Effectiveness of an Onboard Water Spray System During an Oxygen Enriched Cabin Fire

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16. Abstract

Three full-scale fire tests were conducted in a modified DC-10 fuselage to determine the effectiveness of an onboard water spray system in reducing the hazardous effects of an oxygen enriched postcrash cabin fire. Two fuel fire tests were conducted in which pressurized oxygen was introduced into the cabin interior in the vicinity of a pool fire which was adjacent to a fuselage opening. Water was sprayed throughout the cabin during one of the two oxygen fed fire tests in order to determine the benefits of using an onboard spray system. For comparison, a third test was performed using the identical pool fire adjacent to the fuselage opening without the introduction of oxygen into the cabin in order to establish "baseline" data.

The interior of the fuselage was realistically furnished in the area adjacent to the fuel fire and was fully instrumented to measure the various fire hazards. Temperature profiles, smoke levels, gas concentrations and heat flux were monitored throughout the fuselage during the tests. Photographic and video recordings visually documented the progress of the fire. The results showed the water spray to be an effective method for increasing the chances of survival in the event of an oxygen enriched fire by significantly prolonging the period of time that the cabin environment remains habitable.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

EXECUTIVE SUMMARY

Several important regulatory changes have been implemented in the last 5 years aimed at controlling the spread of fire throughout the cabin. Fire blocked seats and low heat release interior panels minimize the contribution of interior materials to a postcrash cabin fire, thus impeding its progress. A safety improvement beyond the fire hardening of cabin interior materials is a low flow rate onboard cabin water spray system. Developed by Safety (Aircraft and Vehicles) Equipment (SAVE) Limited, the system consists of an array of nozzles installed in the cabin and overhead, filling these areas with a fine water mist in the event of a postcrash fire. Three full-scale tests were performed in a modified DC-10 fuselage to determine the effectiveness of a water spray system at suppressing an oxygen enhanced cabin fire. The tests showed that the introduction of water spray into the cabin during this intense postcrash fire scenario created a significantly more survivable environment. Moreover, intensification of the fire by the introduction of oxygen caused a reduction in survival time in excess of 3 minutes.

INTRODUCTION

PURPOSE.

The purpose of this report is to present the results of three full-scale fire tests to determine the significance of oxygen release inside a passenger cabin during a postcrash fire and the effectiveness of a cabin water spray system in controlling the ensuing fire and its harmful effects.

BACKGROUND.

On October 14, 1989, a fire developed on board Delta Airlines flight 1558 in Salt Lake City that was found to be accelerated by a major release in the emergency oxygen carried on board in the forward electronics equipment compartment. The fire intensified quickly, with witnesses reporting dense smoke and loss of visibility within 45 seconds. In addition to this incident, there is evidence that the cause of the rapid fire growth during the US Air accident at Los Angeles Airport on February 1, 1991, was caused by the release of oxygen from the damaged crew emergency oxygen system.

Since a cabin water spray fire suppression system has shown promise in safeguarding cabin interiors against the effects of external fuel fires (reference 1), several tests were performed to determine the ability of a water spray system in controlling the propagation of an oxygen enhanced cabin fire. The system used in this evaluation was developed by Safety (Aircraft and Vehicles) Equipment (SAVE) Limited. The SAVE system was not a prototype, but a "breadboard" design for the purpose of demonstrating concept feasibility only. During the initial phases of the onboard cabin water spray program, 37 full-scale tests were conducted in both narrow and wide body fuselages under various postcrash scenarios. A concurrent study was undertaken to address the various service considerations associated with an inadvertent discharge of water spray while the aircraft is in flight or on the ground. The results of these initial studies will be factored into a benefit analysis to determine the potential for lives saved. If the benefits of such a system outweigh the disbenefits, the next phase will be to optimize the system and, later, to develop design requirements and specifications. The initial full-scale tests in both the narrow and wide body configurations produced favorable results. Although the service considerations and benefit analysis studies were not complete at the time this report was written, preliminary findings indicate that there are no insurmountable problems. In anticipation of this, a series of optimization tests were run in the wide-body fuselage to determine the ability of the water spray system to provide escape times comparable to those previously achieved, with less water and/or less nozzles (references 2 and 3). However, during the oxygen enhanced fire test in which water was sprayed, the complete set of nozzles (324) and water quantity (195 gallons) of the baseline SAVE system in the wide body test article were utilized for the 3-minute spray duration.

DISCUSSION

TEST DESCRIPTION.

Three tests were conducted in a modified DC-10 (TC-10) fuselage which was fully fire hardened and instrumented with thermocouple trees, smoke meters, gas sampling stations, calorimeters, and photographic and video coverage (figure 1). The first test was conducted using a fuel fire adjacent to the opening in the fuselage with a simulated wind condition created by an exhausting fan mounted in the forward bulkhead. During the next two tests oxygen was discharged for approximately 1 minute into the cabin, commencing with the fuel fire ignition. Of the two oxygen enhanced tests, one had the water spray system activated and the other did not. The fire conditions and interior materials were identical in each of the three tests.

The three tests utilized a standard 8 by 10-foot pan fire consisting of 55 gallons of JP-4 fuel adjacent to a type A door opening. The fire was drawn into the fuselage with the aid of a fan located at the forward bulkhead which exhausted at a rate no greater than 5000 cubic feet per minute (CFM).

The furnished section of the aircraft had a total of 39 fire blocked seats (bottom and back) mounted on steel seat frames arranged as follows: three rows centered about the fire, each containing a double, quad, and triple seat. Two additional rows were located forward and aft of the three centered rows consisting of a double and quad seat. Additionally, nine ceiling panels, thirteen sidewall panels, and twelve storage bins were installed. Plastic sheets were also attached to the side and back of each seat frame to simulate side panels and tray tables (figure 2).

The water spray system installed was a duplicate of that developed by SAVE, Limited, the layout of which is shown in figure 3. The spray system consisted of 324 nozzles with the water pressure regulated to 42 pounds per square inch (psi) throughout the system. During the water spray test, the system was activated simultaneous to the fuel pan ignition and lasted for approximately 3 minutes. A fine mist produced by the mixing of the residual water and the remaining pressurized air lasted for an additional 30 seconds.

For the oxygen tests the oxygen was supplied through a 3/8-inch nozzle at a pressure of 1050 psi. The discharge lasted for approximately 1 minute, releasing a quantity of oxygen equivalent to one bottle of breathing oxygen (40 cubic feet), as carried onboard aircraft. A typical emergency breathing oxygen bottle is under 1800 psi of pressure. Since an actual emergency bottle was not available, a larger industrial bottle pressurized to 1050 psi was used, which yielded the desired 40 cubic feet of oxygen. The 3/8-inch nozzle was located at the center of the fire door, mounted to the floor, and pointed inboard at an upward angle of 15^{o} (figure 2).

A full description of the instrumentation used in the TC-10 during the three tests is as follows:

THERMOCOUPLE TREES. Eight thermocouple trees continuously measured the temperatures throughout the cabin. The trees were located at 40, 220, 400, 590, 750, 940, 1180, and 1430 inches from the forward bulkhead. Each tree consisted of eight thermocouples positioned from 1 foot above the floor to 8 feet above the floor in 1-foot increments. The 8-foot location was just below ceiling level.

SMOKE METERS. Smoke meter stations were located at 80, 340, 570, and 1320 inches from the forward bulkhead. Each station contained three smoke meters consisting of a collimated light source and photocell separated by 1 foot. The smoke meters were positioned at 18, 42, and 66 inches from the floor at each station.

GAS ANALYSIS. Continuous gas sampling stations used to measure carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) were located at 60 and 530 inches from the forward bulkhead. Each station had two intakes, one at a height of 42 inches and the other at a height of 66 inches from the floor. In addition to the continuous gas sampling, "grab" sampling stations were also located at 60 and 530 inches from the forward bulkhead at heights of 66 and 42 inches, respectively. These stations measured the acid gas production of hydrogen bromide, hydrogen chloride, and hydrogen fluoride for 30-second intervals from 90 to 120, 150 to 180, 210 to 240, and 270 to 300 seconds from the start of the test. Hydrogen cyanide (HCN) was measured by two methods, amperometric analysis and gas chromatography (GC). The amperometric analysis was performed by a Kin-tech™ analyzer which sampled at 60 and 530 inches from the bulkhead, both locations at a height of 66 inches. In addition, HCN concentrations were determined by the GC method at station 60, 66 inches from floor level.

CALORIMETERS. Calorimeters were used to measure the heat flux at four locations: 80, 590, 940, and 1320 inches. The transducers were all mounted at a height of 42 inches. At stations 80 and 590, the transducers faced aft; at station 1320 the transducer faced forward. The transducer located at station 940 faced the fire door.

TEST RESULTS.

The following analysis compares the results of the three tests based on three parameters: temperature, smoke level, and gas concentrations. In order to determine the effect the various hazards have on survivability, the fractional effective dose (FED) was calculated to establish the time at which the cabin interior became nonsurvivable at different locations (reference 4). Plots of FED versus time were generated by using the temperature and gas concentrations at a particular cabin location at various times during the test. Additionally, the seat damage for each of the three tests was documented, enabling a comparison of the amount of seat material burned during each of the tests.

TEMPERATURE PROFILES. As shown in figures 4, 5, and 6, the temperature profiles at stations 40, 590, and 1430 indicated that the temperature level between 4 and 6 feet above the floor was substantially higher during the non-water spray oxygen enhanced fire. Throughout the duration of the oxygen test in which water was sprayed, the temperatures remained at a fairly low level. The baseline test, as expected, showed a gradual temperature increase as the material involvement grew; and after 3 minutes, the temperatures of the baseline test had surpassed the level obtained during the oxygen test in which water was sprayed. As shown in the figures, the water spray system had to be activated at 4 minutes from the start of the oxygen test because the temperatures inside the cabin were nearing levels which might have damaged the instrumentation and fuselage structure. By spraying water during the last minute of the test, the temperatures were reduced by as much as 400 °F, depending on location.

SMOKE LEVELS. Figure 7 displays the smoke levels between 3 feet 6 inches and 5 feet 6 inches at station 80. There was little difference in smoke levels between the oxygen test and the oxygen test with water spray at this height. After about 90 seconds, the two profiles are virtually the same. However, the light transmission was slightly lower at an earlier time during the test with the water spray activated, but remained at a more favorable level than the nonspray test as time progressed. This trend is more evident at station 570 (figure 8). This trend occurred since the smoke layer stratified during the nonspray test, and slowly descended from the 8-foot ceiling level to the smoke meter levels. When the water spray was activated, the smoke layer was pulled down to the lower cabin levels which more than offset the washing out of smoke particulates by the water spray during the early stages of the test. Later, the effect of the cleansing action of the water spray is greater than the lowering of the smoke layer, causing a "crossover" of the two smoke curves in figures 7 and 8 at approximately 2 minutes.

The baseline test without oxygen release showed a much greater level of visibility until the last 1 to 1 1/2 minutes of the test because there was a much lower burning rate when compared to the oxygen enhanced tests.

The smoke levels at 1 foot 6 inches at stations 340 and 570 (figures 9 and 10) also show the crossover point at approximately 2 minutes during the two oxygen tests. The baseline test showed a high degree of visibility for nearly 4 minutes at this height; the result of reduced material involvement and a stratified smoke layer.

GAS CONCENTRATIONS. Concentration profiles of the two nonsoluble "fire gases," carbon monoxide and carbon dioxide, are shown in figures 11 through 14. The highest levels were measured during the oxygen-fed fire. Although the fire gases are insoluble in water, the concentrations were considerably lower during the water spray test, indicative of a reduced burning rate of materials. This was confirmed in a previous study by measuring the gas concentrations under two scenarios; water was sprayed throughout the cabin, including the seat area, during one scenario; and sprayed throughout the cabin but not in the seat area during the other scenario. The fire gas levels during the full water spray test were significantly reduced (reference 3).

Similarly, the greatest oxygen depletion occurred during the oxygen-fed fires, also indicative of the greater amount of material burning (figures 15, 16). As with carbon monoxide and carbon dioxide, there was less oxygen depletion during the water spray test, again indicating that the water spray reduced the combustion rate of material.

FRACTIONAL EFFECTIVE DOSE CALCULATIONS. Figure 17 shows the fractional effective dose (FED) calculations in the forward most section of the fuselage, station 60, at a height of 3 feet 6 inches. The curves represent the hazard level (FED) versus time for each of the three tests based on measurements of carbon monoxide, carbon dioxide, oxygen, and temperature. Higher numbers correspond to greater hazard levels, with FED = 1.0 corresponding to the point of incapacitation. Both oxygen tests reached 1.0 within the 5-minute test; during the baseline test, an incapacitation level (FED of 1.0) was not reached at this location. The use of water spray during the oxygen-fed test offered a significant additional 2 minutes of survivability over the nonspray case.

Figure 18 displays the FED curves at a height of 5 feet 6 inches at station 60. In addition to the four hazards used in calculating the FED at 3 feet 6 inches, the acid gases hydrogen fluoride (HF), hydrogen chloride (HCl), hydrogen bromide (HBr), and the systemic poison hydrogen cyanide (HCN) were taken into account. The results were similar to the lower height, with an additional 90 seconds of survival time gained by using water spray.

By extrapolating the FED curve of the oxygen test in which water was sprayed, an estimate was made for the survivability at station 550, at 3 feet 6 inches (figure 19). The water spray provided nearly 3 additional minutes before an incapacitation level was reached compared to the nonspray test. This FED calculation was made using seven hazards: CO, CO_2, O_2, temperature, HF, HCl, and HBr. Hydrogen cyanide was not available for this calculation.

Similarly, an FED calculation at a height of 5 feet 6 inches at station 550 yielded 3 additional minutes of survival time during the oxygen test when utilizing the water spray (figure 20). This calculation was made without the use of acid gas and HCN data.

It was observed that the FED reached 1.0 earlier at station 60 than at station 550 for each of the three tests, which was unexpected since station 550 is much closer to the fire door. Although the temperatures were lower at the forward location (station 60), the levels of CO, CO_2, and O_2 depletion were slightly higher at this location. These higher gas concentrations were responsible for driving the FED curves to 1.0 earlier during the tests. The higher gas concentrations at the forward location is caused by the airflow within the fuselage. The exhaust fan draws the airflow towards the forward portion of the cabin where the combustion products collect to form an atmosphere more dense in CO and CO_2 since there is no large opening (such as an exit door) for these gases to escape.

SEAT DAMAGE. Figure 21 details the degree of damage that occurred to each seat bottom and back. As expected, the most damage occurred during the oxygen test, with over 60 percent of the seat cushions sustaining moderate to heavy fire damage. Interestingly, there was less seat damage during the oxygen test in which water was sprayed than during the baseline test. The water spray allowed moderate to heavy damage to only 25 percent of the seats, compared to 35 percent during the baseline test, highlighting the ability of the system to reduce the amount of material that becomes involved during a fire.

SUMMARY OF RESULTS

In general, the oxygen tests showed a considerable increase in hazard level over the baseline test with regard to temperature and gas concentrations. By utilizing the water spray system, the hazard level was significantly reduced and, with respect to temperature, to a level lower than tha which was sustained during the baseline test. Although the CO and CO_2 levels were also significantly reduced during the water spray test, they were not reduced to levels lower than those obtained during the baseline test, as was the case with the temperatures. A slight increase in visibility was eventually realized during the water spray test; the visibility level decreased earlier during the water spray test, but after 2 minutes, it became more favorable than without water spray. The FED curves illustrated incapacitation levels occurred at approximately 2 minutes during the oxygen enhanced tests. By spraying water, an additional 120 seconds of survival time was gained at station 60, 3 feet 6 inches; an additional 90 seconds at 5 feet 6 inches. By extrapolating the FED curves for station 550, an estimated 180 seconds of survival time was gained at both the 3 feet 6 inches and 5 feet 6 inches measurement heights.

CONCLUSIONS

The water spray was most effective at reducing the temperature level within the cabin during the oxygen enhanced tests. The use of water spray lowered the temperatures an average of up to 600 °F, depending upon location and height. During the nonspray oxygen enriched test, the water had to be sprayed after 4 minutes to prevent test article damage; the temperatures were reduced by 300 °F within 1 minute. In addition, lowered levels of nonsoluble fire gases and reduced oxygen depletion during the water spray test indicated a reduction in the burning rate of cabin materials. In combination, the temperature and gas concentration reduction translated to an average of 1.5 to 3 minutes additional survival time when using the water spray, as indicated by the fractional effective dose calculations, for the oxygen-enriched fire tests.

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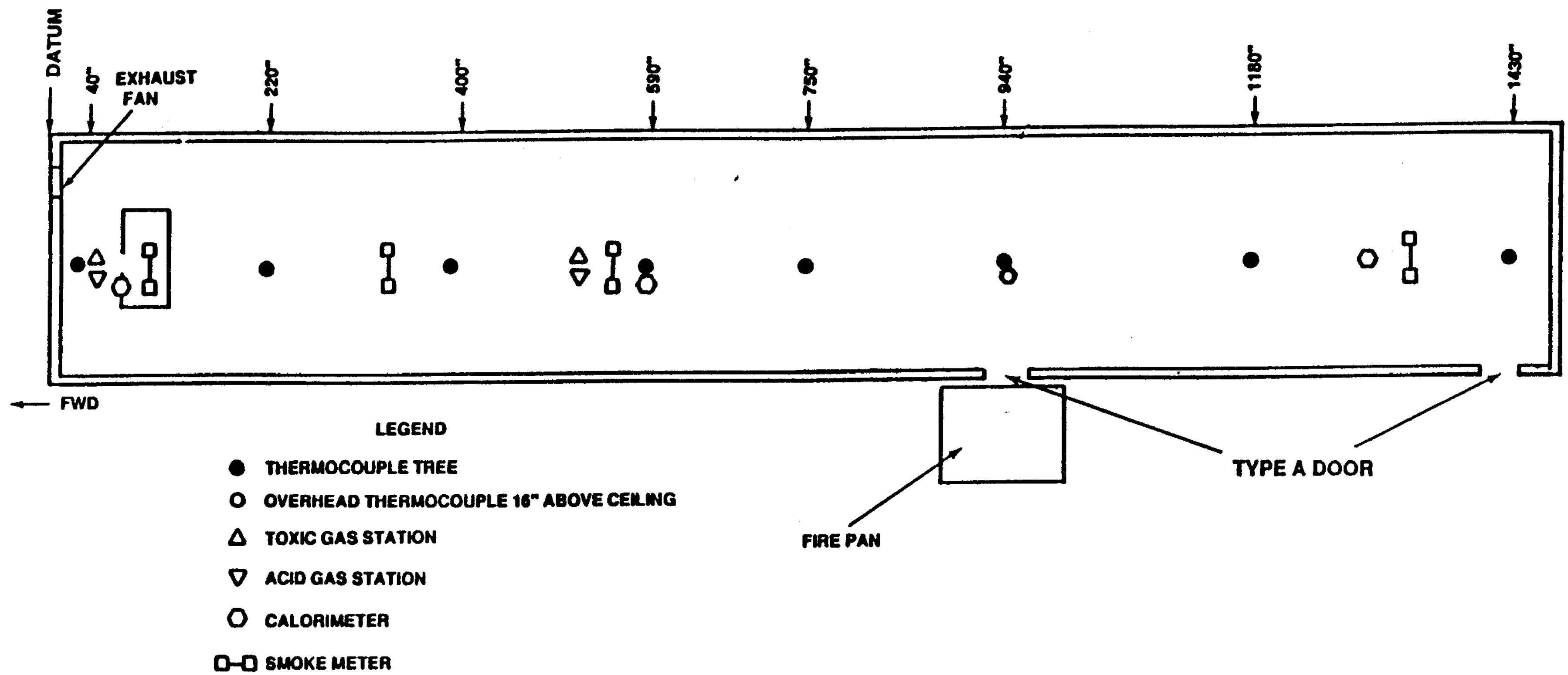

FIGURE 1. LOCATION OF THERMOCOUPLES, SMOKE METERS, GAS STATIONS AND CAMERAS

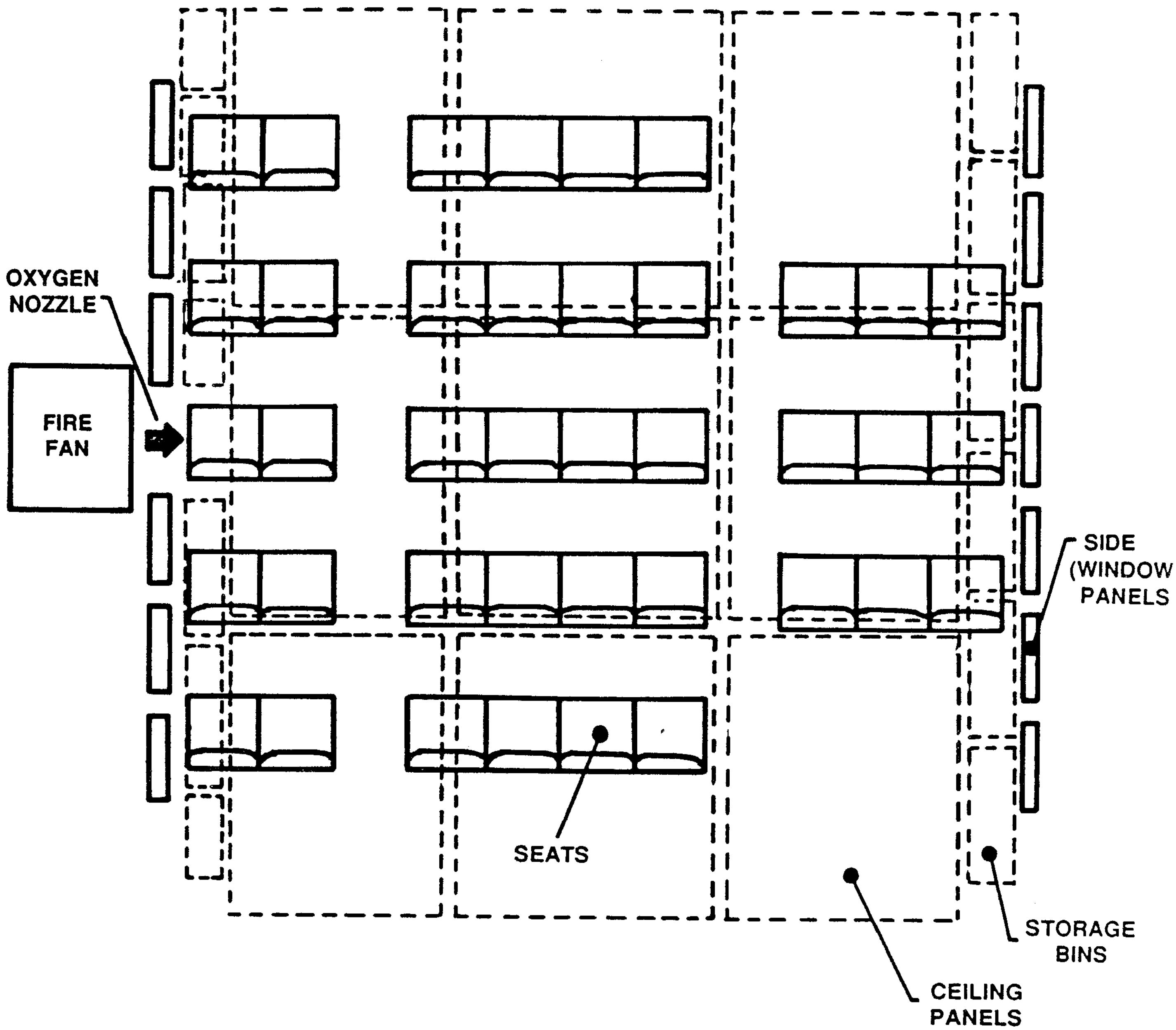

FIGURE 2. FURNISHED SECTION CONFIGURATION

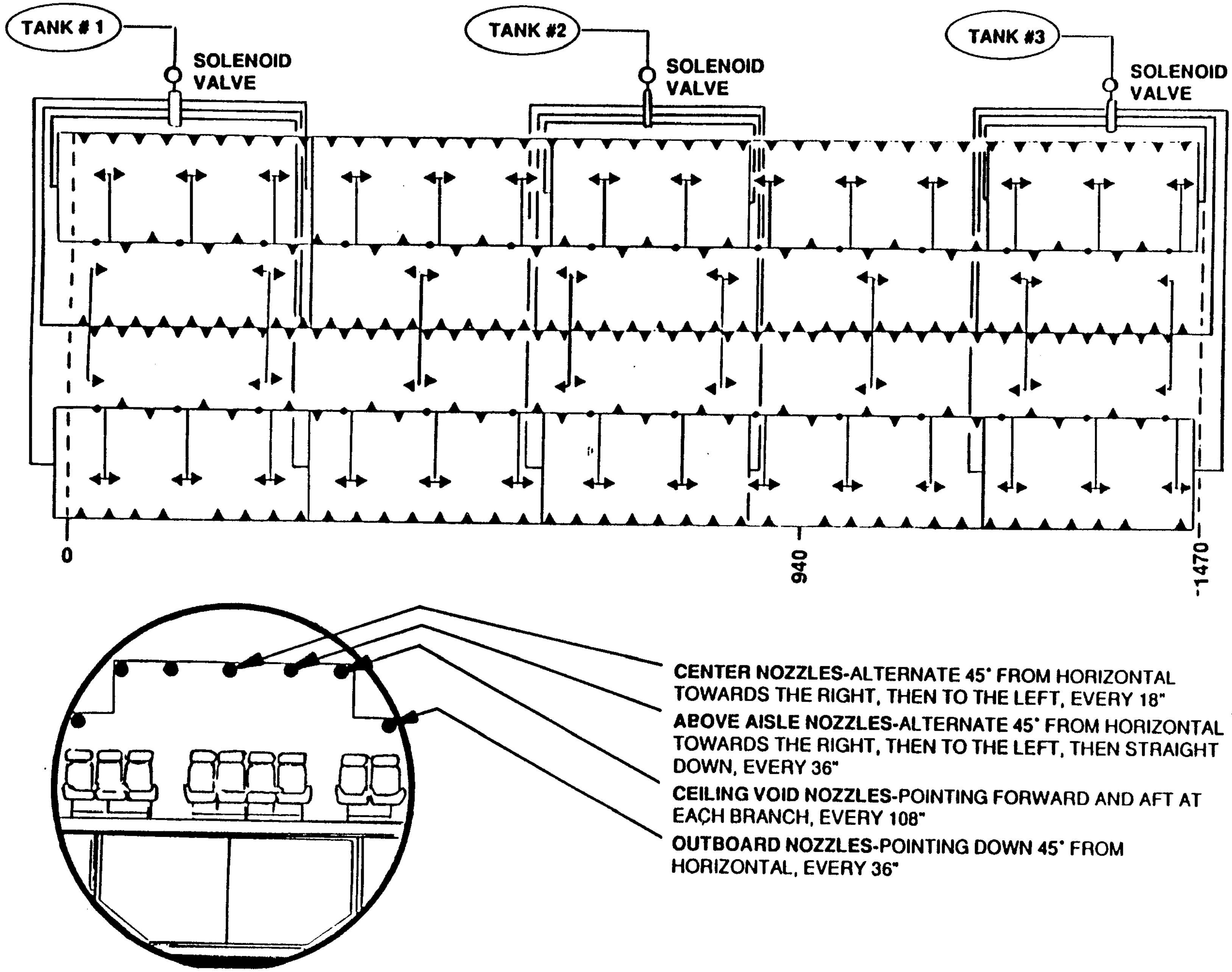

FIGURE 3. TC-10 NOZZLE CONFIGURATION

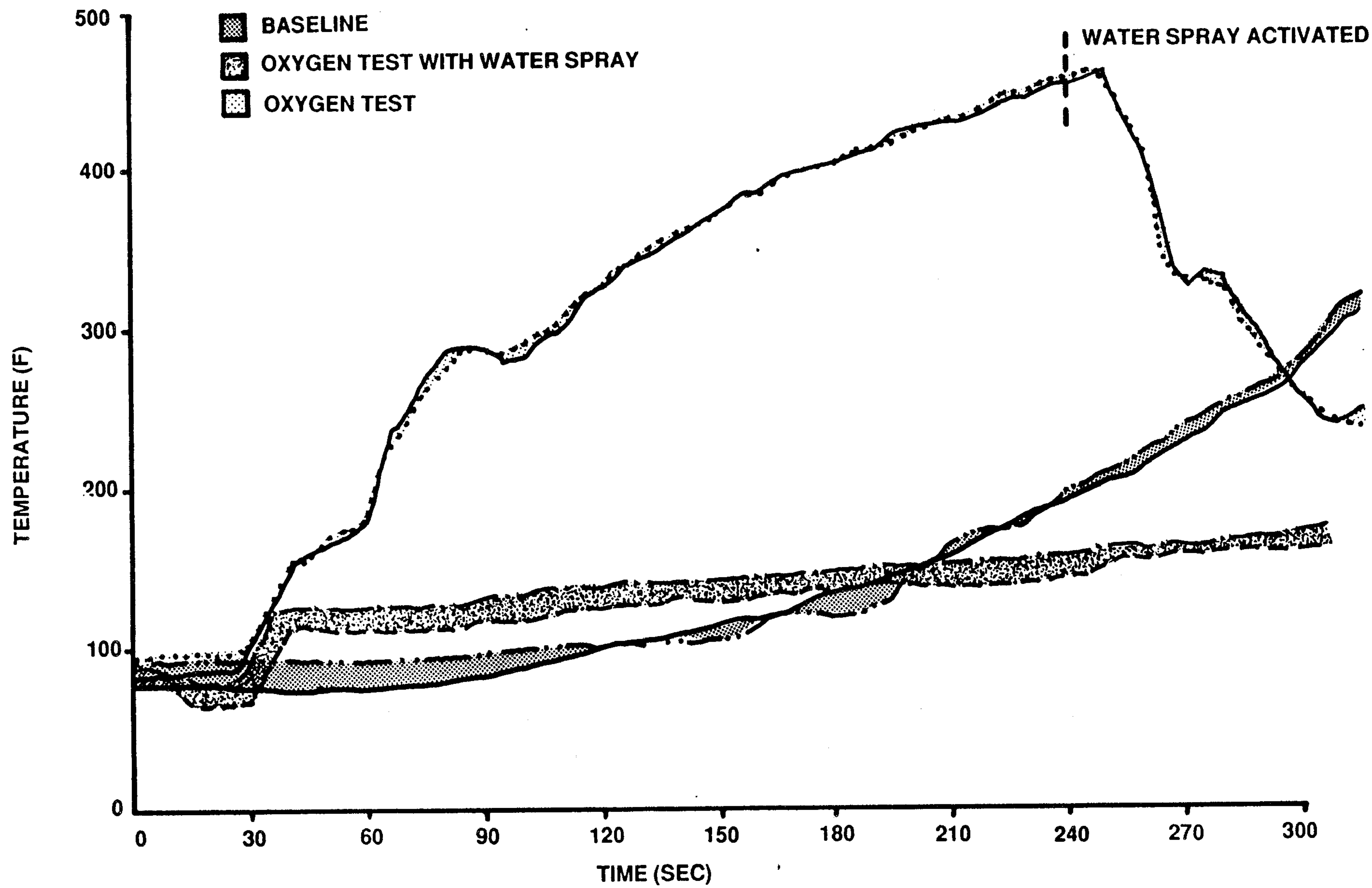

FIGURE 4. TEMPERATURE STATION 40 -- 4 TO 6 FEET

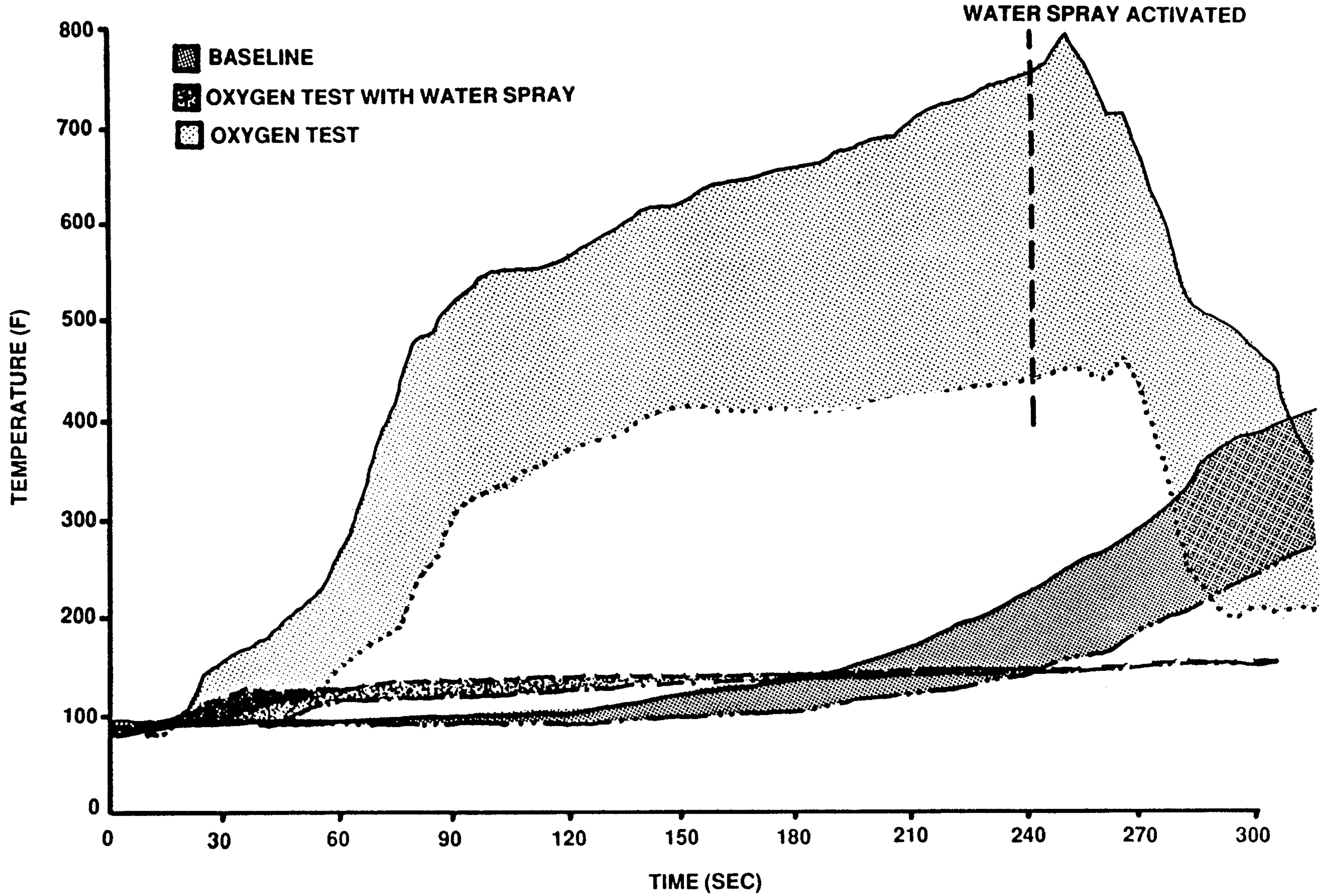

FIGURE 5. TEMPERATURE STATION 590 -- 4 TO 6 FEET

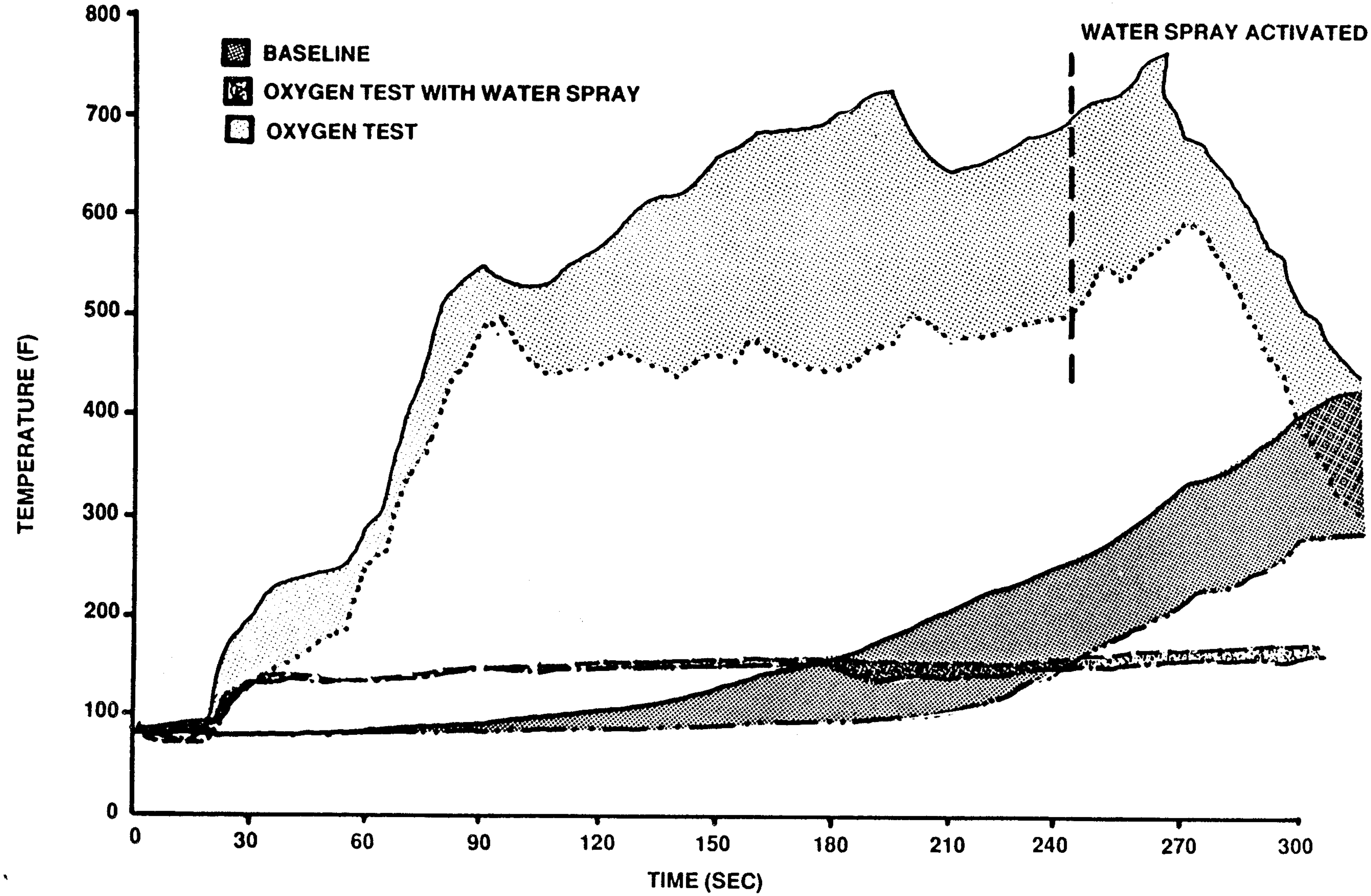

FIGURE 6. TEMPERATURE STATION 1430 -- 4 TO 6 FEET

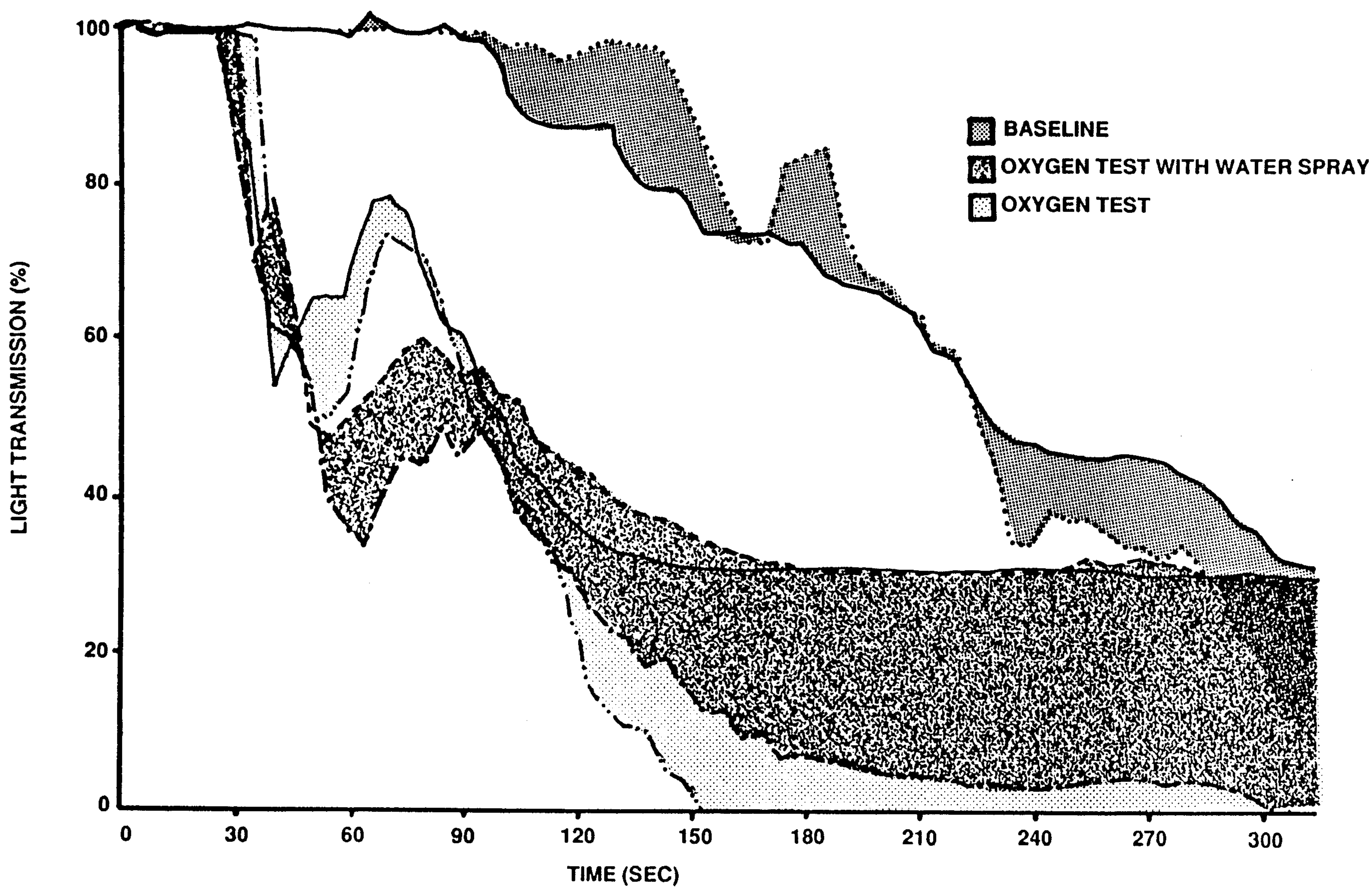

FIGURE 7. SMOKE STATION 80 -- 3 FEET 6 INCHES TO 5 FEET 6 INCHES

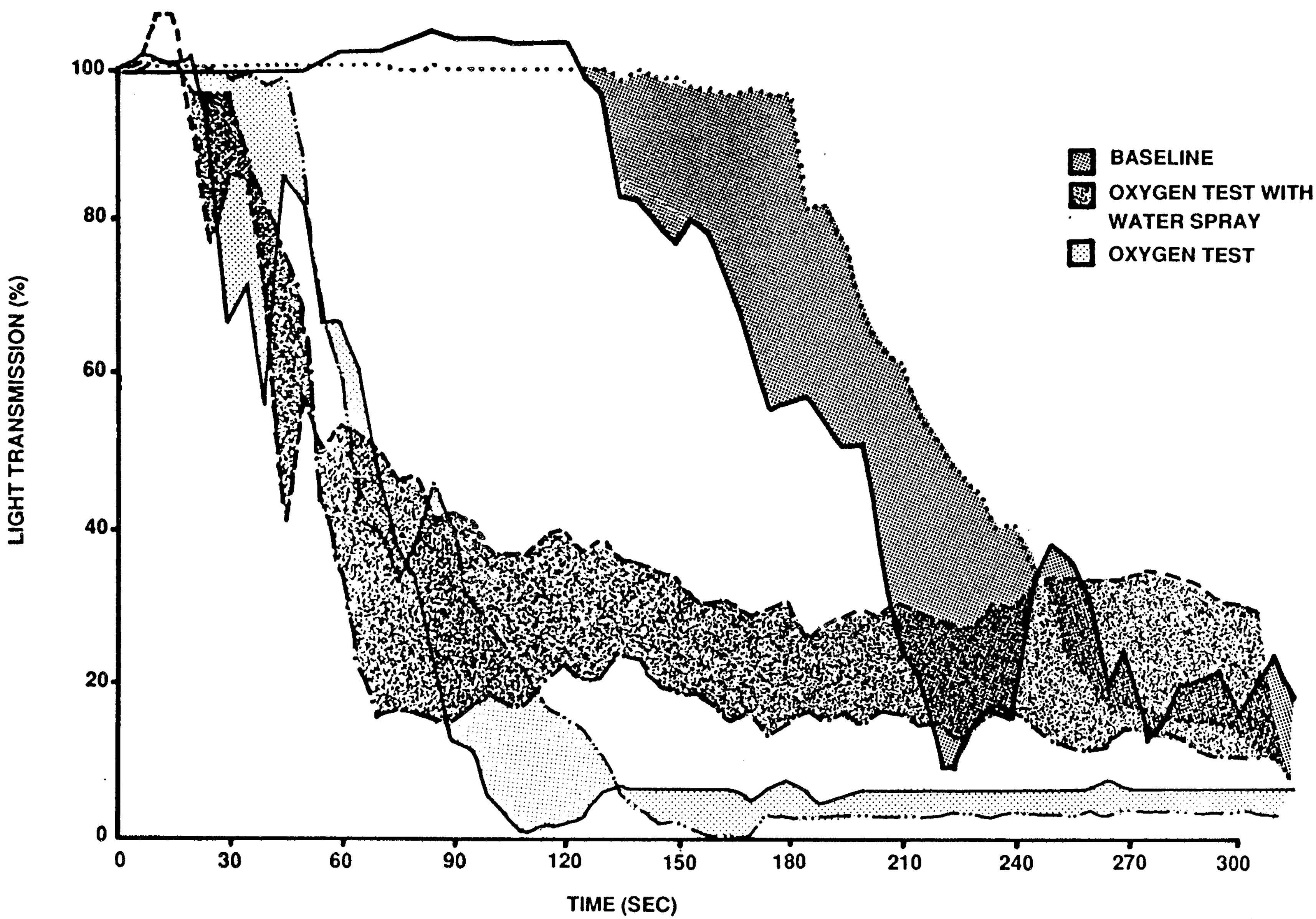

FIGURE 8. SMOKE STATION 570 -- 3 FEET 6 INCHES TO 5 FEET 6 INCHES

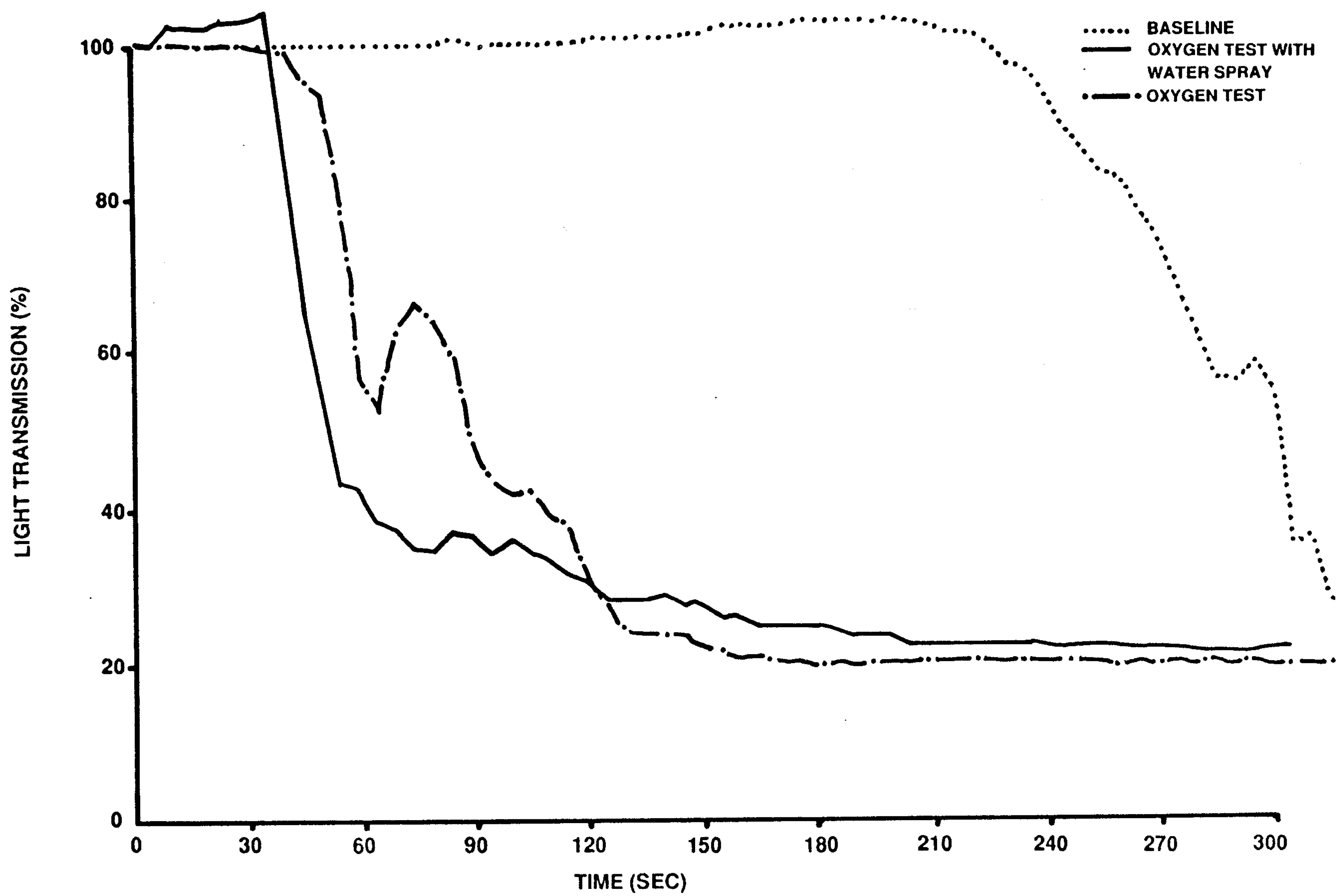

FIGURE 9. SMOKE STATION 340 -- 1 FOOT 6 INCHES

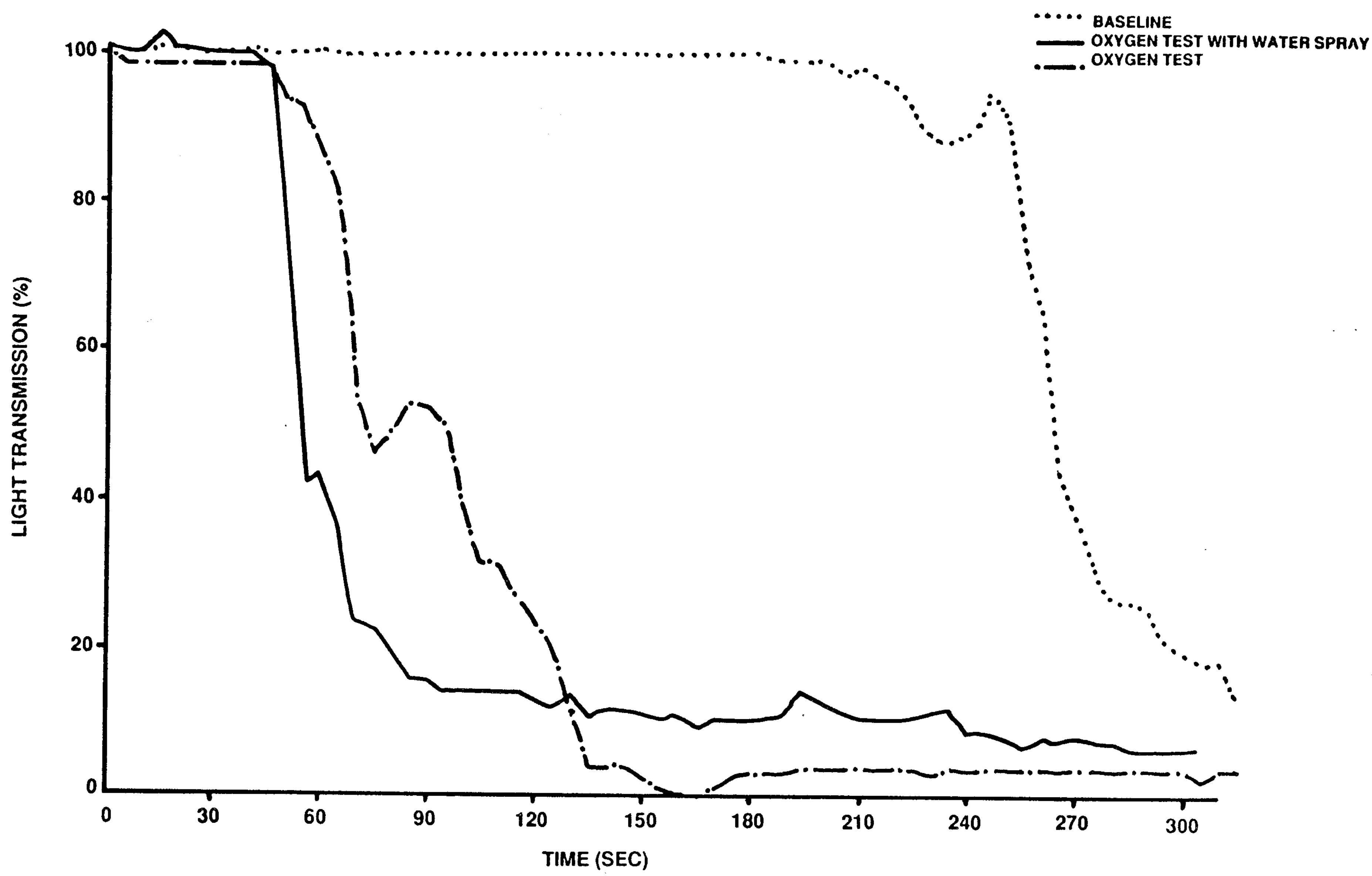

FIGURE 10. SMOKE STATION 570 -- 1 FOOT 6 INCHES

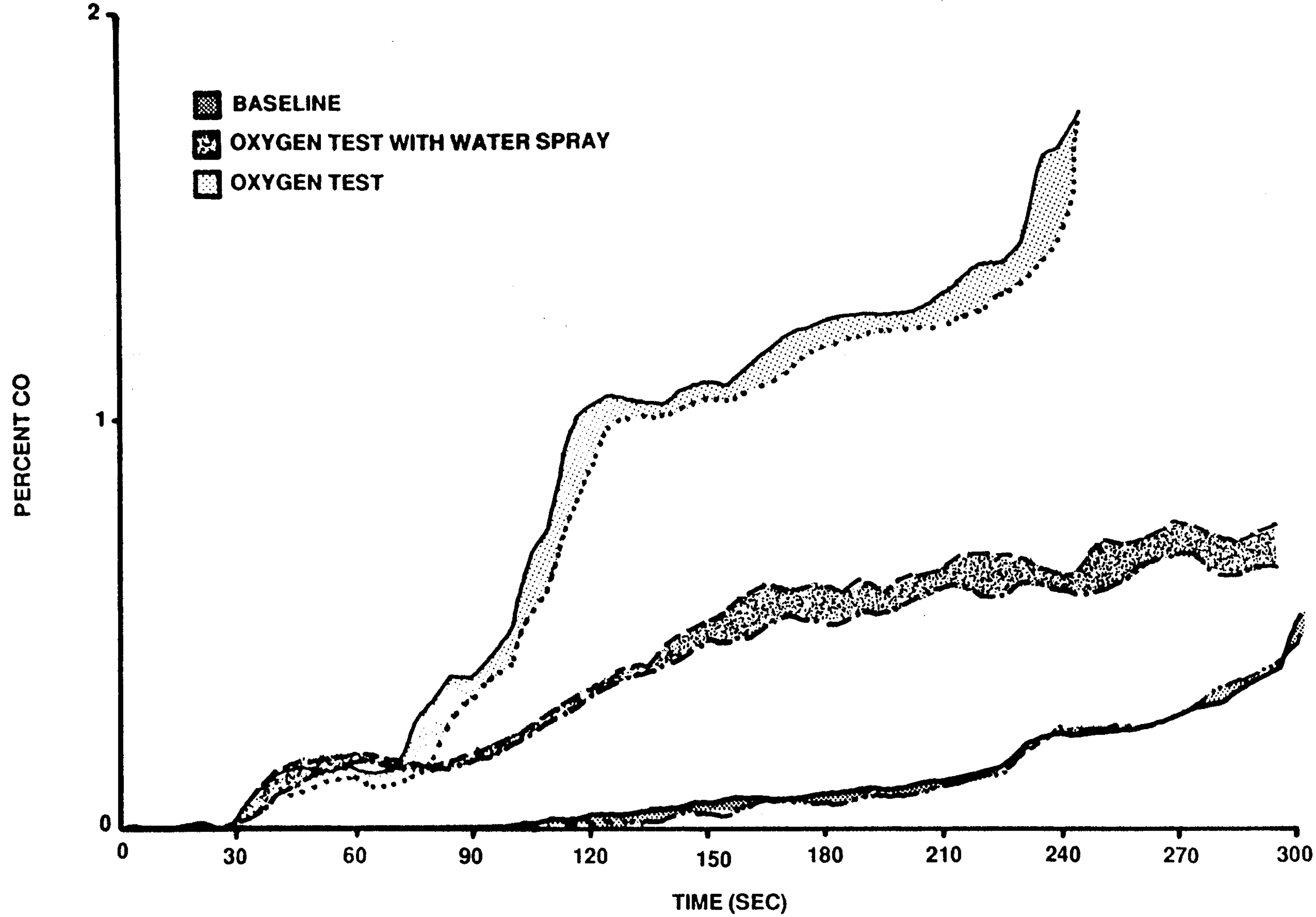

FIGURE 11. CARBON MONOXIDE STATION 60 -- 3 FEET 6 INCHES TO 5 FEET 6 INCHES

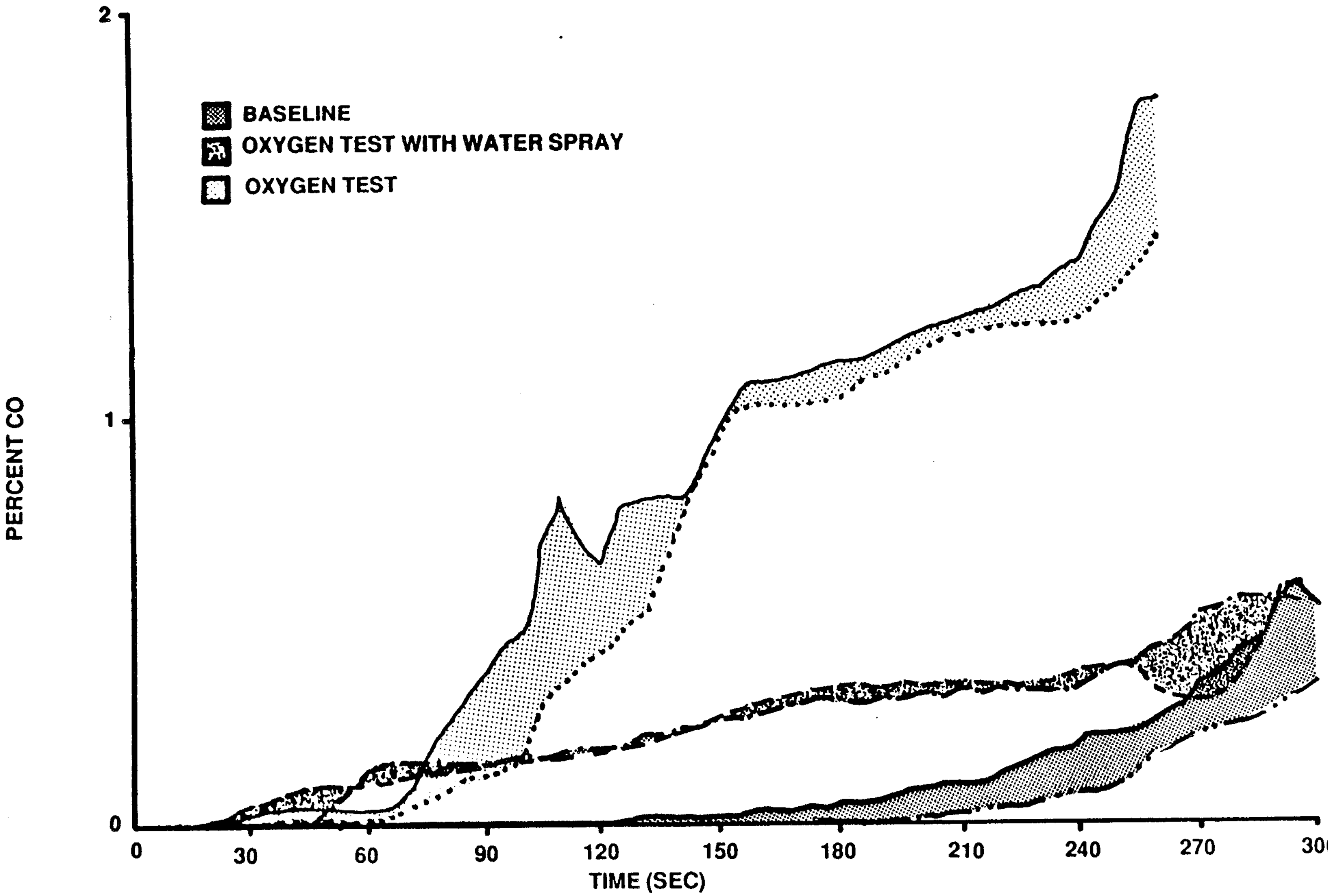

FIGURE 12. CARBON MONOXIDE STATION 530 -- 3 FEET 6 INCHES TO 5 FEET 6 INCHES

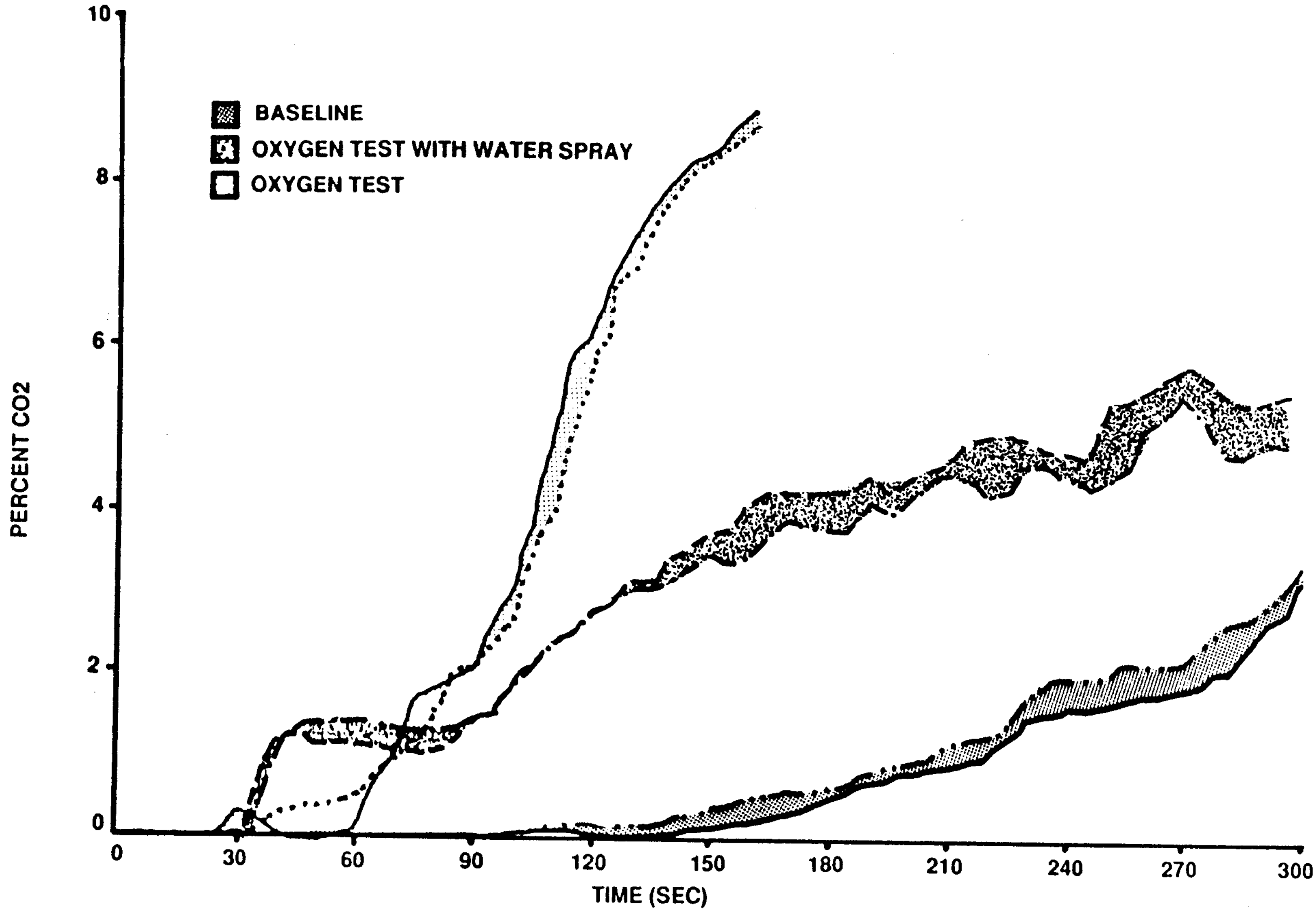

FIGURE 13. CARBON DIOXIDE STATION 60 -- 3 FEET 6 INCHES TO 5 FEET 6 INCHES

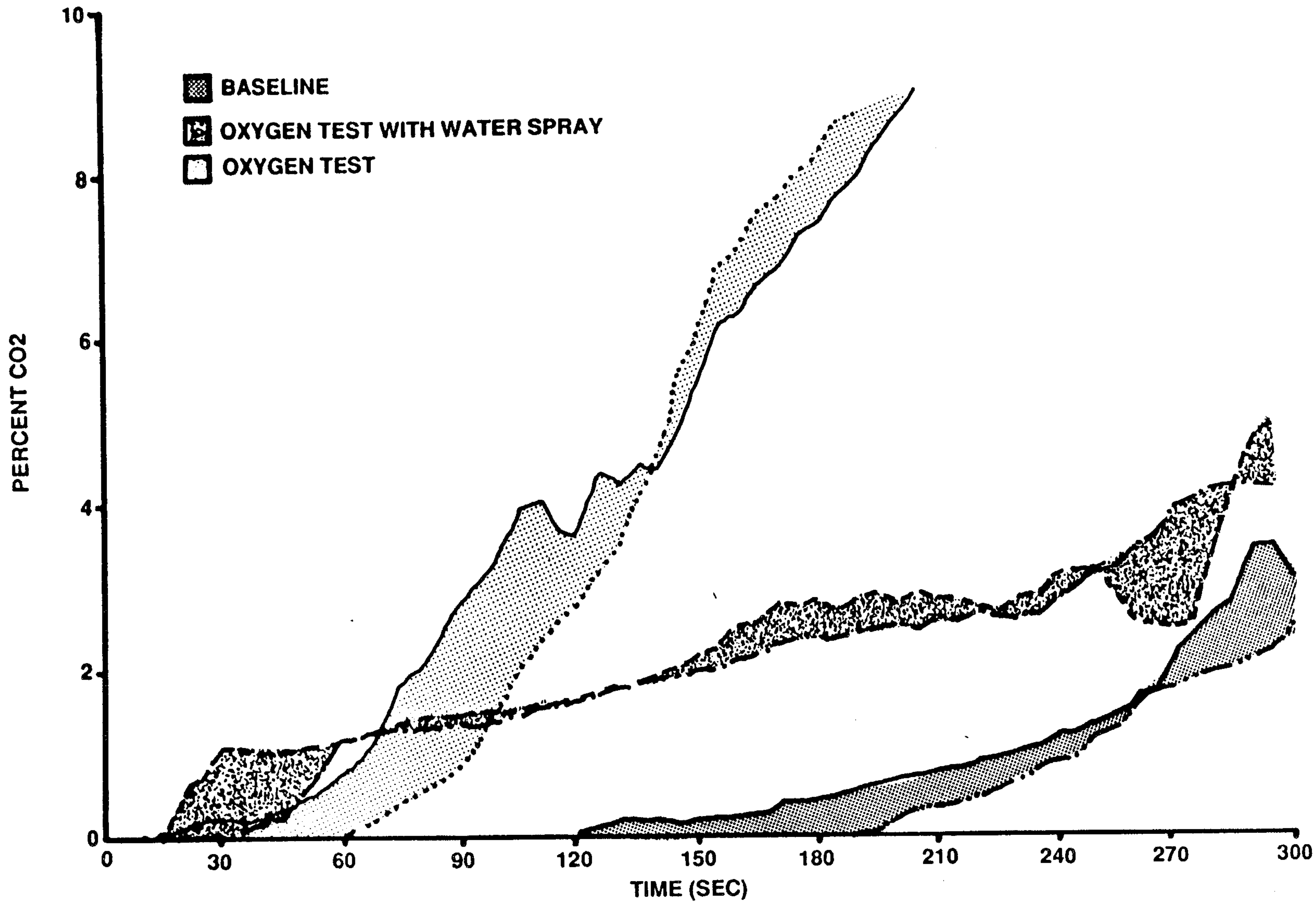

FIGURE 14. CARBON DIOXIDE STATION 530 -- 3 FEET 6 INCHES TO 5 FEET 6 INCHES

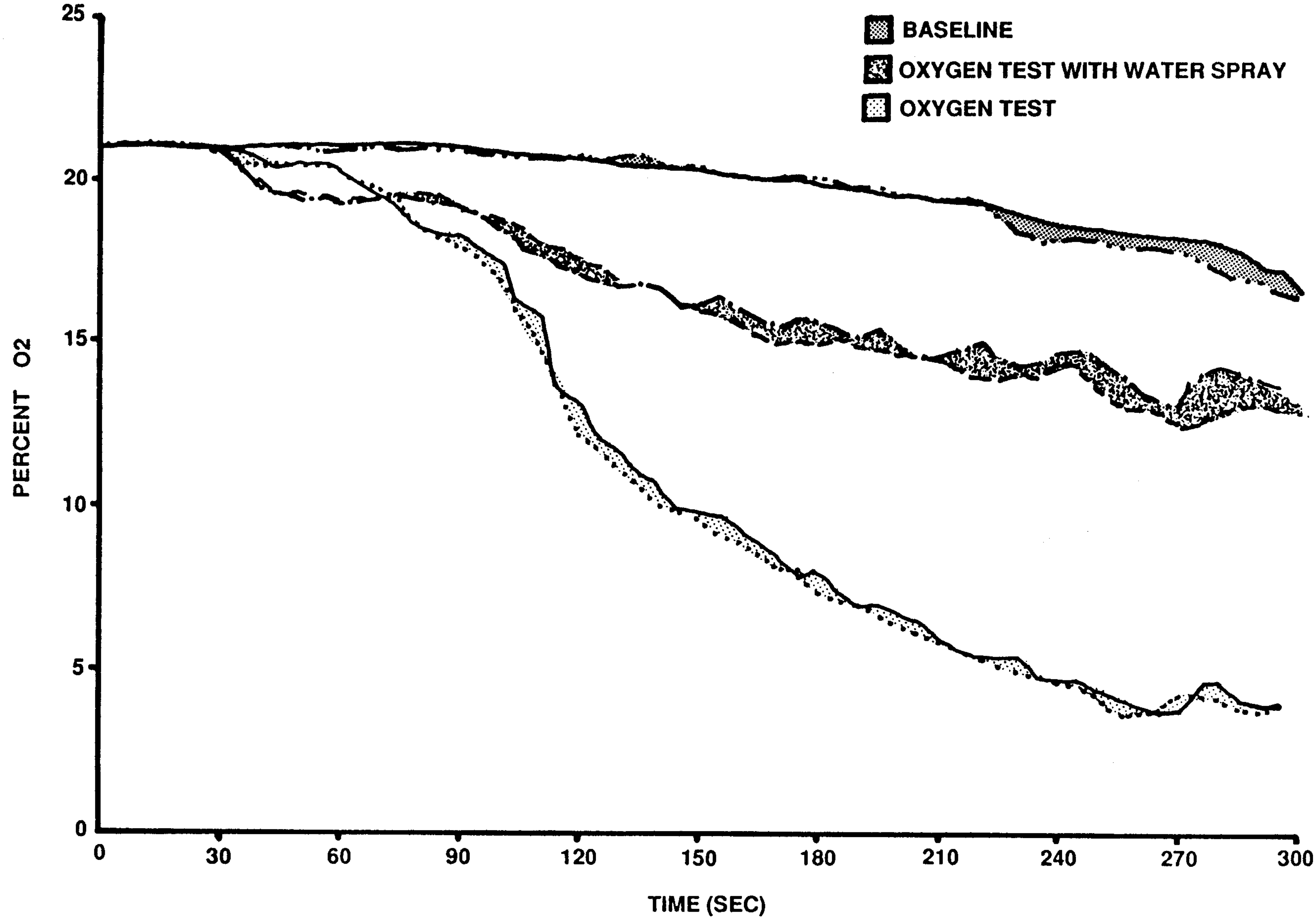

FIGURE 15. OXYGEN STATION 60 -- 3 FEET 6 INCHES TO 5 FEET 6 INCHES

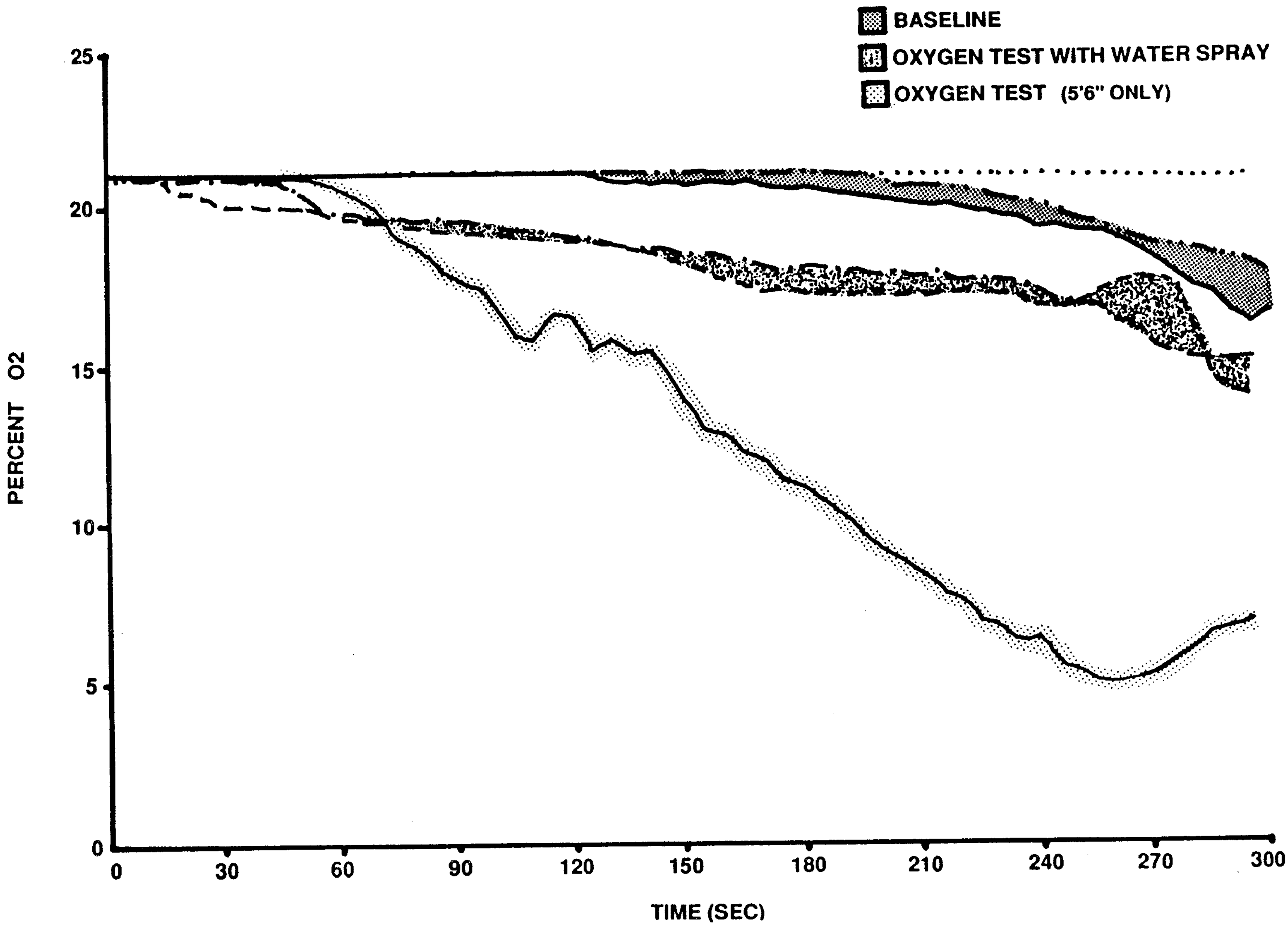

FIGURE 16. OXYGEN STATION 530 -- 3 FEET 6 INCHES TO 5 FEET 6 INCHES

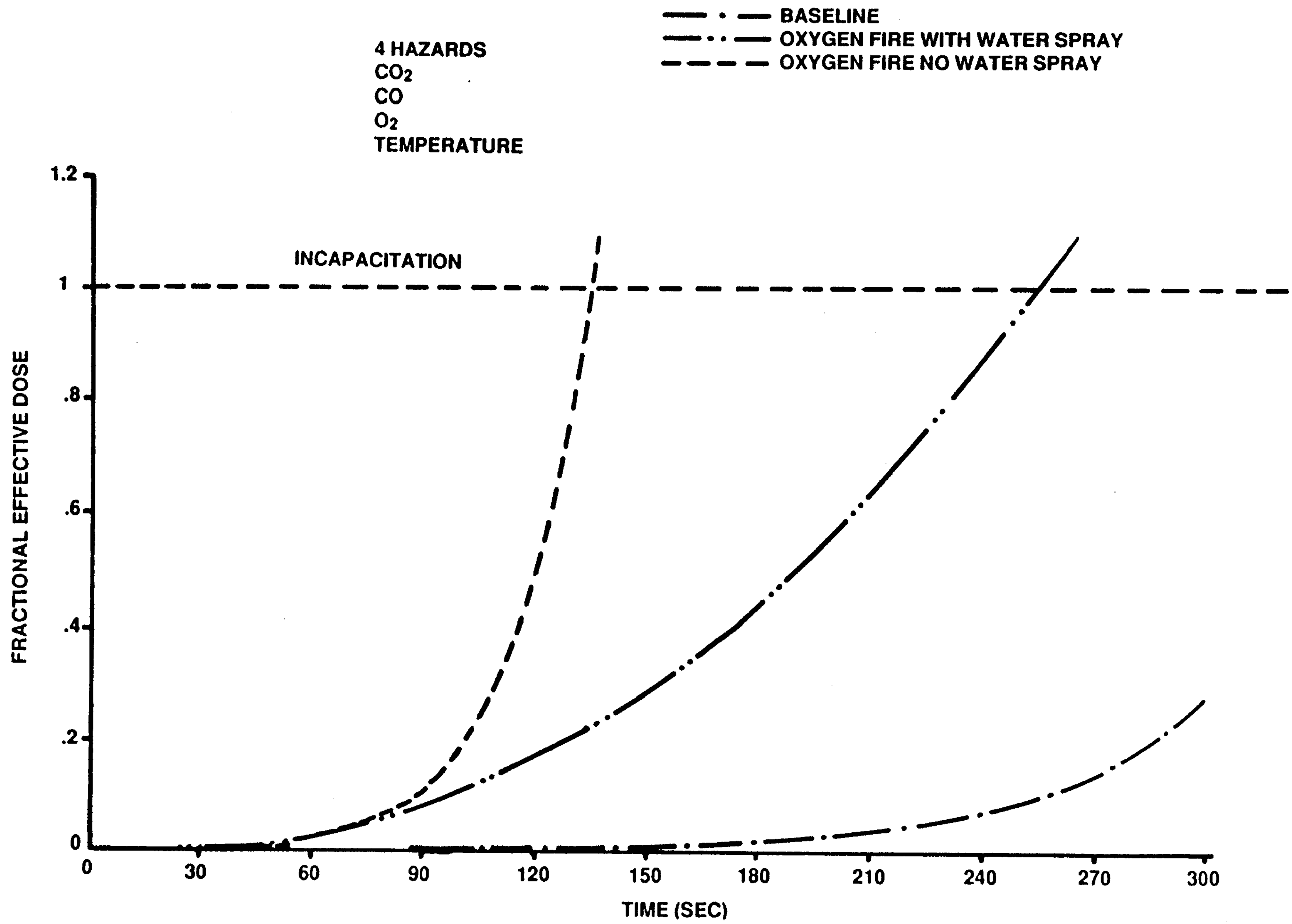

FIGURE 17. FRACTIONAL EFFECTIVE DOSE AT STATION 60 -- 3 FEET 6 INCHES

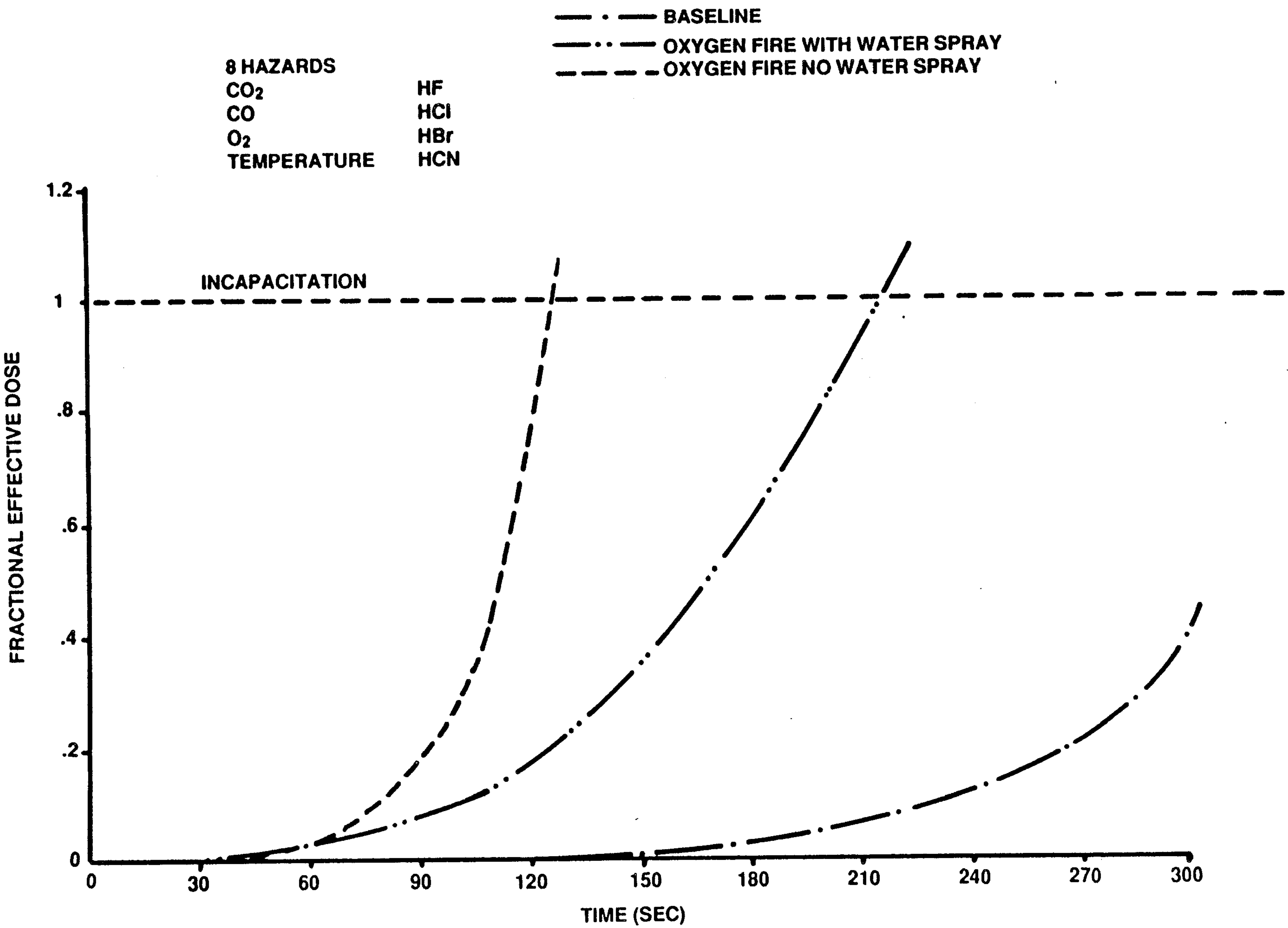

FIGURE 18. FRACTIONAL EFFECTIVE DOSE AT STATION 60 -- 5 FEET 6 INCHES

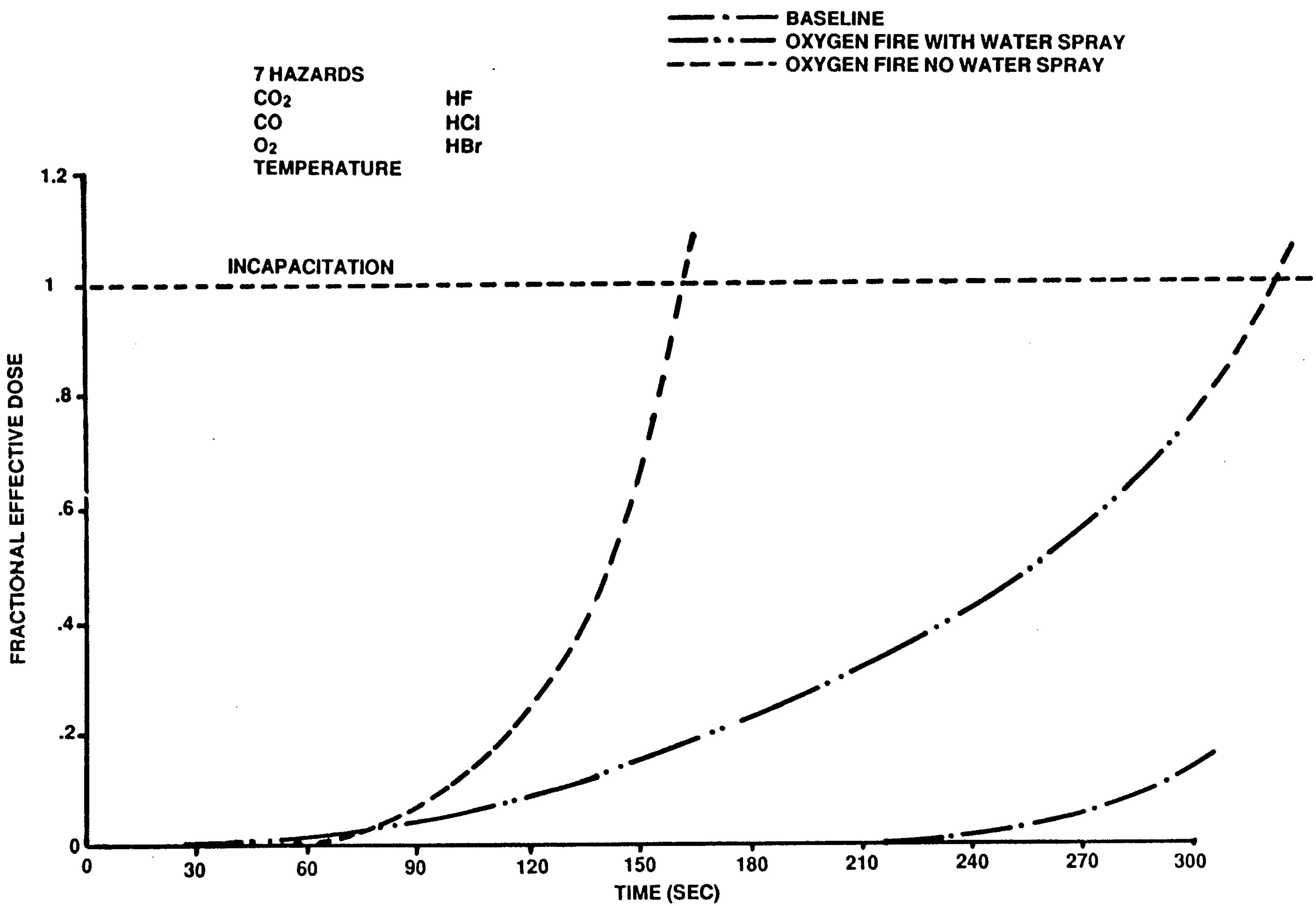

FIGURE 19. FRACTIONAL EFFECTIVE DOSE AT STATION 550 -- 3 FEET 6 INCHES

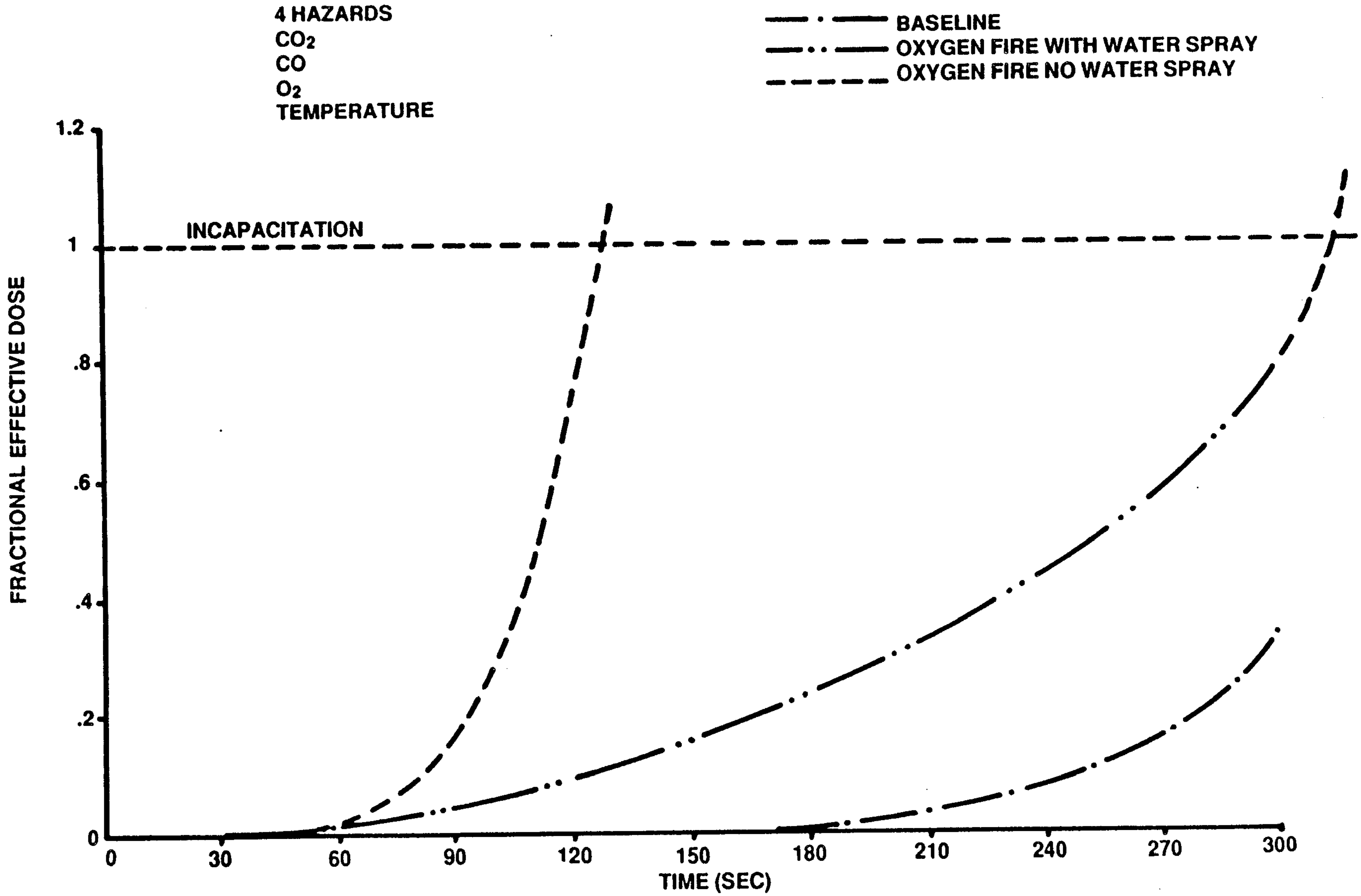

FIGURE 20. FRACTIONAL EFFECTIVE DOSE AT STATION 550 -- 5 FEET 6 INCHES

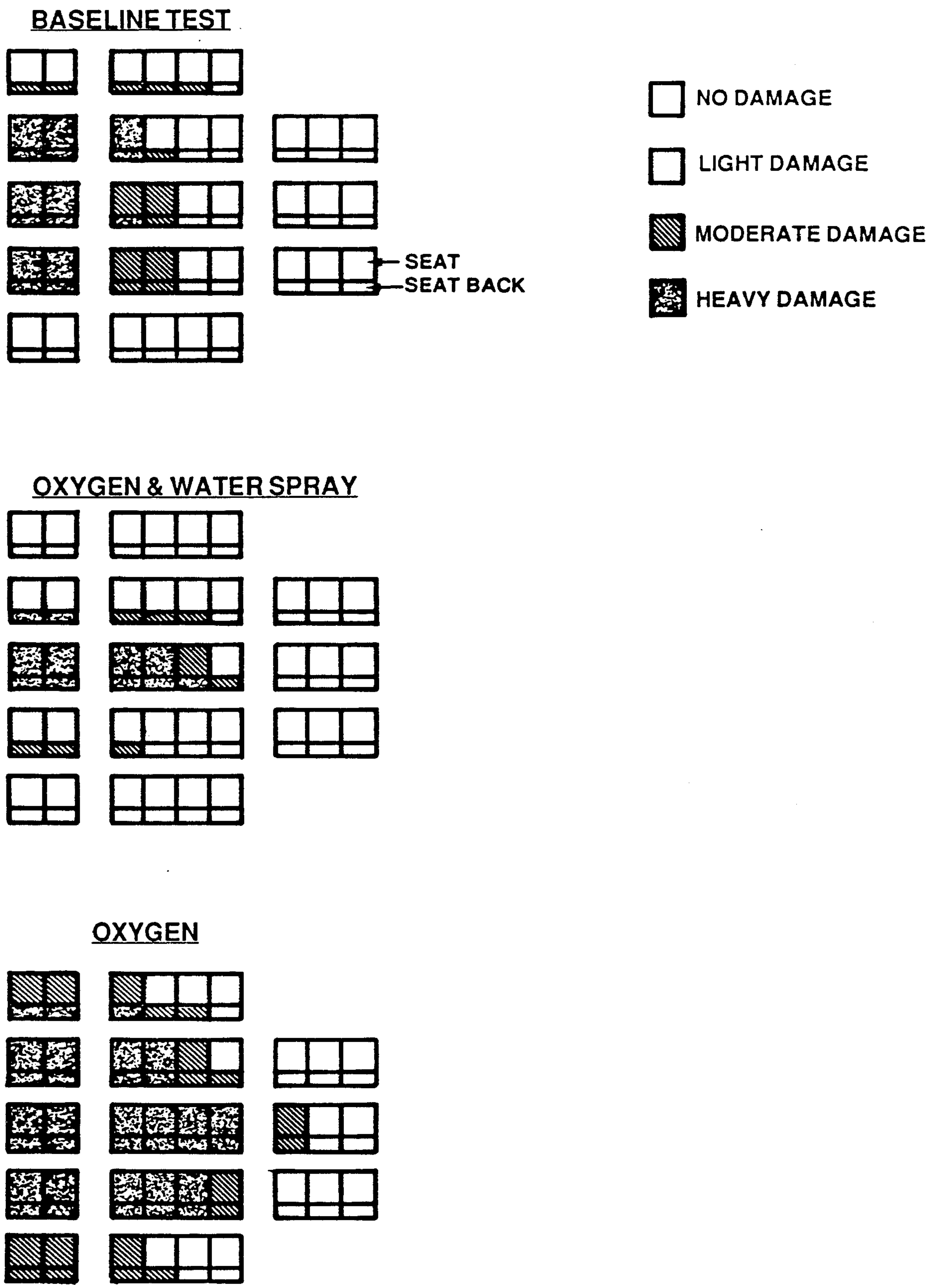

FIGURE 21. SEATING DAMAGE