DOT/FAA/CT-89/25

FAA Technical Center
Atlantic City International Airport
N.J. 08405

Ventilation Effects on Smoke and Temperature in an Aircraft Cabin Quarter-Scale Model

Allan Abramowitz
Franklin Fann

March 1993

Final Report

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

1. Report No. DOT/FAA/CT-89/25	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle VENTILATION EFFECTS ON SMOKE AND TEMPERATURE IN AN AIRCRAFT CABIN QUARTER-SCALE MODEL		5. Report Date March 1993
		6. Performing Organization Code
7. Author(s) Allan Abramowitz and Franklin Fann		8. Performing Organization Report No. DOT/FAA/CT-89/25
9. Performing Organization Name and Address Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code ACD-240
15. Supplementary Notes		

16. Abstract

Fire tests were conducted on a quarter-scale model of an aircraft cabin to determine ventilation effects on temperature and smoke. The ventilation rates were varied between 1 1/4 and 2 1/2 minutes' time for an air exchange (quarter scale). The data indicate that there were no significant changes in the cabin temperatures and in the quantity of heat being removed from the cabin by changing ventilation rates. The increased flows tended to redistribute small quantities of smoke within the cabin and out the exhaust.

17. Key Words Quarter Scale Ventilation Temperature Smoke		18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 33	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

EXECUTIVE SUMMARY

This report represents part of the Federal Aviation Administration's effort to study smoke elimination in aircraft as required under a Congressional mandate. This effort involved the use of a quarter-scale model of an aircraft cabin and represents part of overall effort, which includes full-scale ground tests, half-scale model tests, and in-flight tests.

The reduction of temperature and smoke within the cabin would provide an improved environment for the passengers in the event of an in-flight fire or smoke incident.

The quarter-scale model was designed to simulate the ventilation system and ventilation rates found on today's commercial fleets. A propane gas burner, with an output in the range consistent with a manageable fire in an aircraft cabin, served as the source of heat and smoke for the tests.

The results indicate that increased ventilation flows within the given range of today's current commercial fleet would have a small effect on the temperature and the smoke density within the cabin. The results also indicate that lower intake air temperatures would have a comparable effect on cabin air temperatures. Thus, both increased flows and lower intake cabin air temperatures should be optimized in the event of a fire/smoke incident.

INTRODUCTION

PURPOSE.

The purpose of this project was to study the effects of aircraft ventilation on temperature and smoke in a quarter-scale model of an aircraft cabin, in order to characterize the cabin air environment that might develop during an in-flight fire.

BACKGROUND.

In the event of an in-flight fire or smoke incident, it would be desirable to control heat and smoke buildup within the cabin in order to provide a safer environment for the passengers and crew members.

The technique explored in this report is to vary the aircraft ventilation rates and study their effect on the aforementioned conditions. In theory, higher ventilation flows through the aircraft cabin would result in reduced cabin temperatures, toxic gas concentrations, and smoke density. The question is to what extent do changes in the ventilation rates available on today's commercial aircraft have on these combustion products.

A quarter-scale model was fabricated to represent the cabin of a wide-body aircraft. The ventilation system used in the model was a counterflow design typically found in commercial aircraft (figure 1). Cabin air enters near the ceiling, mixes with the existing air, and exits through exhaust vents located near the floor. The airflow direction is opposite of the buoyant behavior of hot gases, which tend to rise to the ceiling and stratify in layers.

The typical aircraft ventilation rate is an air exchange once every three minutes. This air exchange is either made up of fresh air, or in the case of newer aircraft, a combination of fresh and recirculated air. In present fire/smoke emergency procedures, only fresh air is vented into the cabin. Similarly, only fresh air is vented into the model.

The model was instrumented with thermocouples, smoke meters, and gas analyzers. A propane gas diffusion burner was installed as a fire/smoke source. The propane fuel flow to the burner was held constant while ventilation rates through the model were varied. Data were recorded to study the effects of ventilation while the fire source was active and also after it was turned off. An oxygen consumption measurement technique was used to determine the heat release of the burner as well as providing a check on the calculated airflows through the cabin.

DISCUSSION

DESCRIPTION OF TEST ARTICLE.

The test article was a quarter-scale model of an aircraft cabin and was 4 feet wide, 6 feet long, and 2 feet high (figure 2). Thus it represented a fuselage section 16 feet wide, 24 feet long, and 8 feet high. The cabin was framed out using 1/8-inch mild steel, reinforced at the edges and in the center with 3/4-inch angle iron. The interior surfaces of the cabin were lined with 1-inch-thick Kaowool (TM) board (an inert ceramic fibrous insulating material). The area lined with Kaowool included the floor, roof, and the lower 24 inches of the walls. A 1/16-inch-thick mild steel sheet ceiling rested on 1/4-inch offsets placed every 2 feet, which were supported by a 1-inch ledge formed by the Kaowool board. The gap formed by the 1/4-inch offset spacers acted as intake vents for the cabin. A 3-inch space existed between the metal ceiling and the roof of the model (attic area). This space served as a plenum from which the ventilation air flowed to the cabin intake vents. The Kaowool board lining at the bottom of the removable roof served as a gasket between the roof and the walls of the cabin. The roof was secured using clamps to minimize any leakage from the box. The internal volume of the cabin minus the insulation and instrumentation was 50 cubic feet.

Ventilation was provided by a Dayton Blower, Stock # 4C442, rated at 140 CFM in free air. A Daytom Model 4X796 AC/DC speed control was used to regulate the fan speed and hence the volumetric airflow through the cabin. A 4-foot-long, 4-inch-diameter duct was connected to the intake of the blower. Since low speed regulation of the fan proved to be a problem, the intake of the duct was covered with plastic and a 1-inch-diameter hole was cut in its center. This permitted the blower to operate at a faster speed, eliminating the regulation problem. The blower was mounted to the center of the roof, and an opening was cut into the roof for the air to enter the attic area of the model. A diffuser plate was mounted 1 1/4 inches below the inlet to disperse the stream of air into the attic area. Exhaust outlets were cut along the bottom of both sides of the model and connected to external ducts. The ducts were joined together behind the rear of the model and extended to the outside of the building.

A high temperature glass window, 1-foot-square and 1/4-inch-thick, was installed in the rear wall of the model to allow for visual observation of the cabin during the test (figure 2).

The fire source was a propane gas burner with a 10-inch-square surface area. The burner was centered 19 inches from the front wall and equidistant from the side walls (figure 2). The propane flow rate was 5.45 liters/minute, producing a calculated heat release (Qcalculated) of 8.4 kilowatts (kW).

$$\begin{aligned} Qcal &= \Delta H \rho V \\ Qcal &= (46343\ MJ/kG)(1.96\ G/L)(5.45\ L/Min)(0.0000168\ kW\ Min/J) \qquad (1) \\ Qcal &= 8.4\ kW \end{aligned}$$

Where ΔH is the net heat of combustion of propane, ρ is the density of propane at 0 ^{o}C, and V is the corrected volumetric flow of propane with regard to barometric pressure and temperature. The burner was ignited at the start of the test by electrical sparks.

CONCLUSIONS

The temperatures measured in the model at the front top thermocouple location were 15 ^{o}F cooler at the fastest ventilation rate than those at the slowest ventilation rate. The amount of heat being removed from the model did vary with the ventilation rate; but compared with the total heat being absorbed by the model, the difference was not significant. This was especially true during the first 5 minutes of every test, when the majority of the energy being generated by the fire was being absorbed by the model ceiling and walls.

The results obtained by varying the incoming air temperature were just as effective in lowering cabin temperature as by varying the ventilation rates. Modest changes in incoming air temperature (15 ^{o}F) were equivalent to a doubling of the ventilation rate (1 1/4 to 2 1/2 min/air exchange).

Increased ventilation rates do result in the dilution of the smoke density in the ceiling smoke layer and expedite smoke removal from the cabin once the fire is out. The increased ventilation rates may slightly reduce visibility in the mid and lower areas of the cabin. Maximizing the aircraft ventilation rate, combined with the lowest incoming cabin air temperature would be the most effective method to manage temperature and heat in the cabin.

REFERENCES

1. Sensenig, D. L., <u>An Oxygen Consumption Technique for Determining the Contribution of Interior Wall Finishes to Room Fires</u>, NBS Technical Note 1128, July 1980.

2. McCaffery, B.J., and Rinkinen, W.J., <u>Fire Environment in Counterflow Ventilation(The In-flight Cabin Aircraft Fire Problem)</u>, NBSIR 88-3806, June 1988.

3. Abramowitz, A., and Eklund, T. I., <u>Model Tests of Aircraft Interior Panel Flammability</u>, Journal of Fire Sciences, Vol 3 No. 2, March/April 1985.

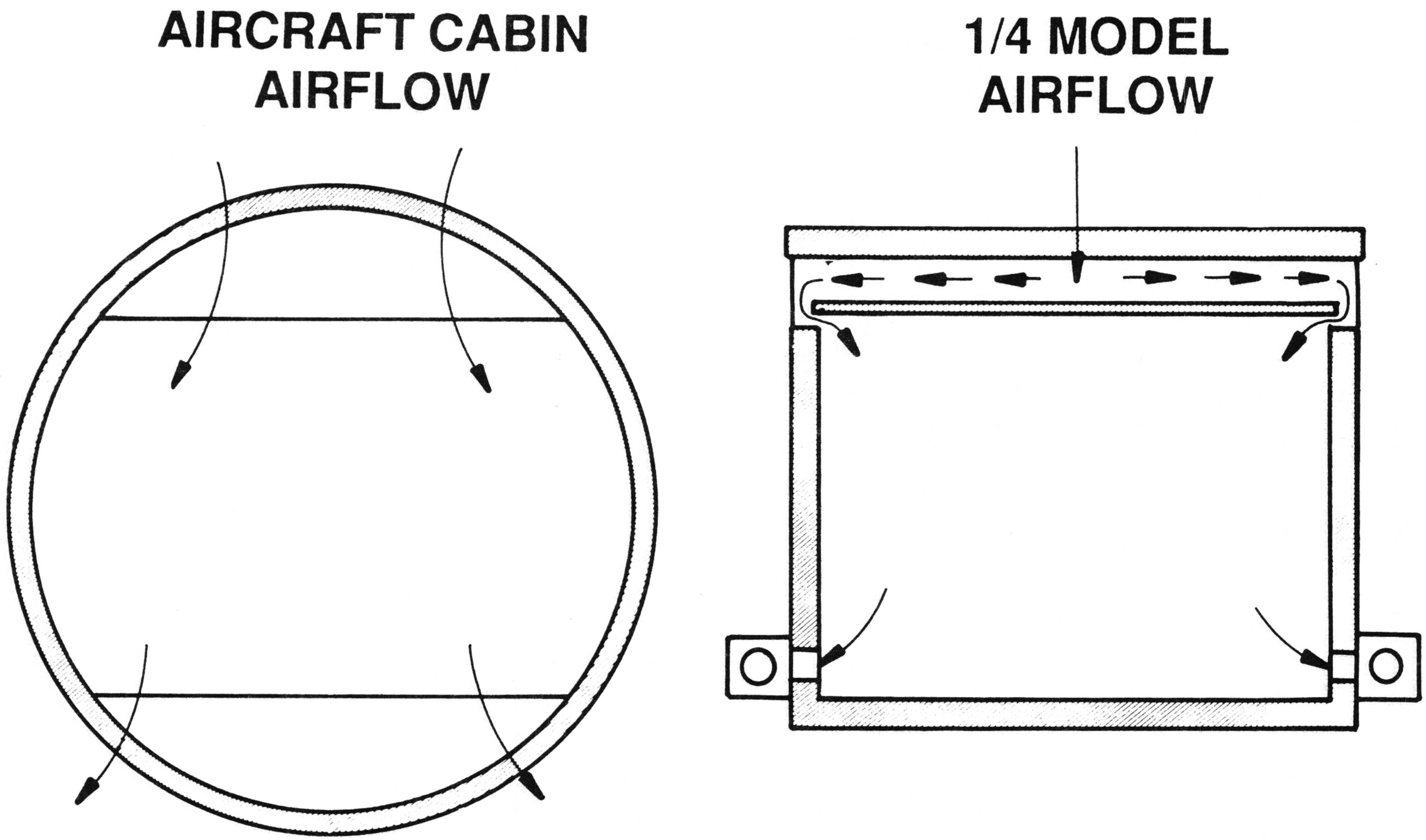

FIGURE 1. QUARTER-SCALE/FULL-SCALE COMPARISON

respective rates. In figure 13 the ambient temperature for the 1 1/4 min/air-exchange rate is 21 °F lower than that of the 2 1/2 minute rate. The total difference at the end of the first 11 minutes (burner on) is 35 °F. Taking the difference in temperature between the two flows in table 4 and adding the ambient temperature difference (15 °F + 21 °F = 36 °F), we have comparable values. Temperatures at the conclusion of the test 9 minutes later show a total difference of 43 °F or an additional spread of 9 °F. Thus, lower intake temperatures result in lower cabin temperatures during both the fire stage and the post-fire stage.

It is important to note that the top smoke meter is located 8 inches below the ceiling, and is indicating the visibility in the upper middle level and not that of the ceiling smoke layer. Figures 14 through 17 represent the average smoke profiles for the three smoke meters at the four air-exchange rates. The 1 7/16 and 1 5/8 min/air-exchange rates are similar in appearance to the 1 1/4 min/air-exchange rate but have higher average visibility readings, while that of the 2 1/2 min/air-exchange rate is considerably different. Figure 18 represents the typical soot corrected smoke profiles for the top, bottom, and exhaust smoke meters at the 1 1/4 min/air-exchange rate. Those for the 1 7/16 and 1 5/8 min/air-exchange rates are similar with higher visibility readings. At the 2 1/2 min/air-exchange rate, only the top smoke meter required soot correction; the corrected data for the top meter along with the original data for all three locations are shown in figure 19. Figure 20 shows typical corrected smoke profiles for the four ventilation rates at the top smoke meter. Comparing the faster ventilation rates with the slowest (table 5) at Time equals 11 minutes, shows that the visibility at each location decreases as the ventilation rate increases. This indicates that increased flows tend to dilute the concentration of smoke in the ceiling area and redistribute it throughout the cabin, as well as expedite its removal from the cabin.

TABLE 5. EFFECTS OF VENTILATION ON SMOKE DISTRIBUTION

VENTILATION RATES	DECREASE IN % TRANSMISSION		
MIN/AIR EXCHANGE	UPPER S.METER	BOTTOM S.METER	EXHAUST S.METER
2 1/2 (REFERENCE)	---	---	---
1 5/8	2	4	6
1 7/16	3	5	7
1 1/4	6	5	8

where S.METER = SMOKE METER
TIME = 11 MINUTES

Figures 14 through 19 indicate that the visibility in the upper area of the model is less than that at the lower area and at the exhaust. This can be expected since the smoke tends to remain suspended in the hot buoyant layer near the ceiling despite any mixing due to the cabin inlet air. Figure 20 also shows that once the fire is out, the rate of smoke removal is slightly greater at the higher ventilation rates.

The temperatures listed in table 4 are representative of those found in four areas in the model. Specifically, they are the means and standard deviations of the front top, back middle, front bottom, and exhaust thermocouples. These data represent at least eight tests for the given scenario and are the data recorded just prior to the burner being shut off, which corresponds to a time of 11 minutes into the test. As expected temperatures at the top level as well as the attic area (not shown) increase as the ventilation rate decreases. Conversely, temperatures at the lower level as well as those in the exhaust decrease as the ventilation rate decreases. The data in table 4 show two points of interest. First, the BMID temperature readings at the slowest ventilation rate were not in keeping with the trend of increasing temperatures with a decrease in the ventilation rate. Secondly, a close look at the standard deviations listed in table 4 appears to indicate distinct groups; the slowest ventilation rate representing that of a relatively nonturbulent environment, and the other three representing those of a more turbulent environment.

TABLE 4. TEMPERATURE MEANS AND DEVIATIONS

VENTILATION MIN/AIR EXCHANGE QUARTER SCALE	FULL SCALE	FTOP TEMP F	BMID TEMP F	FBOT TEMP F	EX TEMP F	FTOP DEV ± F	BMID DEV ± F	FBOT DEV ± F	EX DEV ± F
1 1/4	2 1/2	452	347	309	187	16	6	8	4
1 7/16	2 7/8	457	355	303	184	15	5	12	4
1 5/8	3 1/4	462	357	303	182	13	6	11	5
2 1/2	5	467	338	291	141	3	2	2	1

AT TIME = 11 MINUTES
F=FRONT B=BACK EX=EXHAUST
TOP,MID,BOT = LEVEL ON THERMOCOUPLE TREE

Given a constant heat release from the burner, the temperature within the model should be directly related to the ambient temperature of the air. Test data showed that at the same ventilation rates, the temperature data throughout the test was offset by this difference in ambient temperature. Figures 11, 12, and 13 represent the effects of ambient temperature as seen by the front top thermocouple. Figure 11 compares the two extreme ventilation rates with their initial temperatures normalized to 72 °F. At the end of the first 11 minutes (burner on), a temperature difference of 14 °F existed. At the conclusion of the test 9 minutes later (burner off), a temperature difference of 19 °F existed between the two rates. This indicates that an increased ventilation rate results in lower cabin temperatures. A closer look at the post-fire environment (burner turned off) shows that during the first minute after the burner is turned off, the temperature within the cabin decreases at approximately the same rate for the two extreme ventilation rates; after which time the additional 5 °F temperature difference begins to occur. Thus, increased ventilation rates have a minimal effect on enclosure cooling after the fire is turned off. In figure 12 the ambient temperature for the 1 5/8 min/air-exchange rate is 26 °F lower than that at the 1 1/4 min/air-exchange rate. At the end of the first 11 minutes (burner on), a temperature difference of 17 °F existed; a change of 9 °F, or approximately that calculated using the front top thermocouple readings in table 4 at the

The data recorded for this test series represent lower cabin air inlet velocities than would normally be found in commercial aircraft air supply vents (200 versus 300-900 feet per minute (ft/min) at 3 min/air exchange (full scale). Therefore, additional testing at increased velocities would be necessary to develop a more complete understanding of the effects of aircraft ventilation systems.

RESULTS

The data used in the calculations represent the average of at least eight tests for that given scenario. Unless specifically stated, all data values used are those recorded just prior to the burner being shut off; which corresponds to Time = 11 minutes into the test. Comparison of all absolute temperature data has been normalized or offset to correspond to a ambient reference temperature of 72 ^{o}F. No attempt was made to compensate for any variations in the humidity of the air, as other reports have indicated that this would have only a minor effect on the results.

The values of CO measured throughout the test series was negligible for the four test conditions. Figures 8 and 9 represent typical gas profiles for CO_2 and O_2 at the four ventilation rates. Comparing the graphs of CO_2 and O_2 shows similar mirrored profiles that track each other with respect to time. Balancing the chemical equation of the propane burner in its simplest form yields the following chemical equation:

$$C_3H_8 + 5O_2 \longrightarrow 3CO_2 + 4H_2O \tag{3}$$

This equation indicates that 3 moles of CO_2 are produced for every 5 moles of oxygen consumed. Using the averaged readings for O_2 and CO_2, table 1 shows the normalized values of the two gases.

TABLE 1. NORMALIZED O_2 AND CO_2 RATIOS

VENTILATION MIN/AIR EXCHANGE QUARTER SCALE	FULL SCALE	$O_2/5$ VOL %	$CO_2/3$ VOL %
1 1/4	2 1/2	0.54	0.54
1 7/16	2 7/8	0.62	0.62
1 5/8	3 1/4	0.68	0.69
2 1/2	5	1.10	1.10

At TIME = 11 MINUTES

Where $O_2/5$ equals the sampled value of oxygen depletion in percent divided by 5 and $CO_2/3$ equals the sampled value of carbon dioxide in percent divided by 3, the strong agreement between these values adds credibility to the sampled data.

Of particular importance is the favorable comparison between the calculated heat release based on the propane supply (Qcalculated = 8.4 kW) and the heat release determined by the oxygen consumption technique (table 2).

TABLE 2. HEAT RELEASE

VENTILATION MIN/AIR EXCHANGE QUARTER SCALE	FULL SCALE	VOLUMETRIC FLOW (m^3/sec)	O_2 (%)	HEAT RELEASE (kW) QUARTER SCALE	FULL SCALE
1 1/4	2 1/2	.0185	2.7	8.3	266
1 7/16	2 7/8	.0165	3.1	8.3	266
1 5/8	3 1/4	.0144	3.4	8.2	262
2 1/2	5	.0094	5.5	8.4	269
Qcalculated		-------	---	8.4	269

AT TIME = 11 MINUTES

This agreement is significant in that it confirms the measured velocities and calculated airflow/air-exchange rates through the model.

Using these flow rates, the enthalpy increase of the exhaust gases (Qex in kW) was calculated

$$Qex = mC_p\Delta t \qquad (4)$$
$$Qex = V(ft^3/min)*\rho(lb/ft^3)*C_p(Btu/lb^oF)*\Delta t(^oF)*(0.0175\ kW\ Min/Btu)$$

where V = the volumetric flow of air through the model (ft^3/min), ρ = density of air (0.076 lb/ft^3), C_p = the specific heat of air (0.24 Btu/lb^{o}F), Δt = the average difference between the exhaust and the intake temperatures (^{o}F) at the given ventilation rate.

Table 3 contains both the enthalpy lost through the exhaust as well as the heat lost through the exhaust as a percentage of the overall heat production rate.

TABLE 3. HEAT REMOVED FROM THE MODEL

VENTILATION MIN/AIR EXCHANGE QUARTER SCALE	FULL SCALE	VOLUMETRIC FLOW RATE (FT^3/Min)	ΔT ^{o}F	QEX (kW)	HEAT REMOVED QEX/QCAL*100%
1 1/4	2 1/2	39.3	115	1.4	17.2
1 7/16	2 7/8	34.9	112	1.2	14.9
1 5/8	3 1/4	30.5	109	1.1	12.6
2 1/2	5	20	69	0.4	4.7

AT TIME = 11 MINUTES

The data calculated in table 3 indicate that at 11 minutes, 5 to 17 percent of the heat was removed from the model at 2 1/2 to 1 1/4 min/air-exchange rate, respectively. This represents a 365 percent increase in the quantity of heat being removed from the model during a twofold increase in flow rate. However, the overwhelming majority of heat in either case still remains in the model. Figure 10 represents the percentage of heat ((Qex/Qcal)*100%) being removed from the model with time. Figure 10 also reveals that during the early stages of the test, an even smaller percentage of the heat is being removed from the cabin than the percentage shown in table 3. Conversely, an even greater percentage of heat is being absorbed by the cabin during the early test stage.

INSTRUMENTATION.

An IBM Model AT personal computer was outfitted with Burr Brown data acquisition boards and used to acquire, process, and output test data.

Temperature data were gathered using chromel/alumel (type k) thermocouples placed in the cabin, attic area, intake and exhaust ducts (figure 3). Two thermocouple trees were located along the centerline of the cabin at distances of one and two feet from the fire. Three thermocouples were placed on each tree at heights of 2, 12 (midheight of the cabin), and 22 inches off the floor. A thermocouple was placed in the center of the attic, one in the midpoint of the intake duct, and one in the central exhaust duct.

Smoke density was measured using three National Bureau of Standards half-meter smoke meters. Two were mounted in the model at heights of 8 and 16 inches above the floor: Both were 12 inches from and parallel to the rear wall (figure 3). The third smoke meter was mounted in the central exhaust duct (figure 3). The smoke meters were heavily insulated, and shop air was supplied to both the photo-cells and the light sources to enable them to operate within specified temperature limits. Exhaust lines were also run from the smoke meters out of the model so as not to introduce a secondary air supply in the model. Since the smoke meters were located in the model, deposition of soot particles on the lenses posed a problem. Therefore, a series of tests were conducted to determine a soot-deposition correction factor.

Gas measurements were taken from a sampling port located in the central exhaust duct just preceding the exhaust smoke meter. The gas sampling system used a Beckman OM11EA oxygen (O_2) analyzer and two Beckman model 865 infrared analyzers to measure carbon monoxide (CO) and carbon dioxide (CO_2) (figure 4).

Ventilation volumetric air flow rates were calculated from air velocity measurements made with an Omega HH-615 HT hot wire anemometer, taken in the 4-inch-diameter central exhaust duct just prior to testing. The average velocity was calculated along the cross sectional area of the duct using a technique similar to the one used by Sensenig (reference 1).

Propane gas flow settings were made using a Matheson flow meter, and corrections for temperature and pressure were made by the use of a wet test meter.

HEAT RELEASE USING OXYGEN CONSUMPTION TECHNIQUE.

The oxygen consumption technique used to calculate heat release was the same used by Sensenig. It was accomplished by measuring the exhaust gas concentration of oxygen and determining the volume flow of air entering the model. It assumed a standard concentration of oxygen of 20.9 percent in the air, and the volume flow rate into the model equaled the volume flow rate leaving the model. Equation 2 is used to calculate the total rate of heat release (Q) in kW.

$$Q = 1.67 \times 10^4 (XoVa - XsVs) \qquad (2)$$

Where Xo = volume fraction of oxygen in normal air (20.9 percent); Va = volume flow rate of air into the model (m^3/sec) referred to standard conditions; Vs = volume flow of exhaust gas out of the model (m^3/sec) referred to standard conditions; and Xs = volume fraction of oxygen in the exhaust duct. Negligible quantities of CO were measured during the tests, thereby eliminating an additional correction factor to equation 2.

SCALING RULES.

The model represented a quarter geometric scaling of a real aircraft cabin. Using Froude number scaling, event times differed by a factor of 2 between quarter-scale and full-scale, and the heat release differed by a factor of $2^{(5/2)}$ (reference 2). Thus, a 2-minute interval time for an air exchange in the model would correspond to a 4-minute time in a corresponding full-scale test article.

TEST SERIES.

The initial tests conducted in the model were used to (1) establish the effects of various ceiling materials on temperature, (2) select the ceiling panel used throughout testing, and (3) define a baseline cabin environment. Previous work by Abramowitz & Eklund (reference 3) showed that Kaowool board and typical aircraft panel materials yielded similar thermal profiles. Three materials were tested at different ventilation rates to determine their thermal performance in the cabin. The ceiling materials tested were 1/2-inch-thick Kaowool board, 1/6-inch-thick mild steel, and 1/4-inch-thick Phenolic-fiberglass honeycomb aircraft ceiling panel. The results obtained from this testing showed comparable temperature profiles (figure 5). The sheet steel was selected as the ceiling panel due to its structural integrity and to eliminate possible emissions of gas and smoke.

Figures 6 and 7 represent typical temperature profiles of the model. The higher thermocouples are hotter; and at a given height, those located closest to the fire are hotter than those located behind them, with the exception of the front middle (FMID) thermocouple. Since the temperature of the FMID thermocouple during the first several minutes of the test conforms to the overall pattern, the peculiar behavior is probably the result of the flow pattern occurring in the model. When the convective heat layer reaches the far wall, it travels down the wall and is partially evacuated out the exhaust, the rest being drawn forward. The FMID thermocouple does not sense this hot air source and hence is at a lower temperature than the BMID thermocouple. Calibration checks were conducted to eliminate any possibility that the thermocouple was faulty.

The procedure used for each test was as follows: All instrumentation and sensors were turned on at least 1 hour before the test. The flow rates for propane and ventilation were set at this time, with ventilation rates being reset just prior to each test. The ignitor was then turned on, the computer started to collect ambient data, and approximately 10 seconds later the propane burner was turned on. Flow adjustments were made if necessary, and the ignitor was turned off. The propane was allowed to burn for 11 minutes, after which the burner was turned off and post-fire ventilation data were collected for an additional 9 minutes.

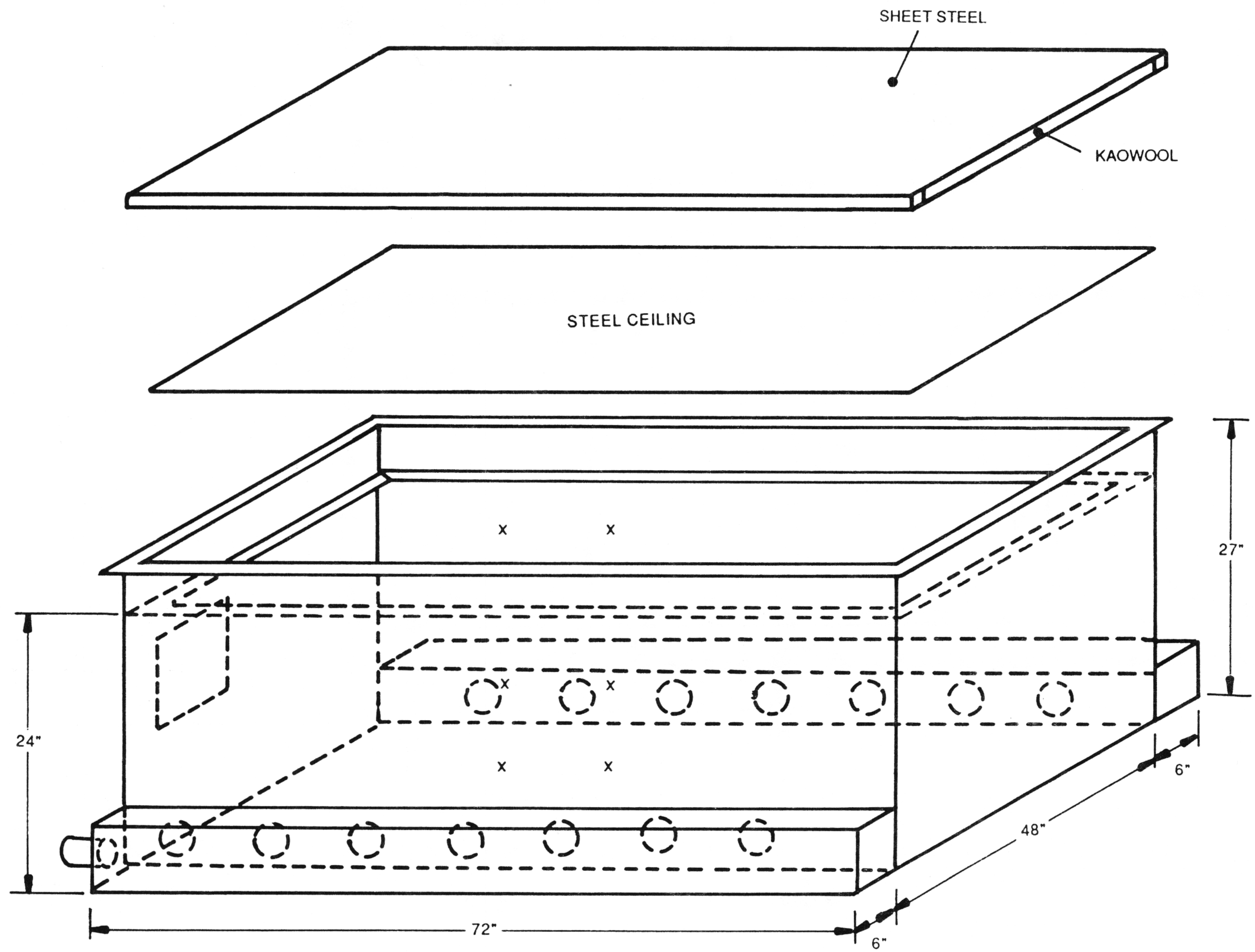

FIGURE 2. 3-DIMENSIONAL MODEL VIEW

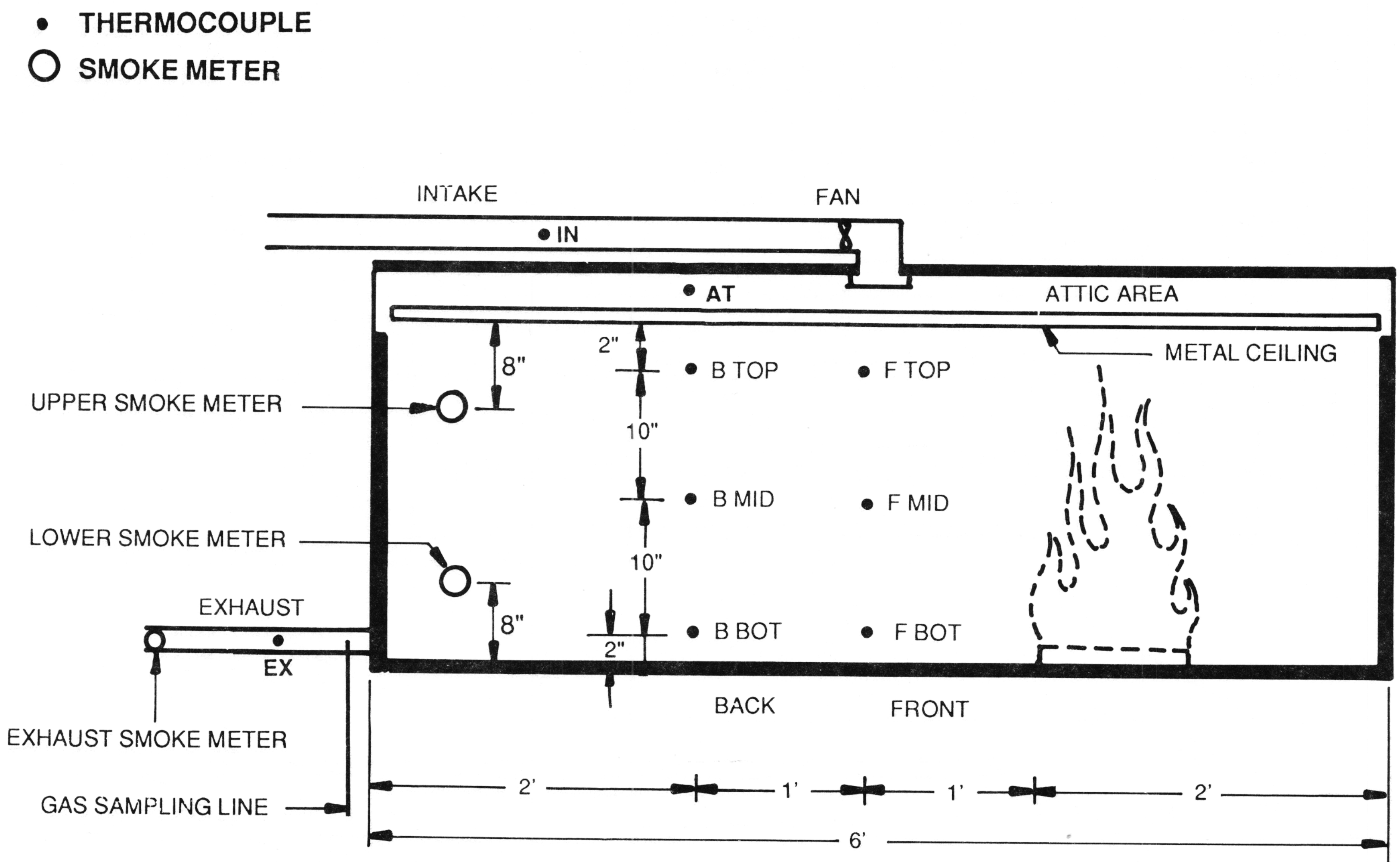

FIGURE 3. INSTRUMENTATION

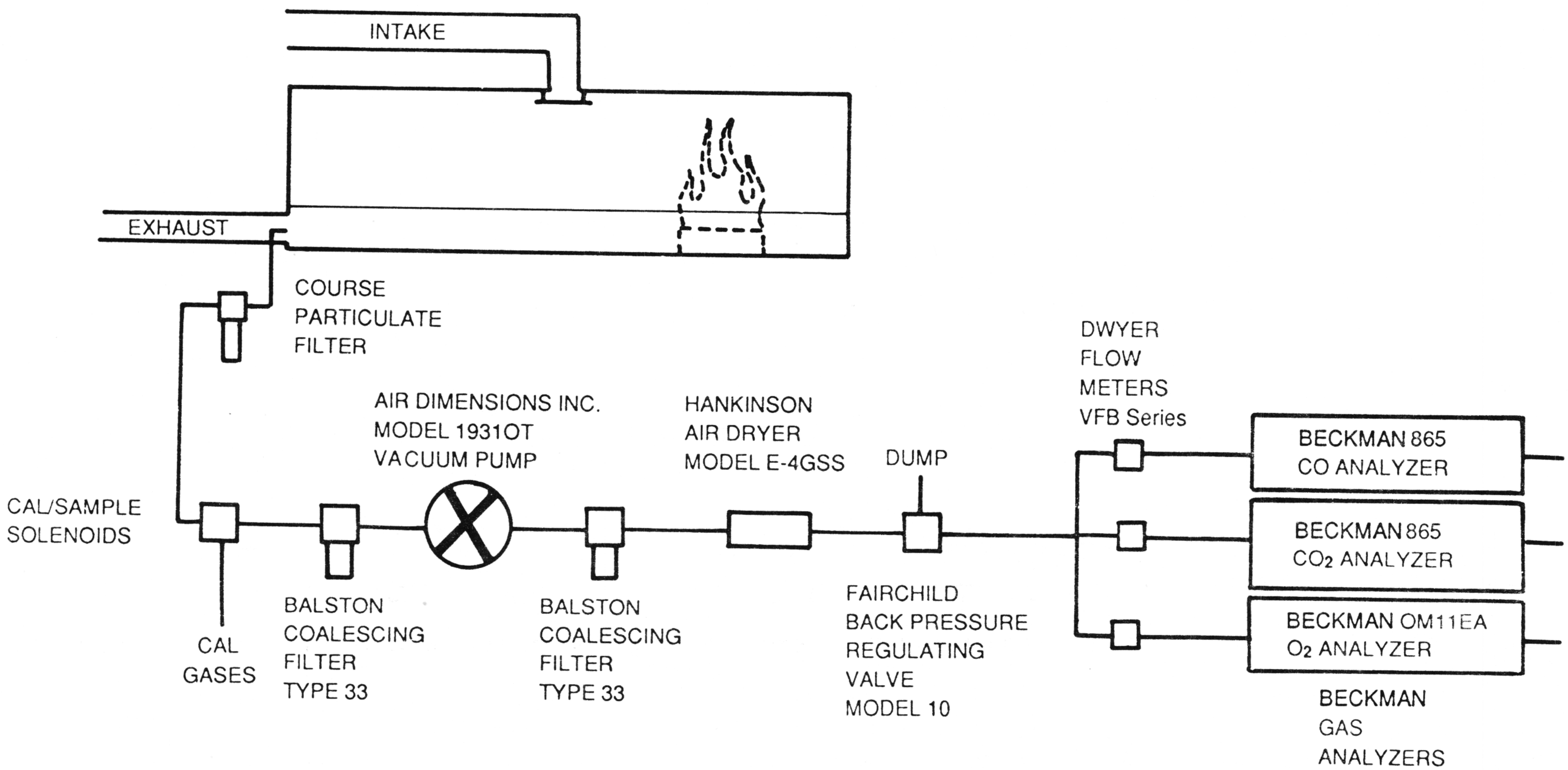

FIGURE 4. GAS SAMPLING SYSTEM

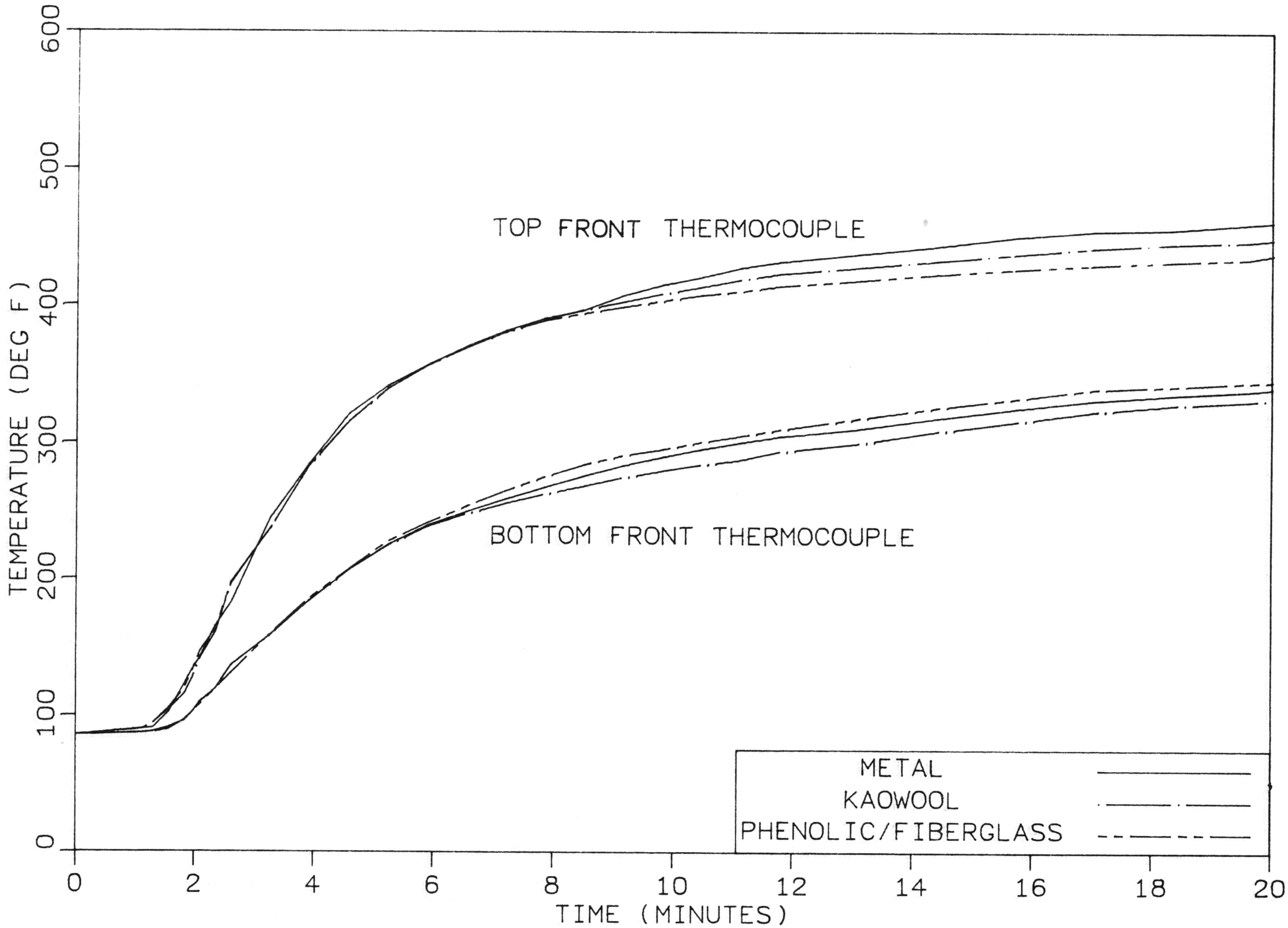

FIGURE 5. MIXED CEILINGS - TOP FRONT TEMPERATURE PROFILES AT 2 1/2 MIN/AIR EXCHANGE

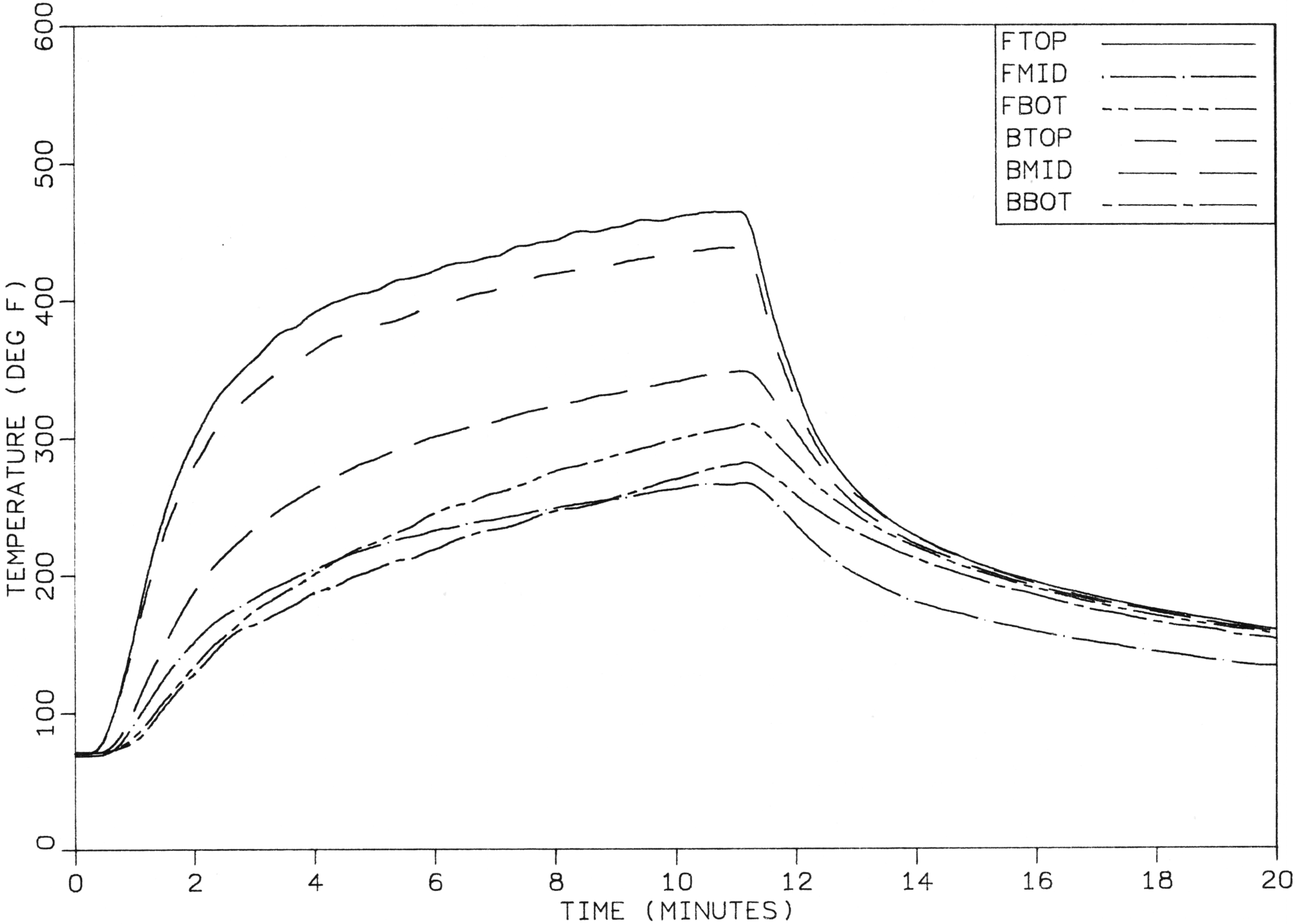

FIGURE 6. TYPICAL INTERIOR CABIN TEMPERATURE PROFILES

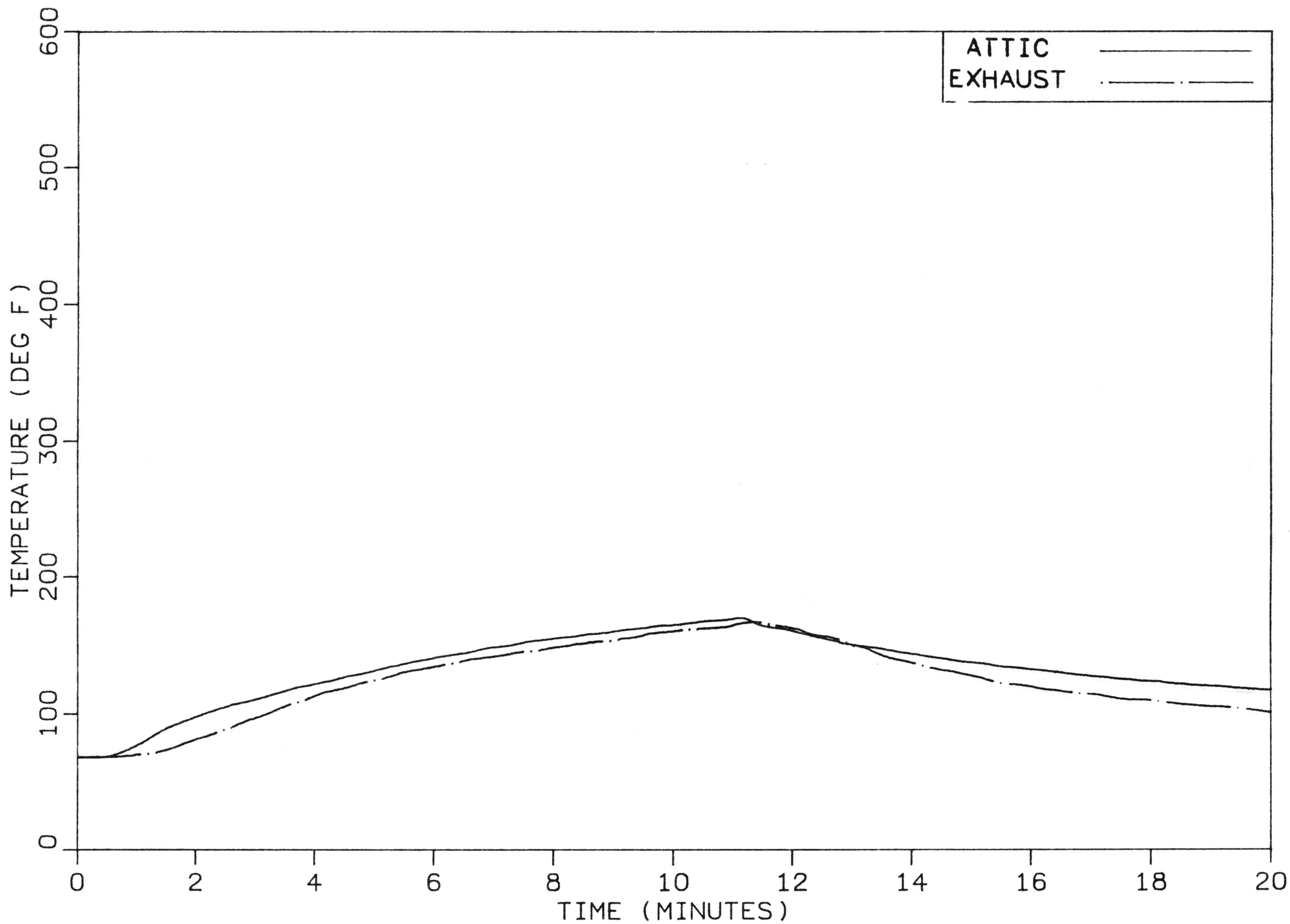

FIGURE 7. TYPICAL ATTIC/EXHAUST TEMPERATURE PROFILES

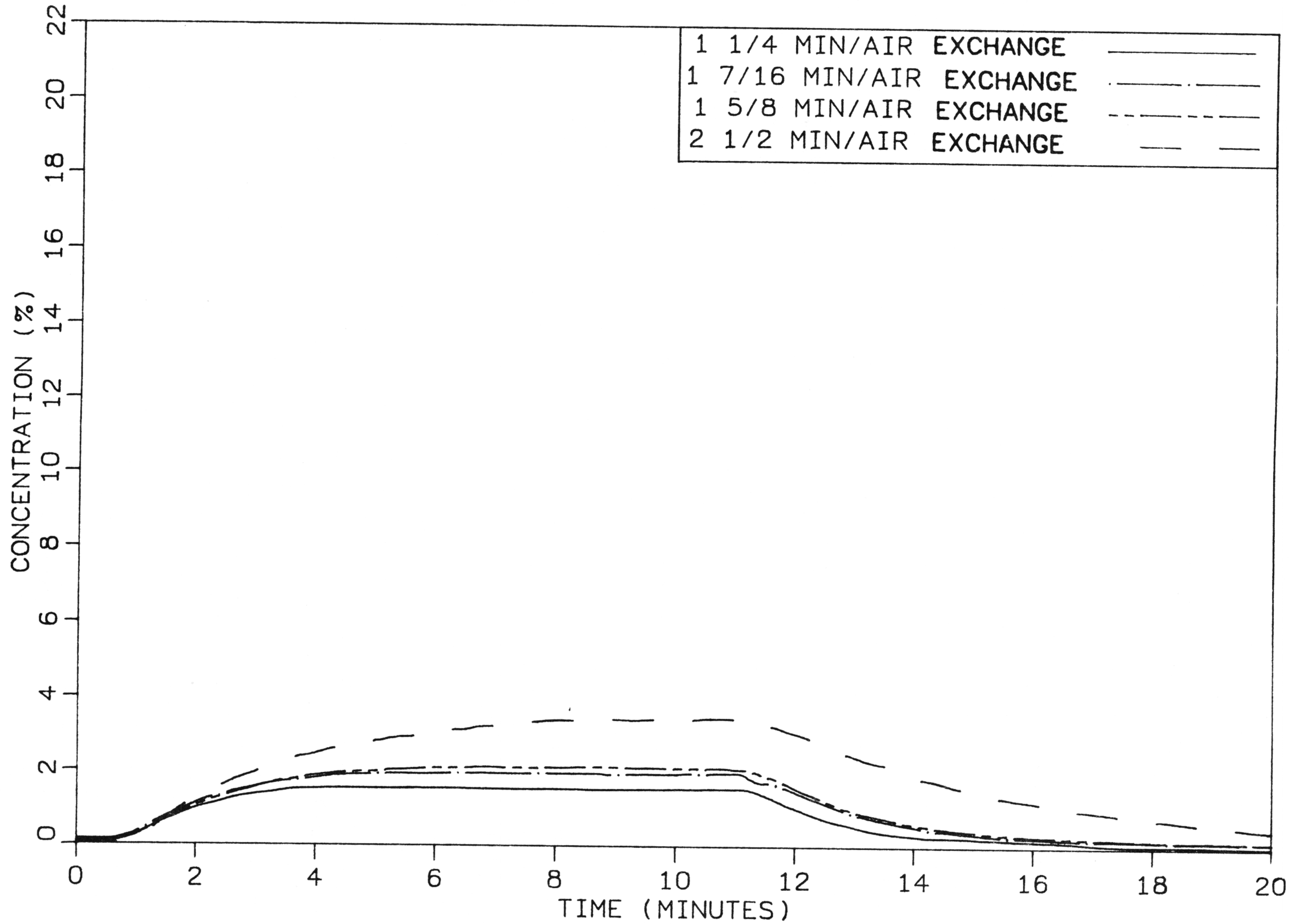

FIGURE 8. TYPICAL CARBON DIOXIDE PROFILES

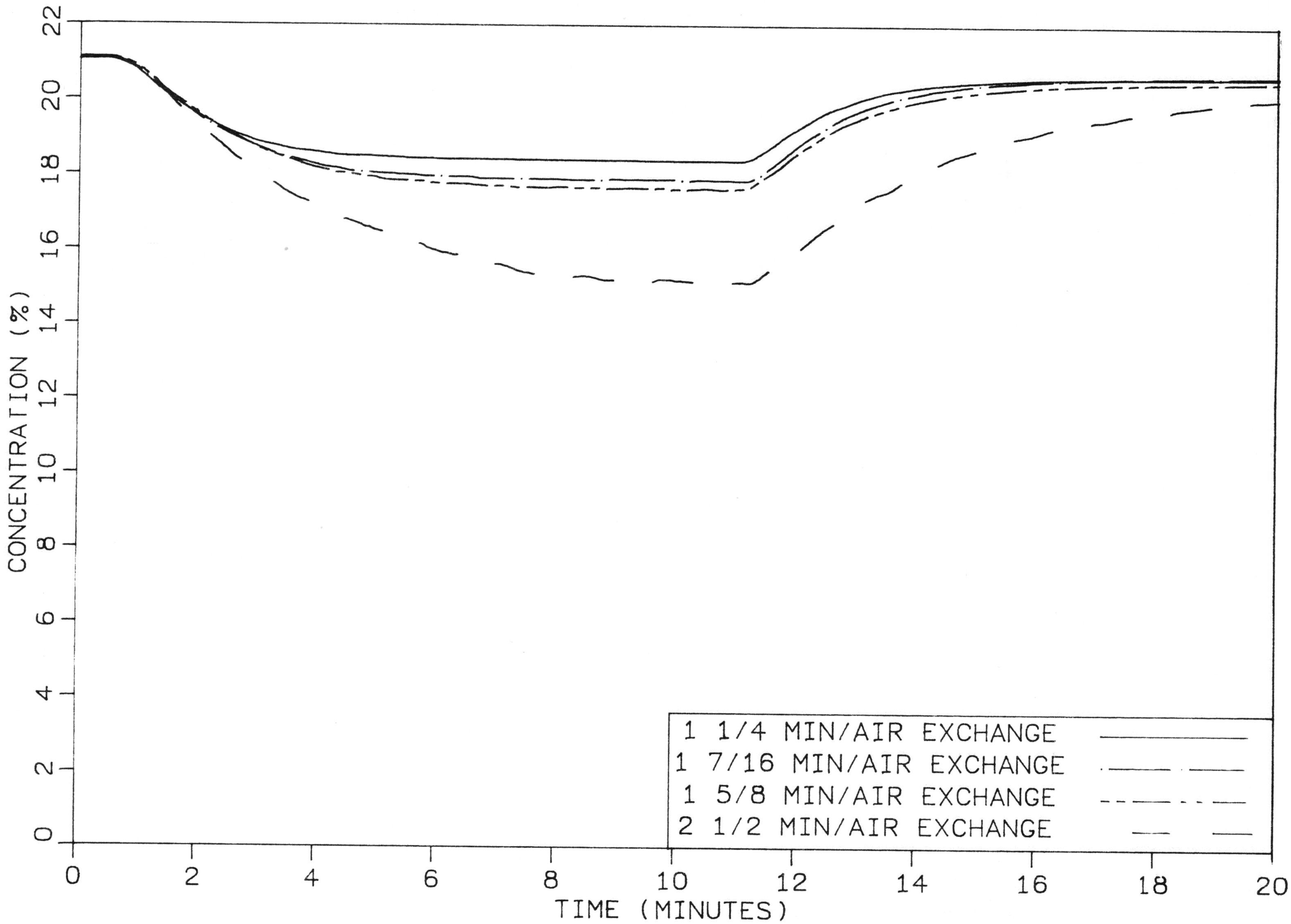

FIGURE 9. TYPICAL OXYGEN PROFILES

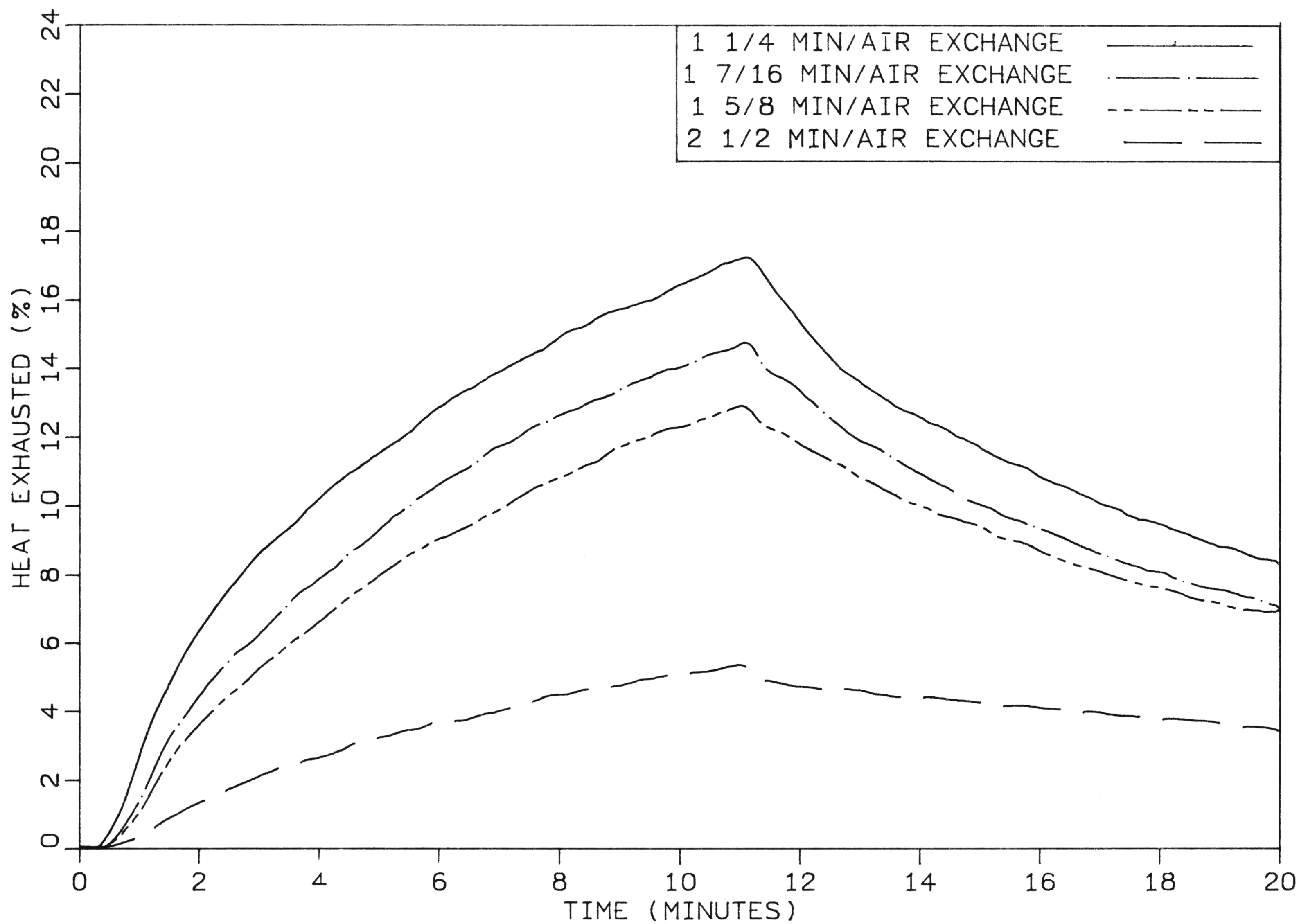

FIGURE 10. PERCENT HEAT EXHAUSTED AT 1 1/4, 1 7/16, 1 5/8, 2 1/2 MIN/AIR EXCHANGE

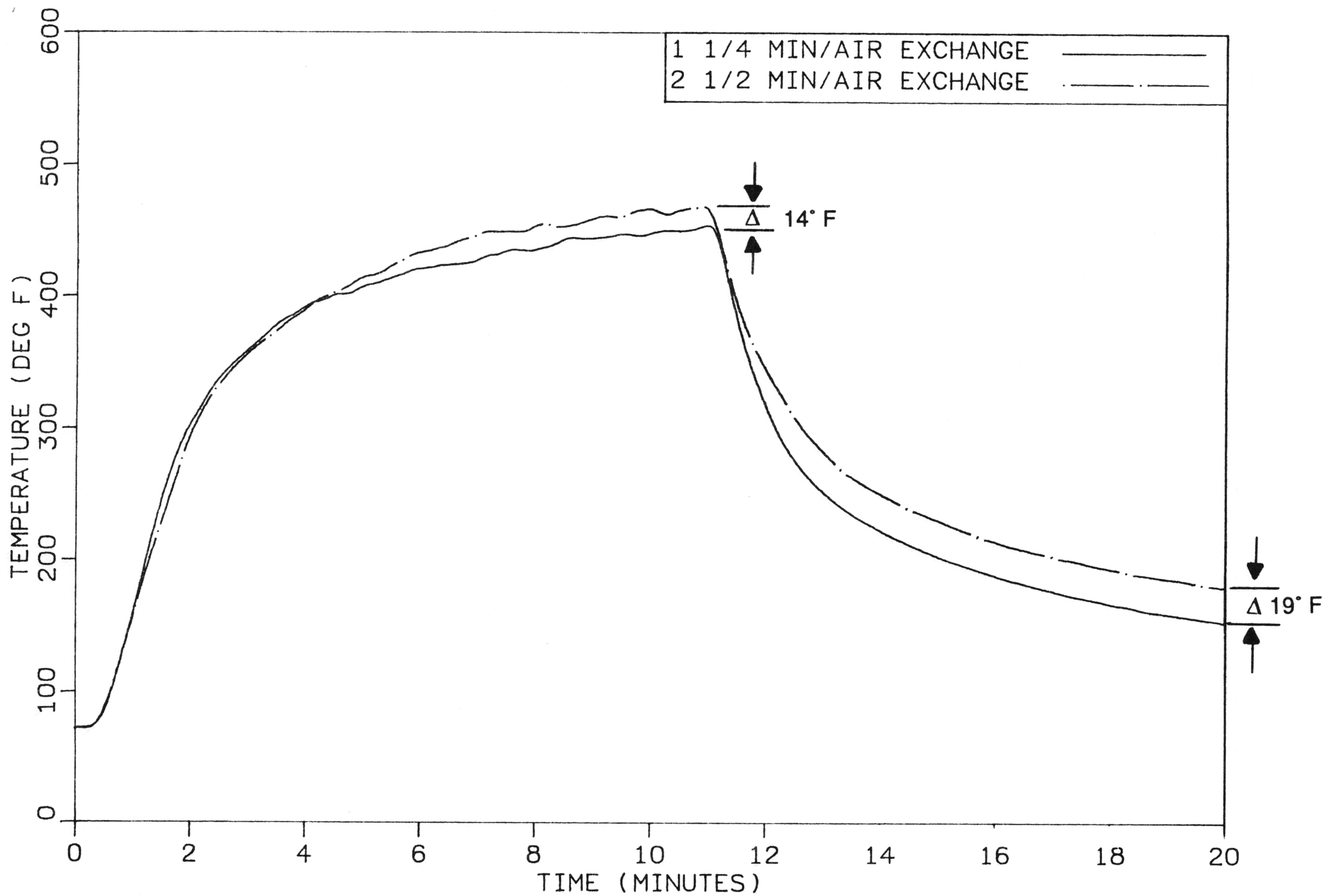

FIGURE 11. TEMPERATURE PROFILES AT 1 1/4 & 2 1/2 MIN/AIR EXCHANGE

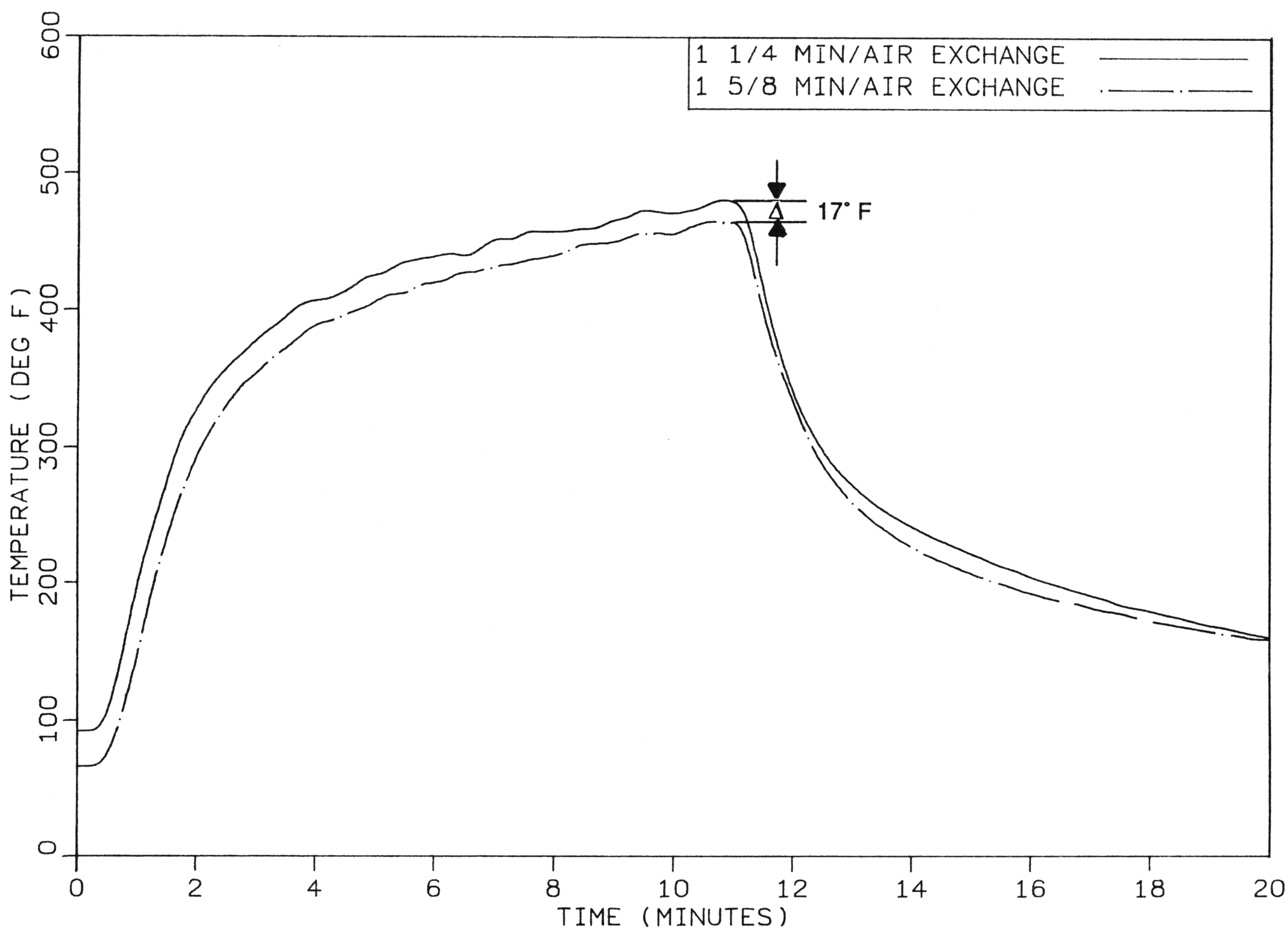

FIGURE 12. TEMPERATURE PROFILES AT 1 1/4 & 1 5/8 MIN/AIR EXCHANGE
(DIFFERENT AMBIENT TEMPERATURES)

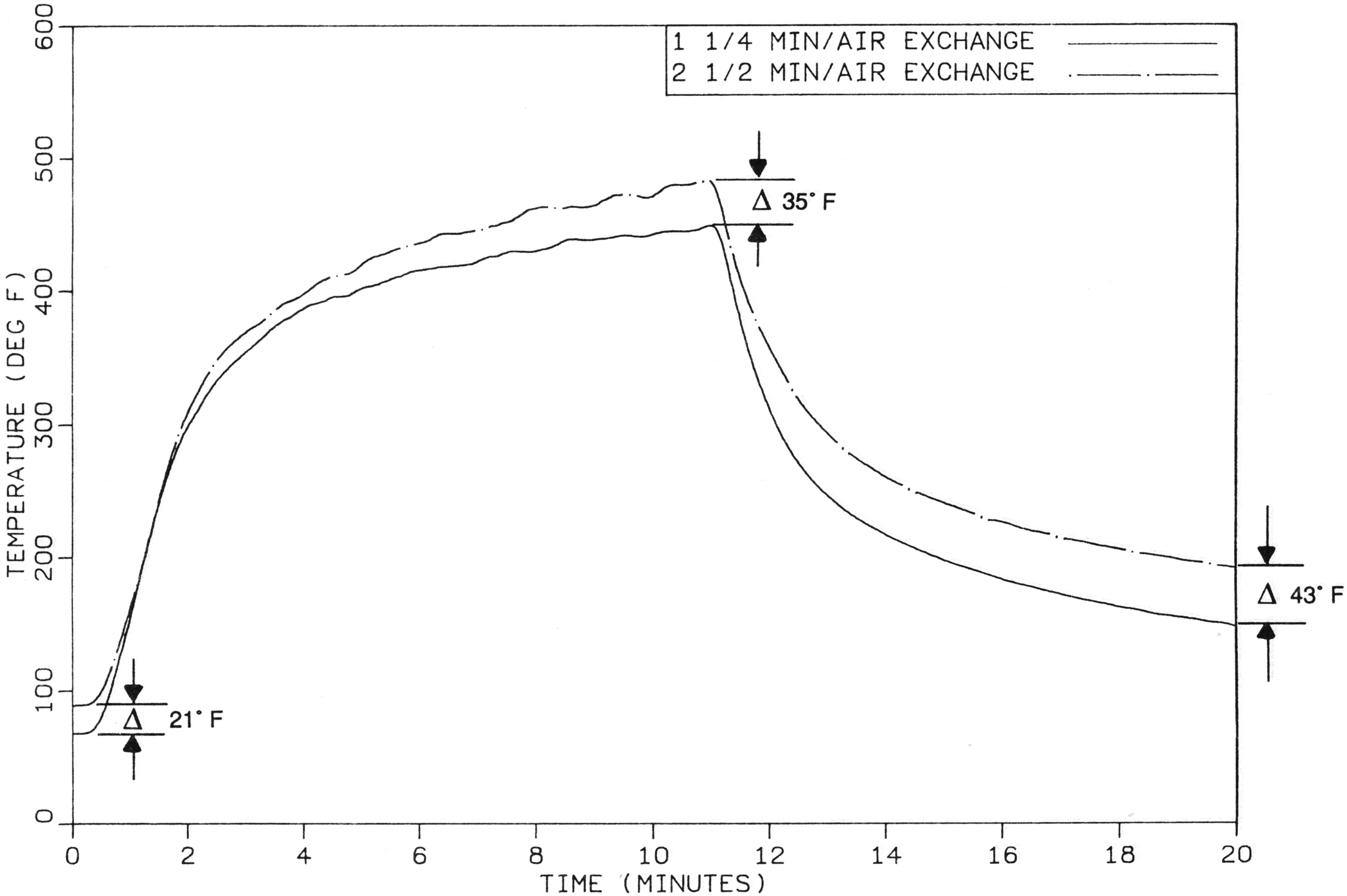

FIGURE 13. TEMPERATURE PROFILES AT 1 1/4 & 2 1/2 MIN/AIR EXCHANGE (DIFFERENT AMBIENT TEMPERATURES)

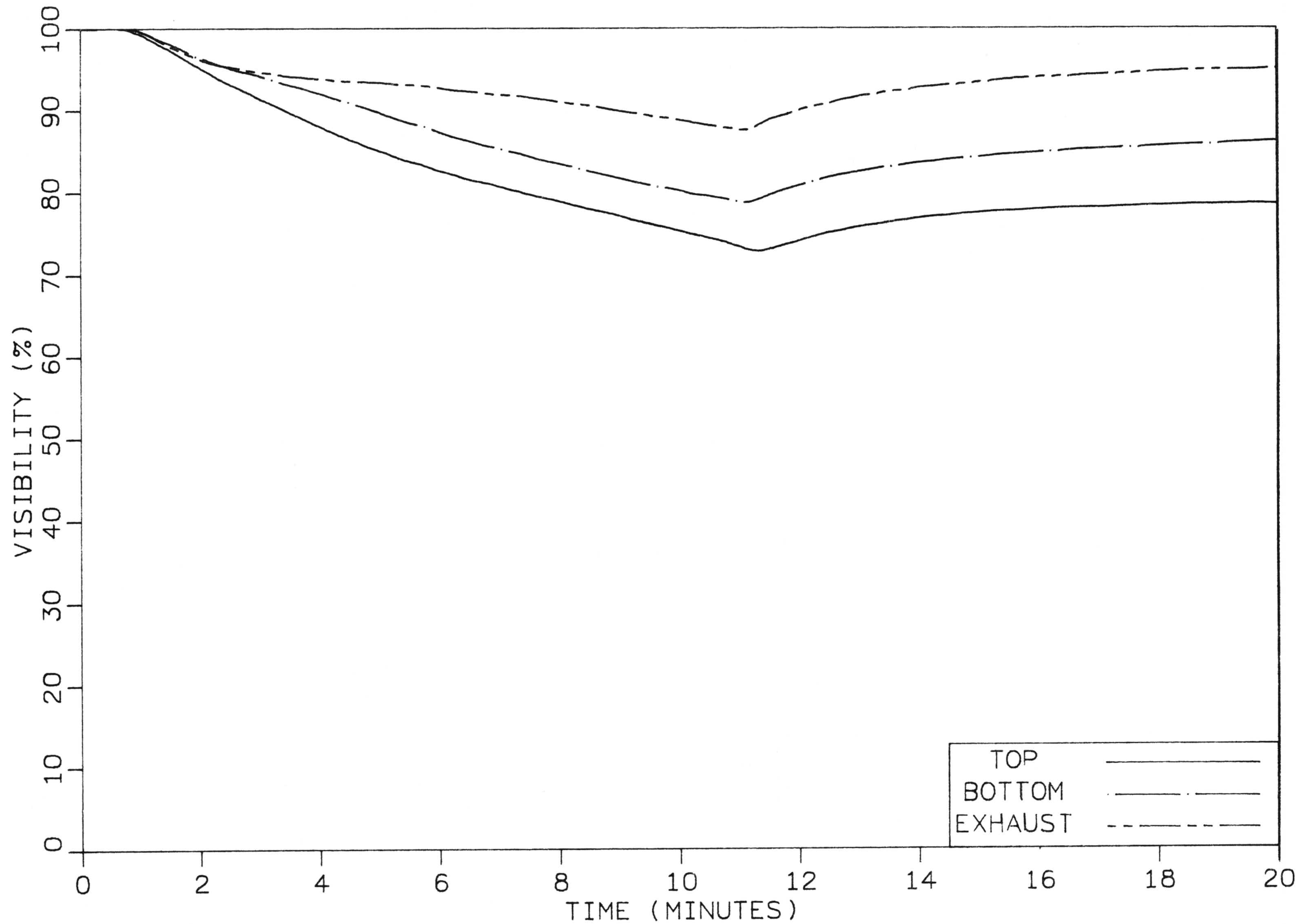

FIGURE 14. TYPICAL SMOKE PROFILES FOR 1 1/4 MIN/AIR EXCHANGE

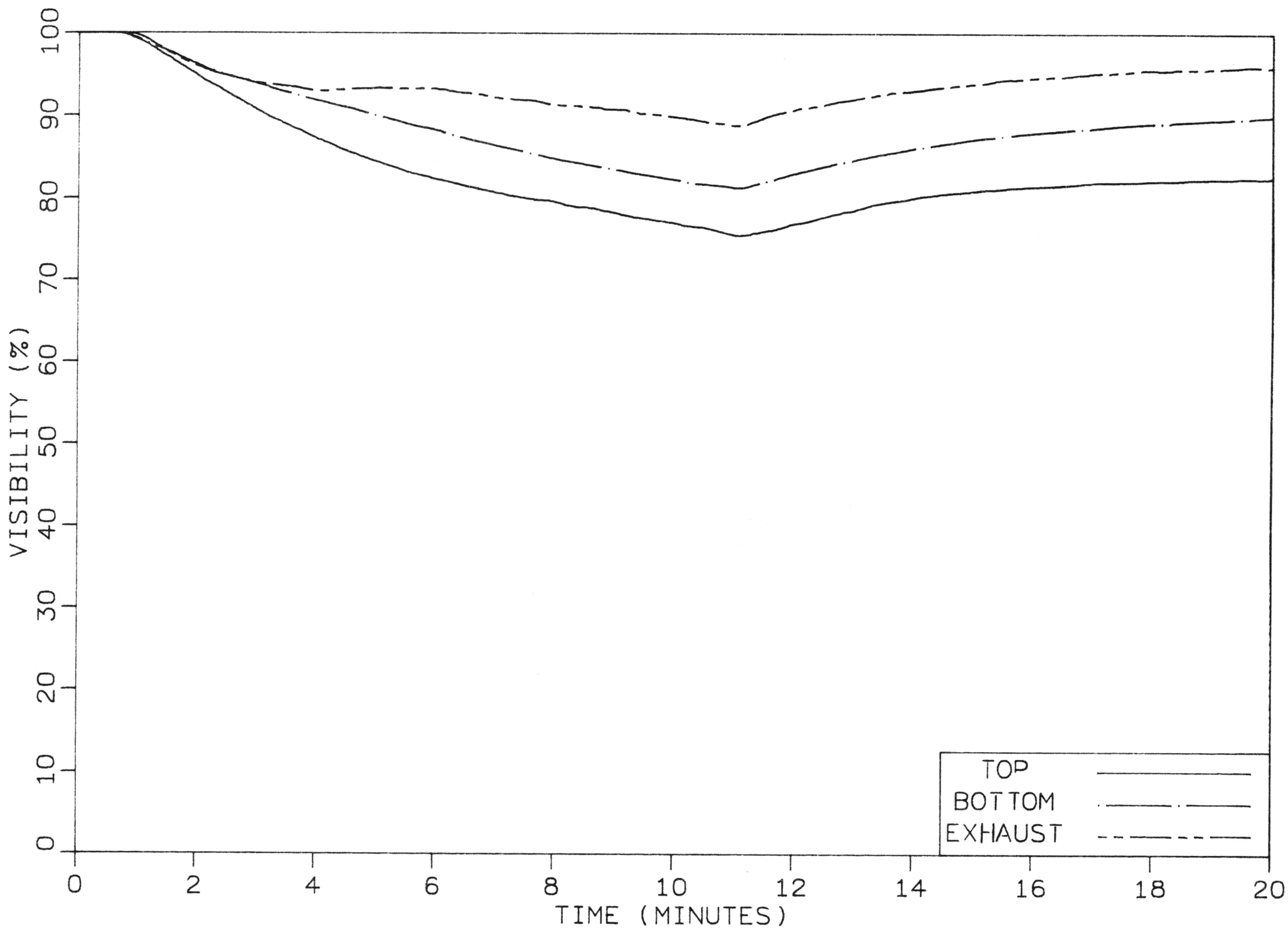

FIGURE 15. TYPICAL SMOKE PROFILES FOR 1 7/16 MIN/AIR EXCHANGE

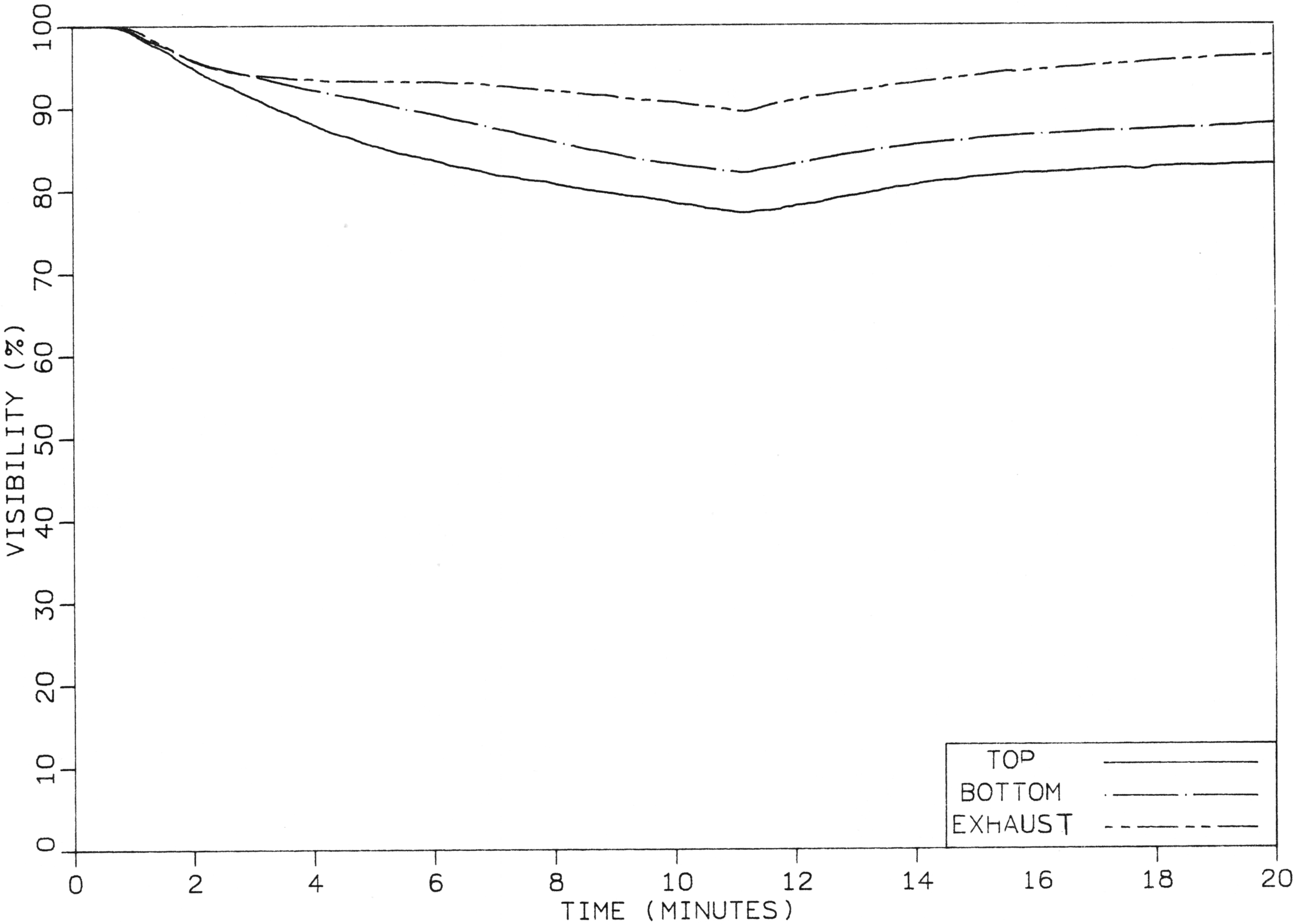

FIGURE 16. TYPICAL SMOKE PROFILES FOR 1 5/8 MIN/AIR EXCHANGE

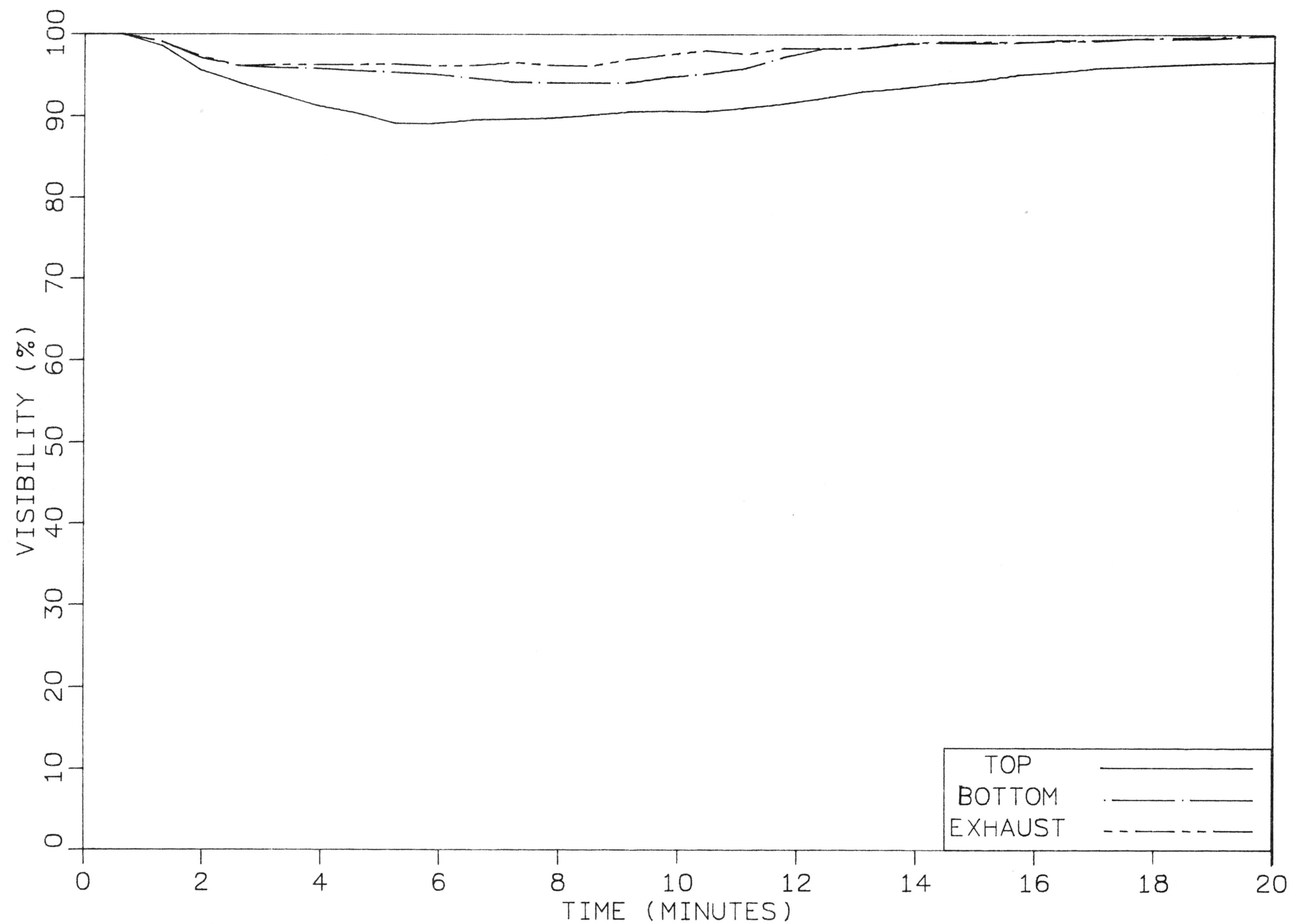

FIGURE 17. TYPICAL SMOKE PROFIES FOR 2 1/2 MIN/AIR EXCHANGE

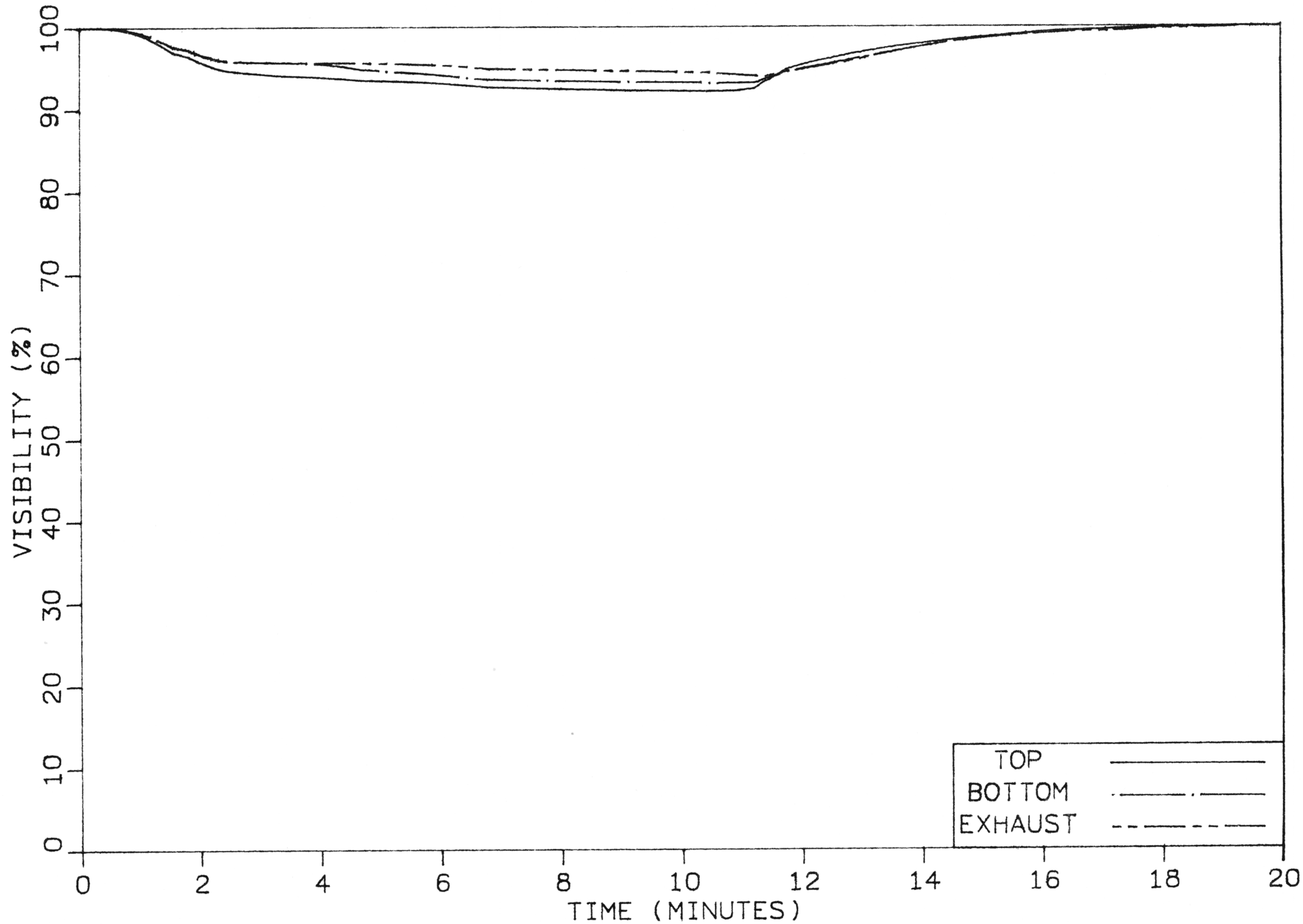

FIGURE 18. TYPICAL SOOT CORRECTED SMOKE PROFILES FOR 1 1/4 MIN/AIR EXCHANGE

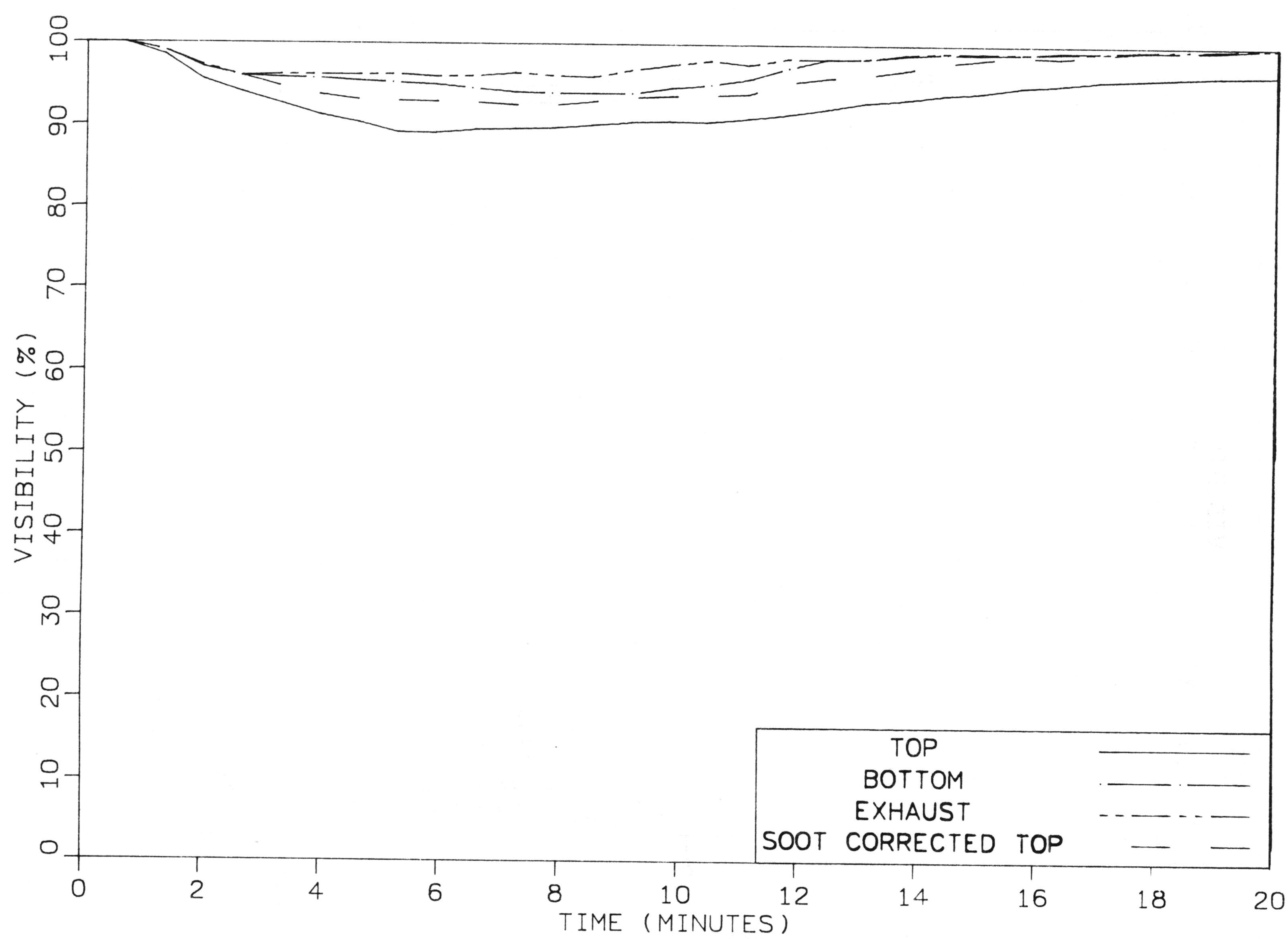

FIGURE 19. TYPICAL SMOKE PROFILE FOR 2 1/2 MIN/AIR EXCHANGE INCLUDING SOOT CORRECTRION

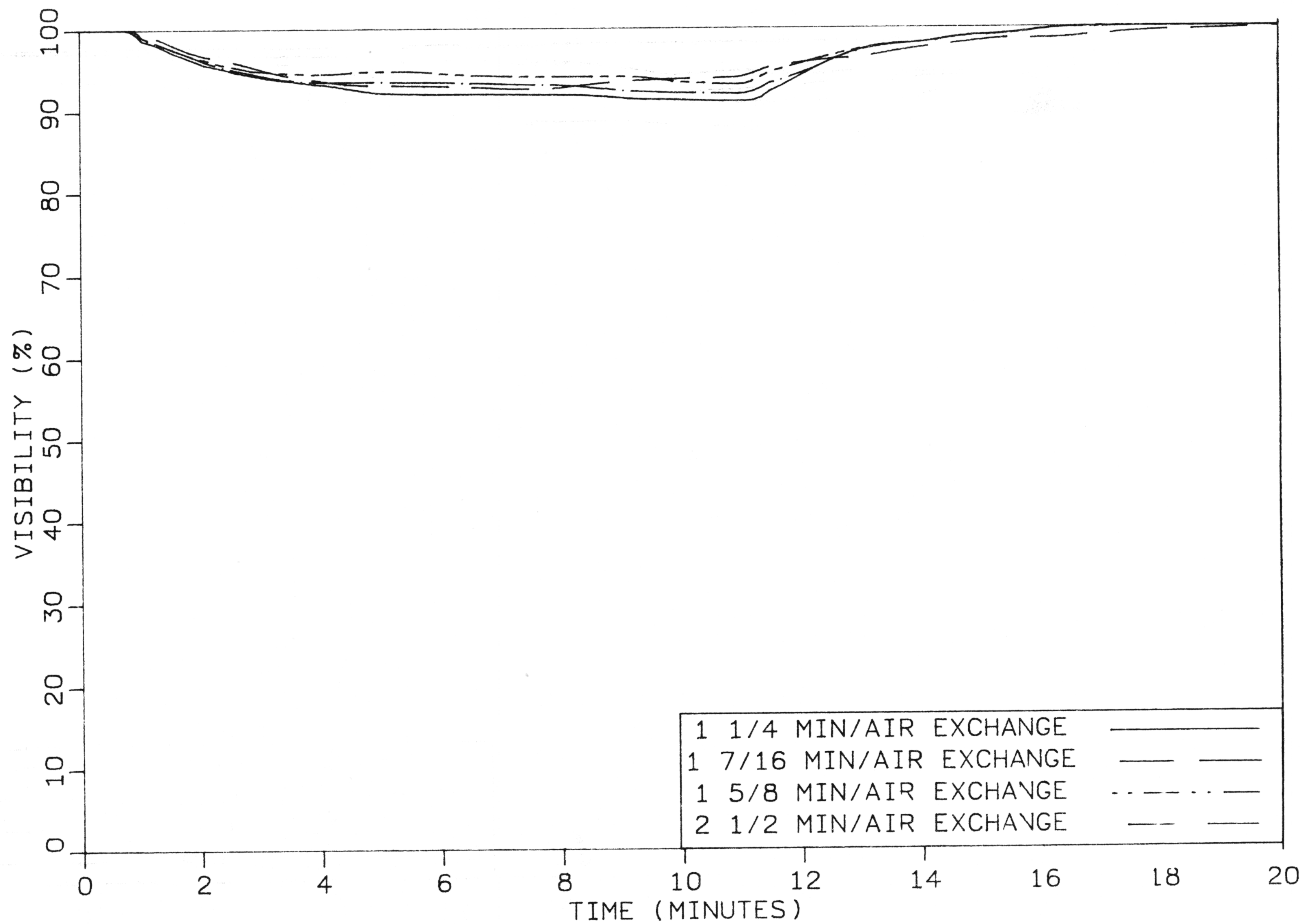

FIGURE 20. TYPICAL SMOKE PROFILES FOR TOP SMOKE METER FOR 1 1/4, 1 7/16, 1 5/8, 2 1/2 MIN/AIR EXCHANGE

☆U.S. GOVERNMENT PRINTING OFFICE: 1993 - 704-078/80054

Correction to TR 82-8

Page 6 Ex. 9 should read

$$\xi = \left[\frac{T_\infty^{2/5} (c_p \rho_\infty)^{1/5}}{g^{2/5}} \right] \frac{u_o}{(\Delta T_o Q_c)^{1/5}} .$$

Page 9 Ex. 18 should read

$$\dot{m} = 0.0054\ Q_c z / (0.166\ Q_c^{2/5} + z_o) \qquad (z < z_\ell) .$$

NOMENCLATURE

$b_{\Delta T}$	plume radius to point where temperature rise is $\frac{1}{2}\,\Delta T_o$ (m)
b_u	plume radius to point where velocity is $\frac{1}{2}\,u_o$ (m)
C_i	mean volumetric concentration (volume fraction) of gas species i (m^3/m^3)
c_p	specific heat of air (kJ/kg•K)
D	diameter of fire source, or effective diameter such that $\pi D^2/4$ = area of fire source (m)
g	acceleration of gravity (m/s^2)
H_c	heat of combustion (kJ/kg)
I	intermittency (-)
L	mean flame height (m)
M	molecular weight of air (-)
M_i	molecular weight of gas species i (-)
$\dot{m}$	mass flow rate in plume (kg/s)
$\dot{m}_f$	mass burning rate (kg/s)
$\dot{m}_i$	mass generation rate of gas species i (kg/s)
N	nondimensional parameter defined in eq (2) (-)
Q	$\dot{m}H_c$, total heat-release rate (kW)
Q_c	convective heat flux in plume (kW)
R	ratio of temperature rises (-)
r	mass stoichiometric ratio, air to volatiles (kg/kg)
T_o	mean centerline temperature in plume (K)
T_∞	ambient temperature (K)
ΔT	mean temperature rise above ambient (K)
ΔT_o	value of ΔT on plume centerline (K)