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# DEVELOPMENT OF AN ON-BOARD WATER SPRAY FIRE SUPPRESION SYSTEM FOR TRANSPORT AIRCRAFT

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## SUMMARY

This paper describes a series of full-scale fire tests to evaluate and optimize an on-board aircraft cabin water spray system for passenger protection against postcrash fires. The initial 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 in both narrow-body and wide-body test articles. An analysis of the hazard measurements using a fractional effective dose model indicated the water spray provided significant improvements in 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. Test results indicated that an optimal zoned system gives more protection and improved visibility than a continuous spray system with approximately 10 percent of the water. Tests were also conducted in a commuter test article to determine the relative effectiveness of a water spray system and improved fire resistant materials.

## 1. INTRODUCTION

With the adoption in recent years of stringent fire tests standards for cabin materials (ref. 1), the United States (U.S.) Federal Aviation Administration (FAA) has sought further improvements in postcrash fire survivability in a joint program with the United Kingdom (U.K.) Civil Aviation Authority and Transport Canada to develop an on-board cabin water spray fire suppression system. The baseline water spray system was designed in the U.K. by Safety Aircraft and Vehicles Equipment, Ltd. (SAVE). It basically consisted 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 purpose of this paper is to summarize the full-scale tests phase of the program to determine the effectiveness of the SAVE continuous discharge water spray system under postcrash fire conditions and to optimize the water spray system by dividing the cabin into zones in order to minimize the weight penalty.

## 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. The discussion in this paper will be limited to a typical scenario comprised of a fuel fire adjacent to a hole (simulated rupture) in the test fuselage the size of Type A door openings (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. Fairly strict control over the fuel fire conditions were maintained because the tests were conducted inside a building, assuring test repeatability.

The 8-by-10-foot pan fire 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. Similar tests with a smaller fuel fire was conducted in a Metroliner commuter aircraft test article.

## 3. EFFECTIVENESS OF CONTINUOUS DISCHARGE (SAVE) SYSTEM

Narrow-Body Test Article. 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).

Initially, a zero ambient wind condition was simulated by not operating the exhaust fan. With the absence 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 highest 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 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 (ref. 3). It assumes that the effect of heat and each toxic gas on incapacitation is additive and that the increased respiratory rate due to elevated carbon dioxide levels is manifested by the enhanced uptake of other gasses. 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 soluble 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.

Wide-Body Test Articles. 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.

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 reduction in visibility due to smoke. For more than half the test duration, because the water spray tends to lower 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. OPTIMIZATION AND DEVELOPMENT OF ZONED SYSTEM

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. 4).

Narrow-Body test Article. 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 degree angle with the vertical transverse plane. Based on preliminary tests, a temperature of 300 degrees Fahrenheit (F) was selected to activate water discharge (manually), although more studies are needed to determine the impact of this parameter on system design. The temperature is measured at the center of the zone, about 6 inches below the ceiling.

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 the test condition.

The calculated FED profiles from the initial series of optimization tests are shown in figure 5. 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 total of 9 water spray zoned tests were conducted, employing 4 water quantities and 3 nozzle flow rates. The results are summarized in figure 6 in terms of the additional available escape time beyond the baseline test without water discharge. The results of the SAVE test are also shown (108 seconds additional escape time). Each of the zoned tests indicated a significant improvement in the additional escape time, which was greater than the improvement with the SAVE system in 5 of the 9 cases. Even with only 4 gallons of water, the zoned system was effective, increasing the available escape time by 53 seconds.

Improved visibility is another advantage of a zoned water spray system since continuously discharging water throughout the airplane tends to lower the ceiling smoke layer. With the zoned system the disruption of the smoke layer is primarily confined to the spray zones. Visibility during the zoned system tests improved by approximately 40-50 seconds compared to the SAVE system test (figure 7).

The efficiency of a water spray system may be define as the ratio of the additional available escape time (seconds) to the quantity of water discharged (gallons), or seconds per gallons (SPG). Figure 8 compares SPG for the various water spray configurations on the basis of nozzle flow rate. It is evident that the optimum zoned system utilizes a medium flow rate nozzle (0.35 gpm) and a water quantity of 8 gallons. The optimum zoned water spray system (SPG = 20.4) is a factor of 13.6 more efficient than the continuous water spray system (SPG = 1.5). It is significant that as much as 20 seconds of additional available escape time per gallon of water discharged may be achieved by a water spray system, operating effectively in a postcrash fire environment, where each second of available escape time is critical.

Wide-Body Test Article. The effectiveness of a zoned water spray system was examined in the wide-body test article. The zoned configuration was similar to the narrow-body arrangement with two exceptions. First, there were six nozzles in each of the two boundary planes. Second, for some tests a half-zone geometry was used; i.e., the zone extended to the cabin symmetry plane rather than across the full cabin width. Another variation in some tests was the spray discharge activation temperature. As in the narrow-body tests, initial activation of spray discharge was set at 300 degrees F; however, subsequent zone activations were delayed until the temperature reached 500 degrees F. This was done with the aim of conserving water for application in the initial zone where the fire intensity was greatest. The total quantity of water was only 21 gallons (vs. 195 gallon with the SAVE system). This was calculated by scaling to the optimum zone system and SAVE system water quantities in the narrow-body test article.

The calculated FED profiles are shown in figure 9. As in the narrow-body test article, the zoned water spray configurations provided a significant increase in survival time, ranging from 86 to 103 seconds under the conditions tested. Again, the medium flow rate nozzle (0.35 gpm) was more effective than the high flow rate nozzle (0.50 gpm), although by a relatively small amount (10 seconds). Small improvements are also seen from split zoning and elevation of discharge activation temperature in secondary zones (7 seconds). Additional tests should be conducted to more extensively evaluate the benefits of those parameters.

## 5. FIRE SAFETY IMPROVEMENTS IN SMALL AIRCRAFT

Currently, commuter aircraft (19 seats or less) are exempt from the stringent U.S. Federal Aviation regulations, requiring seat cushion fire blocking layers and low heat/smoke release panels in large transport aircraft (ref. 1). Therefore, to determine the potential improvements in postcrash fire survivability from the usage of these more fire resistant materials in commuter aircraft, and from a zoned water spray system, a series of full-scale tests were conducted in a Metroliner fuselage.

The test scenario setup for the Metroliner was similar to that used in the large transport test articles, except on a reduced scale; e.g., 4-by-5-foot pan fire adjacent to 20-by-26-inch initial fuselage opening. The water spray system was comprised of 100 inch long zones, with each zone containing six nozzles. Only 5 gallons of water was discharged in the Metroliner.

Figure 10 presents the survival time improvements resulting from fire blocked seats, improved panels and

Figure 10 presents the survival time improvements resulting from fire blocked seats, improved panels and a water spray system. Each fire safety design improvement created finite survival gains. By far the largest increase in survival time was furnished by the water spray system - over 3 minutes. It was shown by other tests that this incremental improvement would also be attained with less fire resistant material arrangements. It is interesting that the survival time improvement for seat fire blocking layers, 45 seconds, is within the range measured previously in large transport full-scale fire tests (ref. 1).

## 6. SUMMARY OF RESULTS

Full-scale fire tests have demonstrated that an on-board cabin water spray system can provide significant increases in survival time in all transport aircraft sizes during a typical postcrash fire. It was shown that the water spray cools the air, suppresses the cabin fire and reduces the concentration of toxic gases. Moreover, a zoned water spray system, utilizing relatively small quantities of water, can further increase the survival time and improve visibility compared to a system that continuously discharges water throughout the cabin. Enhancement in survivability by zoning is attributed to confining the water discharge to areas of the cabin where the fire originated and spread, and to minimizing the degree of lowering of the smoke layer caused by water discharge.

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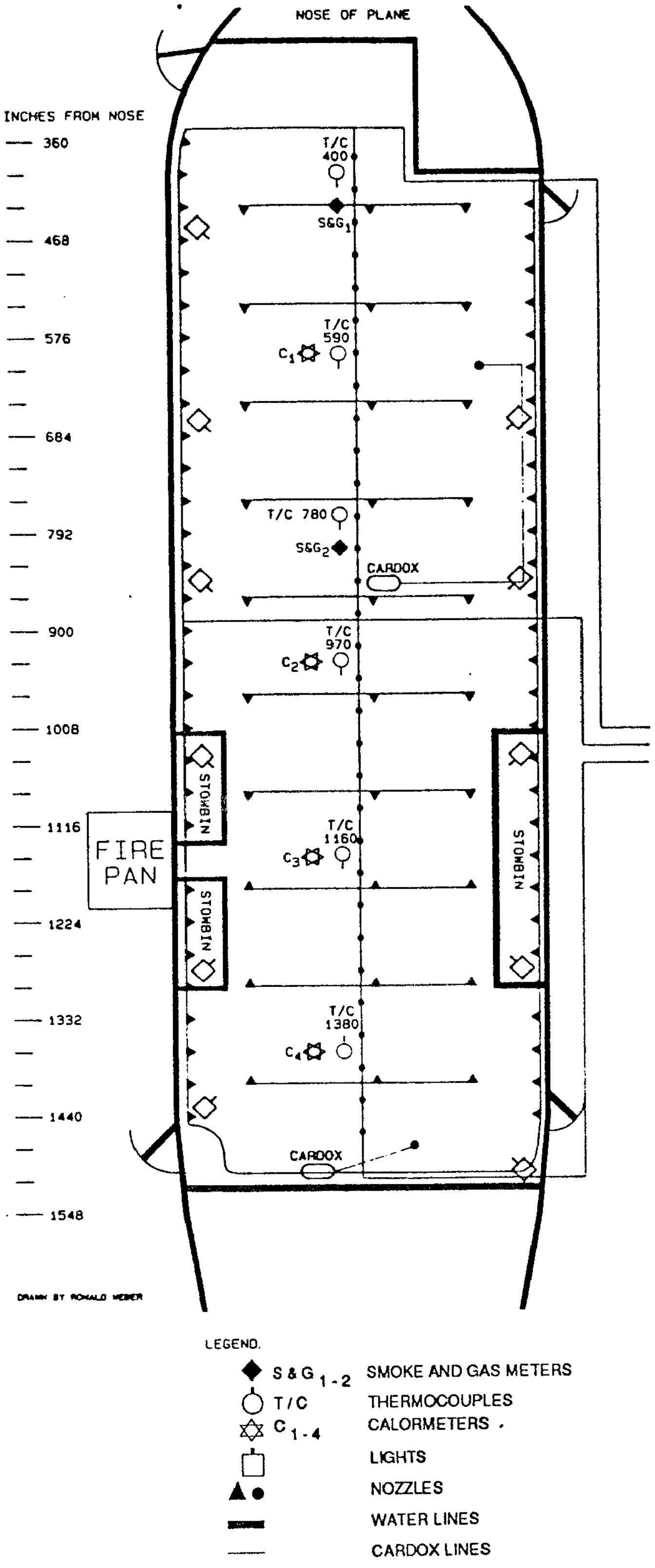
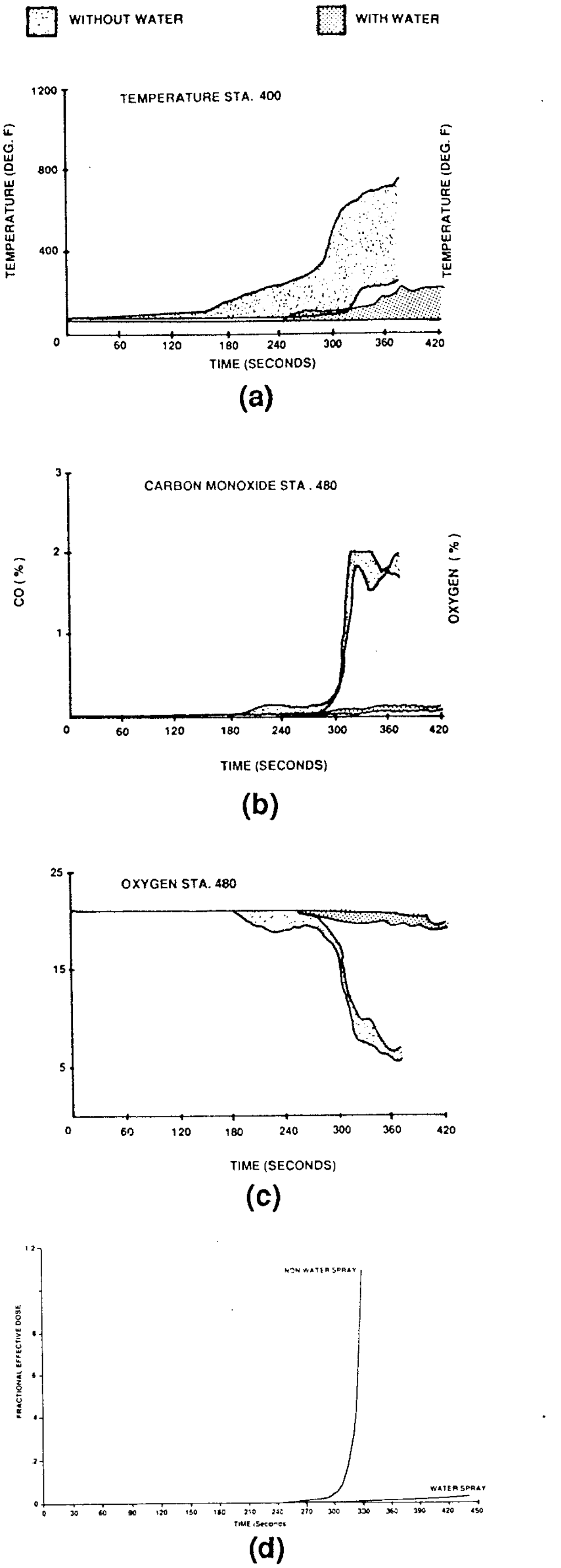


FIGURE 1.
NARROW BODY TESTCONFIGURATION



(a)

(b)

(c)

(d)

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

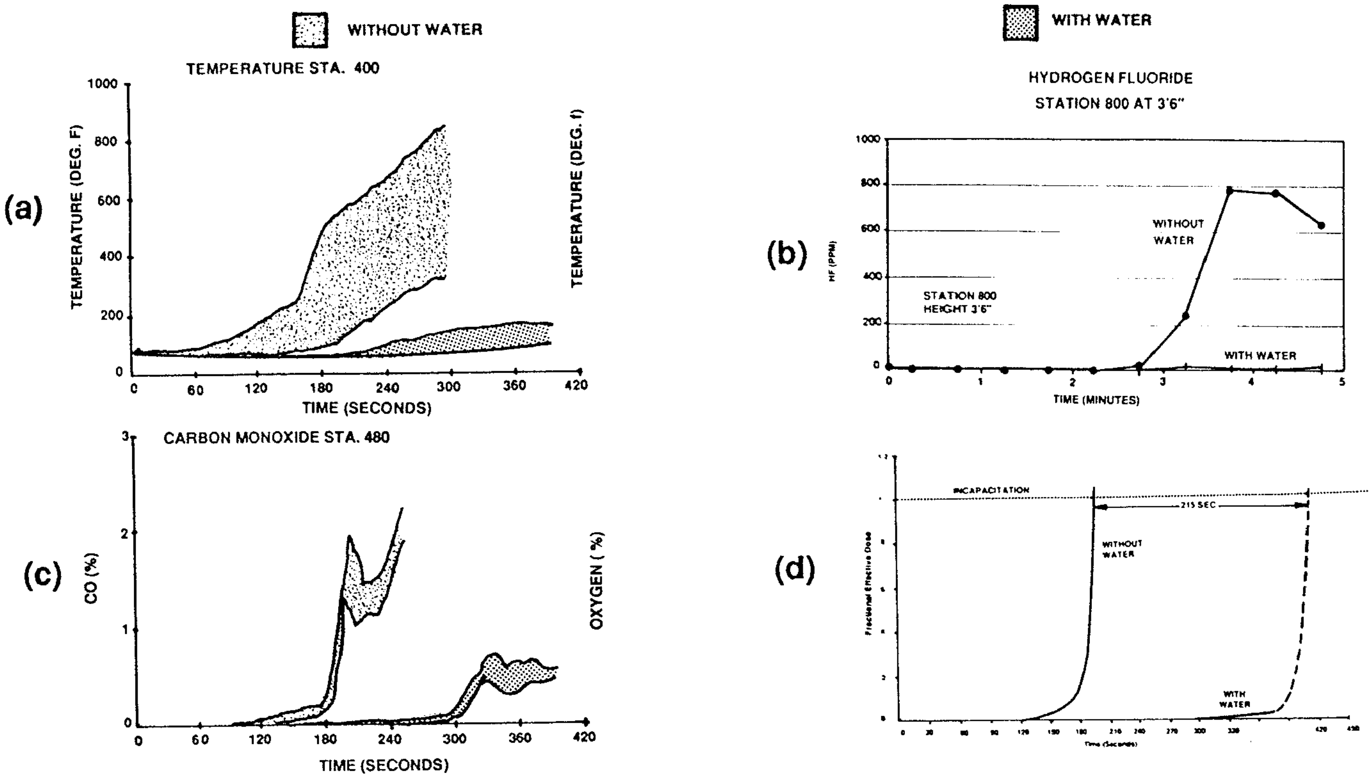


FIGURE 3.
NARROW BODY RESULTS/ SAVE SYSTEM/MODERATE WIND/FUSELAGE OPENING

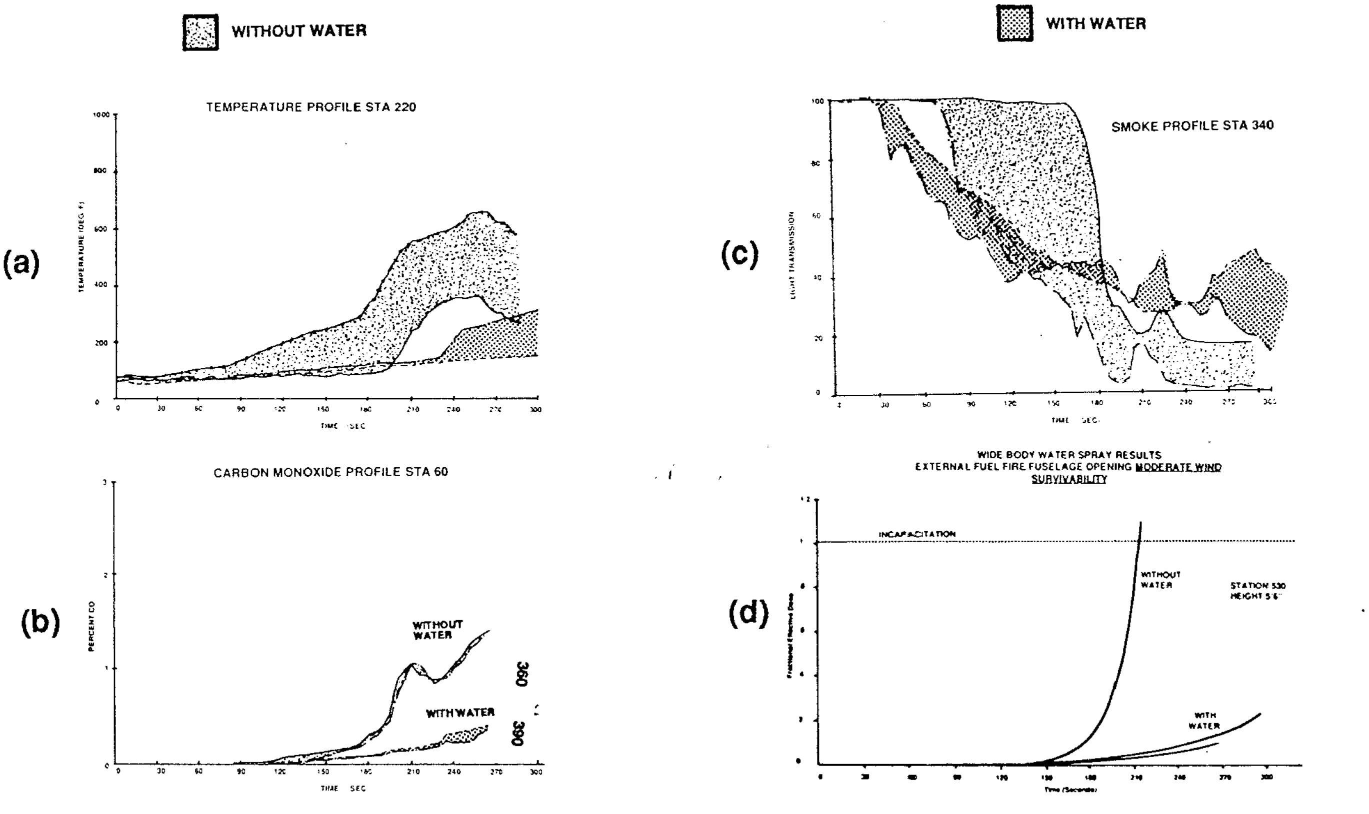


FIGURE 4.
WIDE BODY RESULTS/ SAVE SYSTEM/MODERATE WIND/FUSELAGE OPENING

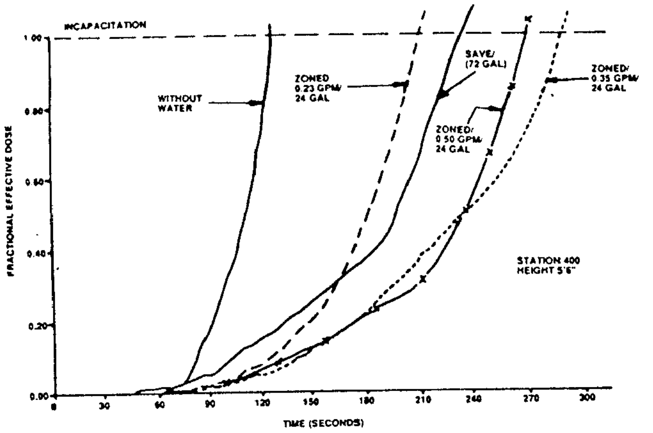


FIGURE 5.
ZONED SYSTEM SURVIVAL TIME
IMPROVEMENT 24 GALLONS

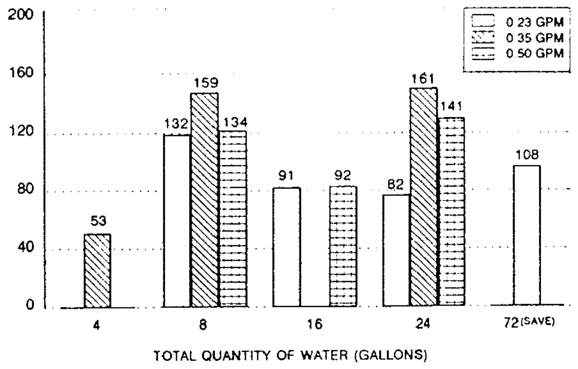


FIGURE 6.
ZONED SYSTEM AVAILABLE
ESCAPE TIME

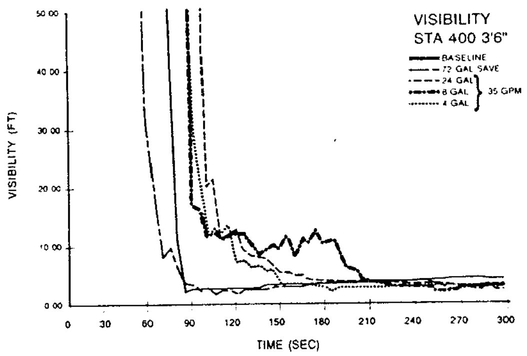


FIGURE 7.
ZONED SYSTEM
VISIBILITY IMPROVEMENT

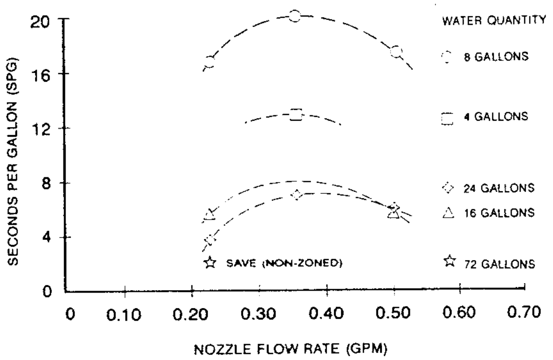


FIGURE 8.
ZONED SYSTEM
OPTIMIZATION

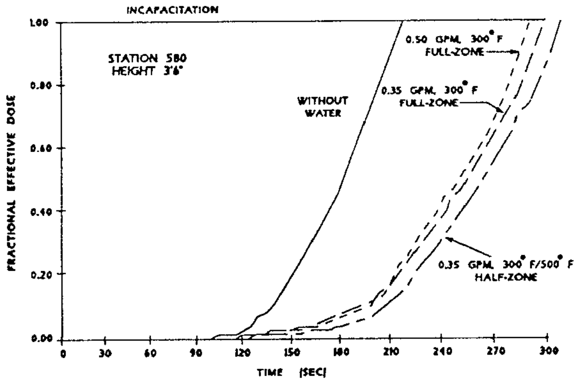


FIGURE 9.
WIDE-BODY ZONED SYSTEM
SURVIVAL TIME IMPROVEMENT

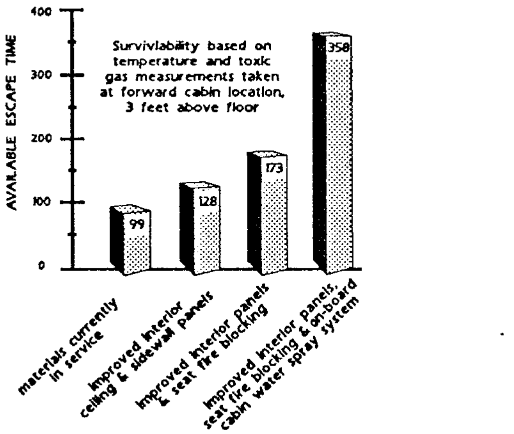


FIGURE 10.
SURVIVABILITY IMPROVEMENTS
IN COMMUTER TEST ARTICLE