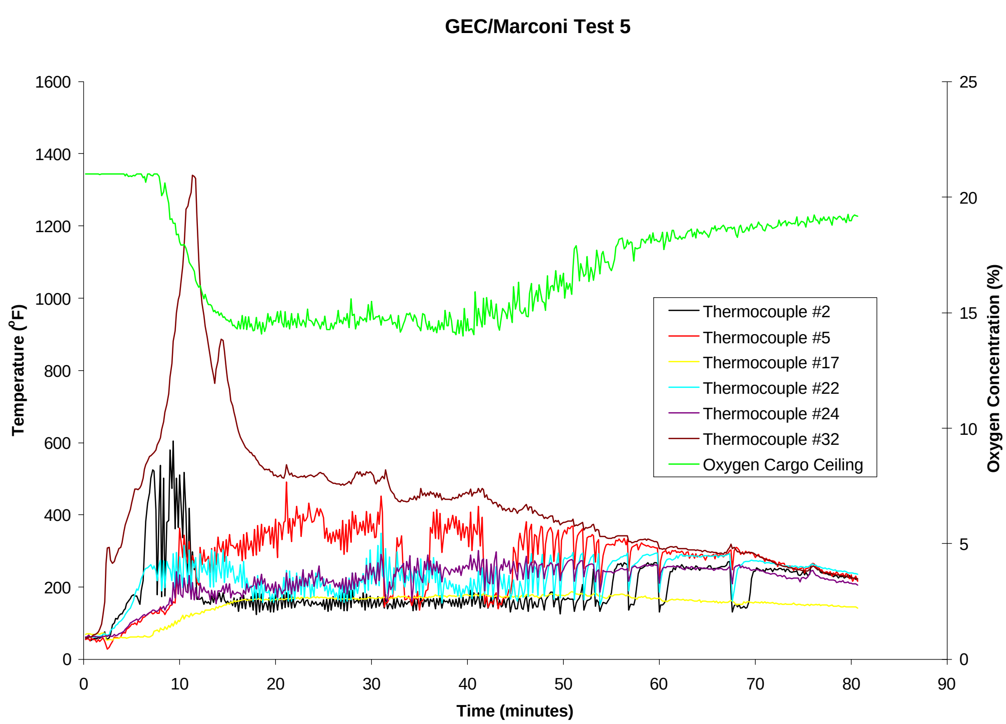



Figure 11. GEC/Marconi Dual Fluid System Test 5 Temperature and Oxygen Profiles

temperature near the test container experienced a rapid temperature rise as a result of the fire burning out of the test container. As shown, the temperature escalated beyond 1200°F at 9 minutes into the test, which also coincided with the temperature excursion on thermocouple #2.

During the remaining three tests, the nozzles were activated for a specific time period following the initial temperature activation (Table 1). If, after the initial 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. 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, but the level of gases was much higher, along with greater oxygen depletion (figure 12). In addition,

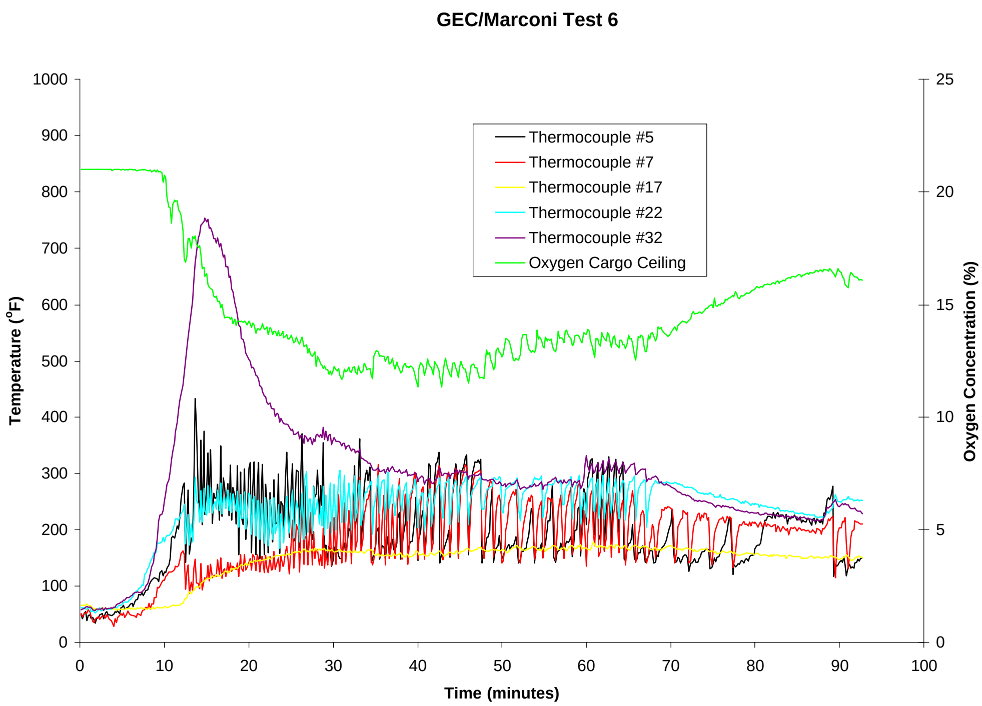



Figure 12. GEC/Marconi Dual Fluid System Test 6 Temperature and Oxygen Profiles

there was a slight increase in visibility during the timed tests compared to the previous tests.

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 the final test, the spray duration was changed to 6 seconds. This spray duration was short enough to initiate 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).

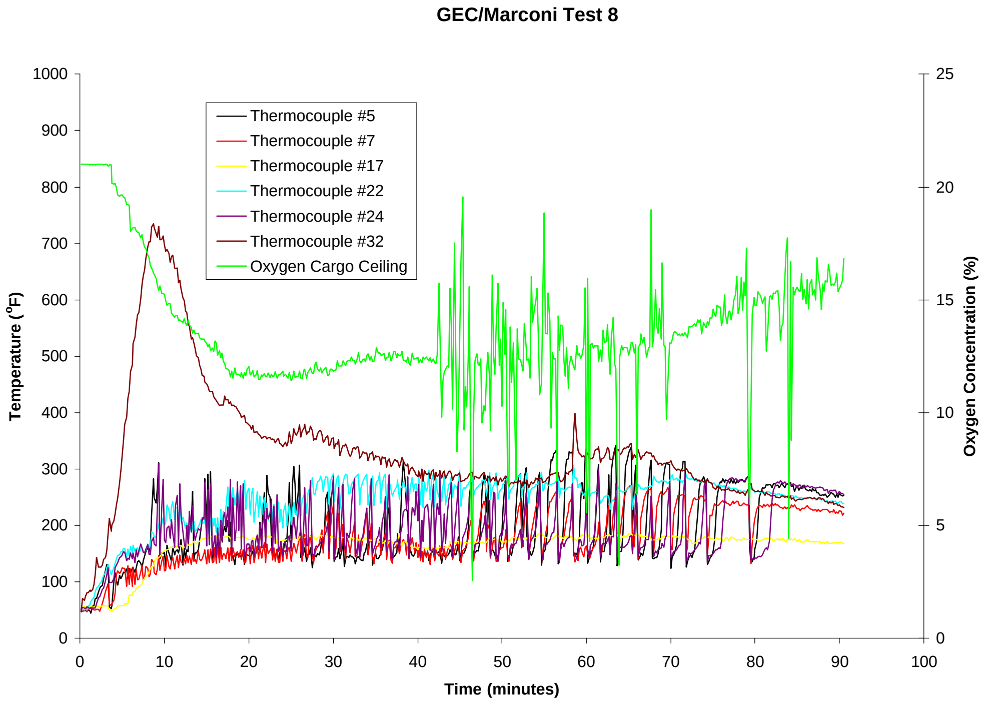



Figure 13. GEC/Marconi Dual Fluid System Test 8 Temperature and Oxygen Profiles

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 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.

## 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 a DC-10 test article. The system was initially divided into 8 identical zones, each containing fourteen MX-8 nozzles that produced a solid cone-shaped spray as shown in figure 14. The nozzles were situated 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 the one used in the aft compartment testing was installed in the forward test compartment. As in the previous tests, following smoke detection, a one-minute delay period was incorporated to simulate normal crew response. After this, the zone temperature logic controlled spray zone activation.

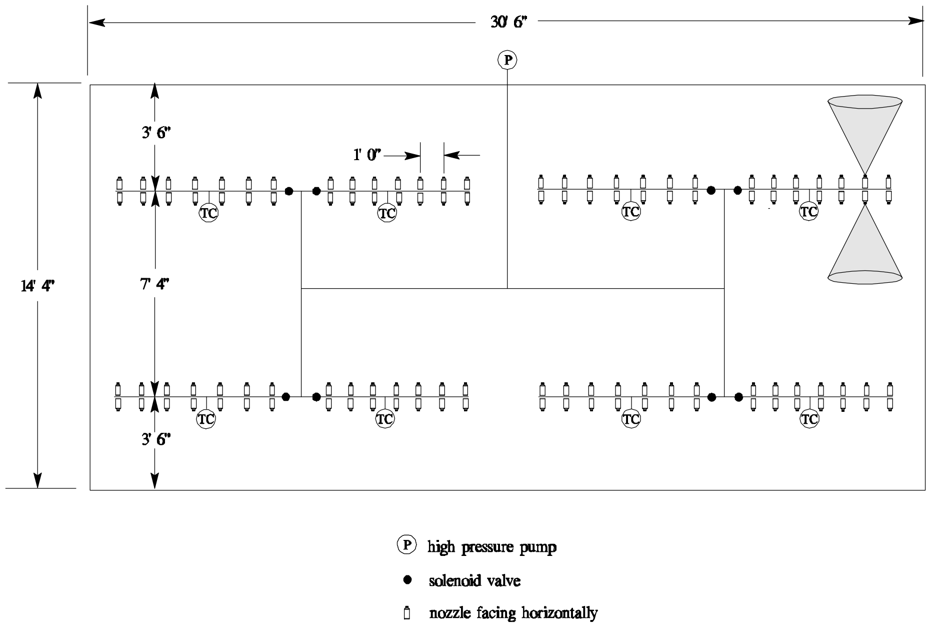
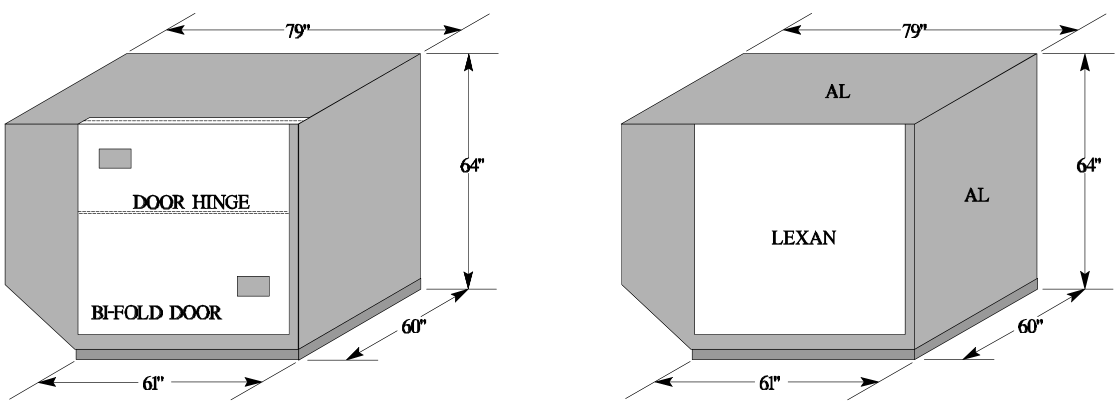



Figure 14. Original Hughes/Reliable High Pressure Spray System

Four tests were initially conducted with the Hughes/Reliable System that were similar to the tests run using the GEC Marconi system. The containerized fire load consisted of one LD-3 container loaded with 33 shredded-paper-filled-boxes positioned between 2 empty LD-3 containers. The bottom center paper-filled box was ignited remotely using a nichrome wire. Figure 15a shows the dimensions of a typical and standardized LD-3 container and 15b shows the location of the ignition source within the standardized test container. Other 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 16.




Typical LD-3 Container

"Standard" LD-3 Test Container

Figure 15a. Dimensions of Typical LD-3 Container and Standardized Test Container


Figure 15b. Placement of Box Containing Ignition Source in LD-3 Container

| | |
|---|---|
| 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-inch |
| 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 inch by 10 inch |
| Ignition Source Location** | Bottom of Shredded Paper Filled Box |
| Loacation 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 inches by 0.50 inches by 10 inches
***A thermocouple is placed on top of and inside the box containing the ignition source to indicate fire

Table 2. Containerized Test Materials and Dimensions

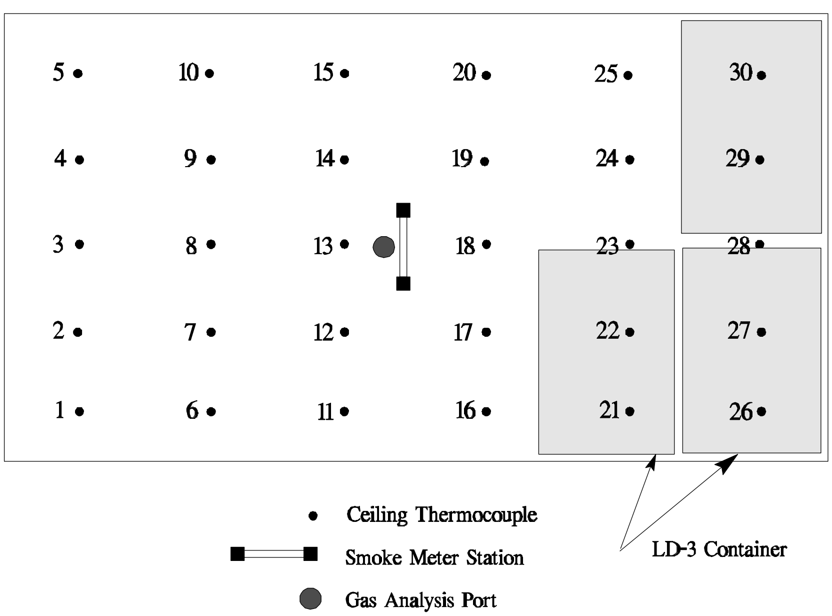



Figure 16. Instrumentation Layout in DC-10 Forward Compartment

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 leakage rate in the forward compartment was calculated at 98.43 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. The forward compartment was constructed from steel framing and corrugated steel for the purpose of conducting test fires only, 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 17):

Leakage rate calculation at 1 foot height:

$\Delta t$ (8% to 2.96%) = 54.42 – 24.58 = 30.84
$\Delta t$ (6% to 2.22%) = 69.42 – 31.16 = 38.26
$\Delta t$ (ave) = 34.55

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

Leakage rate calculation at 2 foot height:

$\Delta t$ (8% to 2.96%) = 43.33 – 23.85 = 19.48
$\Delta t$ (6% to 2.22%) = 50.42 – 28.75 = 21.67
$\Delta t$ (ave) = 20.58

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

Leakage rate calculation at 3 foot height:

$\Delta t$ (8% to 2.96%) = 44.33 – 24.09 = 20.24
$\Delta t$ (6% to 2.22%) = 50.92 – 29.17 = 21.75
$\Delta t$ (ave) = 21.00

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

Leakage rate calculation at 4 foot height:

$\Delta t$ (8% to 2.96%) = 44.83 – 24.08 = 20.75
$\Delta t$ (6% to 2.22%) = 51.75 – 29.17 = 22.58
$\Delta t$ (ave) = 21.67

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

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

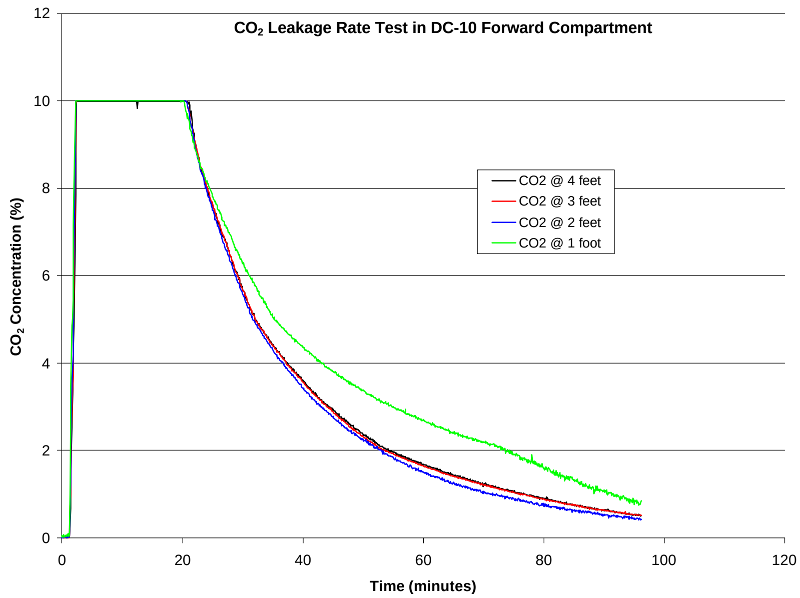



Figure 17. Leakage Rate Tests in DC-10 Forward Cargo Compartment

HUGHES/RELIABLE SYSTEM CONFIGURATION SUMMARY

The water spray system hydraulic pump was set at 1000 psi for all tests, with individual zone flowrate 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, with minimal control of the fire. During tests 2, 3, and 4, the zone size was doubled in order to give 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. During the fourth test the nozzle activation was changed back to 250°F, and the flowrate was increased to 2.1 GPM in the zone nearest the fire threat, but with the exception of a 10 minute period, better control of the fire resulted and the water consumption deceased to 65 gallons (Table 3).

| Date | System Configuration | Smoke Detection Time (sec) | System Pressure (psi) | Fire Zone Flowrate (GPM) | F.Z. Nozzle Flowrate (GPM) | Non-Fire Zone Flowrate (GPM) | N.F.Z Nozzle Flowrate (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 | .5 on/10 o | 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

Table 3. Hughes/Reliable High Pressure System Configuration and Water Consumption

Following the four initial tests, the spraying configuration was optimized in an attempt to better control the fire with less water, and ten additional tests were conducted. During the first two optimized tests, the flowrate in the non-fire 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 tests 3 and 4, the flowrate 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 6 tests, the flowrate was reduced to 1.0 GPM in the fire zone, in an effort to further reduce water consumption.

TEST RESULTS USING HUGHES/RELIABLE SYSTEM

During the first test, only half of the zones (nearest to the fire test container) were active (figure 18). 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.

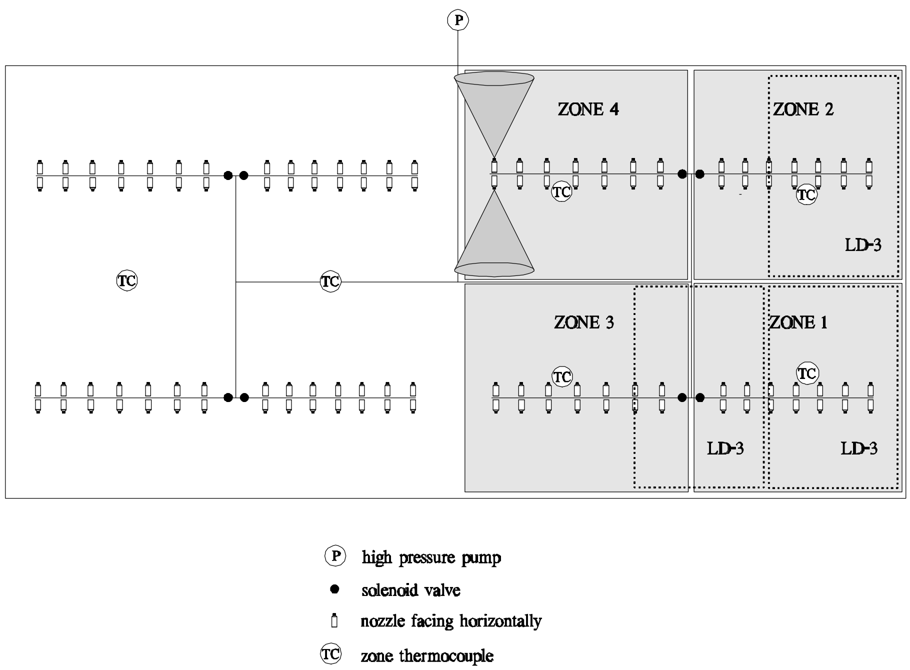



Figure 18. Hughes/Reliable High Pressure Spray System, Test 1

The initial test progressed for 60 minutes, in which time 40 gallons of water were used. 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 4 zones of protection for the entire compartment as shown in figure 19. Each zone contained 28 nozzles, while the activation temperature remained at 250°F for 10 seconds. During the test, temperatures were much more controlled, reaching a peak of approximately 500°F for a period not exceeding several minutes, but the water usage increased slightly to 44 gallons.

Since additional water was needed in the LD-3 test-container area, the nozzle flowrate 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 the 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.

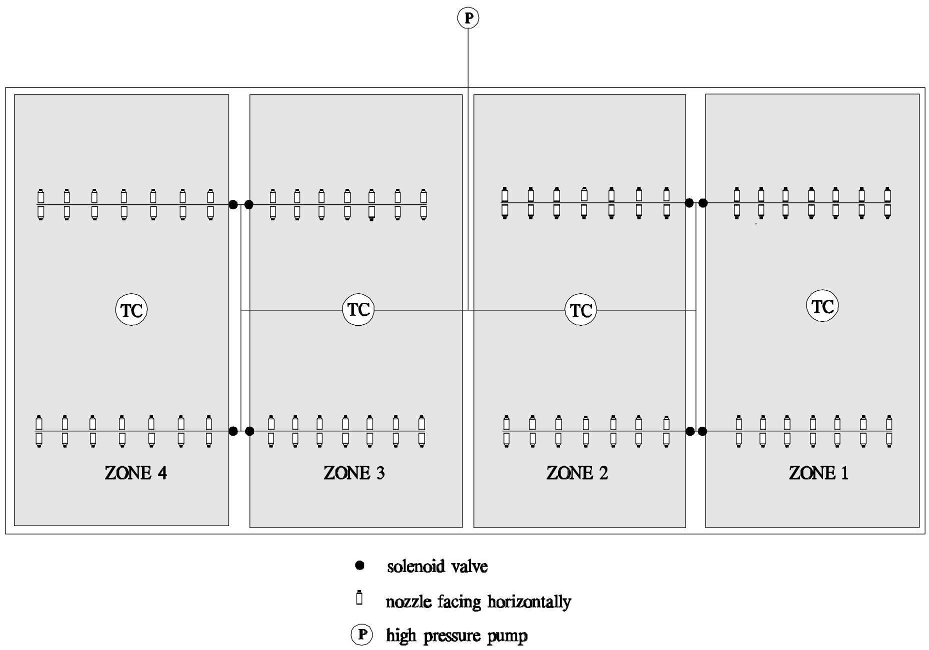



Figure 19. Hughes/Reliable High Pressure Spray System, Tests 2-4

A fourth test was conducted in which higher output nozzles were installed in zone 1, doubling the flowrate 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 the 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°F and 300°F during the 90-minute test, with brief excursions of between 400°F and 500°F (figure 20).

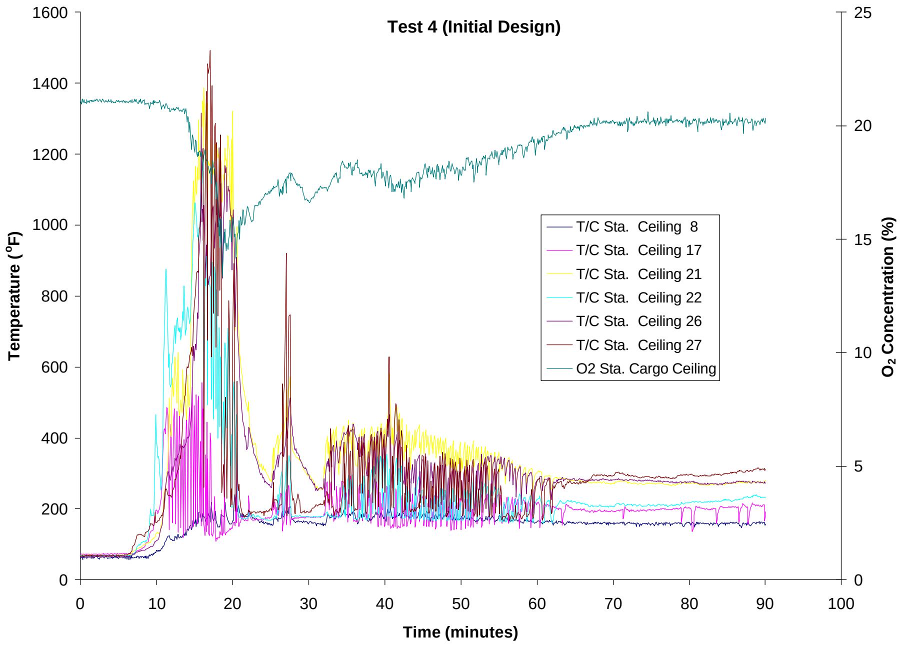



Figure 20. Hughes/Reliable Initial High Pressure Spray Test 4 Temperature and Oxygen Profiles

<u>HUGHES/RELIABLE OPTIMIZED SYSTEM</u>.

An additional 8 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 in previous 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 of, and another series of tests were conducted (figure 21). As shown, the updated nozzle arrangement required a heavy concentration of nozzles around the perimeter of the LD-3 container.

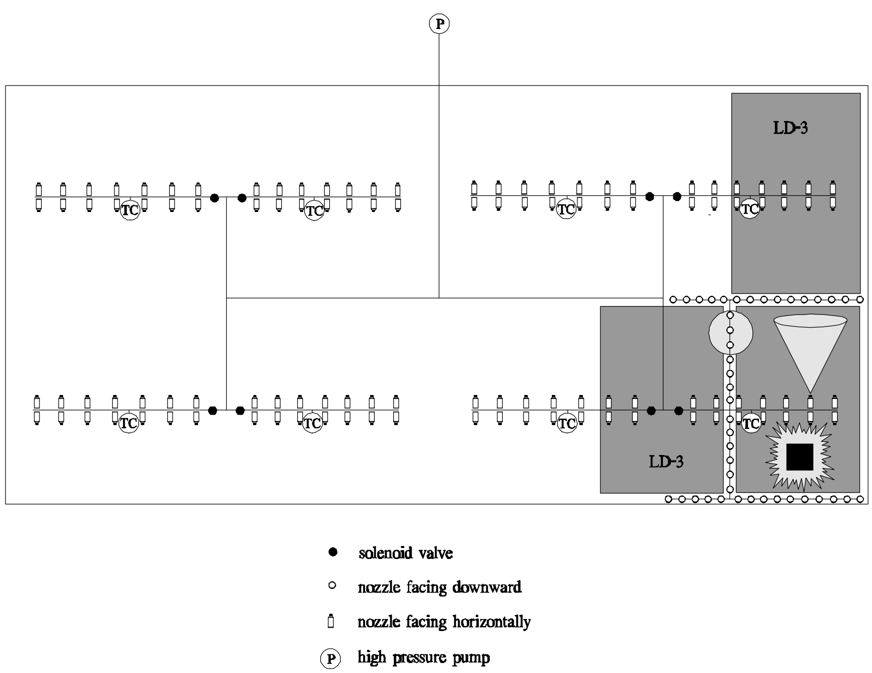



Figure 21. Hughes/Reliable Optimized High Pressure Spray System

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 non-threat areas). In the fire zone, a total of 43 MX-8 type nozzles were arranged at the ceiling of the compartment at the perimeter of the LD-3 container, directed downward toward the floor of the compartment. Additionally, there were 14 MX-8 nozzles arranged in a horizontally opposed fashion at the ceiling of the compartment to cool the area above the container. This 57-nozzle configuration resulted in a flowrate of 2.1 gallons per minute (GPM) in the fire zone, or approximately 0.036 GPM per nozzle. The flowrate of the nozzles located in the non-fire zones was increased substantially from 0.036 GPM to 0.114 GPM for a total flowrate of 1.6 GPM.

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 once the temperature reached 200$^{o}$F, and left on for 20 seconds. The spray in the non-fire zones was activated automatically once the temperature reached 200$^{o}$F and left on until the temperature (measured by the computer once every 10 seconds) dropped below 200$^{o}$F. The system was capable of holding the temperatures in the fire zone below 150$^{o}$F for the duration of the 90-minute test. The adjacent zone did, however, observe five temperature spikes ranging from 400$^{o}$ to 800$^{o}$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 removed and lower flowrate nozzles replaced for the third and fourth tests in an effort to reduce the water consumption. The new nozzles produced 0.028 GPM for a zone flowrate of 1.6 GPM, identical to the non-fire zone flowrate. In test 3, smoke detection occurred at 13 minutes. The spray was activated for a period of 20 seconds when the temperature exceeded 200$^{o}$F. Using this nozzle output, the system was again capable of holding the temperatures in the fire zone below 150$^{o}$F for the duration of the 90-minute test. The adjacent zone did experience several brief temperature excursions ranging between 350$^{o}$F and 500$^{o}$F which lasted on the order of 10 seconds each. These temperatures were comparable to the previous test, in which several excursions ranged between 400$^{o}$F and 800$^{o}$F. Most notably was the 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 a slight increase in water consumption to 37.5 gallons resulted.

After successfully suppressing the containerized fire using 34.1 and 37.5 gallons during tests 3 and 4, the nozzle configuration was again altered in an attempt to further reduce the water consumption. This was accomplished by simply removing every third nozzle, reducing the flowrate by 1/3 to 1.0 GPM in the fire zone (the non-fire zones remained unchanged). During the initial stages of test 5, for a short period (1 to 2 minutes) temperature spikes were observed above 300$^{o}$F in the fire zone and above 600$^{o}$F in the adjacent zone (figure 22). As with the previous tests, these spikes were of short duration. For the remainder of the test, the system was capable of holding the temperatures below 300$^{o}$F, usually around 150$^{o}$F. The reduced flowrate 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.

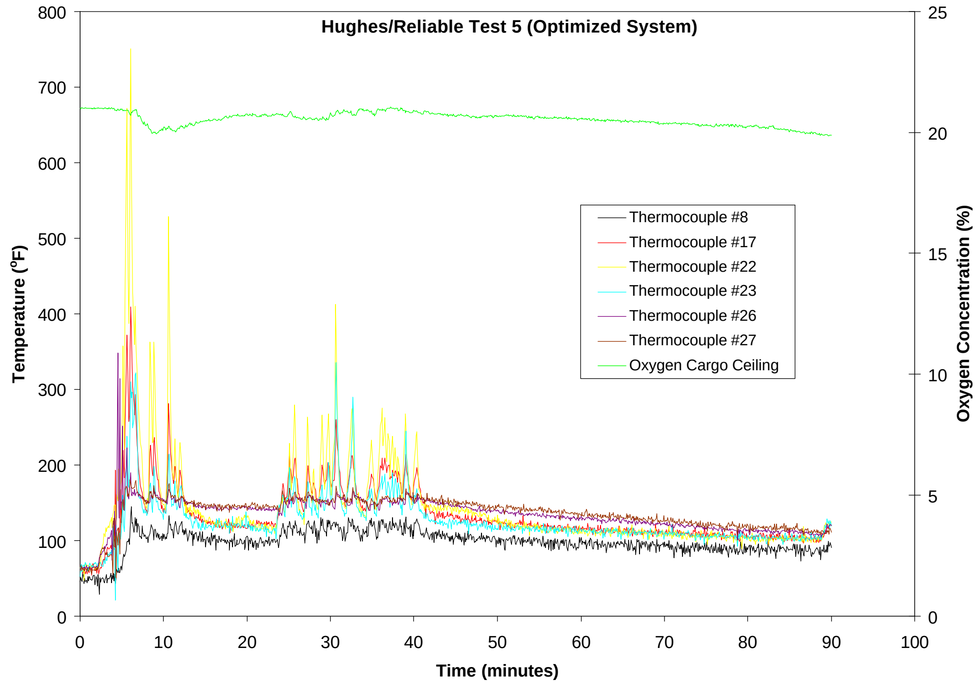



Figure 22. Hughes/Reliable Optimized System Test 5 Temperature and Oxygen Profiles

Further refinements were made to the activation temperature and the spray logic to minimize consumption while maintaining control of the fire. During test 6, the spray was activated manually in the fire zone once the temperature reached 200°F. Once activated, the 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. 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 3 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. At the end of the test, there seemed to be more heat remaining 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 2 excursions above 200°F (figure 23).

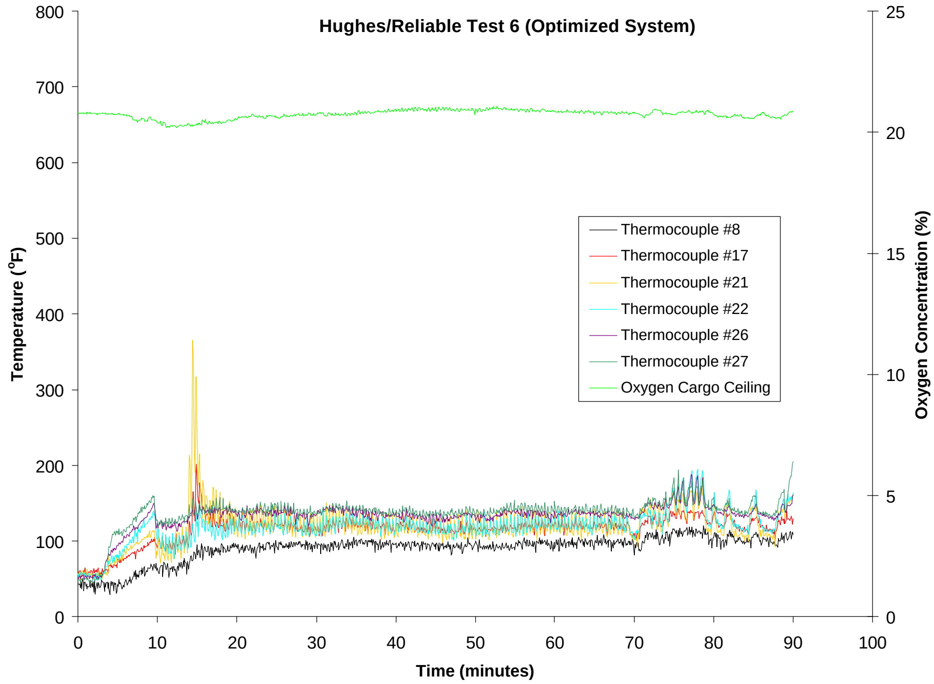



Figure 23.  Hughes/Reliable Optimized System Test 6 Temperature and Oxygen Profiles

A subsequent test was run in which the activation temperature was reduced from 200°F to 150°F (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 when the fire burned more intense, and longer off cycles during less intense periods.  This spray logic resulted in the system being capable of holding the temperatures in and around the fire zone below 150°F for the duration 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 24).

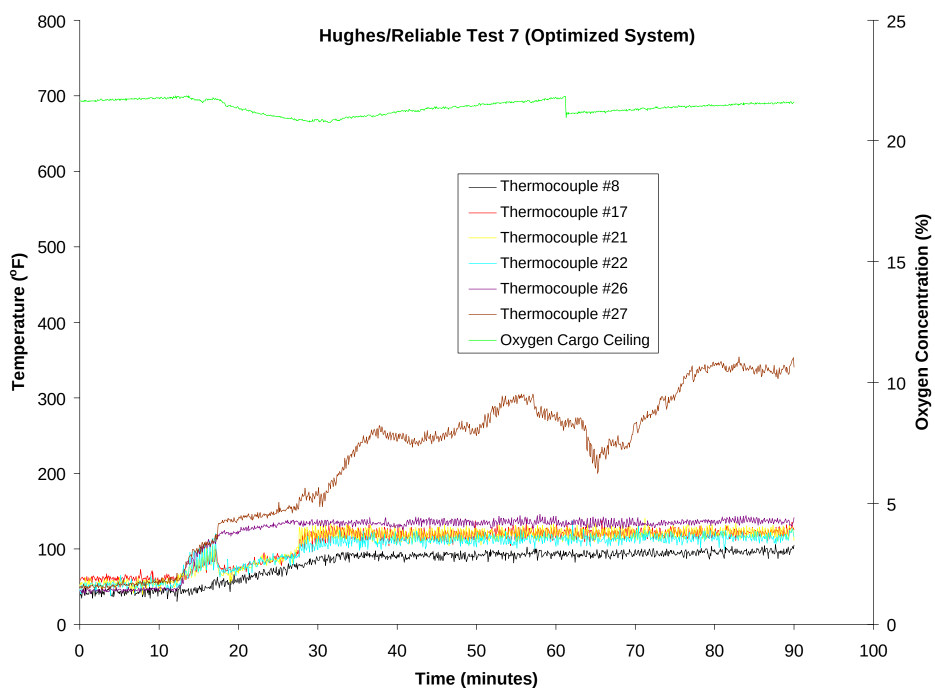



Figure 24.  Hughes/Reliable Optimized System Test 7 Temperature and Oxygen Profiles

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

A final test was conducted in which the activation temperature was increased from 150°F to 250°F.  As in the previous test, spray activation was controlled automatically in the fire zone.  During the test, temperature spikes between 300°F and 400°F were observed in the fire zone and spikes between 400°F and 700°F in the adjacent zone for the duration of the test (figure 25).  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.

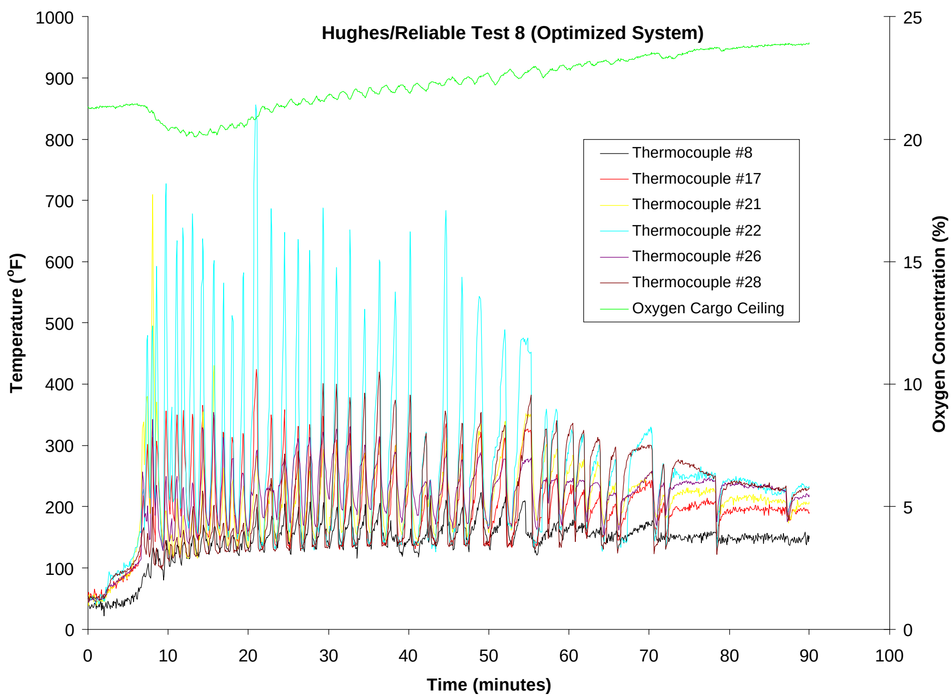



Figure 25.  Hughes/Reliable Optimized System Test 8 Temperature and Oxygen Profiles

Post test 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 was not suppressing the fire directly, but instead cooling the compartment periphery, thereby protecting adjacent areas.

BULK LOADED TEST RESULTS USING IMPROVED HUGHES/RELIABLE OPTIMIZED SYSTEM.

Two additional tests were conducted with simulated bulk loaded cargo with yet a third configuration (figure 26).  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 boxes 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 flowrate in each of these zones remained at 1.0 GPM (identical to the containerized 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. The identical smoke detection system used during the containerized fire load tests was set up. As in the previous tests, following smoke detection, a one-minute delay period was incorporated to simulate normal crew response. After this, the zone temperature logic controlled spray zone activation.

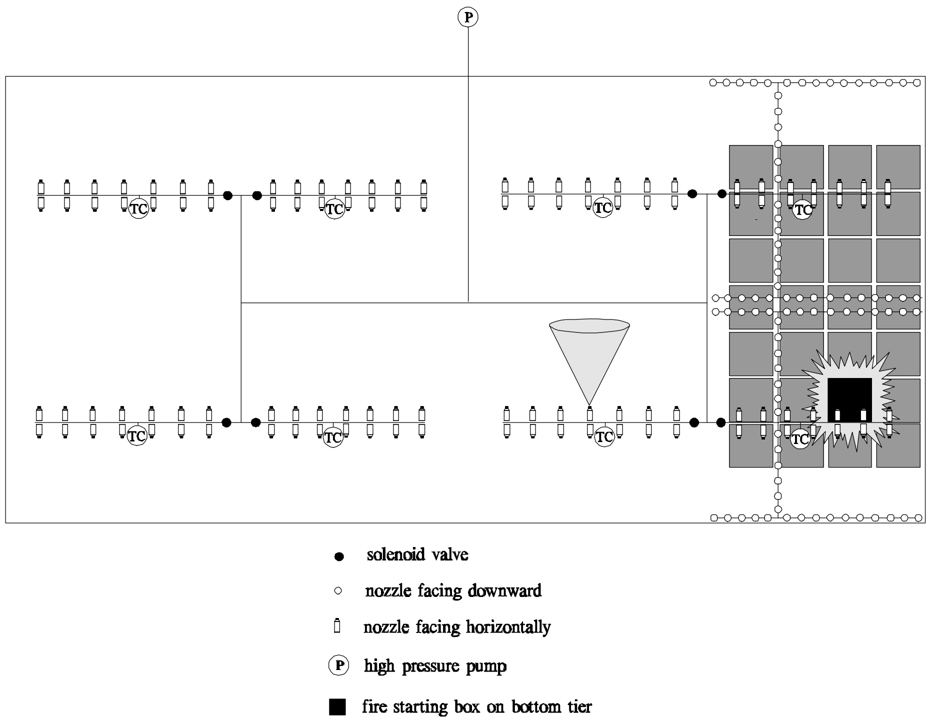



Figure 26. Improved Hughes/Reliable Optimized System for Bulk Loaded Cargo

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°F to 1000°F) during the initial 10 minutes of the test (figure 27). 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 was capable of holding the 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 28). These temperature spikes (as with the other temperature spikes observed during this test series) lasted for approximately 10 seconds.

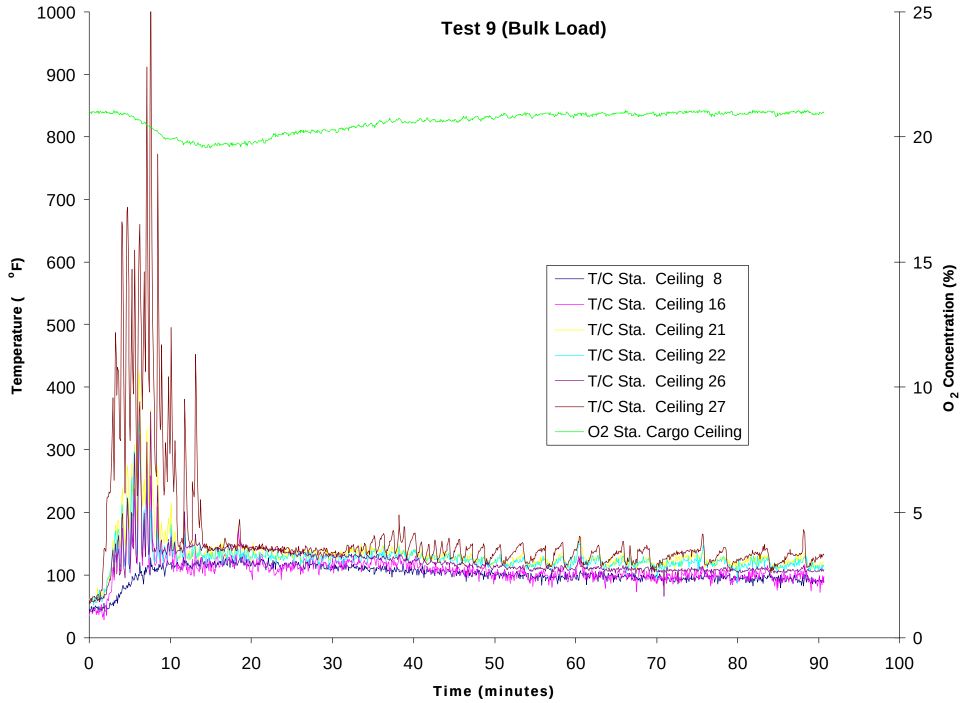



Figure 27. Improved Hughes/Reliable Optimized System for Bulk Loaded Cargo
Test 9 Temperature and Oxygen Profiles

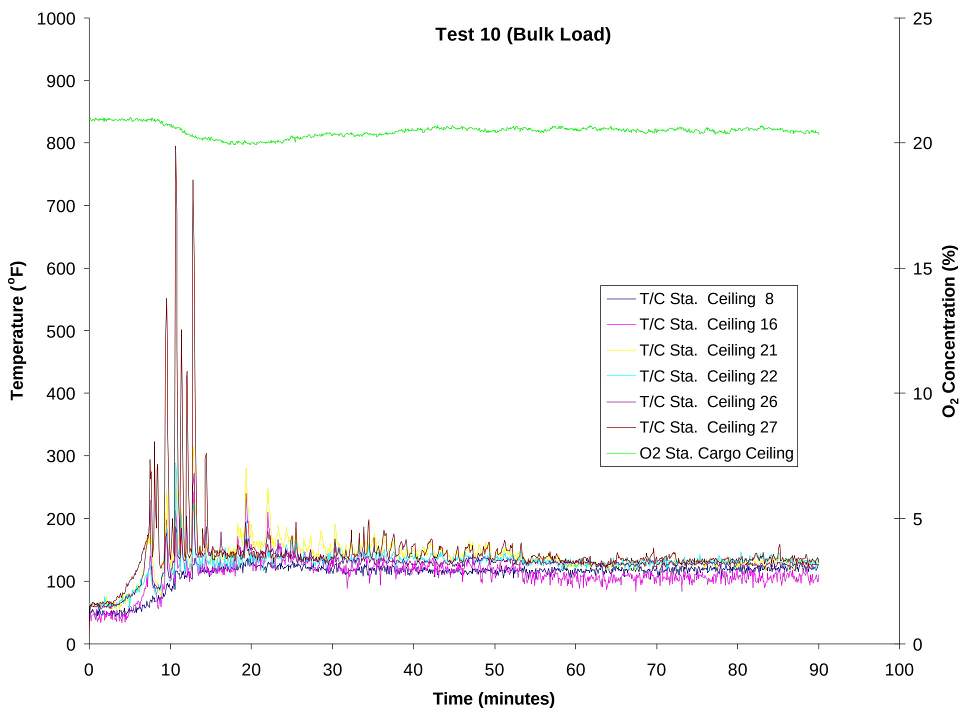



Figure 28. Improved Hughes/Reliable Optimized System for Bulk Loaded Cargo
Test 10 Temperature and Oxygen Profiles

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 compartment, and utilized a high-pressure fog between 800-1200 psi, distributed via 4 thermally activated zones (figure 29). Similar to the previous high-pressure system, the zone activation and deactivation temperatures could be pre-programmed in order to determine optimum settings.

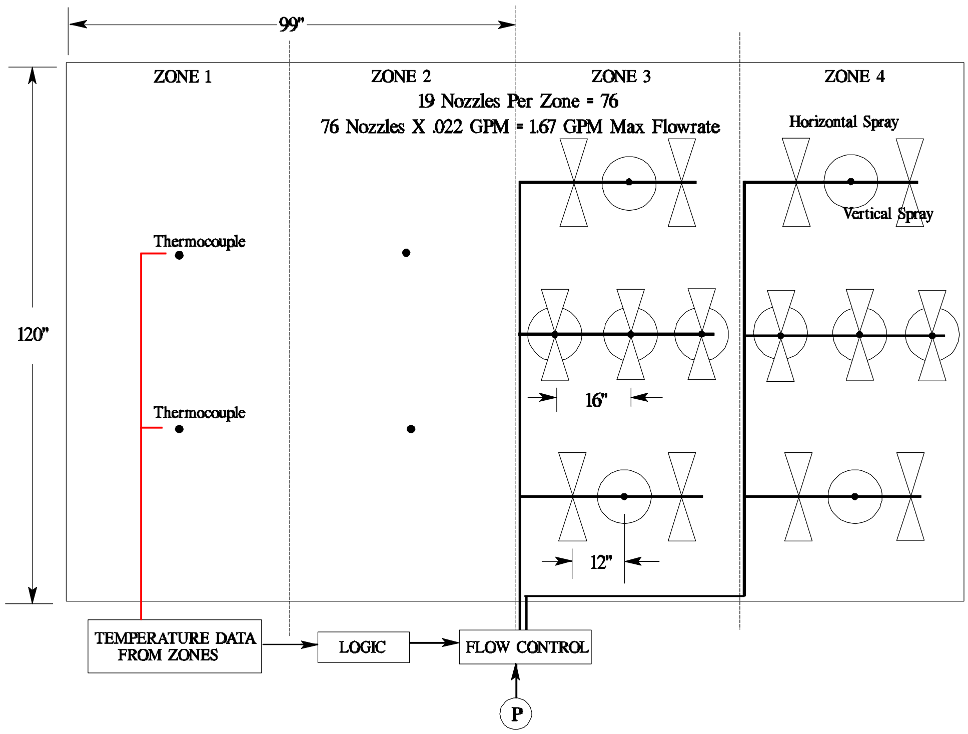



Figure 29. Environmental Engineering Concepts High Pressure Water Mist System Schematic

Two bulk-loaded tests were conducted, both with favorable results. During these initial tests, 10 shredded-paper-filled boxes were arranged in the compartment as shown in figure 30. The purpose of the initial 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.

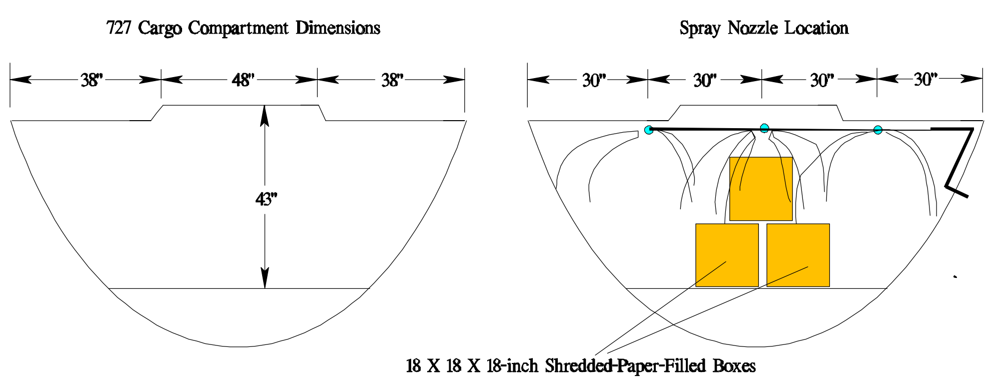



Figure 30. Environmental Engineering Concepts Bulk Load Fire Test Configuration

## CONCLUSIONS

A review of the test data obtained during trials of the 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. In contrast to a gaseous agent such as Halon 1301, the water spray essentially cools the compartment periphery rather than inerting the compartment or attacking the fire directly. During all successful water spray tests, the fire load materials were observed to continue to burn, but under controlled conditions that did not produce a hazard to other areas adjacent to the cargo compartment. Although effective, tests also revealed that 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 widebody configuration, in which 24.8 gallons of water (206 pounds) were required. By comparison, roughly 100 pounds of Halon 1301 would be required to maintain an initial concentration of 5%, and a minimum of 3% 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 have the ability to permeate the seams and holes of a container, transferring agent to the fire load. In contrast, water spray cannot attack the fire threat area as readily, reducing its suppression capability during deep-seeded containerized fires. After numerous successful tests, this viewpoint changed. Test results indicated the water spray system was effective, primarily by keeping the compartment periphery cool.

It became evident that a more severe test of a water spray system would involve the suppression of a ruptured/exploding aerosol can. Halon 1301 has proven its effectiveness against this particular threat. 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 the aerosol can ruptures. For this reason, additional tests will be conducted to determine the ability of water spray to mitigate the potentially devastating effects of an exploding aerosol can. Two test scenarios will be explored: Initially, an aerosol explosion will be induced in the presence of water spray. If the spray has the ability to mitigate this condition, a second test scenario will investigate the ability of the spray at preventing fire growth to adjacent areas of the cabin after an explosion has occurred. During this scenario, panels will be removed in the cargo ceiling and sidewall to simulate damage incurred from the simulated explosion.

## REFERENCES


1. Hill, R.G, Marker, T.R., and Sarkos, C.P., (1993), “Evaluation of an On-Board Water Spray Fire Suppression System in Aircraft,” Presented at the Water Mist Fire Suppression Workshop, National Institute of Standards and Technology, Gaithersburg, Maryland, March 1, 1993.
2. Hill, R.G, Marker, T.R., and Sarkos, C.P., (1991), “Development and Evaluation of an On-Board Aircraft Water Spray System for Postcrash Fire Protection,” SAE Technical Paper 912224, Aerospace Technology Conference and Exposition, Long Beach, California, September 23-26, 1991.
3. Marker, T.R., “Narrow-Body Aircraft Water Spray Optimization Study”, DOT/FAA/CT-TN93/3, February 1993.
4. Marker, T.R., “Widebody Cabin Water Spray Optimization Tests”, DOT/FAA/CT-TN93/29, August 1993.

5. Society of Fire Protection Engineers, Handbook of Fire Protection Engineering 2nd Edition, Copyright 1995, p. 4-135.
6. Eklund, T.I., “Analysis of Dissipation of Gaseous Extinguishing Agents in Ventilated Compartments,”DOT/FAA/CT-83/1, May 1983.