EVALUATION AND OPTIMIZATION OF AN ON-BOARD WATER SPRAY FIRE SUPPRESSION SYSTEM IN AIRCRAFT

Richard G. Hill
Timothy R. Marker
Constantine P. Sarkos

Fire Safety Branch
Federal Aviation Administration Technical Center
Atlantic City International Airport, New Jersey 08405

Paper to be presented at
Twelfth Meeting of United States - Japan Panel
on Fire Research and Safety
Tsukuba and Tokyo Japan
October 27 to November 2, 1992

Evaluation and Optimization of an On-Board Water Spray Fire Suppression System in Aircraft

RICHARD G. HILL
TIMOTHY R. MARKER
CONSTANTINE P. SARKOS
Fire Safety Branch
Atlantic City International Airport, New Jersey 08405

ABSTRACT

This paper describes a series of full-scale fire tests to evaluate the effectiveness of an on-board aircraft cabin water spray system against postcrash fires. The system consisted of an array of nozzles, at the ceiling, which continuously discharged water throughout the cabin for 3 minutes. Several fire scenarios were examined, including a wind-driven external fuel fire adjacent to a fuselage opening and a quiescent fuel fire impinging upon an intact fuselage. Also, both narrow-body and wide-body test articles were utilized. An analysis of the hazard measurements using a fractional effective dose model indicated the water spray provided approximately 2-3 minutes of additional survival time for all but the most severe scenario tested. Additionally, a zoned water spray system was conceptualized, designed and tested under full-scale conditions in an attempt to reduce the weight penalty of water. Initial test results indicated that a zoned system may be designed to give more protection than a continuous spray system with approximately 10 percent of the water.

1. INTRODUCTION

Aircraft crash fires are almost always initiated by the ignition of spilled jet fuel. The intensity and size of a postcrash fuel fire presents a complex and severe design threat for the aircraft manufacturers and regulatory agencies responsible for fire safety in transport aircraft. Since the mid-1980's, the United States (U.S.) Federal Aviation Administration (FAA) has adopted a series of new fire safety standards to enhance postcrash fire survivability (ref. 1). The main focus has been on the improved fire performance of cabin materials. FAA full-scale fire tests have demonstrated that seat cushion fire blocking layers and low heat release panels delay the onset of flashover, providing more time for escape. In addition, it has been shown that heat resistant evacuation slides and floor proximity lighting increase the evacuation rate of passengers.

The FAA has now embarked on a program to develop and evaluate an on-board cabin water spray fire suppression system. The baseline water spray system was designed in the United Kingdom (U.K.) by Safety Aircraft and Vehicles Equipment, Ltd. (SAVE). It basically consists of a large number of small nozzles, mounted throughout the ceiling, which discharge a fine water spray with a mean droplet diameter of about 100 microns for a period of 3 minutes (ref. 2).

The FAA program is comprised of two phases (ref. 3). Phase 1 is essentially completed and was a feasibility study of the baseline SAVE system in terms of the following factors: (1) effectiveness against postcrash fires, (2) potential benefit in past accidents, and (3) adverse impact of an accidental discharge on safety of flight, passengers, and restoration to service. The Phase 1 study indicated that a water spray system is feasible. Phase 2 is underway and includes such tasks as optimization of the system to reduce weight penalty and development of requirements and specifications.

The purpose of this paper is to summarize the results of full-scale fire tests to determine the effectiveness of a cabin water spray system under postcrash fire conditions. In addition, initial test results related to system optimization to minimize weight penalty are presented.

2. TEST SETUP

The test arrangement simulated a survivable aircraft crash involving fuselage exposure to an external fuel fire. The fire source was an 8- by 10-foot pan of burning jet fuel which had been shown previously to be representative of the severe thermal threat created by a large fuel spill fire. Two types of postcrash fire scenarios were evaluated. The most commonly used scenario located the fuel fire adjacent to a hole (simulated rupture) in the test fuselage the size of a Type A door opening (76 by 42 inches). A variable speed exhaust fan in the front of the fuselage created a draft inside the cabin, allowing the degree of flame penetration through the hole and the resultant severity of the fire inside the cabin to be varied. In the second type of scenario the fuel fire was adjacent to an intact fuselage, and fire penetration into the cabin occurred after penetration or burnthrough of the fuselage shell. Fairly strict control over the fuel fire conditions was maintained because the tests were conducted inside a building, assuring test repeatability.

The tests were conducted in both a narrow-body fuselage and a wide-body fuselage. The former is a surplus B-707 airplane while the latter is a 130-foot-long hybrid consisting of a 40-foot DC-10 section married to a 90-foot cylinder.

3. EFFECTIVENESS TESTS

<u>Narrow-Body Test Article.</u> A plan view of the narrow-body test article is shown in figure 1, indicating the SAVE water spray system nozzle arrangement and location of instrumentation and cabin materials. The water spray system consisted of 120 nozzles which discharged 72 gallons of water over a period of 3 minutes. Instrumentation consisted of thermocouples, smoke meters, gas analyzers, gas sampling equipment, calorimeters, and photo and video cameras. A 24-foot-long section of the test article, centered at the external fire pan, was outfitted with 5 rows of passenger seats, ceiling panels, stowage bins, sidewalls, and carpet. All materials were compliant with the current FAA fire test standards (ref. 1).

A zero ambient wind condition was simulated by not operating the exhaust fan. With the absence (initially) of flame penetration through the fuselage opening, the fire threat was dominated by intense thermal radiation. The results of the zero wind tests, with and without water spray, are shown in figure 2. The shaded curves in this and subsequent figures show the range in measurements at a particular fuselage station. In all cases, the hignest readings were at the highest locations, and the readings decreased the closer the measurement location was to the floor. Temperature was measured at 1-foot increments from a location 7 feet high (slightly below the ceiling) to a location 1 foot above the floor. Smoke was measured at three heights: 5 feet, 6 inches; 3 feet, 6 inches; and 1 foot, 6 inches. All gas measurements were at 5 feet, 6 inches and 3 feet, 6 inches.

Figure 2 exhibits a rapid rise in temperature and toxic gas production and a decrease in oxygen concentration at approximately 5 minutes in the test without the water spray. This behavior indicates the development of a flashover condition at 5 minutes. However, when water spray was used, survivable conditions prevailed for the entire 7-minute test duration. The time interval of actual water spray discharge was from 15 seconds until approximately 195-200 seconds into the test. Therefore, in addition to the reduction in cabin fire hazards during the water spray discharge, there were notable improvements in the cabin environment after the discharge was completed.

Survival time was calculated from the measured hazards by employing a fractional effective dose (FED) model developed recently (ref. 4). The model is believed to reflect the current state-of-the-art data in terms of incapacitation of humans subjected to a single toxic combustion gas. It assumes that the effect of heat and each toxic gas on incapacitation is additive. It also assumes that the increased respiratory rate due to elevated carbon dioxide levels is manifested by the enhanced uptake of other gases. The FED plot in figure 2 shows incapacitation at 5 minutes without water spray discharge, corresponding to the time of flashover. Discharge of water spray prevented flashover within the 7-minute test duration and maintained a survivable environment within that increment (FED<0.1 at 7 minutes). Therefore, the increase in survivability provided by water spray discharge was much greater than 2 minutes.

A "moderate" wind scenario was devised, by operating the exhaust fan to induce fuel fire flame penetration through the fuselage opening, in order to create a more severe fire threat than imposed by the zero wind condition. Figure 3 shows the results of those tests. The profiles are quite similar to the zero wind test (figure 2) but are transposed earlier in time by about 2 minutes. Flashover occurred between 150 and 180 seconds without water spray. With water spray, flashover occurred much later (close to 300 seconds) and with a much lower intensity (less temperature rise and gas production). The FED plot shows that the increase in survival time was 215 seconds. Figure 3 also shows the effectiveness of water spray in removing water soluable acid gases such as hydrogen fluoride.

The water spray system was also evaluated against a "high" wind scenario. In this case, the fuel fire flames penetrated across the ceiling practically to the opposite side of the cabin. The fire was so severe that it overwhelmed the water spray, and it became necessary to terminate the test after only 60 seconds. The test illustrated that the benefits of fire safety design improvements are highly dependent upon the fire scenario, and for some scenarios, it is virtually impossible to improve survivability by design changes.

Conversely, the water spray system proved effective against the burnthough scenario. In this case, the fire entered the cabin, at approximately 1 minute into the test, by burning through the floor and sidewall area. FED analysis indicated that 132 seconds of additional survival time was provided by the water spray system.

Wide-Body Test Article. Installed inside the wide-body test article, the SAVE system consisted of 324 nozzles arranged in 5 rows along the length of the fuselage, discharging 195 gallons of water over a period of 3 minutes. The fuel fire conditions, instrumentation, and arrangement of interior materials were similar to the narrow-body test article setup. Again, there were 5 rows of interior materials centered about the fire door, which was located at fuselage station 940 (78 feet from the front of the fuselage). Of course, the quantity of interior materials was far greater; e.g., 9 seats across/double aisle in the wide-body versus 5 seats across/single aisle in the narrow-body.

A "moderate" wind condition, causing fuel fire flame penetration through the fuselage opening, was utilized to evaluate the effectiveness of water spray in the wide-body test article. Figure 4 shows the results of those tests. As in the narrow-body tests, significant reduction in cabin temperatures and toxic gas levels were evidenced during the water spray test. Of some concern is the light transmission profiles reflecting the loss in visibility due to smoke. For more than half the test duration, because the water spray tends to lower and distribute the ceiling smoke layer, there is a greater reduction in light transmission while the water is being discharged. Apparently, the amount of smoke particulate removal or "washing out" by the water spray is more than offset by the lowering of the smoke layer. Later, however, the reduction in light transmission with an unabated fire becomes more significant.

The FED curve indicates a loss of survivability at 215 seconds without the water spray system. Examination of the temperature and gas levels, particularly oxygen concentrations (not shown), indicates the onset of flashover at about 210 seconds. With water spray, flashover was prevented over the 5-minute test duration and the cabin environment (away from the fire source) remained survivable. On the basis of the FED calculation, the improvement in survival time was 85 seconds at the end of the test (5 minutes) but would likely have been considerably longer, perhaps 2-3 minutes, had the test not been terminated.

4. SYSTEM OPTIMMIZATION

Because of payload, weight penalty is an overriding consideration in aircraft design. The weight penalty associated with the SAVE system is somewhat excessive, if not prohibitive. Therefore, a zoned water spray system for the expressed purpose of weight reduction was conceptualized, designed, and tested.

The zoned concept divides an airplane into a series of water spray zones. Discharge of water within each zone is independent of the other zones and triggered by a sensor within the zone. In this manner the quantity of water discharged is dictated by the presence and spread of fire, eliminating the ineffectual and wasteful discharge of water away from the fire as in the SAVE system (ref. 5).

As of the preparation of this paper, an initial zoned water spray system design has been tested in the narrow-body test article. Each zone is 8 feet in cabin length. Four spray nozzles are mounted at the cabin periphery in each of the two boundary planes, with the spray discharge directed toward the center of the zone. Specifically, each nozzle is mounted perpendicular to the supply line and at a 45° angle with the vertical traverse plane (figure 5). Testing to date has been limited to 5 zones, centered about the fire door, comprising approximately 1/3 of the cabin length. Based on preliminary tests, a temperature of 300 °F was selected to activate water discharge (manually). The temperature is measured at the centerline of the zone, about 6 inches below the ceiling. The water supply line from the storage tank is charged with water up to a separate solenoid valve connected to each zone, mounted as close as possible to the zone, in order to minimize lag times and line losses. The plumbing inside the test article is initially dry.

Since the zoned system comprised approximately 1/3 of the test article, the initial series of tests utilized 24 gallons of water (versus 72 gallons for the SAVE system). In effect, the tests were simulating a system failure causing 2/3 of the water supply to be unavailable. Three types of nozzles were evaluated: low, 0.23 gallons per minute (gpm) (SAVE nozzle); medium, 0.35 gpm; and high, 0.50 gpm. A more severe simulated wind condition than employed previously was used as a test condition (external fuel fire/fuselage opening scenario).

The calculated FED profiles from the initial series of optimization tests are shown in figure 6. The SAVE water spray system increased the survival time by 110 seconds. More importantly, the medium and high flow rate nozzles, discharging a total of only 24 gallons of water, increased the survival time beyond the SAVE system by about 55 seconds and 35 seconds, respectively. The improvement provided by the higher flow rate nozzles is apparently due to the application of larger quantities of water where it is needed most--in the immediate fire area. An interesting result is that the medium flow rate nozzles provided more protection than the high flow rate nozzles. A possible explanation is that the discharge time was longer with the medium flow rate nozzles; i.e., 180 seconds versus 140 seconds.

A second series of tests was undertaken to evaluate the impact of an even smaller supply of water. Eight gallons, or 1/9 the SAVE system total, was selected for examination. Figure 7 compares the FED profiles for the low and medium flow rate nozzles at 24 and 8 gallons of water. Figure 8 presents the temperature and carbon monoxide histories for these four tests. In figure 7 it is noteworthy that the survival time is 50 seconds <u>greater</u> at 8 gallons than at 24 gallons for the low flow rate nozzles. Also, the survival times are about equal for the medium flow rate nozzles for both water quantities and are greater than the low flow rate nozzles.

It is difficult to explain the longer survival time at 8 gallons, as compared to 24 gallons, for the low flow rate nozzles. Analysis of the data and the FED calculations indicate the higher levels of CO in the 24 gallon test (figure 8) and the dominant effect of CO in the FED model caused the smaller survival time. What caused the CO levels to be higher in this test is not completely clear. It may be that the longer discharge time at 24 gallons cooled and lowered the smoke layer enough to raise the CO levels at 5 feet, 6 inches. Additional tests are required to analyze these effects. What is clear and most important, however, is that relatively small quantities of water in a zoned system provide a significant improvement in survival time compared to a system that discharges water simultaneously throughout the cabin. For example, 8 gallons of water with a zoned system and medium flow rate nozzles provided a 55-second longer survival time than the SAVE system, which requires 72 gallons of water.

5. SUMMARY

Full-scale fire tests demonstrated the effectiveness of an on-board water spray system, comprised of an array of ceiling nozzles, discharging water throughout an airplane cabin for 3 minutes. Approximately 2-3 minutes of additional survival time were provided for several postcrash fire scenarios in both narrow-body and wide-body test articles. Additional full-scale tests demonstrated that a zoned system, designed to discharge water at 300 °F in each zone, gave even more protection with only about 10 percent of the weight of water.

6. REFERENCES

1. Sarkos, C.P., "Development of Improved Fire Safety Standards Adopted by the Federal Aviation Administration," AGARD-CPP-467, Propulsion and Energetics Panel 73rd Symposium on Aircraft Fire Safety, Sintra, Portugal, May 22-26, 1992.

2. Whitfield, R.T., Whitfield, Q.A., and Steel, J., "Aircraft Cabin Fire Suppression by Means of an Interior Water Spray System," Civil Aviation Authority, CAA Paper 88014, July 1988.

3. Hill, R.G., Sarkos, C.P., and Marker, T.R., "Development and Evaluation of an Onboard Aircraft Cabin Water Spray System for Postcrash Fire Protection," SAE Technical Paper 912224, Aerospace Technology Conference and Exposition, Long Beach, California, September 23-26, 1991.

4. Speitel, L.C., "Toxicity Assessment of Combustion Gases and Development of a Survival Model," Federal Aviation Administration, Report DOT/FAA/CT-91/26, to be published.

5. Marker, T.R., "On-Board Cabin Water Spray System Under Various Discharge Configurations," Federal Aviation Administration, Report DOT/FAA/CT-TN91/42, October 1991.

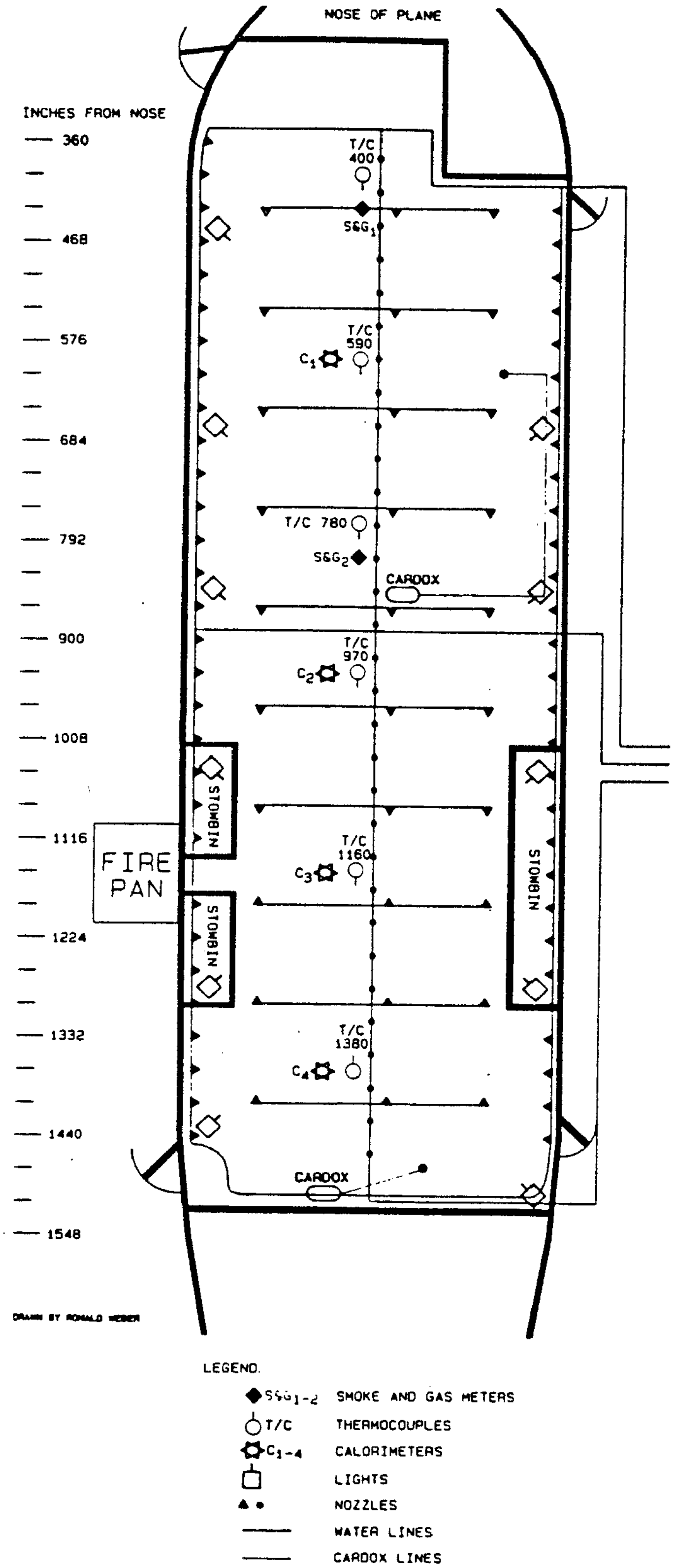

FIGURE 1.
NARROW BODY TESTCONFIGURATION

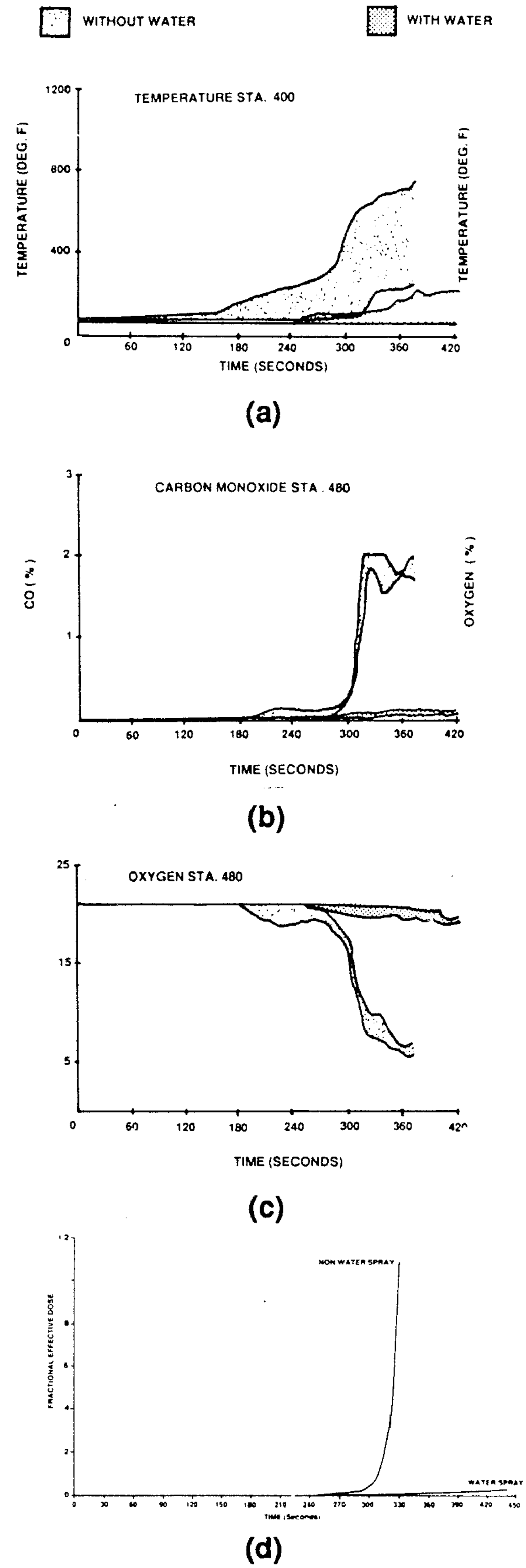

FIGURE 2.
NARROW BODY RESULTS/ SAVE SYSTEM/ ZERO WIND/ FUSELAGE OPENING

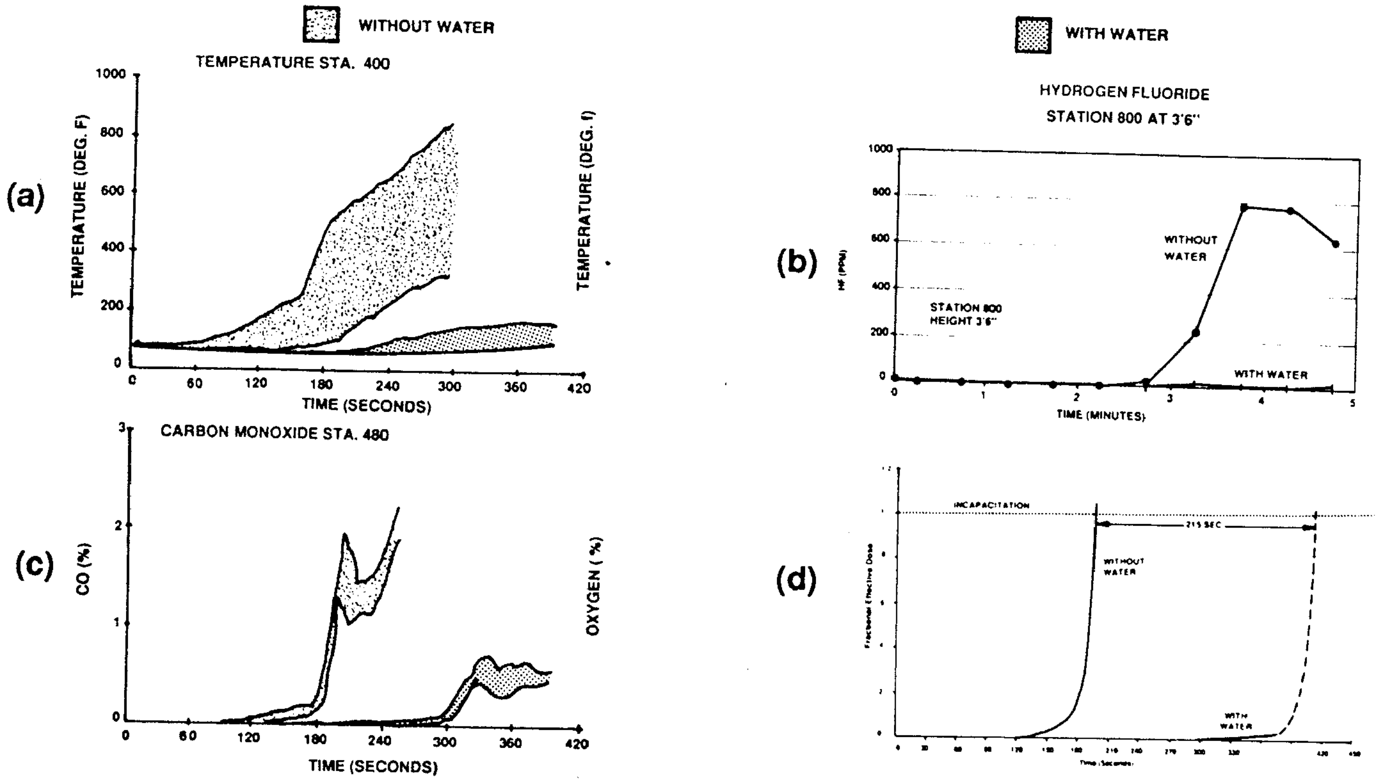

FIGURE 3.
NARROW BODY RESULTS/ SAVE SYSTEM/MODERATE WIND/FUSELAGE OPENING

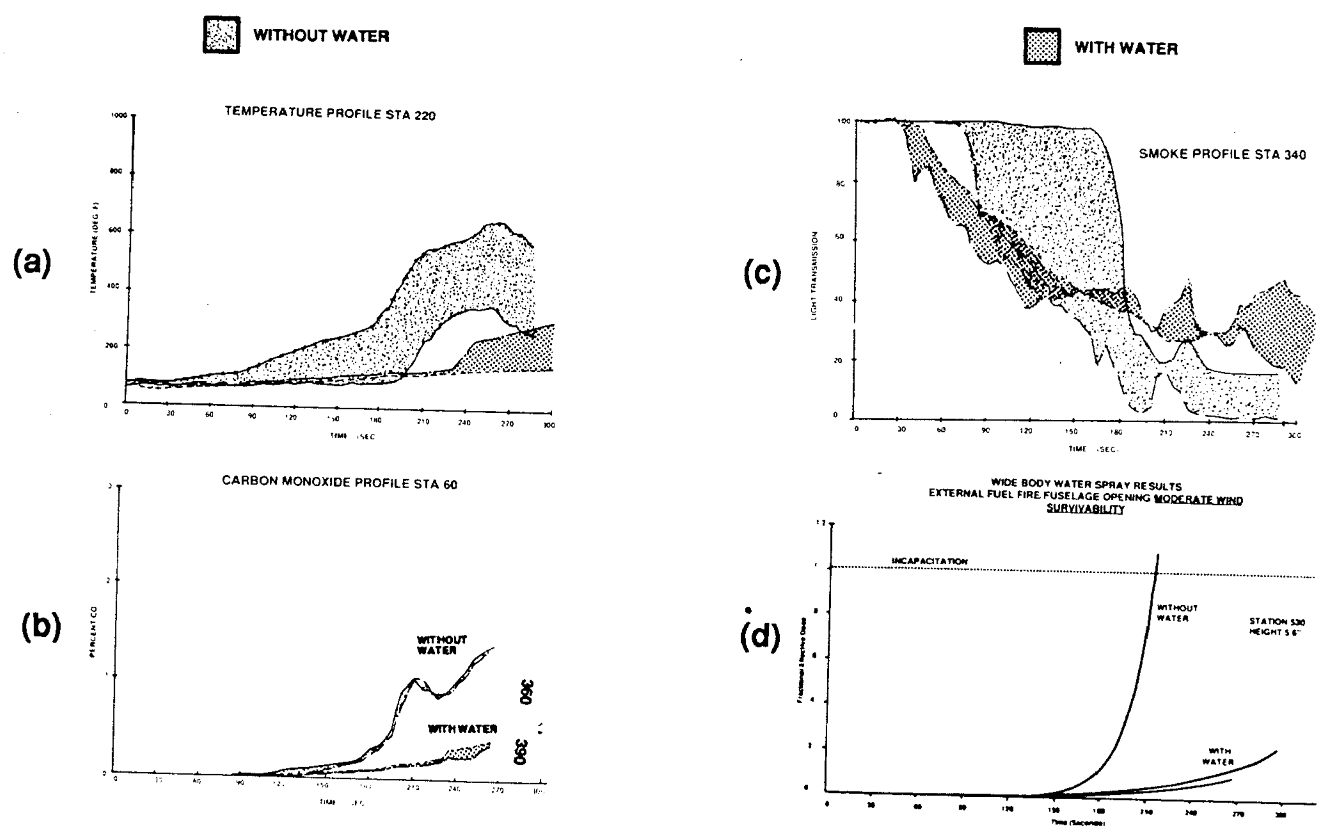

FIGURE 4.
WIDE BODY RESULTS/ SAVE SYSTEM/MODERATE WIND/FUSELAGE OPENING

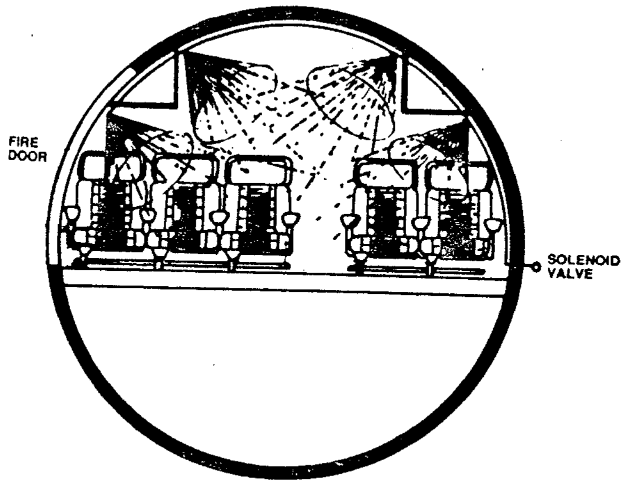

FIGURE 5.
ZONED SYSTEM DISCHARGE PATTERN

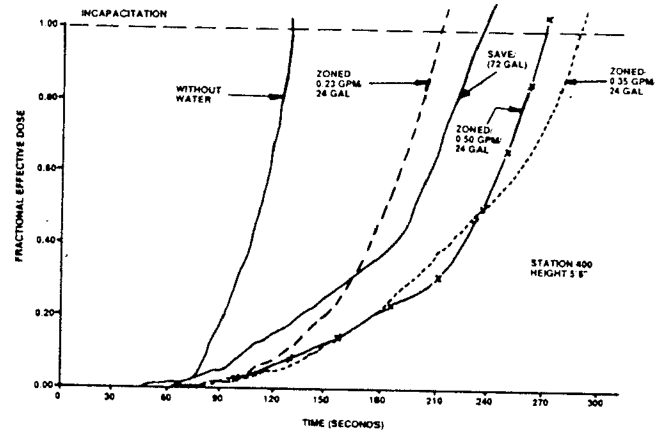

FIGURE 6.
ZONED SYSTEM SURVIVAL TIME
IMPROVEMENT 24 GALLONS

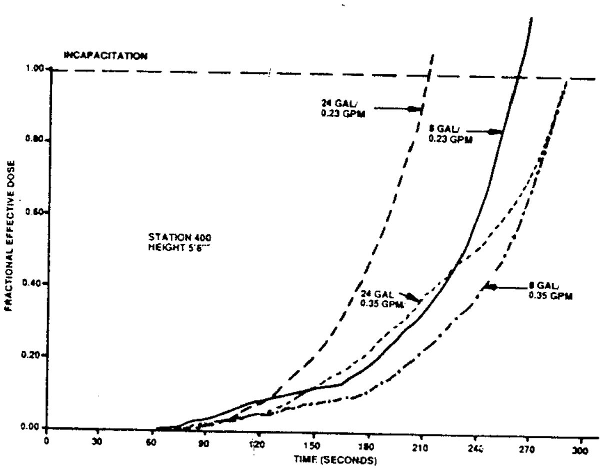

FIGURE 7.
ZONED SYSTEM SURVIVAL TIMES/24
AND 8 GALLONS

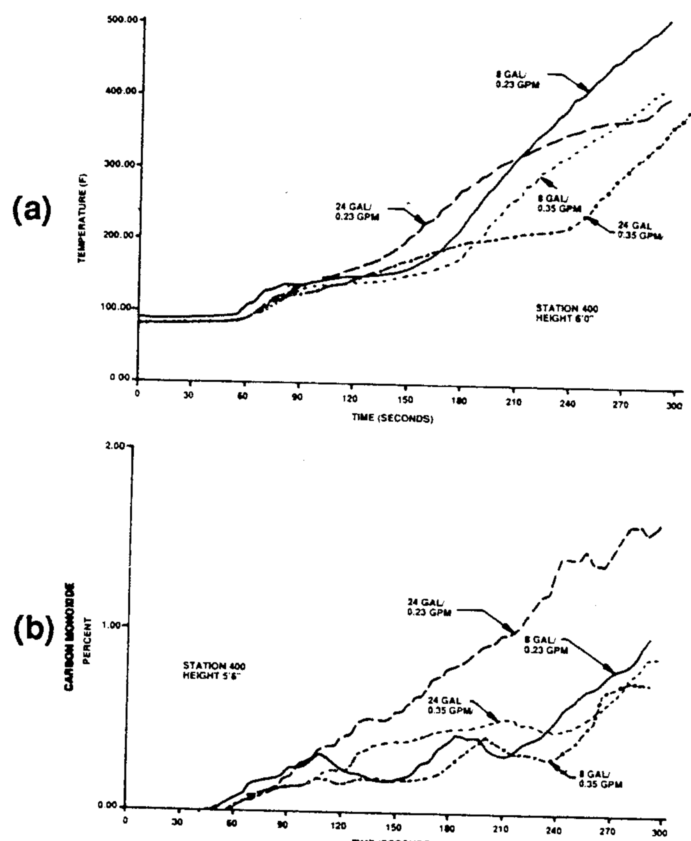

FIGURE 8.
ZONED SYSTEM/TEMPERATURE AND
CARBON MONOXIDE RESULTS/24
AND 8 GALLONS