MSAR 73-13

ALAN K. GUDEMAN

Final Report

to

Department of Health, Education and Welfare
National Institute for Occupational Safety and Health
5600 Fishers Lane
Rockville, Maryland 20852

DEVELOPMENT AND TESTING OF A PROTOTYPE DEVICE TO PROVIDE AIR MEETING THE OCCUPATIONAL SAFETY AND HEALTH ACT OF 1970

(HSM-99-72-5)

January 1973

MSA RESEARCH CORPORATION
DIVISION OF MINE SAFETY APPLIANCES COMPANY
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on

DEVELOPMENT AND TESTING OF A PROTOTYPE DEVICE TO PROVIDE AIR MEETING THE OCCUPATIONAL SAFETY AND HEALTH ACT OF 1970

Contract Number HSM-99-72-5

by

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31 January 1973

MSA RESEARCH CORPORATION
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Contract Number HSM-99-72-5

Final Report

INTRODUCTION

This is the final report on Contract No. HSM-99-72-5, Development and Testing of a Prototype Device to Provide Air Meeting the Occupational Safety and Health Act of 1970. The objective of the program was to develop and test a purification device designed to provide clean air - as defined in the Occupational Safety and Health Act of 1970 - to personnel exposed to automotive exhaust contaminants. Specifically, an air cleaning unit has been assembled which will remove or greatly reduce the levels or concentrations of carbon monoxide (CO), hydrocarbons (HC), nitrogen dioxide (NO_2), dust or particulate matter, and heat/humidity. Design criteria for the unit were based on the results of previous research studies and analyses of numerous air samples. Unit components are standard or "off-the-shelf" items. However, extensive modifications were required in the air cooling system. The completed unit was tested first in a closed 4300 ft^3 chamber and then extensively in the Lincoln Tunnel, a congested traffic artery beneath the Hudson River.

This final report summarizes the design and construction of both the air cleaning unit and the analytical module subsequently used to monitor the inlet and outlet air quality. Test results of the completed unit are also reported herein.

AIR CONTAMINANTS

In the case of tunnels and other working areas where exhaust fumes are present, the following impurities must be considered together with their respective allowable levels as set forth by the Occupational Safety and Health Act of 1970:

Contaminant	Allowable Level
Carbon Monoxide	50 ppm
Nitrogen Oxide	25 ppm
Nitrogen Dioxide	5 ppm
Hydrocarbons (total)	(a)
Particulates (as oil mist)	5 mg/m^3

a. Must be further defined, see below.

1. Measured Impurity Levels in Tunnels

A. CO - Average concentration is about 60 ppm. However, peak traffic periods can produce CO concentrations as high as 300 ppm as shown in the graph of Figure 1. The relative concentration of CO is dependent to some extent on the traffic "mix", i.e., the ratio of gasoline powered to diesel powered vehicles.

B. Hydrocarbons - The spectrum of automotive hydrocarbon emissions ranges from methane and ethane (light hydrocarbons) to the polycyclics - pyrene, coronene, benzperylene (heavy hydrocarbons). The allowable level or TLV for each of these substances differs according to its deliterious effects. Higher boiling hydrocarbons (with more than 3 or 4 carbon atoms per molecule) are generally considered to be responsible for disagreeable odor and eye irritation. Some of the complex hydrocarbons are known carcinogens. Total hydrocarbon levels at peak periods range from 10 to 20 ppm.

C. NO/NO_2 - Considerable controversy has existed with respect to detection and measurement procedures for NO_x. Estimated rush hour levels for NO range from 1 to 24 ppm. The ratio of NO to NO_2 is about 5 to 1 in road tunnels. Hence maximum expected NO_2 levels range from 0.2 to 5 ppm.

D. Particulates - Actual sampling has shown that the density of particulate matter present in tunnels is less than 1 mg/m^3. However it has been suggested that aldehydes and acrolein combine with particulates to cause eye irritation. Polycyclic hydrocarbons may also be considered as particulate matter.

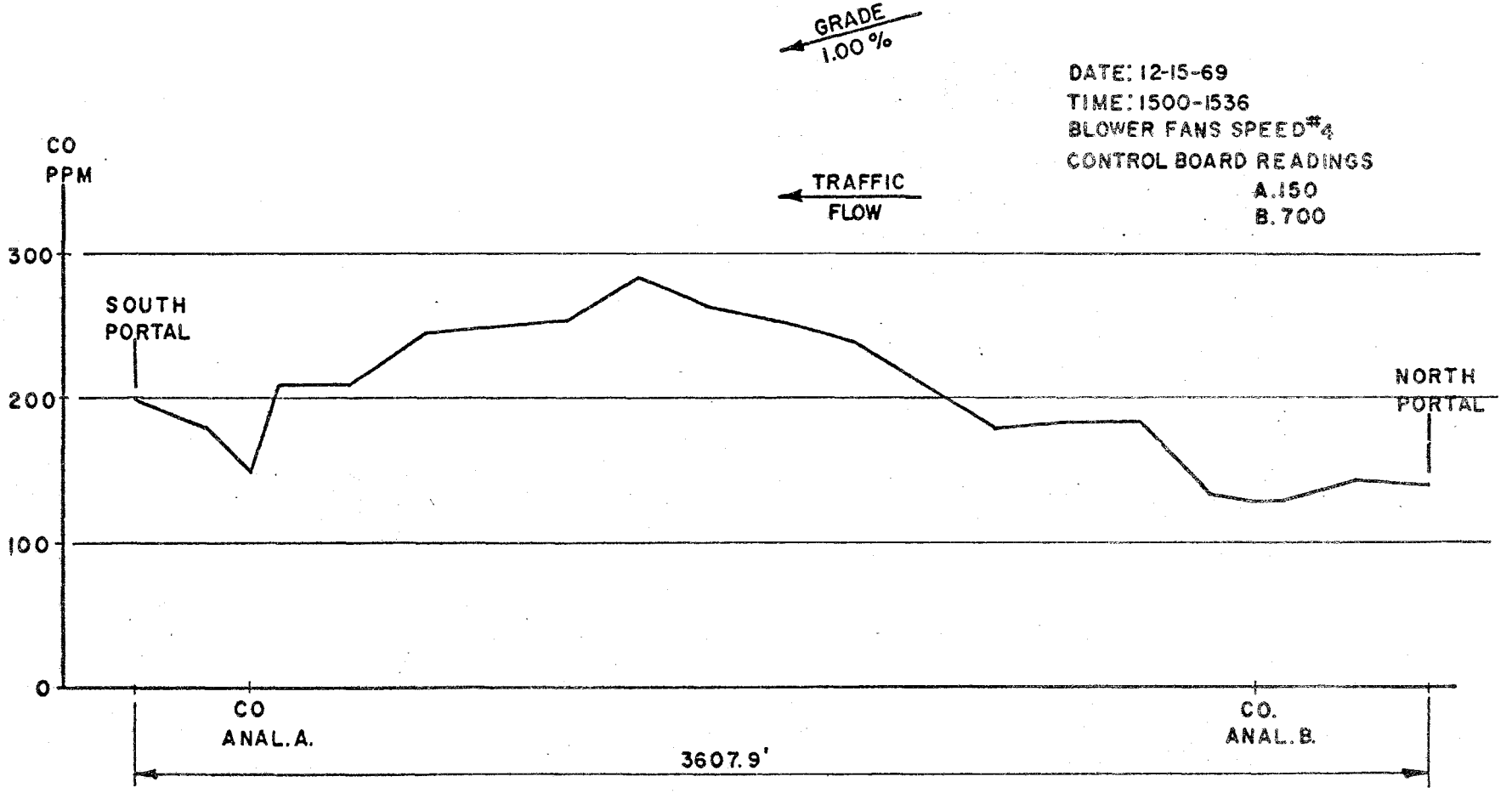

Figure 1 - CO Profile - Fort Pitt (West) Tunnel, Pittsburgh, Pa.

DESIGN AND CONSTRUCTION OF PURIFICATION SYSTEM

The air purification or air cleaning system consists, essentially, of: (1) a filter to remove particulates and aerosols; (2) a catalytic oxidizer to remove certain hydrocarbons and transform CO to CO_2 and NO to NO_2, and (3) a charcoal sorption bed to remove the heavy (more toxic and odorous) hydrocarbons and NO_2. Other required components include an air blower, an air heater, an air cooler and monitoring equipment. A design schematic diagram of the system is presented in Figure 2. The air cleaning unit was designed to purify 50 cubic feet of air per minute. All design components were standard or off-the-shelf items.

1. Filter - An MSA Ultra Aire HEPA (high efficiency particulate air) filter with a 99.97% efficiency for particles 0.3 micron and greater removes particulates. Size of the filter is 8 in. x 8 in. x 6 in. Pressure drop is less than 1 inch W.G. initially. A coarse prefilter is provided to prevent plugging of the HEPA filter with lint and large particles.

2. Catalytic Oxidizer - An 8 in. diameter, 6 in. high bed in a 12 in. long brass chamber contains the catalytic oxidizer. Bed material is 1.75 pounds of Hopcalite, a co-precipitated mixture of 70% MnO_2-30% CuO manufactured by MSA Research Division for commercial use. Hopcalite granules are 4 to 8 mesh. The bed has a ΔP of 2 to 3 inches W.G. An unlimited lifetime can be expected for the catalyst bed if the particulate filter protects the catalyst bed from poisoning.

3. Charcoal bed - Two pounds of 4-8 mesh activated carbon is used to trap hydrocarbons and NO_2. Container size is identical with that used for the catalytic oxidizer. Process air residence time in each bed at 50 cfm is 0.18 sec with a corresponding space velocity of 2,000 hr^{-1}.

4. Air Blower - A two-stage centrifugal blower with a control autotransformer is used to move the air. Process air flowrate can be adjusted over the 0-50 cfm range. The blower is similar to the type used in vacuum cleaners, however the process air does not pass through the motor housing. A separate fan is used to cool the motor.

5. Air Heater - A 2500 watt, 250°F bayonet or immersion type heater is used to heat the process air. This unit preheats the air upstream of the catalyst bed in order to achieve a uniformly heated bed.

6. Air Cooler - Original plan was to use a simple tube-shell heat exchanger. However, additional cooling was required to provide cooler exit air to the charcoal bed. Hence, an 8,000 BTU/hr commercial air conditioner was modified for use in the air cleaning

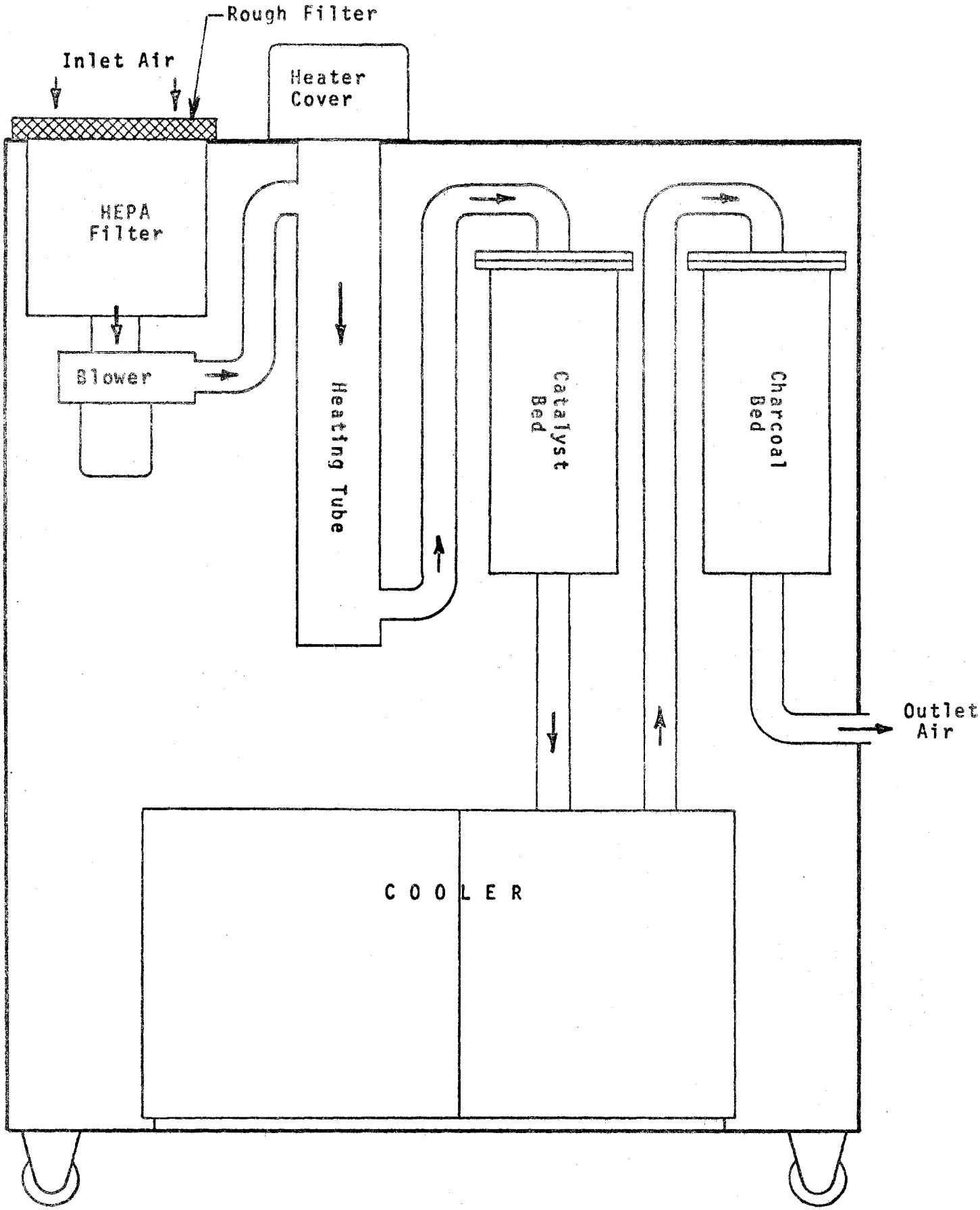

Figure 2 - Purification System Design Schematic

system. Modification consisted of removing the squirrel cage blower and extraneous structural members.

7. Monitoring and Control Equipment - Indicators are provided as follows:

a. A combination temperature controller/readout for catalyst bed temperature employing an electronic pyrometer with thermocouple (Type J).

b. A temperature readout for charcoal bed temperatures also employing an electronic pyrometer with thermocouple (Type J).

c. A differential pressure readout across the charcoal bed employing a magnetic helix type gage.

d. A differential pressure readout across a section of duct upstream of the catalyst bed which indicates the air flowrate of the process air stream also employing a magnetic gage.

e. Blower control - An autotransformer which regulates voltage supplied to the blower motor.

8. Sampling Network - Process air may be sampled at any one of four taps provided by simply opening a 2-position valve and withdrawing (pumping) the sample out of the Air Sampling Port. The locations of the taps are as follows:

a. Inlet air-sampling point located adjacent to heater cover on cabinet top.

b. Filter outlet-sampling point located at blower inlet flange.

c. Catalyst bed outlet-sampling point located in ductwork downstream of bed.

d. Charcoal bed outlet-sampling point located at outlet air port.

A panel layout sketch showing the location of the monitoring/control equipment and sampling valves is presented in Figure 3.

9. Electrical Design - The air purifier is designed to operate on any 230V AC or 208V AC supply which has a common 115 AC tap. The wiring diagram is presented in Figure 4. The main power switch is located on the side of the cabinet while the individual switches for blower, heater, and cooler are located on the front panel (see Figure 3). Main fuses are located inside the rear cabinet door while individual fuses are mounted on panel front.

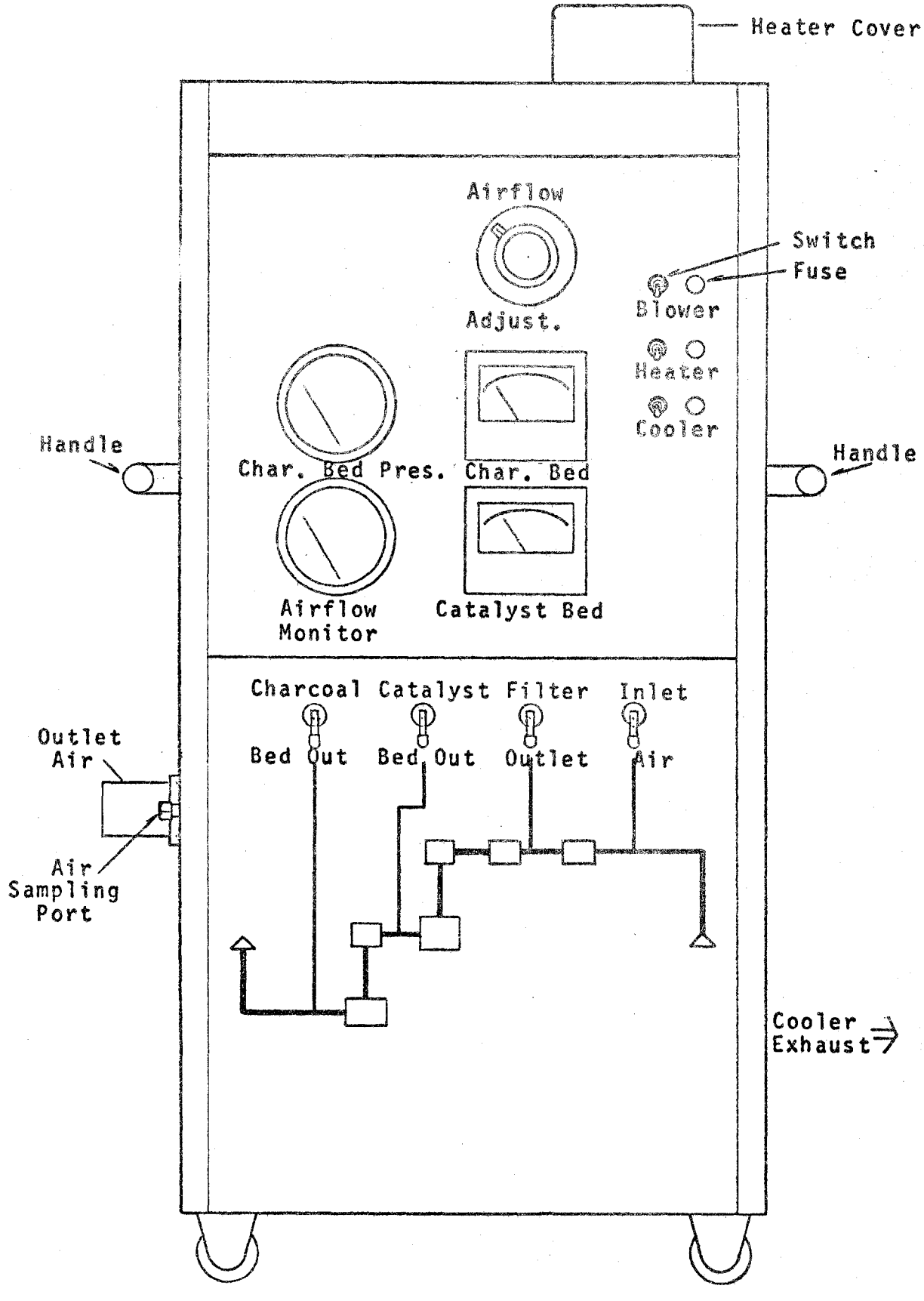

Figure 3 - Purification System Panel Layout

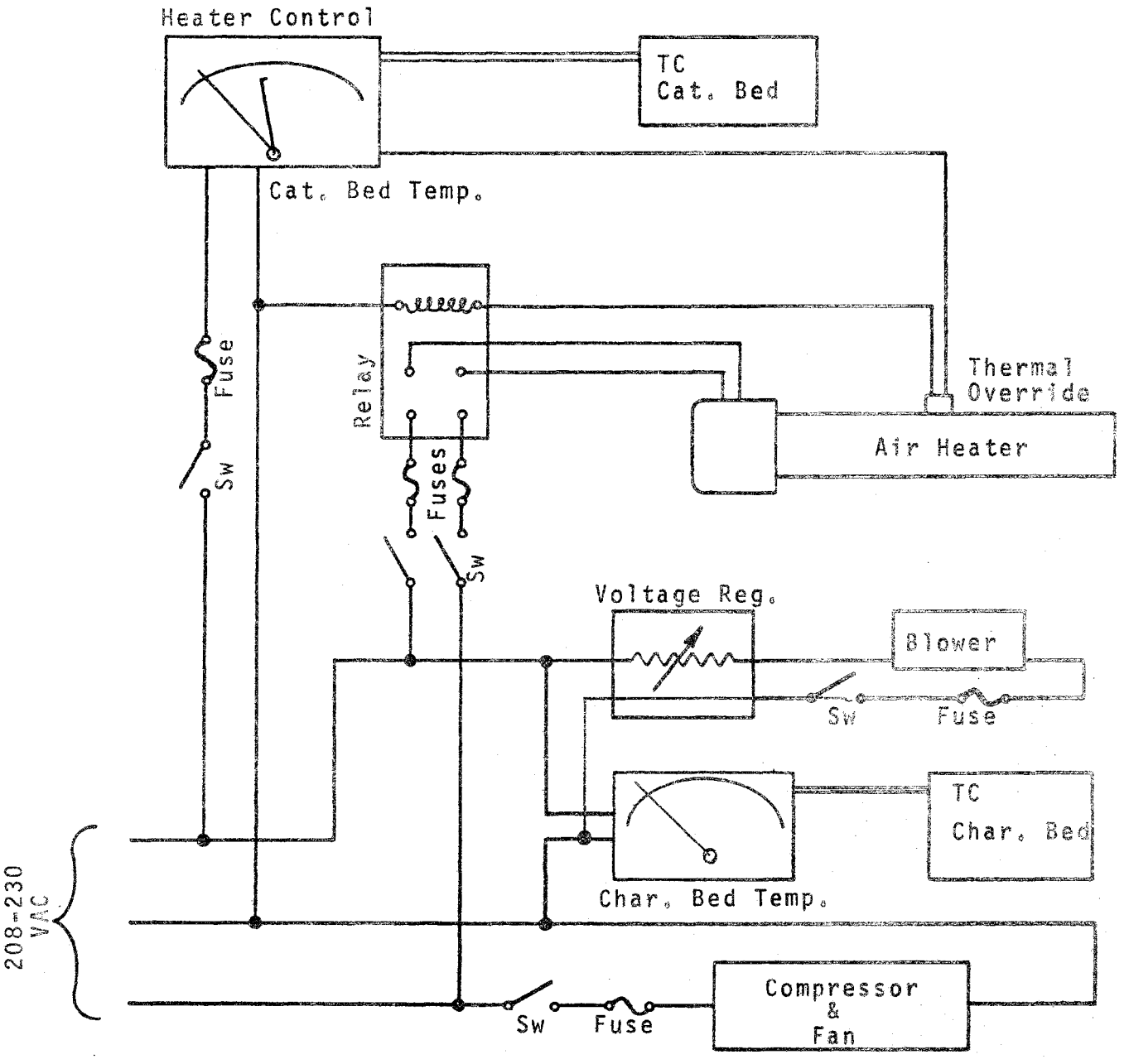

Figure 4 - Purification System Wiring Diagram

10. Housing - The air cleaning unit is housed in a metal cabinet 22 in. x 22 in. x 42 in. with side handles and casters. Process air enters through a square port on the top surface and exits via a duct at the lower side of the unit. If desired, a duct adapter may be added to the square inlet orifice. Heat from the coils of the air cooler is exhausted at the lower part of the side opposite the process air exit port. A full-length access door is provided at the rear of the cabinet.

11. Operating Manual - The operating manual has been submitted as a separate document.

ANALYTICAL MODULE

A monitoring system was designed to provide air quality measurements on both the upstream and downstream sides of the air cleaning unit as well as at intermediate points within the unit. The monitoring system is comprised of the following:

a. A carbon monoxide analyzer of the non-dispersive infrared type.

b. A total hydrocarbon analyzer utilizing a hydrogen flame ionization detector.

c. A device for measuring NO and NO_2 by means of the Saltzman method. This device consists of a series of three bubblers.

d. Sampling pumps (two).

e. Strip chart recorders (two).

f. Flowmeters.

g. Control valves for calibration gas and sample air.

h. (Optional) Relative humidity indicator.

i. (Optional) Particulate sampler - an MSA Fixt-Flo high volume sampler.

A schematic diagram of the monitoring system is presented in Figure 5. These items were incorporated into a single module or cabinet with dimensions of 17 in. x 20 in. x 69 in. high.

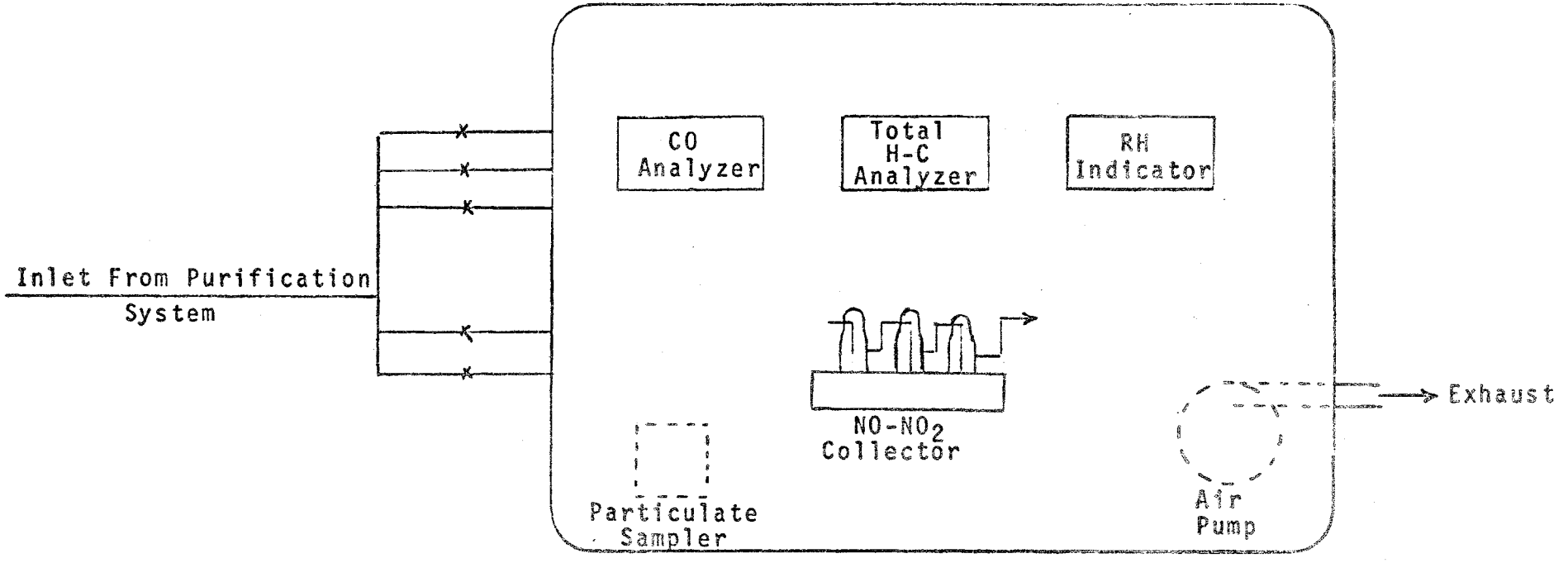

Figure 5 - Monitoring System Schematic

CLOSED CHAMBER TESTING

1. Description of Chamber

Prior to in-field testing both the air cleaning unit and analytical module were pre-tested at MSAR. These tests were accomplished in a 4300 cubic foot steel chamber. Automobile exhaust gas was ducted into the chamber from outside.

From past experience with the same chamber it was known that running the automobile engine under load for about 1.5 min would provide the following levels of impurities in the chamber:

CO	-	300 ppm
T/HC	-	60 ppm
NO	-	2 ppm
NO_2	-	0.2 ppm
Particulates	-	2 mg/m^3

These concentrations are typical of those found in tunnel atmospheres during peak periods.

2. Procedure for Testing

The air cleaning unit, located inside the test chamber was activated and permitted to equilibrate with respect to bed temperatures. Automobile exhaust from an older model vehicle under a simulated load (brake pedal depressed) was then added to the test chamber. After ~1.5 minutes running time, the exhaust source was removed and the chamber inlet duct plugged. Sample gas pollutant concentrations from the air cleaning unit were monitored outside the chamber by running the sample line through the wall of the chamber to the analytical module. The air cleaning unit was located near a chamber port to permit easy access to the four sample tap valves. Air was sampled from each tap sequentially for a period of 5 to 10 minutes per sample. During this period the levels of CO and T/HC were recorded. Occasionally an NO/NO_2 determination was also included. No samples were analyzed for particulate concentration. Temperature and humidity readings were also taken inside the chamber. Exit air from the cleaning unit was exhausted outside the test chamber via a 2.5-inch diameter duct. One liter samples of both contaminated and purified air were also obtained for chromatographic analyses.

In a separate experiment a charge of NO_2 was added to the chamber in order to boost the concentration of that pollutant. The object of these tests was to determine the capability of the purification system.

3. Test Results

The impurity content of the air within the test chamber after loading with automobile exhaust was as follows:

CO	-	250-300 ppm
HC	-	25-30 ppm
NO	-	0.4-0.7 ppm
NO_2	-	∿0.03 ppm

A profile of the hydrocarbon content was obtained by gas chromatography and is presented in Figure 6.

Analyses of the purified air leaving the air cleaning unit were typically as follows:

CO	-	0-2 ppm
HC	-	3-5 ppm
NO	-	∿0.2 ppm
NO_2	-	∿0.01 ppm

Again a profile of the hydrocarbons was obtained and is presented in Figure 7. Comparison with the previous figure show that the heavier hydrocarbons (high boilers) have been removed.

From these test results it is clear that the air cleaning unit is capable of scrubbing from the atmosphere the major gaseous impurities found in tunnel atmospheres. The levels of CO and HC introduced into the chamber were approximately those to be expected in a typical tunnel. The levels of NO/NO_2 introduced were possibly somewhat lower. An attempt was hence made to increase the level of nitrogen oxides present in the chamber. This was accomplished by running the test vehicle for a considerably longer period of time and piping a larger total volume of exhaust gases into the test chamber. Results of this test were as follows:

	Air Cleaning Unit	
	Inlet	Outlet
	ppm	
NO_2	0.56	0.11
NO	4.3	3.3

In this test the level of NO_2 was reduced by about 80% while that of NO was reduced nearly 25% - a satisfactory result.

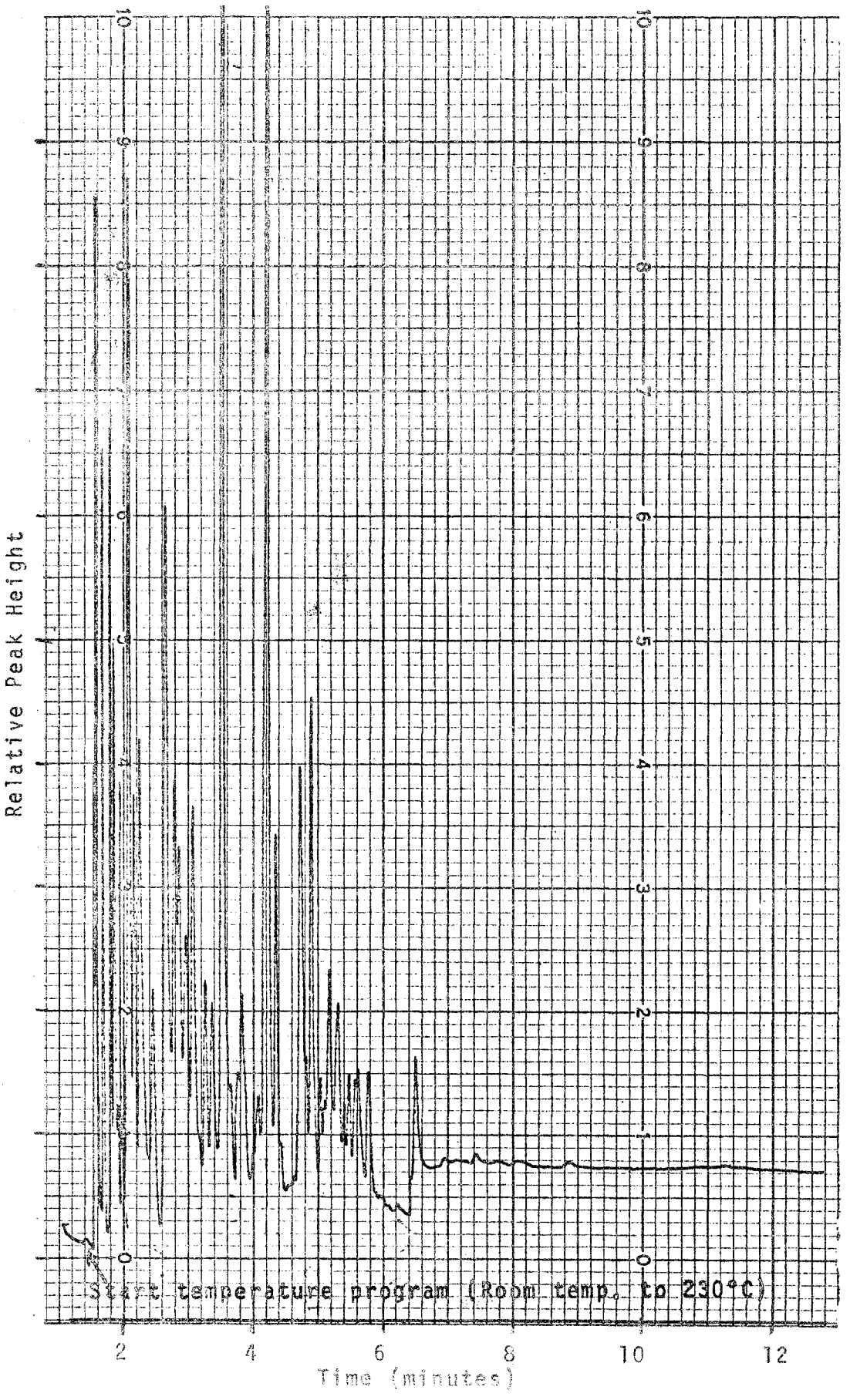

Figure 6 - Hydrocarbon Profile of Exhaust Air

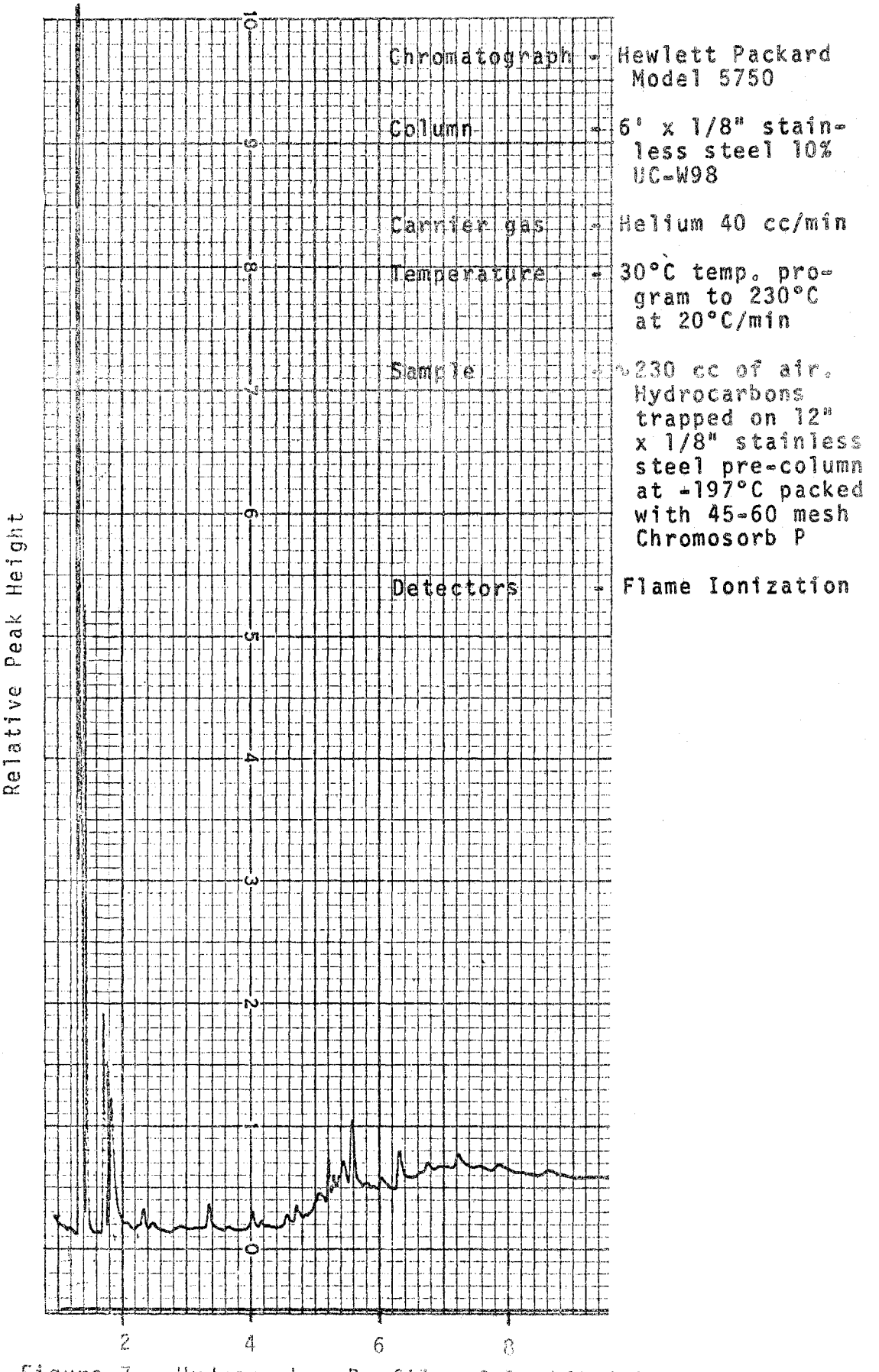

Figure 7 - Hydrocarbon Profile of Purified Air

ON-SITE TUNNEL TESTS

A. Description of Test Site

The on-site testing of the air cleaning unit was conducted at the Lincoln Tunnel, a set of three tubes beneath the Hudson River between New Jersey and midtown Manhatten. The Lincoln Tunnel tubes are each about 8000 ft long. The air cleaning unit as well as the analytical module and all ancillary equipment was stationed in a room located between the North and Center tubes directly beneath the tunnel's control room and at a point 1300 ft from the New Jersey portal at roadway level. Testing was conducted during the month of October - a time of year when atmospheric conditions as well as traffic volume favor the generation of lower pollution levels within the tubes.

The nearest police shelter booth was located over 500 ft away from the selected test station room. The laying of ductwork to purify air from the booth and then return it to the booth was considered impractical. Hence a simulated booth was constructed and placed in an area adjacent to the purification unit and analytical equipment. The simulated booth had a volume of $\sim$200 ft^3 which approximates the size of the booths in the tunnel. It was constructed of polyethylene sheets on a lightweight angle-iron frame. Air was taken from the booth to the air cleaning unit via the same 20-ft long duct used to sample tunnel air from the catwalk area. Purified air was then returned to the booth via a similar duct.

The air cleaning unit was wired to a 208V AC three phase source as discussed previously. A separate 115V AC single phase line was used to supply the analytical module and ancillary equipment.

B. Experimental Procedure

Several sets of experiments were conducted. In one set, air was ducted from the catwalk of the North tube to the air cleaner. In a second set, air was ducted from a similar location in the Center tube. A third set involved recycling air to and from the "booth". A variation was made in some experiments involving the booth whereby air was ducted from the catwalk, purified, and then ducted to the booth. The booth was, of course, not air tight. Experiments were conducted at various hours of the day in order to obtain data from a variety of traffic conditions. In each experiment process airflow was maintained at 45 to 50 cfm. Samples were analyzed from inlet and outlet ports of the air cleaning unit. Occasionally, samples from the catalyst bed outlet

were also analyzed. Data recorded involved the following variables:

1. Carbon monoxide (meter + chart recorder - also control room readings)
2. Total hydrocarbon (meter + chart recorder - also chromatographic analyses)
3. NO/NO_2 (ten-minute wet chemical runs)
4. Particulates (2- to 7-hour samples)
5. Temperature
6. Humidity
7. Traffic count
8. Noise (spot checks with decibelmeter)
9. Air velocity (spot checks with anemometer)

C. Test Results

The following table summarizes the ranges of variables encountered during the ten-day test period in the Lincoln Tunnel. Further explanations follow the table.

Table 1 - Ranges of Tunnel Variables

	Air Cleaning Unit		
	Inlet		Outlet
Carbon monoxide (CO)	20-200	ppm	0-3
Total hydrocarbons (HC)	5-25	ppm	0.5-3
Nitrogen oxide (NO)	0.5-2	ppm	<1
Nitrogen dioxide (NO_2)	0.2-1	ppm	<0.15
Particulates	∿0.3	mg/m^3	0
	- In Tunnel -		
Noise	75-120 DBA		
Temperature	50-75°F		
Relative humidity	30-60%		
Traffic count	5-45 veh/min		
Air velocity	0-900 ft/min		
Gas/diesel mix	3:1-10:1		

The first four of these variables were measured in a study of the same tunnel in 1965 and 1966. Results obtained then were in general agreement with those presented here. The following is a description of the variables altered by the air cleaning unit.

CO - The concentration of carbon monoxide was usually considerably greater in the North tube than in the Center. The two foremost reasons for this are:

1. At the sampling site the North tunnel roadway elevation is uphill (+3.5% grade) whereas the Center tube is downhill (-3.5% grade) at the same site except during a period through the afternoon rush hours. The Center tube is used primarily for buses during the latter periods.

2. The CO level is related to density of gasoline-powered vehicles more so than to diesel-powered buses and trucks.

A table showing the volume of CO generated per foot of tunnel length for an "average" vehicle has been computed and is presented below. The speeds shown cover the range normally encountered in an urban road tunnel. From the table it is seen that a vehicle moving slowly upgrade (114) emits 5 times as much CO as a faster moving vehicle (21) on a downgrade.

Table 2 - Carbon Monoxide Generation

Speed (mph)	Downgrade	Level	Accel.	Upgrade
	(CFM x 10^{-5} CO per foot of tunnel)			
35	21	29	100	44
30	23	33	116	51
25	26	36	138	58
20	29	40	160	66
15	38	51	210	82
10	54	66	296	114

A reproduction of an actual recording of CO concentration is presented in Figure 8. The center portion (BC) shows the level of CO in purified air leaving the air cleaning unit. The lower portion (AB) shows the inlet air from the Center tube while the upper portion (CD) represents the inlet air from the North tube. In no case did the level of CO in the outlet air from the cleaning unit exceed 3 ppm.

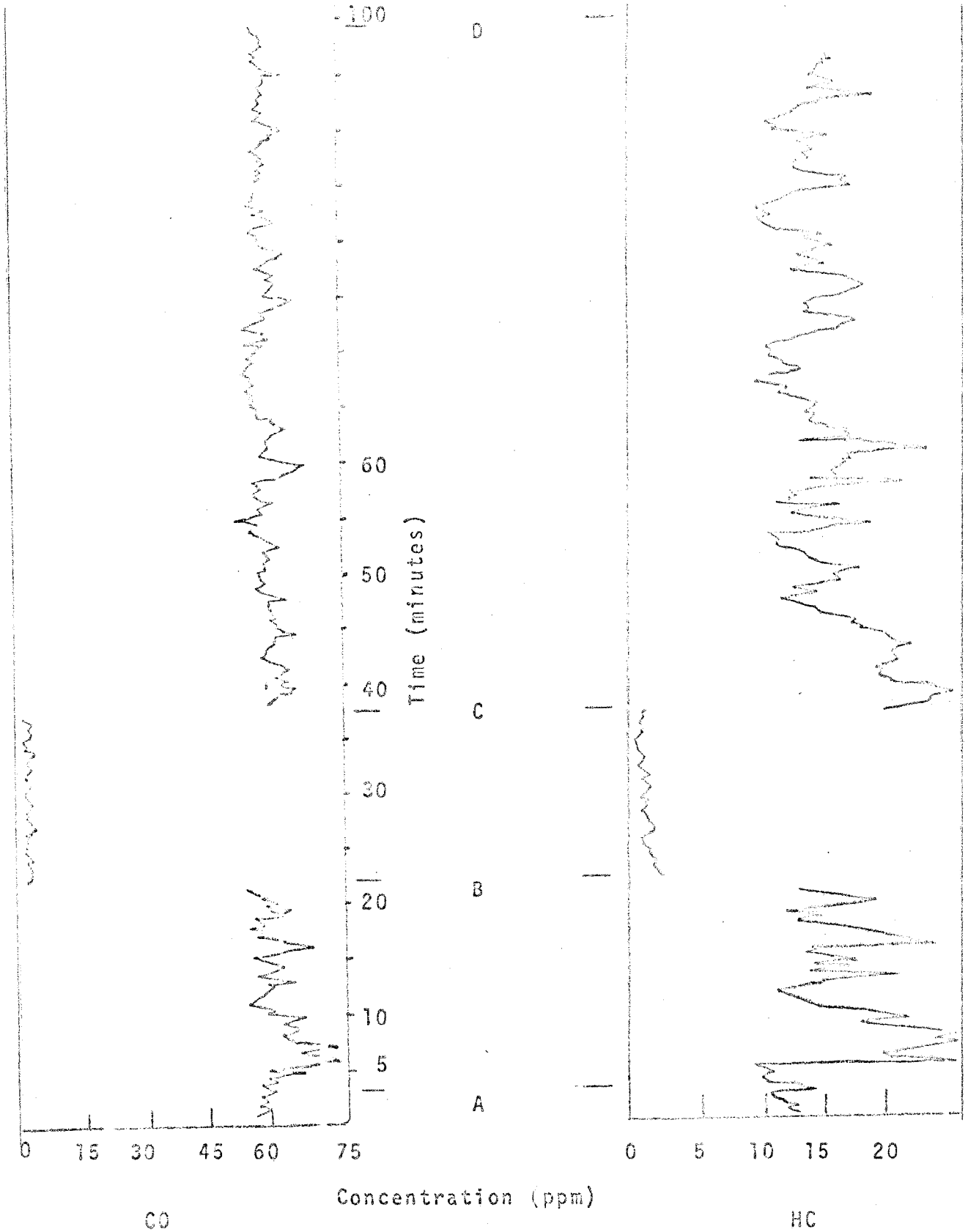

Figure 8 - Carbon Monoxide and Hydrocarbon Profiles in Lincoln Tunnel

HC - Unlike CO, the level of total hydrocarbons detected in the tunnel is not as closely related to the density of gasoline-powered vehicles. Highest values (>15 ppm) were obtained in the Center tube when numerous buses were traveling up-grade. Multi-axle trucks passing the sampling point produced peaks 1.5 ppm above the existing HC level. A comparison between CO and HC strip recordings is presented in Figure 8. The portions of the charts between B and C represent purified air leaving the air cleaning unit. At the lower levels of inlet HC (<∿10 ppm) the outlet level is <1 ppm. At high inlet levels (∿20 ppm) the outlet air contains up to 3 ppm HC. Hence the air cleaner removes about 85% of the total hydrocarbons from tunnel air. In order to characterize the HC present in both tunnel air and purified air, samples of each were analyzed by gas chromatography. HC profiles of these samples are presented in Figures 9, 10, and 11. These graphs show that the heavier hydrocarbons - those responsible for eye irritation and irritating odors - have been either removed or greatly reduced. The exhaust from the purifier was odor-free.

NO/NO_2 - These contaminants were analyzed simultaneously in ten-minute tests. The level of NO_2 present was found to be from 15 to 45% of the level of NO analyzed at the same time. In all cases the level of NO_2 in purified air was reduced to values not exceeding 0.15 ppm. The NO level was reduced up to 50% from tunnel air levels. In a selected series of experiments it was demonstrated that the levels of NO and NO_2 at the outlet of the catalyst bed were lower and higher respectively from their levels in the incoming tunnel air. Hence it was demonstrated that some NO is oxidized to NO_2 by the Hopcalite bed. Subsequent removal of NO_2 is then achieved in the charcoal bed.

Particulates - Initial tests were carried out with personal dust monitors of the type used in the mining industry. These proved ineffective for analyzing the low dust levels found in the tunnel. Later tests utilized large, constant-flow dust samplers with high efficiency, glass fiber filter paper. The results of three samplings were as follows:

Center tube with 2-way traffic - 0.16 mg/m^3
North tube with 1-way upgrade - 0.09 mg/m^3
Purified air from air cleaner - 0.00 $mg/^3$

The higher concentration of particulates in the Center tube may be explained by the fact that two-way traffic eliminates the "piston" effect which is established by one-way traffice. No attempt was made to characterize or to size the particulates sampled.

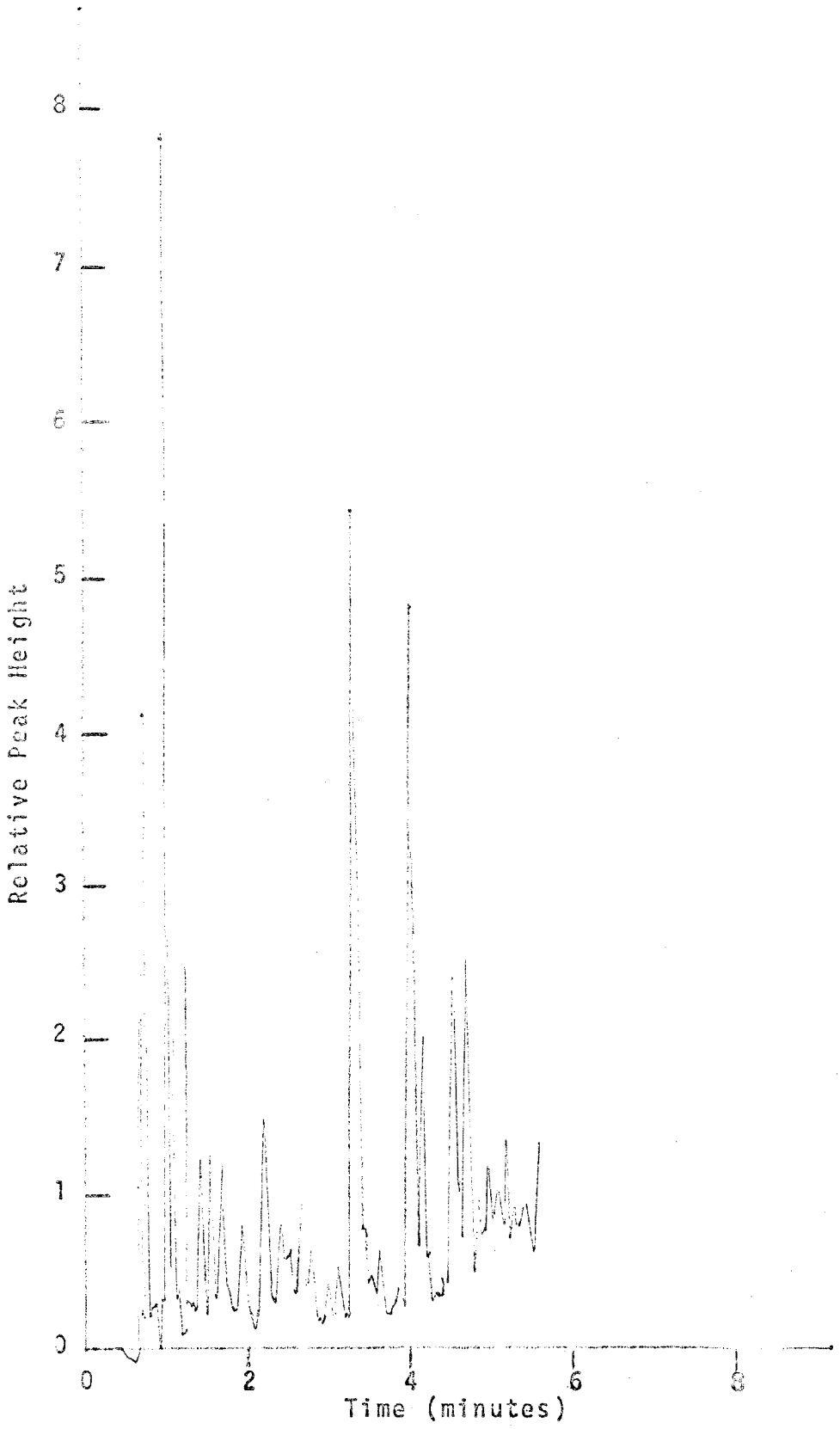

Figure 9 - Hydrocarbon Profile - Lincoln Tunnel North Tube

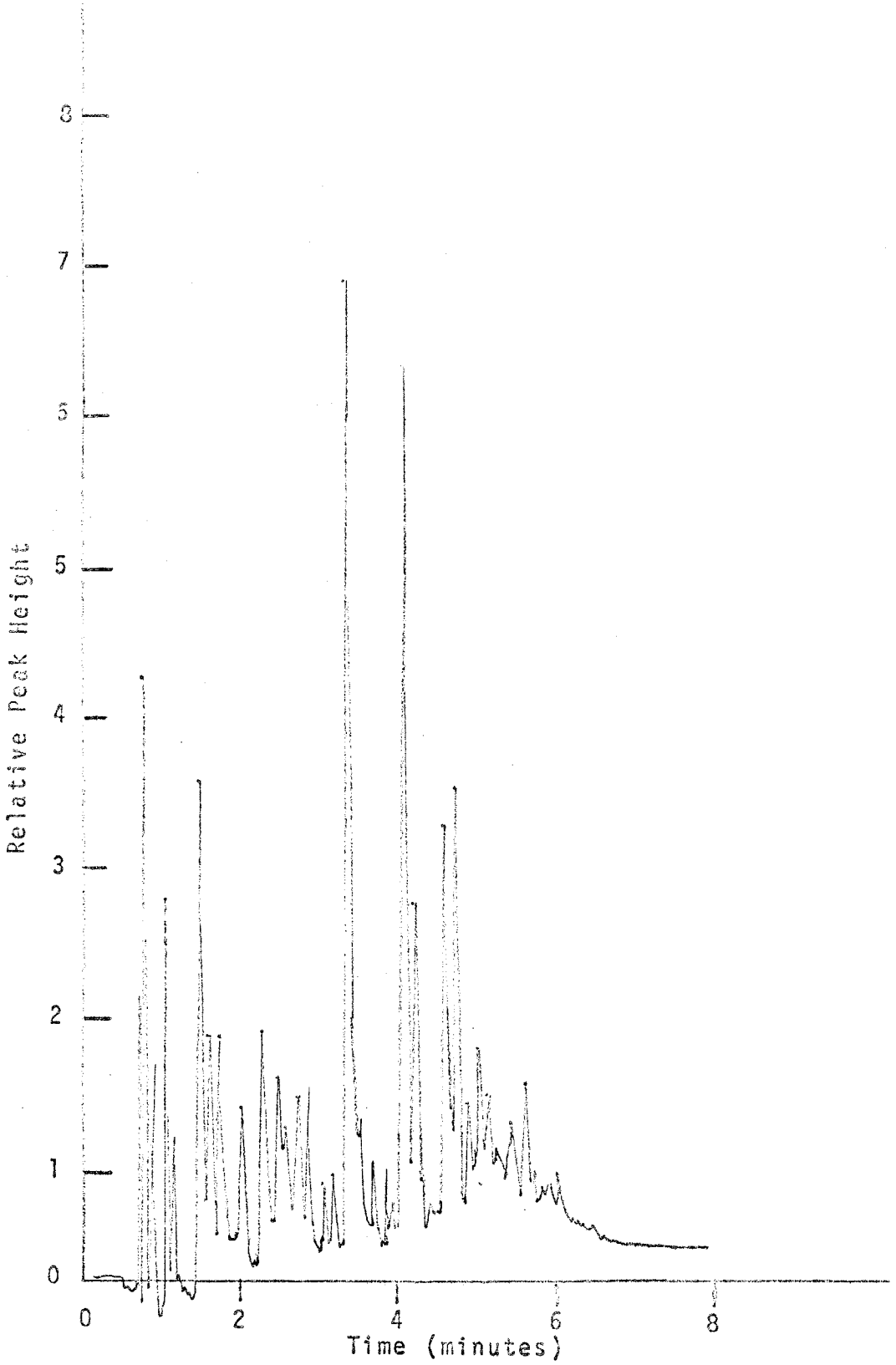

Figure 10 - Hydrocarbon Profile - Lincoln Tunnel Center Tube

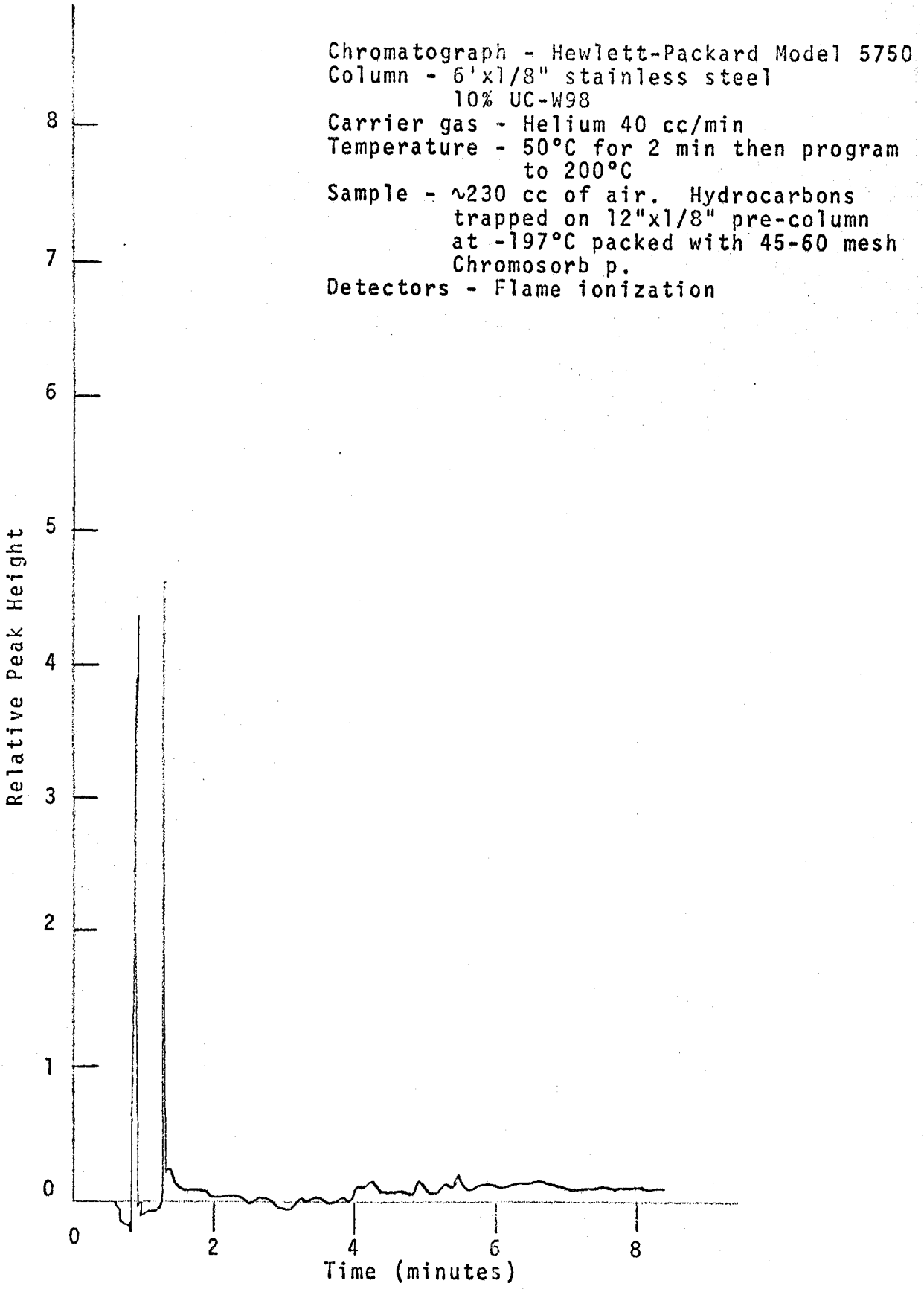

Figure 11 - Hydrocarbon Profile - Purified Lincoln (Center) Tunnel Air

Booth Operation - Initial operations with the simulated booth were successful in that the CO and HC values were reduced from 70 and 6 ppm to 0 and 1.5 ppm respectively within a few minutes These results demonstrate the capability of the purifier to achieve the design goal, i.e., to purify air to levels meeting the Occupational Safety and Health Act of 1970.

OTHER APPLICATIONS

Although this work was directed primarily at providing clean air for tunnel booths, the results indicate that it should perform equally well in any area where automotive exhaust may pose a health hazard. These other areas could include toll booths, parking garage offices, and so on.

The ability to remove CO and hydrocarbons and particulates suggests that the purifier might have other applications, as well. Coke ovens emit these impurities in large quantities and coke oven workers in enclosed areas such as larry car cabs, pusher cabs and so on are exposed to high levels of these contaminants. Results indicate that the purifier would serve to remove these contaminants and provide a healthful environment for coke oven workers. Of course, other impurities are emitted by coke oevens, particularly sulfur compounds and it remains to be seen whether the purifier will remove these compounds.

SUMMARY AND CONCLUSIONS

An air cleaning unit was designed for use in enclosed areas subject to the pollution contaminants emitted by vehicular traffic. The unit was constructed of commercially available components without special regard for volume or weight. The resulting unit was tested in a large chamber and in an urban road tunnel. Experimental data showed that the unit would function as predicted. Further development could result in an air purification package which would be as efficient as the present unit and yet be only 40% as large.