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USE OF VENTILATION TO CONTROL SMOKE IN
SHIPBOARD FIREFIGHTING, FY83

Final Report

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ABSTRACT

The control of smoke and heat during shipboard firefighting remains a serious problem. This report describes three (Tasks 1-3) efforts to improve this control capability.

In Task 1, we investigated the role of ventilation in manual fire suppression of engine-room fires. A series of model engine-room fire tests (encompassing various ventilation-fuel combinations) was conducted at the Camp Parks, California, test facilities. The objective of these tests was to verify the optimum ventilation conditions for smoke control and smoke removal in engine rooms. The test results support the conclusions of a previous analytical study that recommended operation of the exhaust system to remove smoke and heat in all but the largest Class-B fires.

In Task 2, a test plan was developed to demonstrate smoke control and removal for the Collective Protective System (CPS). A survey of the CPS on the LHA-3 revealed three classes of fire threats pertinent to the zones included in the system. A test plan based on fires simulated with air fans and tracer-gases was developed to measure the effectiveness of the available ventilation options for controlling and removing smoke. This plan is enclosed as Appendix A.

Task 3 concerned laundry space fire tests aboard the Coast Guard fire test ship, the Albert E. Watts. Under this task, we provided planning assistance to NSRDC Annapolis and their contractor, Engineering Computer Optecnomics, Inc., in formulating a series of smoke control and removal tests. Our efforts included recommendations for instrumentation and predictions of fire behavior for various fuel-ventilation combinations.

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1.0 INTRODUCTION

In shipboard fire fighting, smoke is frequently a serious problem. The history of fires in Navy ships is replete with accounts of fire-fighters held at bay by heat and smoke. In the confined shipboard environment, fires that should be extinguished in minutes often persist for hours because of inaccessibility due to smoke. Unfortunately, little has been done to alleviate this problem and past efforts to modify the ship's ventilation system for improved smoke control have been slow to gain acceptance.[1]

However, two recent events have drawn attention to the smoke control problem and offer a potential for some progress. First, a review has been made of fire fighting doctrine for engine rooms and of the use of exhaust fans in certain fire situations.[2] Second, the inauguration of a collective protective system (CPS) on the LHA-3 has raised questions about the consequences of fires within the CPS zone on the system and, conversely, the contribution the CPS might make to smoke control. As a direct consequence of these two events, the following tasks were undertaken by SRI under Contract N00014-83-C-2299, to address the smoke control problems:

Task 1. Model engine room fires to answer questions raised and verify the conclusions reached during the 1982 study of the role of engine room ventilation systems in manual fire fighting.

Task 2. Develop a preliminary test plan and procedure to demonstrate smoke control and removal for the collective protection system demonstration model on the LHA-3.

Task 3. Participate in the smoke control tests at the U.S. Coast Guard Fire and Safety Test Facility in Mobile, Alabama.

Although united under the common theme of smoke control, the tasks are significantly different from each other and are treated as separate efforts. Task 1 was an experimental program at the Camp Parks Test Facility, where typical engine room ventilation patterns were examined for their effectiveness in smoke control. Task 2 included a study of the

CPS design and a survey aboard the LHA-3 to determine the potential fire threat, the smoke control options, and nondestructive methods for evaluating the CPS performance under the various combinations of fire threat and smoke control options. Task 3 entailed minimal participation involving planning assistance and recommendations for tests performed by NSRDC Annapolis in conjunction with the DDG-51 ventilation system design and the potentials for smoke control.

2.0 TASK 1. MODEL ENGINE ROOM FIRES IN THE CAMP PARKS TEST FACILITY

2.1 Objective

The objective of this task was to determine the effects of ventilation pattern and rate on.

- Reduction in visibility because of smoke
- Temperature and thermal insult in the compartments
- Burning rate
- Production of combustion products
- Time to clear smoke after fire is extinguished.

2.2 Approach

The steel compartment at Camp Parks was modified to simulate a two-level engine room where the ventilation parameters could be adjusted to model those observed in the 1982 study.(2) Figure 2.1* shows the experimental arrangement, which includes four air supply openings (T_1, T_2, B_1, B_2) and four exhaust ports (T_3, T_4, B_3, B_4), where the T's and B's symbolize top and bottom levels, respectively. Dampers in the air ducts control the ventilation rate and permit any combination of the eight openings to be used.

*Figure and tables are grouped at the end of this task discussion.

Ventilation rates were based on values reported for the 10 engine rooms (See Reference 2), where the minimum and maximum rates of change were, respectively, 2.75 and 0.8 min. In the 1440 ft^3 Camp Parks engine room model, these rates translate to the low value L = 524 cfm and a high value H = 1800 cfm. In addition, the 12 ft^2 opening in the middle deck can be located in the center, as indicated in Figure 2.1, or moved adjacent to the east bulkhead.

Table 2.1 lists the ventilation pattern, rate, and opening position used in each test. Pattern 1 is the one most commonly observed during the engine room surveys. Air is supplied and exhausted at various locations on both levels. Pattern 2 was unique to the Hewitt DD966 where the exhaust was at the uppermost overhead. In this arrangement the buoyancy of the smoke assists its removal. Patterns 3 and 4, respectively, bypass one level and evoke a flow counter to the buoyancy; consequently, they are expected to be less efficient than the normal patterns. Finally, Patterns 5 and 6 correspond to two degrees of securing the ventilation and isolating the fire compartment.

The other test variable, smoke, was generated either with a smoke candle or a fire. The fire burned on the triangular load cell platform in the center of the bottom deck. The amount of smoke was controlled by varying the size of the candle or fire as follows:

- Superior smoke candles

  --3C, generates 40,000 ft^3 of smoke
  ($ZnCl_2$ with a high moisture content)
  and burns 2-3 min.
  --5D, generates 100,000 ft^3 of smoke and
  burns about 5 min.

- Class A Wood Crib Fires

  --17 lb (12.25 kg) Laughridge and Nichols type*
  --54 lb (24.5 kg)

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*The L&N Crib has a square frame of 2 in. by 2 in. lumber that supports the 1 in. by 2 in. lumber across the center area. This arrangement prevents contact between the 1 in. by 2 in. members and prevents a collapse of the structure until all the thin sticks have been consumed.

- Class B Pool Fires JP4 and JP5

  --2500 cc 10-1/8-in. diameter pool
  --7000 cc 17-in. diameter pool.

Reference 2 defines E_V* as the amount of fuel that could be consumed in reacting with the resident air in a sealed compartment. For the Camp Parks model engine room, E_V is about 13.4 lb for wood and 2940 cc for JP5; consequently, the resident air can consume the smallest pool but the other fires will require ventilation. Table 2.1 lists the smoke generators selected for each test.

Where appropriate, six parameters could be monitored throughout the tests (i.e., smoke concentrations, heat fluxes, air temperatures, gas concentrations, air velocities, and weight losses). Table 2.2 lists the instruments used for monitoring and the location of the sensors as shown by the numbers in Figure 2.1. Twenty-five data channels were recorded on a Hewlett-Packard 3052A data acquisition system at a rate of about 15 scans per min. Four channels were monitored continuously with strip chart recorders to provide guidance during the tests.

Test procedures followed a common pattern except for the variations imposed by the smoke generators. Sensors were calibrated at the start of each day's run by the methods listed in Table 2.2. Ventilation conditions were set before smoke initiation and remained unchanged during the tests. Dampers were adjusted to provide the desired supply and exhaust conditions as measured at the duct opening with a hand-held propeller type anemometer. The 27-lb wood cribs were ignited by burning ethanol in a tray under the crib. When 54 lb of wood were used, two 27-lb cribs were placed side-by-side and the fire was allowed to spread from the ignited crib to its neighbor. A small Kaowool® wick at the end

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*E_V = $37V/E\Delta H$ is the amount of fuel that would be consumed in burning the resident air in the compartment where

V = compartment volume (m)

E = combustion efficiency, and

ΔH = heat of combustion (kw min kg^{-1})

of the Class B fuel pan assisted in the ignition of JP5. Smoke candles and Class B fuels burned completely; however, the wood cribs were extinguished with water after the flames had subsided and glowing combustion predominated. When the water from a fixed overhead spray nozzel hit the hot coals, the steam and turbulence generated was marked by a larger spike on the smoke obscuration curves. Typical tests lasted 10 to 20 min with the smoke candles and about 25 to 50 min with the fires.

2.3 Results

In accordance with the stated objectives, our principle concern is the evidence regarding the effects of ventilation pattern and rate on the smoke and heat associated with engine-room fires. This evidence is in the form of curves that show the peak values reached and the spatial and temporal history of the smoke obscuration and thermal insult. At any time during the test, these indicators are functions of compartment volume, rate of smoke and heat production, and the rate of escape. Because the production patterns were quite different for the candles, cribs, and pools, we have segregated the data according to smoke source.

With candles and pool fires, the termination of smoke production is fairly abrupt and well defined; therefore, the smoke clearance curves should depend only on the volume and the ventilation rate. This is not the situation with the wood crib fires, where the cessation of smoke production is poorly defined. In the simple smoke removal model, the smoke is assumed to be uniformly dispersed throughout the volume, and the incoming fresh air mixes instantaneously with the vitiated air. When smoke production terminates, the reduction in smoke concentration should follow an exponential decay.[3] Under these conditions, the concept of a half-life for contamination removal is useful both for comparison and predictive purposes. As the name implies, the half-life is the time $(T_{1/2\ min})$ required to reduce the smoke concentration to one-half the initial value

$$T_{1/2} = \frac{V}{Q} \ln 2 \qquad (1)$$

where

V = Compartment volume (ft^3)

Q = Ventilation rate (cfm).

These half-life values provide a convenient method of comparing smoke removal performance; therefore, we have tabulated half-life values for the various tests even though the uniform density and instantaneous mixing requirements are not strictly satisfied.

2.3.1 Tests with Smoke Candles

In these tests, only channels 11 through 17 from Table 2.1 were measured (i.e., all flow rates and smoke densities). The fixed path length densitometer, channel 17, reached its maximum reading (density = 2) almost immediately and remained there throughout most of the run duration, providing relatively little information. Furthermore, the $ZnCl_2$ smoke deposit on the windows in the light path caused the zero density base line to shift. The laser densitometers were not affected by these limitations; consequently, the data presented here are from the laser measurements.

Figures 2.2 and 2.3 show smoke obscuration curves for 3- and 5-in. candles, respectively. Both figures illustrate the procedure for obtaining half-life times from a smooth curve drawn along the decaying portion of the plot. These half-lives are tabulated in Table 2.3 along with the peak extinction coefficients and other times that indicate the curve width. Both the figures and the tabulated peak smoke concentrations show a substantial departure from the uniform distribution specified for the exponential decay model. A preponderance of the smoke accumulated in the top level, although the candle burned in the bottom level and the smoke passed through the hole in the deck between top and bottom. The location of this hole apparently influenced the distribution of smoke. For example, with a constant airduct pattern and ventilation rate, the ratio of extinction coefficients (top/bottom) was always larger when the hole was in the middle over the candle than when it was next to the east bulkhead. A comparison of the measured and calculated half-lives shows a variety of agreements, as demonstrated by the ratios listed in Table 2.4. For the low ventilation rate, most of the observed values tabulated in columns 3 and 6 were less than the calculated values, whereas the reverse situation applies to columns 4 and 7. For the high ventilation rate, all of the measured half-lives were larger than the calculated values.

Although the initial smoke concentration is not included in the half-life expression (Equation 1), the time required to reduce the concentration to some acceptable level clearly depends on the starting point. According to the exponential decay model, this time is

$$T = \frac{V}{Q} \ln \frac{N_o}{N} \qquad (2)$$

where

$\frac{N_o}{N}$ = Reduction factor

N_o = Initial smoke concentration

N = Acceptable or desired level.

Figure 2.4 shows the ventilation time as a function of the reduction factor for the two ventilation rates used in the Camp Parks tests. For example, if it is desired to reduce the top extinction coefficient in Figures 2.2 and 2.3 down to 0.5, Figure 2.4 predicts ventilation times of 6 and 7.4 minutes, respectively. The corresponding values measured on the graphs are 5.8 and 9.5 min. Considering the departure from the simplifying assumptions of the model and the turbulent fluctuations of the ventilation system (illustrated by air flow shown in Figure 2.5), the dispersion between the observed and calculated values seems reasonable.

According to Equation (2) the half-life or the time to reach any other smoke reduction ratio is directly proportional to the ventilation rate of change V/Q; consequently, the change from 524 to 1800 cfm should reduce these times by a factor of 3.4. A comparison of tests where only the ventilation rate was changed (i.e., Tests 6 versus 10, and 7 versus 11 in Table 2.3) show an average change of 1.8. Most of the half-lives for the high rate were substantially larger than predicted by the model. Although the smoke concentration does not enter this comparison, it should be noted that the peak concentrations were almost identical in the top compartment.

The ventilation pattern does not enter the model of Equation (1) because of the instantaneous mixing and uniform smoke concentration assumptions. Pattern 3 was selected to accentuate the nonuniformities and a comparison of Tests 10, 12, and 16 in Table 2.3 shows that the half-lives in the top section of the compartment are larger for Pattern 3 than for Patterns 1 and 2. Tests 11, 13, and 17 exhibit the same behavior. However, in the bottom compartment there is no significant difference. Patterns 1 and 2 appear to be about equally effective in removing the smoke. Table 2.3 shows no correlation between the peak smoke concentrations in either the top or bottom compartment with the ventilation pattern. Presumably, the high smoke production rate exceeded all the smoke removal rates sufficiently to preclude the appearance of secondary effects introduced by the ventilation pattern.

2.3.2 Tests with Class A Fires (Wood Cribs)

As previously indicated, the ventilation affects both smoke production and removal in the wood fire tests. In these tests, the fuel loadings and ventilation conditions were selected to cover the range from fuel-controlled fires, where additional air will not increase the burning rate or smoke production, to ventilation-controlled fires, where burning and smoke production are limited by the available air.

Figures 2.6 and 2.7 show the fire portrait for a 27-lb crib burning under the extreme ventilation conditions, respectively, of maximum ventilation rate and a ventilation-secured compartment (both with optimum ventilation pattern). In Test 19 (Figure 2.6) sufficient air was available to burn the fuel in 0.9 min; however, the fuel-controlled fire was still burning at 18 min when water was applied. Curves a, b, and c define the thermal threat by the incident heat fluxes and temperatures in the top and bottom levels of the chamber. Both of these parameters are slightly more severe in the secured compartment (Figure 2.7). Curves d and e show the CO_2 and CO concentrations in the chamber. In the secured compartment, the vitiated atmosphere exhibited peak concentrations of 14.3% and 0.22% for CO_2 and CO, respectively, or 4.5 and 13.5 times the comparable quantities in Test 19. Both the thermal flux and CO_2 production are proportional to the burning rate so the curve shapes would be expected to be quite similar, and they are.

The thermal insult and gas concentration data from the graphs and Table 2.5 support the following observations about the 27-lb crib fires:

(1) With ventilation Pattern 2, the heat fluxes and temperatures were insensitive to the range of air flow rates observed in the engine room survey (i.e., from 0.8 to 2.75 min per air change).

(2) The thermal insult was most severe in the secured compartment or reverse flow tests (i.e., Patterns 2, 4, 5, and 6.

(3) Gas concentrations of CO_2 and CO were more sensitive to the ventilation conditions than the thermal parameters.

(4) As expected, with ventilation, the compartment environment improves more rapidly as the fire dies down than in the secured compartment tests.

In addition, the weight loss data show the effect of oxygen starvation in the secured compartment tests. For example, under the low ventilation rate of Test 26, 79% of the fuel weight was consumed in 21 min compared with only 64% or slightly over 1 E_V in Test 27. The same behavior is exhibited by tests 28 through 31 where the fuel loading was increased to 54 lb. In secured chamber Test 28, 48% of the fuel weight was consumed in 38 min. When the exhaust duct dampers were opened (Test 29), the percentage increased to 90% in 38 min. Increasing the ventilation in the inefficient Pattern 3 of Test 30 caused 93% of the fuel to burn in 23-1/2 min.

These fuel consumption values relate more to the shape of the curves than to the peak values. For example, in Table 2.5 the peak heat flux and temperatures are about the same for all of the 54-lb fuel tests; however, the high values persisted longer when the ventilation was not as restricted, as shown in Figure 2.8. Tests 30 and 31 compared the effects of pushing the air with the supply fan versus pulling the air with the exhaust fan. An intentional leak was provided by blocking the door to form a 1/2-in. crack along the latch side. Table 2.5 shows no significant difference in the thermal environment inside the compartment under these conditions; however, the hot gases and smoke pushed through the crack under supply fan pressure would interfere with neighboring areas.

The curves in Figures 2.6f and 2.7f show the extinction coefficient for the well ventilated and secured tests, respectively. In Figure 2.6f, the general shape follows the burning rate pattern deduced from the heat flux and CO_2 concentration (i.e., curves a and b) until 1080 sec, when water struck the fire and generated a cloud of steam. In contrast, the smoke concentrations in Figure 2.7f are substantially greater, particularly in the top chamber, and persist to extinguishment at 1240 sec and beyond. These wood fires were quite clean-burning, and the flames were clearly visible from the observation window throughout the burns.

Table 2.6 lists the maximum extinction coefficients observed during each test, along with the corresponding half-lives. As in Table 2.3, one half-life was measured starting at the peak. A second half-life was measured for the steam spike. No half lives were measured for the sealed chamber tests because the curves did not decay to half their peak values or show a well-defined decay pattern. The half-lives following the peak are substantially larger than the model values or those observed for the candles. Such behavior is to be expected because the fire is continuing to generate smoke throughout this period. After the steam peak, the extinction coefficient decays in a time consistent with the smoke candle values.

2.3.3 Tests with Class-B Fires

All of the Class-B fires were fuel controlled; therefore, the rates of heat release and combustion product generation were essentially independent of the ventilation conditions. As previously mentioned, the smallest pool could be consumed by the resident air (i.e., $E_V = 0.9$). The high ventilation rate used with the 17-in. diameter pool was more than adequate to supply the combustion requirements of this pool. Consequently, these tests were concerned only with the effects of ventilation on diluting the heat and smoke, which were being generated at a nearly constant rate.

Under these conditions, the concentration of heat or combustion products should increase with time until the losses through dilution equal the rate of production. At one extreme, represented by the secured chamber (i.e., no ventilation), this increase in heat content and products should continue throughout the test until losses at the surface of the chamber balance production. At the other extreme of high ventilation rates, equilibrium concentrations will be reached quickly and the measured parameters should remain nearly constant throughout the tests.

Figures 2.9 through 2.11 show portraits for three tests as the ventilation progresses from secured through low to high rates. Several factors, listed below, complicate the comparison and interpretation of these results.

(1) The burning rates are not quite constant throughout the entire burn. Near the end of the test when the fuel depth is small, heat feedback from the pan increases the rate of evaporation and the measured parameters show an increase just before the fire goes out.

(2) The pool area was increased by a factor of 2.8 for the high ventilation rate to enhance product concentration.

(3) In the secured ventilation fire, some JP5 fuel was mixed with the JP4.

Although, the general features of these tests agree with the expectations outlined above, the differences observed for some parameters are not always significant. For example, the maximum thermal insults of heat flux and temperature for secured and low ventilation rates (Figures 2.9 and 2.10) are comparable, although the distribution between bottom and top follows our expectations. The shapes of the product curves (i.e., combustion gases and smoke) show the curve shapes expected in all three ventilation conditions. In no case are the threats more severe with ventilation conditions than in the secured compartment.

Table 2.7 summarizes the smoke data for the Class-B fires. Again we have listed half-lives for smoke clearance after the fire is out. These half-lives are generally higher than those calculated by Equation (1), but they do cover the same range encountered with the smoke candles listed in Table 2.3. Such behavior is to be expected because both the candles and pools stopped smoke production rather abruptly. Table 2.8 summarizes the thermal environment and gas production associated with each fire. Peak values of thermal flux and temperature are about the same for the secured and ventilated compartments; however, ventilation substantially reduces the duration of the elevated values. The ventilation was most effective in reducing the concentration and duration of CO, CO_2, and oxygen depletion.

2.4 Discussion and Conclusions

As previously noted, firemen ventilate fires to remove some of the heat and smoke and thus improve the fire fighting conditions. The danger to be avoided is that the additional air might increase the fire size and create more of a problem than it alleviates. In an earlier study,[2] we concluded that when the fuel loading was less than about 2 E_V, the additional fire growth introduced by the ventilation would be negligible; therefore, the exhaust fans should be used to remove smoke and heat from the engine room as an aid to the firefighters.

The results for the Class-A and Class-B fires reported here indicate that the environment with ventilation is slightly less severe than that of the secured compartment. Therefore, we conclude that

- The peak values of heat flux and temperature are about the same for the ventilated and secured compartments; however, ventilation markedly reduces the duration of the hostile thermal environment.

- Ventilation is effective in reducing both the concentration of combustion products (i.e., CO, CO_2, and smoke) and the duration of the vitiated air in the compartment.

- Ventilation Patterns 1 and 2 are about equally effective in removing smoke as judged by the distribution of smoke between the top and bottom compartment levels and by the half-life.

A few yardsticks are useful to judge the severity of the fire environment and its impact on firefighters' performance. For the heat flux, the pain threshold for exposed flesh is about 0.4 Btu ft^{-2} sec^{-1}. With the Class-A fires, this threshold was usually approached and frequently exceeded; however, it should be recalled that the radiometers measuring the flux were only 5 feet from the center of the fire. Normally, firefighters would attack the flames from a greater distance and protect their skin with clothing; therefore, these heat fluxes should not pose a problem. An upper limit for air temperature fire fighting is about 300°F (149°C) in dry air. This value is commonly exceeded in the top compartment but not near the bottom deck. When water is applied and steam fills the compartment, the temperature threshold for pain drops to less than 200°F (93°C). Frequently this increase in the heat transfer coefficient forces the firefighters to retreat to a cooler or drier region.

A yardstick for visibility is not as easily defined as the thresholds for thermal insults because what can be seen depends both on the light emitted or reflected from the object and the obscuration caused by the absorbing or scattering smoke between the observer and the object. For example, the smoke candles emitted a great deal of smoke and very little light, and thus were soon completely obscured in the darkened room. Conversely, the fires produced less smoke and a large amount of light; hence, they were readily visible throughout the burn, although optical densities along the line of sight reached 2.5.*

With engine-room fires of 1- or 2-E_V magnitude, the anticipated obscuration should permit ready observation of the flames, but other items in the compartment could become completely obscured.

2.5 References

1. Saavedra, F. H., and R. G. Thome, "Fire Integrity and Smoke Removal Study for the DE1078 Class," Naval Ship Engineering Center Report.

2. Alger, R. S., D. D. Lee, and W. H. Johnson, "Ventilation Controlled Fires: The Role of Dedicated Ventilation Systems in the Control of Heat and Smoke from Shipboard Fires in Engine Spaces and Galleys," SRI International Final Report (February 1983).

3. Standard Submarine Damage Control Manual, Chapter 9, Section 9.2.1, "Method of Determining Contaminant Removal Half-Life."

*Optical density $D = \log_{10} I_o/I = KX$, where I_o = initial intensity, I = observed intensity, K = extinction coefficient, and X = smoke sample thickness.

Table 2.1

TEST CONDITIONS, VENTILATION PARAMETERS AND SMOKE GENERATORS

	Test No	Supply Fan	Exhaust Fan	Duct* Pattern	Hole Location
SMOKE CANDLES					
	1	L	L	2	M
	2	L	L	2	M
	3	L	L	2	E
	4	OFF	L	2	E
	5	L	L	3	E
	6	L	L	2	E
	7	OFF	L	2	E
	8	L	L	2	M
	9	OFF	L	2	M
	10	H	H	2	E
	11	OFF	H	2	E
	12	H	H	1	E
	13	OFF	H	1	E
	14	H	H	1	M
	15	OFF	H	1	M
	16	H	H	3	E
	17	OFF	H	3	E
	18	OFF	H	3	M
WOOD CRIB FIRES					
	19	OFF	H	2	M
	20	OFF	OFF	2	M
	21	OFF	H	2	M
	22	OFF	L	2	M
	23	OFF	L	2	M
	24	OFF	OFF	6	M
	25	OFF	L	4	M
	26	OFF	L	4	E
	27	OFF	OFF	6	E
	28	OFF	OFF	6	E
	29	OFF	OFF	5	E
	30	L	OFF	3	E
	31	OFF	L	3	E
JET FUEL POOL FIRES					
	32	OFF	L	3	E
	33	OFF	OFF	3	E
	34	OFF	OFF	6	E
	35	OFF	L	2	E
	36	OFF	L	2	M
	37	L	L	2	M
	38	L	L	2	M
	39	H	H	2	M
	40	OFF	H	2	M
	41	OFF	H	2	E

Table 2.1 (Concluded)

TEST CONDITIONS, VENTILATION PARAMETERS AND SMOKE GENERATORS
(Footnotes)

Note: L = Low ≈524 cfm
H = High ≈1800 cfm
M = Middle
E = East Bulkhead

*DAMPER POSITION FOR VARIOUS DUCT PATTERNS

Duct Pattern	B1	B2	T1	T2	B3	B4	T3	T4
1	1/2 O†	1/2 O	1/2 O	1/2 O	1/2 O	1/2 O	1/2 O	1/2 O
2	O ‡	O	C	C	C	C	O	O
3	O	O	C	C	O	O	C	C
4	C §	C	O	O	O	O	C	C
5	C	C	C	C	O	O	C	C
6	C	C	C	C	C	C	C	C

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† = 1/2 Open
‡ = Open
§ = Closed

Table 2.2

CHANNEL ASSIGNMENTS, INSTRUMENTATION, AND CALIBRATION PROCEDURES

Channel*	Sensor	Calibration Procedure
2	Load Cell #2	Standard Weights
3	Load Cell #3	Standard Weights
4	Load cell #4	Standard Weights
5	CO, IR Absorption Cell	Standard Gas Mixture 5.92% CO_2, 10.15% O_2, 1.10% CO
6	CO_2, IR Absorption Cell	Standard Gas Mixture 5.92% CO_2, 10.15% O_2, 1.10% CO
7	O_2 Conductivity Cell	Standard Gas Mixture 5.92% CO_2, 10.25% O_2, 1.10% CO
8	Hydrocarbon Catalytic Burner	Not used
9	Radiometer Cardon Type	Comparison to New Radiometer
10	Radiometer Cardon Type	Comparison to New Radiometer
11	Standard Voltage Battery	
12	Propeller Anemometer	Comparison to New Anemometer
13	Orifice Type Anemometer	Comparison to New Anemometer
14	Orifice Type Anemometer	Comparison to New Anemometer
15	Laser Type Densitometer	Neutral Density Filters
16	Laser Type Densitometer	Neutral Density Filters
17	Ameco Type Densitometer	Neutral Density Filters
18	Blank	--
19	Blank	--
20	Chromel-Alumel Thermocouple	Used Mv to °C conversion program and Hg thermometer
21	Chromel-Alumel Thermocouple	Used Mv to °C conversion program and Hg thermometer
22	Chromel-Alumel Thermocouple	Used Mv to °C conversion program and Hg thermometer
23	Chromel-Alume Thermocouple	Used Mv to °C conversion program and Hg thermometer
24	Chromel-Alumel Thermocouple	Used Mv to °C conversion program and Hg thermometer

*Channel numbers are the same as location numbers in Figure 2.1

Table 2.3

MAXIMUM EXTINCTION COEFFICIENTS AND HALF-LIVES FOR SMOKE REMOVAL FOR FIRES SIMULATED WITH SMOKE CANDLES

		TOP				BOTTOM			
Test No.	Vent Schedule	Peak* K (m)	Time to Peak (sec)	First Half-Life (sec)	2nd Half-Life (sec)	Peak* K (m)	Time to Peak (sec)	First Half-Life (sec)	2nd Half-Life (sec)
3-INCH CANDLE									
2	LL2M	8.3	83	97	71	0.2			
3	LL2E	6.3	58	142	146	1.3	64	103	97
4	Off L2E	4.6	142	103	126	0.7	256	126	124
5	LL2E	6.5	150	80	150	1.1	150	85	110
5-INCH CANDLE									
6	LL2E	10.5	226	64	128	2.8	144	30	77
7	Off L2E	7.5	185	117	143	4.8	90	50	130
8	LL2M	10.2	90	62	58	0.7	65	111	139
9	Off L2M	6.9	227	148	114	1.7	278	110	136
10	HH2E	10.7	140	74	67	2.3	166	59	59
11	Off H2E	7.5	135	45	38	3.5	21	44	58
12	HH1E	8.5	123	54	53	4.5	82	32	64
13	HH1E	4.0	210	61	61	0.9	220	61	58
14	HH1M	10.0	200	74	46	2.8	220	80	63
15	Off H1M	8.2	118	62	57	0.9	124	71	128
16	HH3E	10.5	155	112	118	5.0	98	39	70
17	Off H3E	8.5	224	155	130	4.0	251	47	73
3-INCH CANDLE									
18	Off H3M	7.5	174	114	119	1.5	195	83	95

*K = Extinction Coefficient.

Table 2.4

COMPARISON OF HALF-LIVES CALCULATED FROM EXPONENTIAL DECAY MODEL WITH THE MEASURED VALUES

Test No.	Vent Schedule	TOP* $\frac{E\ 1/2\ 1st}{T\ 1/2}$	TOP* $\frac{E\ 1/2\ 2nd}{T\ 1/2}$	TOP* $\frac{E\ 1/2\ 1st}{E\ 1/2\ 2\ nd}$	BOTTOM* $\frac{E\ 1/2\ 1st}{T\ 1/2}$	BOTTOM* $\frac{E\ 1/2\ 2nd}{T\ 1/2}$	BOTTOM* $\frac{E\ 1/2\ 1st}{E\ 1/2\ 2nd}$
3-INCH CANDLE							
2	LL2M	0.85	0.62	1.37	--	--	--
3	LL2E	1.25	1.28	0.97	0.90	0.85	1.06
4	Off L2E	0.90	1.11	0.82	1.11	1.08	1.02
5	LL2E	0.70	1.32	0.53	0.75	0.96	0.77
5-INCH CANDLE							
6	LL2E	0.56	1.12	0.50	0.26	0.68	0.39
7	Off L2E	1.03	1.25	0.82	0.44	1.14	0.38
8	LL2M	0.54	0.51	1.07	0.97	1.22	0.80
9	Off L2M	1.30	1.0	1.30	0.96	1.19	0.81
10	HH2E	2.23	2.02	1.10	1.78	1.78	1.0
11	Off H2E	1.36	1.14	1.18	1.33	1.75	0.76
12	HH1E	1.63	1.60	1.02	0.96	1.93	0.50
13	Off H1E	1.64	1.84	1.00	1.84	1.75	1.05
14	HH1M	2.22	1.38	1.61	2.41	1.90	1.27
15	Off H1M	1.87	1.72	1.09	2.14	3.86	0.55
16	HH3E	3.37	3.55	0.95	1.17	2.11	0.56
17	Off H3E	4.67	3.92	1.19	1.42	2.20	0.64
3-INCH CANDLE							
18	Off H3M	3.43	3.58	0.96	2.50	2.86	0.87

* $\frac{E\ 1/2}{T\ 1/2} = \frac{\text{Experimental Half-life}}{\text{Half-life From Model}}$

T 1/2 for L = 114.3 sec.
T 1/2 for H = 33.2 sec.

Table 2.5

THERMAL INSULTS AND COMBUSTION PRODUCTS
GENERATED BY WOOD CRIB FIRES

Test No.	Heat Flux: Peaks ($btu\ ft^{-2}\ sec^{-1}$) Top	Bottom	Heat Flux: 1/2-Width (sec) Top	Bottom	Temperatures: Peak Values (°C) Top	Bottom	Deck	Exhaust	Temperatures: 1/2 Width (sec) Top	Bottom
27# WOOD CRIBS										
19	0.36	0.37	500	600	156	85	45	165	915	910
20	0.56	0.42	670	985	192	124	35	190	>1095*	>1040
21	0.38	0.39	590	830	167	92	50	171	>1000*	> 920
22	0.38	0.35	710	> 940*	160	98	40	160	> 990*	> 920
23	0.39	0.35	710	870	166	100	45	162	>1170*	>1090
24	0.60	0.37	900	>1130*	189	125	38	67 out 78 in	>1170*	>1110
25	0.50	0.42	710	1050	188	132	44	148	>1230*	>1200
26	0.41	0.48	470	750	150	151	44	155	>1160*	>1140
27	0.53	0.51	900	1178*	155	155	41	74 out 64 in	>1260*	>1140
54# WOOD CRIBS										
28	0.53	0.59	1080	1200	161	170	46	118 out 70 in	>2150*	>2100
29	0.55	0.56	2220*	>2330*	220	180	61	160 out 100 in	>2360*	>2280
30	0.57	0.68	960	1240	196	196	135	210	>1340*	>1300
31	0.55	0.62	1320†	1320†	218	201	76	195	>1410	>1340

Table 2.5

THERMAL INSULTS AND COMBUSTION PRODUCTS
GENERATED BY WOOD CRIB FIRES (Concluded)

Test No.	Vent	Schedule	Peak Gas Concentration, Percent: First CO	Second CO	CO_2	1/2-Width CO_2	H_2 On (sec)
27# WOOD CRIBS							
19	Off H	2M	0.025	0.062	3.2	620	1080
20	OffOff	2M	--	--	8	*	1140
21	Off H	2M	0.06	0.145	4.75	715	1060
22	Off L	2M	0.059	0.15	~7	710	1060
23	Off L	2M	0.13	0.55	6.7	755	1160
24	Off Off	6M	1.36	2.7	14.5	1270	1230
25	Off L	4M	0.26	0.52	6.8	760	1315
26	Off L	4E	0.152	0.21	8.2	605	1260
27	Off Off	6E	0.215	0.84	14.3	1240	1240
54# WOOD CRIBS							
28	Off Off	6E	0.275	0.48	8	1960	2270
29	Off Off	5E	0.245	0.29	7.3/7.8	2280	2400
30	L Off	3E	0.057	0.106	6.4	850	1420
31	Off L	3E	0.15	-	6.3	1320	1500

*Did not drop below 1/2 max.

†Partial trace, may not be max. peak

Table 2.6

MAXIMUM EXTINCTION COEFFICIENTS AND HALF-LIVES FOR SMOKE REMOVAL OBSERVED FROM WOOD CRIB FIRES

Test No.	Vent Schedule	Peak K	Width at 1/2 Max. (sec)	1st Half-Life (sec)	2nd Half-Life (sec)	Peak K	Width at 1/2 Max. (sec)	1st Half-Life (sec)	2nd Half-Life (sec)
27-LB WOOD CRIBS									
19	Off H2M	0.34	675	450	110	0.23	525	345	85
20	Off Off 2M	.32	>840*	*	110	.32	>840*	*	525
21	Off H2M	.35	410	195	57	.11	250	131	65
22	Off L2M	.31	370	148	128	.12	360	148	92
23	Off L2M	.27	385	195	80	.14	690	290	92
24	Off Off 6M	1.86	>84	*	*	.37	>960*	*	320
25	Off L4M	.54	290	145	35	.28	495	325	90
26	Off L4E	.85	300	150	80	.46	600	395	75
27	Off Off 6E	1.4	>900*	*	*	.62	>900*	*	380
54-LB WOOD CRIBS									
28	Off Off 6E	1.0	†	*	*	.84	620†	470†	*
29	Off Off 5E	.78	1020	850	140	.28	495	360	490
30	L Off 3E	.29	‡	‡	Δ	.23	‡	‡	Δ
31	Off L3E	>.35	§	345	140	>.5	§	260	65

* Only slight decay before H_2O turned on cannot measure either the width at 1/2 maximum or the half-life.

† Secured compartments do not have smoke removed by ventilation. However, smoke does decrease as fire dies.

‡ Flat smoke curve  H_2O on

Δ Did not follow curve to 1/2 maximum.

§ Missed start on burn.

Table 2.7

MAXIMUM EXTINCTION COEFFICIENTS AND HALF-LIVES FOR SMOKE REMOVAL OBSERVED FOR JET FUEL POOL FIRES

Test No.	Vent Schedule	Peak K*	1st Half-Life (sec)	2nd Half-Life (sec)	Total Burn Time (sec)	Peak K*	1st Half-Life (sec)	2nd Half-Life (sec)	Total Burn Time (sec)	JP
10 1/8-INCH DIA. POOL										
32	Off L3E	1.3	145	150	1440	0.49	155	130	1290	5
33	Off Off 3E	2.7	440	330	1740	1.2	360	230	1740	5
34	Off Off 6E	2.5	660	†	1980	1.0	460	†	1930	4/5
35	Off L2E	1.5	140	110	1210	.7	80	70	1180	4
36	Off L2M	1.6	137	120	1130	.7	100	60	1040	4
37	LL2M	1.5	110	95	1060	.65	105	90	900	4
38	LL2M	1.4	94	95	1080	.65	70	70	970	4
17-INCH DIA. POOL										
39	HH2M	2.4	65	48	840	1.3	70	†	780	4
40	Off H2M	2.3	115	80	1300	1.1	75	60	1300	5
41	Off H2E	2.4	70	52	1320	.9	45	35	1320	5

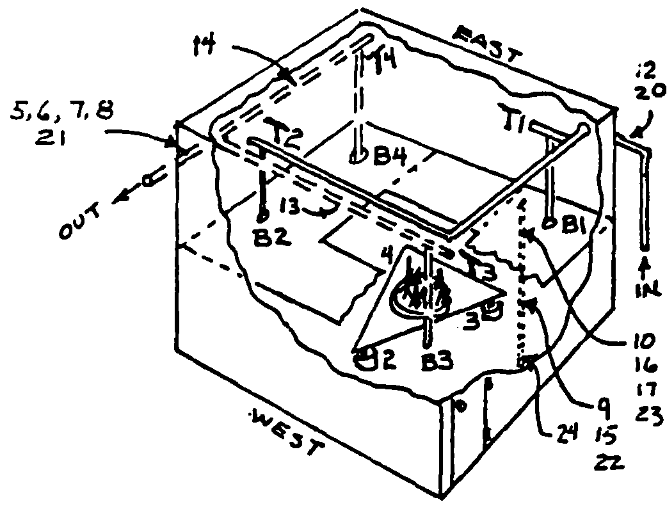
* K = Extinction Coefficient.
† Did not decay this far.

Table 2.8

THERMAL INSULTS AND COMBUSTIONS PRODUCTS
BY JET FUEL POOL FIRES

Test No.	Heat Flux: Peaks Btu Ft^2 Sec^{-1} Top	Bottom	Heat Flux: Width at Half Maximum (sec) Top	Bottom	Temperatures: Peak Values °C Top	Bottom	Deck	Exhaust	Width at Half Maximum (sec) Top	Bottom
10 1/8-INCH DIA. POOL										
32	0.082	0.127	1410	1440	66	62	39	69	1500	1390
33	0.113	0.162	1380	1620	88	88	40	78	1650	1680
34	0.110	0.177	1500	1860	82	86			2160	2080
35	0.103	0.192	900	1020	95	85	48	89	1210	1090
36	0.461	0.175	840	900	100	84	50	100	1220	1020
37	0.142	0.185	870	870	100	72	58	94	1300	1000
38	0.143	0.215	810	940	103	67	48	160	1080	960
17-INCH DIA. POOL										
39	0.410	0.653	660	720	206	175	112	220	840	780
40	0.223	0.358	1250	1340	185	168	79	191	1470	1320
41	0.137	0.361	1280	1350	195	195	107	184	1410	1320

Test No.	Vent Schedule	Peaks: CO (%)	CO_2 (%)	O_2 (%)	Width at Half Maximum: CO (sec)	CO_2 (sec)	O_2 (sec)
10 1/8-INCH DIA. POOL							
32	Off L 3E	0.02	0.9	1.32	1370	1340	1345
33	Off Off 3E	0.057	0.192	3.5	1640	1620	1005
34	Off Off 6E						
35	Off L2E	0.044	0.132	1.75	1020	1080	1050
36	Off L2M	0.042	1.33	2.15	960	970	1005
37	LL 2M	0.035	0.85	1.57	910	995	990
38	LL 2M	0.045	1.14	1.48	960	980	960
17-INCH DIA. POOL							
39	HH 2M	0.067	2.2	3.0	600	720	760
40	Off H2M	0.105	0.24	3.7	1290	1280	129
41	Off H2E		2.3			1290	



T1 = Southeast Air Supply, Top
T2 = Northwest Air Supply, Top
B1 = Southeast Air Supply, Bottom
B2 = Northwest Air Supply, Bottom
T3 = Southwest Air Exhaust, Top
T4 = Northeast Air Exhaust, Top
B3 = Southwest Air Exhaust, Bottom
B4 = Northeast Air Exhaust, Bottom
2,3,4 = Water-Cooled Load Cells under Fuel Support Platform
5 = CO Gas Sampling Inlet
6 = CO_2 Gas Sampling Inlet
7 = O_2 Gas Sampling Inlet
8 = Hydrocarbons - not used
9,10 = Radiometers
12 = Propeller Anemometer, Inlet Air
13,14 = Differential Anemometer, Inlet Air
15,16 = Laser Densitometers
17 = Ameco Densitometer
21,22,23,24,25 = Thermocouples

FIGURE 2.1 TEST ARRANGEMENT WITH A MODEL ENGINE ROOM IN THE CAMP PARKS FIRE FACILITY

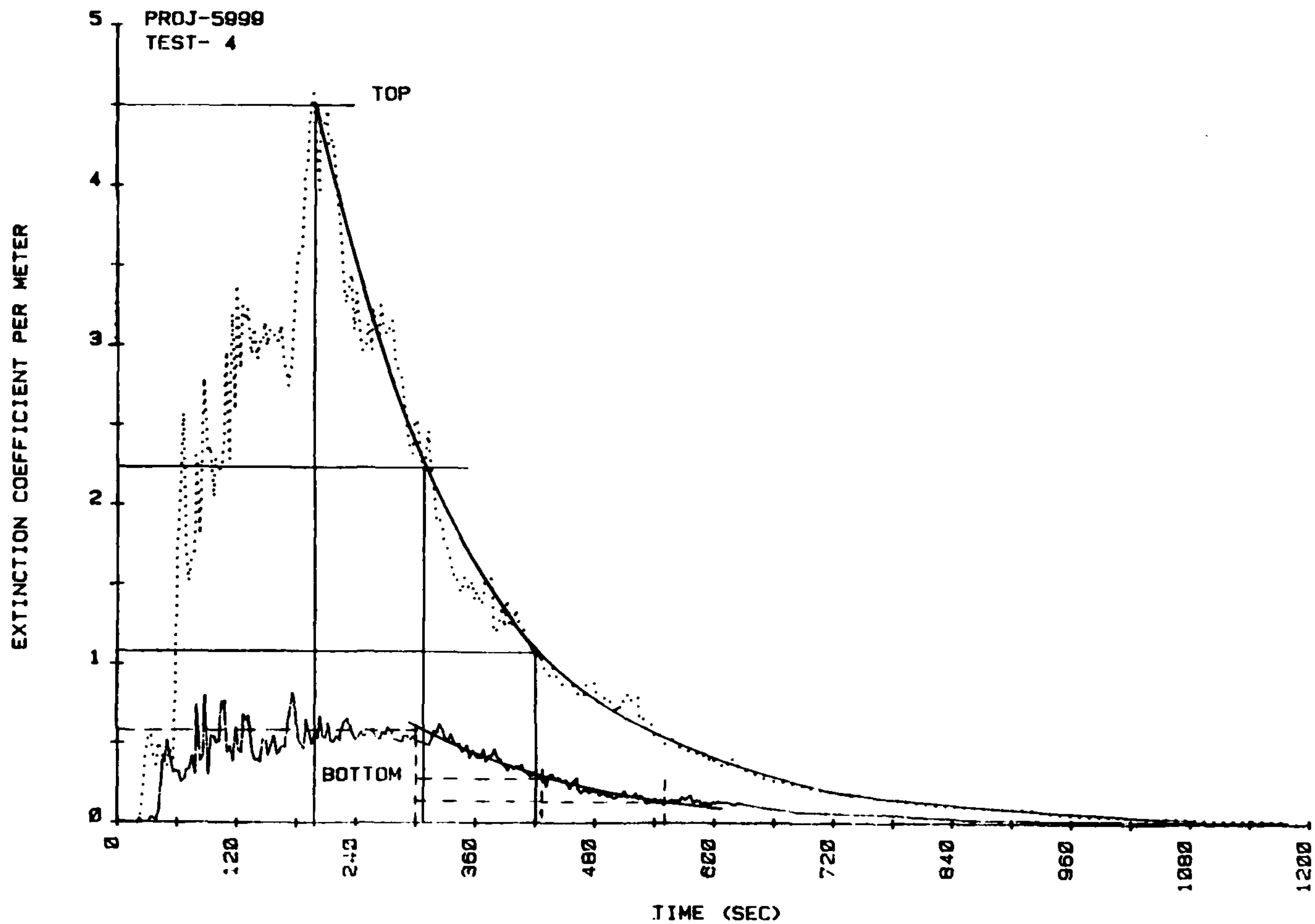


FIGURE 2.2 SMOKE OBSCURATION GENERATED WITH A 3-in. SMOKE CANDLE (Test 4)

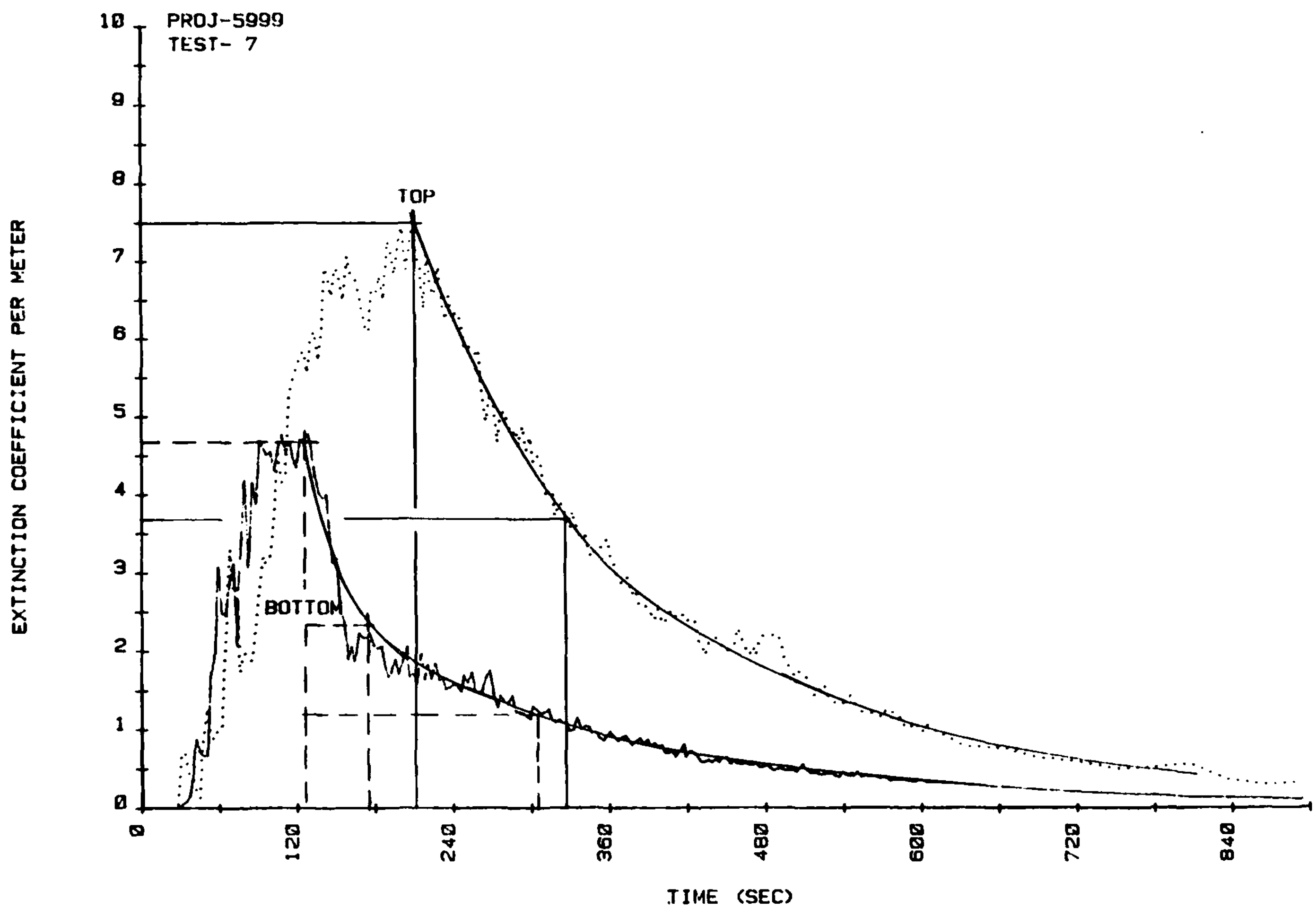


FIGURE 2.3 SMOKE OBSCURATION GENERATED WITH A 5-in. SMOKE CANDLE (Test 7)

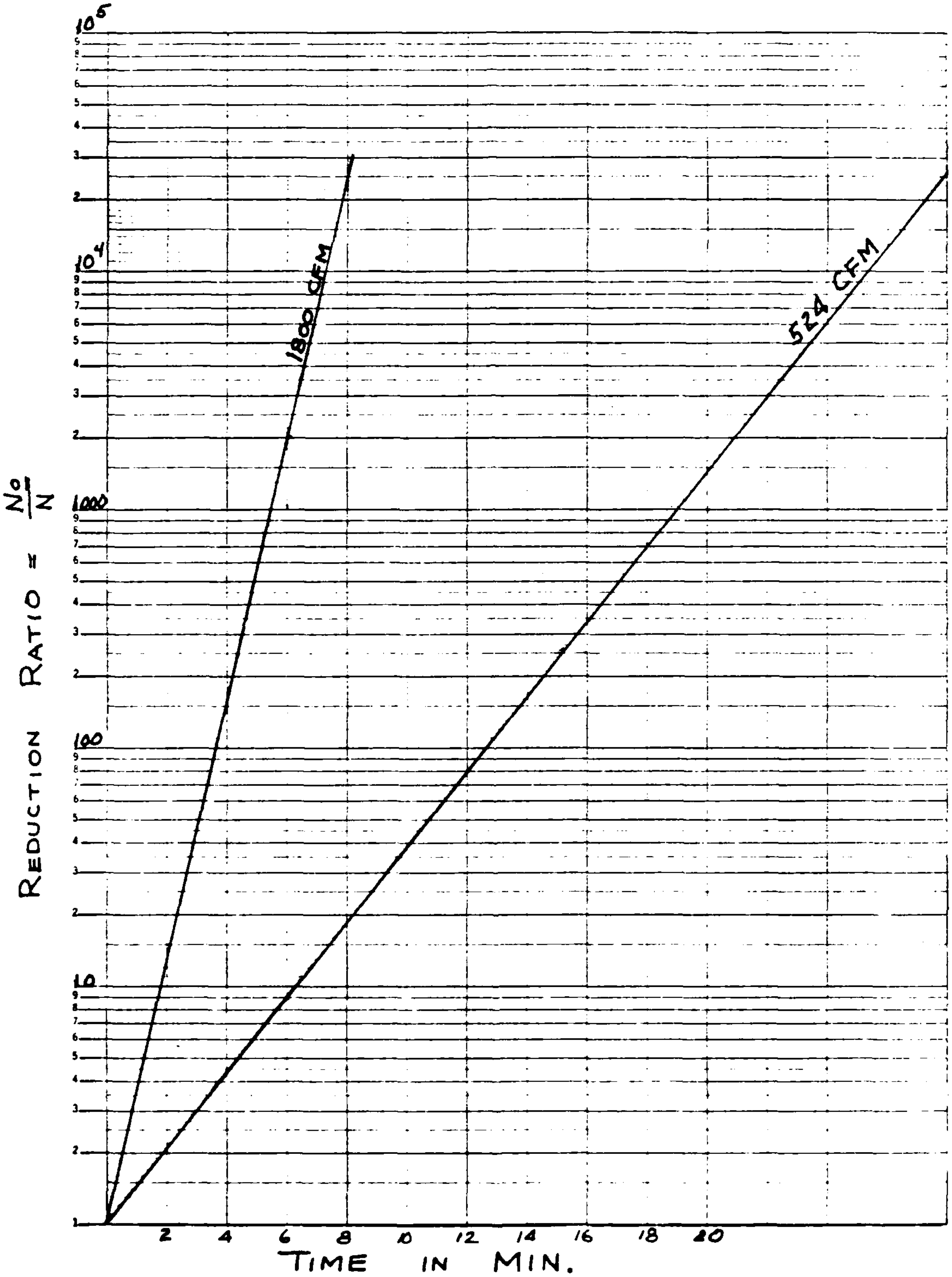


FIGURE 2.4 SMOKE REDUCTION AS A FUCTION OF TIME FOR THE LOW AND HIGH VENTILATION RATES USED IN THE TESTS

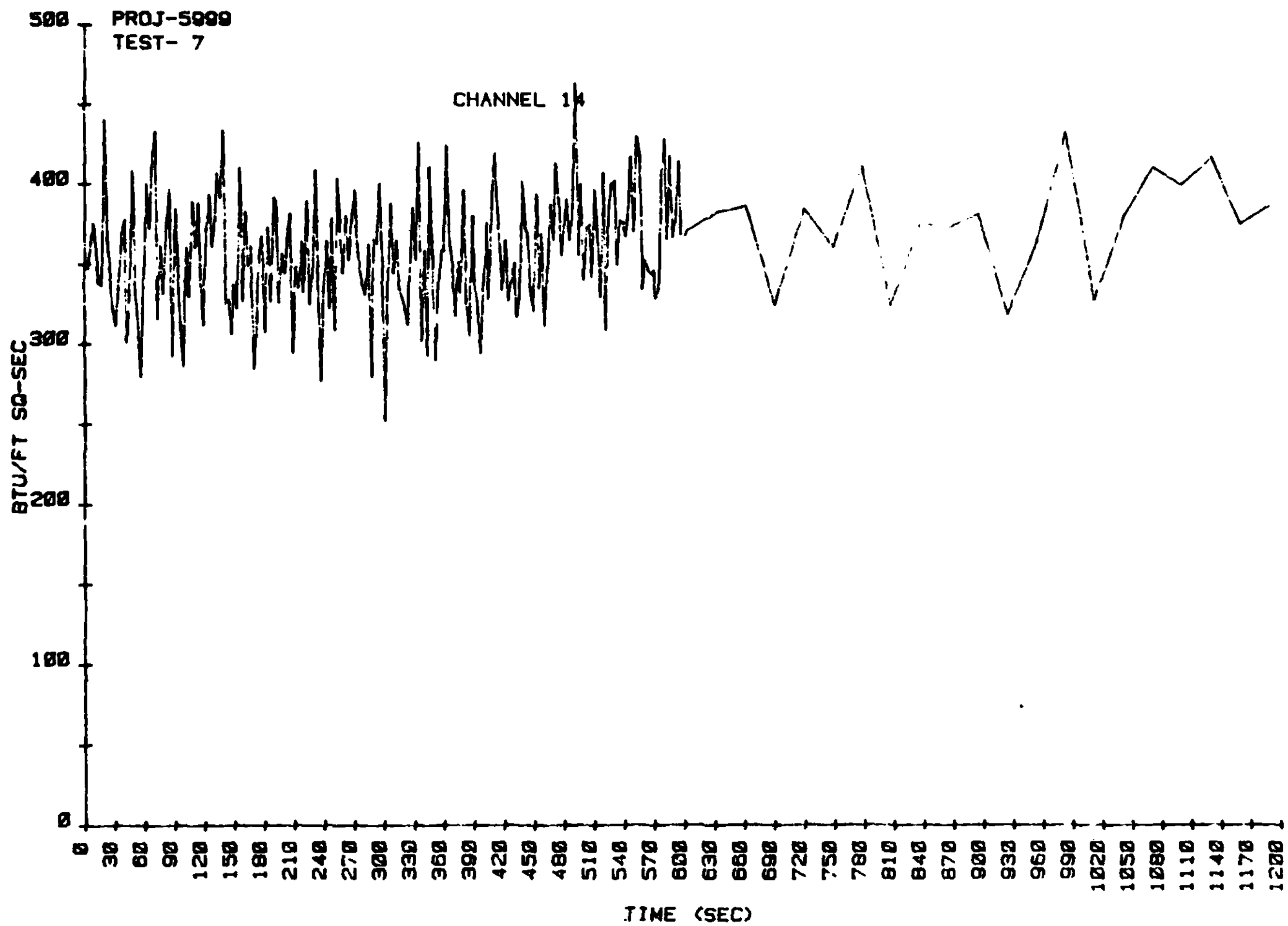


FIGURE 2.5 AIR FLOW FLUCTUATIONS IN THE EXHAUST DUCTS DURING TESTS 7

FIGURE 2.6 PORTRAIT FOR A WOOD CRIB FIRE, HIGH VENTILATION RATE AIR FLOW PATTERN 2 (TEST 19)*

*(a) heat flux, (b) air temperatures in the chamber, (c) supply and exhaust air temperatures, (d) carbon dioxide concentration, (e) carbon monoxide concentration, (f) extinction coefficient.

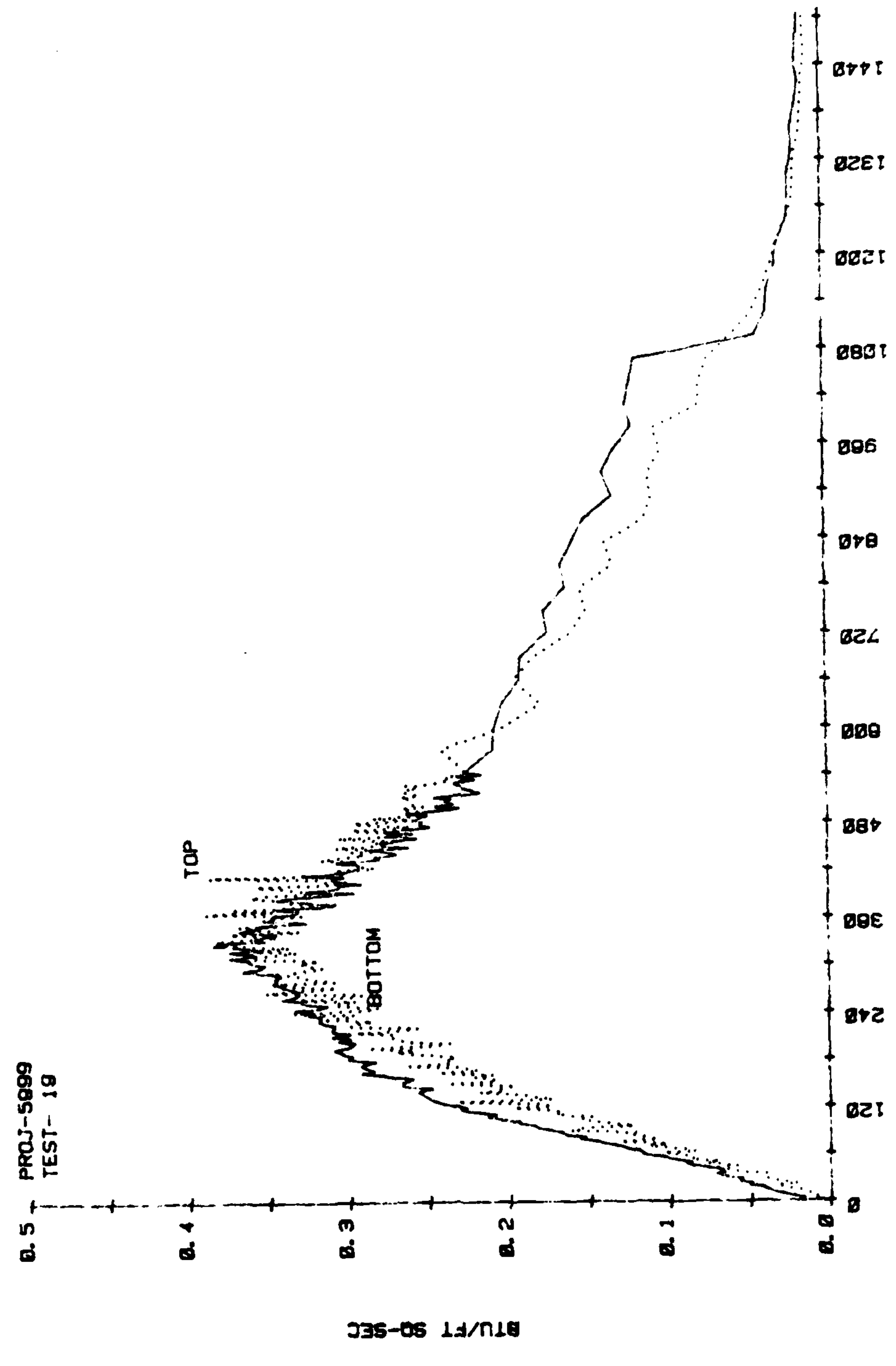

PROJ-5099
TEST- 19
TOP
BOTTOM
0.5
0.4
0.3
0.2
0.1
0.0
BTU/FT SQ-SEC
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
TIME (SEC)

Figure 2.6A

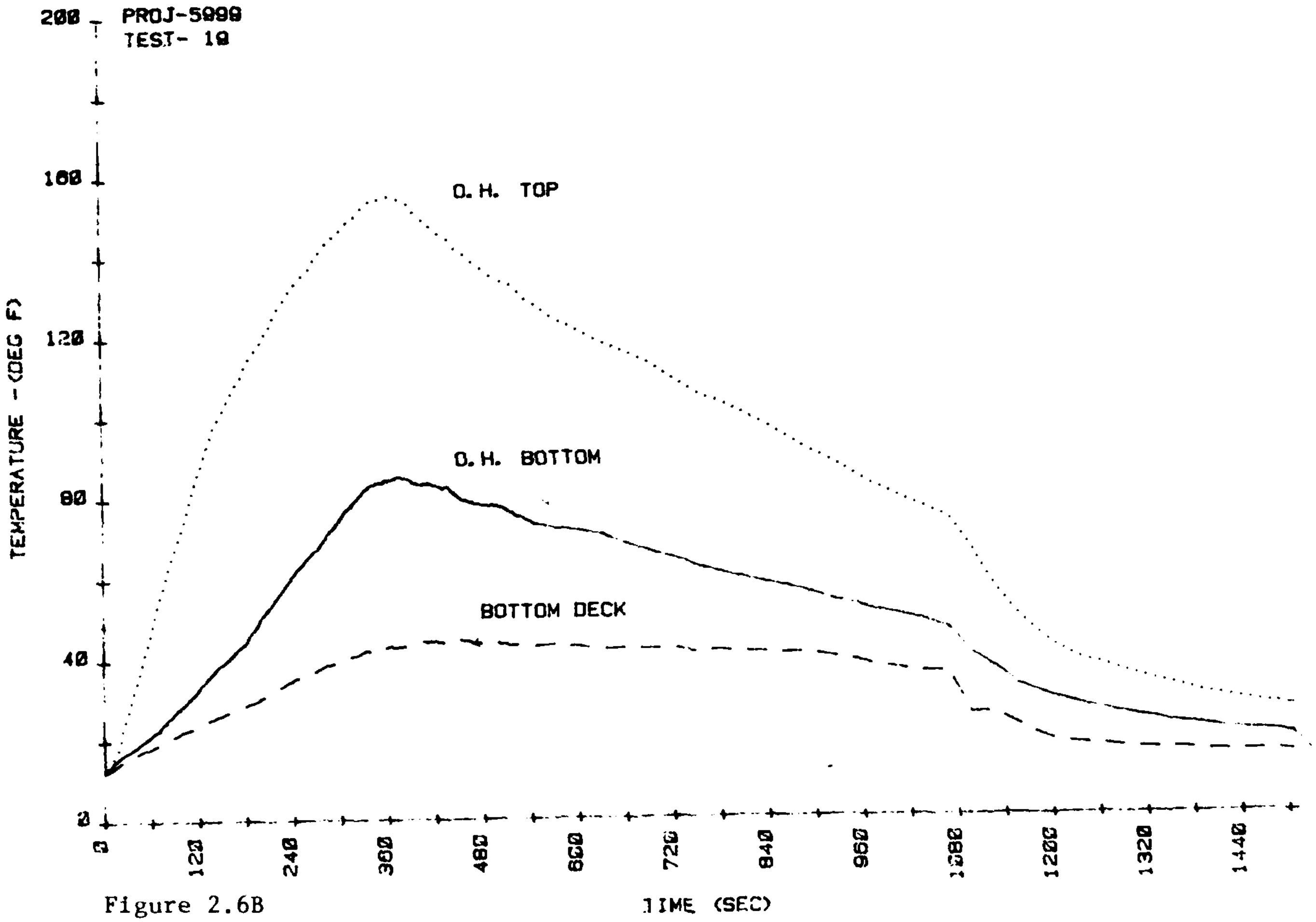

PROJ-5999
TEST- 10
O.H. TOP
O.H. BOTTOM
BOTTOM DECK
TEMPERATURE - (DEG F)
200
160
120
80
40
0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
TIME (SEC)

Figure 2.6B

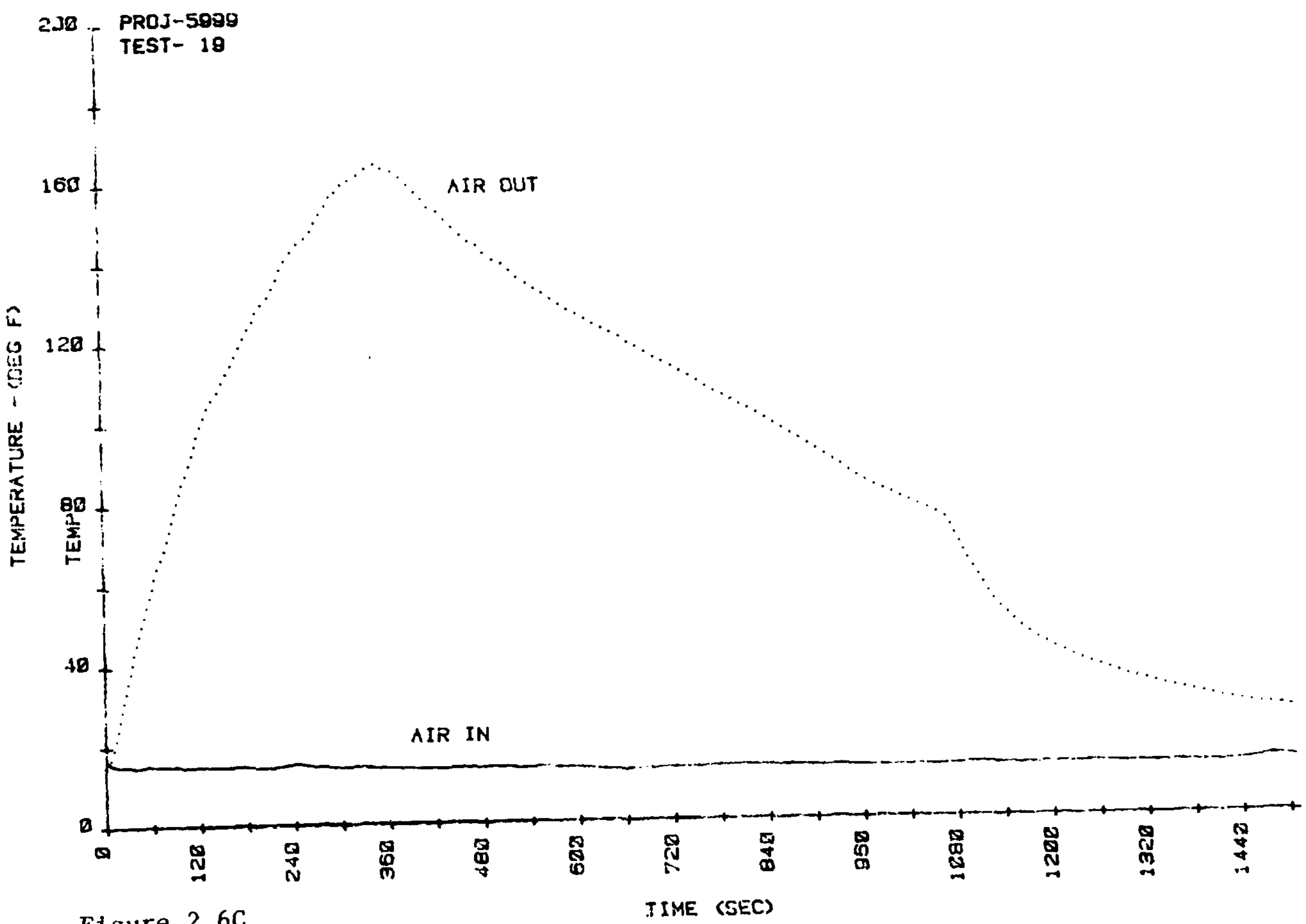

PROJ-5999
TEST- 19
AIR OUT
AIR IN
TEMPERATURE - (DEG F)
TEMP
230
160
120
80
40
0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1442
TIME (SEC)

Figure 2.6C

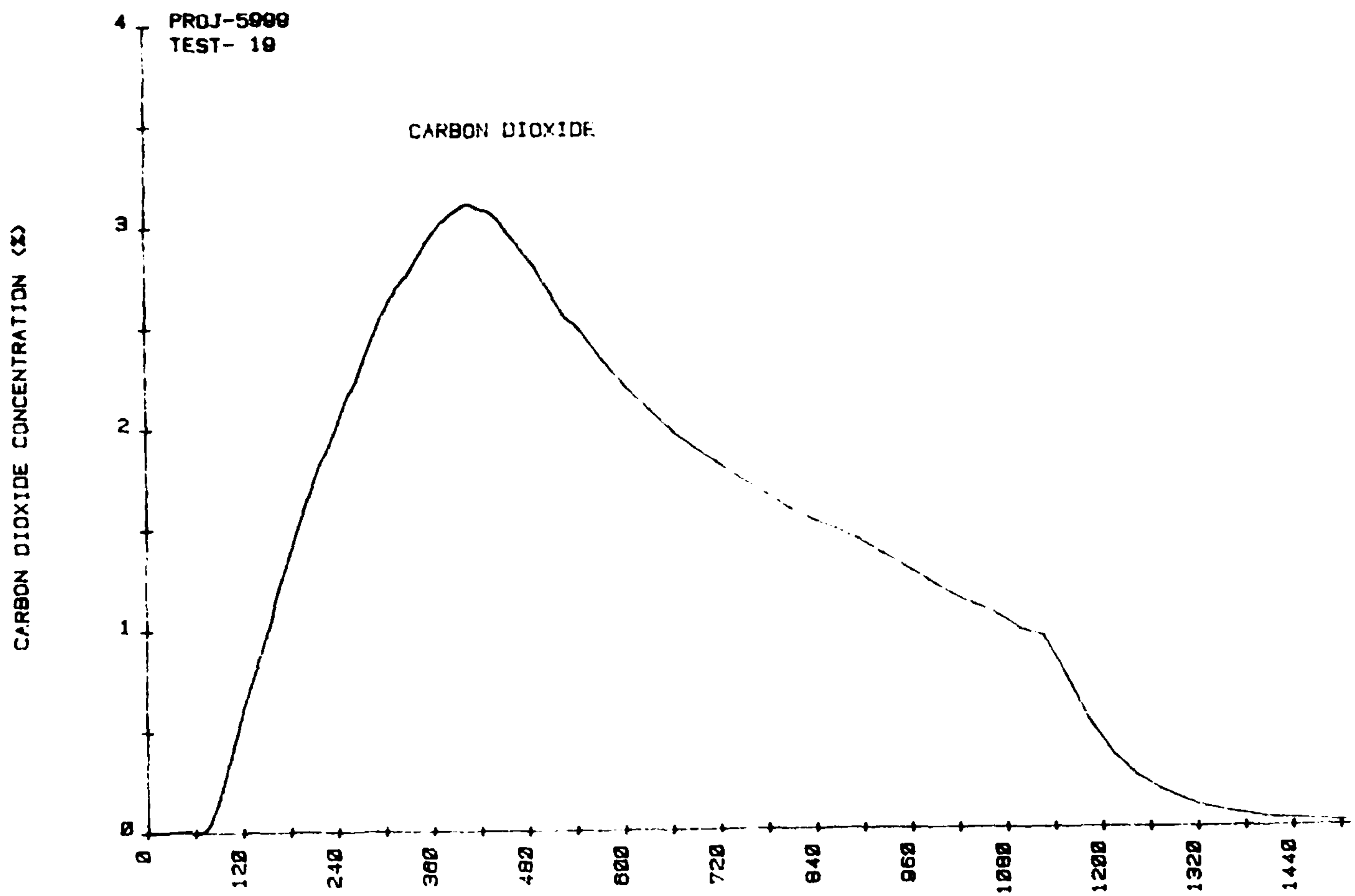

PROJ-5000
TEST- 19
CARBON DIOXIDE
CARBON DIOXIDE CONCENTRATION (%)
0
1
2
3
4
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
TIME (SEC)

Figure 2.6D

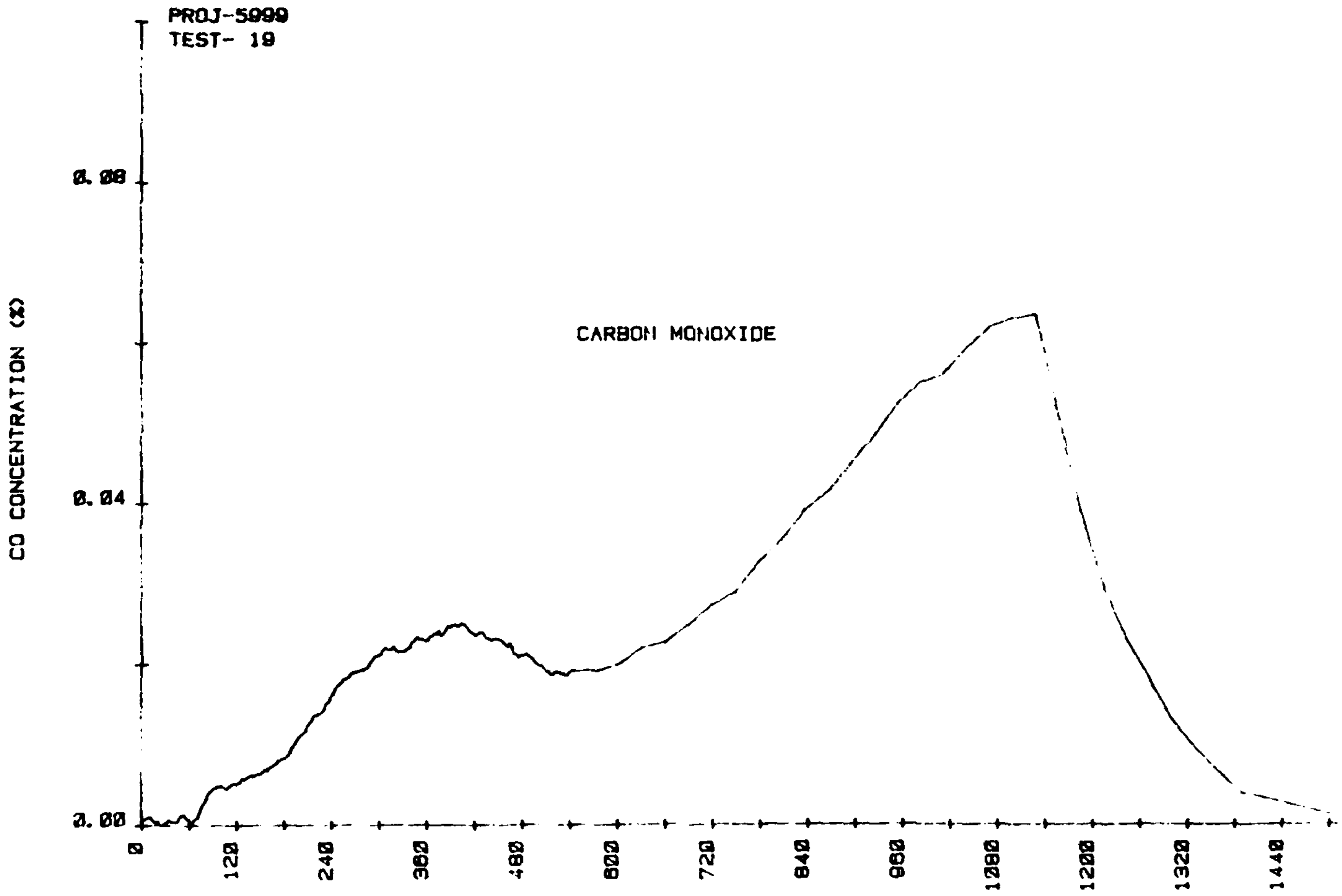

PROJ-5999
TEST- 19
CARBON MONOXIDE
CO CONCENTRATION (%)
0.08
0.04
0.00
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
TIME (SEC)

Figure 2.6E

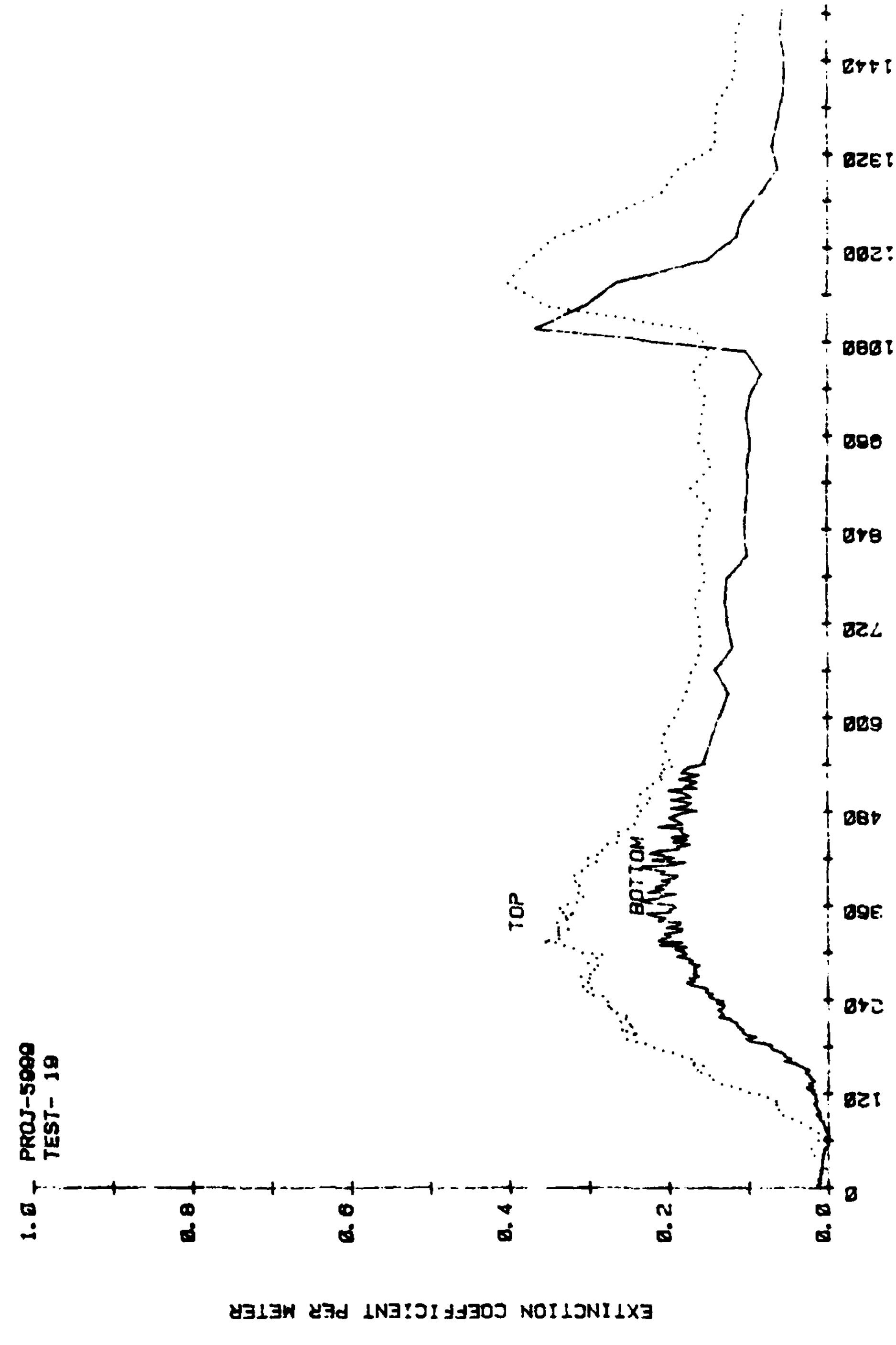

PROJ-5000
TEST- 19
TOP
BOTTOM
1.0
0.8
0.6
0.4
0.2
0.0
EXTINCTION COEFFICIENT PER METER
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
TIME (SEC)

Figure 2.6F

FIGURE 2.7 PORTRAIT FOR A WOOD CRIB FIRE BURNING IN A VENTILATION-SECURED COMPARTMENT, PATTERN 6 (TEST 27)*

*(a) heat flux, (b) air temperatures in the chamber, (c) supply and exhaust air temperatures, (d) carbon dioxide concentration, (e) carbon monoxide concentration, (f) extinction coefficient.

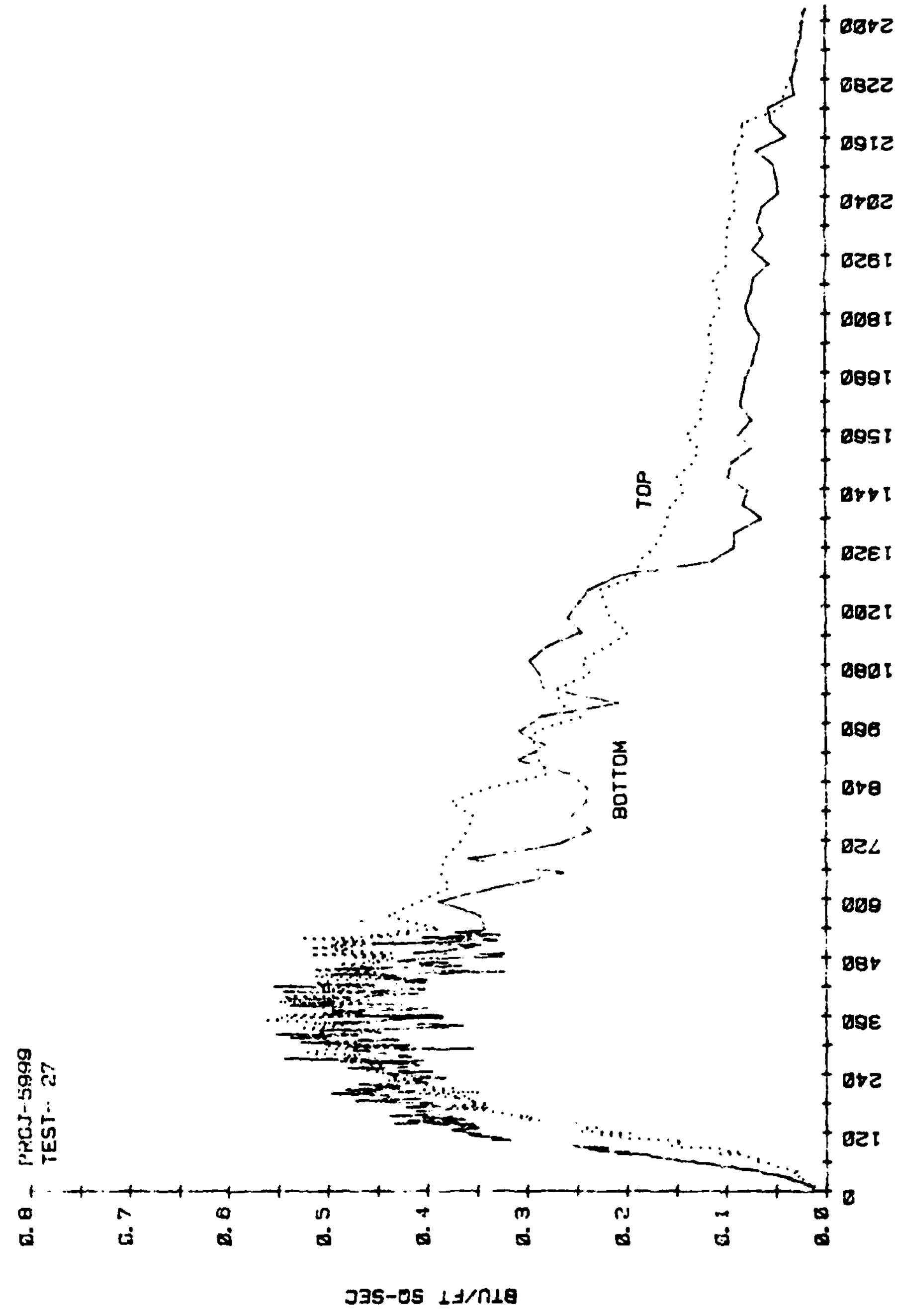

PROJ-5999
TEST- 27
TOP
BOTTOM
BTU/FT SQ-SEC
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
TIME (SEC)
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400

Figure 2.7A

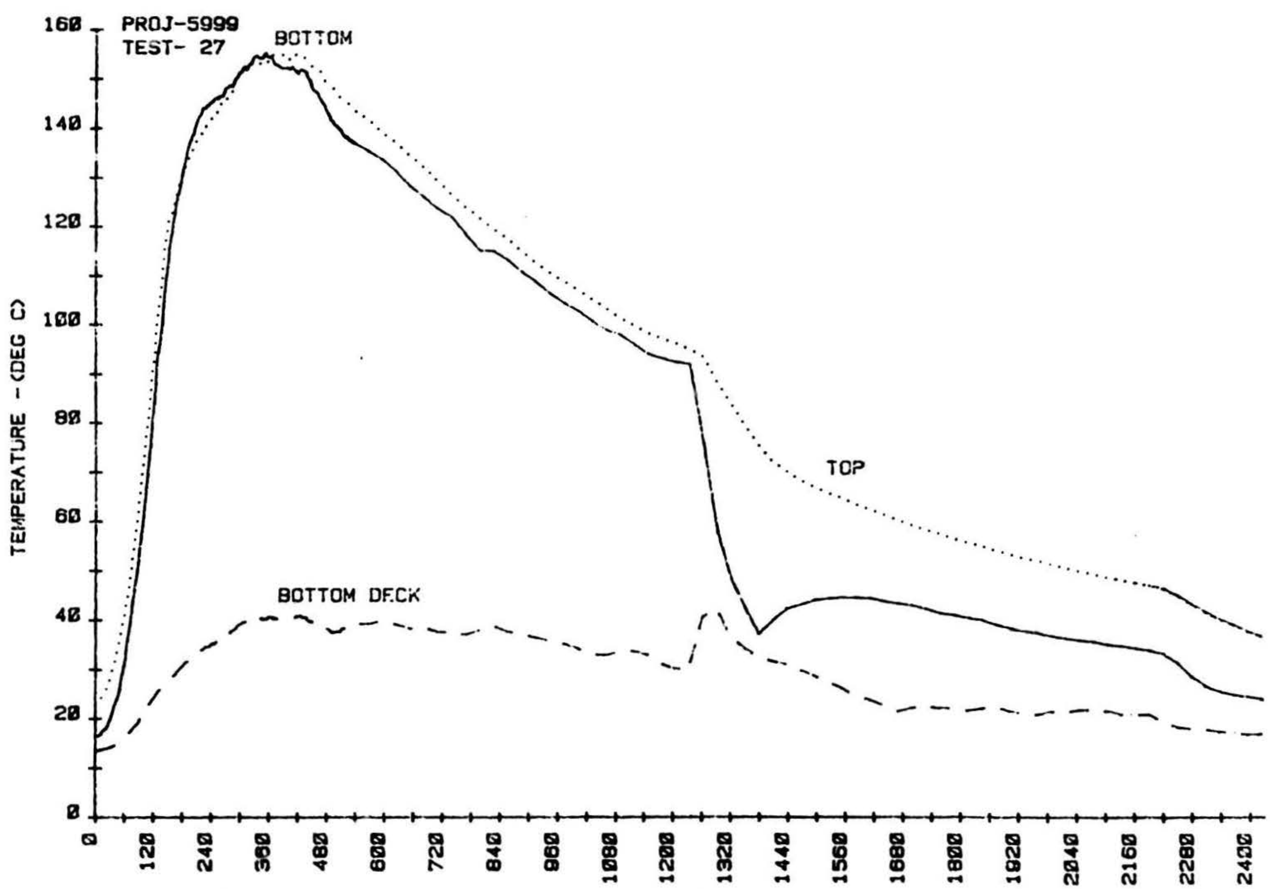

PROJ-5999
TEST- 27
BOTTOM
TOP
BOTTOM DECK
TEMPERATURE - (DEG C)
TIME (SEC)
0
20
40
60
80
100
120
140
160
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400

Figure 2.7B

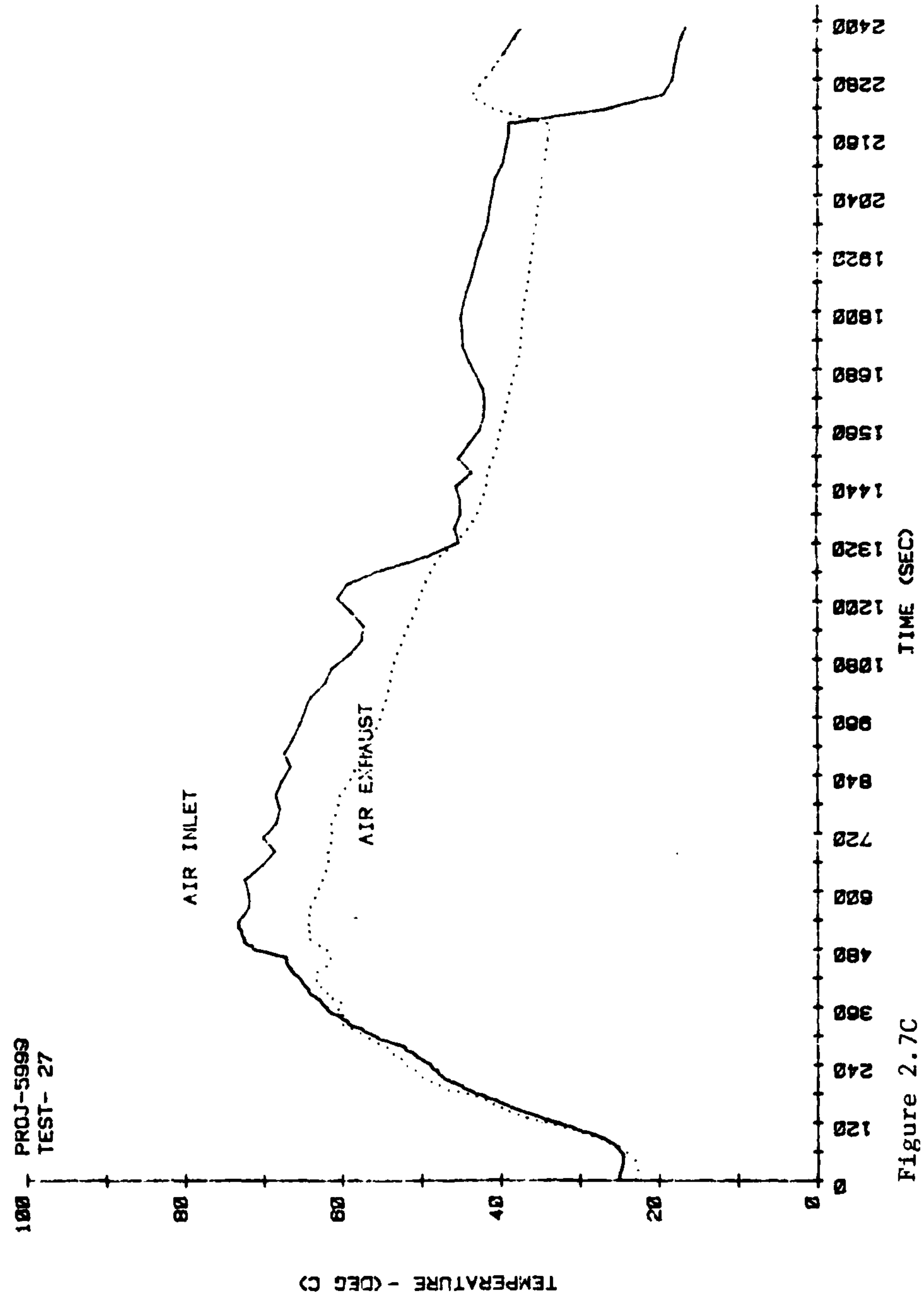
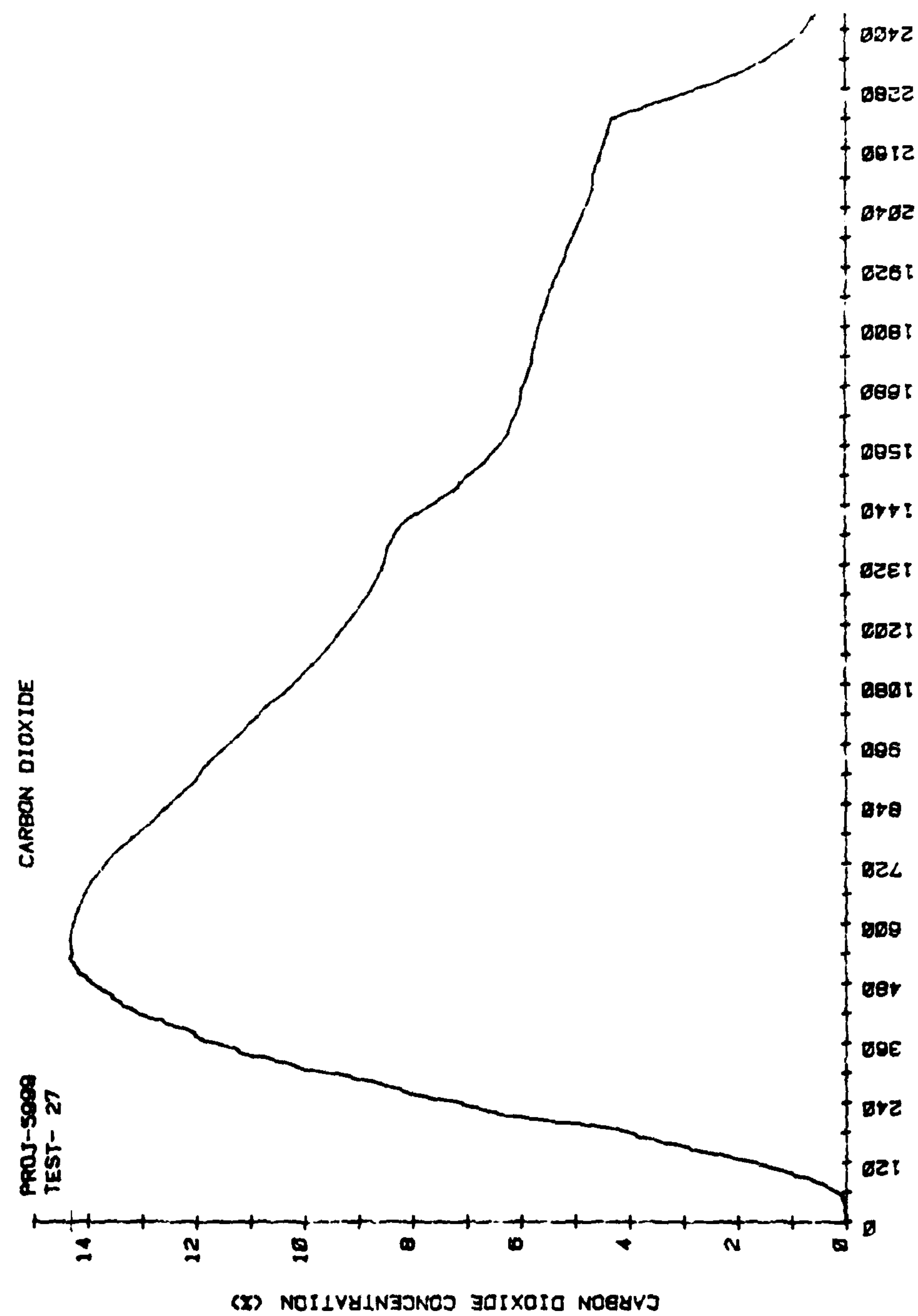

PROJ-5999
TEST- 27
AIR INLET
AIR EXHAUST
TEMPERATURE - (DEG C)
100
80
60
40
20
0
TIME (SEC)
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400

Figure 2.7C



PROJ-5000
TEST- 27
CARBON DIOXIDE
CARBON DIOXIDE CONCENTRATION (%)
0
2
4
6
8
10
12
14
TIME (SEC)
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400

Figure 2.7D

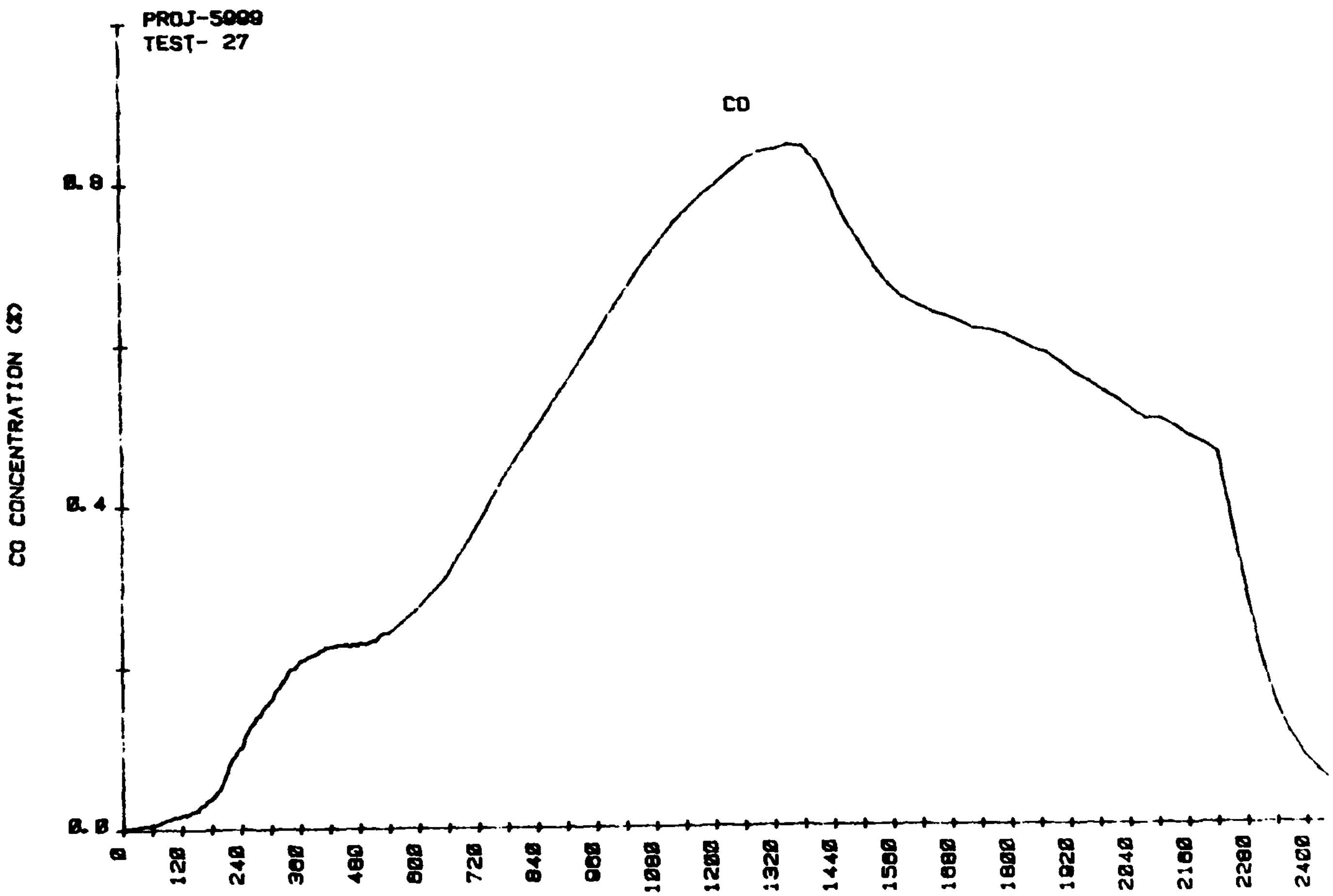

PROJ-5000
TEST- 27
CO
CO CONCENTRATION (%)
0.8
0.4
0.0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
TIME (SEC)

Figure 2.7E

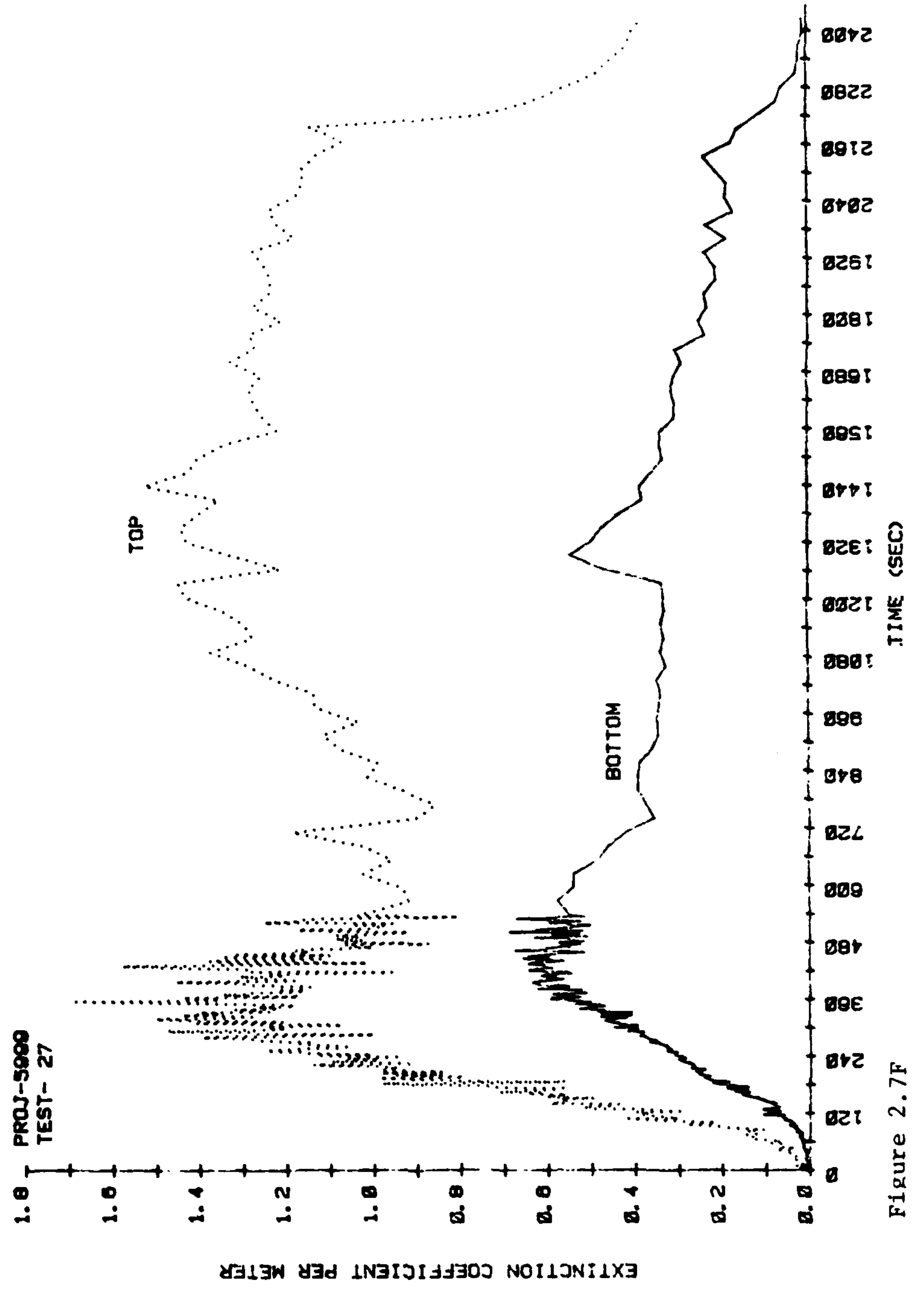
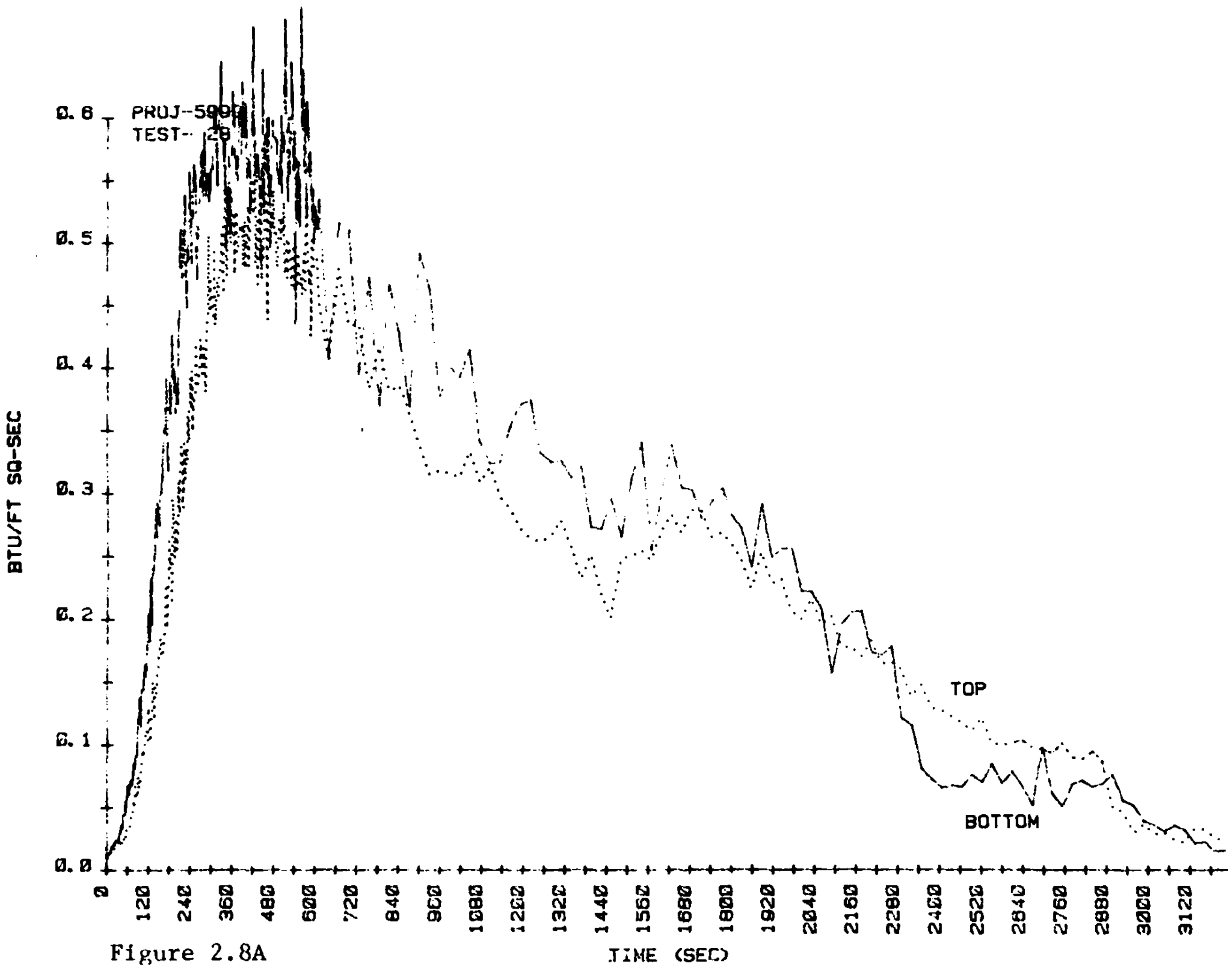

PROJ-5900
TEST- 27
TOP
BOTTOM
EXTINCTION COEFFICIENT PER METER
TIME (SEC)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400

Figure 2.7F

FIGURE 2.8 EFFECT OF AIR LEAKAGE ON THE THERMAL INSULT GENERATED BY FIRES IN COMPARTMENTS WHILE THE VENTILATION IS SECURED (TEST 28, PATTERN 6; TEST 29, PATTERN 5)*

*(a) heat flux, (b) air temperatures in chamber, (c) heat flux (d) air temperature in chamber.


PROJ-5990
TEST- 28
BTU/FT SQ-SEC
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
120
240
360
480
600
720
840
900
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640
2760
2880
3000
3120
TIME (SEC)
TOP
BOTTOM
Figure 2.8A

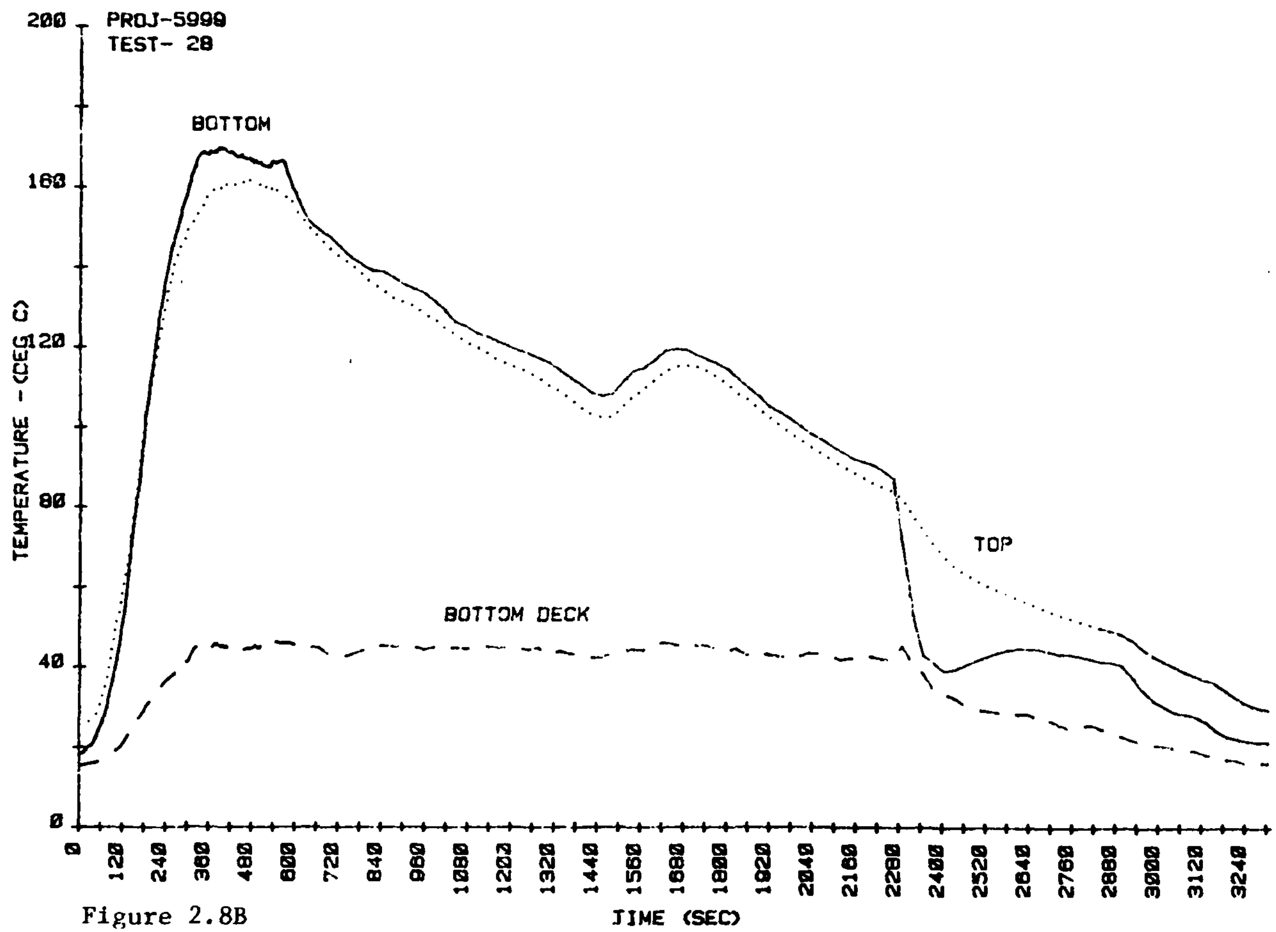

PROJ-5999
TEST- 28
BOTTOM
TOP
BOTTOM DECK
TEMPERATURE - (DEG C)
200
160
120
80
40
0
0 120 240 360 480 600 720 840 960 1080 1202 1320 1440 1560 1680 1800 1920 2040 2160 2280 2400 2520 2640 2760 2880 3000 3120 3240
TIME (SEC)

Figure 2.8B

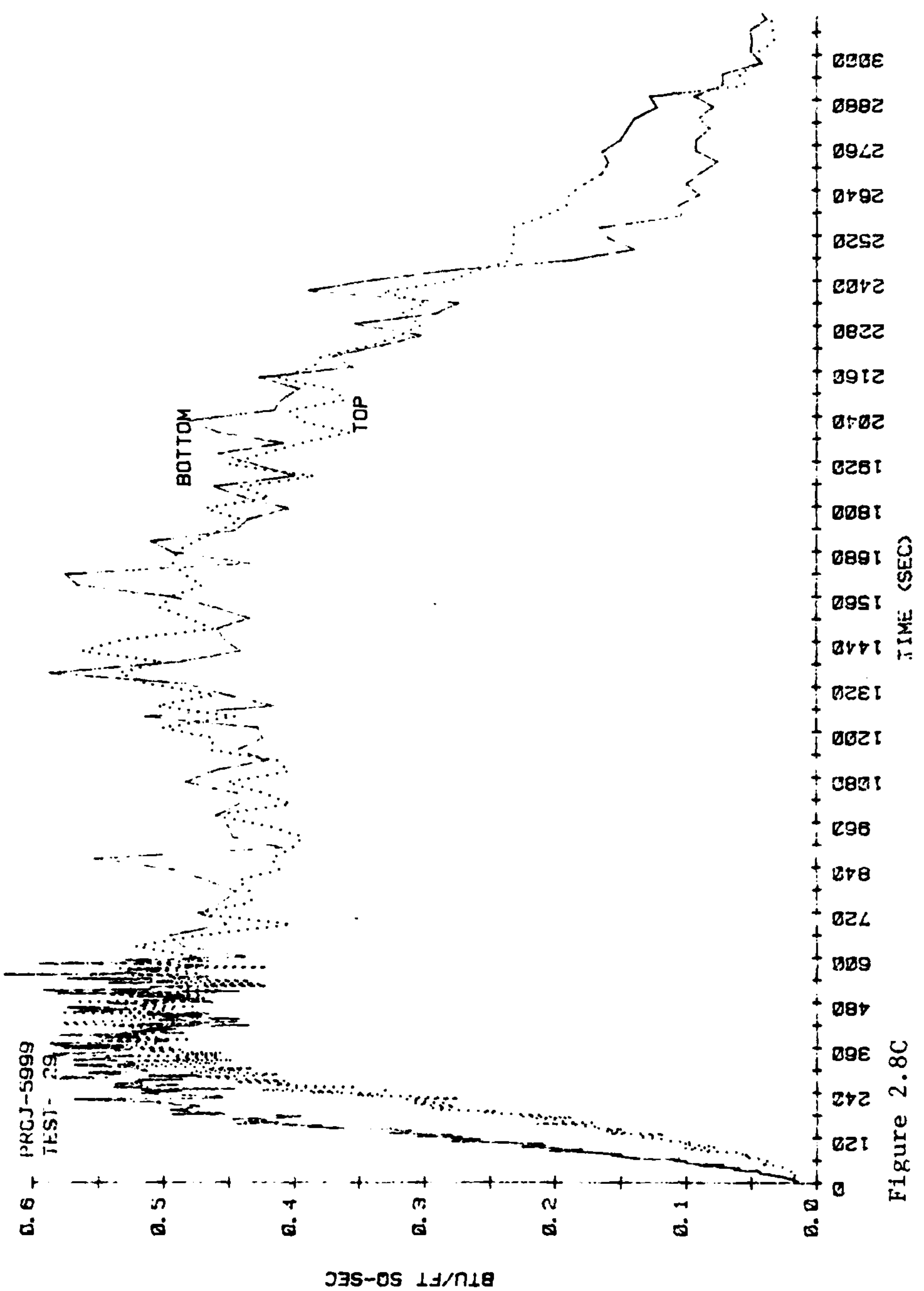

PROJ-5999
TEST- 29
BOTTOM
TOP
BTU/FT SQ-SEC
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640
2760
2880
3000
TIME (SEC)

Figure 2.8C

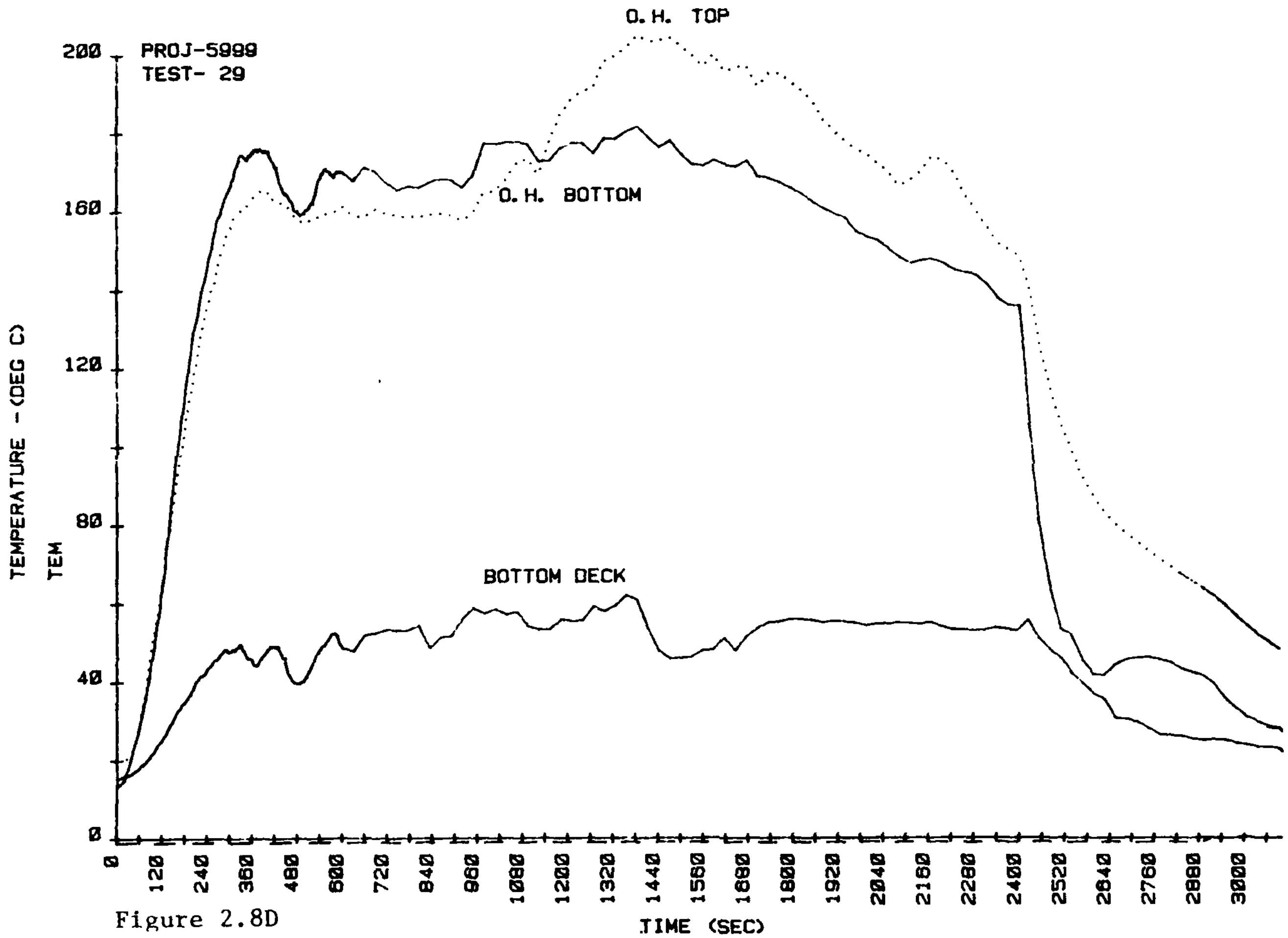

PROJ-5999
TEST- 29
O.H. TOP
O.H. BOTTOM
BOTTOM DECK
TEMPERATURE - (DEG C)
TEM
200
160
120
80
40
0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640
2760
2880
3000
TIME (SEC)

Figure 2.8D

FIGURE 2.9 FIRE PORTRAIT FOR 10-1/8-IN. DIAMETER JET FUEL POOL FIRE BURNING UNDER VENTILATION PATTERN 6 (TEST 34)*

*(a) heat flux, (b) air temperatures in chamber, (c) supply and exhaust air temperature, (d) carbon dioxide concentration, (e) carbon monoxide concentration, (f) oxygen depletion, (g) extinction coefficient.

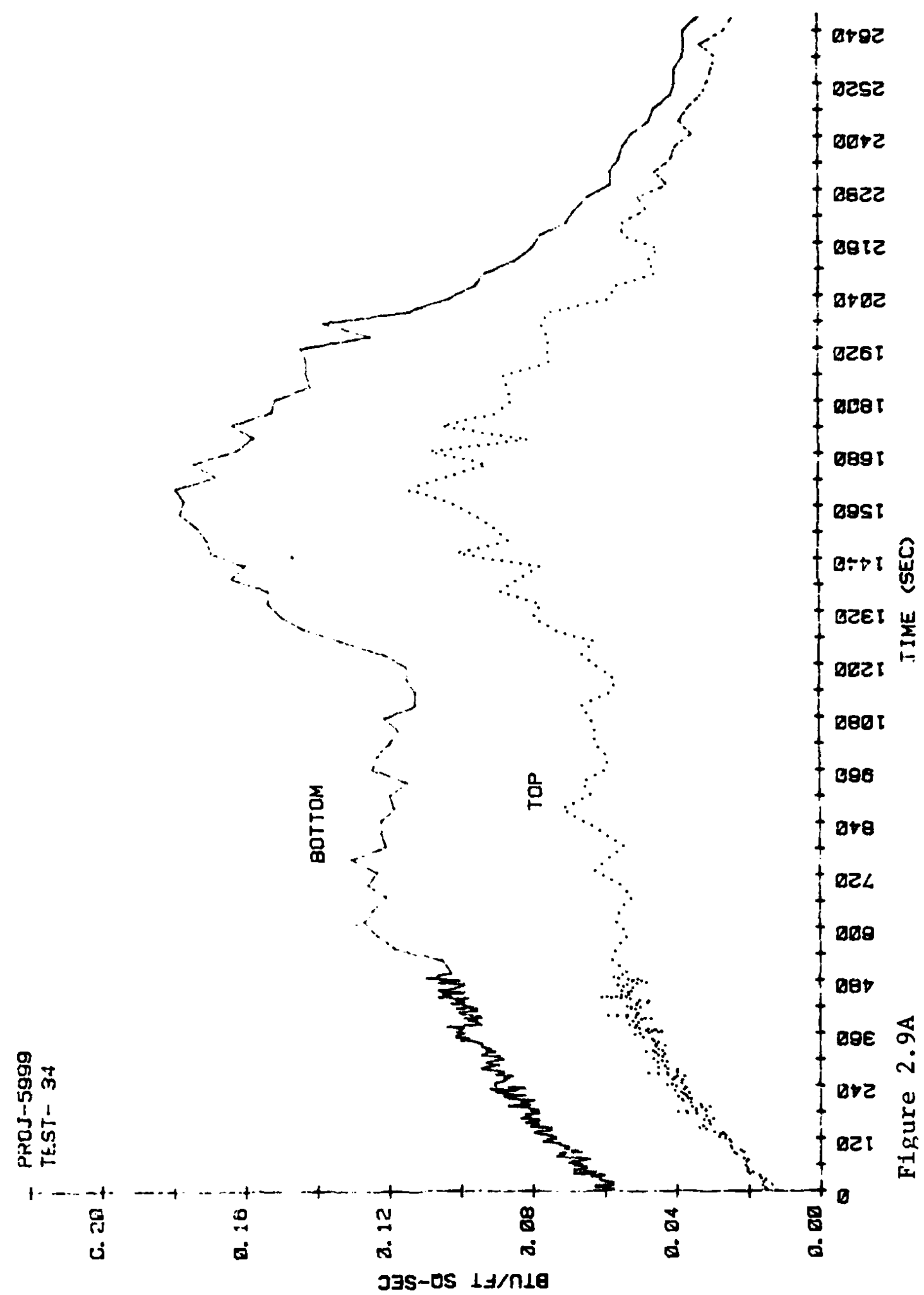

PROJ-5999
TEST- 34
BOTTOM
TOP
BTU/FT SQ-SEC
0.00
0.04
0.08
0.12
0.16
0.20
TIME (SEC)
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640

Figure 2.9A

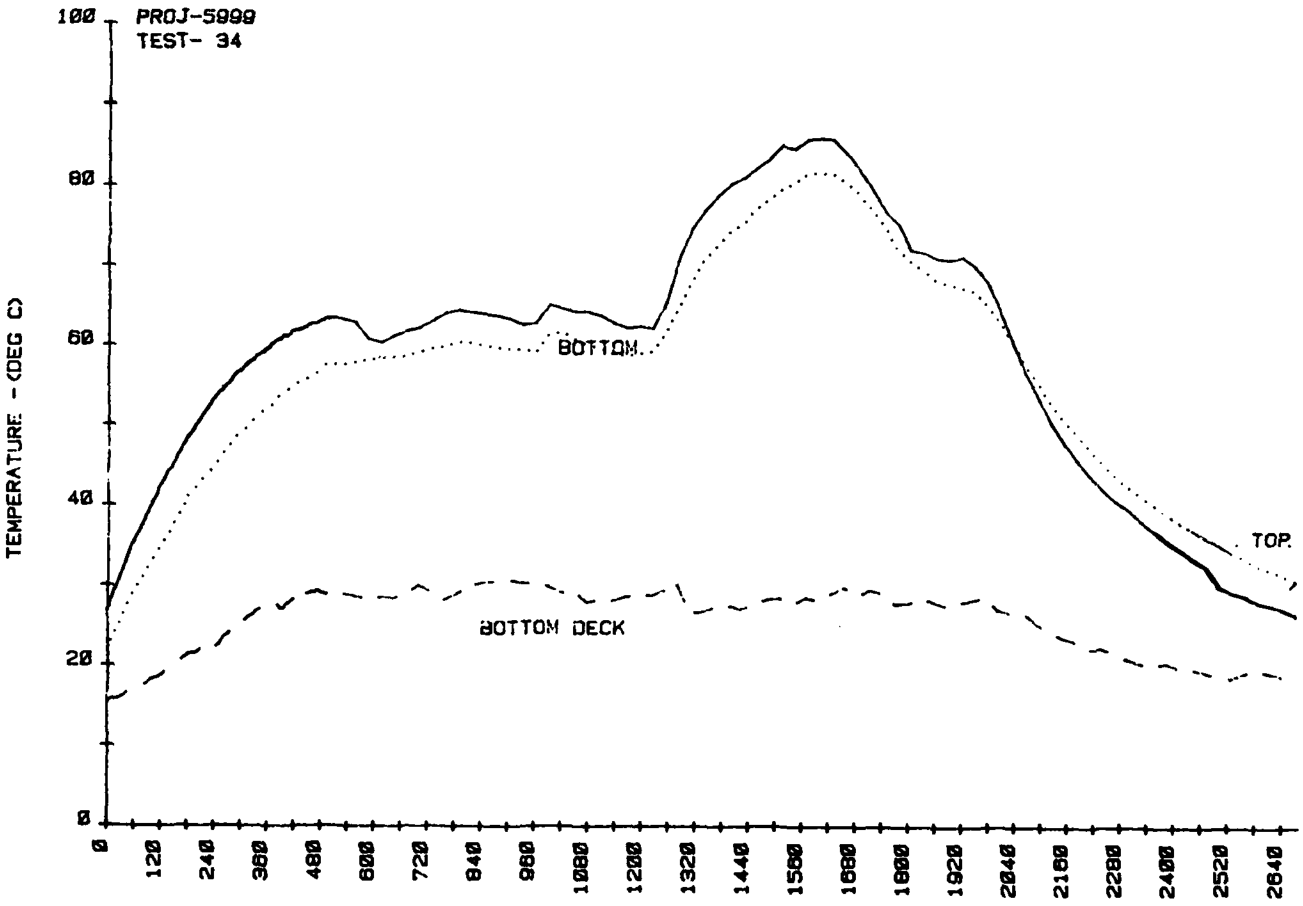
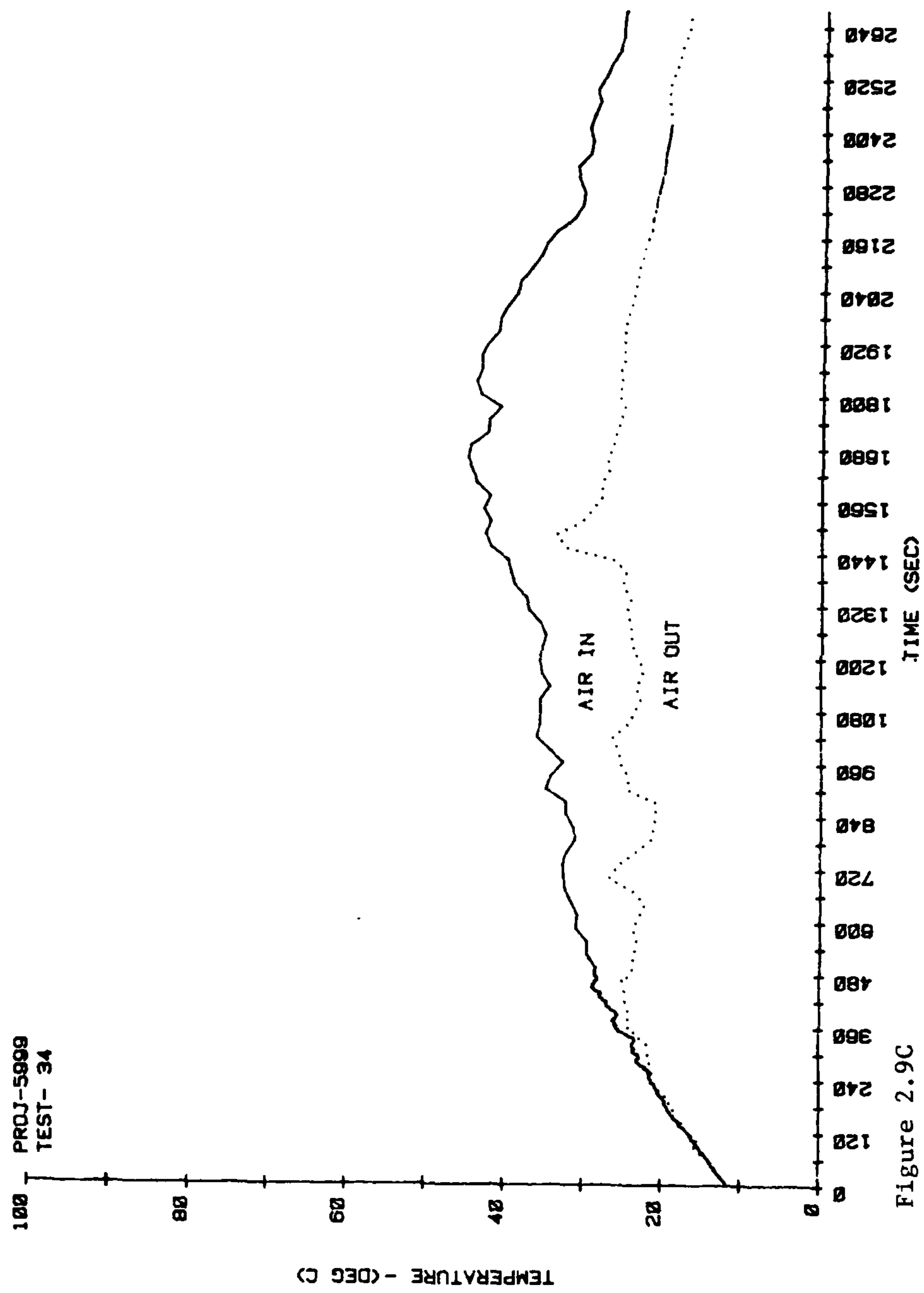

PROJ-5999
TEST- 34
TEMPERATURE - (DEG C)
TIME (SEC)
BOTTOM
TOP
BOTTOM DECK
0
20
40
60
80
100
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640

Figure 2.9B



PROJ-5899
TEST- 34
AIR IN
AIR OUT
TEMPERATURE - (DEG C)
TIME (SEC)
0
20
40
60
80
100
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640

Figure 2.9C

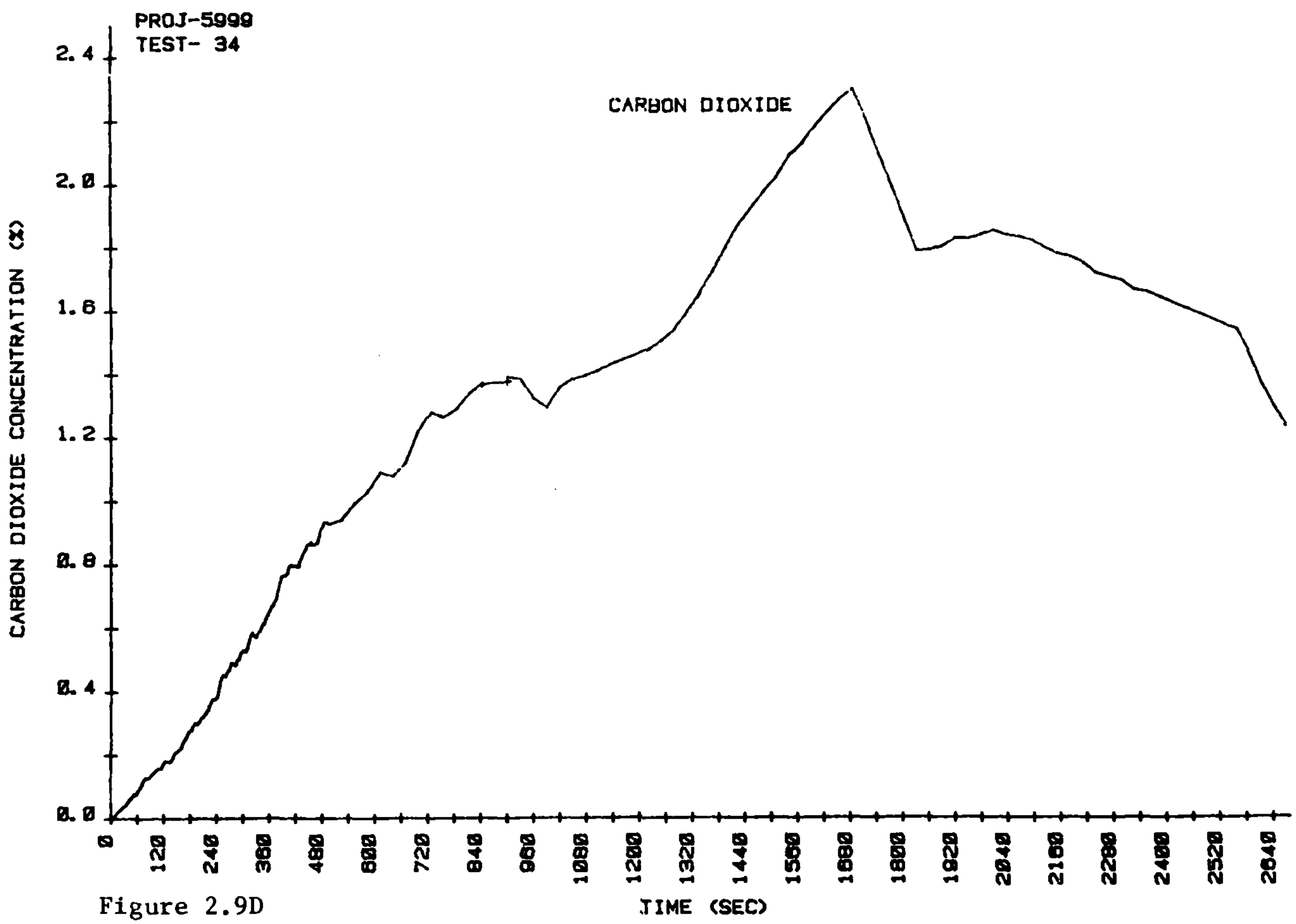

PROJ-5999
TEST- 34
CARBON DIOXIDE
CARBON DIOXIDE CONCENTRATION (%)
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640
TIME (SEC)

Figure 2.9D

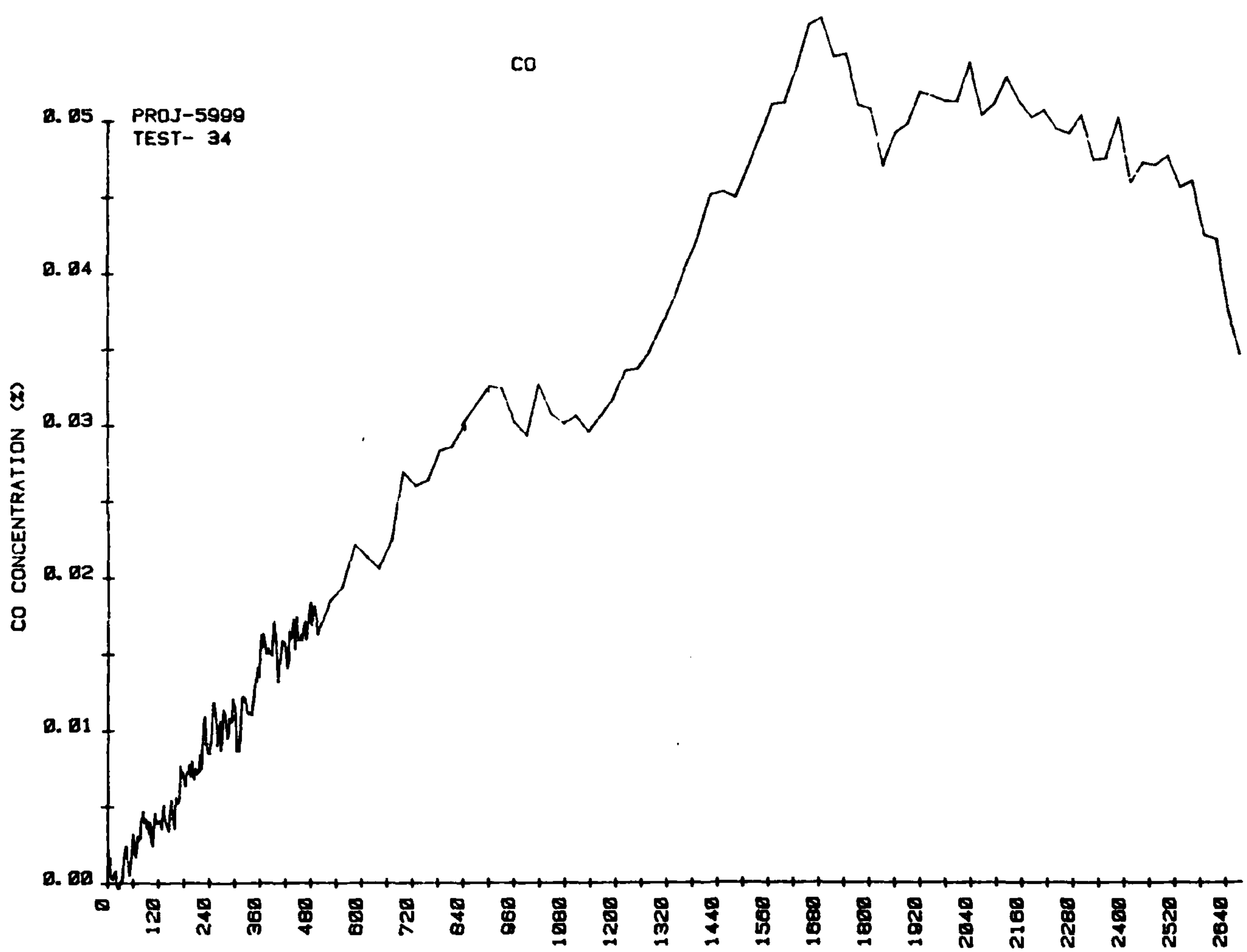

CO
PROJ-5999
TEST- 34
CO CONCENTRATION (%)
0.00
0.01
0.02
0.03
0.04
0.05
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640
TIME (SEC)

Figure 2.9E

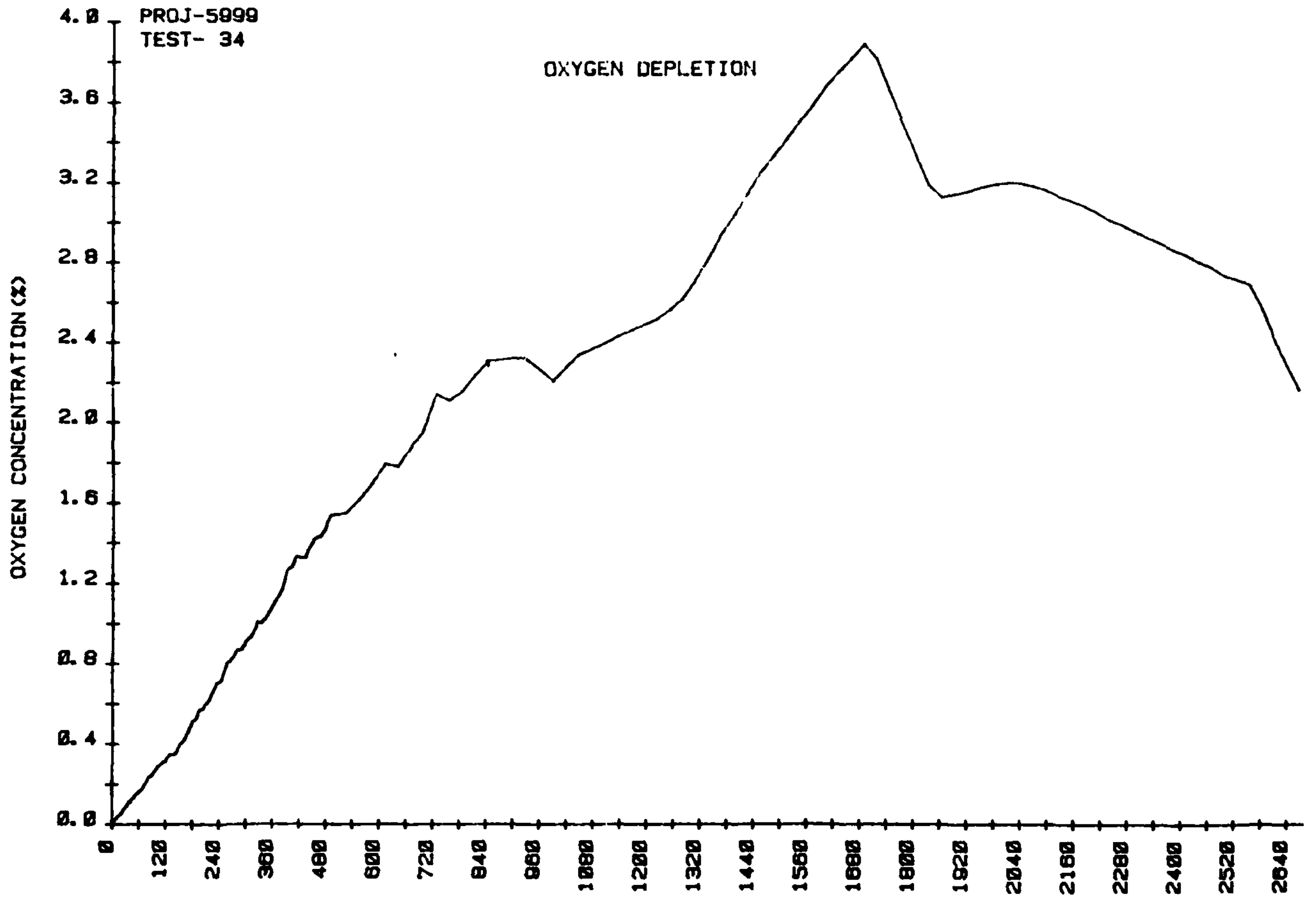

PROJ-5999
TEST- 34
OXYGEN DEPLETION
OXYGEN CONCENTRATION (%)
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
2040
2160
2280
2400
2520
2640
TIME (SEC)

Figure 2.9F

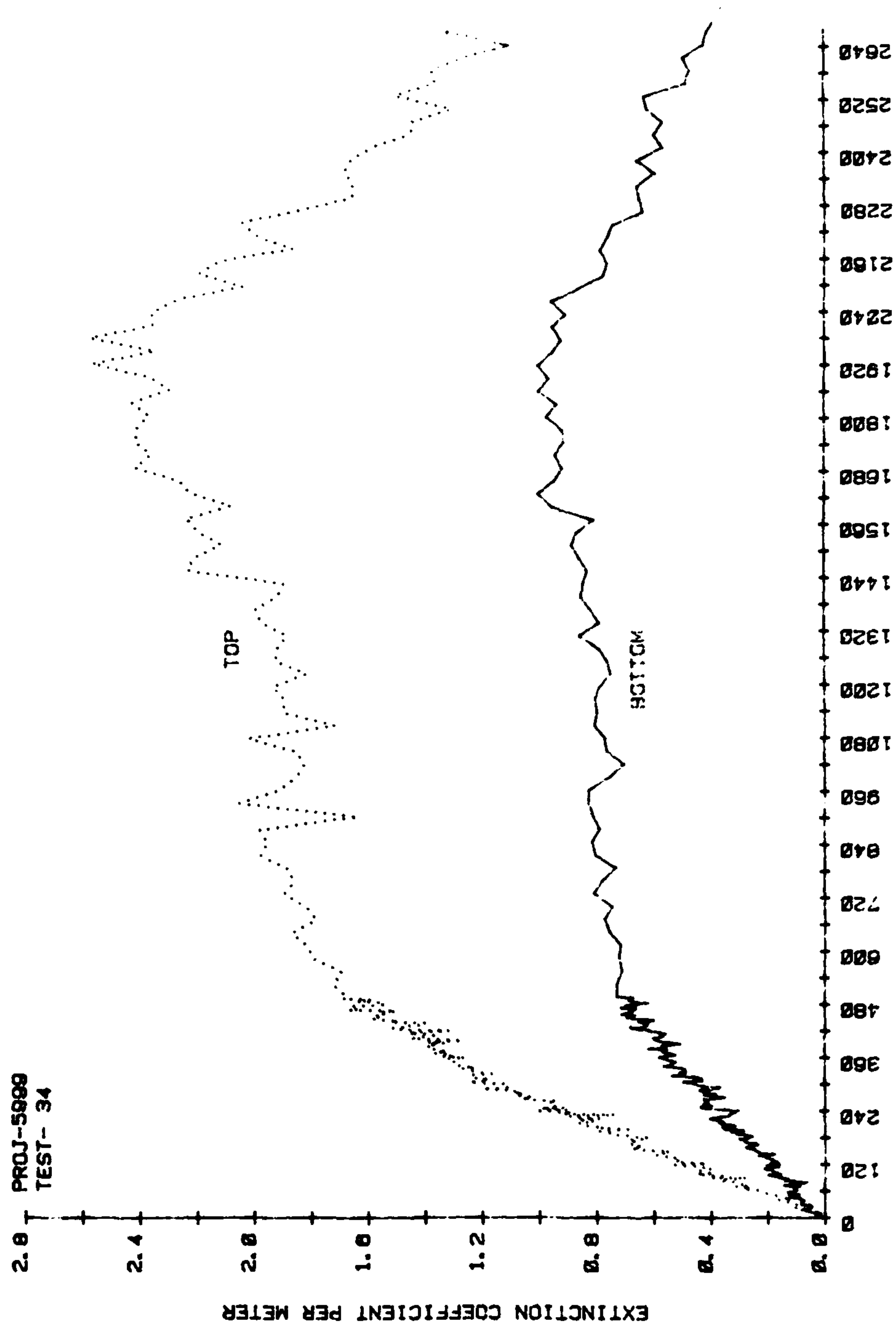
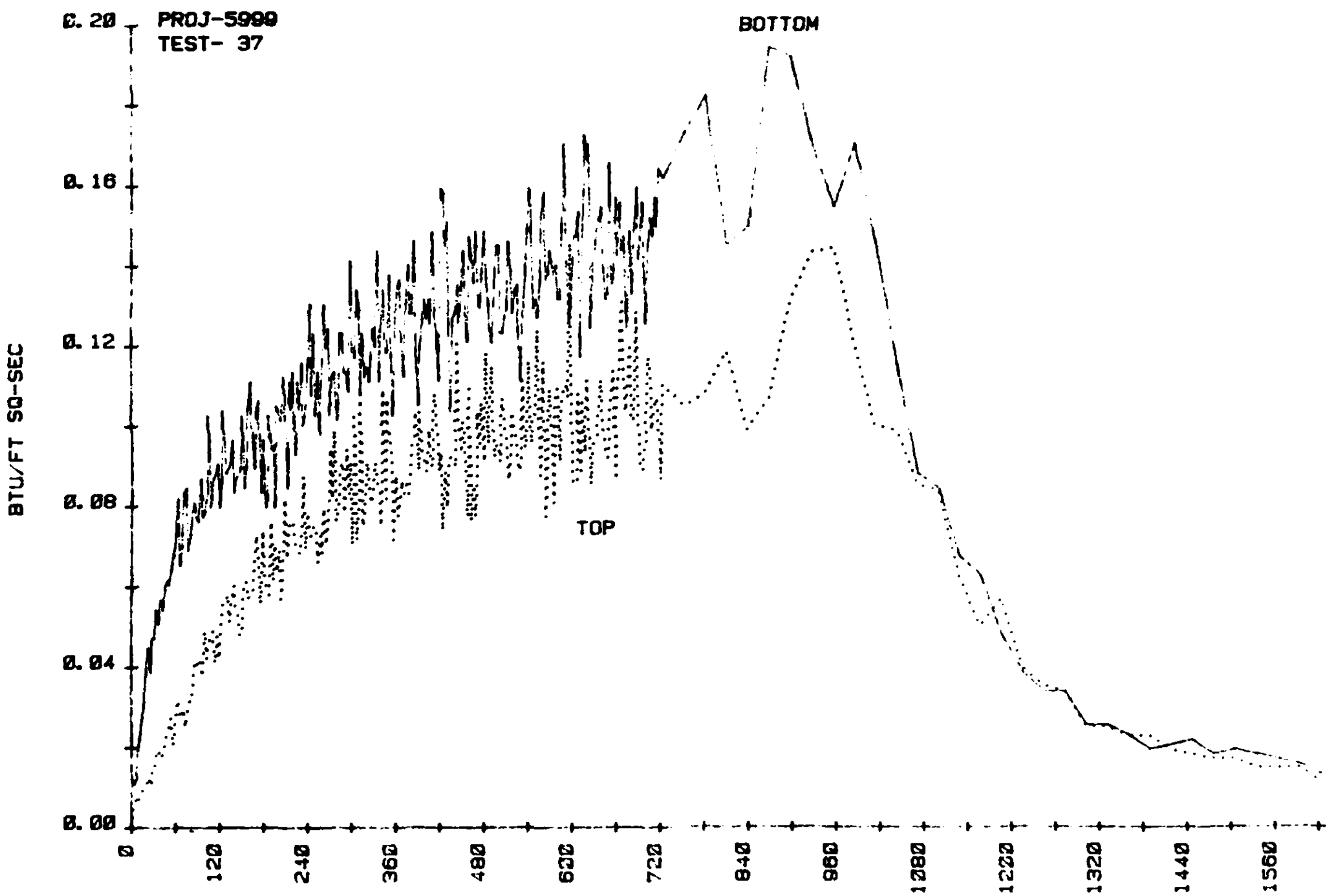

PROJ-5999
TEST- 34
TOP
BOTTOM
TIME (SEC)
EXTINCTION COEFFICIENT PER METER

Figure 2.9G

FIGURE 2.10 FIRE PORTRAIT FOR 10-1/8-IN. DIAMETER JET FUEL POOL FIRE BURNING UNDER VENTILATION PATTERN 2 (TEST 37)*

*(a) heat flux, (b) air temperatures in chamber, (c) supply and exhaust air temperature, (d) carbon dioxide concentration, (e) carbon monoxide concentration, (f) oxygen depletion, (g) extinction coefficient.


PROJ-5999
TEST- 37
BOTTOM
TOP
BTU/FT SQ-SEC
0.20
0.16
0.12
0.08
0.04
0.00
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
TIME (SEC)
Figure 2.10A

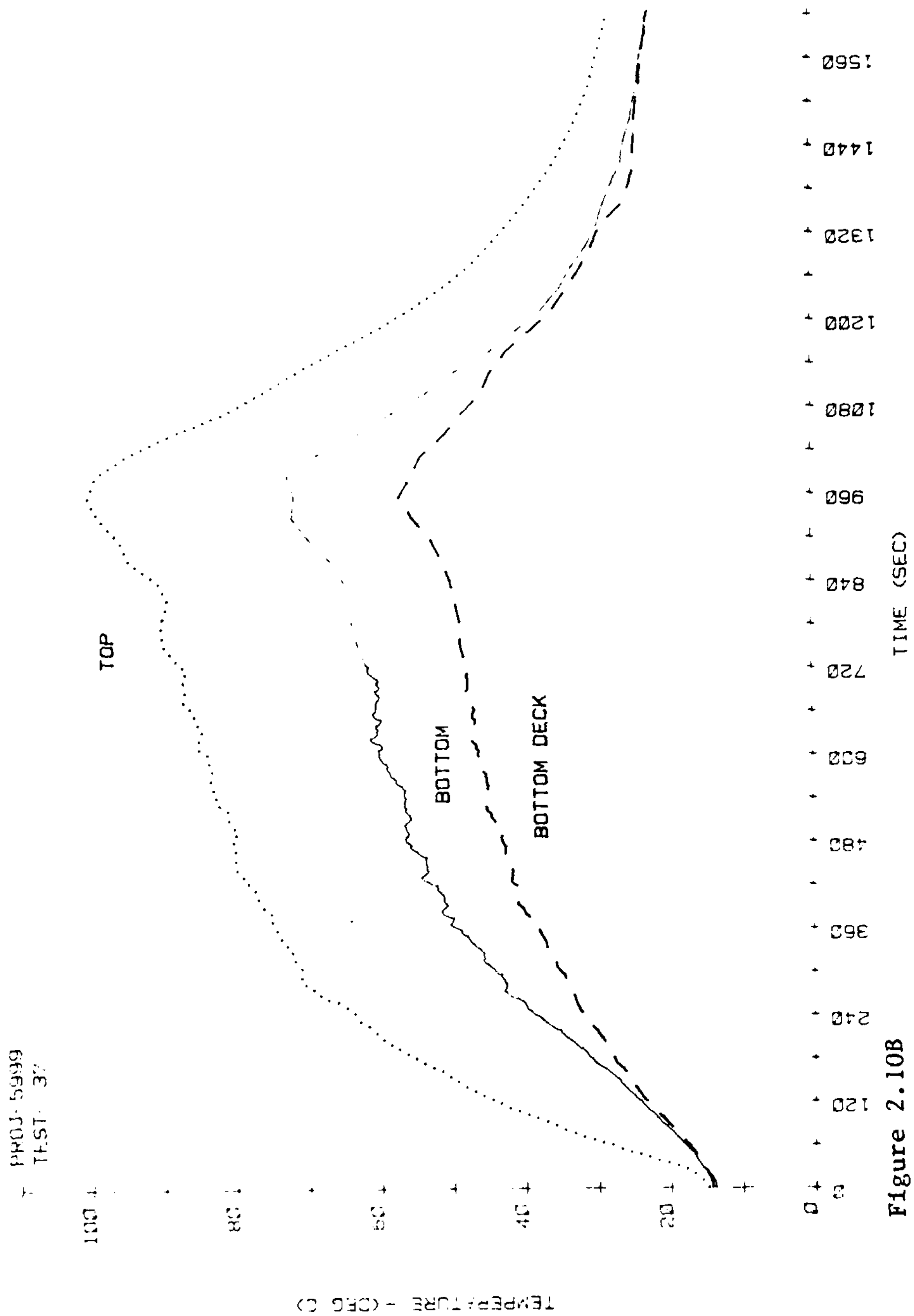

PROJ 5999
TEST 37
TOP
BOTTOM
BOTTOM DECK
TEMPERATURE - (DEG C)
TIME (SEC)
0
20
40
60
80
100
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560

Figure 2.10B

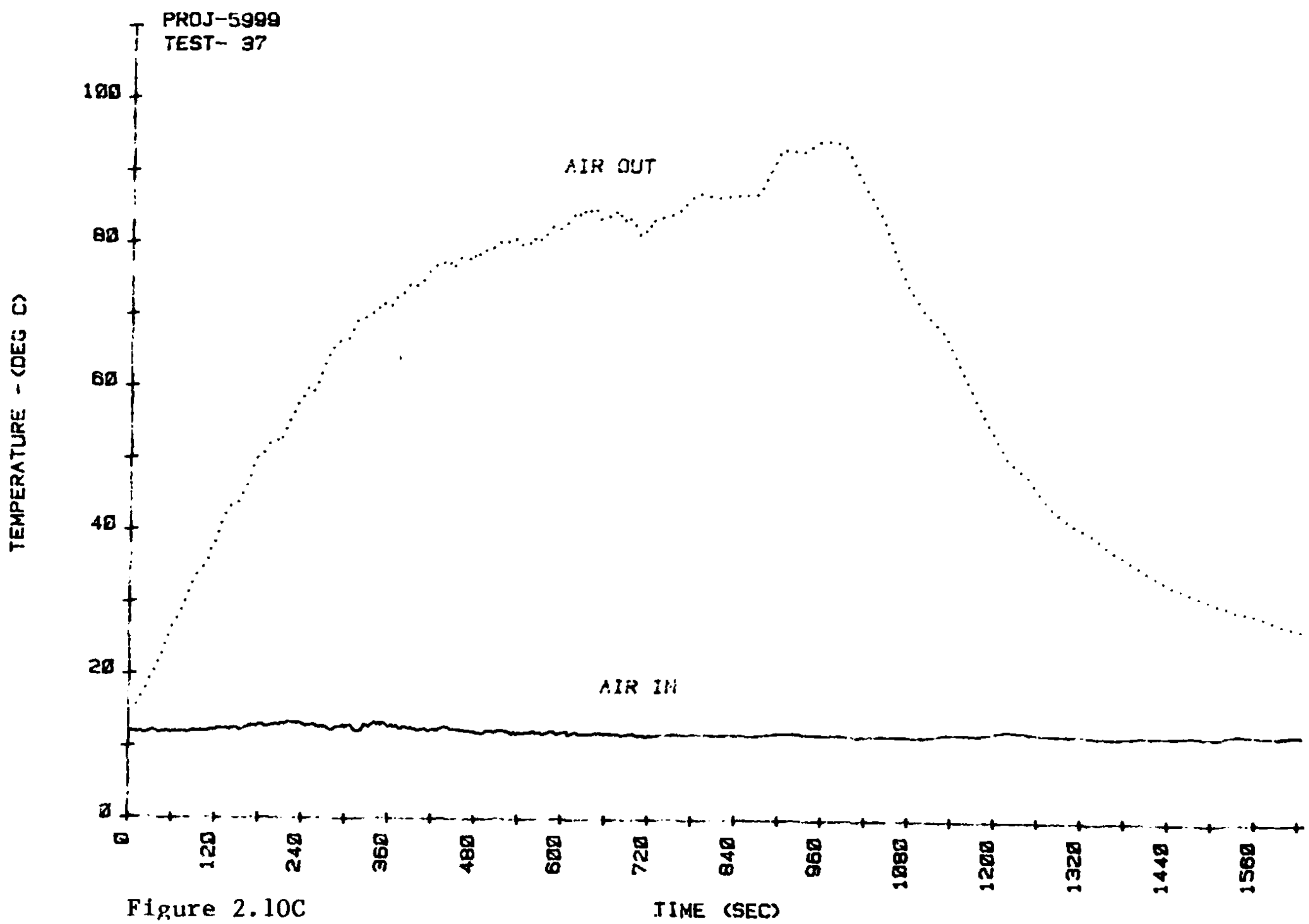

PROJ-5999
TEST- 37
AIR OUT
AIR IN
TEMPERATURE - (DEG C)
0
20
40
60
80
100
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
TIME (SEC)

Figure 2.10C

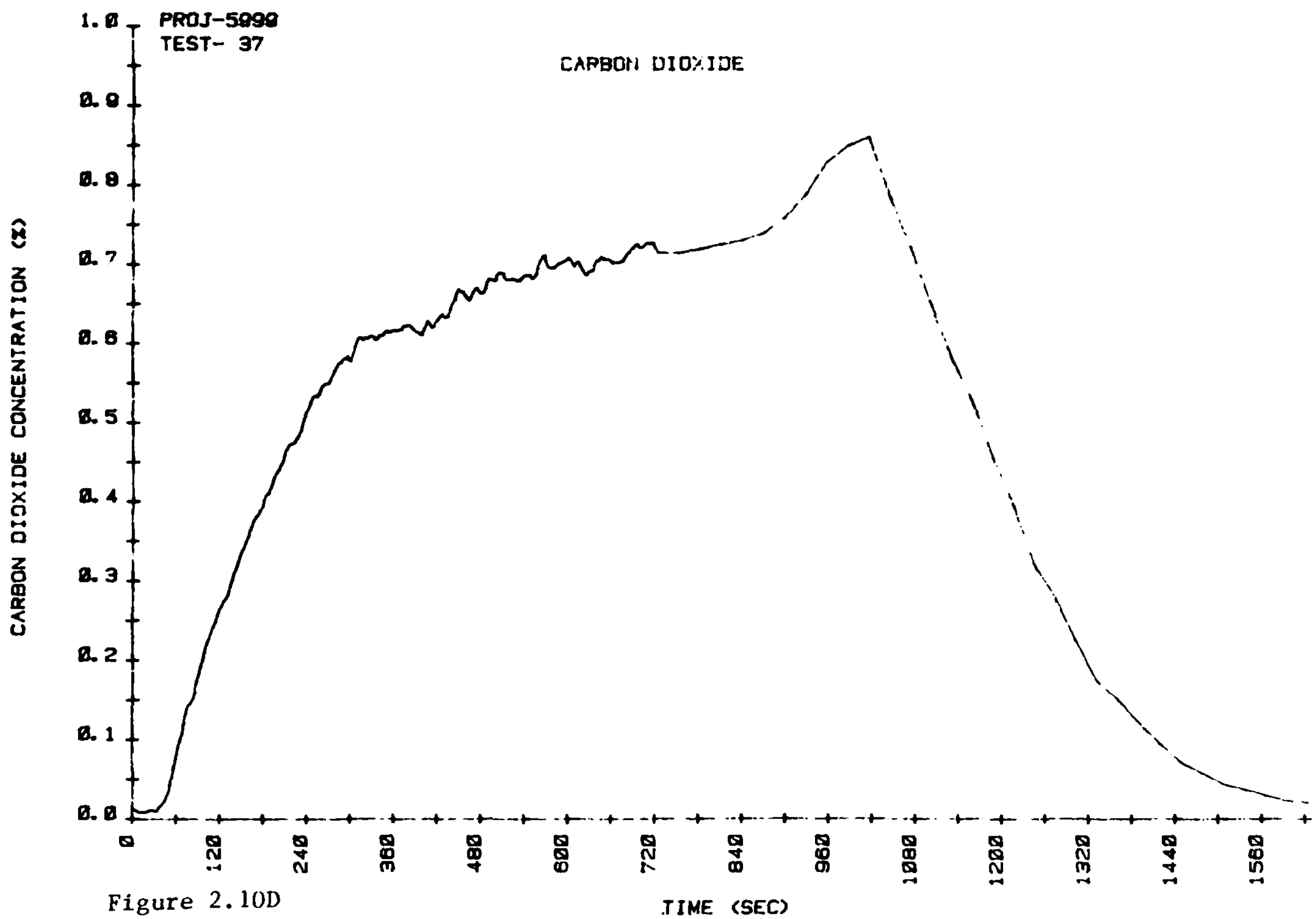

PROJ-5999
TEST- 37
CARBON DIOXIDE
CARBON DIOXIDE CONCENTRATION (%)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
TIME (SEC)

Figure 2.10D

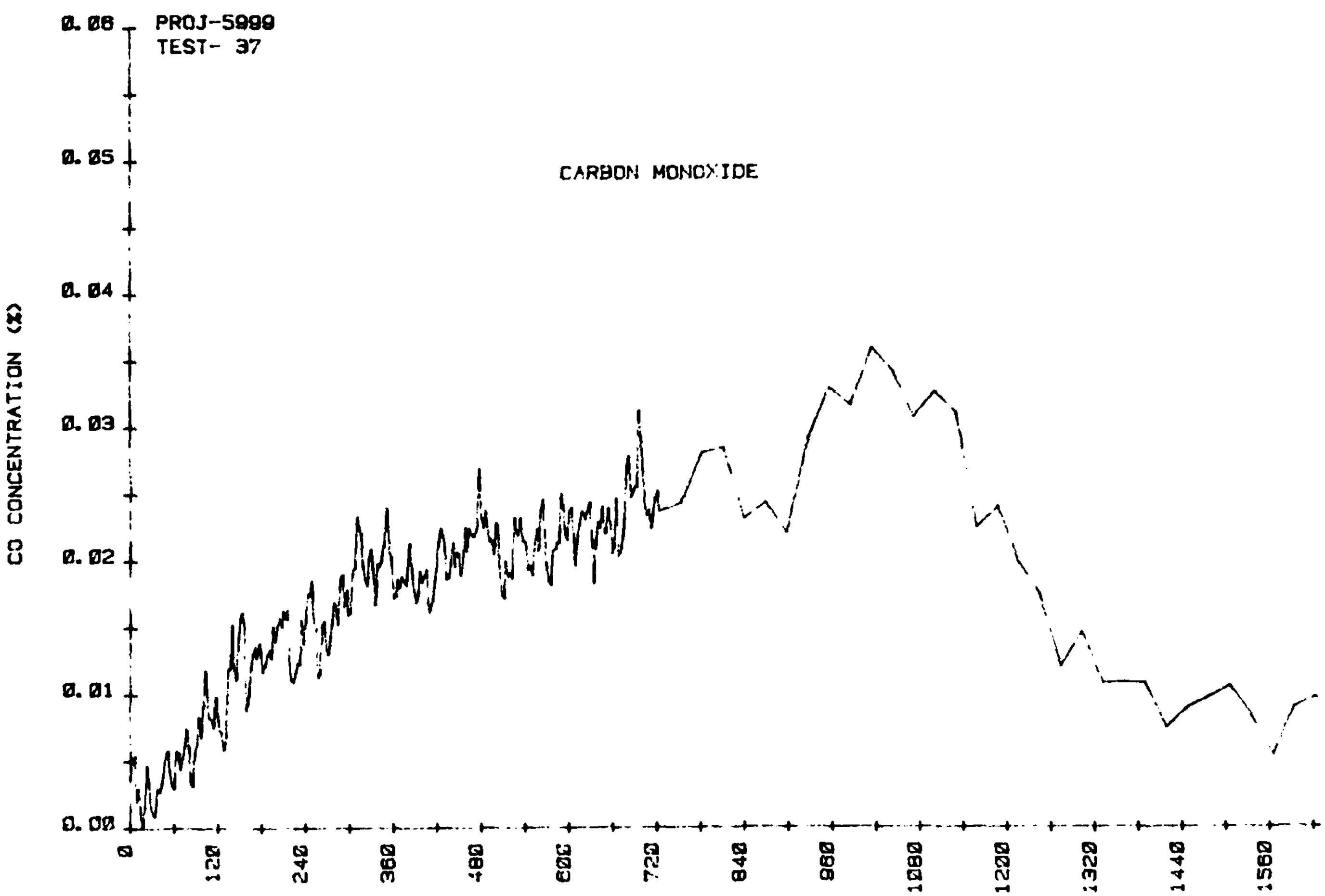

PROJ-5999
TEST- 37
CARBON MONOXIDE
CO CONCENTRATION (%)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
TIME (SEC)

Figure 2.10E

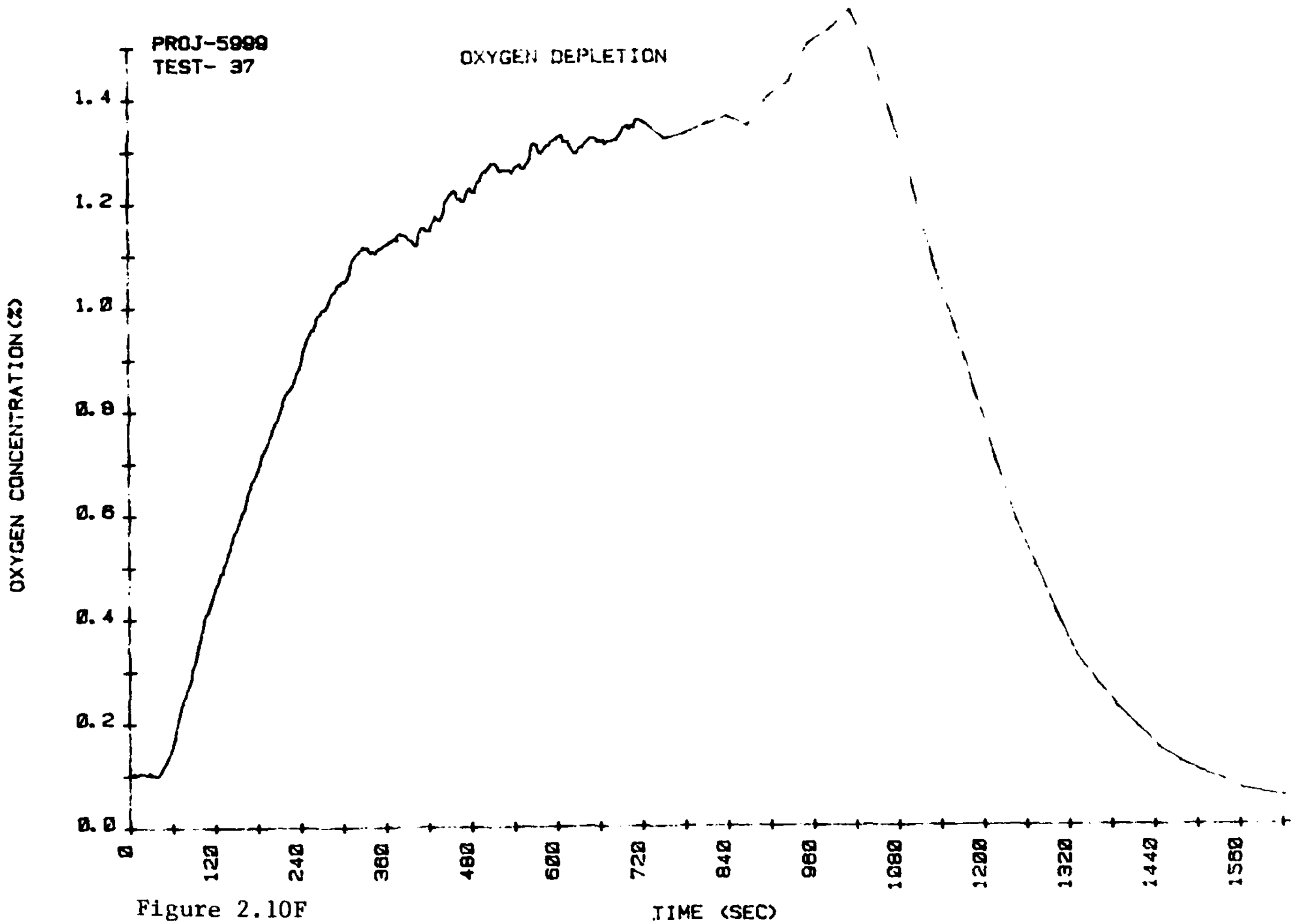
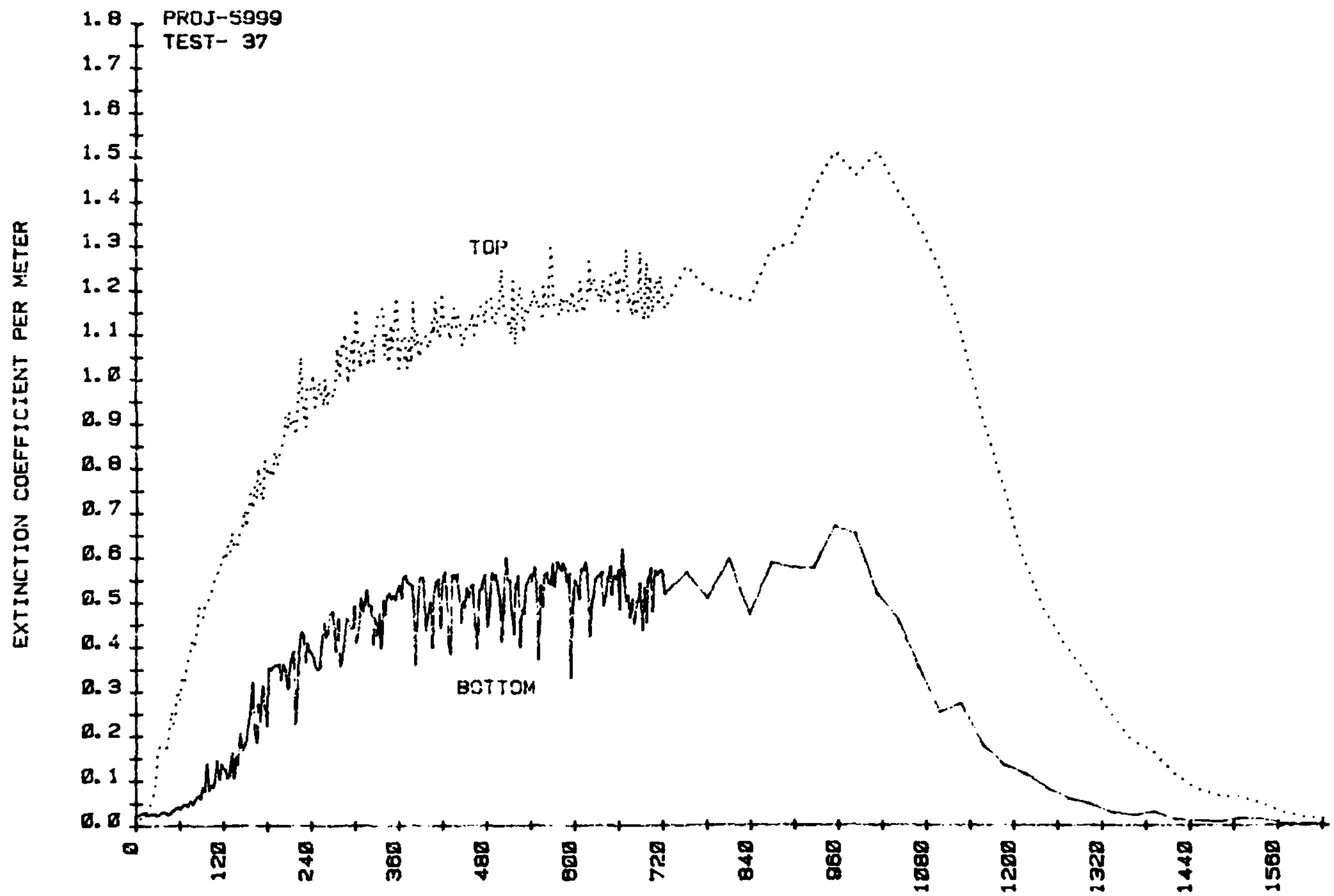

PROJ-5999
TEST- 37
OXYGEN DEPLETION
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
OXYGEN CONCENTRATION (%)
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
TIME (SEC)

Figure 2.10F



PROJ-5999
TEST- 37
TOP
BOTTOM
EXTINCTION COEFFICIENT PER METER
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
TIME (SEC)

Figure 2.10G

FIGURE 2.11 FIRE PORTRAIT FOR 17-IN.-DIAMETER JET FUEL POOL FIRE BURING UNDER VENTILATION PATTERN 2 (TEST 40)*

*(a) heat flux, (b) air temperatures in chamber, (c) supply and exhaust air temperature, (d) carbon dioxide concentration, (e) carbon monoxide concentration, (f) oxygen depletion, (g) extinction coefficient.

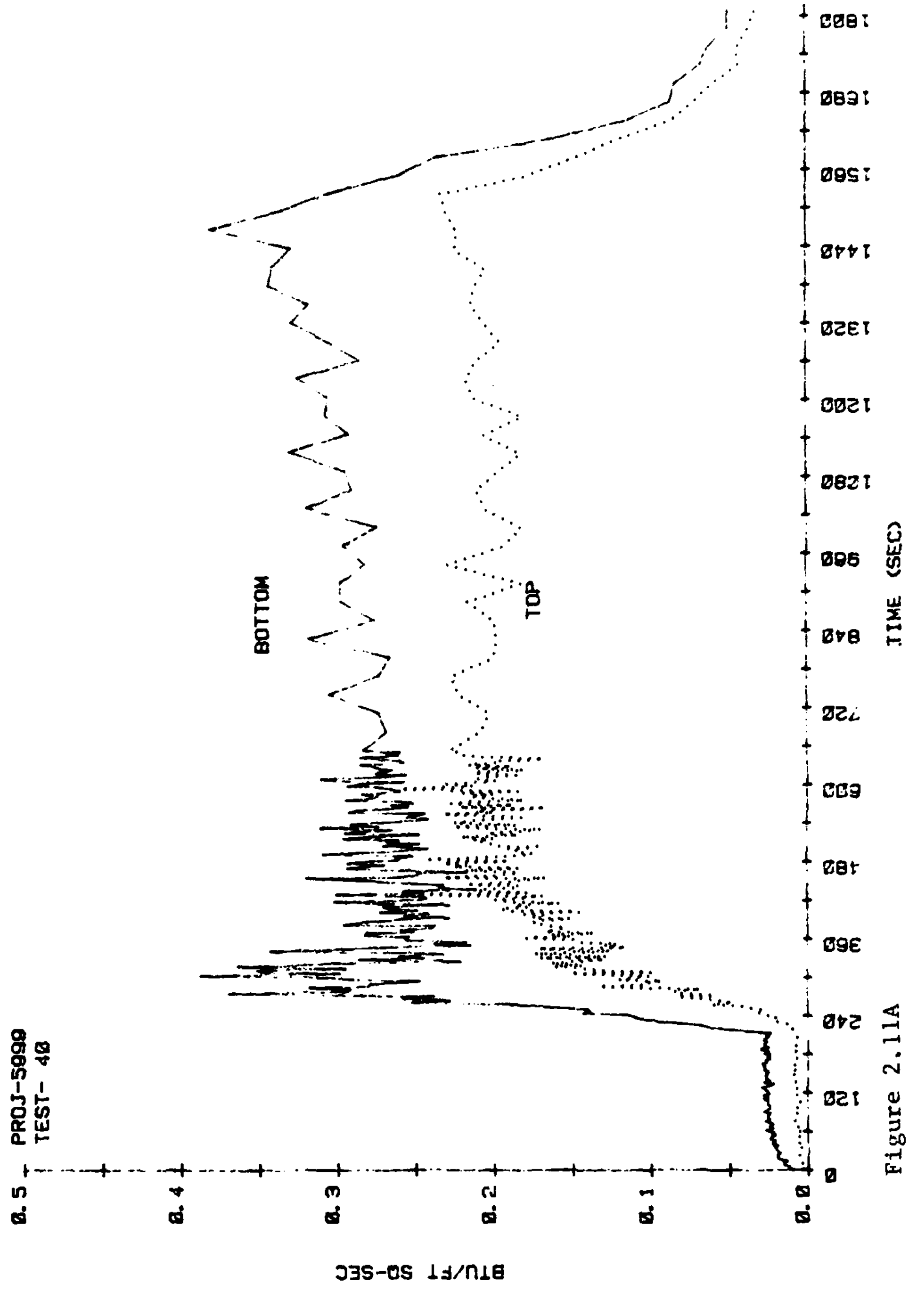

PROJ-5099
TEST- 40
BOTTOM
TOP
BTU/FT SQ-SEC
0.0
0.1
0.2
0.3
0.4
0.5
TIME (SEC)
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800

Figure 2.11A

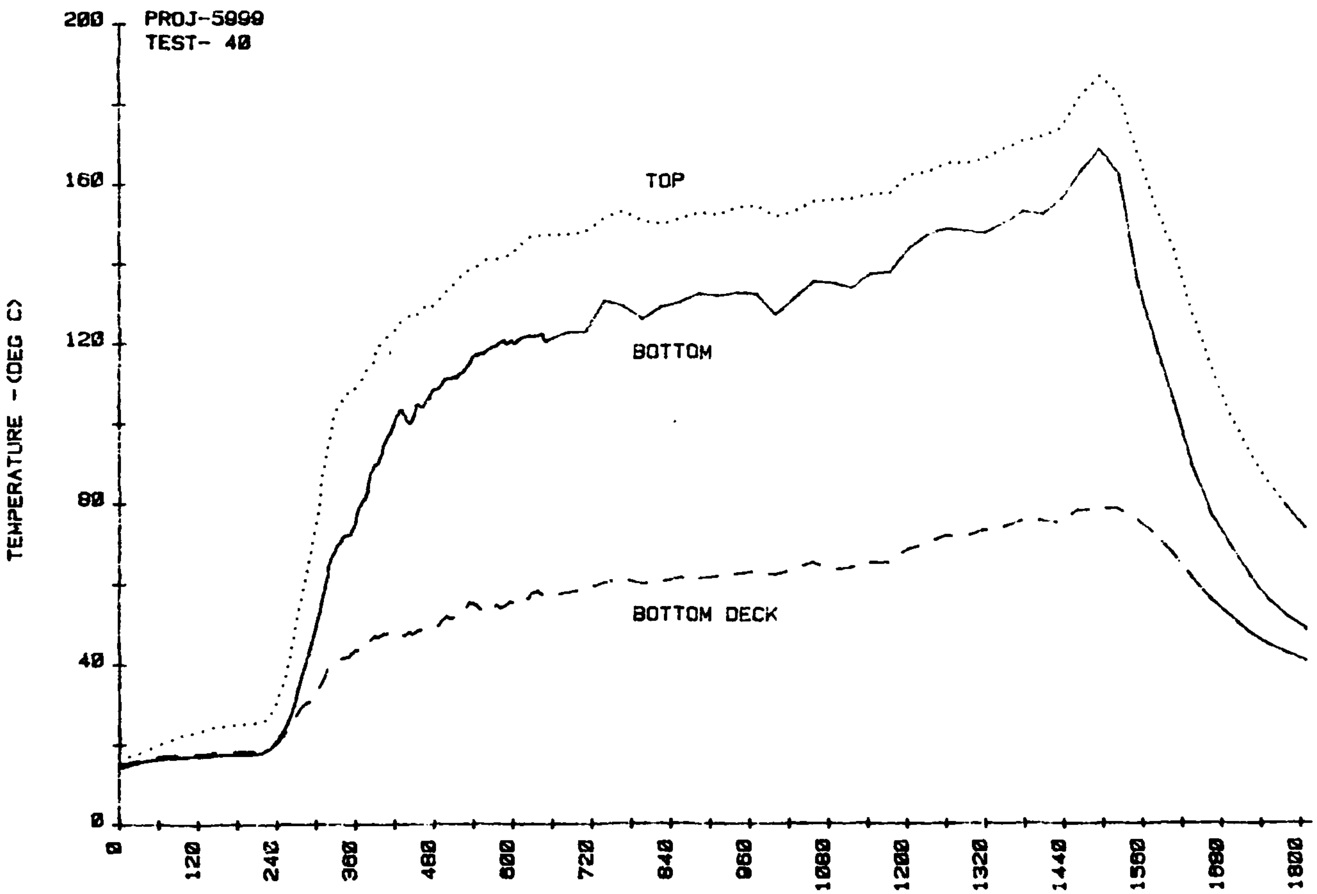

PROJ-5999
TEST- 40
TOP
BOTTOM
BOTTOM DECK
TEMPERATURE - (DEG C)
TIME (SEC)
200
160
120
80
40
0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800

Figure 2.11B

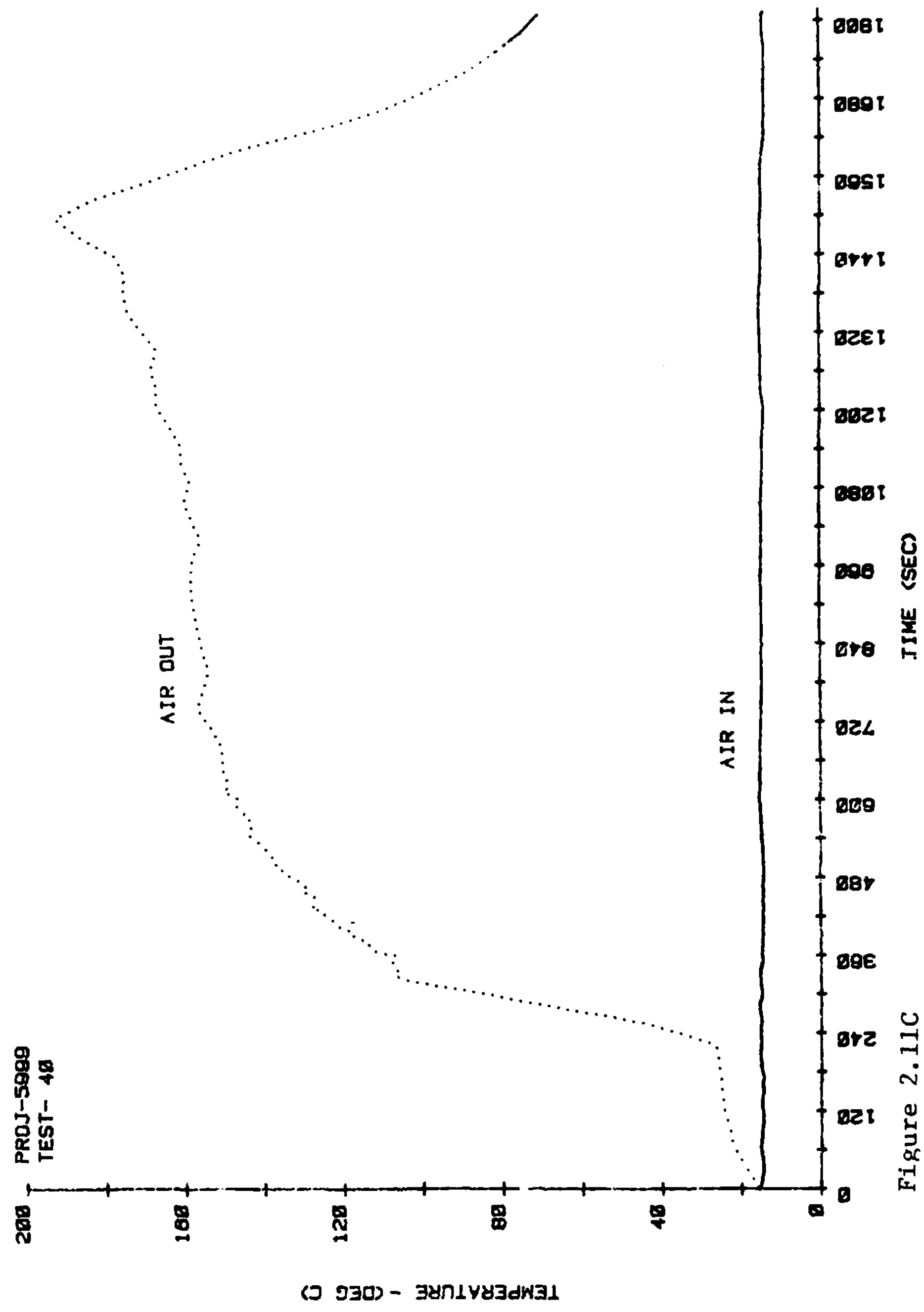

PROJ-5909
TEST- 40
AIR OUT
AIR IN
TEMPERATURE - (DEG C)
TIME (SEC)
0
40
80
120
160
200
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800

Figure 2.11C

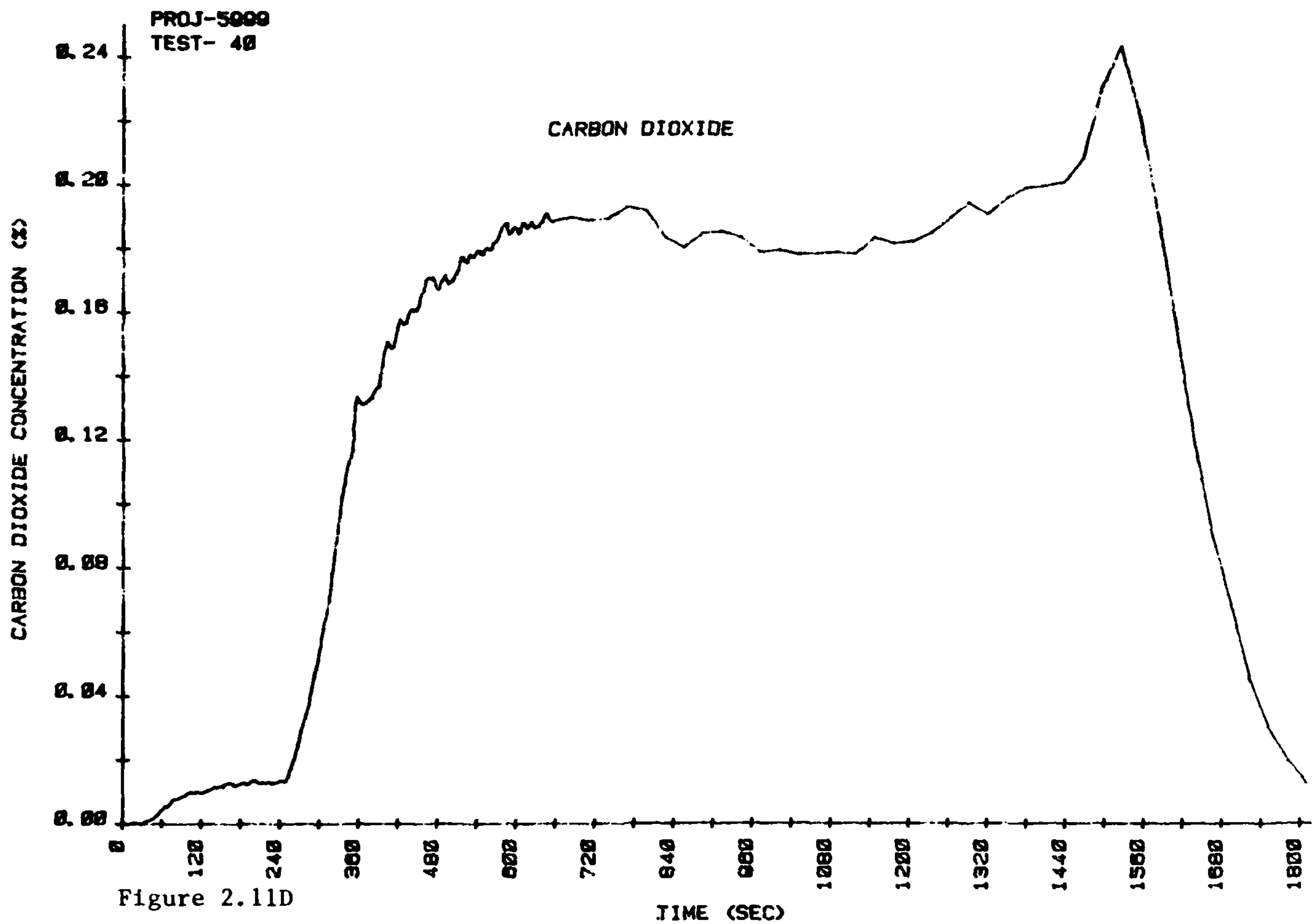

PROJ-5000
TEST- 40
CARBON DIOXIDE
CARBON DIOXIDE CONCENTRATION (%)
0.24
0.20
0.16
0.12
0.08
0.04
0.00
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
TIME (SEC)

Figure 2.11D

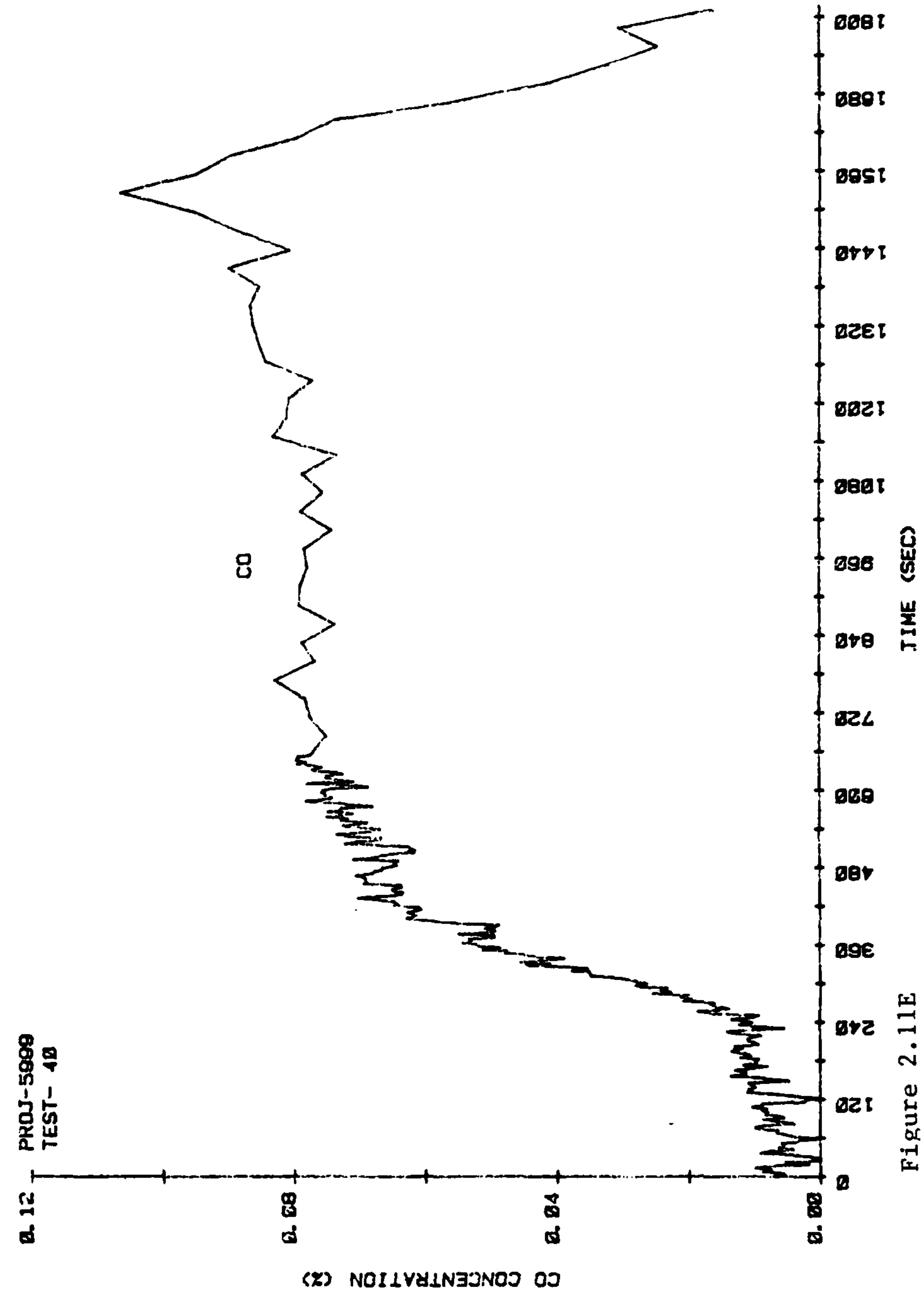

PROJ-5000
TEST- 40
CO
CO CONCENTRATION (%)
0.12
0.08
0.04
0.00
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
TIME (SEC)

Figure 2.11E

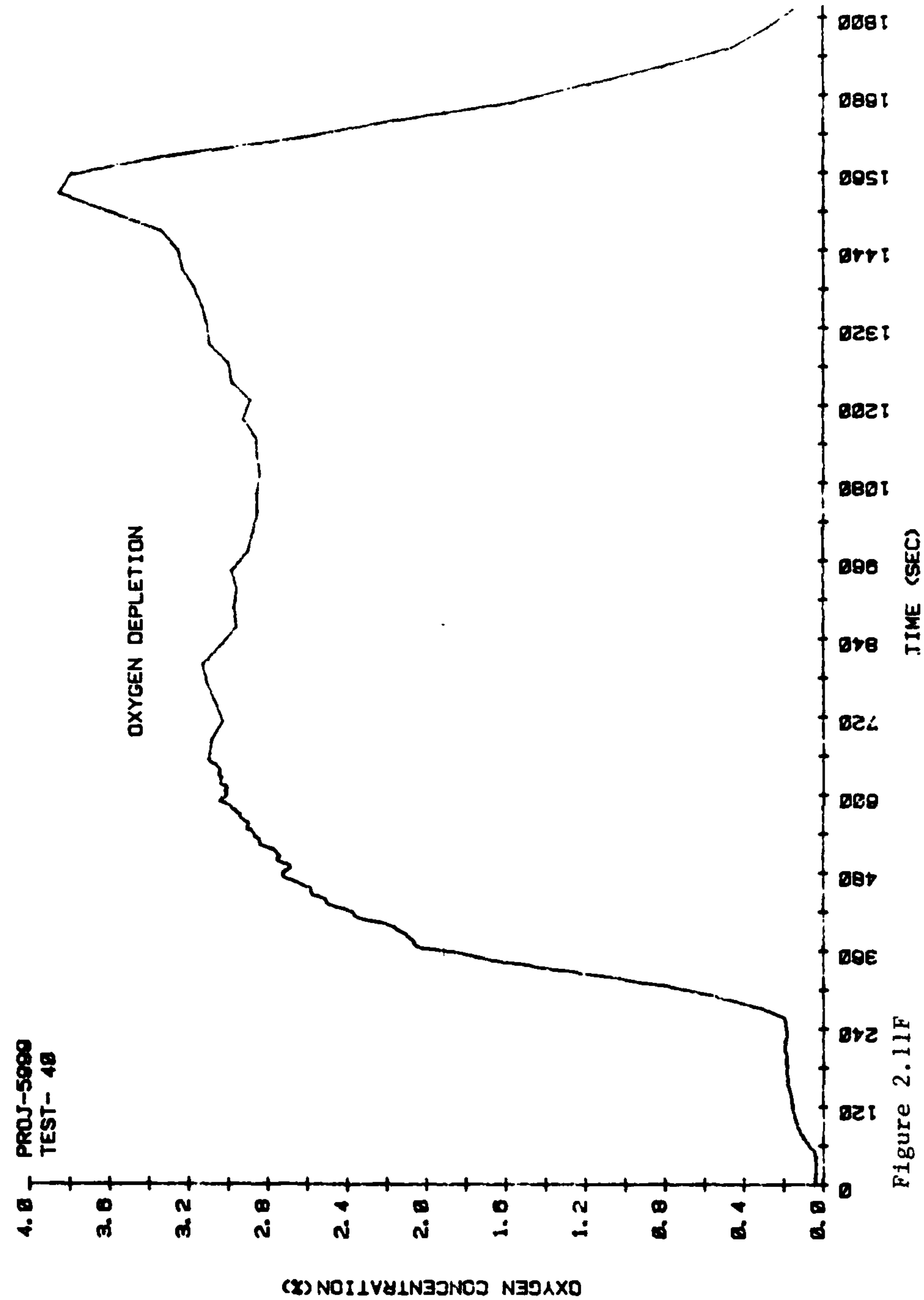
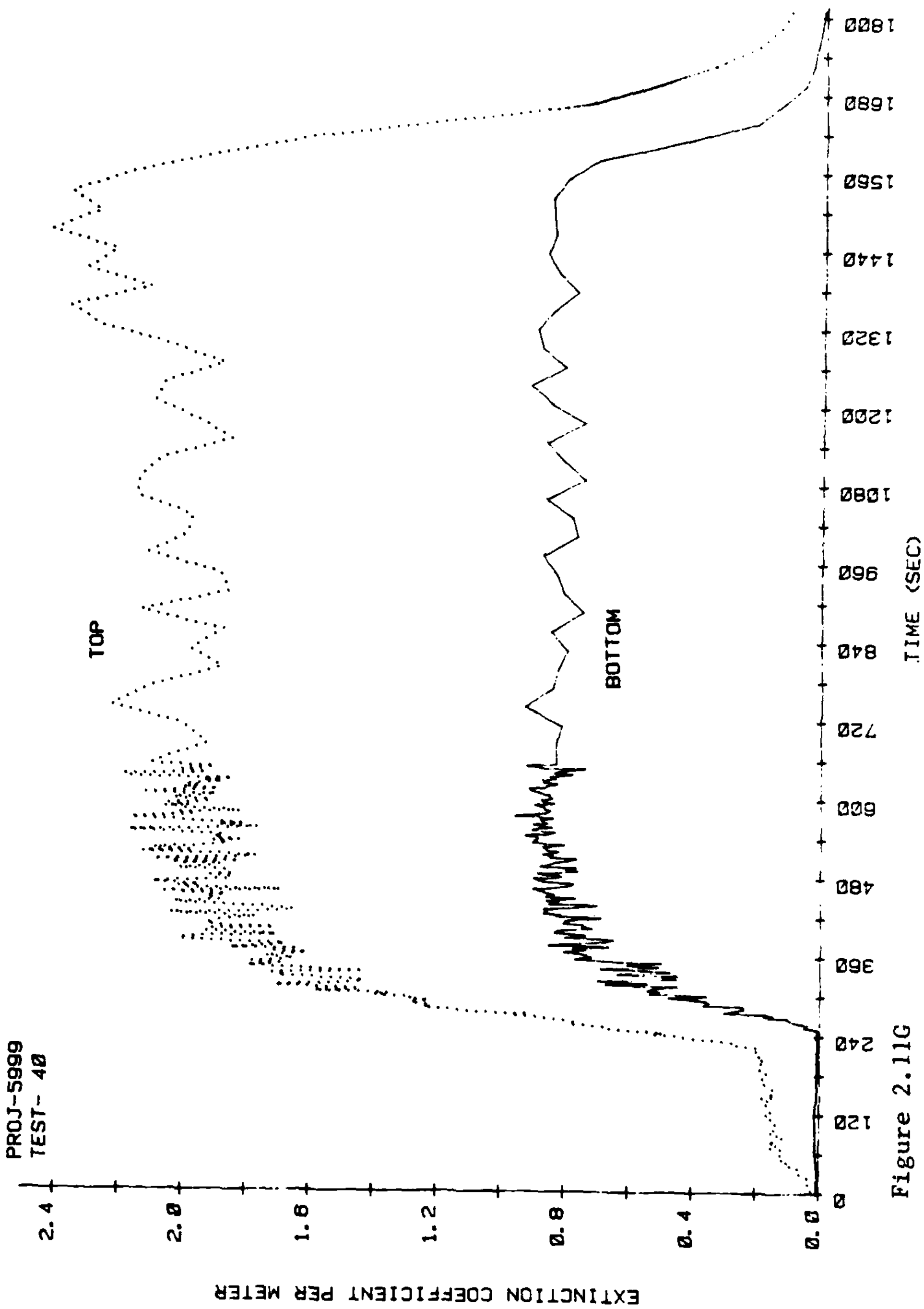

PROJ-5000
TEST- 40
OXYGEN DEPLETION
OXYGEN CONCENTRATION(%)
TIME (SEC)
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
0
120
240
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800

Figure 2.11F


PROJ-5999
TEST- 4Ø
TOP
BOTTOM
EXTINCTION COEFFICIENT PER METER
TIME (SEC)
2.4
2.Ø
1.6
1.2
Ø.8
Ø.4
Ø.Ø
Ø
12Ø
24Ø
36Ø
48Ø
6ØØ
72Ø
84Ø
96Ø
1Ø8Ø
12ØØ
132Ø
144Ø
156Ø
168Ø
18ØØ
Figure 2.11G

3.0 TASK 2. A TEST PLAN FOR SMOKE CONTROL WITH THE LHA-3 COLLECTIVE PROTECTION SYSTEM

This task was initiated on June 16, 1983, at a NAVSEA meeting called to establish test objectives and set forth a schedule. The objectives have remained intact but the availability of the ship for inspection and testing has required numerous revisions of the schedule. Based on the initial rush to have the tests completed in the fall of 1983, on June 30 we submitted "Preliminary Thoughts About Smoke Control Tests for LHA-3 Collective Protection Ventilation Systems." This memorandum reiterated the objectives and listed the current options for smoke control tests. A vigorous response to this memo limited the test options to tracer-gas techniques.

Based on this guidance and a more detailed examination of the CPS design, but still without an opportunity to inspect the ship, we submitted a preliminary test plan on September 29, along with a list of questions to be resolved aboard ship. On December 14 and 15 we were able to board the BELLAUWOOD to inspect candidate test compartments and promising ventilation routes. A few air pressure and air velocity measurements were attempted both at night after most of the crew had departed and during the day when the crew was active. The numerous interruptions during the daytime measurements convinced us that the tests should be conducted at night. After the revised test plan was submitted in January 1984, NAVSEA Code 55X23 requested comments from the pertinent codes. Most of these comments have been incorporated in the test plan of Appendix A. The remaining comments are discussed below.

- "The test compartment should be airtight." Some of the selected compartments are airtight, but others such as the electronics storeroom have louvered doors. This choice is based on the assumption that we should know how best to use the CPS for fire in any of the compartments.

- "What material conditions will be set for the tests and how will these conditions be maintained during the tests?" As indicated in Table A.1 of the test plan, a variety of ventilation conditions are involved; however, in all cases the CPS will operate throughout the tests, including times when the pressurization is sacrificed by opening a door to the weather. The test plan now contains a list of support functions requested from the ship. Foremost among the functions is operation of the ventilation system, including monitoring openings to the weather.

- "Could the tracer gas approach be used to quantify the amount of outside air (contamination) that finds its way into the ship when pressurization is given up?"
  In normal operation this incoming contamination will be a function of the openings and their locations, the ship's speed, and the ambient winds. Preferably, the smoke control tests will be performed in port; thus we plan to control the incoming air with portable blowers and the amount of air will be monitored with anemometers. Although the tracer-gas technique could be used to check incoming contamination under normal operating conditions, a significant effort would be required (i.e., more than the current plan could support).

- "What will be done in peripheral spaces where ventilation may be manipulated by personnel in the space according to what seems to be in their best interest."
  The Minimum Test Series contains no provisions for such extemporaneous modifications to the ventilation. If some such scenarios could be identified, they might be incorporated in the Comfortable Test Series (See Appendix A.)

Current plans for calendar year 1984 include checking the tracer gas simulated fire system in simulated and real fires during the forthcoming NSRDC (Annapolis) smoke control tests at the Coast Guard Mobil Test Facility. It is hoped that this evaluation can be performed before the LHA-3 tests in 1985.

4.0 TASK 3. LAUNDRY SPACE FIRE TEST ABOARD THE ALBERT E. WATTS

This task provided for some assistance to NSRDC Annapolis and their contractor, Engineering Computer Opteconomics, Inc., in planning a series of smoke control and toxic gas removal tests. Our efforts entailed recommendations for instrumentation and predictions of fire behavior based on a model developed for the engine-room fires discussed in Section 2.0. This model is semiempirical in that it uses burning rate curve shapes based on experimental observations with freely ventilated fires. Laundry fires traditionally involve fabrics arranged in various piles. In the absence of curve shape data for such fuels, we used a shape derived from wood-crib fires.

Two ventilation conditions were of interest: (1) all are fans secured so that only the oxygen leaking from other spaces is available and (2) the exhaust fan is restarted 30 seconds after a shutdown that was initiated when the fire was detected. Under these conditions, and with a fuel loading of 400 lb, the model predicted ventilation-controlled fires for both ventilation conditions. This prediction shows reasonable agreement with the test results for the *secured-ventilation* case, but not when the exhaust fan was restarted.

Test data for fuel consumption and gas analysis provided evidence regarding the factor controlling the burning rate. For example, the model predicts that 46 lb of fuel would be consumed in 30 min for the free air compartment volume of 1232 ft^3 and a leakage rate of 125 cfm used in the initial estimates. Data from the secured compartment tests (i.e., 10, 12, and 14) reproduced in Table 4.1 show fuel consumptions at 30 min ranging from 27 to 43 lb. Furthermore, the linear weight loss at times after the resident air has been consumed are appropriate to ventilation control. Finally the low oxygen concentrations (i.e., 8% to 11%) are near the lower limit for flaming combustion.

In the case where the exhaust fan was restarted, assuming an exhaust rate of 1500 cfm, the model yields a fuel consumption of 430 lb in 30 min of ventilation-limited burning, in contrast to the 67 lb listed in Table 4.1 for Test 16. Apparently this arrangement of the fabrics results in a fuel-limited fire and the thermal threat did not approach flashover as appeared marginally possible according to the model. Also, the oxygen concentration indicates the fire was fuel-controlled. Clearly, data are needed on freely burning fabric piles to establish an appropriate energy release rate curve. The water spray in Tests 11, 13, and 15 both reduces the burning rate and prevents weight loss measurements; hence, the model cannot deal with that situation.

Observations with the IR camera through the test compartment window in the starboard bulkhead and visual inspections through the window next to the laser densitometer provide some additional information about the burning characteristics of the fires, particularly the nonuniformity of the burn pattern. In the tests we observed (i.e., 10 through 16) this nonuniformity was pronounced. Usually the fire burned the fuel in the pile on the right of the door entrance and consumed little of the larger pile on the left. Only in Tests 13 and 14 was most of the fire located on the left. In Tests 11, 13, and 15, the water spray extinguished burning or prevented fire spread to most of the fuel; consequently, the amount of fuel consumed was not greatly different from the ventilation-limited cases. However, the presence of the water spray does not explain the asymmetry observed in the even-numbered tests.

Other possible factors include (1) differences in the packing density, material, and geometry of the fuel piles, and (2) nonuniformity in the ignition pattern. Test 16 was unique in this group of tests because it was not sprinkled and had an abundance of air. Nevertheless, only the fuel in the pile to the right burned. The fire failed to establish itself in the principal fuel supply, which was on the left. Consequently, when the small pile of fuel on the right was consumed, the fire died down. Such asymmetrical behavior precludes predicting the fire behavior with a simple model based on ventilation rates and reproducible burning characteristic. Although smoke control and the effectiveness of the sprinkler can be demonstrated without fire uniformity, for prediction purposes it is necessary to remove some of the uncontrolled variables.

Table 4.1

FUEL CONSUMPTION AND COMBUSTION PRODUCTS OBSERVED IN LAUNDRY ROOM FIRE TEST

				Gas Concentration (%)					
			Fuel	O_2			CO_2		CO
Test No.	CPS Condition	Vent Status	Burned (lb.)	Minimum	At 30 Min.	Max	At 30 Min.	Max	At 30 Min.
10 C	Yes	1	27	6	11	10	3.7	2.5	0.6
10 P	Yes	1		19	19	1.7	1.7	1.7	0.4
11 C	Yes	2		9	18	10	2.4	1.8	.01
11 P	Yes	2		22	22	0.09	0.09	0	0
12 C	Yes	1	29.4	8	8	11	10.9	1.6	1.6
12 P	Yes	1		22	22	1.1	1.1	0	0
13 C	Yes	2		17.5	21	5	1.4	0.01	0
13 P	Yes	2		22	22	0.3	0.3	0	0
14 C	No	1	43.4	7	9	18	10.5	1.7	1.7
14 P	No	1		22	22	1.6	1.6	0.5	0.5
15 C	No	2		16	20	7	1.9	0.25	0.25
15 P	No	2		22	22	4	4	0.1	0.1
16 C	No	3	66.7	10	18	11	2.2	0.5	0.3
16 P	No	3		22	22	0.7	0.5	0.12	0.12

C = Compartment at 72-in. elevation
P = Passageway at 48-in. elevation
1 = Sealed
2 = Exhaust restarted + spray in compartment
3 = Exhaust restarted, no spray.

Appendix A

PROPOSED SMOKE CONTROL TESTS FOR LHA-3 COLLECTIVE PROTECTION SYSTEM

1.0 FIRE THREATS IDENTIFIED IN THE CPS ZONES

After an inspection of the LHA-3 and discussions with the crew, three class A and/or C fire scenarios were identified as potential threats to the ship's performance.

1.1 Threat 1 - Small Accidental Fires in Occupied Compartments

When the ship is underway and particularly in the CPS condition, a large majority of the compartments in the superstructure are manned 24 hours per day; consequently, the occupants should detect the fire promptly and successfully extinguish it with portable extinguishers. Because these compartments house valuable and vital electronic equipment, CO_2 is currently the preferred agent. Such prompt action should extinguish the fire before there is time to adjust the ventilation, so ventilation activity is limited to desmoking after the fire.

1.2 Threat 2 - Large Accidental Fire at Sea or In Port

A few compartments such as the electronics spare parts storeroom are unmanned most of the time and, in this example, the high fuel loading of readily combustible cardboard and plastic foam could support an extensive, rapidly developing fire. In port, a large number of compartments were deserted and locked while the crew was ashore, particularly at night; consequently, a fire could reach a high state of fuel involvement before detection. The smoke and heat from such fires could seriously impede the fire fighters in their attack. Saltwater hand lines are the only available system for dealing with such fires and their use will interfere with some of the electrical circuits, perhaps even the ventilator fans.

1.3 Threat 3 Battle Inflicted Fires

If a battle inflicted hit punctures the external CPS zone boundary, a modest hole (e.g., 6-in. diameter) could reduce the zone pressure substantially. With such a modest hole, the escaping air could prevent the entry of contaminants, but with a large hole the CPS would be overwhelmed. In either case, sufficient air would be available to support a sizeable fire, and the compartment occupants would not likely be in condition to attack the fire. As in the case of the large accidental fire, the problem is to reach the fire and extinguish it with hand lines; however, an additional ventilation option has been introduced namely, direct access to the weather through the hole.

2.0 OBJECTIVES

The overall goal of the proposed tests, is to determine the capability of the collective protective ventilation system to control and remove smoke both during and after fires in the CPS zones of the LHA-3. Specifically, four levels of capability are of interest namely, the ability to

(a) Confine smoke to the compartment of origin and a well-defined path to an exhaust point, and prevent leakage to areas where essential functions are performed. Presumably compartments with a dedicated exhaust duct or other direct access to the weather are best suited to this degree of control.

(b) Restrict escaping smoke to zone and level of origin (i.e., minimize interference with vital parts of the ship).

(c) Maintain a cool, clear passageway from an access point to the fire compartment so that firefighters can reach the seat of the fire.

(d) Desmoke area after fire is extinguished; that is determine the time to restore access to the affected area.

The objective achieved will depend on the fire location and the degree of severity. Generally, for the three fire threats identified in Section 1.0, the following objectives should apply:

- Threat 1, small accidental fires, objectives (a) and (d) i.e., extinguish fire and desmoke without loss of CPS conditions or evacuation of neighboring compartments.
- Threat 2, large accidental fires, objectives (d) and (c) i.e., maintain a clear path for the fire fighters.
- Threat 3, large fire from hit, objectives (b) and (d) i.e., control fire without losing battle worthiness and minimize compromise of CPS condition.

3.0 APPROACH

Implementation of the proposed tests is subject to the constraints and variables identified in the following subsections. We also discuss the measurements and instrumentation to be used in the tests.

3.1 Constraints Imposed By the Ship

- Limit ventilation options to rates and patterns that can be achieved with the ship system possibly augmented with portable blowers. There are no reversible supply fans in the system; therefore, only compartments equipped with ventilation exhausts to the weather can be desmoked directly without feeding smoke through a passageway or other compartment.
- No special dampers or bypass ducts are to be used in the tests.
- Many compartments in the CPS zones are filled with valuable electronic equipment and computers; consequently, smoke simulations are limited to trace-gas techniques.
- Normal ship activities, both at sea and in port, with people coming and going, opening and closing of doors, and hatches in uncontrolled patterns would complicate and prolong the test effort; therefore, it would be desirable to conduct the tests just before an overhaul commences.

3.2 Test Variables

3.2.1 The Fire Compartment

With regard to fire analysis, the pertinent characteristics of a compartment are size, ventilation rate and patterns, type of fuel, and the fuel loading. With nearly 100 compartments enclosed in the two CPS zones, the potential variety is substantial. The compartments selected for the tests should permit evaluation of the various options and paths for smoke removal:

- Exhaust through ventilation exhaust ducts to the weather
- Exhaust through air locks or doors that can be unsealed
- Exhaust through the elevator shaft
- Exhaust through pressure control dampers.

Other considerations include protection of the valuable electronic equipment, remoteness from the weather, and competition between the desired smoke flow path and undesired paths such as through hatches to other decks.

3.2.2 Ventilation

Three ventilation parameters are of concern:

- The air flow pattern both within and outside the compartment
- The ventilation rate
- Leakage through intended ports and unintended cracks and joints.

The various smoke control options, will be evaluated by comparing them to the case where the ship's fire fighting doctrine is followed for the test space. Two general ventilation conditions are of concern.

- The CPS zones remain pressurized throughout the smoke removal
- Pressurization is sacrificed in the interest of smoke removal.

3.2.3 Smoke Simulation

Fires come in all sizes as illustrated by the threats described in Section 1.0, but the smoke and heat become a problem only when the fire is large enough to evict personnel in vital compartments or to keep the fire fighters away from the fire. Threats 2 and 3 (Section 2.0) should be simulated by fires that are about as large as the compartment can support in the ventilation-controlled condition before the air supply is secured. Two characteristics of the real fire are of concern in this simulation: (1) the rate of smoke production, and (2) the increased volume of gas that provides a force to drive smoke out of the fire compartment. Appendix (B) discusses the need for several standard smoke production curves and the pros and cons of following various fire development patterns. It is hoped a consensus will be reached before the LHA-3 tests are performed, but for our planning purposes we will assume the following smoke production versus time characteristics.

- The Minimum Test Series would use steady state patterns; for example, Threat 1 simulations, a rectangular pulse of smoke simulant (SF_6) would be released and a stair-stepped pattern would be followed for Threats 2 and 3.

- The Comfortable Test Series would use both the steady state and the transient Smoke Production Patterns.

3.3 Measurements and Instrumentation

Three types of measurements are required to monitor the CPS behavior: (1) concentration of the tracer gas, (2) air flow velocities, and (3) air pressures. Continuously recording instruments are preferable to grab samples or devices that only give indication so that all the data can be accumulated in a small computerized data acquisition system. In the simplest test (i.e., a threat 1 fire) a minimum of 7 channels would be required as listed below.

- 3 gas concentration detectors, e.g., a continuous SF_6 trace-gas analyzer as shown in Figure A.1.

- 1 air flow meter (propeller-type ananometer)

- 1 air temperature thermocouple

* 2 pressure differential gages (one at the compartment and one at the exhaust port).

In most cases we would expect more than one leakage path and a variation of gas concentration with height in the chamber and passageway so additional gas detectors would be desirable, e.g., at least 10 channels. In the comfortable level of effort, about twice that number of channels would be desirable.

Figure A.2 (A-E) shows sensor locations for the various proposed test compartments.

4.0 PROPOSED TESTS

4.1 Minimum Effort

Table A.1 lists 18 proposed minimum effort tests, 8 in Zone 5 and 10 in Zone 6 on the 04 level. Compartment locations were selected to accommodate the indicated fire threats and smoke control objectives. The numbers in the Smoke Control Action column have the following meanings:

(1) Zone is pressurized and normal ventilation persists during the trace-gas release. The compartment is desmoked through normal exhaust ports without sacrificing pressure.

(2) Normal pressure and ventilation during the trace-gas release. Desmoke with CPS fan; however, sacrifice pressure by opening door to fire compartment and air lock doors to RAS station.

(3) Same as (2) but augment desmoking with portable blowers pulling air from opening to weather at forward end of passage to simulate the draft that could be generated by forward motion of the ship.

(4) Zone is pressurized, but recirculation fans are secured during trace-gas release. Desmoke through normal exhaust ports without sacrificing pressure.

(5) Zone CPS fan operates, but pressure is sacrificed throughout the test by opening the air lock doors to the RAS station. Desmoke compartment by opening fire compartment door.

(6) Same as (5) plus augmented air flow as in (3).

(7) Open escape hatch to simulate hole generated by hit. Compartment closed and recirculation secured throughout trace-gas release. Desmoke with CPS fan through normal channels and the simulated battle damage hole.

(8) Same as (7) plus augmented air flow as in (3).

(9) Same as (2) except exhaust to weather through the escape hatch is 4-85-3-Q during desmoking.

(10) Same as (9) plus augment air flow with portable blowers.

(11) Same as (5) except exhaust air through escape hatch is 4-85-3-Q.

(12) Same as 11 plus augment air flow with portable blowers.

(13) Same as (4) except keep exhaust fan operating throughout test.

The time required to conduct the tests will depend strongly on the time required to desmoke the zone, but a week of uninterrupted effort should be adequate, with an additional three days to install the analysis equipment in 04-77-1-Q.

4.2 Comfortable Efforts

This effort includes all the steady state tests of the minimum effort plus a series of transient tests where the simulation scenario follows the temporal pattern of fire development and fire suppression. The sequence of events in such a scenario is as follows:

- Time t_0: While the compartment is under normal ventilation conditions, the simulated fire is initiated.
- Time t_1: Intervention is initiated, and the compartment ventilation supply is secured. (If there is a dedicated exhaust, it may be continued.)
- Time t_2: The ventilation option to control the smoke is initiated if it involves starting other fans or opening discharge ports.

- Time t_3: Fire fighters open the compartment door slightly to simulate an attack on the fires. Commence reduction of smoke release rate. Increase air supply in room to simulate pressure increase and mixing caused by steam generation when water is applied to a real fire.

- Time t_4: Fire is extinguished; secure tracer gas.

- Time t_5: Commence desmoking procedure; i.e., either a continuation of the operation commenced at t_3 or another alternative such as the addition of portable blowers.

- Time t_6: Test is complete when the smoke level (i.e., the tracer gas concentration in the fire) soon reaches one-half the value observed at t_5.

These times will be selected on the basis of the fire's burning rate curve and the typical times needed to be performed the various initiation steps.

Table A.1 also lists these additional tests (19-22). Most of these more realistic fire exercises involve the previously used compartments on the 04 level; however, several tests would also take place on the 05 level.

5.0 SUPPORT REQUIRED FROM SHIP

To minimize the interference between the tests and other activities aboard ship, we proposed to perform the tests at night. Some of the test equipment--such as the portable blowers required in Tests 3, 6, and 8 and the fan to disperse the tracer gas in the fire test room will--interfere with traffic and routine operations. In addition to accommodating this interference, ship manpower and support will be required to perform the following functions:

(a) Operate the CPS and control the doors between zones or to the weather (i.e. to maintain the CPS condition).

(b) Monitor the ship's Magnehelic pressure gages and record the readings as needed.

(c) Operate the local ventilation system (i.e., those affecting the fire test room and its neighbors).

(d) Supply electrical power to the blowers and test instruments.

(e) Provide communication over the ship's speaker and or phone system (i.e., between the assisting ship manpower and the civilian test personnel).

6.0 ANTICIPATED RESULTS AND THEIR PRESENTATION

We expect the test results can be analyzed to provide a report containing three catagories of information:

(1) A determination of system performance: Specifically patterns and rates of smoke spread and half-life for smoke removal should be determined for the various modes of smoke control.

(2) Contribution to the ship's fire fighting doctrine: The tests should indicate the most effective use of the system and portable fans for smoke control in the event of fire.

(3) Design guidance to improve smoke control: Examples include establishment of smoke removal routes and location of emergency escape scuttles, together with use of portable fams for smoke removal.

Table A-1

PROPOSED SMOKE CONTROL TESTS

Test No.	Zone	Room	Fire Threat	Smoke Pattern	Smoke Control Objective	SRI Figure No.	Smoke Control Action
	Minimum Test Program						
1	5	04-73-1-C	1	 1 min	Desmoking after fire	2A-1	(1)
2	"	"	"	"	"	"	(2)
3	"	"	"	"	"	"	(3)
4	"	"	2		Maintain clear passage and keep	"	(4)
5	"	"	"	"	smoke out of other compartments	"	(5)
6	"	"	"	"	"	"	(6)
7	"	04-65-1-C	3	"	"	2A-2	(7)
8	"	"	"	"	"	"	(8)
9	6	04-79-3	1		Desmoking after fire	2B-1	(1)
10	"	"	"	"	"	"	(9)
11	"	"	"	"	"	"	(10)
12	"	04-85-1-A	2		Maintain clear passage and keep	2B-1	(4)
13	"	"	"	"	smoke out of other compartments	"	(11)
14	"	"	"	"	"	"	(12)
15	"	"	"	"	"	"	(13)
16	"	04-85-3-Q	"	"	"	2B-3	(4)
17	"	"	"	"	"	"	(11)
18	"	"	"	"	"	"	(12)
	Comfortable Test Program						
19	5	04-73-1-C	2	Transient	Maintain clear passage and keep	2A-1	(5)
20	"	"	"	"	smoke out of other compartments	"	(6)
21	"	04-65-1-C	3	"	"	2A-1	(7)
22	"	"	"	"	"	"	(8)

ATMOSPHERIC
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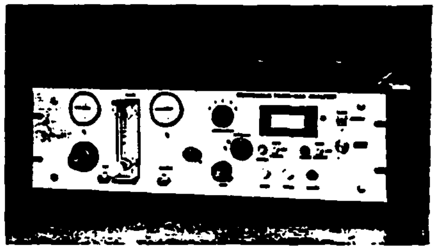
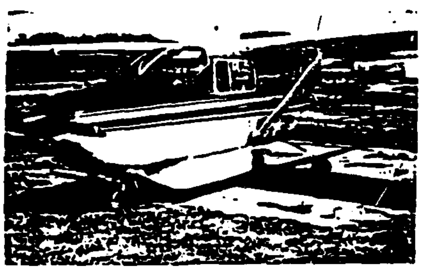
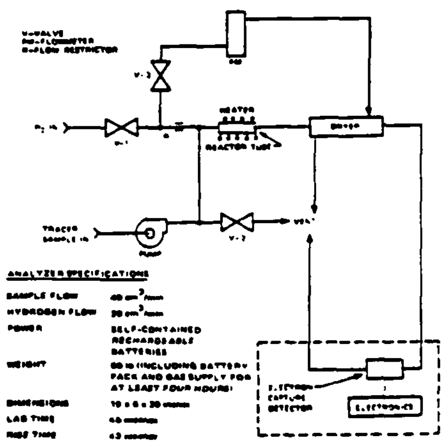
CONTINUOUS SF_6 TRACE-GAS ANALYZER

DESCRIPTION

The trace gas analyzer provides a new proven capability for continuous, real-time measurement of very low concentrations of inert tracer gases, including SF_6, freons, and perfluorocarbons. The instrument is based on a design by R. Dietz of Brookhaven National Laboratory, and J. Lovelock, University of Reading, England. A heated reactor is used to remove interfering atmospheric gases and oxygen from the air sample, and an electron capture detector is the sensing element. The analyzer is field portable, and its fast response time (~3 sec) and high sensitivity (~5 ppt) make it ideal for use in micro- and mesoscale transport and diffusion experiments using both aircraft and mobile, surface sampling vehicles. The analyzer is also well-suited for use in studies of building infiltration, ventilation, and pollutant source reconciliation.







FLOW DIAGRAM OF CONTINUOUS REAL-TIME SF_6 ANALYZER

Figure A.1

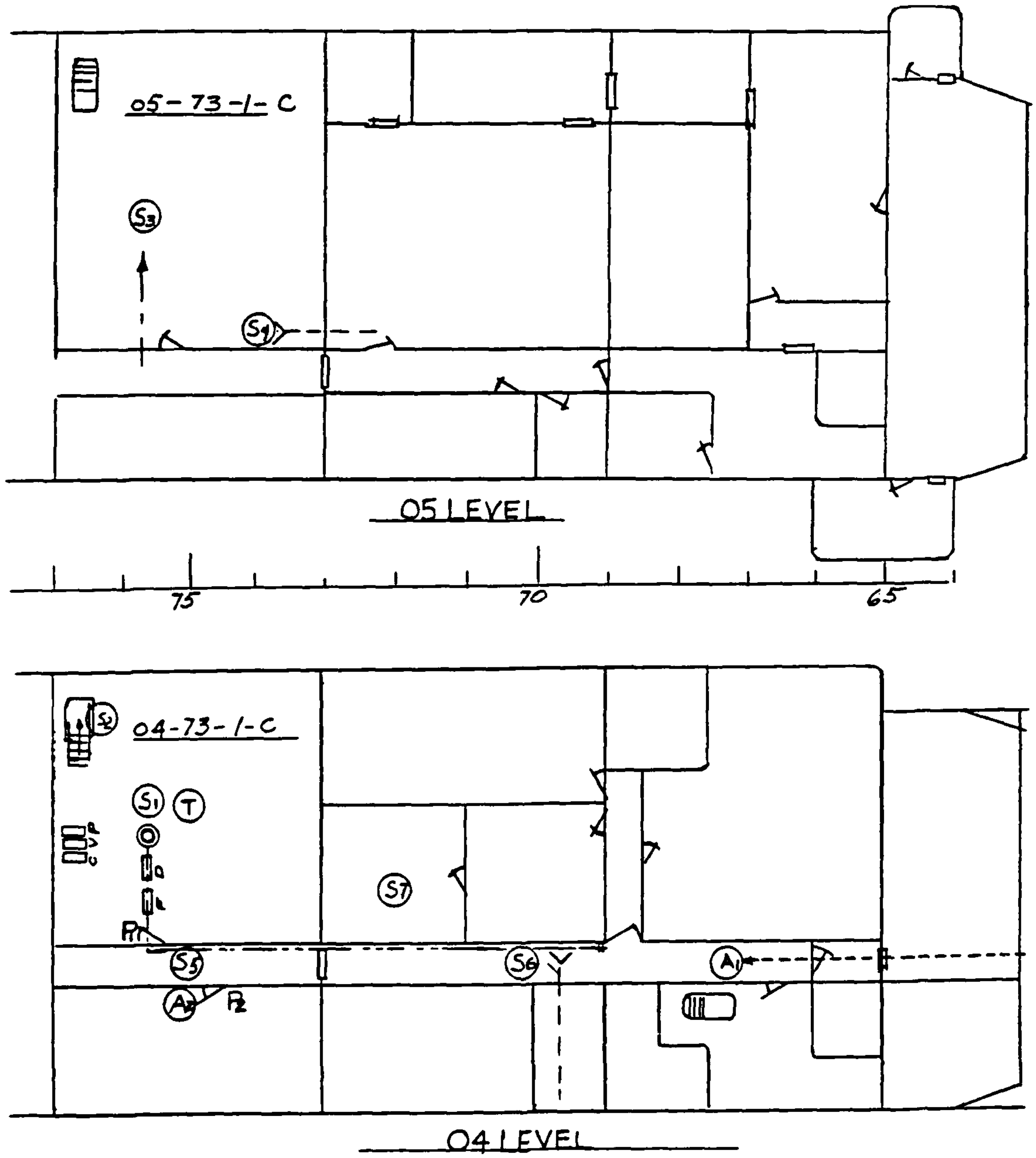


Figure A.2(a) TEST EQUIPMENT LOCATIONS FOR TESTS 1,2,3,4,5,6,19,20

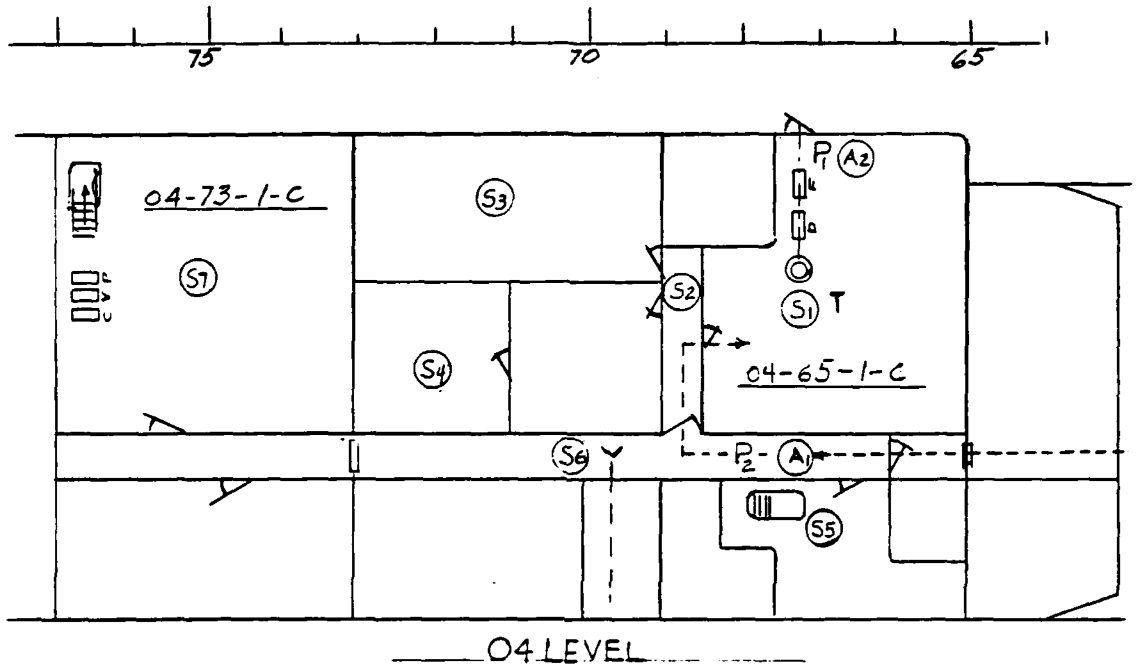


Figure A.2(b) TEST EQUIPMENT LOCATIONS FOR TESTS 7,8,21,22

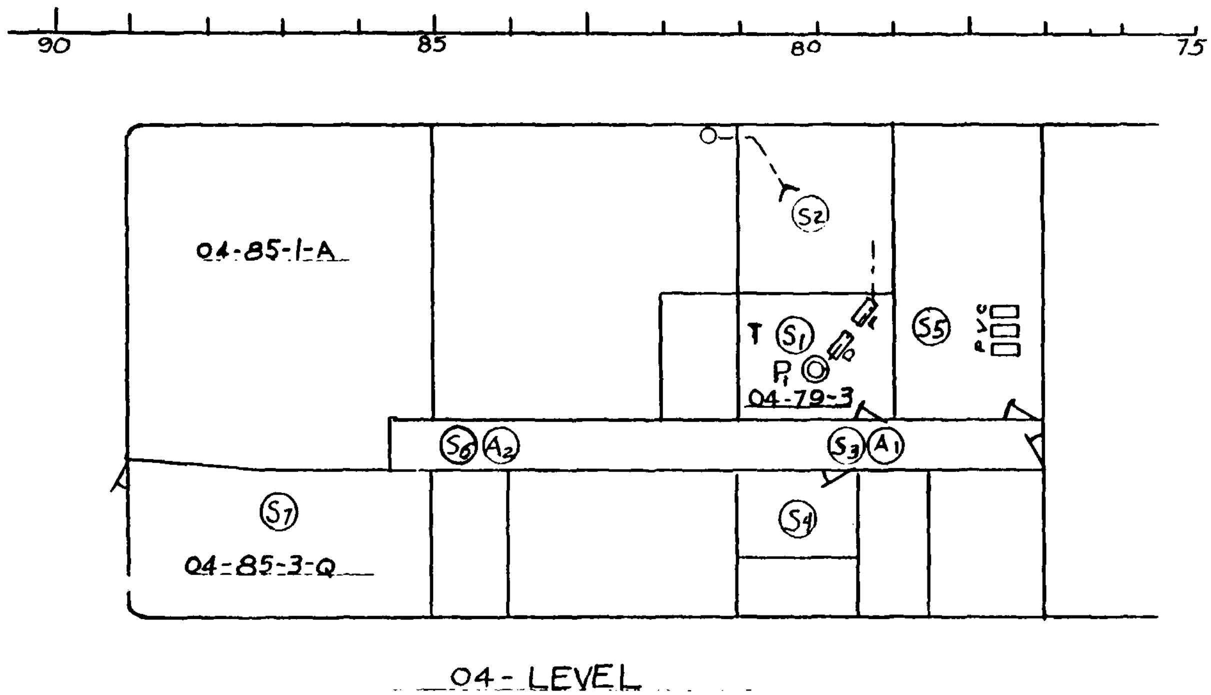


FIGURE A.2(c) TEST EQUIPMENT LOCATIONS FOR TESTS 9,10,11

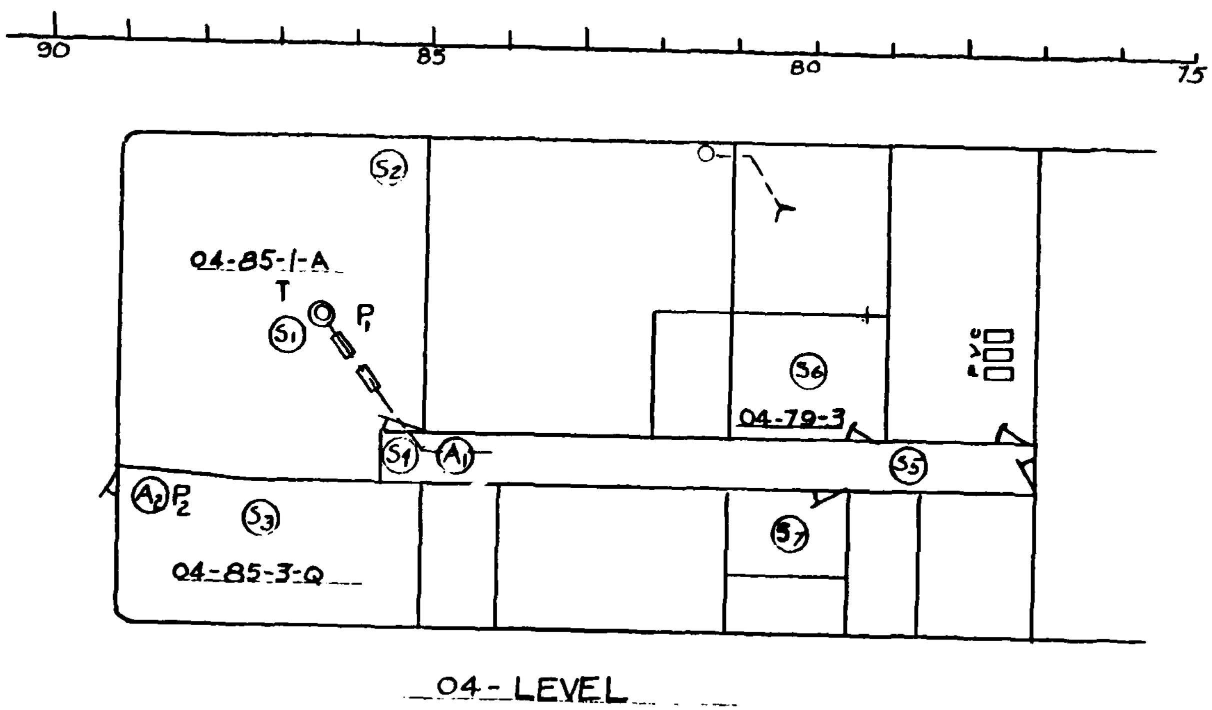
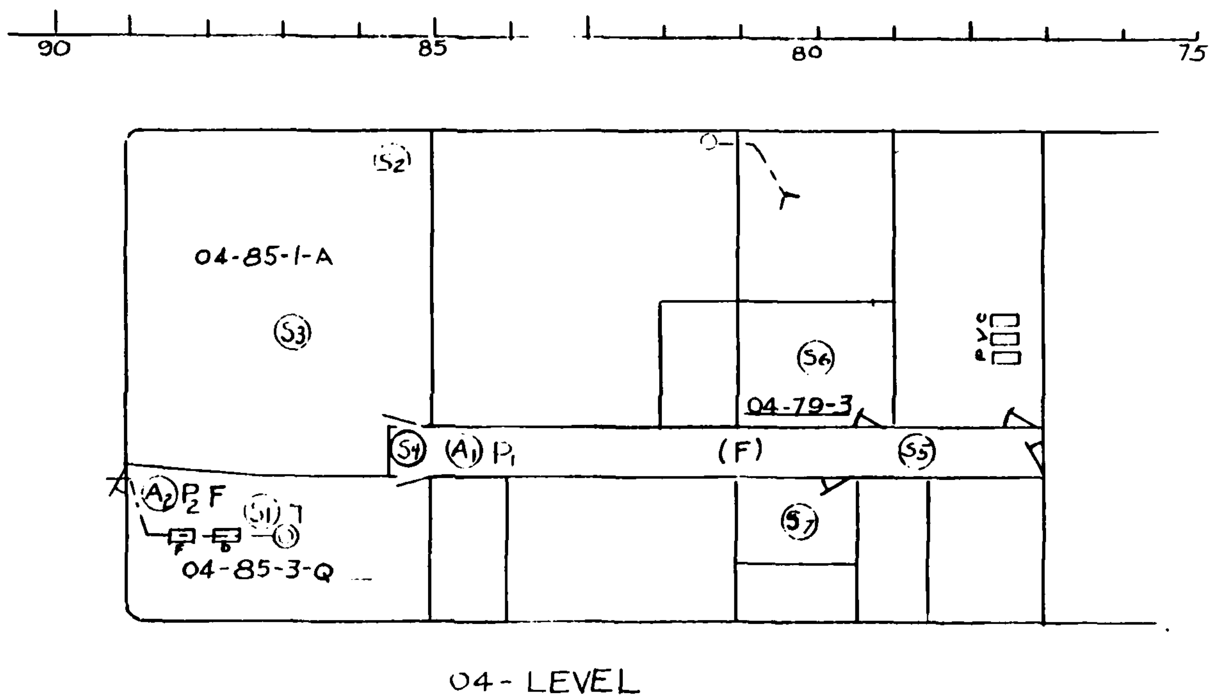


Figure A.2(d) TEST EQUIPMENT LOCATIONS FOR TESTS 12,13,14,15



Figures A.2(e) TEST EQUIPMENT LOCATIONS FOR TESTS 16,17,18

Appendix B

MEMO

TO Mr. David Kay
Code 55X23
Naval Sea Systems Command
Washington, DC 20362

DATE 12/13/83

FROM R. S. Alger

LOCATION PS-157

SUBJECT Simulated fires for smoke control tests

CC

References:

1. J. B. Fang, "Fire Endurance Tests of Selected Residential Floor Construction" NBS IR 82-2488, April 1982.

2. C. D. Coulbert, "Enclosure Fire Hazard Analysis using Relative Energy Release Criteria", JPL Publication 78-51, Dec. 1978.

3. R. S. Alger et al., "Ventilation Controlled Fires", SRI Report on Contract N00014-82-K-2026, Feb. 1983.

1.0 General Requirements

Existing and proposed smoke control programs in the Navy involve several organizations and a potential for tests in various ships and experimental compartments. Under such conditions, it is desirable to have some standards or yardsticks by which the results from different tests and different organizations can be compared. The use of one or more standard fires would be a step toward comparability. This memo outlines some test objectives and the types of fires and tests suitable for achieving these objectives.

2.0 Test Objectives

The following performance characteristics of the smoke control system are of interest:

- Steady State capacity of the system + procedure; i.e. the rate of smoke production the system can handle continually without smoke migration away from the fire compartment and the exhaust path. In this case the rate of smoke production should increase slowly with time so that a quasi-steady state smoke concentration is maintained. The pattern of the increase is not critical as long as the growth is not too fast.

- Transient capacity of the system + procedure. Most serious compartment fires can overwhelm the smoke control equipment existing aboard ship; however, some time is required for a real fire to reach this point and this time is very crucial to the performance of the fire suppression efforts. In this case the shape of the smoke production curve is all important and it should follow the pattern expected for a real fire in that compartment.

SRI 2903 2/78

- Smoke leakage path tests. After the smoke production exceeds the steady state value, smoke will migrate away from the exhaust path into other parts of the ship. This migration path is of interest, particularly when critical spaces are involved. Such observations can be included in the steady-state or transient capacity tests as long as the smoke production rate is well above the steady-state value; e.g. at the ventilation controlled fire value.

- Desmoking after the smoke production has stopped. If we measure the time to reduce the smoke concentration to 1/2 the value at the start of desmoking, the smoke density is not particularly important and the desmoking tests can be carried out after any of the preceding tests.

3.0 Description of Test System and Procedures

Figure B.1 shows schematically the essential feature of the test system configured for a CPS ship.

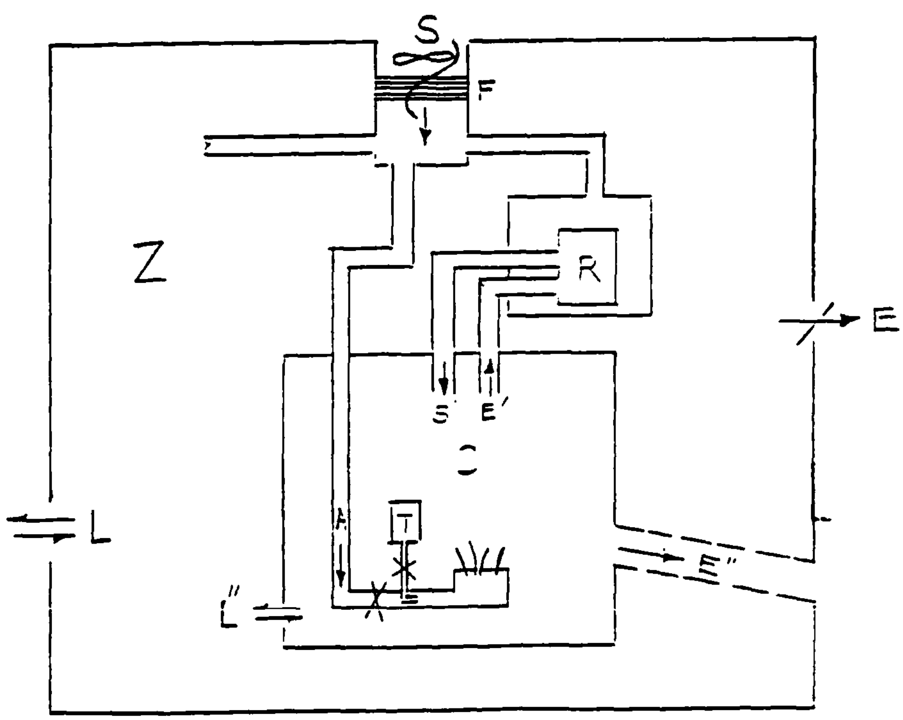


FIGURE B.1 TEST SYSTEM FOR A CPS SHIP

Z = CPS zone

C = The fire compartment, i.e. some location within the zone.

S = The supply fan to the zone which forces air through filters F to meet the clean air requirements and pressurizes the zone.

R = The recirculation system that provides air to compartment C. The exhaust (E') may return air to the recirculation fan by duct as shown or by using a passage for the return.

E & E" are exhaust paths to the weather. E includes the pressure control valve and all intended exhausts. E" is the smoke exhaust path selected for this test. It may be a dedicated exhaust fan but more generally it is a path through passageways or other compartments to reach an opening in the zone envelope.

L's are leaks both from chamber C to the zone and from the Zone Z to the weather.

A & T are used to simulate the fire. A is air which becomes contaminated with the tracer gas T before it is dispersed in the compartment. The air flow A is equal to the expanded volume of the air heated in a fire and T is proportional to the smoke production; consequently, A & T are adjusted to match the simulated fire. A provides the driving force to push T through the leaks and exits in compartment C.

The procedures apply to the control of the various fans and the exhaust openings E. For example, in a steady state test, the ventilation conditions would be set and allowed to reach equilibrium before the simulated fire was initiated. Generaly, the recirculation system would be secured. All exits other than E" would be closed; E" would be established including portable fans if they were part of the plan; then AT would be started for the test. In a transient test, the ventilation system would be in its normal mode of operation at the time of fire initiation and all subsequent adjustments to the system and the fire are part of the test. Times to secure fans and establish exhaust paths can have a pronounced effect on the time to loss of smoke control. As previously indicated, the fires' characteristics are also very important in this case.

4.0 Options for Standard Fires, i.e. Smoke Production Patterns

4.1 Simulating the Fire by Tracer Technique, Assumptions for.

Two characteristics of the real fire are of concern in this simulation: (1) the rate of smoke production, and (2) the increased volume of gas which provides a force to drive smoke out of the compartment of origin. We will assume the rate of smoke production is proportional to the burning rate of the fuel. Actually the rate also varies with the combustion efficiency which in turn changes during the course of a fire as the available air and feedback energy change; however, our knowledge does not permit this degree of refinement and such refinement is not essential to an evaluation of ventilation systems. In rather smokey fuels such as JP5, about 2% by weight of the fuel appears as smoke under poor ventilation conditions so we will suggest 2% of the fuel burning rate as the rate of smoke production. Of course the amount of tracer gas would be a much smaller fraction, i.e. a few parts per million but the release rate (T) would follow the same temporal pattern as the burning rate for the selected standard fire and could be converted by the fraction to a predicted smoke concentration.

The driving force embraces 2 components: (a) gas or vapors generated from the fuel, and (b) an expansion of gas in the chamber due to heating. If we assume a simple fuel made up of linear chains of

```
H H H
C-C-C __
H H H
```

burning to form CO_2 and H_2O, then for every 3 O_2 molecules consumed, 4 molecules, i.e. $2CO_2$ and $2H_2O$ appear. Consequently, we can multiply the burning rate of O_2 by 1/3 to get the increase volume for (a). Assuming the combustion products obey the perfect gas law, the change in volume due to heating becomes

$\Delta V = V_1 \left(\frac{T_2}{T_1} - 1\right)$ where V_1 = the initial gas volume at absolute temperature T_1

and T_2 is the final heated temperature. Actually this ΔV term is complicated by two factors. First, the gas in the compartment is not at a constant temperature, i.e. T_1 and T_2 vary throughout the volume. Second, V_1 consists of two components, the volume of gas in the chamber initially at temperature T_1 and volume introduced by ventilation initially at ambient temperature.

To simulate a fire, we need to know how both the temperature and burning rate or energy release rate vary with time. Obviously, these two parameters are related; however, the relationship is not unique because it varies in a complex way with the characteristics of the compartment or environment. Consequently, standard fire tests specify and control either the temperature or the release rate but they cannot control both, e.g. the E119 standard thermal insult and the NBS fire endurance test suggested in Ref. 1 specify a time temperature curve. The energy release criterion has been used to characterize fires expected in particular compartments or environments, e.g. see references 2 and 3. In addition to the controlling parameter, there is also a matter of severity, i.e. what is the maximum temperature or rate of heat release allowed and what is the permissible rate of growth. The E119 and the suggested NBS time temperature curves were designed to test materials and assemblies of materials under the worst case conditions, i.e. the worst thermal insult absorved in compartment fires. Actually, the proposed NBS test, Figure 2, is more severe than the E119 curve at earlier

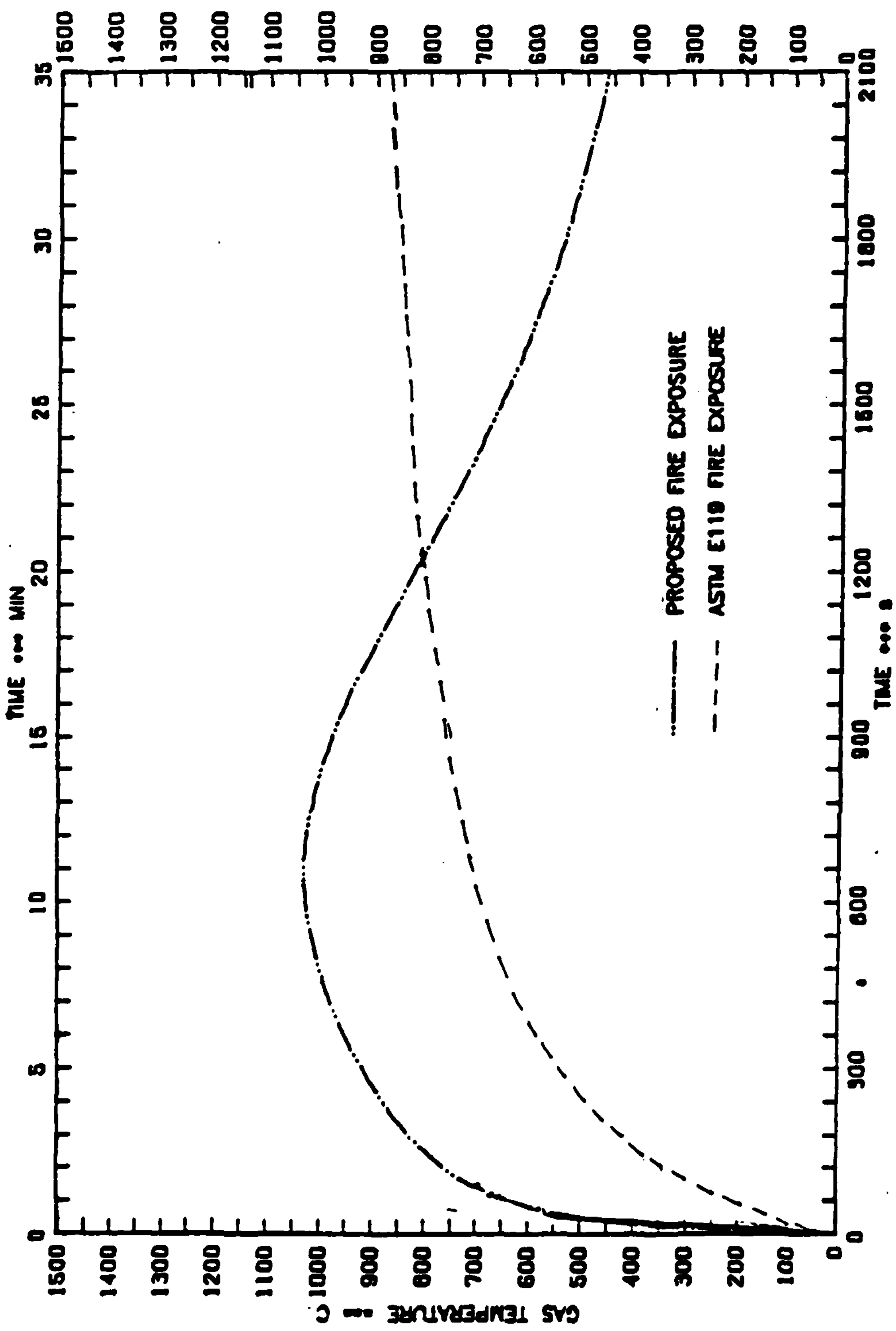


FIGURE B.2 — AVERAGE FURNACE GAS TEMPERATURE MEASURED WITH FAST RESPONSE THERMOCOUPLES times because modern residential construction permits a faster fire growth than was encoutnered when the E119 curve was established. Such severe conditions cannot be achieved in some ship compartments for lack of sufficient ventilation and/or fuel. Furthermore, most class A fuels and configurations exhibit a longer induction period before the rapid temperature rise occurs. The curves selected in reference 3 allow for this slower growth at early times and adjusts the width and height of the normal curve according to the fuel loading. For relative performance measurements of smoke control systems, the fixed curve is adequate but for a measurement of the expected performance for a specific compartment, the tailored curve would be preferable.

4.2 Steady State Test

Here we are looking for the smoke generation rate that exceeds the smoke control capacity of the system. A linear pattern of smoke production rate with time will be satisfactory as long as the slope is not too steep. Figure 3 shows such a pattern (ruled line) terminating at a maximum value which is determined by the maximum fire that can be achieved in compartment C.

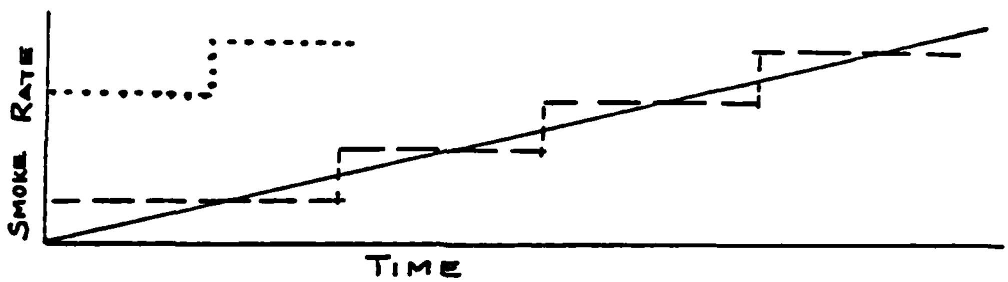


FIGURE B.3 TEMPORAL PATTERN OF SMOKE PRODUCTION

If the air flow and tracer gases are regulated manually, it would be easier and probably more reproducible to follow a stair step curve as indicated by the dashed curve in Figure 3. For the steady state tests, there is no need to start with small increments. As experience is gained with various systems, a large initial step as illustrated in the dotted curve would shorten the time required to reach the balance between smoke production and removal.

4.3 Transient Smoke Control Capacity

Two possibilities can be considered: (1) to test the ventilation distribution of smoke without smoke control procedure, and (2) to test under various scenarios for smoke control ranging from securing the ventilation in the compartment to an attempt at removing smoke to the weather along a path such as "E" in Figure 1. Both cases give times to smoke obscuration that depend on the shape of the smoke production and driving force curves. In case (1) relative times can be obtained using one of the standard time-temperature curves; however, in case (2), such curves lead to a contradiction unless they are modified to account for changes in the available air, e.g. if the compartment is secured tightly so that no air enters, the burning rate would drop to zero and the temperature cannot continue to rise. For case (2), it is easier to calculate the effects of ventilation on the burning rate curve than directly on the temperature; therefore, I prefer to work from burning rates instead of temperature curves. Again for manual control of the tracer gas and the driving force A (Fig. 1), it would be desirable to approximate the smooth temperature or burning rate curves with a stair step function.

5.0 Recommendations

- For steady-state tests, use the stair step curve shown in Figure 2.
- For transient smoke tests to provide relative comparisons without procedures, either the standard time temperature curves or a burning rate curve would be satisfactory.
- For transient smoke tests of specific compartments and procedures for smoke control, use a burning rate or energy release rate curve based on the available fuel and oxygen. If desired, the fuel controlled port of the burn could be based on the fuel consumption curve required to generate either the E119 or the proposed NBS time temperature curves. Ref. 1 contains such experimental data.