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RECREATIONAL BOATING SAFETY VENTILATION PROJECT: DESIGN GUIDELI--ETC(U)

JAN 78 W E MARTINSEN, J R WELKER, J N ICE DOT-CG-42355A

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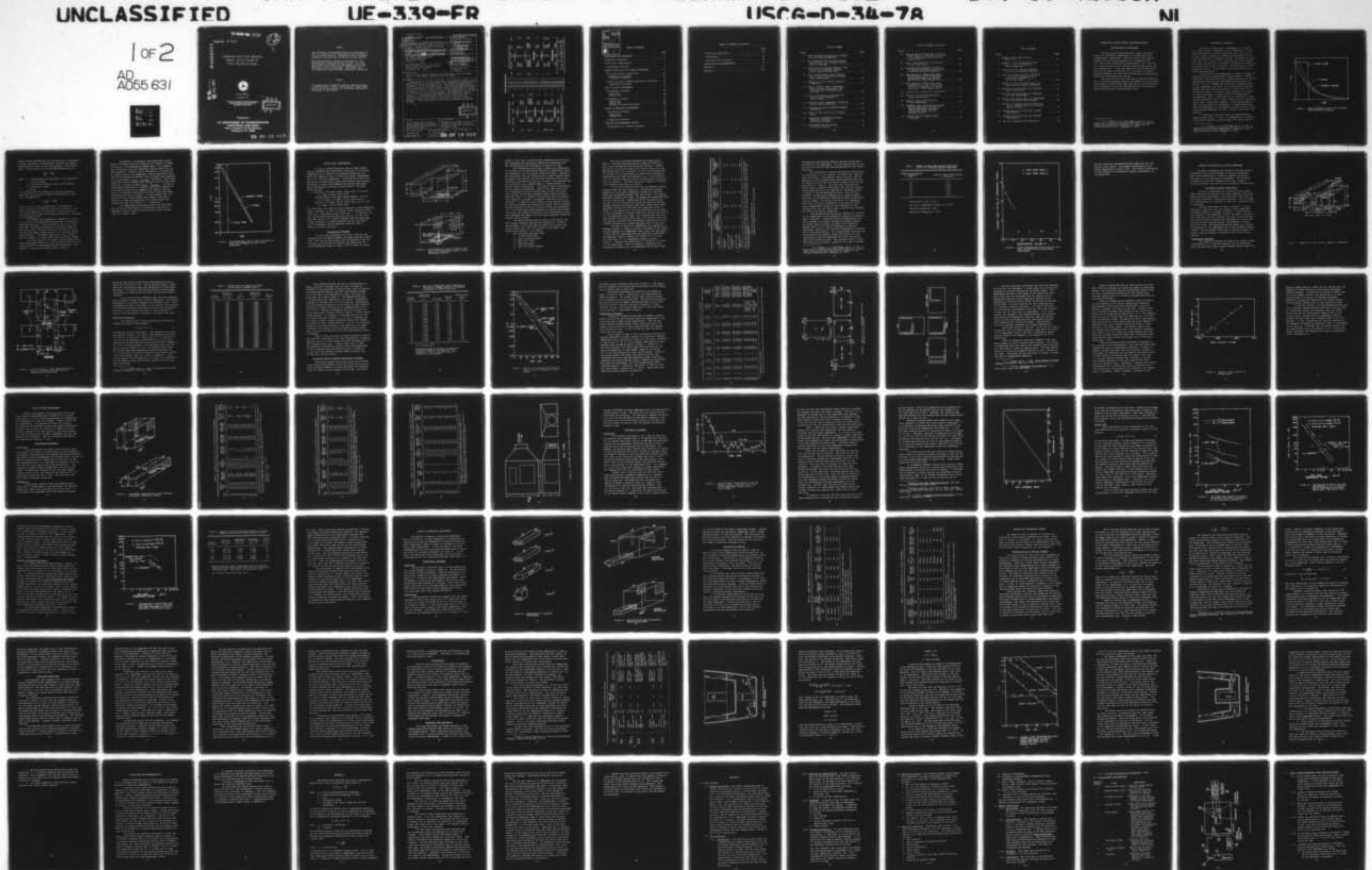

Report No. CG-D-34-78

RECREATIONAL BOATING SAFETY VENTILATION PROJECT: DESIGN GUIDELINES AND SYSTEM COMPLIANCE TEST METHOD

FINAL REPORT

JANUARY 1978

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NOTICE

NOTICE

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16. Abstract

The objectives of this study were to develop some empirical data (guidelines) on recreational boat engine compartment ventilation systems and to develop procedures for a ventilation standard based on performance of the installed system. The proposed standard requires that the powered ventilation system reduce a contaminant gas concentration to 7 percent of its initial concentration within 1.5 minutes of operation of the ventilation system. The compliance test requires use of a gas concentration measurement device and three sensor locations. The concentration reduction for each of the three gas sensors is to be compared with the standard. Guidelines are suggested which should produce compliance of power-ventilated compartments. Other guidelines are provided for natural ventilation systems.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

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RECREATIONAL BOATING SAFETY VENTILATION PROJECT

INTRODUCTION AND BACKGROUND

The test program described here is part of a study concerning ventilation requirements for recreational boat inboard engine compartments. Previous work on this subject[1] compared the ventilation standards of or proposed by the U. S. Coast Guard, Underwriter's Laboratories, Inc., National Fire Protection Association, Boating Industry Association, and Wyle Laboratories. It was concluded that none of these standards was entirely satisfactory since they did not require a system performance test that would confirm that the ventilation system did indeed perform as desired.

The objectives of this study were to develop procedures for a ventilation standard based on performance of the installed system, and to generate some empirical data on ventilation systems (guidelines) to aid the boat manufacturer in designing a system that would pass the performance test.

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[1] J. R. Welker, S. P. Muhlenkamp, and J. N. Ice, "A Comparison of Proposed Ventilation Requirements for Inboard Engine Recreational Boat Compartments," Report No. CG-Contract DOT-CG-42,355-A (December 15, 1975).

THEORETICAL DISCUSSION

The goal of ventilating a compartment is to remove fuel vapor in order to prevent a fire or explosion. It would also be worthwhile to remove liquid fuel, but ventilation is at best a poor technique for removing liquid because of the long time required to evaporate the fuel. To reduce the hazard from liquid fuel spills, the available pooling area should be minimized, perhaps even to the extent of providing a sump where the liquid fuel could be collected. The sump could be closed except for a drain, and the drain could be protected with a flash arresting screen.

Ventilation of the compartment to reduce the vapor concentration can be accomplished by either natural or forced ventilation, but most craft will probably prefer to use forced ventilation because natural ventilation has uncertain reliability. If it is assumed that there are no stagnant zones in the compartment, the limits on ventilation fall somewhere between plug flow and perfect mixing. In plug flow, it is assumed that there is no mixing, and as fresh air is brought into the compartment, an equal volume of contaminated air is exhausted. When a volume equal to the compartment volume has been exchanged, there is only fresh air in the compartment and no vapor contamination remains. If the concentration of vapor in the exhaust air is measured, it remains unchanged until the compartment is ventilated, at which time the concentration drops immediately to zero. Figure 1 illustrates this behavior.

In practice, plug flow cannot be obtained because mixing always occurs. In fact, in compartments with approximately equal dimensions, mixing tends to be nearly perfect[1].

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[1] J. R. Welker, S. P. Muhlenkamp, and J. N. Ice, "A Comparison of Proposed Ventilation Requirements for Inboard Engine Recreational Boat Compartments," Report No. CG- Contract DOT-CG-42,355-A (December 15, 1975).

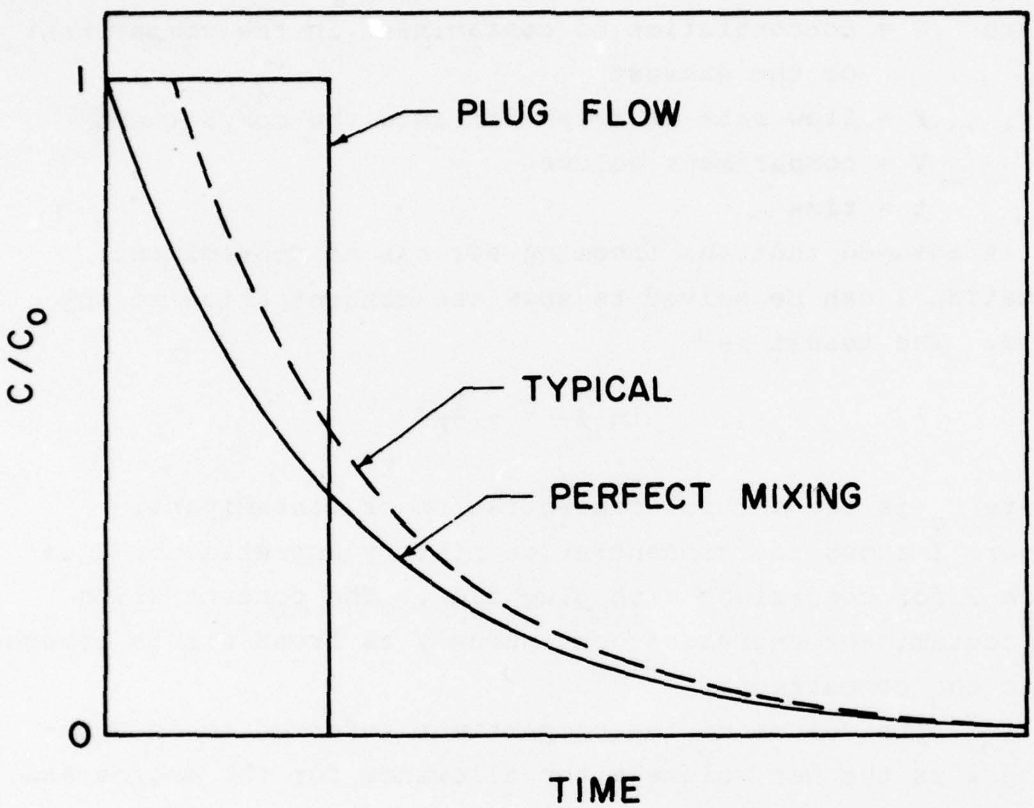

FIGURE 1. VAPOR CONCENTRATION RATIO FOR DIFFERENT FLOW AND MIXING MECHANISMS.

Perfect mixing implies that the concentration of contaminant is equal throughout the compartment, and that the exhaust concentration is equal to the concentration in the compartment. Perfect mixing can be described mathematically as

$$\frac{dC}{dt} = - \frac{F\,C}{V} \tag{1}$$

where C = concentration of contaminant in the compartment or the exhaust

F = flow rate of fresh air into the compartment

V = compartment volume

t = time

It is assumed that the incoming air has no contaminant. Equation 1 can be solved to show the concentration at any time. The result is

$$\ln \frac{C}{C_o} = - \frac{F\,t}{V} \tag{2}$$

where C_o is the initial concentration of contaminant. Figure 1 shows the concentration history expressed by Equation 2 for comparison with plug flow. The concentration of contaminant decreases continuously as fresh air is brought into the compartment.

The volume of the compartment referred to in Equation 2 is the net volume after allowance for the engine and associated equipment. The flow rate is the actual system flow rate, not the rate specified on the blower nameplate. The actual system flow rate depends on the restrictions to flow and the blower voltage as well as on the basic blower design capacity. The design capacity is usually based on free air movement (no restriction) and full design voltage.

In actual practice, the mixing inside a power ventilated compartment tends to be nearly perfect once the airflow pattern inside the compartment has been established. This behavior is shown as the typical case in Figure 1.

If Equation 2 is plotted on semi-logarithmic coordinates, a straight line with a slope of -F/V results, as shown in Figure 2. For unobstructed compartments, it is expected that the mixing within the compartment during venting will be nearly perfect[1]. However, due to variations in the localized air velocity within the compartment, certain areas might show rates of concentration reduction that are higher than predicted for perfect mixing ($F_{local} > F_{average}$); conversely, other areas might show rates of concentration reduction that are lower than predicted for perfect mixing ($F_{local} < F_{average}$). The rate of concentration reduction at a specific site can be compared to the perfect mixing rate by comparing the slopes of the two time vs concentration curves when plotted on semi-logarithmic coordinates as shown in Figure 2. A slope steeper than -F/V (perfect mixing) implies higher than average localized air velocity; a slope less steep than -F/V implies lower than average localized air velocity (i.e., stagnation).

If a compartment has perfect mixing, the ventilation rate can be increased only by increasing the flow rate or decreasing the net volume to be ventilated, either of which leads to a steeper slope.

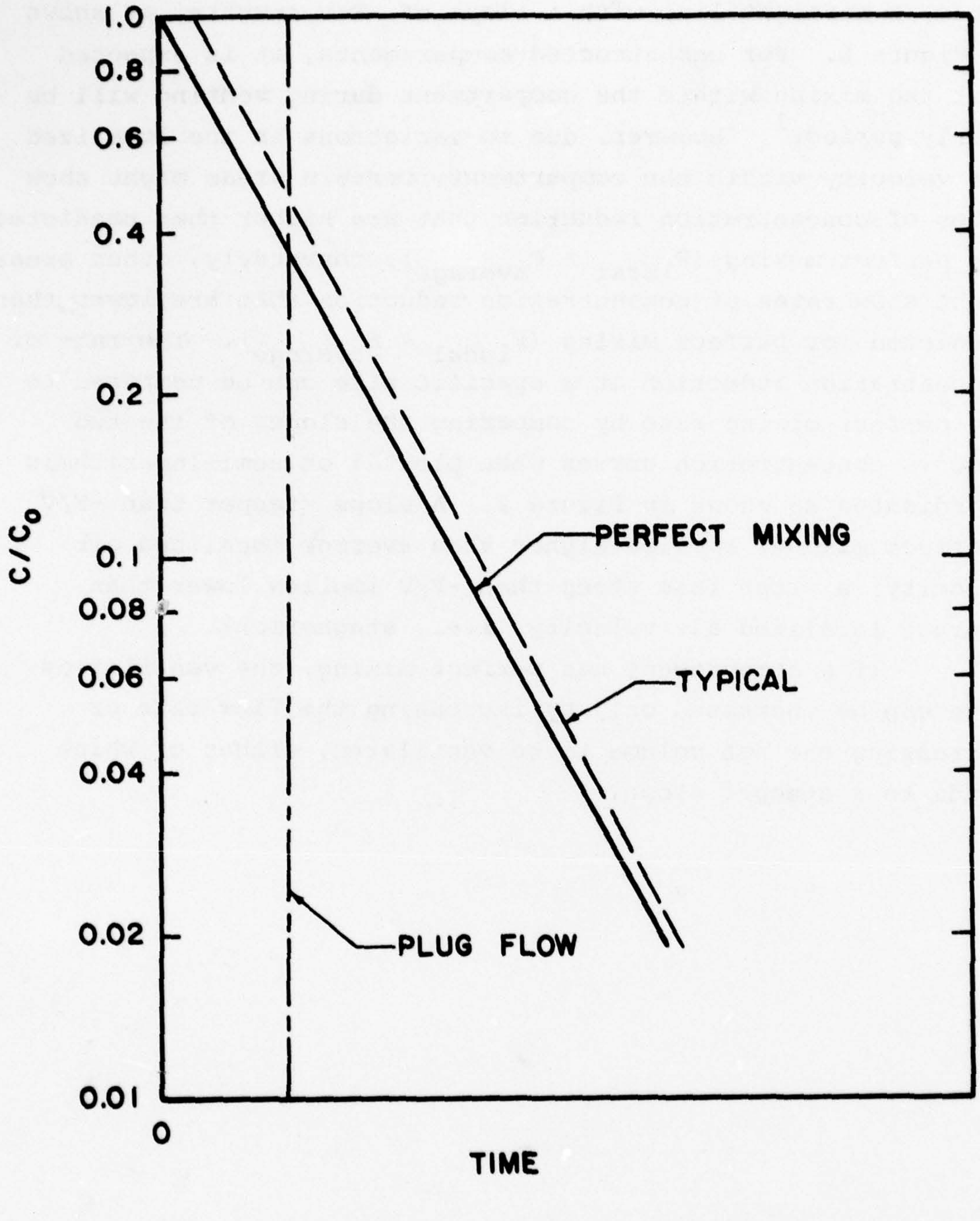

FIGURE 2. SEMI-LOGARITHMIC PLOT OF VAPOR CONCENTRATION RATIO FOR DIFFERENT FLOW AND MIXING MECHANISMS.

INITIAL FUEL CONCENTRATION

In order to develop empirical data on vapor concentrations generated from significant fuel spills in the engine compartment over a range of environmental conditions, six tests were conducted; four in actual boat engine compartments and two in a mock-up compartment. The objective of this test series was to observe worst case concentrations under average conditions to ensure that proposed test methods were appropriate for possible high-range concentrations. The three boats used were:

Glas Ply, 1975 model 181SL, deep V-hull, 18 ft long, 7 ft beam, 140 hp, stern drive.

General Marine, 1975 model Ranger TRV1800, tri-hull, 17.5 ft long, 7 ft beam, 130 hp, stern drive.

Sea Ray, 1975 model 180 10, deep V-hull, 16.5 ft long, 7 ft beam, 165 hp, stern drive.

All three boats were used for tests conducted at Lake Thunderbird, Norman, Oklahoma, in order to simulate actual operating conditions (e.g., warm engine, wind, waves, etc.). In addition, one test was conducted with the Glas Ply boat on a trailer, one test used the 43.3 ft^3 "typical runabout" mock-up compartment (shown in Figure 3) inside a building, and one test used a 56 ft^3 rectangular engine compartment mock-up (shown in Figure 3) inside a building.

Experimental Procedure

For the tests conducted on the lake, each boat was operated until the engine reached its normal operating temperature. The boat was then docked, the instrumentation was put in place, and one gallon of gasoline was poured into the engine compartment sump (at least 1 inch of water was always

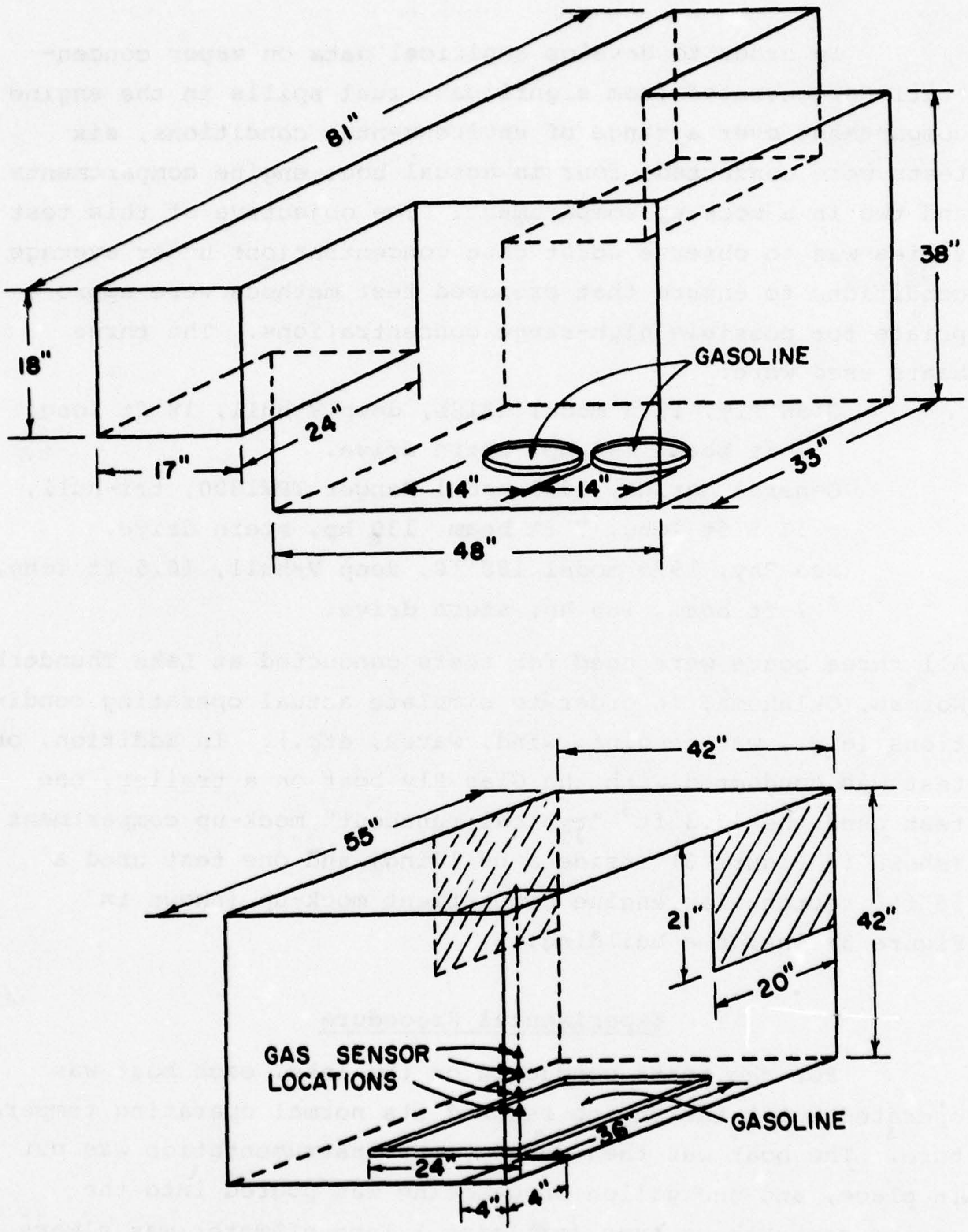

FIGURE 3. CONFIGURATION OF TYPICAL RUNABOUT (TOP) AND 56 FT^3 RECTANGULAR (BOTTOM) ENGINE COMPARTMENT MOCK-UPS.

present in the sump to assure uniform temperature distribution). The compartment was immediately closed and temperatures and gas concentrations were recorded as a function of time.

Two thermocouples were used to measure the temperature of the water in the sump and the ambient air temperature within the compartment (near the engine rocker-arm cover). Because it was anticipated that gas concentrations at some locations might be several times greater than the lower explosive limit (LEL), combustible gas detectors could not be used. Gas concentrations were monitored using a Beckman Model F3 oxygen analyzer to measure oxygen concentration. The gasoline vapor concentration was calculated by difference. Samples were taken from within each compartment by using a vacuum pump to draw the air/gas vapor mixture through small diameter copper tubes located as described below. An automatic multiposition valve was used to allow samples to be drawn, in sequence, from each of the five positions. In addition, pure nitrogen gas and ambient outside air were also sampled and analyzed for oxygen content following the same sequence as the five locations within the compartment (i.e., all seven vapor phase streams were sampled and analyzed once during one complete revolution of the multiposition valve). This procedure was used so that the oxygen analyzer calibration could be easily checked.

The tests using the Glas Ply boat on the trailer and the "typical runabout" mock-up were conducted in a similar manner except in the first case the engine was not hot, and in the latter case, there was no water in the "sump" (the gasoline was placed in a 2.1 ft^2 pan).

The gas sensor locations were:

1. 2 inches above sump
2. Above rocker-arm cover
3. Near vent inlets
4. Undercarburetor
5. Near vent outlet blowers

The results and test parameters are summarized in Table 1. The gas concentrations are listed for locations 1 and 5 (near the sump and near the outlet blowers). Concentrations at the locations other than directly above the sump were rarely above 1 or 2 percent. At such low concentrations, the accuracy of the measurement was questionable because the concentration was found by difference (e.g., a gas concentration of 1 percent causes the oxygen concentration to change by only 0.21 percent). The data from sensor locations 2 through 5 are therefore qualitative in nature.

It is obvious from the data that considerable layering occurred under the test conditions. Layering was expected because all of the major components of gasoline have vapor densities considerably greater than that of air. The layering persisted throughout the tests, and became more pronounced after the first few minutes. Immediately after the gasoline was spilled, the four locations not relatively near the sump had somewhat higher concentrations than their steady state values. Apparently, either the light ends that evaporated first resulted in less layering or there was some mixing of the vapor in the air because of convective motion as the fuel was spilled and the compartment was closed. The concentration above the sump reached its maximum value within a few minutes after fuel was spilled; thereafter the concentration remained relatively constant, showing only a slight decrease within a half hour.

The test in the 56 ft^3 compartment was conducted in a different manner in order to provide an estimate of the concentration gradient in a compartment when liquid fuel was present. In this test the compartment was not sealed but instead had two openings, each 21 inches by 20 inches (15 in^2 of vent area for each 1 ft^3 of compartment volume) as shown in Figure 3. Gasoline was poured into a 6 ft^2 pan on the floor of the compartment. After 10 minutes, a combustible gas detector was lowered into the compartment and gasoline vapor

TABLE 1. SUMMARY OF DATA FROM GASOLINE SPILL TESTS

Test Designation	Average Gasoline Vapor Concentration (%) Sensor 1	Sensor 5	Temperature of Liquid in Sump (°F)	Temperature of Air in Compartment (°F)	Approximate Gasoline Spill Area (ft^2)	Approximate Net Compartment Volume (ft^3)
Glas Ply on Trailer	28	< 1	83*	65	3	50
Glas Ply on Lake	21	6	81	102	3	50
General Marine on Lake	20	2	80	87	4.7	25
Sea Ray on Lake	8	< 1	82	92	4.4	25
Typical Runabout Mock-up	14	< 1**	68	60	2.1	38.8

Gasoline vapor concentration averaged over the time interval from 30 min to 90 min after spill.

Wind speed was approximately 5 mph for all tests except Typical Runabout Mock-up, which was run in the laboratory.

* Sump liquid was warmed before test.

** Sensor 4: Sampling valve for No. 5 malfunctioned.

concentration readings were taken at various heights above the bottom of the compartment. The gas detector used in this test was the catalytic bead type manufactured by Mine Safety Appliances.

The calibration of the gas detector was accomplished by subjecting it to a 0.7 percent (50 percent LEL) gasoline vapor-air mixture. The gasoline used in the test (and the calibration) was unleaded regular grade automotive gasoline. The results of this test are listed in Table 2 and are shown graphically in Figure 4. Note that when the sensor was placed within 8 inches of the bottom, the catalytic element became saturated due to the presence of hydrocarbon vapors in excess of the stoichiometric mixture. Once this has occurred, the gas sensor readings are no longer accurate. Therefore, no concentration measurements could be made below about 10 inches. The results from the 56 ft^3 compartment tests are not strictly comparable to the tests on actual engine compartments because of the differences in test configuration, but the results show a similar sharp gradient and offer a qualitative comparison.

Equilibrium concentrations for gasoline-air mixtures at the temperatures in the compartments during the tests are about 50 percent[1]. These equilibrium concentrations were never reached in the tests, probably for several reasons. The strong layering effect is probably most important, because mixing in the vertical direction is strongly suppressed, leading to high vertical concentration gradients due to high vapor density. The concentrations very near the liquid surface are probably nearer equilibrium, so that vaporization rates are suppressed due to the low driving force near the fuel surface. The important result is that the concentration reached a maximum of less than 30 percent

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[1] J. R. Welker, S. P. Muhlenkamp, and J. N. Ice, "A Comparison of Proposed Ventilation Requirements for Inboard Engine Recreational Boat Compartments," Report No. CG-Contract DOT-CG-42,355-A (December 15, 1975).

TABLE 2. SUMMARY OF DATA FROM GASOLINE SPILL TEST IN A 56 FT^3 SIMULATED ENGINE COMPARTMENT

Distance Above Bottom of Compartment (in)	Gasoline Vapor Concentration (volume %)
20	0.03
18	0.04
16	0.08
14	0.56
12	1.70
10	3.80

Gasoline Spill Area = 6 ft^2

Vent Area ÷ Compartment Volume = 15 in^2/ft^3

Gasoline Temperature = 63°F

Ambient Air Temperature = 67°F

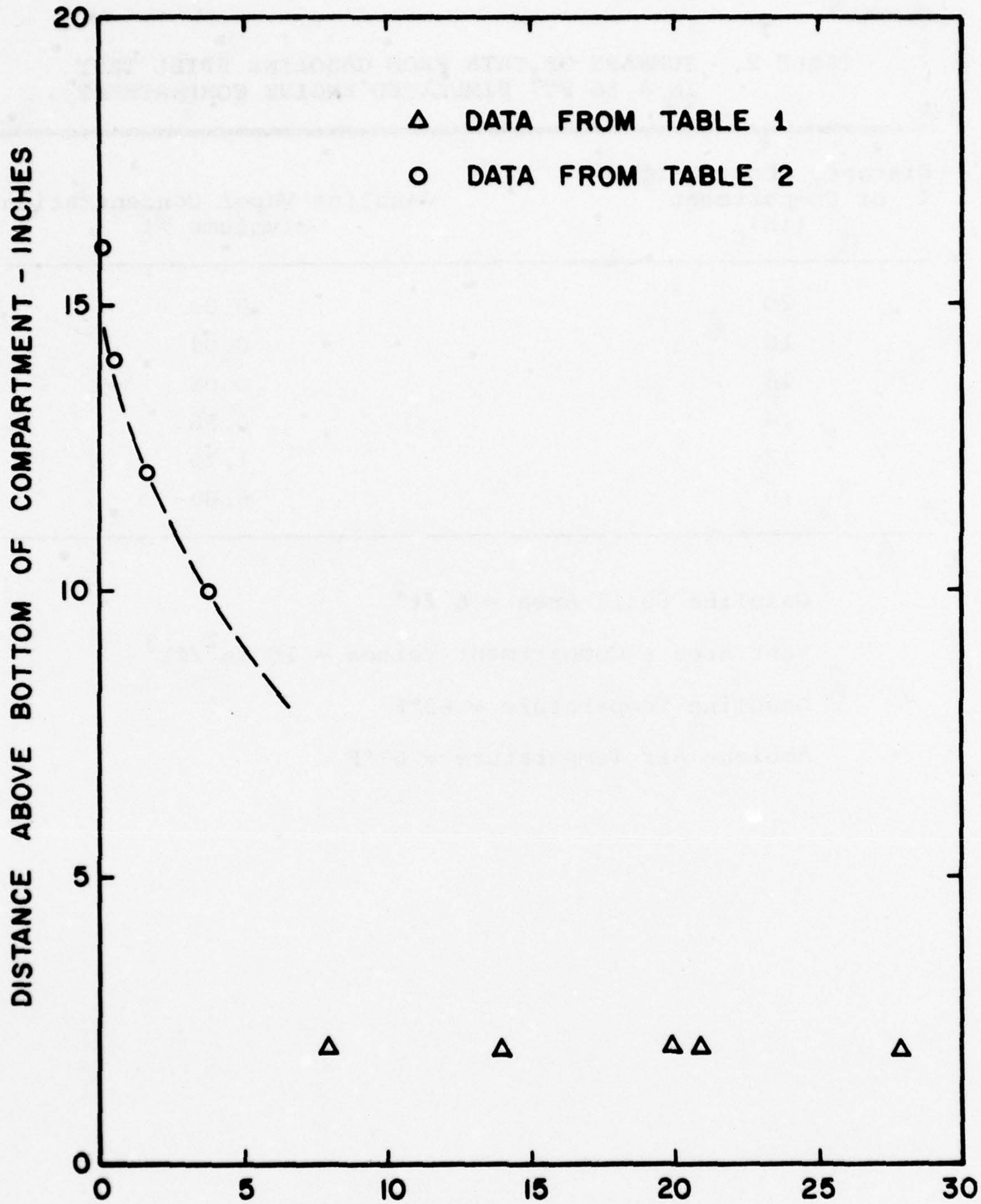

FIGURE 4. VAPOR CONCENTRATIONS DURING GASOLINE SPILL TESTS IN SIMULATED AND ACTUAL ENGINE COMPARTMENTS.

and that such high concentrations were found only near the surface of the liquid. The average concentration in the engine compartments was much lower. The average concentration is more important for determining venting requirements, as discussed later.

POWERED VENTILATION OF A SINGLE COMPARTMENT

In order to determine the effects of various operating parameters on the venting behavior of typical recreational boat engine compartments, a number of powered ventilation tests were run in a rectangular compartment. The variables included inlet velocity, volumetric flow rate, number of inlets and outlets, and inlet and outlet ducting configurations.

Gas Sensor Location Sensitivity

In order to determine the locations for gas sensors which would provide data that would best represent ventilation system operating performance, nine preliminary tests were run with three gas sensor locations for each test. These provided gas concentrations as a function of time for 27 locations within a compartment.

The test compartment is shown in Figure 5. It was designed to represent a typical runabout engine compartment. Gas sensor locations are shown in Figure 6. Inlets and outlets located in the compartment "wings" are shown in Figure 5. One inlet had no ducting attached; the other inlet was ducted with 3-inch flexible ducting which terminated at a point near the front of the simulated engine, approximately 16 inches above the floor. The powered outlet was ducted to the center of the bottom of the compartment with 3-inch diameter flexible ducting. The non-powered outlet had no ducting attached, and, since it was not powered, it acted as a third inlet during venting.

Experimental Procedure

The quantity of methane gas required to produce a vapor concentration of 0.75 LEL was injected into the compartment. After the three gas sensor readings reached steady values, the

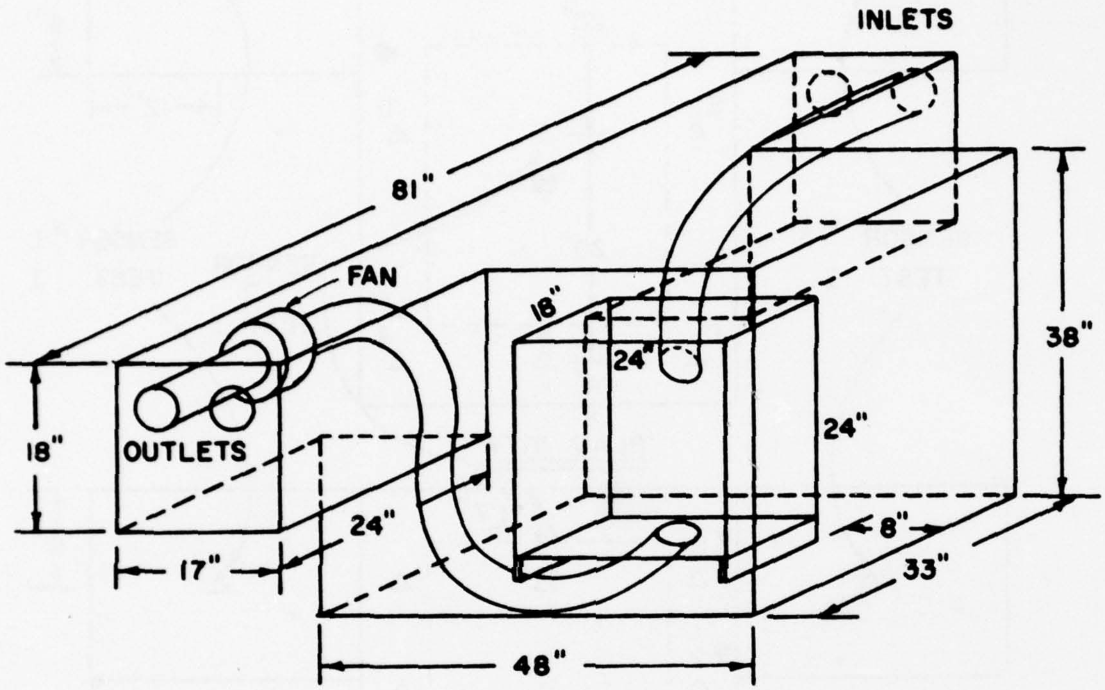

FIGURE 5. DIMENSIONS OF THE "TYPICAL RUNABOUT" COMPARTMENT.

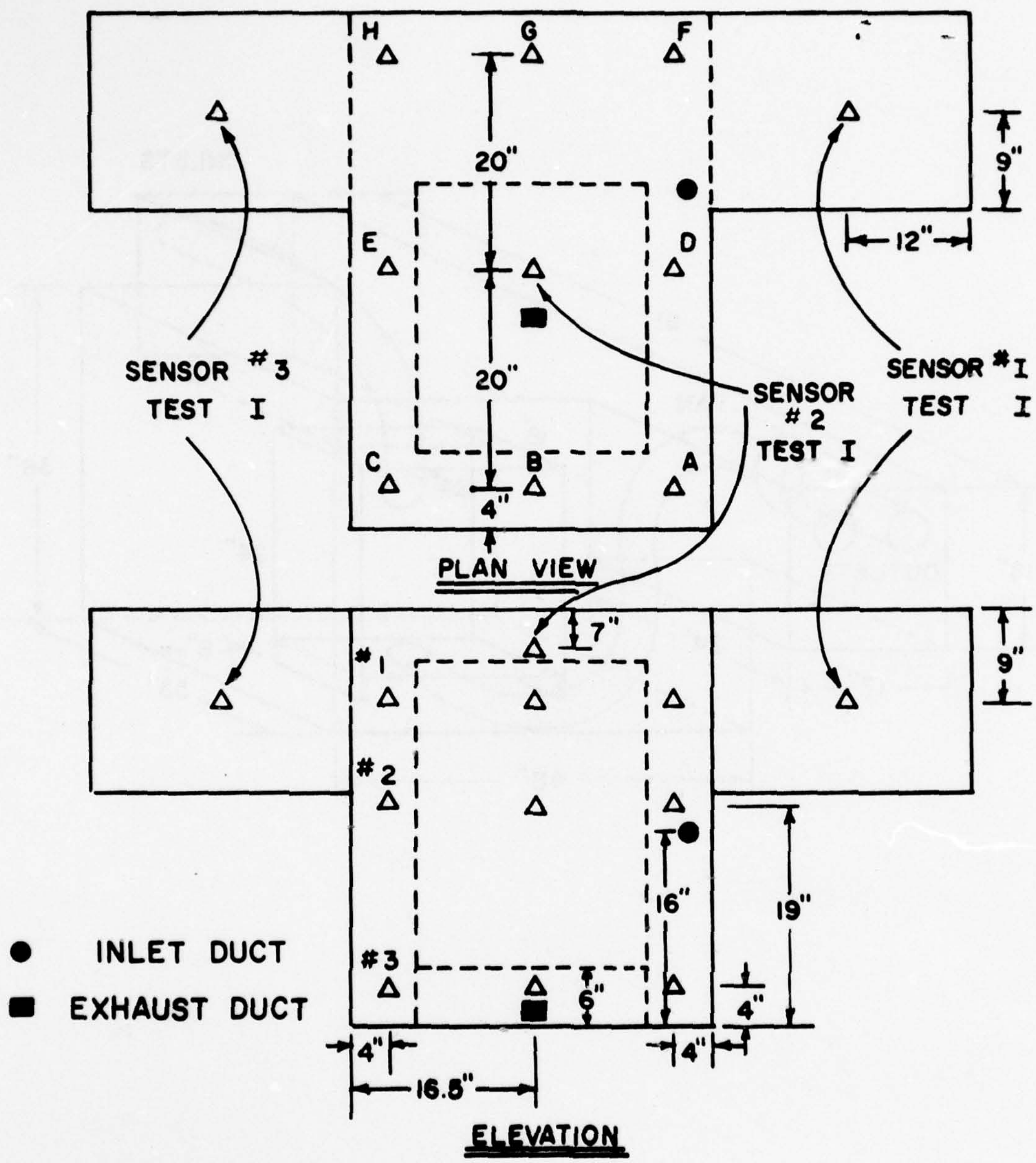

FIGURE 6. TYPICAL RUNABOUT ENGINE COMPARTMENT MOCK-UP SHOWING GAS SENSOR LOCATIONS AND DUCT TERMINATIONS FOR EACH TEST.

outlet fan was turned on and the gas concentrations were recorded as a function of time. The gas detectors used in these tests were the catalytic bead type manufactured by Mine Safety Appliances. The outputs from the gas detectors were recorded continuously on Leeds and Northrup Model 680 XL potentiometric recorders.

Air flow rates were calculated from velocities measured with a Datametrics Model 800-L hot wire anemometer. The velocity was measured in a tubular extension of the blower outlet. This measurement was made in the center of the tube and the volumetric flow rate was calculated from the velocity with an appropriate correction factor applied to account for the variation in velocity from the center of the tube to the edge of the tube[2].

Discussion of Results

The concentration vs time recordings were analyzed by regression analysis to the equation

$$\ln C/C_o = K't + K_o \qquad (3)$$

to determine the best value for K'. The results of the tests are reported in Table 3 in terms of the regression coefficient (K') and the venting ratio (-K'V/F) which is an indication of how the rate of reduction in concentration at a given point compares to the rate predicted by the perfect mixing assumption (K' = -F/V in perfect mixing). The average venting ratio for the 27 locations tested is 1.08. The average venting ratio for a power ventilated compartment would be expected to be 1.0. A discussion of possible reasons for the average venting ratio being greater than 1.0 is given in Appendix A. Based on that analysis and the behavior of the data, the compartment can be assumed to have nearly perfect mixing once mixing has been established.

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[2] J. G. Knudsen and D. L. Katz, Fluid Dynamics and Heat Transfer, McGraw-Hill, New York (1958).

TABLE 3. VENTING DATA FOR VARIOUS LOCATIONS IN THE TYPICAL RUNABOUT MOCK-UP

Sensor Location	Volumetric Flow Rate (ft^3/sec)	F/V (sec^{-1})	Regression Coefficient (sec^{-1})	Venting Ratio
A1	.714	.0193	-.0206	1.07
A2	.714	.0193	-.0206	1.07
A3	.714	.0193	-.0190	.98
B1	.723	.0195	-.0204	1.05
B2	.723	.0195	-.0205	1.05
B3	.723	.0195	-.0222	1.14
C1	.746	.0201	-.0206	1.02
C2	.746	.0201	-.0204	1.01
C3	.746	.0201	-.0220	1.09
D1	.700	.0189	-.0192	1.02
D2	.700	.0189	-.0194	1.03
D3	.700	.0189	-.0201	1.06
E1	.700	.0189	-.0178	.94
E2	.700	.0189	-.0169	.89
E3	.700	.0189	-.0184	.97
F1	.684	.0185	-.0206	1.11
F2	.684	.0185	-.0198	1.07
F3	.684	.0185	-.0205	1.11
G1	.700	.0189	-.0226	1.20
G2	.700	.0189	-.0220	1.16
G3	.700	.0189	-.0215	1.14
H1	.700	.0189	-.0197	1.04
H2	.700	.0189	-.0198	1.05
H3	.700	.0189	-.0219	1.16
I1	.700	.0189	-.0225	1.19
I2	.700	.0189	-.0229	1.21
I3	.700	.0189	-.0230	1.22

The standard deviation for the 27 venting ratios is about 8 percent of the mean value of 1.08. In order to determine if the variations in venting ratio from one location to another were meaningful, one test, with sensors located at A1, A2, and A3, was repeated five times. The data from these tests are given in Table 4. The standard deviations in venting ratios for locations A1, A2, and A3, expressed as a percent of the mean, are 4, 8, and 6 percent, respectively. Thus the standard deviation for five tests run under identical conditions is nearly as large as the standard deviation for all 27 tests. However, by comparing the venting ratios for the various sensor locations listed in Table 3, certain trends become apparent. For example, the average venting ratio for the twelve locations in Tests F, G, H, and I is greater than the overall average, thereby indicating higher than average localized air flow at those locations. This is to be expected because of the close proximity of the sensors to the inlets. Conversely, the venting ratios for sensors located farther away from the inlets and the outlet duct were generally below the average.

Figure 7 shows the data for sensor locations G1 and E1. Note that the intercepts of the lines determined by regression analysis are not 1.0 but the data do follow straight lines on this semilogarithmic plot. Figure 7 shows that it takes approximately 10 seconds for the air flow to be established at the E1 location once the ventilating fan is turned on. A time lag is also present at other sensor locations that are far away from the inlets.

Parametric Study of Powered Ventilation Variables

Twenty-four powered ventilation tests were conducted using various combinations of inlet and outlet ducting locations, different numbers of inlets and outlets and different inlet air velocities and volumetric flow rates. The values

TABLE 4. RESULTS OF REPETITIVE TESTS CONDUCTED IN THE TYPICAL RUNABOUT MOCK-UP TO DETERMINE VARIABILITY OF VENTING RATE DATA

Sensor Location	Regression Coefficient (sec^{-1})	Intercept	Venting Ratio	Time to Reach ½ LEL* (sec)
A1	-.0206	1.45	1.07	147
A1	-.0206	1.52	1.07	149
A1	-.0201	1.46	1.04	151
A1	-.0216	1.53	1.12	143
A1	-.0197	1.33	1.02	150
A2	-.0176	1.21	0.91	162
A2	-.0206	1.43	1.07	147
A2	-.0205	1.52	1.06	150
A2	-.0219	1.69	1.13	145
A2	-.0207	1.58	1.07	150
A3	-.0182	1.13	0.94	153
A3	-.0190	1.10	0.98	145
A3	-.0206	1.30	1.07	142
A3	-.0202	1.20	1.05	141
A3	-.0202	1.31	1.05	145

$F/V = 0.0193\ sec^{-1}$

*Calculated based on results of regression analysis of data to fit Equation 3 and assuming an initial gasoline vapor concentration of 10 percent.

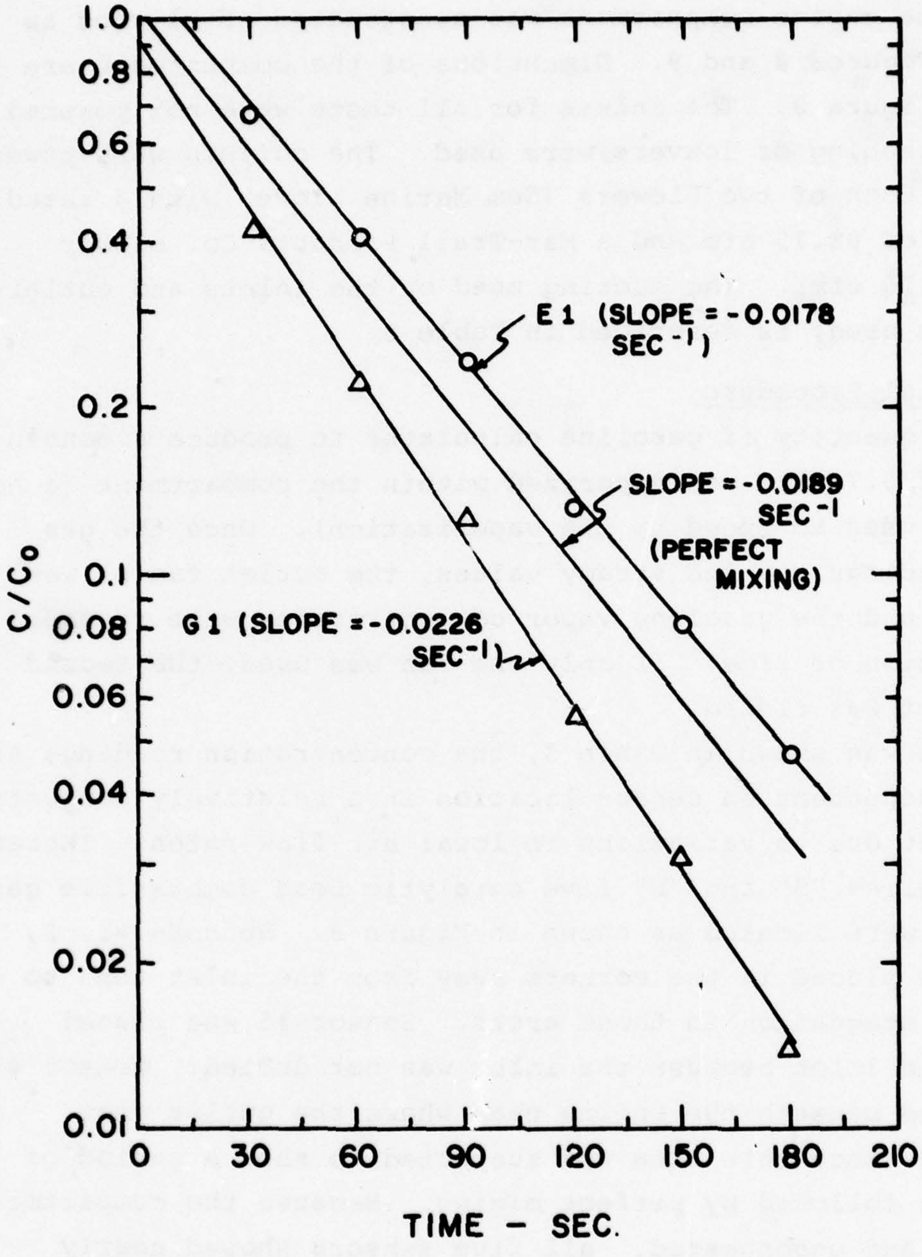

FIGURE 7. RATE OF CONCENTRATION REDUCTION FOR TESTS E1 and G1 COMPARED TO PERFECT MIXING.

for these various parameters are given in Table 5. The results for the regression coefficient and venting ratio are the average for the sensors used in each test.

The engine compartment was constructed of plywood as shown in Figures 8 and 9. Dimensions of the compartment are shown in Figure 8. The inlets for all tests were not powered and no screening or louvers were used. The outlets were powered by one or both of two blowers (Gem Marine blower with a rated flow rate of 98.75 cfm and a Mar-Trail Products Co. blower rated at 116 cfm). The ducting used on the inlets and outlets, if any was used, is described in Table 5.

Experimental Procedure

A quantity of gasoline calculated to produce a concentration of 0.75 LEL was vaporized within the compartment (a hot plate was used to speed up the vaporization). Once the gas sensor readings reached steady values, the outlet fan(s) was turned on and the gasoline vapor concentrations were recorded as a function of time. If only one fan was used, the second outlet duct was closed.

As was shown in Table 3, the concentration readings are somewhat dependent on sensor location in a relatively congested compartment due to variations in local air flow rates. Therefore, in test series "S" and "N" five catalytic bead combustible gas detectors were located as shown in Figure 8. Sensors #1, 2, and 4 were placed in the corners away from the inlet vent to check for stagnation in these areas. Sensor #5 was placed next to the inlet because the inlet was not ducted. Sensor #3 was located beneath the engine near where the outlet duct terminated since this area was suspected to show a period of stagnation followed by perfect mixing. Because the compartment was large and uncongested, all five sensors showed nearly identical behavior. Therefore, test series "F" and "DD" used only three sensor locations (#1, 2, and 4). These tests also substituted normal pentane for gasoline.

TABLE 5. SUMMARY OF POWER VENTILATION DATA FOR LARGE SIMULATED ENGINE COMPARTMENT

Test No.	No. of Inlets	Inlet Dia. (in)	Inlet Area (in^2)	No. of Outlets	Inlet Velocity (ft/min)	Volumetric Flow Rate (ft^3/sec)	F/V (sec^{-1})	Regression Coefficient (sec^{-1})*	Venting Ratio*	Inlet Ducting Termination	Outlet Ducting Termination
1F	1	3.00	7.07	1	453	.371	.0041	-.0045	1.10	None	Beneath engine
2F	2	3.00	14.14	1	491	.804	.0089	-.0102	1.15	None	Beneath engine
3F	3	3.00	21.21	1	523	1.283	.0142	-.0163	1.15	None	Beneath engine
1N	1	4.25	14.18	1	490	.804	.0084	-.0087	1.04	None	Beneath engine**
2N	2	3.00	14.14	1	491	.804	.0084	-.0082	.98	None	Beneath engine
3N	4	2.12	14.12	1	492	.804	.0084	-.0083	.99	None	Beneath engine
4N	4	2.12	14.12	2	484	.791	.0082	-.0079	.96	None	Beneath engine
5N	2	3.00	14.14	2	472	.772	.0080	-.0079	.93	None	Beneath engine
6N	1	4.25	14.18	2	451	.740	.0077	-.0075	.97	None	Beneath engine
1S	1	2.12	3.53	1	1372	.560	.0058	-.0071	1.21	None	Beneath engine**
2S	1	2.12	3.53	2	1646	.672	.0070	-.0091	1.30	None	Beneath engine
3S	1	3.00	7.07	1	941	.769	.0080	-.0080	1.00	None	Beneath engine
4S	1	3.00	7.07	2	1264	1.034	.0108	-.0116	1.08	None	Beneath engine
5S	1	4.25	14.18	1	588	.965	.0100	-.0093	.93	None	Beneath engine
6S	1	4.25	14.18	2	833	1.368	.0143	-.0146	1.02	None	Beneath engine
1DD	1	3.00	7.07	1	923	.755	.0084	-.0099	1.18	None	Beneath engine
2DD	1	3.00	7.07	1	959	.785	.0087	-.0095	1.09	Middle of side	Beneath engine
3DD	1	3.00	7.07	1	1039	.850	.0094	-.0096	1.02	Beneath engine	Beneath engine
4DD	1	3.00	7.07	1	1015	.831	.0092	-.0094	1.02	Beneath engine	Middle of side
5DD	1	3.00	7.07	1	1015	.831	.0092	-.0103	1.12	Middle of side	Middle of side
6DD	1	3.00	7.07	1	1099	.899	.0100	-.0116	1.16	None	Middle of side
7DD	1	3.00	7.07	1	1323	1.083	.0120	-.0134	1.12	Middle of side	None
8DD	1	3.00	7.07	1	1297	1.061	.0118	-.0134	1.14	Beneath engine	None
9DD	1	3.00	7.07	1	1542	1.262	.0140	-.0153	1.09	None	None

*Average for all gas sensors.

**In test series N and S, no engine was provided. The outlet duct terminated beneath the normal engine location.

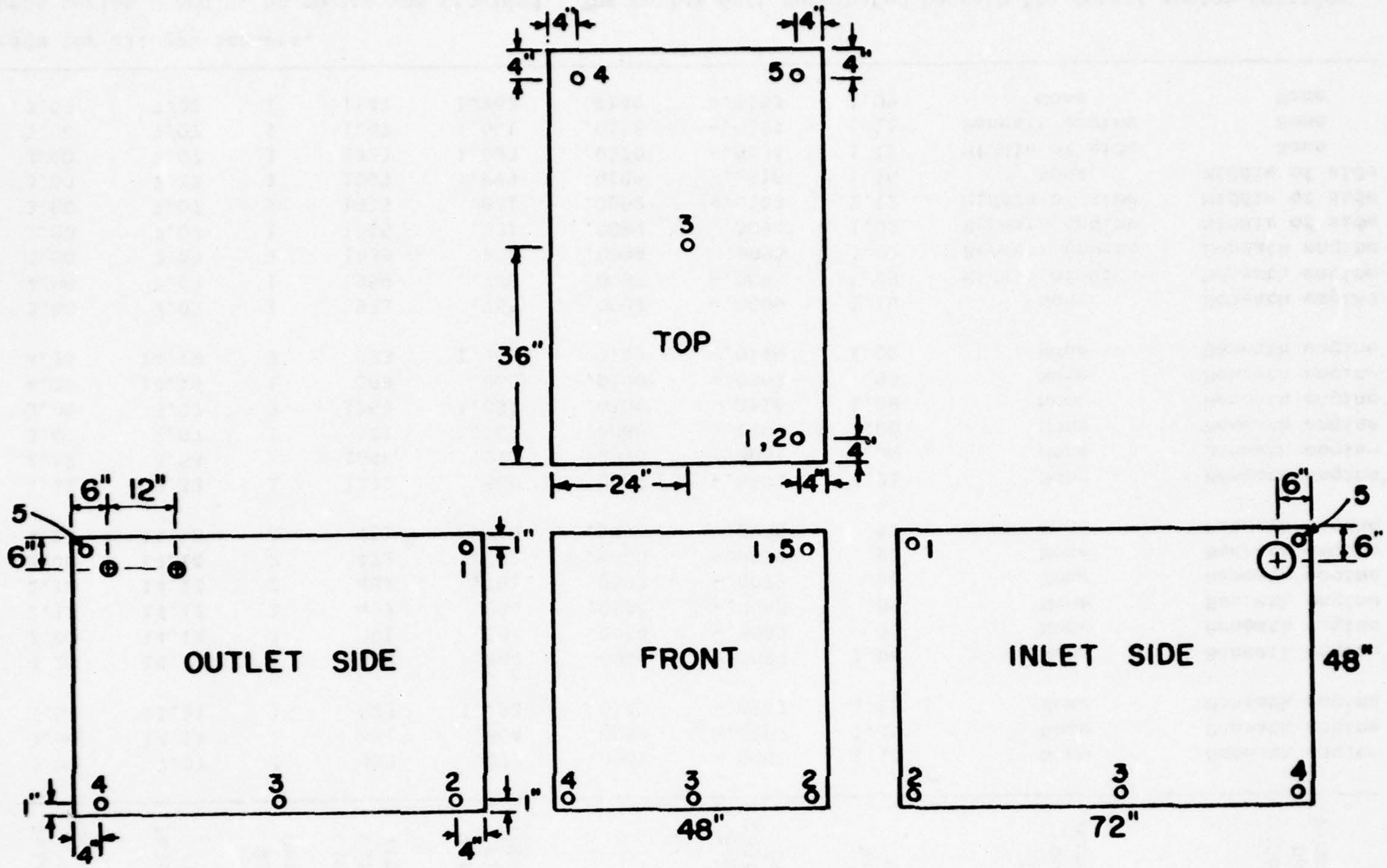

FIGURE 8. SIMULATED ENGINE COMPARTMENT DIMENSIONS AND GAS SENSOR LOCATIONS.

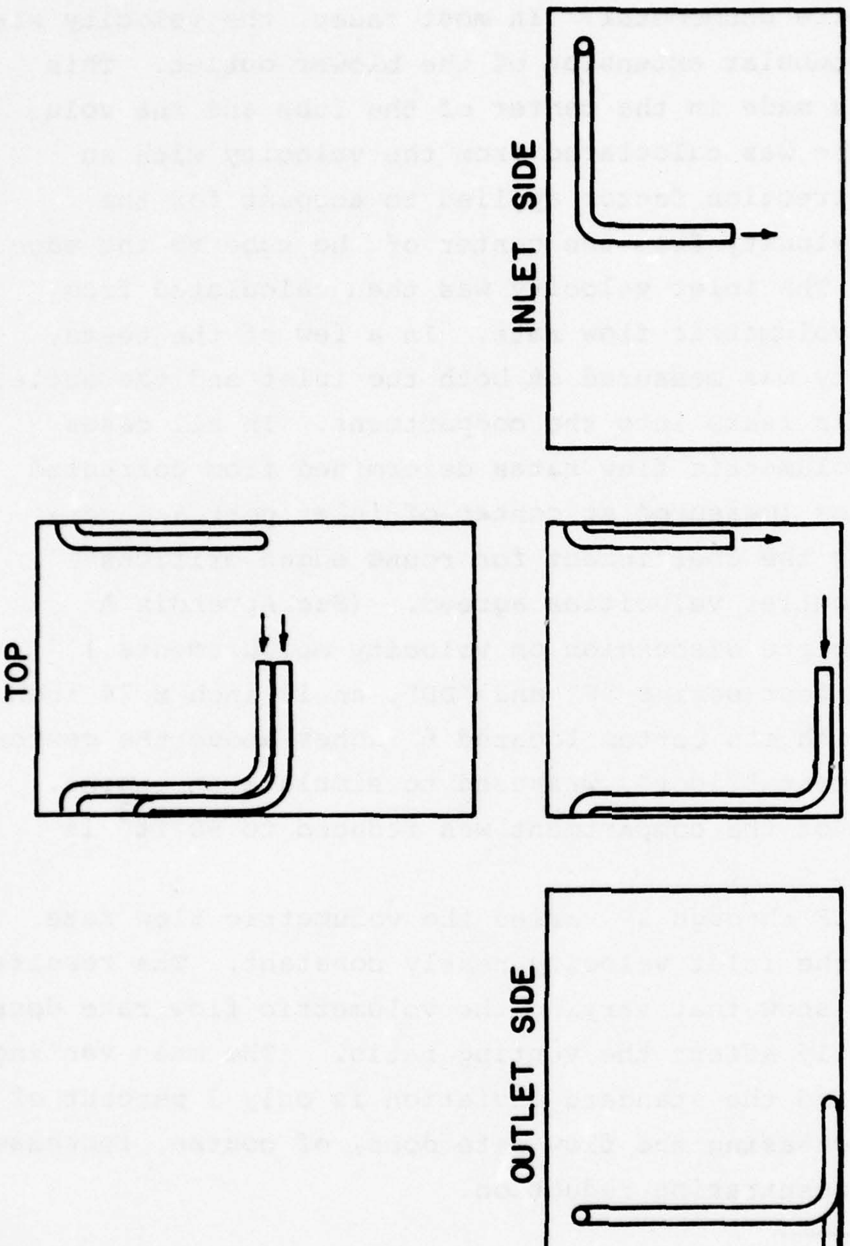

FIGURE 9. LOCATIONS OF VENTS IN SIMULATED ENGINE COMPARTMENT.

Air flow rates were calculated from velocities measured with the hot wire anemometer. In most cases, the velocity was measured in a tubular extension of the blower outlet. This measurement was made in the center of the tube and the volumetric flow rate was calculated from the velocity with an appropriate correction factor applied to account for the variation in velocity from the center of the tube to the edge of the tube[2]. The inlet velocity was then calculated from the corrected volumetric flow rate. In a few of the tests, the air velocity was measured at both the inlet and the outlet to check for air leaks into the compartment. In all cases checked, the volumetric flow rates determined from corrected inlet velocities (measured at center of inlet port and corrected by using the coefficient for round edged orifices[3]) and corrected outlet velocities agreed. (See Appendix A for a more complete discussion on velocity measurements.)

During test series "F" and "DD", an 18 inch x 24 inch x 24 inch box, with its bottom located 6 inches above the center of the compartment "floor", was used to simulate an engine. The net volume of the compartment was reduced to 90 ft^3 in these tests.

Tests 1F through 3F varied the volumetric flow rate while keeping the inlet velocity nearly constant. The results of these tests show that varying the volumetric flow rate does not significantly affect the venting ratio. (The mean venting ratio is 1.13 and the standard deviation is only 3 percent of the mean.) Increasing the flow rate does, of course, increase the rate of concentration reduction.

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[2] J. G. Knudsen and D. L. Katz, Fluid Dynamics and Heat Transfer, McGraw-Hill, New York (1958).

[3] J. K. Vennard, Elementary Fluid Mechanics, 3 ed., John Wiley & Sons, New York (1957).

Tests 1N through 6N held the inlet velocity and volumetric flow rate constant but varied the number of inlets and outlets. Such variations did not significantly affect either the rate of concentration reduction or the venting ratio. (The mean venting ratio is 0.96 and the standard deviation is 5 percent of the mean.)

Tests 1S through 6S were designed to show the effect of inlet velocity on the rate of concentration reduction. Unfortunately, difficulties were encountered in trying to maintain a constant flow rate for each test. However, since test 1F through 3F showed that volumetric flow rate was not significant in affecting the venting ratio (i.e., the standard deviation for the venting ratio was less than the 4 to 8 percent for identical tests), the results of these inlet velocity tests should not be significantly affected by the changes in volumetric flow rate. Figure 10 shows the effect of inlet velocity on the venting ratio. The general trend is that the venting ratio increases as the inlet velocity increases. This effect is not very large but a least squares line that best fits the data (Figure 10) shows that a correlation does exist between inlet velocity and venting ratio (correlation coefficient = 0.96).

Tests 1DD through 9DD were designed to determine if the location of the terminations of the inlet and outlet vents affected the rate of concentration reduction. In order to compare the data from tests that have different volumetric flow rates, the discussion will be based on the venting ratio. The mean value of the venting ratio for these 9 tests was 1.10 and the standard deviation was 6 percent of the mean. This standard deviation is the same range as that determined for identical tests. Therefore, it appears that ducting arrangements have no significant effect on venting ratio if only the average venting ratio of all sensors in the compartment is considered. Tests A through I, conducted in the

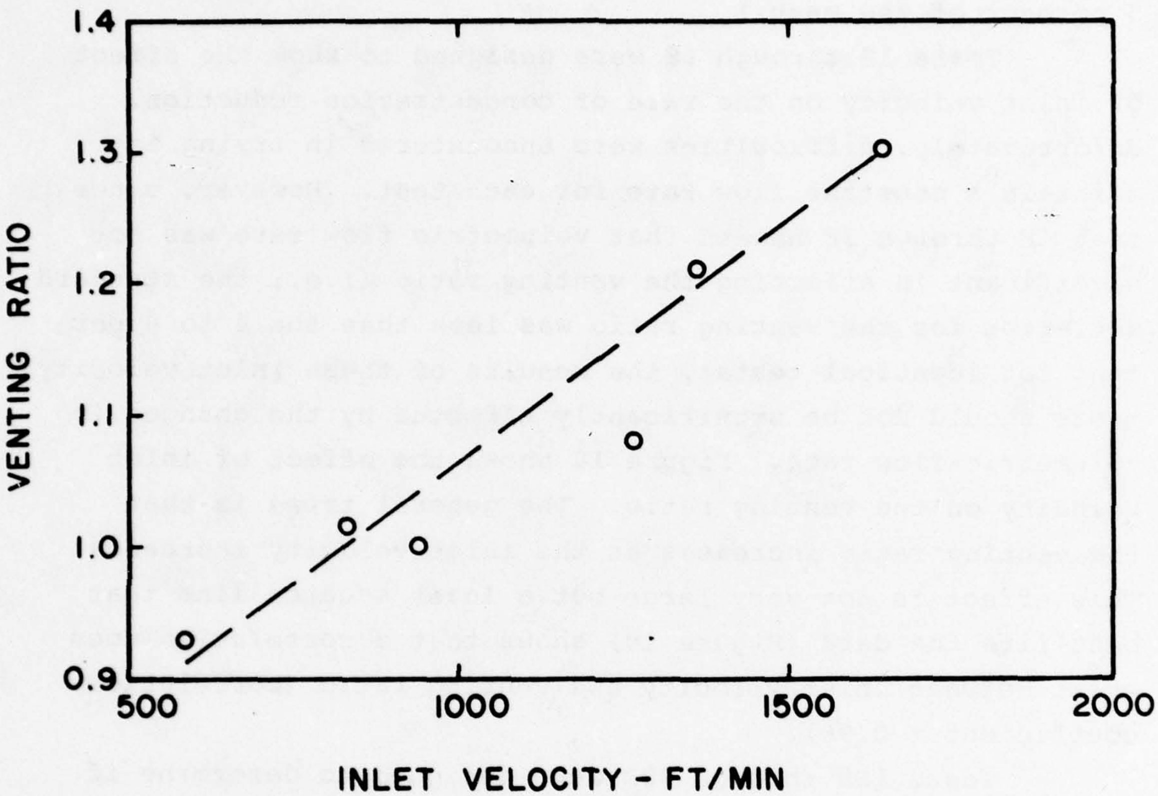

FIGURE 10. EFFECT OF INLET VELOCITY ON VENTING RATIO.

typical runabout mock-up, showed that the venting ratio was dependent on sensor location if the ducting arrangement remains unchanged. It would thus be logical to expect that for a given sensor location, the venting ratio for that location might be a function of ducting arrangement. Appendix A discusses the reasons why the overall venting ratio should be constant even if local variations occur.

In the final analysis, the data demonstrate that none of the variables tested strongly affected the venting ratio. The significant variable is volumetric flow rate (which affects the rate of concentration reduction but not the venting ratio), provided that the compartment volume is constant and that there are no stagnant zones in the compartment. In fact, considering the relative simplicity of the equipment and measuring techniques, there is surprisingly little variation in the data when the slopes measured from the concentration ratios are compared to the "theoretical" slopes calculated from measured flow rates and compartment volume (see Appendix A).

OPEN OR CLOSED COMPARTMENTS

Natural (non-powered) ventilation tests of two different mock-up compartments were conducted in a low speed "wind tunnel" in order to develop guidelines for determining if a compartment is "open" or "closed." Figure 11 shows the two compartments. One measured 42 inches x 42 inches x 55 inches and was designed to simulate an engine compartment. The other was 9 inches x 18 inches x 48 inches and was designed to simulate a gas tank enclosure. The large compartment had two openings and the small compartment had one (see Figure 11 for locations). The test parameters and results are summarized in Tables 6, 7 and 8.

Experimental Procedure

Liquid Fuel

A test compartment was placed inside the wind tunnel (see Figure 12 for details of wind tunnel) and the combustible gas detectors (calibrated by the procedure previously described) were placed inside the compartment at locations shown in Figure 11. Gasoline was poured into a shallow pan in the center of the test compartment floor (0.5 inch depth of gasoline) and 10 minutes later the wind tunnel driving fan was turned on. The reduction in gasoline vapor concentration with time was recorded. Of particular interest was the time that elapsed between turning on the wind tunnel fan and reducing the concentration to below LEL and 1/2 LEL. The wind tunnel fan was run for 10 minutes in each test.

Gaseous Fuel

An additional series of tests was conducted using these same two compartments in the wind tunnel but employing methane gas rather than liquid gasoline as the "fuel." In these tests, the compartment vents were sealed and methane

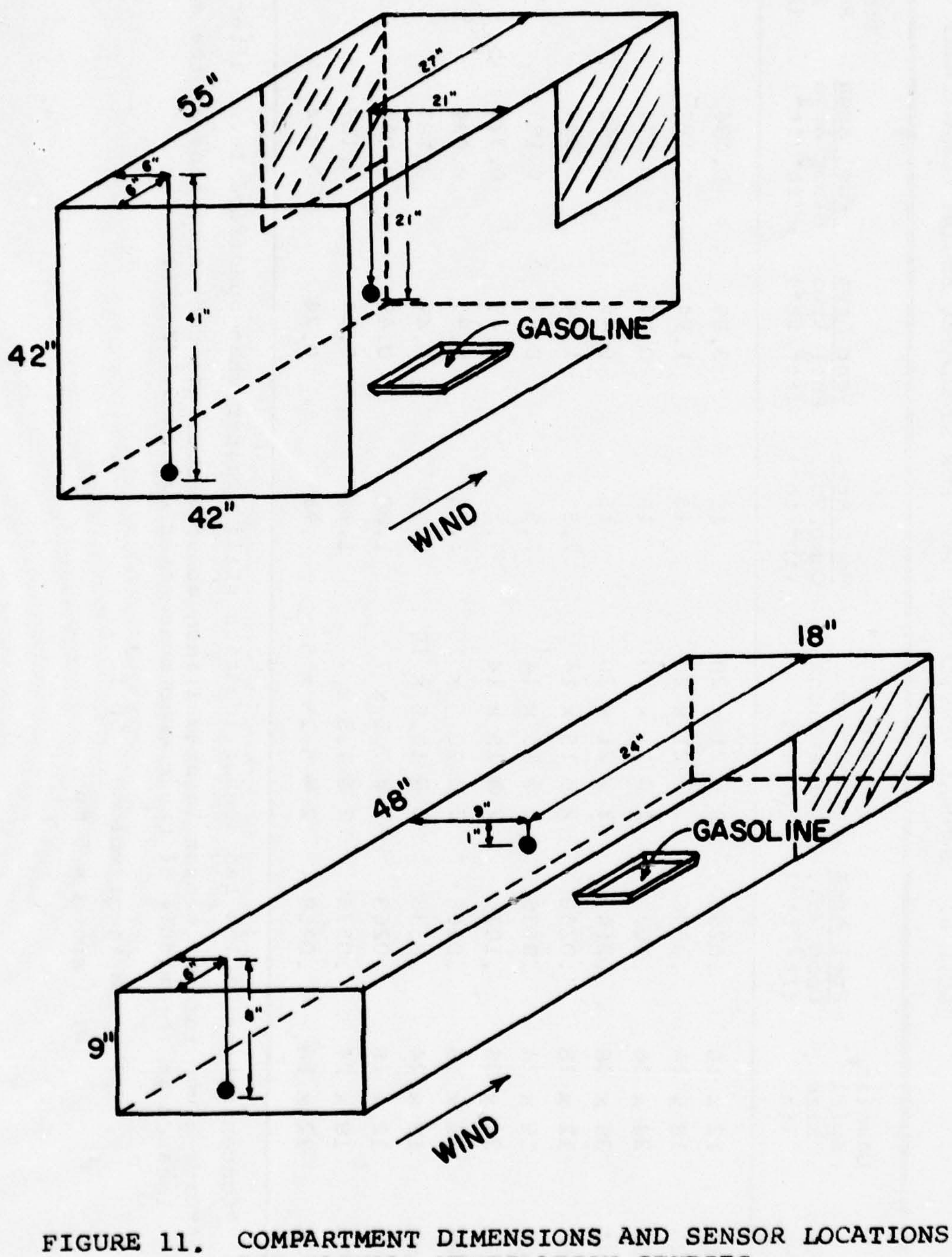

FIGURE 11. COMPARTMENT DIMENSIONS AND SENSOR LOCATIONS FOR NATURAL VENTILATION STUDIES.

TABLE 6. NATURAL VENTILATION DATA FOR SIMULATED ENGINE COMPARTMENT

Test No.	Gasoline Spill Size (in)	Fuel Area / Comp. Vol. (ft^2/ft^3)	Vent Opening Dimensions (in)	Vent Area / Comp. Vol. (in^2/ft^3)	Vent Area / Fuel Area (ft^2/ft^2)	Fuel Area / Floor Area (ft^2/ft^2)	Time to Reach LEL** (sec)	Time to Reach 1/2 LEL** (sec)
1A	12 x 18	.0268	2 @ 21 x 20	15	3.89	0.094	26	35
2A	18 x 24	.0536	2 @ 21 x 20	15	1.94	0.187	39	472
3A	24 x 36	.107	2 @ 21 x 20	15	0.97	0.374	*	*
4A	36 x 48	.214	2 @ 21 x 20	15	0.49	0.748	*	*
5A	12 x 18	.0268	2 @ 15 x 14	7.5	1.94	0.094	59	159
6A	18 x 24	.0536	2 @ 15 x 14	7.5	0.97	0.187	180	*
7A	24 x 36	.107	2 @ 15 x 14	7.5	0.49	0.374	*	*
8A	12 x 18	.0268	2 @ 10.5 x 10	3.75	0.97	0.094	79	273
9A	18 x 24	.0536	2 @ 10.5 x 10	3.75	0.49	0.187	206	*
10A	12 x 18	.0268	2 @ 7.5 x 7	1.88	0.49	0.094	393	*
11A	18 x 24	.0536	2 @ 7.5 x 7	1.88	0.24	0.187	*	*
12A	12 x 18	.0268	2 @ 5.25 x 5	.94	0.24	0.094	*	*

*Concentration at low gas sensor location still greater than specified level after 10 minutes.

**Data given for gas sensor located 1 inch above floor; gas concentrations at the sensor located in the middle of the compartment never exceeded 1/2 LEL.

Compartment volume = 56 ft^3.

Wind speed = 5 mph.

TABLE 7. NATURAL VENTILATION DATA FOR SIMULATED FUEL TANK COMPARTMENT

Test No.	Gasoline Spill Size (in)	Fuel Area / Comp. Vol. (ft^2/ft^3)	Vent Opening Dimensions (in)	Vent Area / Comp. Vol. (in^2/ft^3)	Vent Area / Fuel Area (ft^2/ft^2)	Fuel Area / Floor Area (ft^2/ft^2)	Time to Reach LEL** (sec)	Time to Reach 1/2 LEL** (sec)
1B	6 x 12	.111	8 x 12	21.3	1.33	0.083	62	128
2B	12 x 12	.222	8 x 12	21.3	0.67	0.167	68	335
3B	12 x 24	.444	8 x 12	21.3	0.33	0.333	*	*
4B	12 x 48	.888	8 x 12	21.3	0.17	0.667	*	*
5B	6 x 12	.111	5.5 x 8.5	10.4	0.67	0.083	91	223
6B	12 x 12	.222	5.5 x 8.5	10.4	0.33	0.167	114	273
7B	6 x 12	.111	4 x 6	5.3	0.33	0.083	*	*
8B	12 x 12	.222	4 x 6	5.3	0.17	0.167	*	*

*Concentration at low gas sensor location still greater than specified level after 10 minutes.

**Data given for gas sensor located 1 inch above floor; gas concentrations at the sensor located 1 inch below the top of the compartment never exceeded 1/2 LEL except for Test 4B, during which the concentration approached, but never exceeded, LEL.

Compartment volume = 4.5 ft^3.

Wind speed = 5 mph.

TABLE 8. NATURAL VENTILATION DATA FOR COMPARTMENTS WITH ONLY GASEOUS FUEL PRESENT

Test No.	Compartment Volume (ft^3)	Wind Speed (mph)	Number of Vent Openings	Vent Opening Dimensions (in)	Vent Area / Comp. Vol. (in^2/ft^3)	Regression Coefficient* (sec^{-1})	Time to Reach LEL** (sec)	Time to Reach ½ LEL** (sec)
1G	56	5	2	17 x 16.5	10.0	-.0215	94	126
2G	56	10	2	17 x 16.5	10.0	-.0342	59	80
3G	56	0	2	21 x 20	15.0	-.0132	114	167
4G	56	5	2	21 x 20	15.0	-.0313	64	85
5G	56	10	2	21 x 20	15.0	-.0536	38	51
6G	56	5	2	24 x 23	19.7	-.0363	55	72
7G	56	10	2	24 x 23	19.7	-.0617	32	44
8G	4.5	5	1	5.5 x 8.5	10.4	-.0107	196	261
9G	4.5	10	1	5.5 x 8.5	10.4	-.0307	70	93
10G	4.5	0	1	7.5 x 9	15.0	-.0074	149	243
11G	4.5	5	1	7.5 x 9	15.0	-.0137	144	194
12G	4.5	10	1	7.5 x 9	15.0	-.0518	39	53
13G	4.5	5	1	8 x 12	21.3	-.0178	114	153
14G	4.5	10	1	8 x 12	21.3	-.0635	32	41

*For Tests 1G - 7G, the regression coefficient given is the average for the two sensor locations; for Tests 8G - 14G only one sensor was used.

**Calculated based on results of regression analysis of data to fit Equation 3 and assuming initial gasoline vapor concentration of 10 percent.

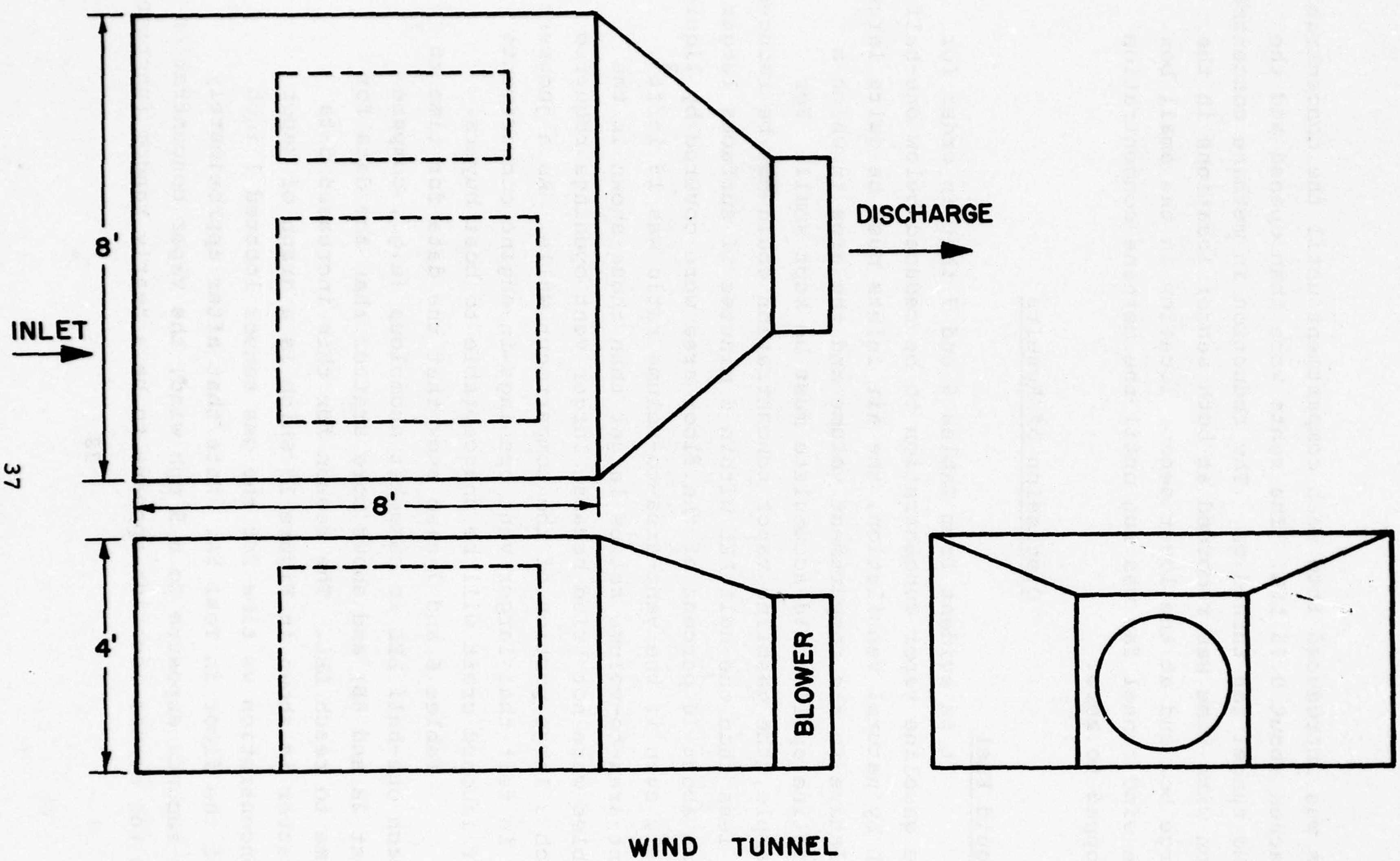

FIGURE 12. WIND TUNNEL USED FOR NATURAL VENTILATION STUDIES.

gas was introduced into each compartment until the concentration reached about 0.75 LEL. The vents were than opened and the wind tunnel fan turned on. The reduction in methane concentration with time was recorded at both sensor locations in the large box and at the lower sensor location in the small box. The wind tunnel fan was run until the methane concentration dropped to zero.

Discussion of Results

Liquid Fuel

It is evident from Tables 6 and 7 that in order for the gasoline vapor concentration to be reduced below one-half LEL by natural ventilation, the air inlets must be quite large relative to the compartment volume and the area in which a gasoline spill could accumulate must be kept small. For example, the gasoline vapor concentration could not be reduced to less than one-half LEL within 5 minutes if surfaces larger than about 10 percent of the floor area were covered by liquid fuel, even if the vent-area-to-volume ratio was 15 in/ft^3. Vent-area-to-volume ratios larger than those shown in the tables were not tried because larger vent openings required such a large portion of the compartment walls. As a judgment, it is felt that larger vent openings in engine compartments for inboard craft will be unacceptable to boat buyers.

Tables 6 and 7 also show that the data for time to reach one-half LEL is somewhat anomolous (e.g., compare Test 2B and 6B) and shows more scatter than the data for time to reach LEL. The reason for this increased data scatter is shown in Figure 13 which is a graph of vapor concentration vs time for the gas sensor located 1 inch off the floor in Test 5A. Note that after approximately 90 seconds exposure to a 5 mph wind, the vapor concentration at the sensor location appears to be a nearly random function

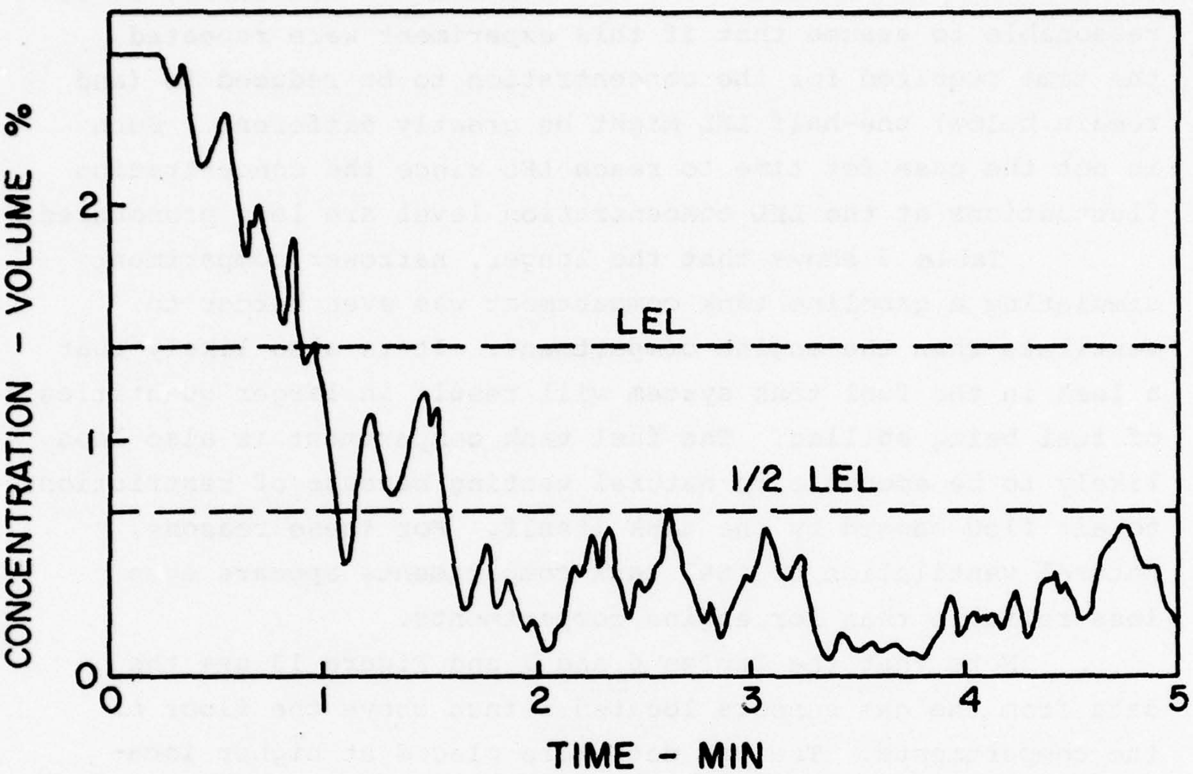

FIGURE 13. GASOLINE VAPOR CONCENTRATION AT THE GAS SENSOR LOCATED 1 INCH ABOVE THE FLOOR OF THE COMPARTMENT DURING TEST 5A (LIQUID FUEL).

of time, and that the concentration peaks continue to approach the one-half LEL level even after 5 minutes. Therefore, it is reasonable to assume that if this experiment were repeated, the time required for the concentration to be reduced to (and remain below) one-half LEL might be greatly different. Such is not the case for time to reach LEL since the concentration fluctuations at the LEL concentration level are less pronounced.

Table 7 shows that the longer, narrower compartment simulating a gasoline tank compartment was even harder to ventilate than the engine compartment. It is also likely that a leak in the fuel tank system will result in larger quantities of fuel being spilled. The fuel tank compartment is also less likely to be amenable to natural venting because of restrictions to air flow caused by the tank itself. For these reasons, natural ventilation of fuel tank compartments appears even less reliable than for engine compartments.

Note that the Tables 6 and 7 and Figure 13 use the data from the gas sensors located 1 inch above the floor of the compartments. The gas detectors placed at higher locations in the boxes showed that considerable layering of the gasoline vapors occurred before the wind tunnel fan was turned on. Once the wind was imposed, the layering effect decreased. In general, the concentration at the lower sensors was greater than twice the LEL before the fan was turned on. At this same time, the higher sensors were indicating less than one-half LEL. After the fan was turned on, the concentration at the higher sensors increased somewhat but never exceeded one-half LEL except for Test 4B, during which the concentration sometimes approached, but never reached, LEL. The data thus indicate that layering persisted, although to a lesser extent than before venting was started. Without the imposed wind, little venting effect was found.

It should be noted that the high concentrations at the lower sensors prior to turning the fan on are quite variable for two reasons. First, the temperature of the gasoline and the surrounding air varied from test to test (generally in the range from 55°F to 65°F). Secondly, the catalytic bead type gas detectors are not accurate when the gas concentrations exceed 2 or 3 times the LEL.

Assuming a typical summer grade gasoline has a Reid vapor pressure of 10 psia[4] and using available nomographs[5, 6], it is possible to determine the actual vapor pressure of the gasoline at any given temperature (see Figure 14). At 55°F the vapor pressure would be 4.5 psia while at 85°F it increases to 8.0 psia. Therefore, changing the temperature of the gasoline spill from 55°F to 85°F should have nearly the same effect as doubling the gasoline spill area at 55°F (i.e., the amount of gasoline vaporized per unit time is approximately doubled). It is therefore apparent that natural ventilation will be even more inefficient as the temperature inside the compartment increases.

It should also be noted that during the natural ventilation tests, no louvers or screens were used to cover the vent openings in the tests, and both would probably be required for an actual engine compartment of similar size. Either would reduce the ventilation rate.

It is assumed elsewhere that the goal in power venting engine compartments should be to reduce the average fuel vapor concentration to one-half LEL within 90 seconds. If this same goal is applied to natural venting, the compartment could be classified as "open" if the average concentration was reduced under conditions of a 5 mph air flow to one-half LEL in

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[4] Technical Data Book--Petroleum Refining (New York: American Petroleum Institute, 1966).

[5] Theodore Baumeister and Lionel S. Marks, Standard Handbook for Mechanical Engineers, 7th ed. (New York: McGraw-Hill, 1958).

[6] W. L. Nelson, Petroleum Refinery Engineering, 4th ed. (New York: McGraw-Hill, 1958).

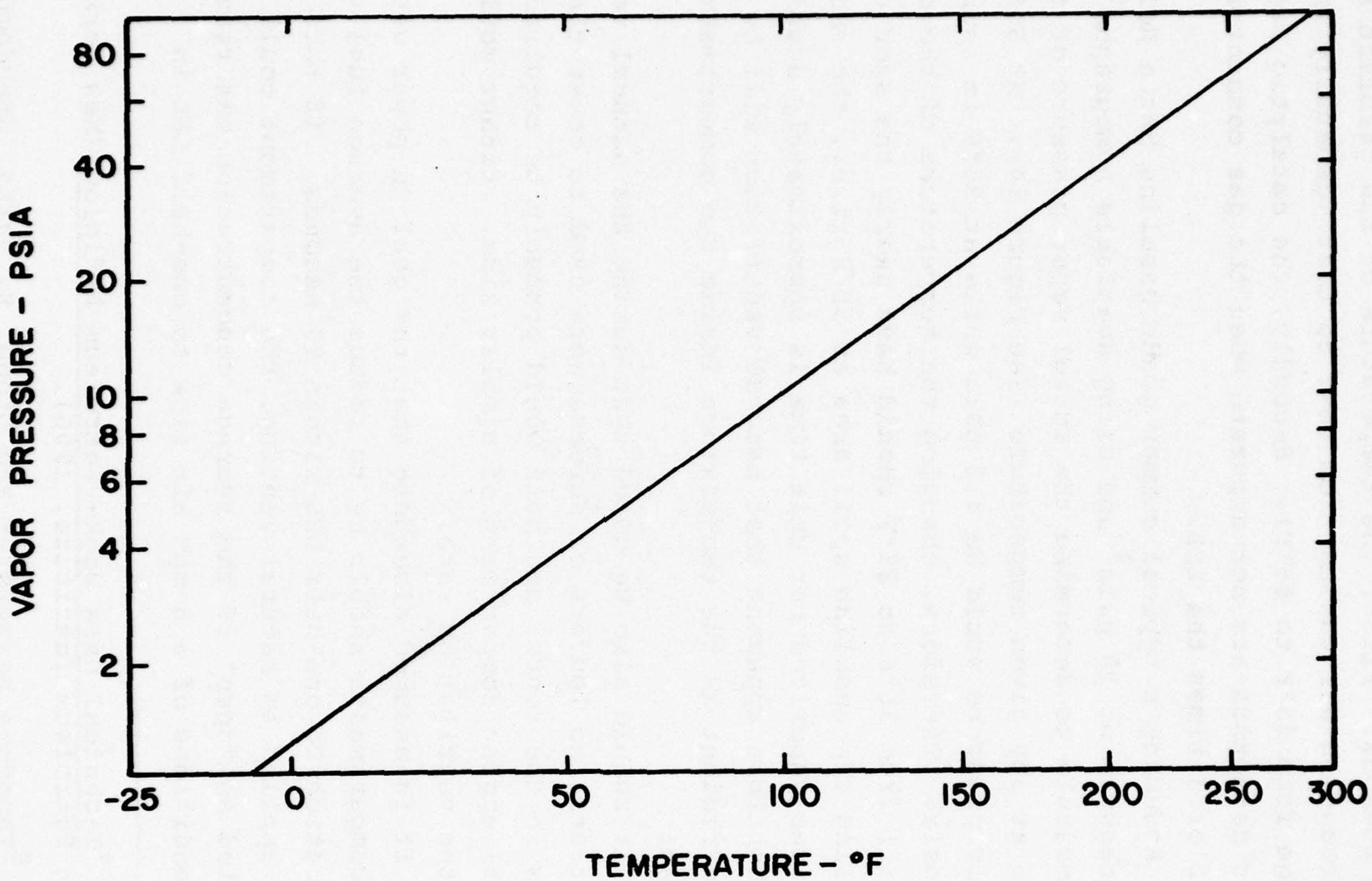

FIGURE 14. ACTUAL VAPOR PRESSURES OF GASOLINE AT VARIOUS TEMPERATURES.

90 seconds, regardless of the vent area. Based on this assumption, only the configuration used during Test 1A would be considered to be an "open" compartment. Even this configuration might have failed the 90 seconds criterion, if the test had been repeated, due to the concentration fluctuations discussed previously.

Gaseous Fuel

The concentration vs time recordings for the tests using methane gas were analyzed by regression analysis to the equation

$$\ln C/C_o = K't + K_o \tag{3}$$

as previously described. By using the constants determined by the regression analysis (given in Table 8) it is possible to calculate the time required for the methane concentration to be reduced to a given fraction of its original value. For example, Figure 15 shows the time required to reduce the vapor concentration from 10 percent to 1.4 percent. This is equivalent to the time required to reduce the concentration of gasoline vapors (no liquid present) from 10 percent to the LEL. On this basis, the data can then be compared with data from the powered ventilation tests which had only gaseous fuel present. The data listed in Table 8 show that with only gaseous fuel present and with a 10 mph imposed wind, five of the six compartment configurations tested vented fast enough to yield a C/C_o of less than 0.07 at 90 seconds. Therefore, under these test conditions, five of the compartment configurations could be considered "open." Similarly, two of the larger compartment configurations (Test 4G and 6G) could also be considered "open" under a 5 mph imposed if only gaseous fuel is present.

Figure 16 shows the time required to reduce the vapor concentration in the 56 ft^3 compartment to the LEL with only

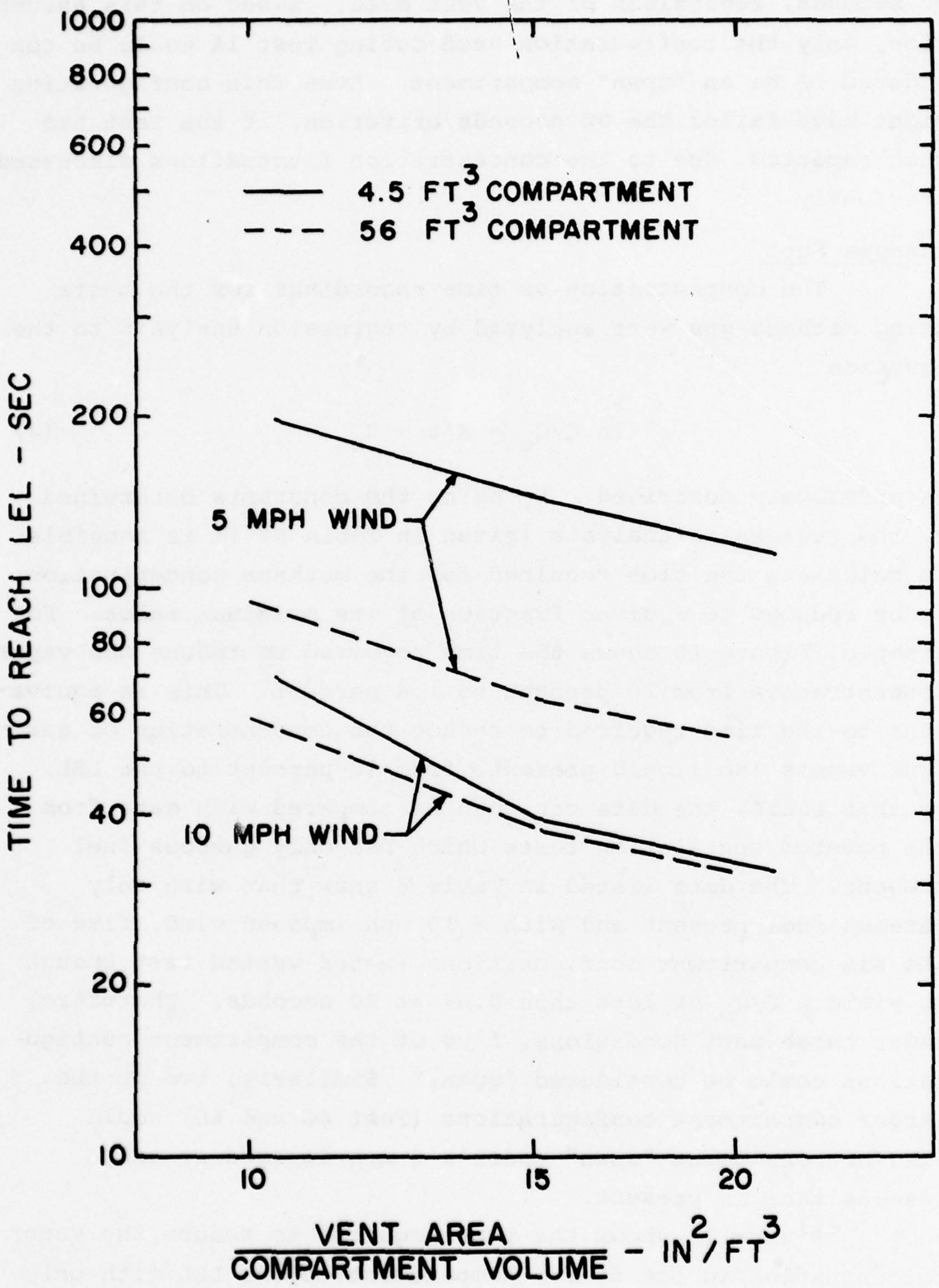

FIGURE 15. CALCULATED TIME REQUIRED TO REDUCE A 10% GASEOUS FUEL VAPOR CONCENTRATION TO LEL WITH NATURAL VENTILATION.

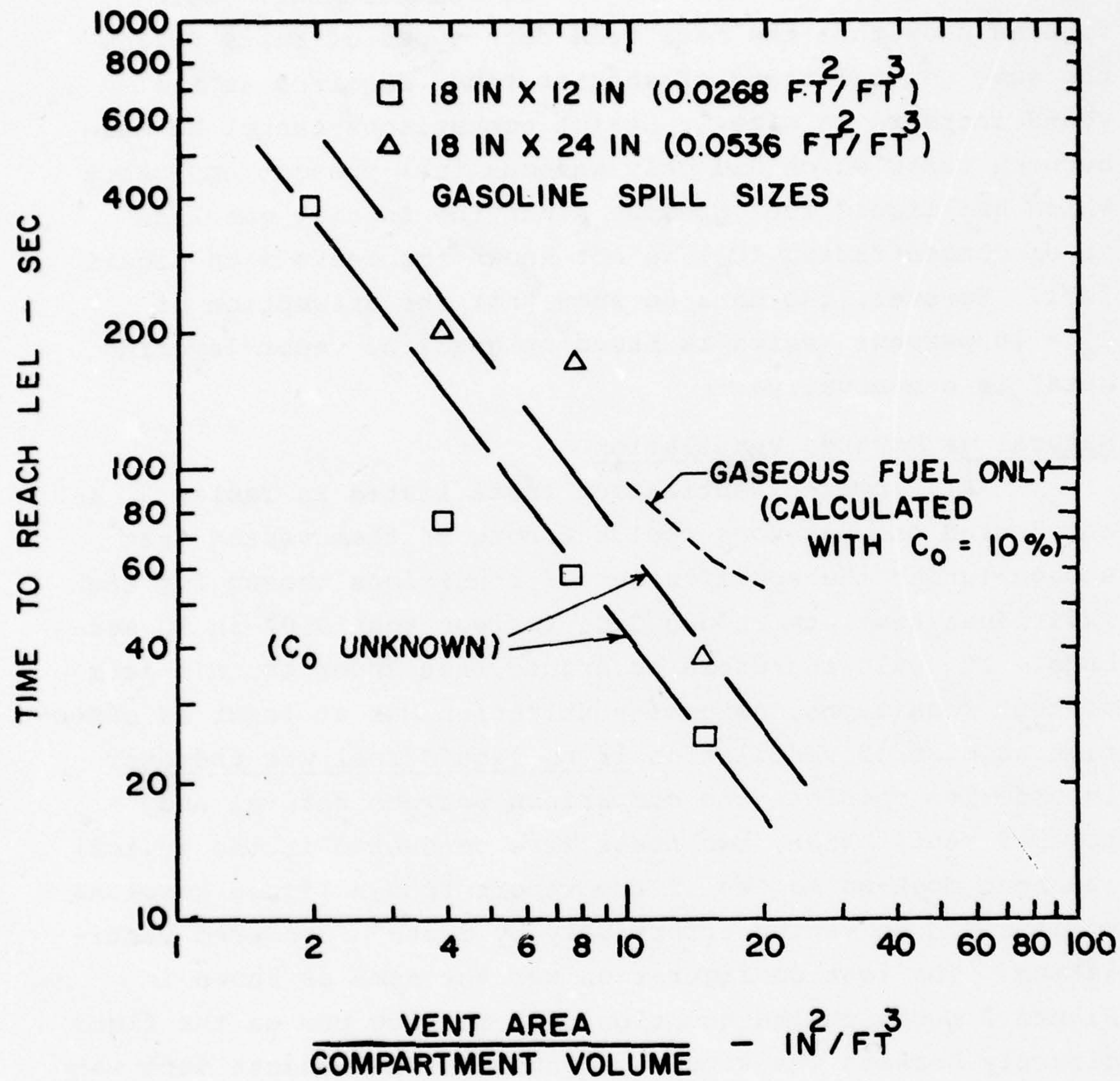

FIGURE 16. TIME REQUIRED TO REDUCE FUEL VAPOR CONCENTRATION TO LEL IN SIMULATED ENGINE COMPARTMENT WITH NATURAL VENTILATION (5 MPH IMPOSED WIND).

gaseous fuel present (calculated by assuming an initial gasoline vapor concentration of 10 percent and with liquid fuel present under an imposed 5 mph wind. Figure 17 shows the same information for the 4.5 ft^3 compartment. Both figures show that the data from both types of tests follow the same general trend of shorter times required as the vents increase in size. Strict comparisons cannot be made between tests which had only gaseous fuel present and tests which had liquid fuel present since the initial gasoline vapor concentration (C_o) is not known for tests with liquid fuel. However, the data do show that the assumption of C_o = 10 percent (which is based on gasoline vapor layering data) is conservative.

Natural vs Powered Ventilation

All powered ventilation tests listed in Tables 3, 4, and 5 used only gaseous fuel and none of them vented fast enough (under the specific set of conditions chosen for each individual test) to reduce C/C_o to less than 0.07 in 90 seconds. It could therefore be argued that under certain sets of test conditions, natural ventilation was at least as effective as powered ventilation if no liquid fuel was present. In order to complete the comparison between natural and powered ventilation, two tests were conducted in the typical runabout mock-up to see if the vapors from a liquid gasoline spill could be vented effectively by means of powered ventilation. The test configuration was the same as shown in Figure 5 but with the addition of a shallow pan on the floor directly beneath the simulated engine. The exhaust duct was taped to the bottom of the simulated engine so the bottom of the duct was about 2 inches above the liquid gasoline. The test parameters and results are given in Table 9.

The tests were conducted in the same basic manner as the liquid fuel natural ventilation tests. Gasoline was poured into the pan beneath the engine to a depth of about

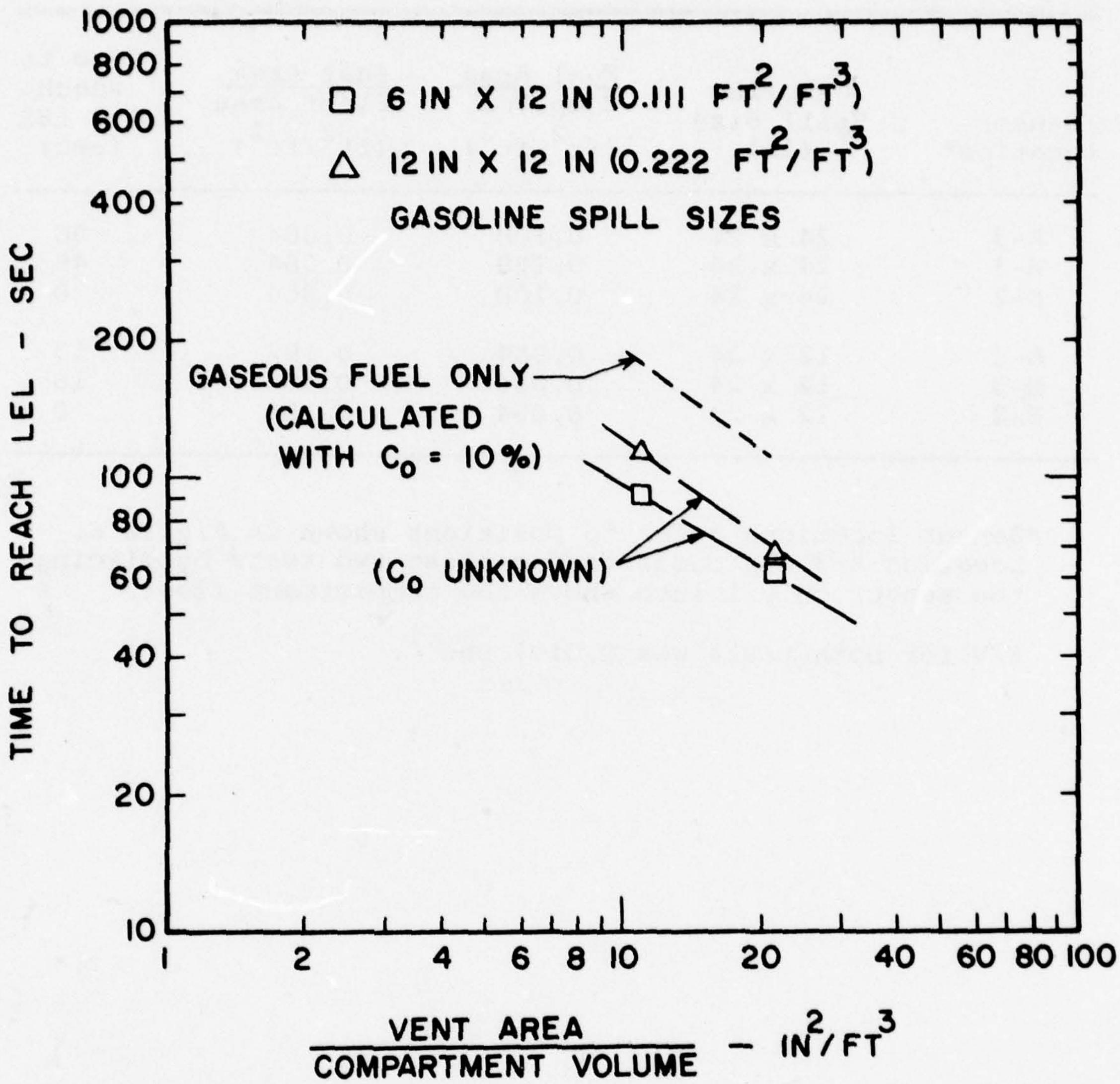

FIGURE 17. TIME REQUIRED TO REDUCE FUEL VAPOR CONCENTRATION TO LEL IN SIMULATED FUEL TANK COMPARTMENT WITH NATURAL VENTILATION (5 MPH IMPOSED WIND).

TABLE 9. RESULTS OF POWERED VENTILATION TESTS IN TYPICAL RUNABOUT MOCK-UP WITH LIQUID GASOLINE PRESENT

Sensor Location*	Gasoline Spill Size (in)	Fuel Area / Comp. Vol. (ft^2/ft^3)	Fuel Area / Floor Area (ft^2/ft^2)	Time to Reach 1/2 LEL (sec)
A-3	24 x 24	0.108	0.364	96
H-3	24 x 24	0.108	0.364	46
E-2	24 x 24	0.108	0.364	0
A-3	12 x 24	0.054	0.182	33
H-3	12 x 24	0.054	0.182	16
E-2	12 x 24	0.054	0.182	0

*Sensor locations refer to positions shown in Figure 6. Location A-3 was modified for these two tests by placing the sensor only 1 inch above the compartment floor.

F/V for both tests was 0.0197 sec^{-1}.

0.5 inch. Ten minutes after placing the gasoline in the pan, the powered ventilation blower was turned on. The gasoline vapor concentrations at the three sensor locations were monitored continuously during the test. At sensor locations H-3 (4 inches above the bottom) and A-3 (modified to be 1 inch above the bottom), the gasoline vapor concentration was greater than three times the LEL in both tests before venting began. The gasoline vapor concentration at sensor location E-2 (19 inches above the bottom) never exceeded one-half LEL. Once the powered ventilation fan was turned on, it took only a short time for the concentrations at the two lower sensor locations to be reduced to less than one-half LEL. After the concentrations had dropped below one-half LEL, they continued to decrease and showed no tendency to fluctuate as was the case during natural ventilation.

This difference in behavior can be attributed to the different mechanisms by which the vapors are removed from above the gasoline spill. During natural ventilation, the gasoline vapors generated by the liquid spill must mix with incoming air and then be swept out of the compartment. During the powered ventilation tests, the outlet duct terminated directly above the liquid spill and could therefore exhaust the vapors being generated by the liquid with only a minimum amount of mixing. If the powered ventilation test configuration were changed so that the outlet duct terminated at a location far from the spill, more mixing and transport would be required to exhaust the vapors. Such a test would be expected to show venting behavior similar to that observed during natural ventilation.

CLOSED OR CONNECTING COMPARTMENTS

The question of whether a non-vented compartment that is attached to a vented compartment is considered to be connecting or closed was addressed by testing four different small compartments (shown in Figure 18) attached to two different large compartments. In one test series, the large compartment was the power ventilated simulated engine compartment (96 ft^3) previously described (see Figure 8). In the other test series the large compartment was the naturally ventilated box (56 ft^3) previously described (see Figure 11).

Experimental Procedure

Liquid Fuel

For the power ventilated tests, the two compartments were joined together as shown in Figure 19. One gas detector was located in each compartment. Gasoline was poured into a shallow pan (located in the small attached compartment) to a depth of 0.5 inches and the compartments were sealed. After 10 minutes, the outlet fan was turned on and the gas vapor concentration was recorded for 5 minutes. The natural ventilation tests were run in the same manner but the compartments were inside the wind tunnel and an imposed wind of about 5 mph was used rather than powered ventilation.

Gaseous Fuel

The test series in which only gaseous fuel was present consisted of three tests using the 4.5 ft^3 compartment shown at the top of Figure 18 joined to the 56 ft^3 box as shown at the bottom of Figure 10. This series used natural ventilation only, with the size of vents on the larger compartment being the test variable. Wind speed was 10 mph and the opening between the two compartments was set at 7.5 inches by 9 inches

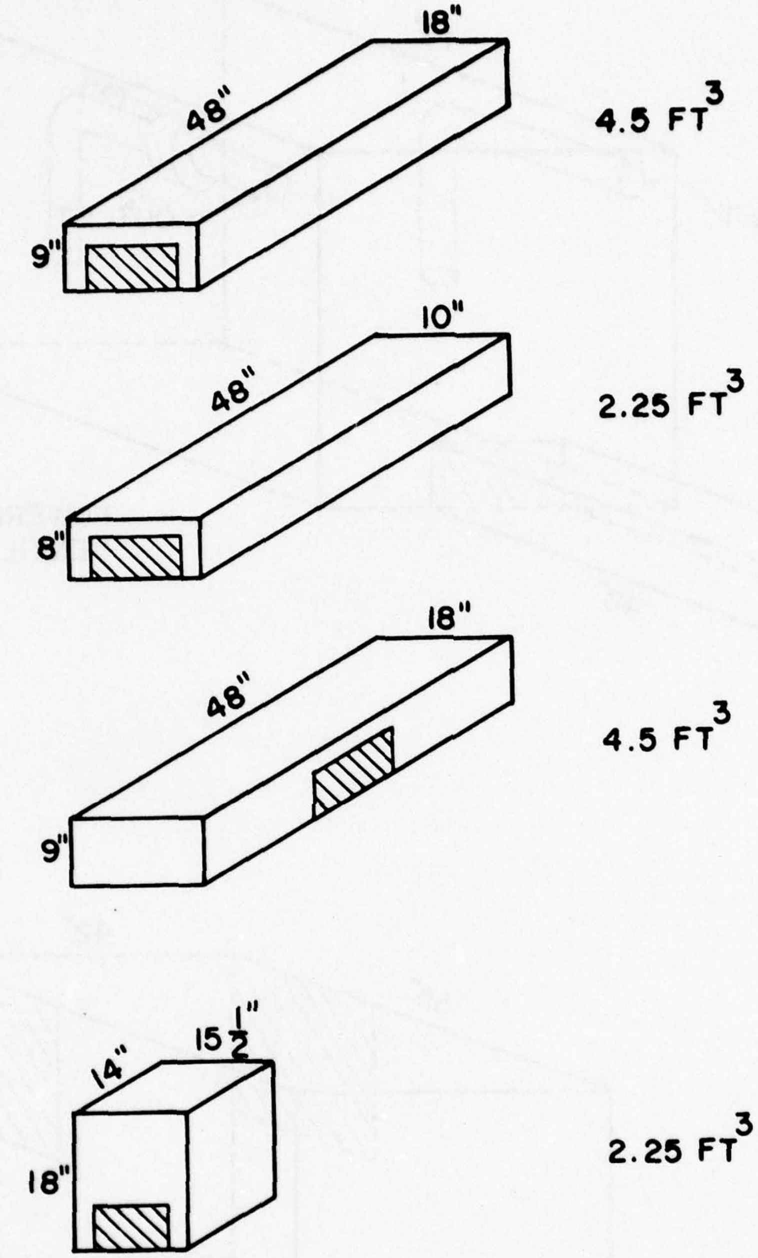

FIGURE 18. CONFIGURATION OF ATTACHED COMPARTMENTS.

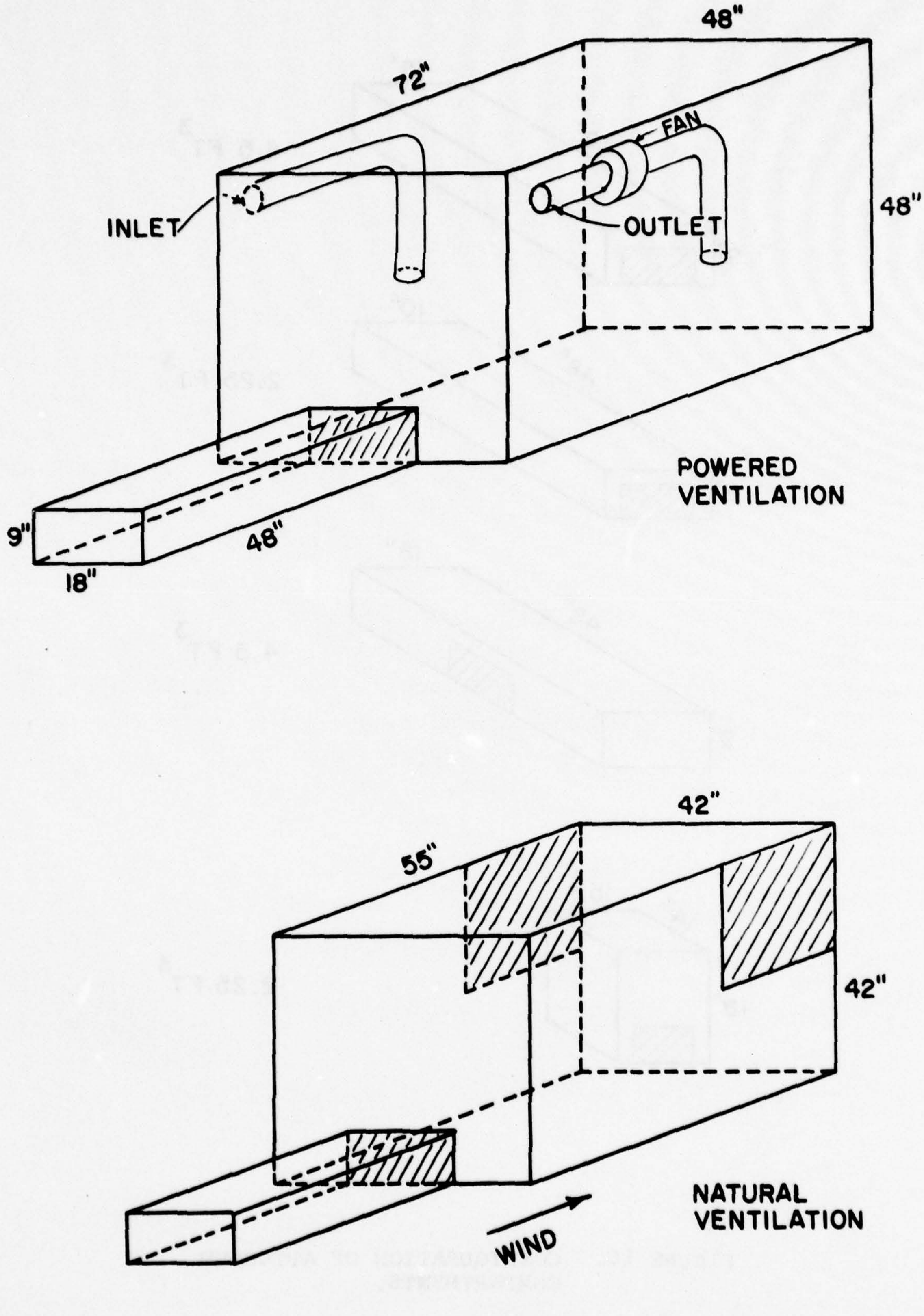

FIGURE 19. POSITION OF ATTACHED COMPARTMENTS DURING VENTING TESTS.

($15 \ in^2/ft^3$ based on the smaller compartment volume). Methane gas was injected into the smaller compartment until a steady reading of about 0.75 LEL was obtained. The wind tunnel fan was then turned on and the reduction in methane concentration with time was recorded. The wind tunnel fan was run until the methane concentration dropped to zero.

Discussion of Results

It is quite apparent from the results listed in Tables 10 and 11 that compartments without external air inlets attached to ventilated compartments are extremely difficult to ventilate. This result is to be expected based on the results obtained using natural ventilation in a $4.5 \ ft^3$ compartment (see Tables 7 and 8 for data). With only one opening into a compartment, the opening must act as both inlet and outlet. Obviously this is not a very efficient venting scheme.

It is thought that much different results might have been obtained had the ducting been arranged differently in the power ventilated test series. For example, if the inlet duct terminated within the small attached compartment, mixing would have been greatly enhanced. A similar effect would be expected if an inlet opening were cut in the attached compartment, especially if the inlet were located on the side opposite the opening between compartments.

A "connecting" compartment can be defined as one in which the average concentration decreases to less than one-half LEL within 90 seconds after ventilation is started in the major compartment. Within this definition, which is consistent with the goal of powered ventilation and the definition of an open compartment, none of the attached compartments could be considered to be connecting.

TABLE 10. POWERED VENTILATION DATA FOR ATTACHED COMPARTMENTS

Test Number	Attached Compartment Dimensions (in) LxWxH	Size of Opening Between Compartments (in) WxH	Connect.Area / Comp.Vol. (in^2/ft^3)	Gasoline Spill Size (in)	Fuel Area / Comp.Vol. (ft^2/ft^3)	Inlet Air Velocity (fpm)	Volumetric Flow Rate (ft^3/sec)	Fuel Area / Floor Area (ft^2/ft^2)	Time to Reach LEL (sec)
1CP	48x18x9	18x7.5	30	6x6	.0555	770	.63	0.042	*
2CP	48x10x8	10x6.75	30	3x6	.0555	770	.63	0.038	*
3CP	48x18x9	18x7.5	30	6x6	.0555	770	.63	0.042	*
4CP	15.5x14x18	10x6.75	30	3x6	.0555	770	.63	0.083	*

*Concentration still greater than LEL in small compartment after 5 minutes.

Inlet (3 inch diameter) ducted to middle of same side.

Outlet (3 inch diameter) ducted to middle of same side.

Ambient temperature in small compartment during tests varied from 59°F to 66°F.

TABLE 11. NATURAL VENTILATION DATA FOR ATTACHED COMPARTMENTS

Test Number	Attached Compartment Dimensions (in) LxWxH	Size of Opening Between Compartments (in) WxH	Connect. Area / Comp. Vol. (in^2/ft^3)	Gasoline Spill Size (in)	Fuel Area / Comp. Vol. (ft^2/ft^3)	Vent Opening Dimensions (in)	Vent Area / Comp. Vol. (in^2/ft^3)	Fuel Area / Floor Area (ft^2/ft^2)	Time to Reach LEL (sec)
1CN	48x18x9	18x7.5	30	6x6	.0555	2@21x20	15	0.042	*
2CN	48x10x8	10x6.75	30	3x6	.0555	2@21x20	15	0.038	*
3CN	48x18x9	18x7.5	30	6x6	.0555	2@21x20	15	0.042	*
4CN	15.5x14x18	10x6.75	30	3x6	.0555	2@21x20	15	0.083	*
5CN	48x18x9	7.5x9	15	NA	NA	2@17x16.5	10	NA	259**
6CN	48x18x9	7.5x9	15	NA	NA	2@21x20	15	NA	212**
7CN	48x18x9	7.5x9	15	NA	NA	2@24x23	20	NA	203**

*Concentration still greater than LEL after 5 minutes.

Ambient temperature in small compartment during tests 1CN - 4CN varied from 59°F to 66°F.

NA = Not Applicable since methane gas was used.

**Calculated based on regression analysis of data to fit Equation 3 and assuming an initial gasoline vapor concentration of 10%.

STANDARD FOR COMPARTMENT VENTING

Two questions must be answered in determining a standard for venting engine compartments on boats. First, what is the goal to be reached, i.e., what is the desired level of safety and how shall it be judged whether the level provided is safe enough? Second, what relatively simple test can be used to assure compliance with the standard?

Determination of a Venting Standard

Previous sections of this report have discussed the results of a number of tests performed under different conditions to determine the venting characteristics of engine compartments. Tests run in both actual engine compartments and simulated engine compartments show a strong tendency of fuel vapors to layer in the compartment, with high concentrations reached near the floor and lower concentrations near the top. The gasoline evaporates fast enough to make it difficult or impossible to assure that all points in the compartment can be ventilated sufficiently to prevent fire if liquid gasoline covers a substantial part of the floor area. In fact, if liquid gasoline is present, it will always be at a temperature above its flash point; ignition of the fuel can always occur just above the liquid surface.

While ignition of a volatile liquid fuel cannot be absolutely prevented by venting, the probability of ignition can be reduced substantially and the occurrence of explosions from vapor accumulations in closed compartments can probably be prevented. The reason that explosions can be prevented while fires cannot is that an explosion requires that a fuel-air mixture in the explosive concentration range be present in the vapor phase; such a mixture can be vented. Fires can be absolutely prevented only by assuring that no liquid fuel is present, and venting alone cannot reach that goal.

One of the most obvious ways that can be used to reduce the chance of a fire or explosion is to limit fuel spillage. If fuel is spilled, the compartment should be designed to limit the area covered by the liquid in order to reduce the surface area from which vapors can be generated. Ideally, a sump should be provided that would contain the fuel and be connected to the engine compartment by a drain that is protected with a flash arrester. Practically, such a sump may be difficult to design, but the design goal should nevertheless be to restrict the surface area of any spilled fuel.

The tests described earlier showed that powered venting could be successful in reducing the concentration of fuel vapor in an engine compartment. More important, the tests show that a mathematical relationship can be used to express the reduction in fuel vapor concentration in the compartment. The mathematical relationship is

$$\ln \frac{C}{C_o} = - \frac{K F t}{V} \tag{4}$$

where K is an empirical coefficient called the venting ratio that is a measure of the deviation from perfect mixing in the compartment. If there is no holdup of vapor due to poor mixing in the compartment, i.e., if there are no stagnant zones, the venting ratio will be greater than or equal to one, and venting will be more rapid than if the compartment were well mixed. Venting actually behaves between plug flow and perfect mixing; venting cannot be better than plug flow nor worse than perfect mixing if there are no stagnant zones.

Equation 4 can be used in compartment design to determine the venting rate required to reduce the concentration of gasoline vapor to a safe level. The design requires that standards be chosen for three of the parameters, the initial concentration (C_o), the concentration to be reached for safe operation (C_s), and the time allowed to reach the safe concentration (t_s). Equation 4 then becomes

$$\ln \frac{C_s}{C_o} = - \frac{K F t_s}{V} \quad (5)$$

The values for the three design parameters must be chosen on a rational basis, within physical restraints. The initial concentration should be the average concentration in the compartment. Tests reported here showed that the gasoline vapor concentration rarely exceeded about 25 percent (about 18 times the LEL), and that such a concentration was found in only the first few inches above the bottom of the compartment. To be conservative, assume the compartment has four parallel, horizontal zones of equal volume, and that the concentration reaches 25 percent in the lowest zone and 5 percent in each of the other three zones before venting is started. The average initial concentration is thus chosen to be 10 percent.

The concentration must be reduced to a level below the lower explosive limit in order to assure that no explosion can occur. Generally, that goal can be reached by reducing the concentration to the LEL. However, because of potential turbulence in the compartment and the possibility of partially stagnant zones where air flow is restricted, the safe concentration should be chosen at a lower level, and will be set at one-half the LEL. For gasoline, the LEL is about 1.4 percent[7] so C_s is assigned the value of 0.7 percent.

While both C_s and C_o can be specified on the basis of physical properties and test data, the time allowed for reaching a safe level is subjective and open for choice. It seems intuitively that the time chosen should depend at least to some extent on the size of the compartment to be vented. A large boat, such as a yacht, would require more time to get underway, and a longer venting period can be tolerated without serious risk that the owner will disconnect any interlock

[7] National Fire Protection Association, Fire Protection Guide on Hazardous Materials, NFPA Standard 325M, NFPA, Boston (1975).

system. However, for small runabouts, it is unlikely that the owner will be sufficiently patient to wait more than a short time before he attempts to start the engine. Therefore, the time to reach a safe level has been chosen as 1.5 minutes; this preliminary value for t_s may need to be increased for compartments with more than a few hundred cubic feet of volume if power requirements exceed electrical system capacity. If it is found that a longer time represents an unreasonable delay and will result in disconnect by the owner, greater blower capacity and perhaps a higher capacity electrical system will be required.

The value for the venting ratio is taken as one because it cannot be less than one unless there are zones of stagnant air in the compartment. Then, based on Equation 5 and the assigned values,

$$\ln\left(\frac{0.7}{10.0}\right) = -(1.0)\,\frac{F}{V}\,(1.5) \qquad (6)$$

from which it can be found that

$$\frac{F}{V} = 0.0295\ \mathrm{sec}^{-1} = 1.77\ \mathrm{min}^{-1} \qquad (7)$$

The result shows that 1.77 air changes per minute are required for a duration of 1.5 minutes to reduce the concentration to the chosen level of one-half LEL.

Assuming, as was done above, that venting is to be accomplished in 1.5 minutes, the flow rate required to assure proper venting can be calculated using Equation 7. For example, the powered ventilation system for a 50 ft^3 compartment must provide at least 1.77 times 50 or 88.5 cfm in order to provide the specified reduction in vapor concentration within 1.5 minutes. It is important to draw a distinction between the rated flow of the venting fan and the actual flow delivered in the installed configuration. The installed capacity will frequently be less than the rated capacity because of additional flow restriction in the installed condition and potential low battery voltage that reduces fan performance. If the actual blower output per minute is twice the gross compartment volume, the suggested standard should be met in most cases. (A blower output of 1.77 times the net compartment volume would theoretically meet the standard. However, in anticipation of low battery voltage and an element of flow stagnation in certain parts of the compartment, an actual blower output of twice the gross compartment volume is suggested as a good starting point.)

Testing for Compliance

The discussion above suggests that an acceptable standard for venting of engine compartments is to require powered ventilation with the fan large enough to reduce the fuel vapor concentration to less than one-half the lower explosive limit in 1.5 minutes. The time limit is somewhat arbitrary, and is based on judgment and common practice rather than specific technical knowledge.

The information presented earlier shows a simple way to provide a design that will meet the suggested standard. The compartment to be vented is simply measured to determine its net volume and the required, actual blower capacity (or actual system capacity for more than one blower) is calculated. The blower must be chosen with the goal of providing the proper venting rate under low battery conditions and be designed for the pressure loss in the installed configuration. The installed system must also be tested to assure that it complies with the goal of the standard. A simple, reliable compliance test is required.

The compliance test suggested here is based on experience and the analysis of the venting measurements performed during this work. The most important findings in devising the compliance test are that Equation 4 represented the vapor concentrations in the compartment and that the value of F/V can be determined experimentally by measuring vapor concentrations in the compartment. Further, F/V can be found by measuring concentration ratios, regardless of the initial concentration, because the air in the compartment is well mixed with the vapor, regardless of the chemical or physical nature of the vapor. Thus, the compliance test need not use gasoline as the vapor source. Indeed, no flammable concentration of gas is required.

A compliance test can be run by positioning three sensors in the compartment, one near the floor at the side of the engine, one near the carburetor, and one near the alternator or generator. The positions are chosen because of their potential as a spill accumulation area, spill source, and ignition source. Using the typical runabout mock-up as an example these locations would be roughly equivalent to sensor locations D3 (or E3), I2, and B2 respectively. After positioning the sensors, a gas can be injected into the compartment and mixed with the air to a uniform concentration as shown by the sensors. The blower will then be turned on and the concentration of gas measured as the venting is completed. A plot is then drawn of $\ln C/C_o$ vs t for each sensor and the slopes of the resulting lines are determined; if the average of the slopes is steeper than that required, i.e., $-1.77\ \text{min}^{-1}$, the venting system passes the test. (Note that the slope is negative, so that a steeper slope implies a smaller number. Also recall that a smaller negative number is the one with the greater absolute value.)

An even more simple test can be devised. For example, the concentration data need not be recorded continuously throughout the test. Instead, the test might specify that the gas concentration should be reduced to 7 percent of its initial value (at each location) within 1.5 minutes, which is the same as having a slope of $-1.77\ \text{min}^{-1}$ on the plot of $\ln C/C_o$ vs t and an intercept of 1.0.

The gas chosen to be used during the compliance test should be relatively inexpensive; easily available; easy to detect and measure with simple, reliable equipment; and amenable to measurement in non-flammable conditions. Various types of gas sensing equipment are available that meet these requirements; e.g., catalytic bead combustible gas detectors, thermal conductivity devices, infrared analyzers, and zirconium oxide electrolytic oxygen detectors. Each type of detector has its advantages and disadvantages. Thermal conductivity and infrared devices require that the gas to be analyzed must flow from the sampling location, through a tube to the analyzing cell. This causes their response time to be quite long and rules out their use if continuous monitoring of the concentration is desired. The zirconium oxide electrolytic oxygen detector must have fresh air on one side of the electrolytic cell to act as a reference. This makes it difficult to mount the sensor totally within a compartment. Also, since it measures oxygen concentration, the concentration of the tracer gas would have to be determined by difference, thus requiring high concentrations of the tracer in order to have acceptable accuracy. Catalytic bead combustible gas detectors would require that the tracer gas be combustible. Even though the starting concentration would be chosen to be below the LEL (e.g., 2 percent methane might be used) there is still the possibility that the engine compartment might accidentally be filled with an explosive gas/air mixture. On the other hand, this is the only one of the detectors listed here that can conveniently be mounted inside the engine compartment and that has a quick enough response time to allow continuous monitoring of the tracer gas concentration.

After considering all the various factors noted previously, two test methods appear to be viable candidates for a compliance test. The first method would involve placing three catalytic bead combustible gas detectors in the compartment and injecting methane gas into the compartment until a steady state concentration of 2 percent (0.4 LEL) had been attained. Then the ventilating blower(s) would be turned on and the methane concentration would be recorded continuously for at least 90 seconds. From the recorded curve of concentration vs time, the operator would determine the value of C/C_o at 90 seconds after ventilation began. If all three values of C_{90}/C_o were less than 0.07, the venting system would pass the test.

The second method would require that gas samples be withdrawn from three locations within the compartment, using a vacuum pump and metal or plastic tubing. Each sample would be drawn through the analyzing cell of a thermal conductivity or infrared analyzer. The first set of three samples would be withdrawn and analyzed after injecting enough neon, krypton, or carbon dioxide gas into the compartment to give a starting concentration of about 10 percent. The ventilation system blower(s) would then be turned on and allowed to operate for exactly 90 seconds, at which time they would be turned off and all vents or other openings into the compartment would immediately be covered. The second set of three samples would be withdrawn and analyzed as soon as possible after shutting off the ventilation system blower(s). If each of the second set of concentrations was less than 7 percent of the corresponding initial concentration, then the ventilation system would pass the test.

Although the second method might appear to be simpler and is probably less expensive (no recorder device is required), it might prove to be impractical for certain engine compartment configurations that have a multiplicity of vents or other holes that would have to be plugged simultaneously at the instant the blower(s) is stopped. It is also reasonable to expect that the second method would show greater statistical variation than the first method since some of the test variables in the second method might be difficult to control (e.g., total time the blower(s) is operated, and the time required to plug all inlets to the compartment). Therefore, we recommend that the first method be used.

Alternatives

There are some alternatives that might be suggested as being equally effective as venting in reducing the potential for explosions and fires in engine compartments. For example, an interlock that prevents starting if a combustible gas detector registers the presence of flammable vapors might be used. It might be better in very large compartments, especially. The design of the detector and its location would require careful choices because of the potential of saturating the detector. Such a system could also warn of flammable vapors during ordinary operation.

An even simpler system could consist of an interlock that prevents the engine from being started unless the engine compartment is opened. The philosophy behind such a system is that the operator should readily notice the presence of fuel (liquid or vapor) in the compartment and ascertain that the fuel was removed before attempting to start the engine. Such an interlock could be simple, reliable, and designed so that there would be little delay or waiting in its use. It does rely on the operator for performance, but there is no question that gasoline vapors could be detected at concentrations lower than the one-half LEL chosen to represent an acceptable safe level.

Compliance Test Evaluation

The three test boats (previously described in the Powered Ventilation section) were tested in accordance with the proposed method. Three combustible gas detectors were calibrated with 2.0 percent methane gas and were then placed inside the engine compartments. A small 12 volt blower (rated at 98.75 cfm) was also placed in the compartment to insure a well-mixed atmosphere. The compartment was then closed. No special provisions were made to seal cracks or other small leaks into the compartment since intent was to test the ventilation system in an actual boat configuration.

The small recirculating blower within the compartment was turned on and methane gas from a pressurized cylinder was injected into the compartment through a 0.25 inch tube. When the gas detectors indicated approximately 60 percent LEL (3.0 percent methane), the flow of methane was stopped, the internal blower was stopped, and the blower in the boat's ventilation system was started. The gas detector outputs were then recorded for about five minutes.

The initial gas concentration, C_o, and the gas concentration after 90 seconds of blower operation, C_{90}, were read from the charts. The concentration after 90 seconds was then divided by the initial concentration. The three values for C_{90}/C_o were compared to the desired maximum value of 0.07.

The results of these tests, listed in Table 12, showed that none of the ventilation systems met the proposed standard. However, measurements of the compartment volumes and venting system flow rates showed that at least the Ranger and Glas Ply venting systems met the BIA standard[8] of exhausting one volume equal to the net compartment volume in 1.5 minutes. A venting system must be capable of exhausting at least a volume equal to 1.77 times the net compartment volume in 1 minute in order to have any chance of passing the proposed standard. None of the boats tested had sufficient blower capacity to pass the proposed standard.

Further tests were conducted to see if the ventilation systems could be improved. The Glas Ply engine compartment (Figure 20) is basically a large rectangular shape with four

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[8]Boating Industry Association, "1976 BIA Certification Handbook: BIA-147-72 and ABYC H-2-72."

TABLE 12. DATA FOR COMPLIANCE TEST EVALUATION

Test Boat	Combustible Gas Detectors Number	Combustible Gas Detectors Location	C_{90}/C_o	Average C_{90}/C_o	Approximate Compartment Volume (ft^3)	Volumetric Flow Rate (ft^3/min)	Location of Inlet Ducts	Location of Outlet Ducts
Ranger (Stock)	1	Carburetor	0.27	0.27	25	48	Ducted to near floor at rear of compartment. (See Figure 22)	One powered outlet ducted to lower rear corner of engine. (See Figure 22)
	2	Sump	0.32					
	3	Below outlet fan	0.22					
Ranger (Modified)	1	Carburetor	0.13	0.11	25	48	Ducted to near front of engine valve cover.	One powered outlet ducted to lower front corner of engine.
	2	Sump	0.12					
	3	Below outlet fan	0.09					
Sea Ray (Stock)	1	Carburetor	0.26	0.23	25	--	Two inlets, one on each side, ducted about halfway to floor in rear of compartment.	Two non-powered outlets ducted to below left rear corner of engine. One powered outlet ducted below right rear corner of engine.
	2	Sump	0.21					
	3	Middle of engine side	0.21					
Glas Ply (Stock)	1	Carburetor	0.34	0.24	50	53.5	Ducted to near floor on side of compartment. (See Figure 20)	One powered outlet ducted to lower rear corner of engine. (See Figure 20)
	2	On floor in front of engine	0.27					
	3	Sump	0.11					
Glas Ply (Modified)	1	Carburetor	0.12	0.07	50	99.3	No ducted inlets. Normal inlet used for powered outlet.	Two powered outlets; one ducted to lower rear corner of engine, one to lower front corner of engine.
	2	Below inlet area	0.02					
	3	On floor in front of engine	0.08					

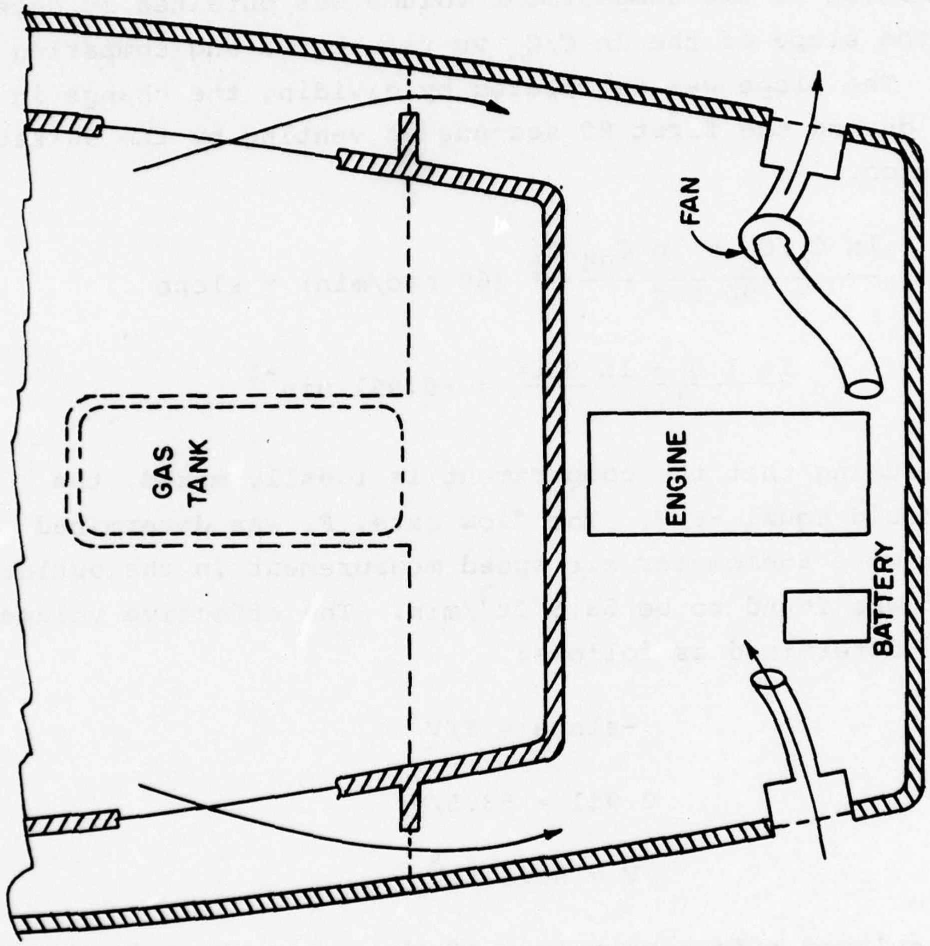


FIGURE 20. GENERAL LAYOUT OF THE GLAS PLY ENGINE COMPARTMENT.

smaller rectangular areas attached. Of the three boats tested, this one was most closely simulated by the 96 ft^3 mock-up in which the powered ventilation tests had been conducted. Therefore, the results of the powered ventilation tests should apply most directly to it. The volume of the compartment was estimated to be about 50 ft^3 (the exact volume would be very difficult to determine due to the curved surfaces involved). Another approximation of the compartment volume was obtained by determining the slope of the ln C/C_o vs time curve and comparing it to F/V. The slope was calculated by dividing the change in ln C/C_o during the first 90 seconds of venting by the 90 second time period.

$$\frac{\ln C_o/C_o - \ln C_{90}/C_o}{90 \text{ sec}} (60 \text{ sec/min}) = \text{slope}$$

$$\frac{\ln 1.0 - \ln 0.24}{1.5} = -0.951 \text{ min}^{-1}$$

Then, assuming that the compartment is ideally mixed, the slope should equal -F/V. The flow rate, F, was determined by a hot wire anemometer air speed measurement in the outlet duct and was found to be 53.5 ft^3/min. The effective volume was then determined as follows:

$$-\text{slope} = F/V$$

$$0.951 = 53.5/V$$

$$V = 56.3 \text{ ft}^3$$

This calculated effective volume of the compartment is nearly the same as the net volume estimated previously. The effective volume of 56.3 ft^3 was used to determine the flow rate that would be necessary to reach the desired 7 percent of C_o level in 90 seconds (slope of -1.77 min^{-1}).

$$-\text{slope} = F/V$$

$$1.77 = F/56.3$$

$$F = 99.65 \text{ ft}^3/\text{min}$$

A second outlet blower was placed in the compartment. It was arranged so that it drew air from below the front of the engine and exhausted it out what had been the air inlet. Therefore, inlet air had to come through holes in the front of the compartment. These holes were located in the area between the hull and the inner surface of the boat body as shown in Figure 20. This area connects to the inside of the boat through large openings which are often used for stowing small carry-on articles.

The total air flow rate was measured to be 99.3 ft^3/min and the average C_{90}/C_o was 0.07. Therefore, the assumption of an "effective volume" of about 56 ft^3 appears to be valid. It should be noted here that the two blowers had a total rating of 232 ft^3/min but delivered only 99.3 ft^3/min in the system. Thus the effective flow rate delivered by the blowers was only about 40 percent of the rated capacity.

Figure 21 shows ln C/C_o vs time for the three gas detectors used in this test. The straight lines were drawn by eye to best fit the data. The slopes of the three lines are -1.96, -2.02, and -1.59 min^{-1}, resulting in an average slope of -1.86 min^{-1}. This average agrees quite well with the slope of 1.76 min^{-1} predicted by -F/V (i.e., 99.3 ft^3/min divided by 56.3 ft^3). Had the slope been calculated using the estimated volume of 50 ft^3, it would have been -1.99 min^{-1}, again quite close to the average of the measured values.

It is important to note that although the average slope for the three sensors was steeper than -1.77 min^{-1}, the ventilation system would not have passed the proposed compliance test since one sensor location showed a slope of only

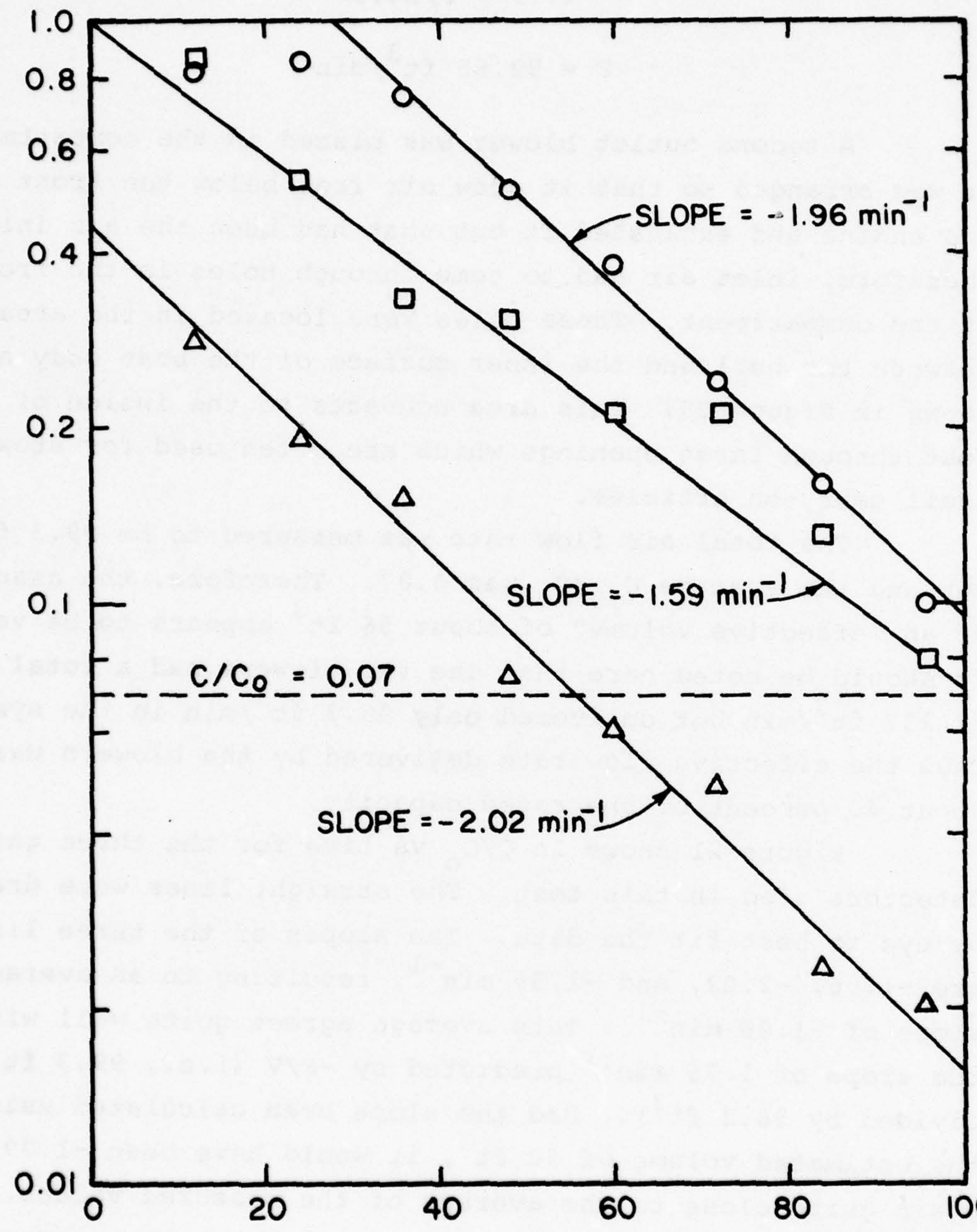


FIGURE 21. FLAMMABLE VAPOR CONCENTRATIONS DURING POWERED VENTILATION OF GLAS PLY ENGINE COMPARTMENT (MODIFIED VENTILATION SYSTEM WITH TWO POWERED OUTLETS).

$-1.59\ min^{-1}$ and the concentration ratio at two sensor locations was still above 0.07 after 90 seconds.

The engine compartments in the other two boats, the Sea Ray and the Ranger, were very similar to each other but were significantly different from the Glas Ply. These two compartments, as shown in Figure 22, had four main elements; a narrow rectangular area reaching from one side of the boat to the other, a rectangular area projecting out the front of the previous area (this contained most of the engine), and two side areas between the hull and the interior surface of the boat (similar to those described for the Glas Ply). Openings were also present in the two latter areas similar to those for the Glas Ply boat. The ducted inlet(s) and outlets(s) were all located in the first rectangular area. This arrangement, in effect, makes the area in which most of the engine is contained appear to be a separate compartment joined to the first by a relatively large opening. However, the clearances between the engine and the compartment walls are very small (less than 4 inches in most places). This arrangement makes it quite difficult to ventilate the compartment surrounding the engine adequately because air flow into the area near the front of the engine is severely restricted.

The Ranger ventilation system was tested first in its stock (as built) configuration and then tested again after modifying the ducting arrangement. In the stock ducting arrangement, inlet and outlet ducts both terminated in the compartment to the rear of the engine. For the second test, this was modified so that both ducts terminated in the compartment surrounding the engine. In both tests, the air flow rate was about 48 cfm. The average C_{90}/C_o for the stock venting system was 0.27; for the modified system it was reduced to 0.11. The total engine compartment volume was estimated from simple measurements to be 25 ft^3. If the

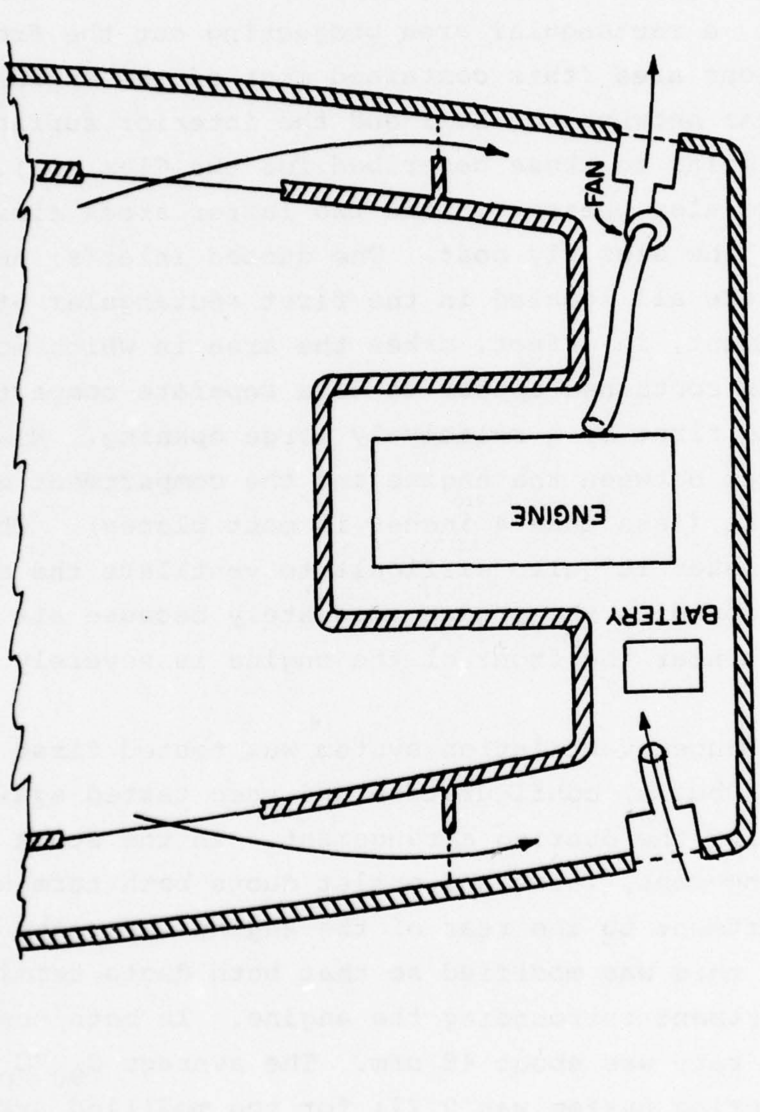


FIGURE 22. GENERAL LAYOUT OF RANGER ENGINE COMPARTMENT.

compartment were ideally mixed, a total air flow rate of 44.25 ft^3/min would be sufficient to give an average C_{90}/C_o of 0.07. The "effective volume" (determined as in the case of the Glas Ply boat) is 32.4 ft^3 if C_{90}/C_o is 0.11. It is difficult to imagine that the actual volume could be that much larger than the estimate, 25 ft^3, which was based on measured dimensions. Apparently, the air flow around the engine is restricted to the point of causing some stagnation.

It appears obvious from these tests that the complex shapes of some engine compartments might cause difficulties when trying to design an efficient, powered ventilation system based on the assumption of ideal mixing. It is also obvious that the relative location of inlet and outlet ducts can have a significant effect on venting efficiency in some engine compartment configurations. Furthermore, the actual air flow rate of an installed blower is less than its rated capacity; and compartment volume, particularly net volume, is very difficult to determine. These factors will all cause some degree of uncertainty when designing a ventilation system. However, certain steps can be taken to help assure that the ventilation system will be adequate to meet the requirements of the test.

1. If the engine compartment is relatively large and unobstructed, the total per minute capacity of the power ventilation blowers, as installed, must be at least 1.77 times as great as the compartment volume. Even higher blower capacities may be required for congested compartments.

2. Inlets close to the termination of outlet ducting should be avoided because this arrangement allows "flow channeling" which causes some stagnation in other areas of the compartments.

3. The termination of the outlet duct should be below the engine in order to scavenge gasoline vapors from the sump where they will tend to collect because their density is greater than air density.

4. The termination of the outlet ducting and inlet ducting should be located at opposite ends of congested compartments. This arrangement will aid the overall mixing by causing air to be drawn into the congested areas which might otherwise be stagnant.

5. The gross compartment volume should be used to determine the required blower capacity.

CONCLUSIONS AND RECOMMENDATIONS

Several conclusions can be reached based on the results of the experiments and an analysis of the behavior of fuel-air mixtures in ventilated compartments:

A warm fuel with a vapor pressure as high as that of gasoline will vaporize so fast that it is impossible to prevent ignition at the liquid surface except by precluding all ignition sources. However, powered venting can prevent explosions and substantially reduce the probability of fires. Venting will be considerably more effective if the liquid fuel surface area is reduced; draining to a sump through a flash arrestor appears to be best, if technically feasible.

Natural ventilation is not effective unless the vent area is large and the spill area is small. Powered ventilation is preferred because of its certain ability to provide proper reduction of fuel vapor in a compartment. The duct to the venting outlet should terminate near the floor and the inlet should admit air near the top in order to take advantage of layering in reducing vapor concentrations. Within the range studied, the number and size of either inlet or exhaust ports made little difference in powered venting effectiveness at a given venting rate.

The venting rate should be sufficient to reduce the vapor concentration from an average of about 10 percent to 0.7 percent (one-half LEL) in 1.5 minutes; the concentrations are based on physical measurements and the time on judgment. Practically, this goal can usually be reached by requiring the actual volumetric venting rate (in ft^3/min) to be 1.77 times the compartment volume (in ft^3). A simple rule of thumb, including an allowance for low battery voltage and minor flow loss due to ducting, is to make the system flow capacity per minute equal twice the gross compartment volume.

A flammable gas sensor installed in the compartment or an interlock that requires the compartment to be opened before the engine can be started may be as effective in preventing fire and explosion as a venting system.

The single recommendation from this study is for a simple but effective compliance test:

The compliance test should require that a gas be mixed with the air in the compartment. The gas concentrations near the alternator (or generator), near the carburetor, and near the bottom of the compartment should each be reduced to 7 percent of the respective initial concentration within 1.5 minutes of starting the blower. A suggested procedure for performing such a test is given in Appendix B.

APPENDIX A

The equation that describes the rate of concentration reduction with time in a perfectly mixed system is

$$\ln C/C_o = -\frac{Ft}{V}$$

where C_o = initial concentration of contaminant
C = concentration of contaminant at time t
t = time
V = compartment volume
F = volumetric flow rate of fresh air into the compartment

In order to compare the actual rate of concentration reduction at a given sensor location to the rate predicted by the perfect mixing equation, the concentration vs time curve for a particular test is analyzed by regression analysis to fit the equation

$$\ln C/C_o = K't + K_o$$

where K' = regression coefficient
K_o = constant

The comparison between actual rate of concentration reduction and the rate predicted by perfect mixing can then be made by dividing the regression coefficient by -F/V to obtain the venting ratio

$$K = \frac{K'}{-F/V}$$

where K = venting ratio

A venting ratio of 1.0 indicates perfect mixing. Due to local variations in air flow within a compartment, the venting ratio for a particular sensor location might be greater than or less than 1.0. However, if enough locations within a given compartment are analyzed, the average of all the individual venting ratios would be expected to be 1.0 because the compartment appears to be well-mixed.

For the powered ventilation test series described in this report, the average venting ratio was greater than 1.0, even for the series in which 27 different locations were tested within one compartment. This result leads to a suspicion of systematic error in the test procedure. The only variables in the perfect mixing equation and regression analysis equation are compartment volume, flow rate of fresh air into the compartment, concentration of contaminant, and time.

The time for all tests was measured by the linear movement of the chart paper in the strip chart recorders. The chart speed of each recorder was checked by stop watch for a period of 5 minutes. No errors in chart speed could be detected.

The volume of each compartment was checked by re-measuring each. Since the compartments were composed of simple rectangular components, the volumes were very simple to compute and, as expected, the second set of measurements agreed with those used in the report. The expected error in measurement is less than 2 percent.

The fuel vapor concentrations were measured from the gas detector output as displayed on the strip chart recorder. (The signal from the gas sensor element is converted by the control module to a millivolt signal. This signal is converted into mechanical motion of a pen by the recorder.) The gas detectors were calibrated at least once a day even though such a calibration was not strictly necessary since, for powered ventilation, absolute concentrations were never used; only the rate of change in concentration with time was important. Therefore, mis-calibration is ruled out as a cause of the disagreement. Serious non-linearity of the gas sensor control module output or of the recorder pen motion would have caused the plots of ln C/C_o vs time to be curved rather than straight. Such behavior was not found to be the case.

The air flow rates into a compartment was calculated from the air velocity and the size of the inlet or outlet at which the velocity measurement was taken. A correction factor was applied to the velocity to correct it for flow through a pipe (if measured in the outlet tube) or flow through an orifice (if measured at an inlet). The air flow rates on a few tests were calculated from the corrected velocities at the inlet and in the outlet tube. These air flow rates showed excellent agreement. Therefore, the disagreement in venting ratios cannot be attributed to the velocity correction factors. It is also unlikely that measurements of the inlet or outlet diameters caused any problem since they were measured repeatedly. This leaves only the actual measurement of the air velocity as a probable cause of average venting ratios different from 1.0. The hot-wire anemometer used for these tests was purchased new, just before testing began, and was factory calibrated. Nevertheless, it was compared to two other similar hot-wire anemometers in a low speed wind tunnel. None of the three agreed with either of the others. Comparison with an absolute standard, such as a manometer and pitot tube, was not feasible because, in the range of air velocities of interest, the level changes in the manometer would have been too small to be read accurately. Other procedures, such as using a wet test meter, could have been employed but the time and cost of setting up such a procedure was excessive. The anemometer could have been returned to the manufacturer for re-calibration, but, since the original calibration was suspected of being in error, it was expected than any new calibration done by the same people using the same technique would also be suspect. Therefore, the anemometer readings were used as is, without any correction for suspected errors in calibration.

Perhaps the most gratifying result of the powered ventilation tests is that, in spite of all the possible sources of error, the average venting ratio for all tests is within 10 percent of the expected value of 1.0. For a relatively simple test using rather unsophisticated equipment, this experimental error does not seem excessive. More sophisticated equipment and techniques might reduce the magnitude of the error, but it is doubtful if the extra time and expense is justifiable.

APPENDIX B

1.0 TEST PROCEDURE

1.1 General Description - The engine compartment shall be visually inspected upon receipt to verify that all normal components are present and are in the as-built condition (i.e., no modifications from stock). All identifying data with respect to the power ventilation system shall be noted and documented: e.g., manufacturer, date of manufacture, model number, serial number, and capacity of the blower(s); number, size, and location of all vents and associated ducting; and any other observations pertinent to the test. The engine compartment shall be instrumented with three catalytic bead type combustible gas detectors. Methane gas shall then be supplied to the engine compartment until the concentration in the compartment is above 2 percent, but less than 3 percent. The power ventilation system shall be turned on and the methane concentration at all three sensor locations shall be recorded with time. After 90 seconds of blower operation, the methane vapor concentration shall have been reduced below 7 percent of the initial concentration.

1.2 Test Conditions

1.2.1 Test Article - The test article shall consist of a gasoline engine powered inboard motor boat and its powered ventilation system composed of one or more electrically powered blowers, inlet and exhaust ducting (if used), and inlet and exhaust vent louvers (or similar devices for directing air into or out of the engine compartment). The configuration of the test setup shall be the actual installation of the test article within the engine compartment as received from the boat manufacturer.

1.2.2 Test Article Identification - The test article shall be identified with a test number immediately upon receipt at the test facility. This identification shall be attached to the test article for the duration of the testing process. As a minimum, the following photographs shall be taken:

a. An as installed view or views,
b. Close-up views of individual components of the system, and
c. A view of the test configuration.

1.2.3 Personnel - A minimum of two (2) people shall be required to perform this test and adequately monitor and document the results. In addition to these two people, two additional people may be required for safety and proper verification of the test.

1. Test Engineer
2. Technician
3. Quality Assurance Inspector (may only be required part time)
4. Safety Monitor

1.2.4 Storage and Handling - All test components shall be handled in accordance with the manufacturer's requirements, if specified, or in accordance with accepted industry practice and standards. In no event shall the item be stacked, carried, dropped, or otherwise mishandled such that the results of the subsequent testing could be altered.

All test components shall be stored in accordance with the manufacturer's requirements with respect to time, temperature, humidity, etc. If no requirements are specified, normal conditions consistent with prudent engineering judgment shall be utilized.

1.3 Safety Requirements - The following safety related items are recommended as minimum requirements to ensure the performance of a safe test to both equipment and personnel.

1. The test area should be adequately vented.
2. The test area should be located such that access by unauthorized personnel can be prevented.
3. Test personnel should position themselves no closer than is necessary for performance of the test.
4. Test personnel should wear protective glasses.
5. A safety monitor shall approve and periodically review the test setup to assure that the planned conduct of the test presents no fire or explosion hazard.
6. No smoking shall be allowed in the test area.
7. Adequate precautions relating to the high pressure methane shall be observed.
8. Any company, local, state, or federal rules, regulations, or laws shall take precedence over any of the above and shall be in addition to the above.

1.4 Receiving Inspection - Immediately upon receipt, or as soon as possible thereafter, the test component or system shall be subjected to an inspection. The inspection shall consist of at least the following items being observed and recorded.

1. Date received
2. Name of component or system and quantity
3. Manufacturer
4. Date of manufacture
5. Model number
6. Serial number
7. Capacity, rating, or any other useful information observed
8. Shipping or transport damage

9. Quality of workmanship
10. Conformity to manufacturer's documentation and maintenance manuals
11. Dents, dings, abrasions; loose or missing screws, bolts, clamps, B-nuts; other defects (not attributable to shipping) noted
12. Proper identification in accordance with Paragraph 1.2.2 of this procedure
13. Inventory list to include any and all equipment items received as a part of this test procedure.

Any discrepancies noted above shall be documented and, if possible, photographed for a permanent record.

1.5 Special Requirements

1.5.1 Verification - All operations performed by the test facility in conjunction with this test procedure are subject to USCG verification at unscheduled intervals.

1.5.2 Non-Conformance - The presence of methane gas in excess of 7 percent of the original concentration after 90 seconds of powered ventilation as determined by this test procedure shall be classified as a non-conformance test. A formal notice of non-conformance shall be made to the USCG compliance monitor within a period of three working days after such a determination. Other discrepancies which may be noted during the performance of this test procedure shall not be classified as non-conformance per this procedure, but shall be documented and reported.

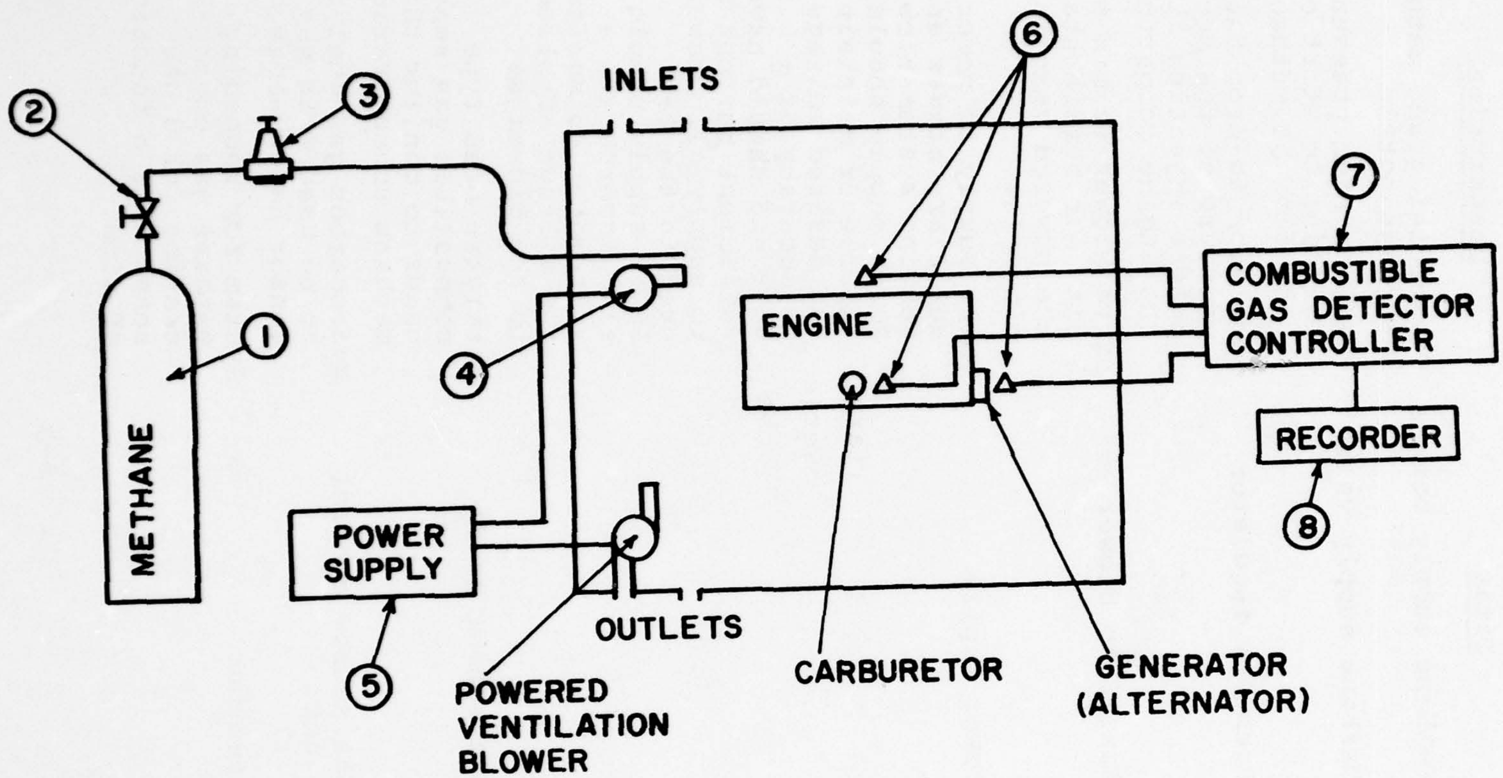
1.5.3 Equipment - None other than as specified in Paragraph 1.6 of this procedure.

1.5.4 Constraints - This test shall be accomplished only with the explicit knowledge and approval of the safety engineer.

1.5.5 Pre-Test Conditions and Assumptions - None.

1.6 Test Equipment and Materials

Component Number	Title	Description
1	Methane supply bottle	Commercial grade methane storage bottle
2	Methane supply valve	Valve on high pressure cylinder to start or stop flow of methane.
3	Pressure regulator	Regulator to drop the pressure of the methane before injecting it into the engine compartment.
4	Auxiliary blower	Extra blower to mix methane with air before starting the powered ventilation blower(s).
5	Power supply	Power supply to power the auxiliary blower and venting system blower(s). Power supply should be capable of maintaining the desired voltage to an accuracy of $\pm$ 0.5 volt and should have sufficient current output to supply all blowers used in the test. Power supply should also incorporate a volt meter to monitor the voltage supplied to the blower(s).
6	Gas sensor heads	Catalytic bead type combustible gas sensor heads to monitor the methane concentration.
7	Gas sensor control unit	Hydrocarbon gas analyzer to be used with gas sensor heads above.
8	Recorder	System for recording methane gas concentration for 3 gas sensors as a function of time.



TEST PROCEDURE SCHEMATIC

1.7 Test - Engine Compartment Power Ventilation Test

1.7.1 This procedure shall be used to perform a test on the power ventilation system of the engine compartment. It will determine if the ventilation system will effectively reduce the fuel vapor concentration within the compartment to a safe level.

1.7.2 Visually inspect the system to be tested. Review the results of receiving inspection and verify the system is acceptable and ready for testing.

1.7.3 Mount the auxiliary blower in the engine compartment. Place the end of the low pressure methane line next to the auxiliary blower so that the methane will be injected into the air stream from the blower.

1.7.4 Connect the auxiliary blower and powered ventilation system blower(s) to the power supply. The blowers should be wired to the power supply in such a way that the powered ventilation system blower(s) and the auxiliary blower cannot be run at the same time.

1.7.5 Set the power supply voltage to the nominal voltage of the engine's electrical system. Supply voltage must remain within $\pm$ 0.5 volt of this setting during the test.

1.7.6 Calibrate the three gas sensors in accordance with the manufacturers instructions. Place the sensors in the compartment as follows:

a. One sensor shall be placed at the same height as the carburetor intake and within 4 inches of the carburetor, if possible.

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RECREATIONAL BOATING SAFETY VENTILATION PROJECT: DESIGN GUIDELI--ETC(U)
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b. One sensor shall be placed at the same height as the alternator (generator) centerline and within 4 inches of the alternator (generator) if possible.

c. One sensor shall be placed 2 inches above the compartment floor and within 2 inches of the engine at the lateral centerline of the engine, is possible. If the carburetor is located toward one side of the engine, then this sensor should be placed on the opposite side.

d. Certain engine compartment configurations might preclude placing the sensors exactly as desired. In such a case, the sensors shall be located as closely as possible to the desired locations and such deviations shall be documented.

1.7.7 Make a sketch of the engine compartment giving special attention to the locations of the gas sensors and the locations of inlets and outlets (including any ducting). Take photographs of the installation as directed in 1.2.2C.

1.7.8 Close the compartment and verify that, except for the electric wires and low pressure methane line, the overall configuration of the engine compartment is as it would be during normal boat operations and that no fuel has been spilled in the compartment.

1.7.9 Verify that all safety precautions are in effect and that the system and test personnel are ready for the test to start. Verify that a CO_2 or equivalent fire extinguisher is available.

1.7.10 Inject methane into the compartment (while the auxiliary blower is on) until the methane concentration is 2.0 percent ± 0.25 percent by volume. Turn off the methane supply and the auxiliary blower.

1.7.11 Verify that the recorders are operating properly.

1.7.12 Turn on the power ventilation blower and mark the recorders simultaneously.

1.7.13 After 2 minutes of blower operation the recorders, the blower, and the gas sensors can all be turned off.

1.7.14 The concentrations at time = 0 and time = 90 seconds after starting the ventilation blower shall be read from the charts for each sensor.

1.7.15 Divide the concentration at 90 seconds by the initial concentration. If the result is equal to or less than 0.07 for all three gas sensors, the power ventilation system shall be deemed acceptable according to the requirements of this procedure.