AUTOMOBILE GENERATED AIR POLLUTION

by

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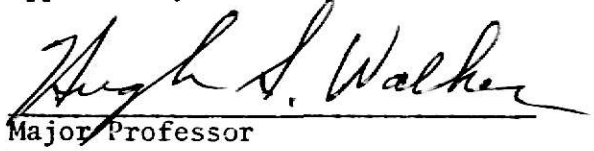

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CHAPTER I

INTRODUCTION

According to a definition "Air pollution means the presence in the outdoor atmosphere of one or more contaminants, such as dust, gas, mist, odor, smoke or vapor, in quantities, of characteristics, and of duration such as to be injurious to human, plant or animal life or property, or which unreasonably interfere with the comfortable enjoyment of life and property". [1]

Atmospheric contamination that accompanies industrial society arises from the exhaust generated by industrial plants, power plants, refuse disposal plants, domestic and commercial heating, and transportation. These pollutants, which are in the form of dirt, smog, odors and undesirable gases, arise from combustion processes and in addition to particulates contain trace amounts of gases such as oxides of sulfur, oxides of nitrogen, hydrocarbons, and carbon monoxide. The expanding needs of society for more energy, and advancing transportation technology, coupled with the rapid growth of urban areas has led to ever increasing amounts and concentrations of pollutants in the atmosphere.

The table below lists the estimates by weight of major pollutants added to atmosphere in the United States.

TABLE 1.1

NATIONWIDE EMISSION ESTIMATES, 1969 (U.S. Environmental Protection Agency)

(10^6 tons/year)*

Source category	SO_x	Particulates	CO	HC	NO_x
Transportation	1.1	0.8	112.0	19.8	11.2
Fuel combustion in stationary sources	25.0	6.4	1.8	0.9	10.2
Industrial Processes losses	5.9	14.3	12.0	4.7	0.2
Solid waste disposal	0.2	1.4	7.9	2.0	0.4
Agricultural burning	Neg	2.4	13.8	2.8	0.3
Miscellaneous	0.2	2.1	6.3	5.0	0.2

*(Table from Ref. 2)

From these figures one readily concludes that the automobile is the nation's largest contributor of air pollution-Carbon monoxide 73%, Hydrocarbons 56% and Oxides of Nitrogen 50% of weight.

An attempt to minimize air pollution would be to put effective controls to the various emmitors of it, and it is ironically true that the technology today faces the most difficult problem with the chief pollutor, the automobile.

What makes it the most difficult problem is that,

1. It is operated under various conditions of load and speed, that is accelerating and decelerating.
2. It is small and therefore rarely serviced.
3. It has millions of prototypes on the highways.

This report discusses the causes and effect of auto generated air pollution, the instrumentation and federal procedures involved, the controls which may be feasible and the future prospects.

CHAPTER 2

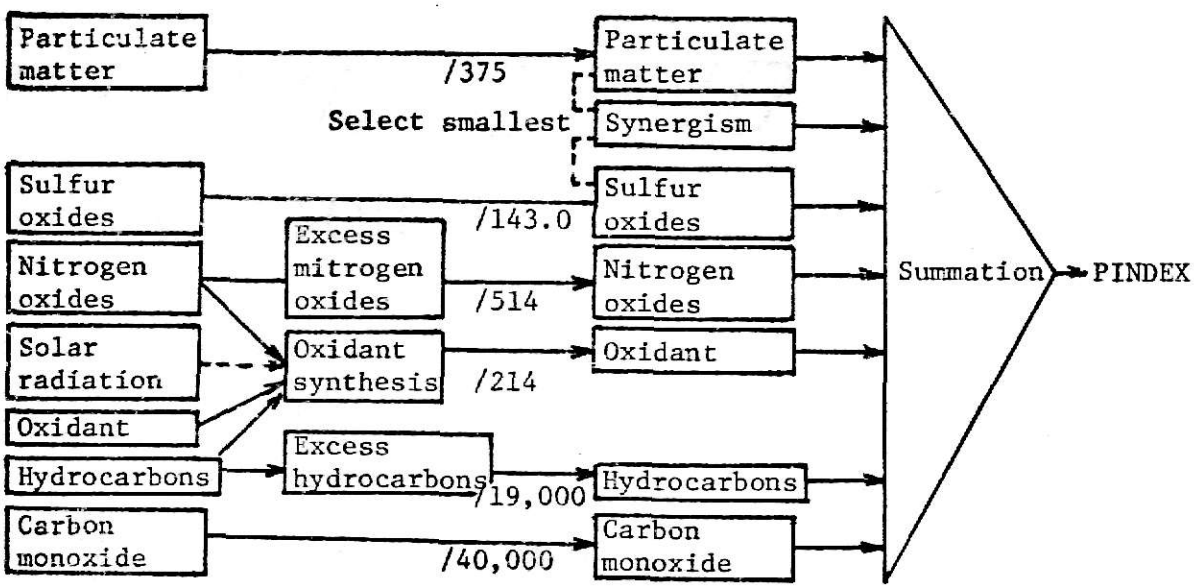
FUNDAMENTALS OF AIR POLLUTION

1. Pindex Scheme for Assessing Air Pollution Severity

The chief compound emitted by the automobile is carbon dioxide. However, compared to other gases (pollutants) carbon dioxide is relatively harmless. For example in terms of health effects a ton of SO_2 is worse than 25 tons of carbon dioxide. A more meaningful assessment of pollution severity can be made by considering the harmfull effects of the pollutant in addition to the quantity emitted. In effect, weighting factors can be developed for each constituent.

One scheme for assessing air pollution severity termed "Pindex" has been proposed. This method considers the contribution to air pollution of particulate matter, sulfur dioxide, nitrogen oxides, carbon monoxide, hydrocarbons, oxidant, solar radiation and particulate-sulfuroxide synergism. Each compound is assigned a weighting or tolerance factor which in the Pindex system is based upon air quality criteria [3].

Figure 2.1 shows a schematic of the Pindex method*



First the atomospheric concentration of each emitted compound is calculated in terms of microgram per cubic meter, in addition, hydrocarbons, oxides of nitrogen and oxidant are converted to micro mole/m^3. For this calculation hydrocarbons are assumed to be methane, oxides of nitrogen NO_2,

*Fig. 1.4, Ref. [3].

and oxidant O_3. Next it is assumed that oxides of nitrogen and hydrocarbons react with sunlight to form additional oxidant. The assumption made is that one mole of hydrocarbon reacts with one mole of nitrogen dioxide to form one mole of oxidant. The amount of additional oxidant assumed to be formed is calculated by multiplying the molar concentration of nitrogen oxides or hydrocarbons, whichever is least by $6X10^{-4}$ and this product by solar radiation in cal/cm^2-day (average value 375). The original concentration of hydorcarbons and nitrogen oxides are corrected by subtracting the moles of each which have reacted to form oxidant.

Next the corrected concentrations are divided by tolerance factors. Then the particulate matter-sulfur oxide synergism term is calculated. This term recognizes that both constituents together are harmfull to health than separately. The synergism term is assumed to be smaller of either of the particulate matter or the sulfur oxide concentrations corrected by the tolerance factors. Finally the sum of the seven terms is computed, which is termed Pindex rating.

Table 2.1 shows air quality data for several U.S. cities and the calculated Pindex levels. It can be readily seen that the Pindex provides a ready means of ranking air pollution severity.

Table 2.1

Air Quality Data for U.S. Cities*

	PM ($\mu g/m^3$)	SO_x (ppm)	NO_x (ppm)	CO (ppm)	HC (ppm)	Oxidant (ppm)	
Chicago	124	0.14	0.14	12.0	3.0	0.01	
Cincinnati	154	0.03	0.06	6.0	3.0	0.02	
Denver	126	0.01	0.07	7.9	2.4	0.03	
Los Angeles	119	0.02	0.13	11.0	4.0	0.05	
Philadelphia	154	0.08	0.08	6.8	2.0	0.01	
Saint Louis	143	0.04	0.07	5.8	3.0	0.04	
San Diego	69	0.01	0.05	3.0	6.0	0.03	
San Francisco	68	0.01	0.14	3.2	3.0	0.02	
San Jose	92	0.01	0.12	5.0	4.0	0.02	
Washington	77	0.05	0.07	6.0	3.0	0.02	
Pindex Levels							Total
Chicago	0.47	0.42	0.56	0.38	0.11	0.10	2.04
Los Angeles	0.34	0.06	0.52	0.34	0.15	0.50	1.91
Saint Louis	0.42	0.14	0.26	0.18	0.11	0.36	1.47
Philadelphia	0.49	0.24	0.32	0.21	0.07	0.10	1.43
San Jose	0.26	0.03	0.48	0.16	0.15	0.30	1.38
Denver	0.35	0.03	0.29	0.25	0.09	0.29	1.30
Cincinnati	0.44	0.09	0.24	0.19	0.11	0.20	1.27
San Francisco	0.19	0.03	0.56	0.16	0.11	0.20	1.25
Washington	0.26	0.15	0.28	0.18	0.11	0.20	1.18
San Diego	0.19	0.03	0.20	0.09	0.22	0.30	1.03

*Table 1.4, Ref. [3].

To exemplify the Pindex calculations, one given set of data is calculated here [3].

Given Information:

Particulate matter	(PM)	= 143 $\mu g/m^3$
Sulfur Oxides	(SOX)	= 123 $\mu g/m^3$
Nitrogen Oxides	(NOX)	= 136 $\mu g/m^3$
Carbon Monoxide	(CO)	=7250 $\mu g/m^3$
Hydrocarbons	(HC)	=2157 $\mu g/m^3$
Oxidant	(OOO)	=43.2 $\mu g/m^3$
Solar Radiation	(SR)	= 400 cal/cm^2 day

Convert reactants to $\mu mol/m^3$

NOX = 136/46 = 3.0 $\mu mol/m^3$
HC = 2157/16 = 134.5 $\mu mol/m^3$
OOO = 43.2/49 = 0.9 $\mu mol/m^3$

Determine limiting reactant for oxidant synthesis (NOX or HC): NOX is limiting.

Create Oxidant

OOO = 0.0006 (SRX) (limiting reactant)
OOO = 0.0006 (400) (3.0) = 0.72 $\mu mol/m^3$

Determine total oxidant and excess HC and NOX:

OOO = 0.9 + 0.72 = 1.6 mol/m^3
HC = 134.5 - 0.72 = 2140 mol/m^3
NOX = 3.0 - 0.72 = 2.3 mol/m^3

Convert reactants back to weight basis

OOO = 1.5 (48) = 77.3
HC = 133.5 (16) = 2140
NOX = 2.3 (46) = 105

Apply tolerance factors

PM = 143/375 = 0.381
SOX = 123/1430 = 0.086
NOX = 105/514 = 0.204
CO = 7250/40,000 = 0.181
HC = 2140/19,300 = 0.111
OOO = 77.3/214 = 0.361

Determine synergism term (SYN)

SYN = SOX or PM (whichever is smaller)
SYN = SOX = 0.086

SUM terms to determine Pindex
Pindex = PM+SOX+NOX+CO+HC+OOO+SYN
Pindex = 1.41

Table 2.2*

MAXIMUM PERMISSIBLE CONCENTRATIONS OF HARMFUL SUBSTANCES IN THE AIR OF POPULATION CENTRES

Pollutant	Maximum permissible concentration (mg/m³)	
	Maximum on one occasion	Average over 24 hours
1. Nitrogen dioxide	0.085	0.085
2. Nitric acid calculated as HNO_3	0.4	0.4
calculated as hydrogen	0.006	0.006
3. Acrolein	0.03	0.03
4. α-Methylstyrene	0.04	0.04
5. α-Naphthoquinone	0.005	0.005
6. Amyl acetate	0.10	0.10
7. Amylene	1.5	1.5
8. Ammonia	0.2	0.2
9. Aniline	0.05	0.03
10. Acetaldehyde	0.01	0.01
11. Acetone	0.35	0.35
12. Acetophenone	0.003	0.003
13. Benzene	1.5	0.8
14. Benzine, from petroluem (low-sulfur fraction, calculated as C)	5.0	1.5
15. Benzine, from shale (calculated as C)	0.05	0.05
16. Butane	200.0	—
17. Butyl acetate	0.10	0.10
18. Butylene	3.0	3.0
19. Butanol	0.1	—
20. Tributyl triphosphate (butiphos)	0.01	0.01
21. Valeric acid	0.03	0.01
22. Vanadium pentoxide	—	0.002
23. Vinyl acetate	0.15	0.15
24. Hexamethylenediamine	0.001	0.001
25. Hexachlorocyclohexane	0.03	0.03
26. Divinyl	3.0	1.0
27. Diketone	0.007	—
28. Dimethylaniline	0.0055	0.0055
29. Dimethyl sulfide	0.08	—
30. Dimethylamine	0.005	0.005
31. Dimethyl disulfide	0.7	—
32. Dimethylformamide	0.03	0.03
33. Dinyl (24% of diphenyl+76% of diphenyl oxide)	0.01	0.01
34. Dichloroethane	3.0	1.0
35. 2,3 Dichloro-1,4 naphthoquinone	0.05	0.05
36. Diethylamine	0.05	0.05
37. Isopropyl benzene	0.014	0.014
38. Iso-octanol	0.15	—
39. Isopropyl benzene hydroperoxide	0.007	0.007
40. Propane-2-ol (isopropyl alcohol)	0.6	0.6
41. Caprolactam (fumes, aerosol)	0.06	0.06
42. Caproic acid	0.01	0.005
43. Carbophos	0.015	—
44. Xylene	0.2	0.2
45. Intrathion (M-81)	0.001	0.001
46. Maleic anhydride (fumes, aerosol)	0.2	0.05
47. Manganese and its compounds (calculated as MnO_2)	—	0.01
48. Butyric acid	0.015	0.01
49. 2,4,6-Trimethylaniline (mesidine)	0.003	0.003
50. Methanol	1.0	0.5
51. Parathion-methyl (metaphos)	0.008	—
52. Metachlorophenyl isocyanate	0.005	0.005
53. Methyl acrylate	0.01	0.01
54. Methyl acetate	0.07	0.07
55. Methyl mercaptan	9×10^{-6}	—
56. Methyl methacrylate	0.1	0.1
57. Monomethylaniline	0.04	0.04
58. Monoethylamine	0.01	0.01

* Annex I, Ref [4]

Table 2.2 (continued)

Pollutant	Maximum permissible concentration (mg/m³)	
	Maximum on one occasion	Average over 24 hours
59. Arsenic (inorganic compounds, except hydrogen arsenide, calculated as As)	—	0.003
60. Naphthalene	0.003	0.003
61. Nitrobenzene	0.008	0.008
62. Nitrochlorobenzene (*o*- and *p*-)	—	0.004
63. Parachloroaniline	0.04	0.01
64. Parachlorophenyl isocyanate	0.0015	0.0015
65. Pentane	100.0	25.0
66. Pyridine	0.08	0.08
67. Propylene	3.0	3.0
68. Propanol	0.3	0.3
69. Dust, non-toxic	0.5	0.15
70. Mercury, metallic	—	0.0003
71. Soot	0.15	0.05
72. Lead and its compounds (except tetraethyl lead), calculated as Pb	—	0.0007
73. Lead sulfide	—	0.0017
74. Sulfuric acid calculated as H_2SO_4	0.3	0.1
calculated as hydrogen	0.006	0.002
75. Sulfur dioxide	0.5	0.05
76. Hydrogen sulfide	0.008	0.008
77. Carbon disulfide	0.03	0.005
78. Hydrogen cyanide	—	0.01
79. *Hydrochloric acid* calculated as HCl	0.2	0.2
calculated as hydrogen	0.006	0.006
80. Styrene	0.003	0.003
81. Tetrahydrofuran	0.2	0.2
82. Thiophene	0.6	—
83. Tolyl di-isocyanate	0.05	0.02
84. *Toluene*	0.6	0.6
85. Triethylamine	0.14	0.14
86. Trichloroethylene	4.0	1.0
87. Carbon monoxide	3.0	1.0
88. Carbon tetrachloride	4.0	2.0
89. Acetic acid	0.2	0.06
90. Acetic anhydride	0.1	0.03
91. Phenol	0.01	0.01
92. Formaldehyde	0.035	0.012
93. Phosphorus pentoxide	0.15	0.05
94. Phthalic anhydride (fumes, aerosols)	0.1	0.1
95. Fluorine compounds (calculated as F) gaseous compounds (HF, SiF_4)	0.02	0.005
readily soluble inorganic fluorides (NaF, Na_2SiF_6)	0.03	0.01
sparingly soluble inorganic fluorides (AlF_3, $NaAlF_6$, CaF_2)	0.2	0.03
admixed with gaseous fluorine and fluorides	0.03	0.01
96. Furfural	0.05	0.05
97. Chlorine	0.10	0.03
98. Chlorobenzene	0.10	0.10
99. *m-Chloroaniline*	—	*0.01*
100. Chloroprene	0.10	0.10
101. Trichlorfon (chlorophos)	0.04	0.02
102. Chlorotetracycline (for mixing with animal feed)	0.05	0.05
103. Hexavalent chromium (calculated as CrO_3)	0.0015	0.0015
104. Cyclohexane	1.4	1.4
105. Cyclohexanol	0.06	0.06
106. Cyclohexanone	0.04	—
107. Cyclohexanone oxine	0.1	—
108. Epichlorohydrin	0.2	0.2
109. Ethanol	5.0	5.0
110. Ethyl acetate	0.1	0.1
111. Ethyl benzene	0.02	0.02
112. Ethylene	3.0	3.0
113. Ethylene oxide	0.3	0.03
114. Ethylenimine	0.001	0.001

3. Emission Standards

Table 2.3 summarizes past and future emission limits for the typical automobile engine, fixed by the Environmental Protection Agency.

TABLE 2.3*

New Vehicle Standards Summary (Light-Duty Vehicles Under 6,0000 lb)

Year	Standard	Cold start test	Hydrocarbons	Carbon monoxide	Oxides of nitrogen
			grams per mile		
1970	State & Federal	7-mode	2.2	23	no std.
1971	State &	7-mode	2.2	23	4
	Federal	7-mode	2.2	23	-
1972	State	7-mode or CVS-1	1.5 or 3.2	23 or 39	3.2
	Federal	CVS-1	3.4	39	-
1973	State	CVS-1	3.2	39	3
	Federal	CVS-1	3.4	39	3
1974	State	CVS-1	3.2	39	2
	Federal	CVS-1	3.4	39	3
1975	State	CVS-1	1.0	24	1.5
	Federal	CVS-2	0.41	3.4	3
1976	State	CVS-1	1.0	24	1.5
	Federal	CVS-2	0.41	3.4	0.41

7-mode is a 137-second driving cycle test.

CVS-1 is a constant volume sample cold start test.

CVS-2 is a constant volume sample cold start test, average with a constant volume sample hot start test, both with the federal 22-minute driving cycle.

Hot 7-mode.

State refers to California.

4. Air Quality Criteria

The air quality criteria for different pollutants, as determined by the National Air Pollution Control Administration is given in the following pages (Figs. 2.2 - 2.7).

5. Nationwide Emission Trends (1940-1970)

Tables 2.4 to 2.11 present the nationwide pollution trends for different pollutants from 1940-1970, the last four tables being the breakdown for the year 1970.

*Table 6.3, Ref. [1].

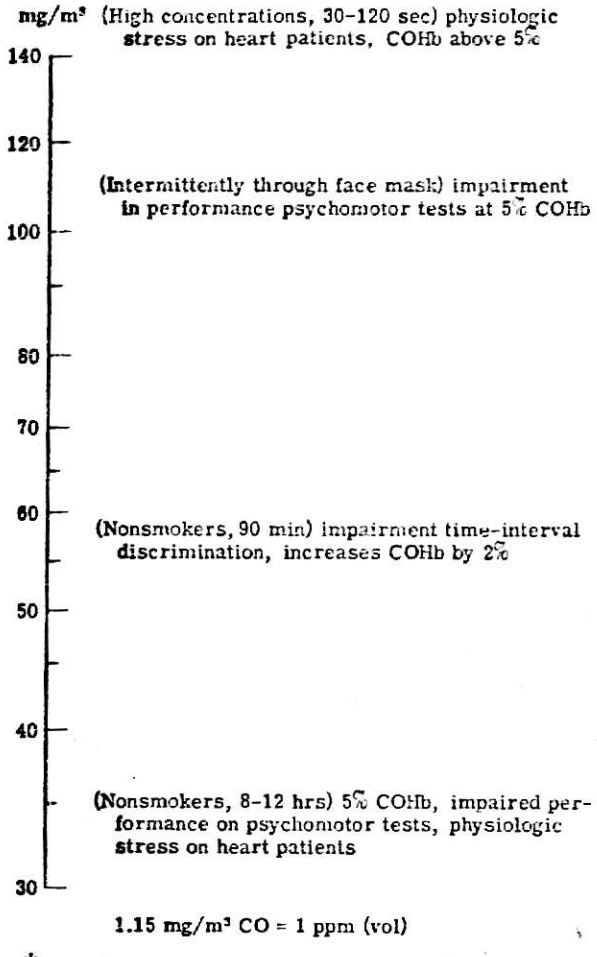
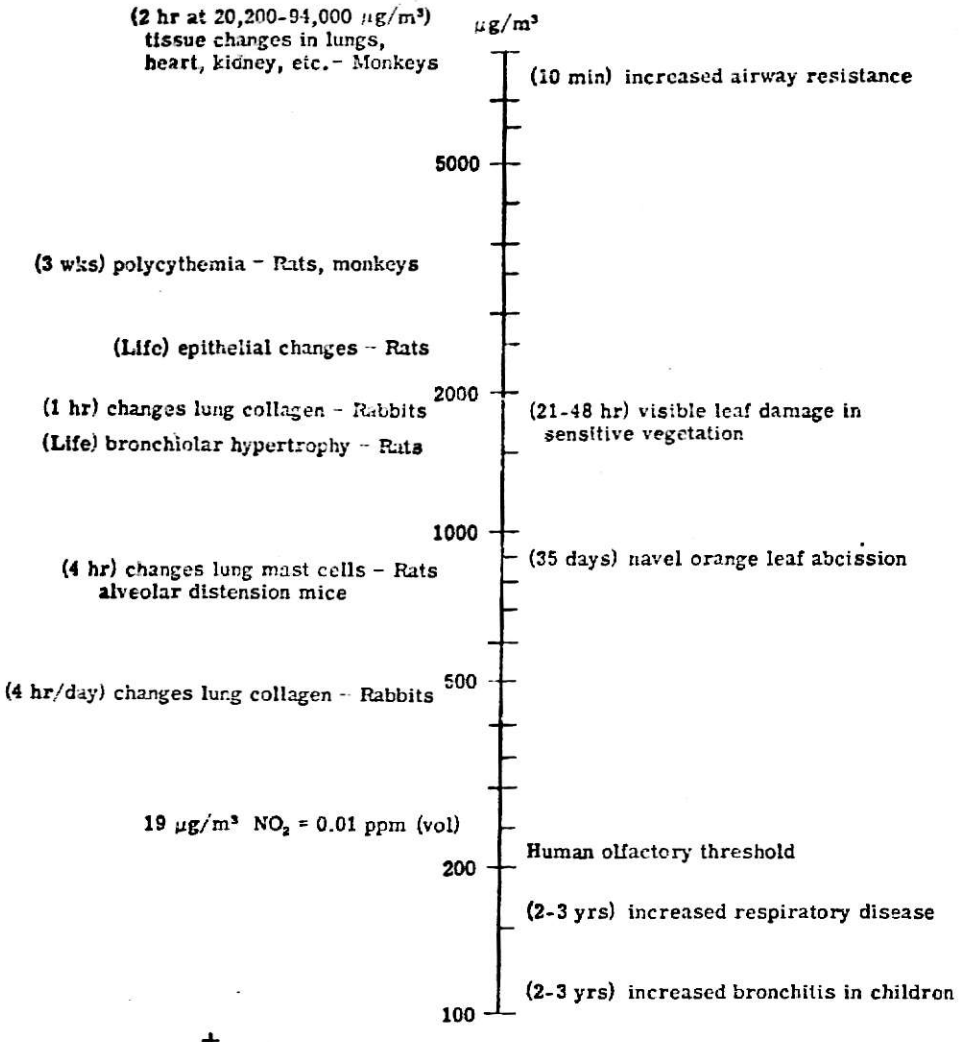


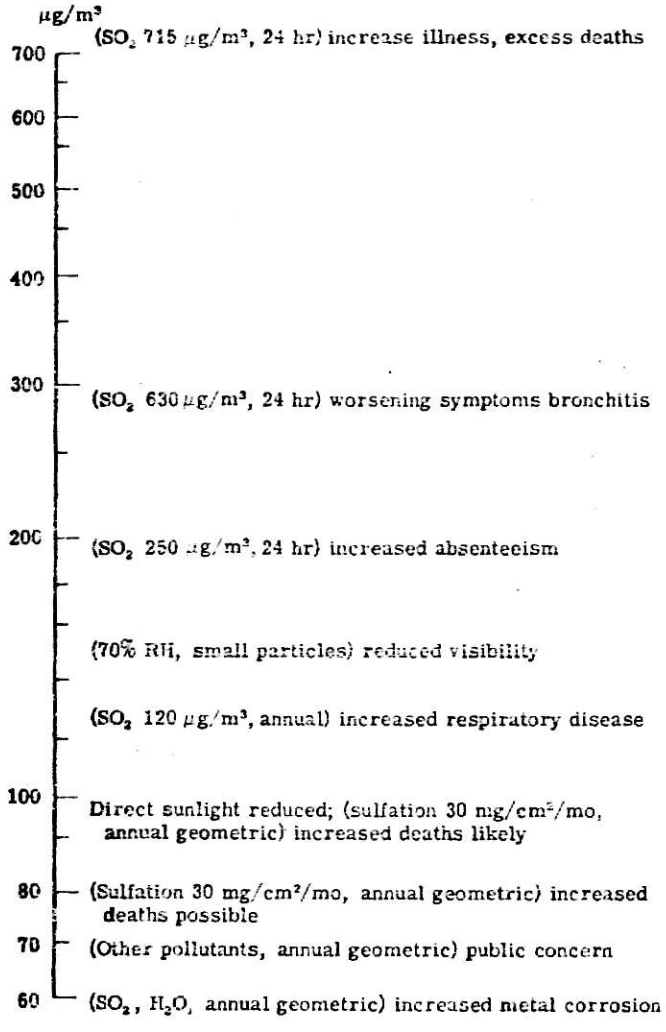
*FIG. 2.2 Air-quality criteria for carbon monoxide.

*Fig. 13-4, Ref. [5].



+FIG. 2.3 Air-quality criteria for nitrogen dioxide.

+Fig. 13-2, Ref. [5].



†FIG. 2.4 Air-quality criteria for particulates.

†Fig. 13-1, Ref. [5].

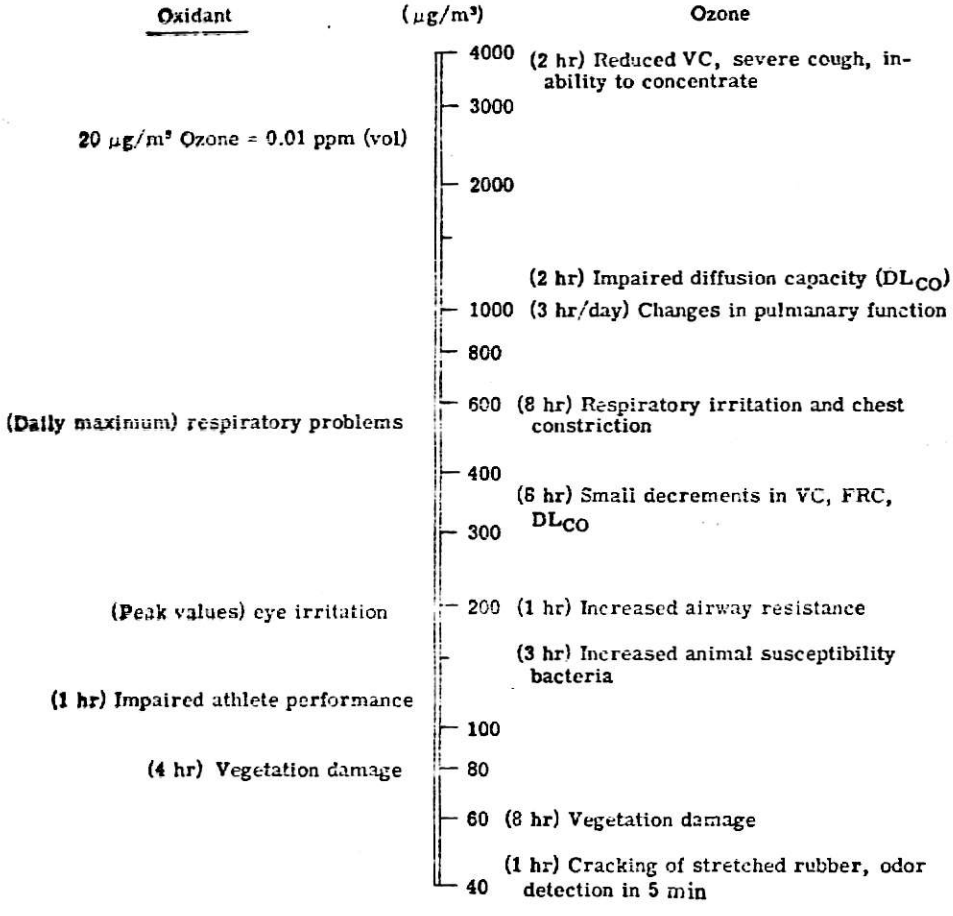


*FIG. 2.5 Air-quality criteria for photochemical oxidants.

1. No demonstrable, direct health effects of gaseous hydrocarbons in ambient air

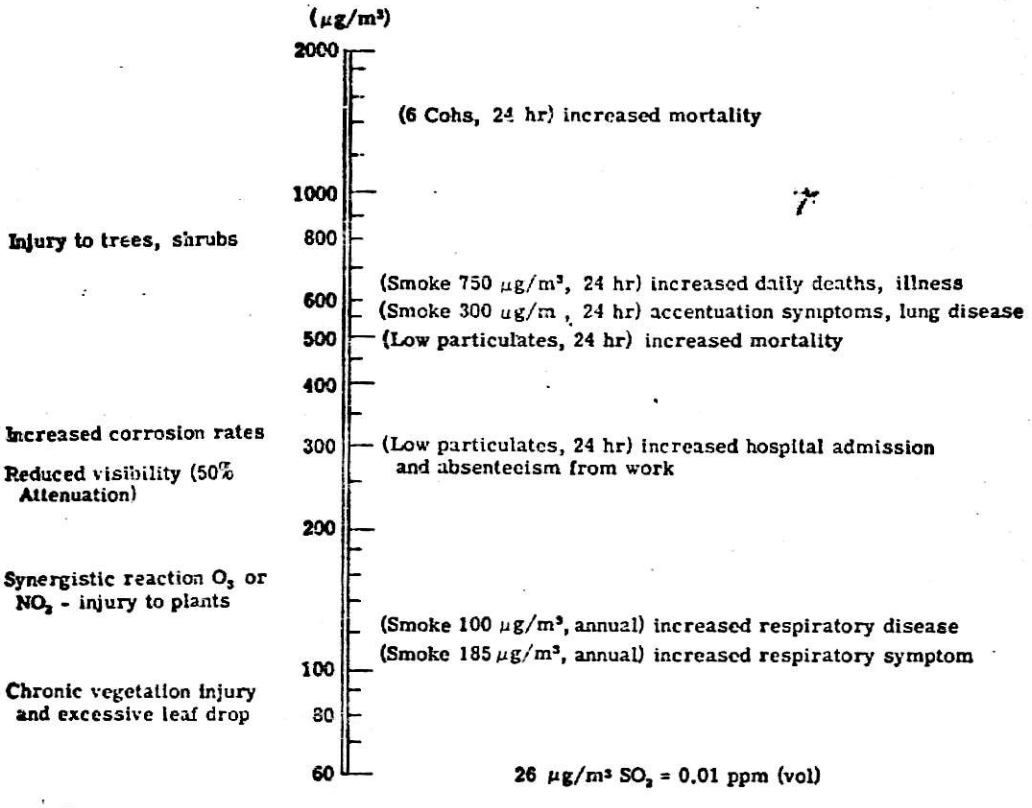
2. Injury to sensitive plants with ethylene concentrations of 1.15-575 μg/m³ (0.001-0.5 ppm) over time period of 8-24 hr

3. Nonmethane hydrocarbon concentrations of 200 μg/m³ (0.3 ppm C) for a 3-hr period from 6:00 to 9:00 AM can be expected to produce a maximum hourly average oxidant concentration of up to 200 μg/m³ (0.1 ppm) near midday

+FIG. 2.6 Air-quality criteria for hydrocarbons.

*Fig. 13-3, Ref. [5].

+Fig. 13-6, Ref. [5].



† Fig. 2.7 Air-quality criteria for sulfur oxides.

†Fig. 13-6, Ref. [5].

5. Nationwide Emission Trends 1940-1970

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Table 2.4 NATIONWIDE ESTIMATES OF CARBON MONOXIDE EMISSIONS, 1940-1970
(10^6 tons/year)

Source category	1940	1950	1960	1968	1969	1970
Fuel combustion in stationary sources	6.2	5.6	2.6	2.0	1.8	0.8
Transportation	34.9	55.4	83.5	113.0	112.0	111.0
Solid waste disposal	1.8	2.6	5.1	8.0	7.9	7.2
Industrial process losses	14.4	18.9	17.7	8.5	12.0	11.4
Agricultural burning	9.1	10.4	12.4	13.9	13.8	13.8
Miscellaneous	19.0	10.0	6.4	5.0	6.3	3.0
Total	85.4	103.0	128.0	150.0	154.0	147.0

*Table 5, Ref. [2].

+Table 2.5 NATIONWIDE ESTIMATES OF HYDROCARBON EMISSIONS, 1940-1970
(10^6 tons/year)

Source category	1940	1950	1960	1968	1969	1970
Fuel combustion in stationary sources	1.4	1.3	1.0	1.0	0.9	0.6
Transportation	7.5	11.8	18.0	20.2	19.8	19.5
Solid waste disposal	0.7	0.9	1.3	2.0	2.0	2.0
Industrial process losses	3.3	5.2	4.3	4.4	4.7	5.5
Agricultural burning	1.9	2.1	2.5	2.8	2.8	2.8
Miscellaneous	4.5	4.2	4.4	4.9	5.0	4.4
Total	19.1	25.6	31.6	35.2	35.2	34.7

+Table 7, Ref. [2].

Table 2.6 NATIONWIDE ESTIMATES OF NITROGEN OXIDE EMISSIONS, 1940-1970
(10^6 tons/year)

Source category	1940	1950	1960	1968	1969	1970
Fuel combustion in stationary sources	3.5	4.3	5.2	9.7	10.2	10.0
Transportation	3.2	5.2	8.0	10.6	11.2	11.7
Solid waste disposal	0.1	0.2	0.2	0.4	0.4	0.4
Industrial process losses	Neg[a]	0.1	0.1	0.2	0.2	0.2
Agricultural burning	0.2	0.2	0.3	0.3	0.3	0.3
Miscellaneous	0.8	0.4	0.2	0.2	0.2	0.1
Total	7.9	10.4	14.0	21.3	22.5	22.7

†Table 6, Ref. [2].

xTable 2.7 NATIONWIDE ESTIMATES OF PARTICULATE EMISSIONS, 1940-1970
(10^6 tons/year)

Source category	1940	1950	1960	1968	1969	1970
Fuel combustion in stationary sources	9.6	9.0	7.6	6.5	6.4	6.8
Transportation	0.4	0.4	0.5	0.8	0.7	0.7
Solid waste disposal	0.4	0.6	1.0	1.4	1.4	1.4
Industrial process losses	8.8	10.8	11.9	13.8	14.3	13.3
Agricultural burning	1.6	1.8	2.1	2.4	2.4	2.4
Miscellaneous	6.4	3.3	2.1	1.7	2.1	1.0
Total	27.1	25.9	25.3	26.6	27.3	25.6

xTable 4, Ref. [2].

*Table 2.8 NATIONWIDE ESTIMATES OF CARBON MONOXIDE EMISSIONS, 1970

Source category	Emissions, 10^6 tons/year	Percent of total
Transportation	111.0	74.5
Motor vehicles	96.6	64.8
Gasoline	95.8	64.3
Diesel	0.8	0.5
Aircraft	3.0	2.0
Railroads	0.1	0.1
Vessels	1.7	1.2
Other nonhighway use of motor fuels	9.5	6.4
Fuel combustion in stationary sources	0.8	0.6
Coal	0.5	0.3
Fuel oil	0.1	0.1
Natural gas	0.1	0.1
Wood	0.1	0.1
Industrial process losses	11.4	7.7
Solid waste disposal	7.2	4.9
Agricultural burning	13.8	9.3
Miscellaneous	4.5	3.0
Forest fires[a]	4.0	2.7
Structural fires	0.2	0.1
Coal refuse burning	0.3	0.2
Total	149.0	

[a]Includes prescribed burning.

*Table 20, Ref. [2].

+Table 2.9 NATIONWIDE ESTIMATES OF HYDROCARBON EMISSIONS, 1970

Source category	Emissions, 10^6 tons/year	Percent of total
Transportation	19.5	55.9
Motor vehicles	16.7	47.9
Gasoline	16.6	47.6
Diesel	0.1	0.3
Aircraft	0.4	1.1
Railroads	0.1	0.3
Vessels	0.3	0.9
Nonhighway use of motor fuels	2.0	5.7
Fuel combustion in stationary sources	0.6	1.7
Coal	0.2	0.6
Fuel oil	0.1	0.3
Natural gas	0.3	0.8
Wood	Neg[a]	–
Industrial process losses	5.5	15.8
Solid waste disposal	2.0	5.7
Agricultural burning	2.8	8.0
Miscellaneous	4.5	12.9
Forest fires[b]	0.3	0.9
Structural fires	0.1	0.3
Coal refuse burning	0.1	0.3
Gasoline and solvent evaporation	4.0	11.4
Total	34.9	

[a]Negligible (less than 0.05 x 10^6 tons/year).
[b]Includes prescribed burning.

+Table 21, Ref. [2].

*Table 2.10 NATIONWIDE ESTIMATES OF NITROGEN OXIDE EMISSIONS, 1970

Source category	Emissions, 10^6 tons/year	Percent of total
Transportation	11.7	51.3
Motor vehicles	9.1	39.9
Gasoline	7.8	34.2
Diesel	1.3	5.7
Aircraft	0.4	1.8
Railroads	0.1	0.4
Vessels	0.2	0.9
Nonhighway use of motor fuels	1.9	8.3
Fuel combustion in stationary sources	10.0	43.8
Coal	3.9	17.1
Fuel oil	1.3	5.7
Natural gas	4.7	20.6
Wood	0.1	0.4
Industrial process losses	0.2	0.9
Solid waste disposal	0.4	1.8
Agricultural burning	0.3	1.3
Miscellaneous	0.2	0.9
Forest fires[a]	0.2	0.9
Structural fires	Neg[b]	–
Coal refuse burning	Neg	–
Total	22.8	

[a]Includes prescribed burning.
[b]Negligible (less than 0.05 x 10^6 tons/year).

*Table 22, Ref. [2].

+Table 2.11 NATIONWIDE ESTIMATES OF PARTICULATE EMISSIONS, 1970

Source category	Emissions, 10^6 tons/year	Percent of total
Transportation	0.7	2.7
Motor vehicles	0.4	1.5
Gasoline	0.3	1.1
Diesel	0.1	0.4
Aircraft	0.1	0.4
Railroads	Neg[a]	–
Vessels	0.1	0.4
Nonhighway use of motor fuels	0.1	0.4
Fuel combustion in stationary sources	6.8	26.1
Coal	5.6	21.5
Fuel oil	0.4	1.5
Natural gas	0.2	0.8
Wood	0.6	2.3
Industrial process losses	13.3	51.0
Solid waste disposal	1.4	5.3
Agricultural burning	2.4	9.2
Miscellaneous	1.5	5.7
Forest fires[b]	1.4	5.3
Structural fires	Neg	–
Coal refuse burning	0.1	0.4
Total	26.1	

[a]Negligible (less than 0.05 x 10^6 tons/year).
[b]Includes prescribed burning.

+Table 19, Ref. [2].

CHAPTER 3

SOURCES OF AUTO GENERATED POLLUTION

There are four main sources of automobile generated pollutants. They are; [6]

1. The exhaust pipe: This is the primary source and discharges burned and unburned hydrocarbons, various oxides of nitrogen, carbon monoxide, and traces of alcohols, aldehydes, ketones, phenols, acids, and other organic compounds. Exhaust pipe contributes to 65 to 85 percent of pollutants.
2. The crankcase breather: This contributes to nearly 20 percent, and discharges burned and unburned hydrocarbons because of the blowby.
3. The fuel tank breather: This is a contributing factor in the hot weather with evaporation losses of the more volatile raw hydrocarbons. This could contribute upto 5% of the total pollution due to automobile.
4. The carburetor: It is a factor, especially with the stop and go driving in hot weather, with evaporation and spillage losses of raw fuel (5-10%).

Now we will discuss these emission sources with a particular emphasis on the major three pollutant gases, that is carbon monoxide, hydrocarbons, and oxides of nitrogen.

To understand the various phenomenon we present Table 3.1 which provides the information regarding the effect of various modes of driving on the pollutants.

TABLE 3.1*

Typical Exhaust Gas Constituents

Pollutant	Idling	Acceleration	Cruising	Deceleration
Carbon monoxide % vol.	4-9	0-8	1-7	2-9
Hydrocarbons; ppm	500-1000	50-80	200-800	3000-12000
Oxides of nitrogen; ppm	10-50	1000-4000	1000-3000	5-50

*Table I, Ref. [18].

The Exhaust Pipe

To discuss the various causes we break up the section into the individual paragraphs on the constituent pollutants [3].

i) CO: Carbon monoxide concentration in the exhaust is primarily a function of Air/Fuel ratio, unchanged by load or speed. Fig. 3.1 shows that when the mixture is richer than chemically correct, substantial amounts of CO appear in the exhaust. The CO curve shows that nearly 3% CO decrement occurs per one air-fuel ratio increment. The reason the CO concentration does not drop to zero even when the mixture is chemically correct and leaner arises from a combination of cycle to cycle and cylinder to cylinder fuel maldistribution.

Hydrocarbons: Hydrocarbon exhaust emissions may arise from three sources: wall quenching, incomplete combustion and exhaust scavenging as in a two-cycle engine.

Wall Quenching: Wall quenching is the predominate source of exhaust hydrocarbons in a four stroke cycle engine. It is a combustion phenomenon which arises when a flame tries to propagate in the vicinity of a wall. Normally the effect of the wall is a slowing down or stopping of the reaction. The wall quenching was observed when it was noted that a flame was incapable of propagating through a premixed mixture confined between two plates if the spacing was too small. It has been found that the quench distance is almost inversely proportional to combustion chamber pressure and to the square root of the absolute temperature.

The quench distance is also influenced by several variables such as equivalence ratio (the actual ratio of propane to air divided by stoichometric ratio), wall surface material including combustion deposits (these may act as a sponge to soak up raw fuel during the intake and compression strokes. This fuel may be vaporized and expanded into the exhaust during the later part of the expansion stroke and exhaust process).

Incomplete Combustion: Under engine operating conditions where mixtures are extremely rich or lean or where exhaust dilution is excessive incomplete flame propagation may occur in some cycles. Ocassionally a complete misfire may occur. Normally the carburetor does provide a

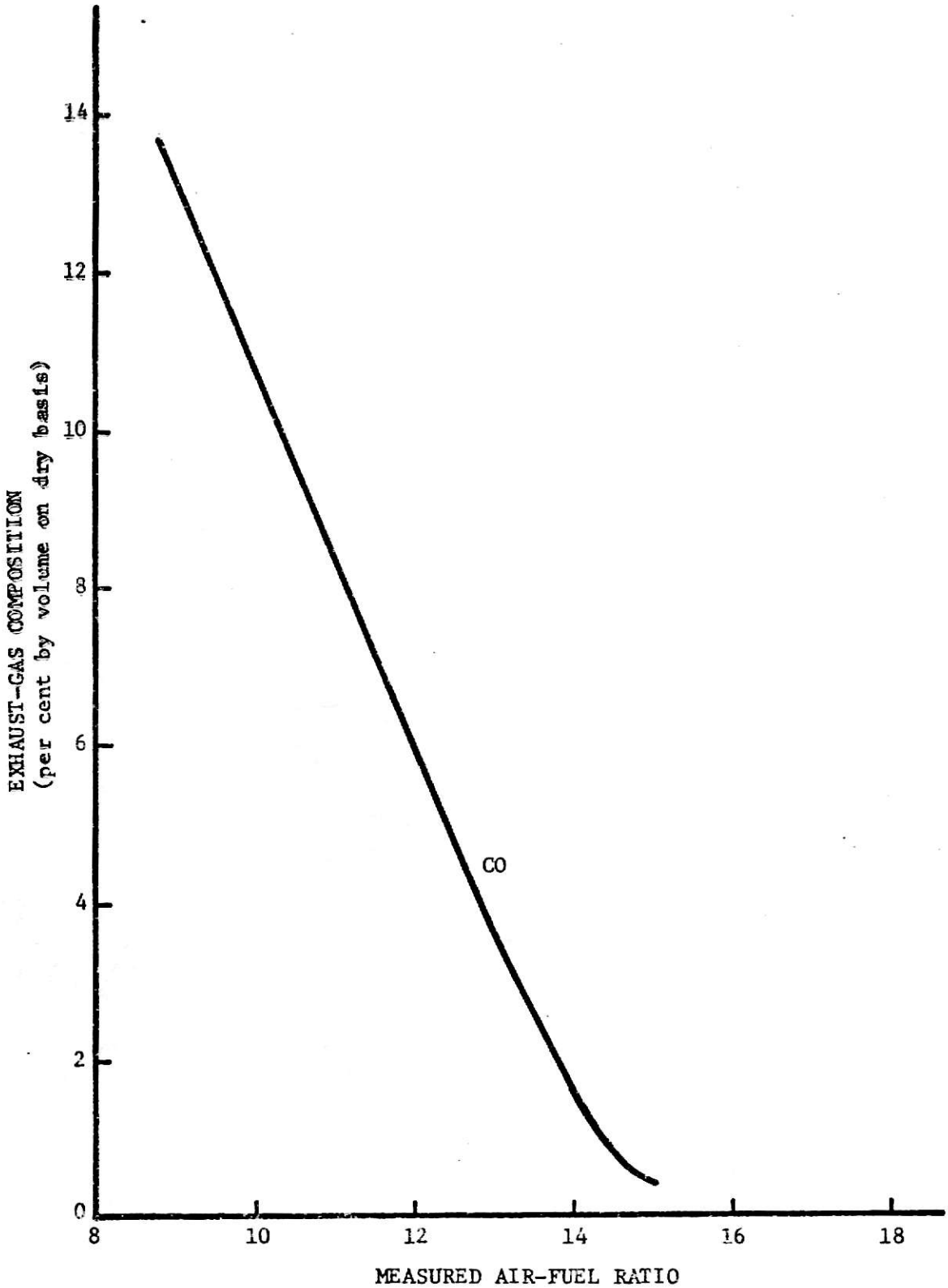


*Fig. 3.1 Exhaust Gas Composition Versus Measured Air-Fuel Ratio, for Unsupercharged Automotive-type Engines Fuel C_8H_{17}.

*Fig. 3.1, Ref. [3].

mixture in the burnable range. Thus incomplete flame propagation may usually result from exhaust gas dilution arising from high vacuum operation such as idle or deceleration. When incomplete flame propagation occurs the hydrocarbon emissions from that cycle are very high. Factors which promote incomplete flame propagation and misfire include

(a) poor condition of the ignition system including spark plugs
(b) low charge temperature
(c) poor charge homogenity
(d) too rich or too lean gaseous air fuel ratio in the cylinder
(e) large exhaust residual quantity
(f) lack of combustibles in residual as determined by previous cycle
(g) poor distribution of residual within cylinder.

Scavenging: In a two cycle gasoline engine a third source of hydrocarbon emission results from scavenging the cylinder with a fuel air mixture part of which blows through the cylinder directly into the exhaust and escapes the combustion process completely. Super charged gasoline engines may have some hydrocarbon emission from this source also.

OXIDES OF NITROGEN The emissions of nitric oxide are governed by two parameters - the availability of O_2 for the reaction, and high enough temperatures to promote this reaction.

As far as the first part is concerned there are two seperate reaction mechanisms which have been proposed.

1. Zeldovich chain reaction mechanism has the pattern

$$O_2 \rightleftharpoons 2O$$

$$O+N_2 \rightleftharpoons NO+N$$

$$N+O_2 \rightleftharpoons NO+O$$

The chain reactions are initiated in eq II by the atomic oxygen which is formed in eq I from the dissociation of oxygen molecules at the high temperatures reached in the combustion process. In eq II the oxygen reacts with a nitrogen molecule and produces nitric oxide and a nitrogen atom. In eq III the nitrogen atom reacts with the oxygen molecule and

forms nitric oxide and atomic oxygen.

2. Lavoie,Heywood and Keck extended the above mechanisms in the following manner

$$N+OH \rightleftharpoons NO+H$$

$$H+N_2O \rightleftharpoons N_2+OH$$

$$O+N_2O \rightleftharpoons N_2+O_2$$

$$O+N_2O \rightleftharpoons NO+NO.$$

3. Fenimore however studied the effect of different fuels on the NO formation rate in flames using CO hydrogen and various hydrocarbons. By measuring the rate of NO formation in the primary zone of the different flames he postulated that the NO formation in hydrogen/air flames results from an attack of carbon or hydrogen radicals on nitrogen molecules.

Newhall and Shahed used spectroscopic techniques to record directly the time rate of formation of NO in the immediate vicinity of the flame front propagating through a high pressure combustion vessel. The result obtained by their experiments show that the NO formation occurs predominantly in the post flame combustion products.

THE CARBURETOR

Carburetor hydrocarbon vapor losses typically are about 10 to 30 grams per test. They arise from distillation of the fuel in the float bowl. It has been observed that whenever carburetor fuel temperature rises to 160^{o}F approximately 25-30% by volume of the fuel will be boiled off [3].

During most engine operation the vapors generated are vented internally into the intake system. During hot soak vapors continue to be generated and are vented into the carburetor air horn. Many of these vapors find their way to the atmosphere through the air cleaner snout.

Carburetor fuel temperatures often reaches 130^{o}F during warm weather engine operation and may rise upto 180^{o}F during a hot soak which may cause a significant fraction of the fuel in the bowl to be boiled off. A large fraction of this finds its way to the atmosphere.

The basic factors governing the mass of fuel distilled from a carburetor during a hot soak period are

i) maximum fuel bowl temperatures
ii) amount of fuel in the bowl
iii) amount of after fill and
iv) distillation curve of the fuel

Fuel Tank Breather

The hydrocarbon vapor losses from a fuel tank of typically 50 grams per test arise primarily from an evaporation process. Because the tank temperatures change slowly the evaporation process is nearly an equilibruim one.

At night the tank cools and both liquid and vapor contract thereby allowing ambient air to be inhaled into the vapor space of the tank. During the day especially during and after severe hot cycle operation tank temperatures rise perhaps to 120°F or more. As a result of such increases in tank temperatures the liquid and vapor increase in volume and the tank expels some hydrocarbons vapor air mixture. In addition because the vapor pressure of each constituent of the gasoline increases with temperature additional vaporization of each fuel component occurs until the vapor pressure is satisfied for the constituent at the new temperature. Thus additional vapor is expelled.

The basic factors governing the mass of fuel evaporated from a heated fuel tank are:

i) The initial and final fuel temperatures.
ii) The vol. of the tank not filled with the fuel.
iii) The composition of the fuel.
iv) The presence of a pressure relief cap.
v) The area of liquid vapor surface.
vi) The length of time or degree of agitation of the tank near its maximum temperature.

The Crankcase Breather

Crankcase emissions are composed of (1) engine blow-by gases (2) ventilation air and (3) crankcase lubricant fumes. From the air

pollution atand point the most important of these is blowby. A small amount of gases in the combustion chamber escapes past the pistons into the crankcase mostly during the compression stroke. These blowby gases are composed of approximately 70 to 80% fresh air fuel mixture and the remainder is the residue combustion products of the previous cycle.

The addition however in 1963 of the positive crankcase ventilation system virtually eliminated all blowby gases. Hence this has now become a thing of the past.

CHAPTER 4

INSTRUMENTATION AND FEDERAL TEST PROCEDURES FOR AUTO EXHAUST

Because the automobile is the major source of hydrocarbons and other gaseous pollutants in the urban atmospheres, considerable attention has been placed on the measurement and control of unburned hydrocarbons, carbon monoxide and oxides of nitrogen in automotive exhaust.

Assesment has been made of the state of emission measurement technology to determine whether measurement techniques are sufficiently well advanced to support the development of the implementation of emission standards. The conclusion drawn from this assesment is that current measurement technology will meet most of the requirements of an emission control program.

A number of organizations, both private and government, are engaged in manufacturing and use of various kinds of instrumentation. However, a list of instrumentation used and recommended by Environmental Protection Agency is given here [19].

Carbon monoxide: Non Dispersive Infra Red Analyzer. (NDIR) [3].
Hydrocarbons: Flame Ionization Detector. (FID), Gas Chromatograph (GC).
Oxides of Nitrogen: Chemiluminescent Analyses Method. (CLA).

A brief description of the principle and working of these instruments is given in the following pages.

Nondispersive Infrared Analyzer

Principle: In the Nondispersive Infrared Analyzer (NDIR) the exhaust gas species being measured are used to detect themselves. The method of detection is based on the principle of selective absorption; the infrared energy of a particular wave length, peculiar to a certain gas will be absorbed by that gas. Infrared energy of other wave lengths will be transmitted by that gas, just as energy of the absorbed wave lengths will be transmitted by other gases. Therefore, in effect certain gases match up with certain wave lengths in the infrared energy band. An example of this can be seen in figure 4.1.

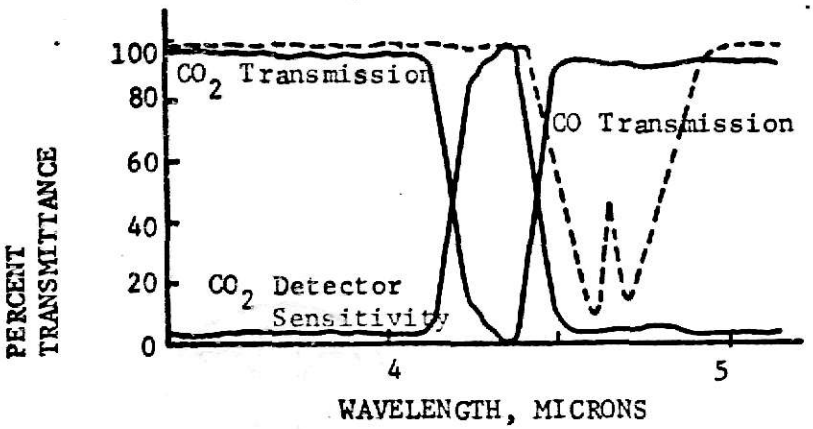
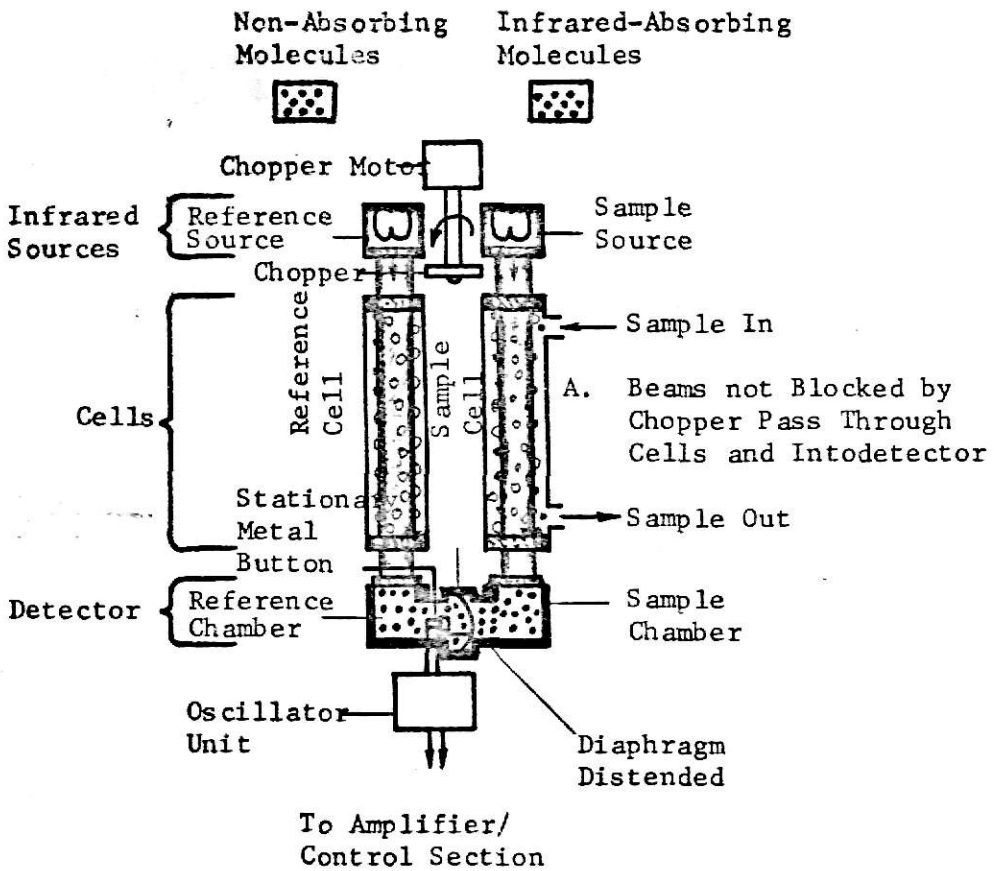


*Fig. 4.1 Infrared Absorption for CO and CO_2.

*Fig. 9.1, Ref [3].



+Fig. 4.2 The Non-Dispersive Infrared Analyzer, with Radiation Transmitted to the Cells. (Notice that the diaphram is Deflected Away From the Button).

+Fig. 3, Ref. [20].

Infrared absorption for CO and CO_2

It is clear from the above figure that Carbon dioxide absorbs infra-red energy in the wave length band of 4 to 4.5 microns and transmits energy of surrounding wave lengths, and that the absorption band for Carbon monoxide is between 4.5 to 5 microns.

Construction of the Instrument. The construction of the NDIR is shown in Figure 4.2. Two identical infrared sources direct infra-red radiation through two separate cells, a sample cell and a reference cell. After passing through these cells the infrared radiation is received in two separate detector cells, which are full of the gas whose concentration is to be measured. The two detector cells contain equal amounts of this gas and are separated by a flexible diaphram. This diaphram together with a stationary metal button constitute a capacitor, whose capacitance is varied proportionally to the distance between them.

The sample cell is a flow-through tube that receives a continuous stream of the mixture of gases to be analyzed. When the particular gas to be analyzed is present in the sample, it absorbs the infrared radiation at its characteristic wave lengths. The percent of radiation absorbed is proportional to the molecular concentration of the component of interest in the sample. The cells have quarts windows which do not absorb infrared energy in the region of interest. The length of the cells varies according to the application. Low concentrations are best measured by longer cells so that more molecules of interest are present.

The reference cell is sealed and is physically identical to the sample cell. It is filled with an inert gas (usually nitrogen) which does not absorb the infrared energy of the characteristic wave length of the species of interst.

The radiant energy, after passing through the cells, heats the gas in the corresponding chamber in the detector. Since no radiant energy is absorbed in the reference cell, the corresponding chamber in the detector is heated more and its pressure becomes higher than that in the other chamber. This pressure differential causes the diaphram to move and vary the capacitance. Therefore the variation in the capacitance

is proportional to the concentration of the species of interest in the exhaust sample. A chopper is placed between the infrared source and the cells. When the chopper blocks the radiation, the pressure in the two compartments of the detector is equal because there is no energy entering either chamber of the detector. This allows the diaphram to return to its neutral position. As the chopper alternately blocks and unblocks the radiation, the diaphram fluctuates causing the capacitance to change cyclically. This sets up an AC signal, which is impressed on a carrier wave provided by a radio frequency oscillator. The reason for using the chopper to produce an AC signal is that the amplifiers of the AC signals have better drift-free characteristics than the amplifiers of the DC signals. Additional electronic circuitry in the oscillator unit demodulates and filters the resultant signal. This signal is then amplified and rectified to a DC signal which is measured by a meter or a recorder. The final DC signal is a function of the concentration of the species of interest in the exhaust sample.

Calibration: The instrument is calibrated by passing gases of known concentration through the sample cell. The zero and span controls can be adjusted so that any scale is arbitrary. With the known concentration and their associated meter readings, a calibration curve is constructed. In practice, the curve is usually drawn between two points and linearity is assumed. For linear interpolation the length of the tube should be chosen so that the readings are in the linear region of the relation between concentration and energy absorbed.

The relation between the incident energy, the absorbed energy, the length of the cell, and the concentration of the species of interest can be given by the following equation:

$$E_a = E_i(1-e^{-kcl})$$

where:

E_a = energy absorbed

E_i = energy incident

k = absorption constant

c = concentration of interested species

l = length of cell

if the value of kcl is very small compared to unity, then under this condition:

$$e^{-kcl} = 1-kcl$$

and then the above equation reduces to:

$$E_a = E_i(kcl)$$

It is quite obvious from the above equations that the absorbed energy is directly proportional to the concentration c under the condition that, kcl is small. This shows that if the concentration (c) is high, the length of the cell should be short and the product kcl very small compared to unity, in order that linearity of the scale could be assumed. The choice of the length of the cell should take into consideration the sensitivity of the instrument as well as the linearity of the scale. In general longer cells give better sensitivity but less linearity. On the other hand they take a longer time to purge and do not respond to transients as rapidly.

Flame Ionization Detector

Principle: The principle of operation of the Flame Ionization Detector (FID) is illustrated in Figure 4.3.

It is based on the phenomenon that pure hydrogen/air flames produce very little ionization, but if a few hydorcarbon molecules are introduced, these flames produce a large amount of ionization. The ionization is proportional to the number of carbon atoms present in the hydrocarbon molecules. All classes of hydrocarbons (paraffins, olefins, aromatics, etc.) are measured with equal response. This conclusion does not apply to hydrocarbon molecules which contain oxygen or nitrogen atoms.

Construction of the Instrument: Figure 4.4 shows a schematic drawing of the FID. It is composed of the burner assembly, the ion collector and the electric circuitry. The burner consists of a central cappillary tube

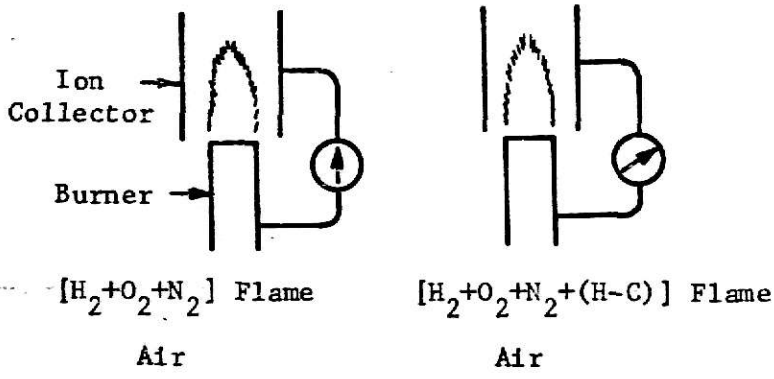
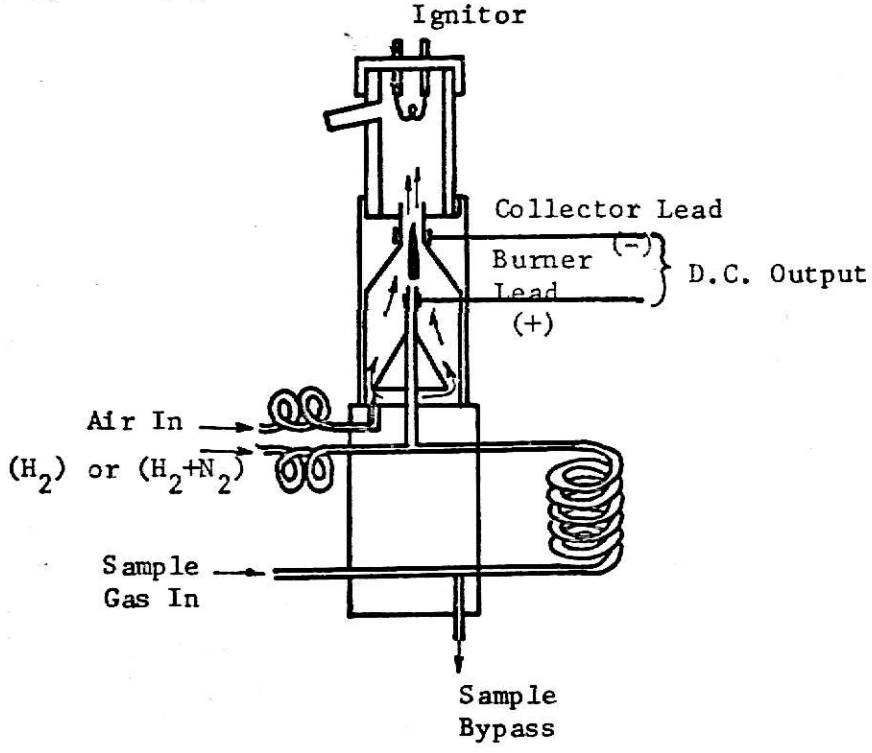


*Fig. 4.3 Effect of Hydrocarbon Compounds in Sample in Ionization of Hydrogen-Air Flame.

*Fig. 9.7, Ref. [3].



+Fig. 4.4 Flame Ionization Detector.

+Fig. 9.8, Ref. [3].

through which flows a mixture of nitrogen and hydrogen and the gas sample. Relatively pure hydrogen is used. The required air for combustion is introduced from around the capillary tube. The combustible mixture formed is ignited by a hot wire at the top of the burner assembly. The flame produced is of the diffusion type.

The collector and the capillary tube form part of an electric circuit. An electric polarizing battery is used to produce an electrostatic field in the vicinity of the flame. This causes the electrons to go to the burner jet and the positive ions to the collector. The DC signal produced is proportional to the number of ions formed and the number of ions formed is proportional to the number of carbon atoms in the flame. The DC signal generated is attentuated by a modulator and then fed to an AC amplifier and a demodulator.

Flow System: The sensitivity of the FID is affected by the flow rates of the sample and the hydrogen-nitrogen mixture. One of the methods used to control the rate of flow of each of these gases is to allow each to pass through a capillary as shown in the above figure. The rate of flow depends upon the cross section of the capillary, the length, and the pressure drop across the capillary. To ensure reproducibility the capillary should be clean and the pressure ahead of the capillary should be regulated and kept constant.

Although the FID has a very low sensitivity to water vapor, it is essential that condensation of water in the sample system be prevented to avoid blocking the system. This results in erratic responses in the unheated flame ionization detector. In the heated flame ionization detector, the burner assembly and the sampling tubes are heated to 350-400°F. This will reduce the condensation of the heavy hydrocarbons on the walls. Probably under this condition the water in the sample will pass through the system as vapor.

Chemiluminescent Analyses of Nitrogen Oxides

The chemiluminescent analysis method has been adopted for measurement of automotive NO_x emissions. The perfection of this type of exhaust analyzer permitted the establishment of a Fedral NO_x standard for 1973.

Principle: Figure 4.5 shows a schematic drawing of the chemiluminescent instrument sample containing NO is flowed to a cylindrical plug flow reactor which is maintained at a low pressure, typically five to seven torr. Simultaneously, ozone manufactured in a built-in ozonator is introduced into the reactor and well mixed with the NO sample in the region near the detector. A reaction between NO and O_3 occurs which produces some electronically excited NO_2 molecules. The decay to the ground state of these excited molecules emits light (photons) in the wave length region 0.6 to 3μ. This light is detected by a photomultiplier. The signal is then amplified and fed to a recorder.

The following reaction mechanism has been proposed [21]:

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad -(1)$$

$$NO + O_3 \rightarrow NO_2^* + O_2 \qquad -(2)$$

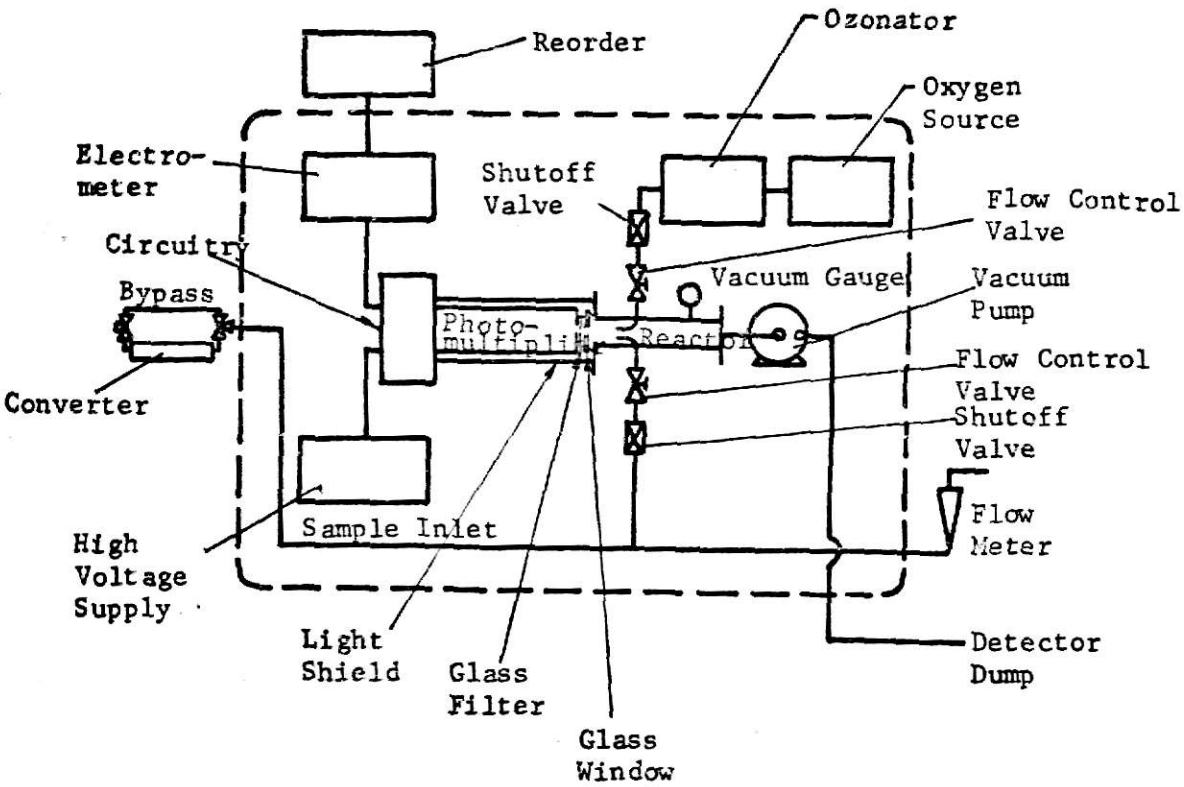
$$NO_2^* \rightarrow NO_2 + h \qquad -(3)$$

$$NO_2^* + M \rightarrow NO_2 + M^* \qquad -(4)$$

$$I = \frac{I_o(NO)(O_3)}{M} \quad \text{light intensity.}$$

Equations 1 and 2 show that only a fraction of NO is converted to excited NO_2^*. It was determined that the excited yield is 10% at 80°F. Thus calibration and operation must be at the same reactor temperature. It is also noted that deactivation of excited NO_2^* can be proceed according to equation 4, in which a thermal collision between NO_2 and some other molecule can cause deactivation and result in a low reading of light. A large excess of O_3 in the reactor has been recommended to avoid differences in the rate of the quenching reaction 4 due to differences in the reactor gas composition with varying gas samples.

Interferences: It has been checked for interferences from other exhaust constituents and it has been found that it is safe to assume that interferences are negligible. Data of typical results is supplied here:



+Fig. 4.5 Schematic of Chemiluminescent NO Analyzer as Shown in in Federal Register.

+Fig. 1c, Ref. [22]

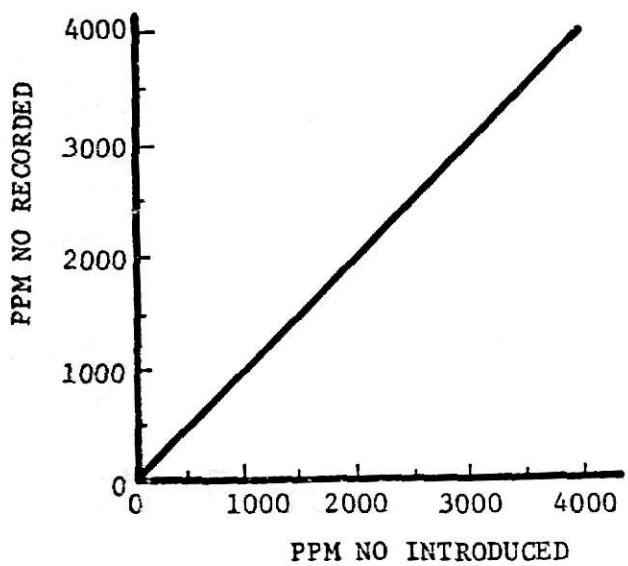


*Fig. 4.6 Calibration of Chemiluminescent Analyzer. Response is linear to sample NO.

*Fig. 9.21, Ref. [3].

*TABLE 4.1

Interference of Typical gases on the NO Determination as measured by Chemiluminescent Analyzer

Sample flow = 32cc/min gas composition	O_3 = 125cc/min interference (ppm NO)
53.5 ppm NO + 100 ppm ethylene	0
450.0 ppm NO + 100 ppm ethylene	0
53.5 ppm NO + 2.02%CO+4.42% CO_2	-0.2 ppm
53.5 ppm NO + 50% N_2	-0.5 ppm
53.5 ppm NO + 500 ppm CH_4	0
53.5 ppm NO + 20% H_2	-5 ppm
505 ppm CH_4 + 460 ppm NO	0
505 ppm CH_4 + 1995 ppm NO	0
500 ppm C_3H_8 + 460 ppm NO	0
500 ppm C_3H_8 + 1995 ppm NO	0
100 ppm NO_2 + 460 ppm NO	0
50% blended air + 460 ppm NO	0
50% blended air + 1995 ppm NO	0
5.3% CO + 460 ppm NO	0
5.3% CO + 1995 ppm NO	0

Linearity and Response: Because of the operating principle, the response is theoretically linear with NO concentration. Fig. 4.6 shows a calibration curve.

Range: The range of the instrument is limited by the photomultiplier tube. With a cooled tube, the range can be 10^{-2} to 10^{3} ppm. Commercial units for auto exhaust normally do not use cooled tubes and consequently a useful range of 1 - 1000 ppm is expected.

The Gas Chromatograph: Chromatography is a physical method of separating a mixture into its individual constituents so that each constituent can be analyzed separately. Exhaust gas hydrocarbon analysis involves partition chromatography.

Components of the Gas-Liquid Chromatograph:

1) Carrier gas supplier and controller
2) Sample injection device
3) The column
4) The oven and thermostat
5) The detector
6) The recorder.

*Table 9.5, Ref. [3].

Below is a brief description of a chromatographic method used by the Ford Motor Company to separate and measure the 200+ hydrocarbons found in the exhaust of the gasoline engines. Figure 4.7 shows a schematic drawing of the basic system. Three columns are used. Column 1 is used to separate the lightest hydrocarbon molecules: methane, ethane and ethylene. Column 2 separates the rest and column 3 subtracts all the paraffins.

First the vacuum pump draws the sample into the 3 cc sample loop. (Fig. 4.8) After the sample loop is filled the sample valve is switched allowing the sample gas to be injected directly into the column 1. The flow switching valve is set in the dotted position. Column 1 is initially placed in a dry slurry (ice) at $-78^{o}C$ and condenses all the hydrocarbons except methane. The methane passes unimpeded through columns 1 and 2 and is detected by the FID & recorded. Next column 1 is allowed to warm in air, during which time ethane and ethylene pass through and are detected. The carrier gas flow through column 1 is then reversed and the column warmed by placing it in the room temperature water. By the time column 1 has reached room temperature, the remaining hydrocarbons have been flushed into column 2, a capillary column, where they are once again stopped. Column 2 is located in a temperature programmed oven which is initially cooled to $-30^{o}C$ by blowing liquid nitrogen vapor over the column.

This sequence of events is suggested in the Figure 4,9 , points A through G. The figure is for oven temperaure program and consequently indicates the temperature of column 2 only. At point G, 7 minutes after the analysis has started, the oven temperature is gradually raised and the remaining hydrocarbons separated.

In Fig. 4.10 is shown an actual exhaust chromatogram at 30 mph cruise with indolene fuel. The complete analysis is run twice. The second time the sample is passed first through column 3 so that only the paraffins remain in the sample to be analyzed.

Federal Emission Test Procedures [6]

Federal exhaust emission test procedures for light duty vehicles under 6000 lb GVW covering the period 1972 to 1975 assess hydrocarbon,

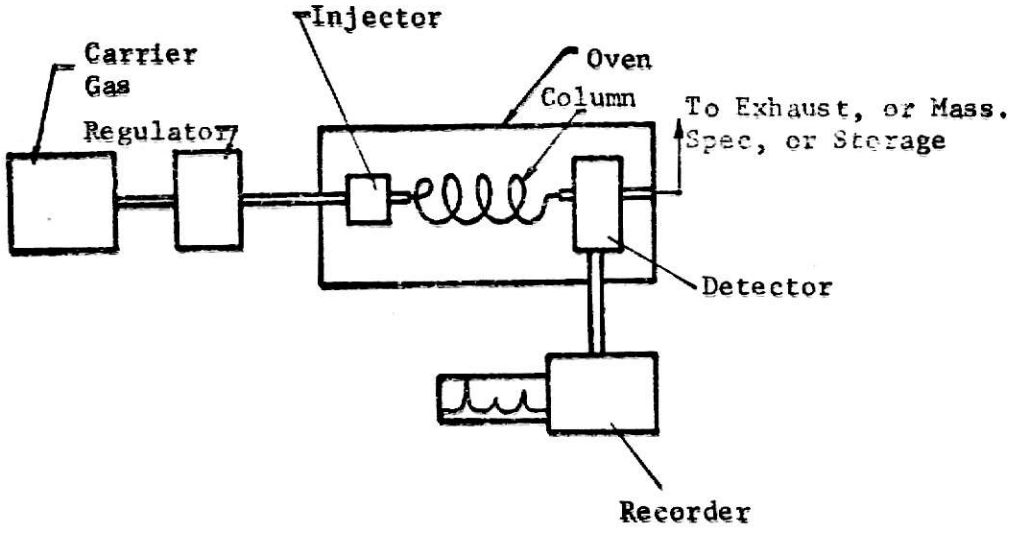
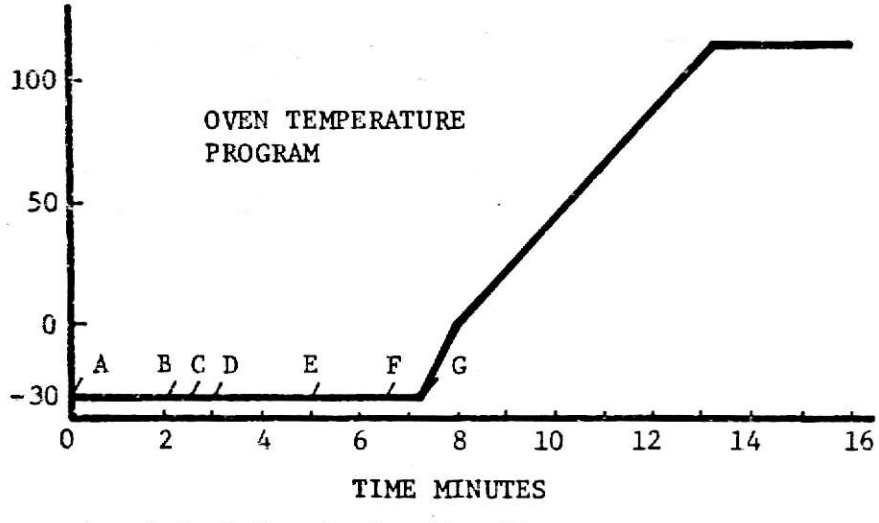


*Fig. 4.7 Main Components of the Gas Chromatograph.

*Fig. 9.12, Ref. [3].



A - Col. 1 Put in Dry Ice Slurry
B - Tape Recorder Started - Sample Loop Evacuated
C - Sample Loop Filled
D - Sample Injected
E - Dry - Ice Removed
F - Flow Switching Valve Activated - Col. 1 Put in Water
G - Oven Cooling Stopped - Program Started

Fig. 4.9 Sequence of Analytical Technique. (Fig. 9.18, Ref. [3])

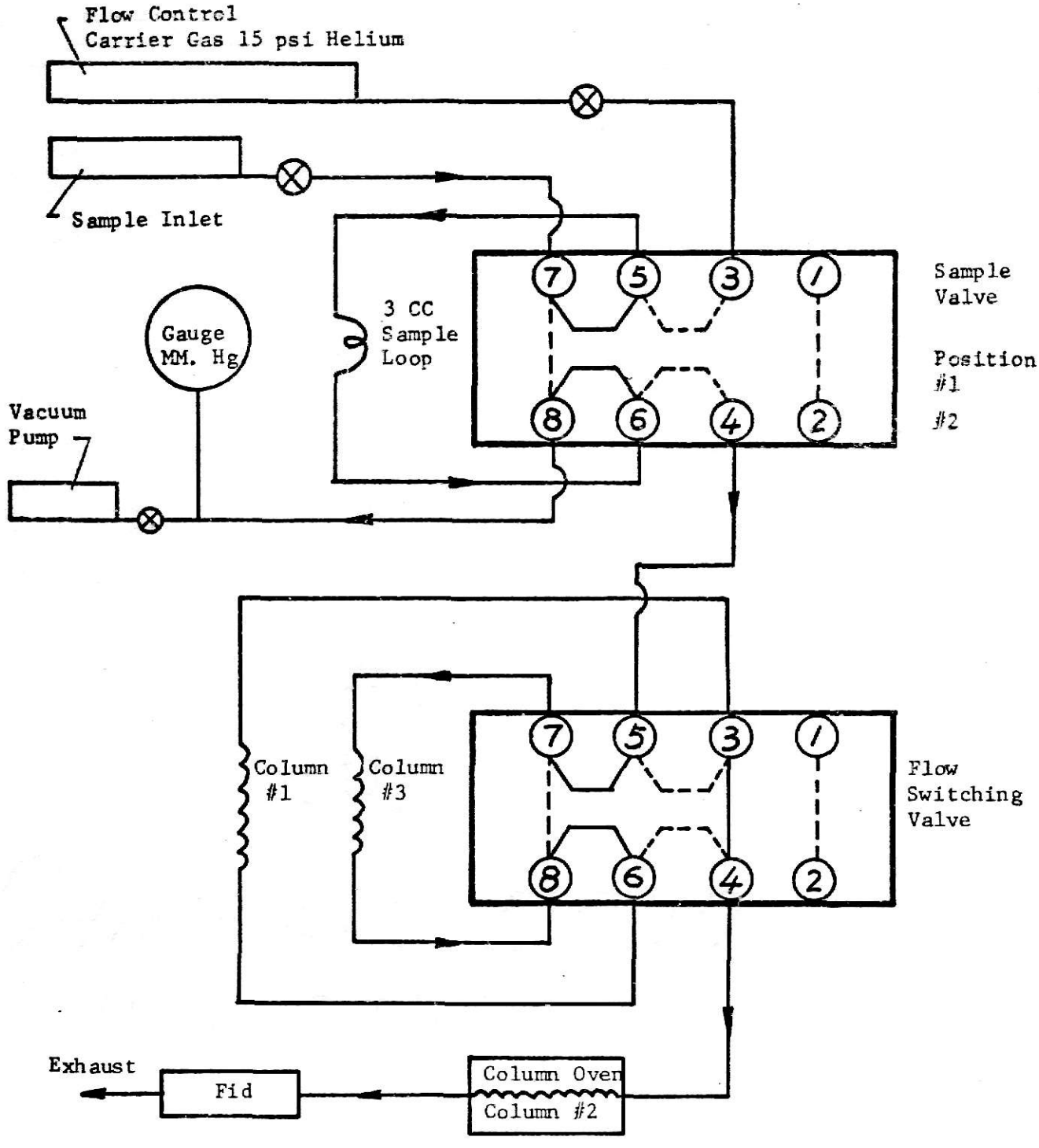


*Fig. 4.8 Column and Valve Arrangement.

*Fig. 9.17, Ref. [3].

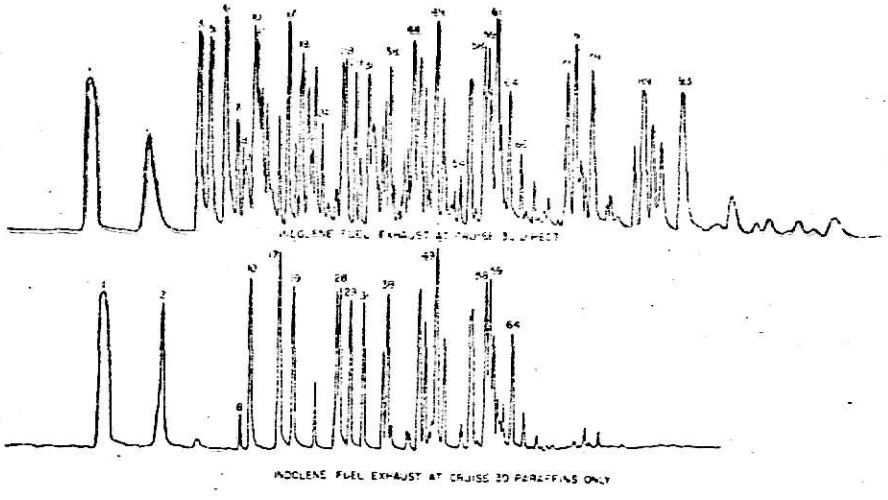


*Fig. 4.10 Gas chromatogram at 30 mph cruise.

*Fig. 9.19, Ref. [3].

carbon monoxide and nitric oxide emissions in terms of mass emissions emitted over a 7.5 mile chassis dynomometer driving cycle. Results are expressed as grams of pollutants emitted per mile.

Two test procedures using the same test equipment have been used. One, which is called CVS-1, employs a single bag to collect a representative portion of the exhaust for the subsequent analysis. This procedure was used for 1972, 1973 and 1974 vehicles. The second procedure, termed as CVS-3 uses three sampling bags and is designed to give a more realistic weighing to the cold start portion of the test. This three-bag system applies to the testing of 1975 and 1976 vehicles.

Driving Cycles:

FTP: Federal Test Procedures (1968-71): California 7 mode test (1962-71), for light duty (LD: under 6,000 lb) vehicles. A light traffic urban driving pattern (16 min = 6 miles) on chassis dynomometer with (a) variable rolls to simulate acceleration-deceleration restraints and (b) with assigned power settings (plus 10% for air conditioners), to correspond with the mass of the particular vehicle. Cold start, 1-min warm up allowed. Continuous test of four repetitive cold cycles, three repetitive hot cycles, each, 7 modes: idle (20 sec); moderate (2.2 mph/sec) acceleration to 30 mph; cruise (15 sec); mild (-1.4 mph/sec) deceleration to 15 mph; cruise (15 sec); mild (1.2 mph/sec) acceleration to 50 mph (max speed); mild (-1.2 mph) and moderate (-2.5 mph/sec) decelerations, to idle of next cycle.

Continuous NDIR analysis; each emission concentration for each mode averaged, time weighed, hot or cold weighed, and averaged to yield the test concentration. The test concentration converted (semi-empirically) to mass emission (g/mile).

CVS Federal Urban Driving Schedule: (1972-) For light duty (under 6,000 lb) vehicles. A heavy-traffic urban driving pattern on FTP dynamometer (23 min = 7.5 miles). Continuous test (one cycle) begins from cold start (includes high reactive emissions from choke and cranking) many (=70) modes; mild, moderate, and severe accelerations-decelerations

(57 mph max speed); nonconstant cruise speeds; ends 5 sec after ignition cut off to include after run emissions (about 1380 sec).

9-Model Federal Test: (1970-) For heavy duty (over 6,000 lb) gasoline engine trucks simulating a light traffic urban driving pattern, Engine dynomometer, constant speed (2,000 rpm, except idle). Cold start, 5- min warm up allowed. Load measured by manifold vacuum. Continuous test, four repetitive cycles, each, 9 modes (idle, modes made at the beginning and end of the test): Idle (2); cruise (16); acceleration (10); cruise (16); deceleration (19); cruise (16); full load (3); cruise (16) closed throttle (max).

13- Model Federal Test: For heavy duty diesel trucks simulating a light traffic urban driving pattern. Engine dynamometer, no accelerations or decelerations. Cold start, warm up allowed. Noncontinuous test of two continuous cycles, each, 13 modes (1) Idle (2,3,4,5,6) max toque speed at 100, 75, 50, 25, 2% load; (7) idle (8,9,10,11,12) rated speed at 100,75,50,25,2% load; (13) idle. Shutdown, 8 hr; allowed warm up, and cycle repeated.

The Constant Volume Sampler: CVS-1 System: The CVS-1 system, sometimes termed as variable dilution sampling, is designed to measure the true emissions (mass) [22]. The system is shown in the figure 4.11. A large positive displacement pump draws a constant volume flow of gas through the system. The exhaust of the vehicle is mixed with filtered room air and the mixture is then drawn through the pump. Sufficient air is used to dilute the exhaust in order to avoid vapor condensation, which could dissolve some pollutants and reduce measured values. Excessive dilution on the other hand results in very low concentrations with attendant measurements problem. A pump with capicity of 300-350 cfm provides sufficient dilution for most vehicles.

Before the exhaust air mixture enters the pump its temperature is controlled to within $\pm 10^{\circ}F$ by the heat exchanger. Thus constant density is maintained in the sampling system and pump. A fraction of the diluted exhaust stream is drawn off by pump P_2 and ejected into an initially evacuated plastic bag. Preferably, the bag should be opaque and manufactured of Teflon or Tedlar. A single bag is used for the entire test sample in the CVS-1 system.

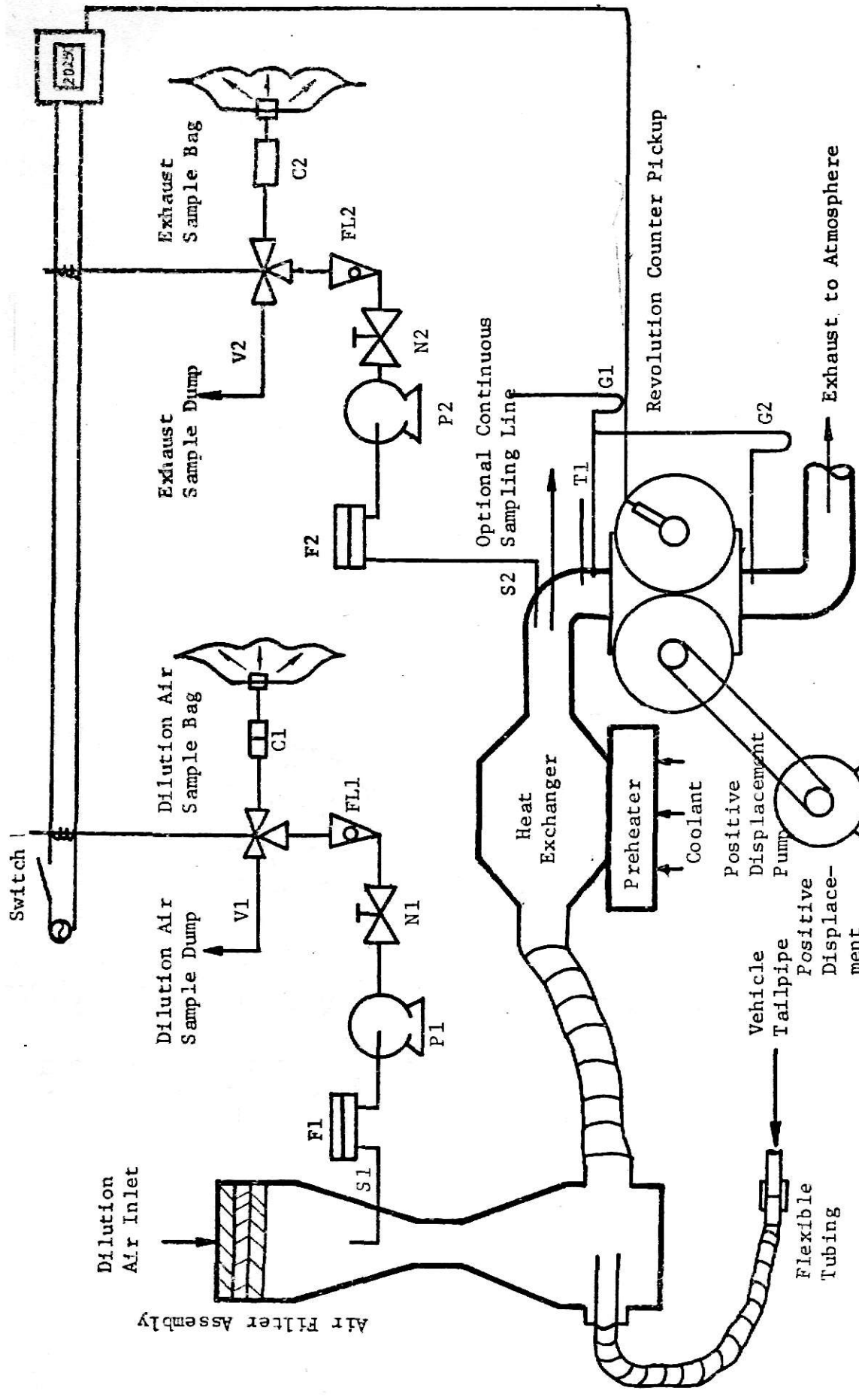


Fig. 4.11 CVS-1 System as Specified in Federal Register. (Fig. 1a, Ref. [22]).

Because of high dilution, ambient traces of HC, CO or NO_x can significantly increase the concentrations in the sample bag. A charcoal filter is employed for leveling ambient HC measurement. To correct for ambient contamination a bag of dilution air is taken simultaneously with the filling of the exhaust bag.

Calculation of Emission Results: HC, CO and NO_x measurements are made on a wet basis using FID, NDIR and chemiluminescent detectors respectively. Instruments must be constructed to accurately measure the relatively low concentrations of the diluted exhaust. Concentration values used in the calculations are those of the dilute exhaust sample minus those of the ambient air sample. The emission mass in gram/mile is calculated as follows:

$$HC_{mass} = V_{mix} \times HC \times \frac{HC_{conc}}{10^6} \times \text{ppm C}$$

$$CO_{mass} = V_{mix} \times co \times \frac{CO_{conc}}{10^6} \times \text{ppm CO}$$

$$NO_{x\ mass} = V_{mix} \times no_2 \times \frac{KHXNO_{conc}}{10^6} \times \text{ppm NO}$$

where

HC = density of $CH_{1.86}$ in gm/ft^3 at 528^oR and 760 mm Hg = 16.33 gm/ft^3

co = 32.97 gm/ft^3

NO_x = 54.16 gm/ft^3 assuming NO_x is NO_2

V_{mix} = total dilute wet exhaust volume in ft^3/mile corrected to 528^oR and 760 mm Hg

KH = experimentally determined humidity correction factor for NO_x

$$= \frac{1}{1-0.0047(H-75)}; \qquad H = \text{grains of water/lbm dry air}$$

Now,

$$V_{mix} = K_1 (V_o)(N)\left(\frac{P}{T}\right)_p$$

where

$$K_1 = \frac{528^{\circ}R}{760 \text{ mm of HgX}7.5 \text{ miles}} = 0.09263$$

V_o = volume pumped per one revolution of pump

P_p, T° = pressure and temperature of dilute exhaust entering pump

N^P = number of revolutions of the pump per 7.5 mile test

Bags should be collected and analyzed as quickly as possible preferably within ten minutes after the test because reactions such as those between NO, NO_2 and HC can occur within the bag quite possibly and can change the test results.

CVS-3 System: The CVS-3 system is identical to the CVS-1 system except that three exhaust sample bags are used as shown in Fig. 4.12. The normal test is run from a cold start just like the CVS-1 test. After deceleration ends at 505 secs the diluted exhaust flow is switched from the transient bag to the stabilized bag and revolution counter no. 1 is switched off and no. 2 is activated. The transient bag is analyzed immediately. The rest of the test is completely in the normal fashion and the stabilized bag analyzed. However, in the CVS-3 test ten min after the test ends the cycle is begun again and run until the end of deceleration at 505 sec. This second run is termed the hot start run. A fresh bag collects what is termed as the hot transient sample. It is assumed that the second half of the hot start run is the same as the second half of the cold start run and is not repeated. In all three exhaust sample bags are collected. An ambient air sample bag is also filled simultaneously.

Calculations of Emission Results:

Compound Y may be hydrocarbons, carbon monoxide, or oxides of nitrogen.

$$Y_{w\,m} = (0.43\,Y_{et} + 0.57Y_{ht} + Y_s)/7.5$$

where

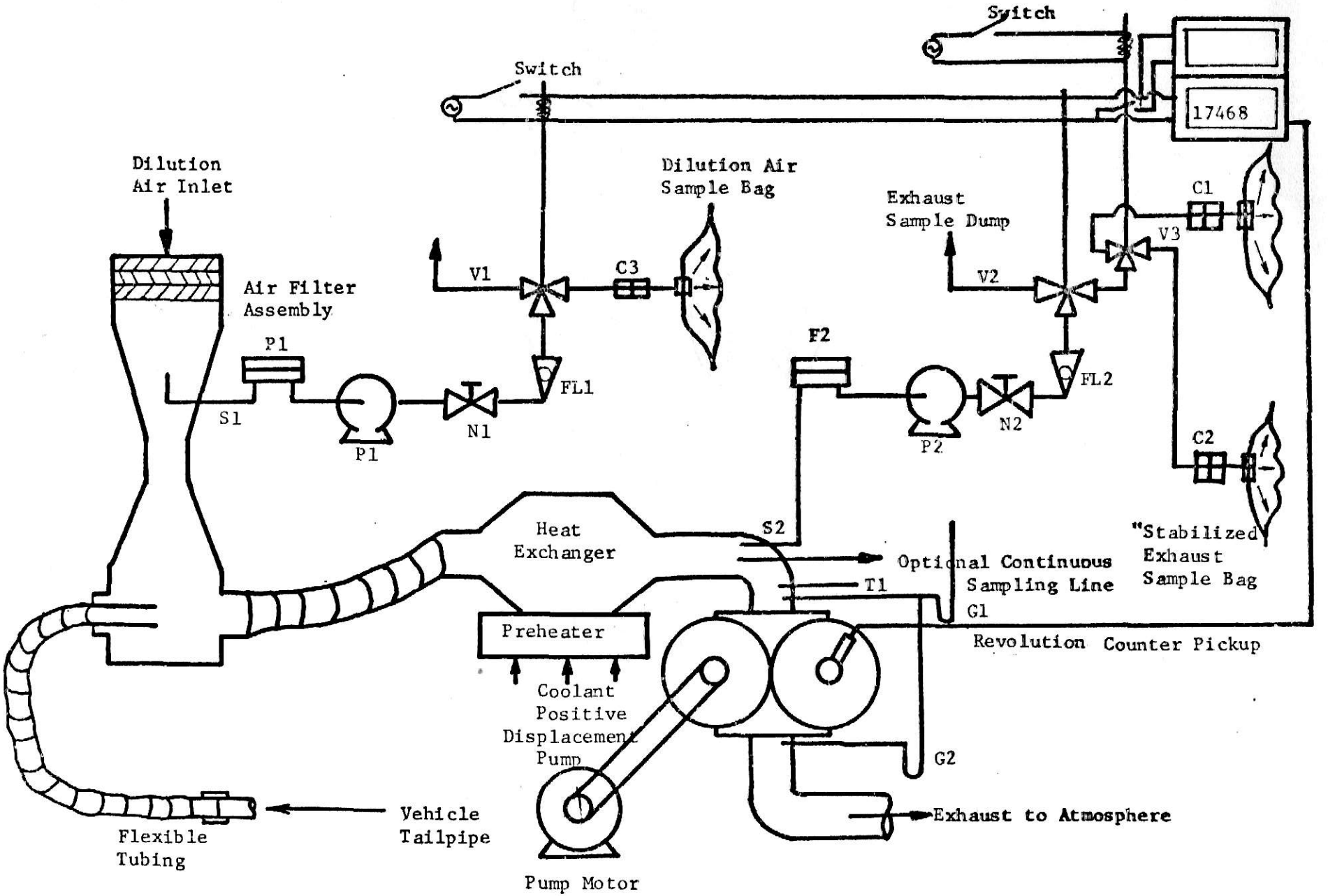


Fig. 4.12 CVS-3 System as Specified in Federal Register. This Differs from CVS-1 in that Two Sample Bag Attachments are Provided. (Fig. 2a, Ref [22]).

$Y_{w\,m}$ = Weighted mass emissions of each pollutant, ie HC, CO or NO_x in gm/mile.

Y_{et} = Mass emissions as calculated from the transient phase of the cold start, test, in gm/test phase.

Y_{ht} = Mass emissions as calculated from the transient phase of the hot start test, in gm/test phase.

Y_s = Mass emissions as calculated from the stabilized phase of the cold start test, in gm/test phase.

The mass emission of each pollutant for each phase of both the cold start test and the hot start test, is determined from the following:

(1) Hydrocarbon Mass:

$$HC_{mass} = V_{mix} \times Density_{HC} \times \frac{HC_{conc}}{1{,}000{,}000}$$

(2) Oxides of nitrogen Mass:

$$NO_{x\ mass} = V_{mix} \times Density_{NO_2} \times \frac{NO_{x\ conc}}{1{,}000{,}000} \times K_H$$

(3) Carbon monoxide Mass:

$$CO_{mass} = V_{mix} \times Density_{co} \times \frac{CO_{conc}}{1{,}000{,}000}$$

Meaning of symbols

HC_{mass} = Hydrocarbon emissions, in grams per test phase.

$Density_{HC}$ = Density of hydrocarbons in the exhaust gas, assuming an average carbon to hydrogen ratio of 1:1.85 in grams per cubic foot at $68^{o}F$ and 760 mm Hg pressure.

HC_{conc} = Hydrocarbon concentration of the dilute exhaust sample corrected for background, in ppm carbon equivalent, ie equivalent propane X 3.

$HC_{conc} = HC_e - HC_d(1-1/DF)$

where:

HC_e = Hydrocarbon concentration of the dilute exhaust sample as measured in ppm carbon equivalent.

HC_d = Hydrocarbon concentration of the dilution air as measured, in ppm carbon equivalent.

$NO_{x\ mass}$ = Oxides of nitrogen (density) in grams per test phase.

$Density_{NO_2}$ = Density of oxides of nitrogen in the exhaust gas, assuming they are in the form of nitrogen dioxide, in grams/cu ft. at 68°F and 760 mm of Hg pressure.

$NO_{x\ conc}$ = Oxides of nitrogen concentration of the dilute exhaust sample corrected for background, in ppm.

$$NO_{x\ conc} = NO_{x\ e} - NO_{xd}(1-1/DF)$$

where:

NO_{xe} = Oxides of nitrogen concentration of the dilute exhaust sample as measured in ppm.

NO_{xd} = Oxides of nitrogen concentration of the dilution air as measured in ppm.

CO_{mass} = Carbon monoxide emissions, in grams per test phase.

$Density_{co}$ = Density of carbon monoxide in gm/cu ft at 68°F and 760 mm Hg.

CO_{conc} = Carbon monoxide conc of the dilute exhaust sample corrected for background, water vapor and CO_2 extraction, in ppm.

$$CO_{conc} = CO_e - CO_d(1-1/DF)$$

where:

CO_e = Carbon monoxide conc. of the dilute exhaust sample volume corrected for water vapor and carbon dioxide extraction, in ppm. The calculation assumes the hydrogen-carbon ratio of the fuel is 1.85:1

$$CO_e(1-0.01925CO_{2e}-0.000323\ R)CO_{d_m}$$

where:

CO_{em} = Carbon monoxide conc. of the dilute exhaust sample as measured in ppm.

CO_{2e} = Carbon dioxide conc. of the dilute exhaust sample, in mole %

R = Relative humidity of the dilution air, in percent.

CO_d = Carbon monoxide conc. of the dilution air corrected for water vapor extraction, in ppm.

$$CO_d = (1-0.000323\ R)\ CO_{dm}$$

where:

CO_{dm} = Carbon monoxide conc. of the dilution air sample as measured in ppm.

$$DF = \frac{13.4}{CO_{2e} + (HC_e + CO_e)\ X_{10}{}^{-4}}$$

V_{mix} = Total dilute exhaust volume in cubic feet per test phase corrected to standard conditions (528° R and 760 mm Hg.)

$$V_{mix} = V_o\ X\ N(P_p/760\ \text{mm Hg})\ (528^{\circ}\ R/T_p)$$

where:

V_o = Volume of gas pumped by positive displacement pump, in cubic feet per revolution. This volume is dependent on the pressure differential across the positive displacement pump.

N = Number of revolutions of the pump during the test

P_p = Absolute pressure of the dilute exhaust gas

T_p = Average temperature of the dilute exhaust entering positive displacement pump., in ^{0}R.

K_H = Humidity correction factor

$$K_H = \frac{1}{1-0.0047\ (H-75)}$$

where:

H = Absolute humidity in grains of water per pound of dry air.

CHAPTER 5

THE EFFECTS OF AIR POLLUTION

Damage of Health

Of all air pollution effects, damage to health is undoubtly the foremost one. Air is necessary for the survival of man. Air is life supporting but it could also be life damaging if the balance between its important constituents, oxygen, nitrogen, and carbon dioxide is sufficiently disturbed or if sufficient amounts of contaminants are present. At some concentration in air any gas or aerosol will damage health, if through no other means than dilution of oxygen. The specific concentration at which a contaminant will damage health depends on how the word health is defined, the nature of the pollutant, the length of the time the contaminated air is breathed, and the state of health of the receptor.

General Effects of Pollutants on Human Physiological System:

The air pollutants can be inhaled through the respiratory system where they can enter the body blood chemistry, through ingestion by mouth, resulting in gastrointestinal absorption, by absorption through the skin where it can also enter into the body blood chemistry. Once in the blood the pollutants may be absorbed by body tissues or may be deposited in the body organs. The most susceptible organs are the liver, kidneys, lungs, heart and brain [8].

Superficial irritation by pollutants of the skin, eyes, and the respiratory system may occur immediately upon contact with the pollutant. The damage also may be more extensive and not become evidenced for a relatively long period of time. Phenol, for example, irritates the skin. However, it is also absorbed into the blood stream and destroys body tissues. Absorption of sufficient amounts causes death in a few minutes. Beryllium oxide on the other hand, may become deposited in the lungs and remain there for years before damage is noticed. During this time, the beryllium oxide irritates the surfaces contacted by mechanical abrasion.

It is often possible for the body to clean itself by the normal elimination process and thereby eliminate the pollutants or the reaction products from the pollutants. The damaged tissues and organs then may

recover from the pollution damage. Organs such as the liver, which purify other parts of the body, can become poisoned themselves during the clean up operations.

It is also possible for the pollutants to damage the body by only temporarily displacing some other substances. Bonoxia, which is death from lack of oxygen, can be caused by the presence of excessive amounts of simple asphyxiants, such as carbon dioxide, in air. When this happens the lack of oxygen destroys brain cells and slows down the central nervous system.

One of the most disastrous effect of pollutants is via the respiratory system, and to understand this one has to have a basis of the anatomy and physiology of the lungs.

Anatomy: Breathing takes place through either the nose or mouth. The nose contains tortuous channels which allow the inspired air to be exposed to a maximum surface area, Fig. 5.1 [9]. These channels warm and moisten the air, and highly soluble substances are prevented from entering the deeper lung structures when inhalation occurs through the nose. The nasopharynx connects the nose with the pharynx which in turn ends in the larynx. Below the larynx, the airway continues via a single tube, the trachea. Inside the chest, the trachea subdivides into progressively branching tubes of decreasing size. As a consequence of the increasing number of branches, there is an increase in cross sectional area, so that inflowing air decreases its velocity when it reaches the very small airways. As a consequence of changing dimensions of the airways, most of the resistance to airflow is normally located in airways whose diameters are approximately 3-7 mm in diameter. The airways are designed to distribute the air as uniformly as possible to the many millions of minute air sacs called alveoli where gas exchange occurs. The airways are designed to minimize the volume of the conducting tubes (which do not participate in gas exchange) but at the same time not so small that the resistance to airflow is excessive (this would increase the work of breathing). The airways are lined by cells called epithelial cells. These cells contain various elements designed to protect the lungs from trauma. These elements vary in different depth of the lungs: the larger airways contain goblet cells which secrete

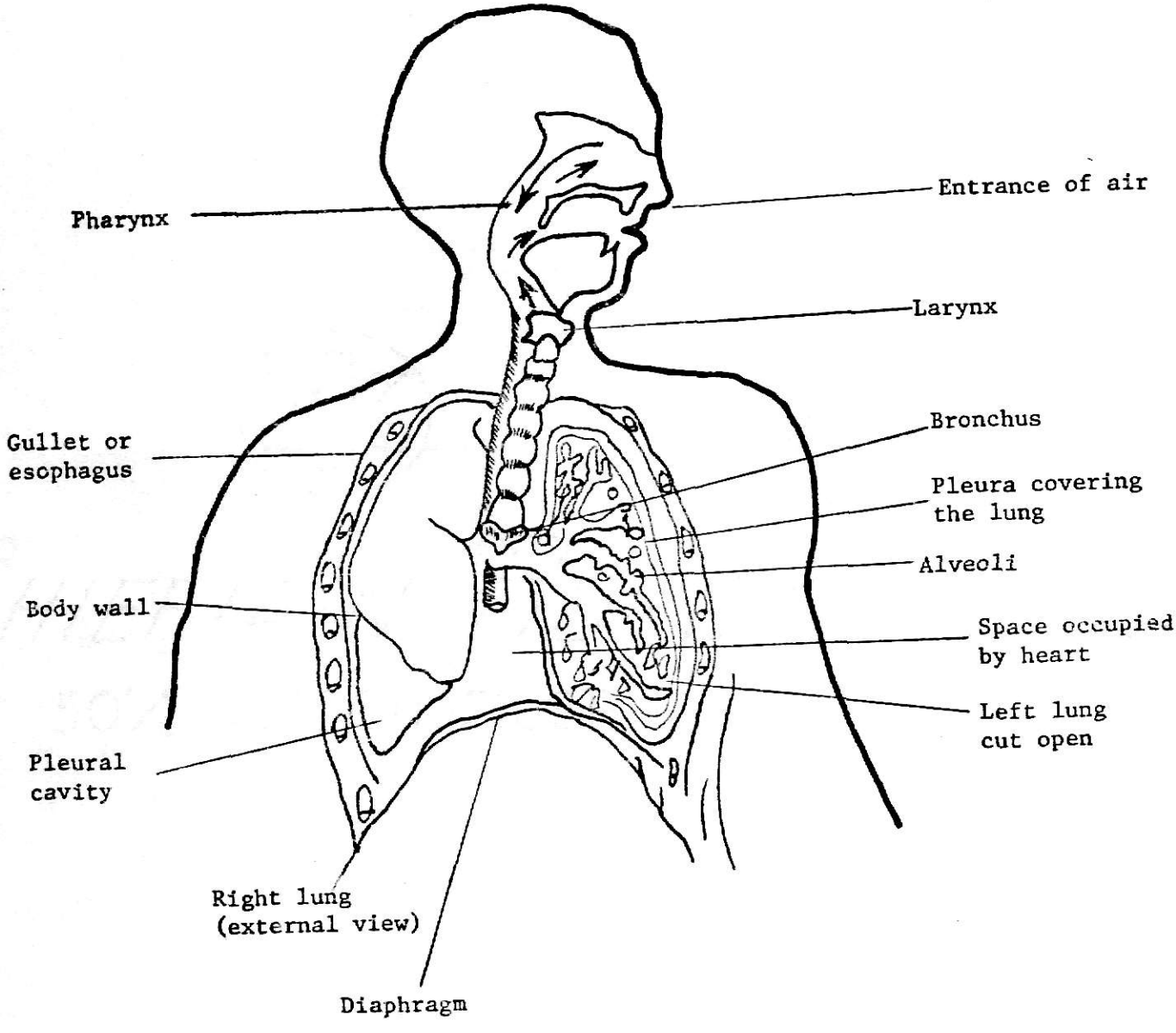


*Fig. 5.1 The human respiratory system.

*Fig. 14.1, Ref. [1].

mucus, which coats the airways. In disease, these mucus-producing cells sometimes becomes enlarged and produce an abnormal amount of mucus which plugs the airways. On the tips of the epithelial cells are cilia, fine hairlike structures which sweep rythmically, pushing material on the surface of the airways toward the nasopharynx where they can be eliminated; cilia exists in airways at all levels, and assist the cough mechanisim in cleaning the airways. Some noxious materials paralyze the cilia thus allowing the accumulation of the mucus and other materials which deposit on the surface of the airways to accumulate.

The airways contain nerve endings which are close to the surface of the airways and which respond to mechanical or chemical irritation. Simulation of these nerve endings results in cough, a reflex which protects the organs by propelling materials out of the airways. Cough is efficient in removing materials only from the large conducting airways where the velocity of flow is sufficient; in small airways, airflow is slow and forces are insufficient to shear foreign materials from their walls, so only ciliary activity functions at these levels to remove foreign materials.

The walls of the airways contain smooth muscle which has the capacity of contacting and thus narrowing the diameter of the airway. Contraction of the smooth muscle increases the resistance to airflow and increases the work of breathing; in some diseases, this smooth muscle contraction may be severe (e.g, asthama) and lead to marked dysfuction of the respiratory apparatus. The airway smooth muscle may contract due to direct simulation or indirectly via reflexes.

The airways ends in minute air sacs called alveoli. Inspired gas is carried into the alveoli during inspiration where it comes into close contact with the blood which flows through the pulmonary circulation; the blood travels into the lungs via two large pulmonary arteries which divide into progressively smaller vessels until they form minute capillaries which have thin walls and are in intimate contact with the alveolt. Thus, gas exchange occurs at the level of the alveolar-capillary membrane, where the distance for diffusion is small (less than 0.1 micron thick) and O_2 can move into the blood and CO_2 can be removed from the blood. There are about 300 million alveoli, which are so designed to provide a

vast and extremely thin surface for the transfer of gases between air and blood. The blood tubes are also designed to allow a large area for gas exchange but at the same time to minimize the resistance to blood flow.

The alveoli act like bubbles which expand during inspiration and contact during expiration. They are lined by a thin layer of a material called surfactant which lowers surface tension and allows the small alveoli to remain open even when the alveoli become small (e.g, during expiration). When this surfactant is destroyed or inactivated, the lungs tend to collapse. Certain toxic materials which reach the alveoli may injure the lungs by interfering with normal surface activity.

Mobile cells, called marcrophanges, engulf and carry away insoluble particulates which deposit deep in the lung spaces. The purpose of this process is to prevent these particles from injuring the alveor epithelium and to facilitate removal of the particles. However, certain dusts may be injurious to the phagocytic cells and ultimately cause their death, and this may interfere with normal clearance mechanism.

Effects of air pollutants on human respiratory system:

1. LUNGS: The effects of inhaled substances on the lungs depends to a large extent on the physiocochemical characteristics of the material: when gaseous materials are inhaled, the site of their effects depends greatly on the solubility of the gas [9]. SO_2 is highly soluble and is removed from inspired air in the large conducting airways, so that very little of the material reaches the distal airways and alveoli. Nitrogen dioxide, on the other hand, is less soluble and reaches the tiny airways and alveoli where it causes its damage. When particulates are inhaled, the size and other physical characteristics of the particles determines the site of deposition (and thus the site of primary action).

2. AIRWAYS: Sulfur dioxide is the model of the substance which has its major effect on the airways. When SO_2 is inhaled, its concentration decreases rapidly, so that almost no SO_2 penetrates lower than the larynx. In low concentrations (2-5 ppm) inhalation of SO_2 constricts the lower airways by stimulating receptors in the large airways. These receptors fire electrical signals which are transmitted to the central nervous

system and thence back to the airways smooth muscle via another nerve called the vagus. This reflex contraction of the airway smooth muscle narrows the airways. In higher concentrations, the airway narrowing becomes more severe and may hamper ventilation. SO_2 causes constriction in doses which may be too small to be detectable by the subject (i.e, by taste or smell). The airway constriction can be prevented by administration of drugs which paralyze the smooth muscle prevent it from contracting.

Airways may also narrow the airways by causing swelling of the membranes lining the airways, by enlargement of the glands which produce mucus, or by plugging the airways by mucus after it has been discharged from the mucus glands, by direct action of the irritation on the airway smooth muscle.

Alveoli and Lung Tissue: i Acute effects: Materials which reach the alveoli may injure the lining epithelial cells, the capillaries or may interfere with the alveolar surfactant. As a result of this, the alveoli may collapse or may become filled with so called edema fluid; these damaged alveoli may not ventilate properly and inspired air may not reach the appropriate lung capillaries, causing serious physiological consequences.

ii Chronic effects: Recurrent injury to lung tissue may result in the production of scar tissue which contracts and also interferes with proper gas exchange. Some inhaled materials have no serious acute effects when inhaled, but they are deposited in lung tissue and remain there, (ie., silica). After many years, the silica particles stimulate a reaction of the lung tissue, and progressive scarring of the lung occurs.

iii Patients with lung diseases: Some patients with obstructive airway diseases (e.g., asthama and bronchitis) react to inhaled irritants such as sulfur dioxide by constricting their airways and by coughing at a dose of the irritants which would be expected to have no effect on healthy individuals. In addition, further narrowing of airways can result by inhaled irritants in patients who already have more serious consequences than it would have in healthy individuals.

Effects of Specific Pollutants

In this section the effects of specific pollutants will be discussed and the air quality standards will also be quoted for individual pollutants.

Carbon monoxide:

Air quality standard $\mu g/m^3$

(National Air Pollution Control Administration, Department of Health Education and Welfare).

	Primary (human health)	Secondary (all other effects)
8-hour max	10,000	10,000
1-hour max	40,000	40,000

When considered as a pollutant, it is the second most abundant atmospheric pollutant in urban atmosphere (the first being carbon dioxide) [8]) Carbon monoxide is not toxic in itself and is non-cumulative. The dangers with carbon monoxide occur because of the strong affinity the hemoglobin has for carbon monoxide (about 300 times that for oxygen). This causes oxygen to leave the tissues resulting in anoxicity. The effects are headaches, loss of visual acuity and decreased muscular cordination.

Normal blood contains about 20 cc of oxygen per 100 milliliters of blood and there are about 5000 milliliters of blood in the body. As the carbon monoxide replaces the oxygen on the blood hemoglobin, this is called saturating the blood. Oxygen capacity of the hemoglobin is slightly over 20 ml 0/100 ml blood. The following calculation is for 50% saturation:

$$(5{,}000 \text{ ml blood}) \frac{20 \text{ ml gas}}{100 \text{ ml blood}} \quad (0.50) = 500 \text{ ml gas}$$

This shows that 500 ml of carbon monoxide gas taken into the blood would result in 50% saturation of the blood. If air contained 700 ppm carbon monoxide, then:

$$(500 \text{ ml}) \qquad \frac{10^6 \text{ parts air}}{700 \text{ parts CO}} = 700 \text{ liters}$$

Therefore, 700 liters of air must be inhaled with this CO concentration

and if all the CO remains in the blood, it will cause a 50% saturated condition. If the alveolar ventilation rate is 3.5 liters per minute, the time required to reach 50% saturation is found by dividing the 700 liters by 3.5 liter per minute, giving a value a little less than 200 minutes. The actual degree of saturation depends upon the original carbon monoxide saturation in the blood as well as the concentration of CO in air and the exposure time. A concentration of 100 ppm may or may not be safe depending on the individual, the length of time of exposure and the individual burden. People exposed to high concentration of CO by smoking (there is up to 40,000 ppm CO in cigarette smoke) are already burdened by an initial saturation of as much as 15%. 1000 ppm would normally cause immediate death after a short, continuous exposure. Table 4.1 shows the nervous system effects due to carbon monoxide as expressed in percent saturation.

TABLE 5.1*

Typical Central Nervous System Effects Due to CO expressed in % saturation [8]

Effects	Short Exposure	Long Exposure
None	0-10	0-10
Slight Headache	10-20	10-20
Collapse, coma, brain damage, death	40-50	30-40

Hydrocarbons: These are a vast number of different compounds containing carbon and hydrogen [8]. Some hydrocarbons such as methane and acetylene, are simply asphyxiants and dilute the air by removing oxygen to a level which is not adequate to support life (similar to CO_2). Methane typically exists in urban air at concentrations of about 9 ppm. Other hydrocarbons, such as anthracene, are nontoxic but are carcinogenic and produce cancers because of the impurities they contain organic compounds which are derived from hydrocarbons, such as phenol, can quickly poison the body by effecting the central nervous system. These pollutants may be either inhaled or absorbed through the skin. Absorption of phenol has caused death in as short a time as thirty minutes. Prolonged breathing of these types of compounds causes digestive disturbances, difficulty in swalling, excessive salivation, nervous disorders and skin eruptions.

With these few examples of hydrocarbons and their effects, it is readily obvious why concentration of hydrocarbons in the air should be low.

The following figures show the National Air Quality Standards for Hydrocarbons. (National Air Pollution Control Association) [11].

	$\mu g/m^3$
3-hour max (6-9 A.M.)	160 (Primary, human health)
	160 (Secondary, all other effects)

Oxides of Nitrogen

	Air quality standard, $\mu g/m^3$ [12]
Annual arithmetic mean	100 (Primary, human health)
	100 (Secondary, all other effects)

These effect the body by irritating the nose, eyes, and the lungs. Nitrogen dioxide can be smelled at 3 ppm. From short time exposures: nose and eye irritation begins at 10 ppm; chest discomfort is noticed at concentrations of 25 ppm; focal pneumonitis occurs when the concentration is from 50- 100 ppm, and death occurs when the concentration is greater than 500 ppm. Nitrogen dioxide is suspected of accelerating tumor growth and decreasing the resistance of the body to diseases.

Sulfur Dioxide: SO_2 appears to damage man by increasing the hear rate, lowering the tidal volume, decreasing the mucus flow, increasing eye blinking and is also thought to effect the central nervous system [8]. Like many other pollutants, sulfur dioxide affects young and old people and those with respiratory problems more so than healthy individuals. Also it is more detrimental when combined with particulates than in clean air containing only the sulfur dioxide pollutant. Larsen presents the following equation relating deaths and the combined effects of SO_2 and particulates

$$D = 0.65\ SP$$

where D is the number of excess deaths during an air pollution episode and S and P are conc. of SO_2 in ppm and suspended particles in $\mu g/m^3$. The equation was derived from regression analyses of the episode data from London and New York City.

Sulfur dioxide odor is noticed at 3 ppm. From short time exposure, bronchial constriction is observed at 5 ppm, mucus flow increases at about 11 ppm the upper respiratory system becomes irritated at 20 ppm and the ciliary movement decreases at 25 ppm.

Air quality standard $\mu g/m^3$ [13]

	Primary (human health)	Secondary (all other effects)
Annual arithmetic mean	80	60
20-hour max	365	260
3-hour max	-	1,300

Particulate matter: a detailed survey of the effects of all the particulates is beyond the scope of this report, hence only lead, which is the most commonly found particulate in the auto exhaust will be discussed here.

Lead: This includes lead, the lead oxides (PbO, Pb_2O_3 and Pb_3O_4), as well as lead salts (PbClBr and $PbNH_2Cl$) which originate from auto exhaust. Lead is a cumulative poison. It damages the nerves causing deadening of the nerve sense receptors. A burning feeling of the feet is noticed in cases of lead poisoning. It also causes anemia which is a deficiency of red blood cells and therefore prevents absorption of vitamin B_{12} resulting in malnutrition. Lead poisoning also causes bleeding. Probably no other chemical has a greater compilation of toxilogical literature than does lead.

Lead compounds can be inhaled; this makes it extremely important that the tetraethyl lead and tetramethyl lead additives in gasoline should be removed to prevent air pollution of lead due to auto exhaust. Lead can be absorbed through the skin and by ingestion. Air pollution deposited on plants can be eaten by foraging animals which can in turn be eaten by man resulting in lead poisoning to man. Man can also directly eat lead poisoned plants. Other foods that can contain lead include water and beverages.

An annual geometric mean of 1.0 microgram per cubic meter of elemental lead is suggested.

Air quality standard for particulates ($\mu g/m^3$) [14].

	Primary (human health)	Secondary (all other effects)
Annual geometric mean	75	60
24-hour max	260	150

We will end this section by quoting the three common means which have been used in the past and can be used for future research.

The three means are,

1. Experimental exposures of man and animals:-

While exposures of men must be of necessity be limited to concentrations and dosages of pollutants that will not result in serious illness, experimentation on animals under controlled conditions can yield valuable information as to mode of action of a pollutant the dependence of effects on other variables, and cumulative effects over several generations. For example experiments were carried by Tomson, Hacatrjan and others in the USSR on the accumulation of lead in white rats exposed for 3-5 months at various distances ranging from 300m to 40 Km from industrial sources of atmospheric polluation with lead.

Tomson kept white rats for 5 months in polluted air at a distance of 300 m from the source [4]. The air where the experimental animals were kept was found to contain upto 0.02 mg/m^3 of lead. The lead content of the bodies of the experimental animals was determined by spectrum analysis of the various tissues and organs and compared with that for the controls which have been kept in clean air outside the town.

The results are as follows.

TABLE 5.2*

Lead content (mg/100g)

	Controls	Experimental animals
bone	1.21	9.55
liver	0.87	2.30
skin	0.18	1.36
muscle	0.08	1.23
lungs	0.12	1.15
testicles	0.09	0.75
heart	0.06	0.68

*Table 6, Ref. [4].

The table clearly shows that lead had accumulated in the organs of animals exposed to a lead content atmosphere of 0.02 mg/m^3. Similar work was done by Zykova who studied cats that had lived 2-7 years at a distance of 100-200 meters from another source. Table 4.3 provides the summary of his results.

TABLE 5.3*

Lead content mg/Kg

Exposed cats	Age of cat (years)	tibia	femur	brain	kidney	liver
A	2	120	200	300	65	175
B	3	180	260	400	125	90
C	4	1000	880	140	120	-
D	7	2000	1640	200	70	150
Control cats	4	20	10	0	30	70

However, it should be bore in mind that problems arise when relating effects on test animals to that on man. The animals may have no diaphrams, may have different heart beat rate, body temperature, type of blood flow and feather or dense hair covering.

Besides the animals already cited, bees, Japanese quail, guniea pigs and dogs are also sometimes used as experimental animals.

2. Clinical Studies: Clinical studies predominantly involve observations made on subjects who are, or were exposed to atmospheric pollutants under uncontrolled conditions [15]. Thus patients visiting physicians to complain of symptoms supposedly caused by living in polluted areas may upon observation yield clinical data of importance. Studies of downtown traffic police truck drivers and other occupational groups may yield valuable information.

In addition to the standard medical clinics, special clinics are frequently set up for pollution studies, examples are a submarine room atmosphere used to examine children, and automotive smog chamber to study eye irritation.

3. Epidemiological Studies: Epidemiology is the study of the factors involved in the distribution of a disease process in a given population. In terms of air pollution these studies analyze the effects from ambient

*Table 7, Ref. [4].

exposures on groups of people actually living in the community. However there are a number of difficulties involved in such studies. It should be bore in mind that;

i) There are a very large number of variables in large population studies for example, smoking habits, socioeconomic levels, population density, local climate, ethinic background of the population (certain groups have high susceptibility to certain diseases). Before air pollution can be cited as the cause of health effects the interactions of these other variables must be investigated.

ii) Different pollutants may cause similar effects yet it is difficult to get large populations exposed to individuals pollutants. Furthermore, the concentrations of different pollutants do not necessarily follow the same function of time during the day, month or year.

As an example of an epidemiological study we quote here the analyses done by Winkelstein et al (1967, 1968, 1969) in Buffalo and Erie county, New York [1]. They measured suspended particulates, dust fall, and oxides of sulfur. Four levels of pollution were established for particulates as 1 less than 80 $\mu g/m^3$ (two year average). Level 2, 80-100 $\mu g/m^3$. Level 3, 100-135 $\mu g/m^3$ and level 4, 135 $\mu g/m^3$. Each area was also fitted into five different economic classes based on income. Conclusion from the study are noted in the following three figures. (Fig. 5.2-5.4).

Average annual death rate from the following listed causes. The graphs show the death rate per 1,000 population for white males between 50 and 69 years of age for four levels of particulate matter.

Damage to plants

Plants are very useful indicators for pollutants and are often the first evidence that an air pollution problem is developing. The pollutants often produce characteristic marking on given plant species thus providing a means of pollutant identification. Vegetation first indicated a new problem in Los Angeles in 1945 which we now recognize as photo chemical air pollution. Vegetation surveys made at regular intervals revealed the gradual spread of pollution in the Los Angeles basin as well

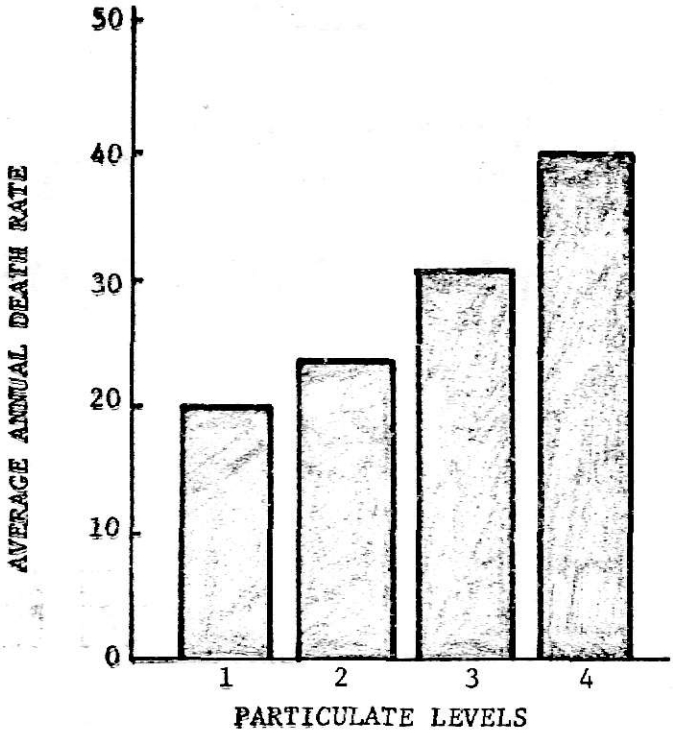


Fig. 5.2 Average annual death rate from all causes. (Fig. 14.8, Ref. 1)

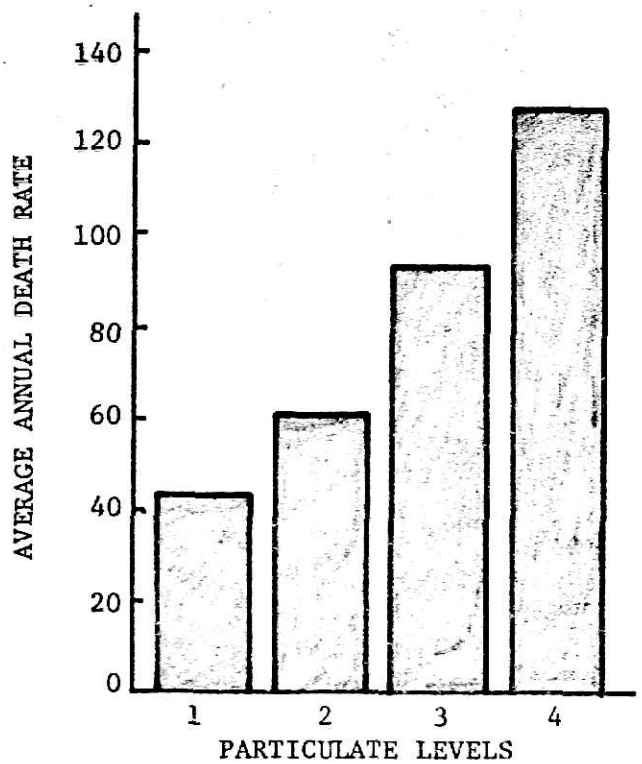


Fig. 5.3 Average annual death rate from asthma, bronchitis, or emphysema indicated on the death certificate. (Fig. 14.9, Ref. 1)

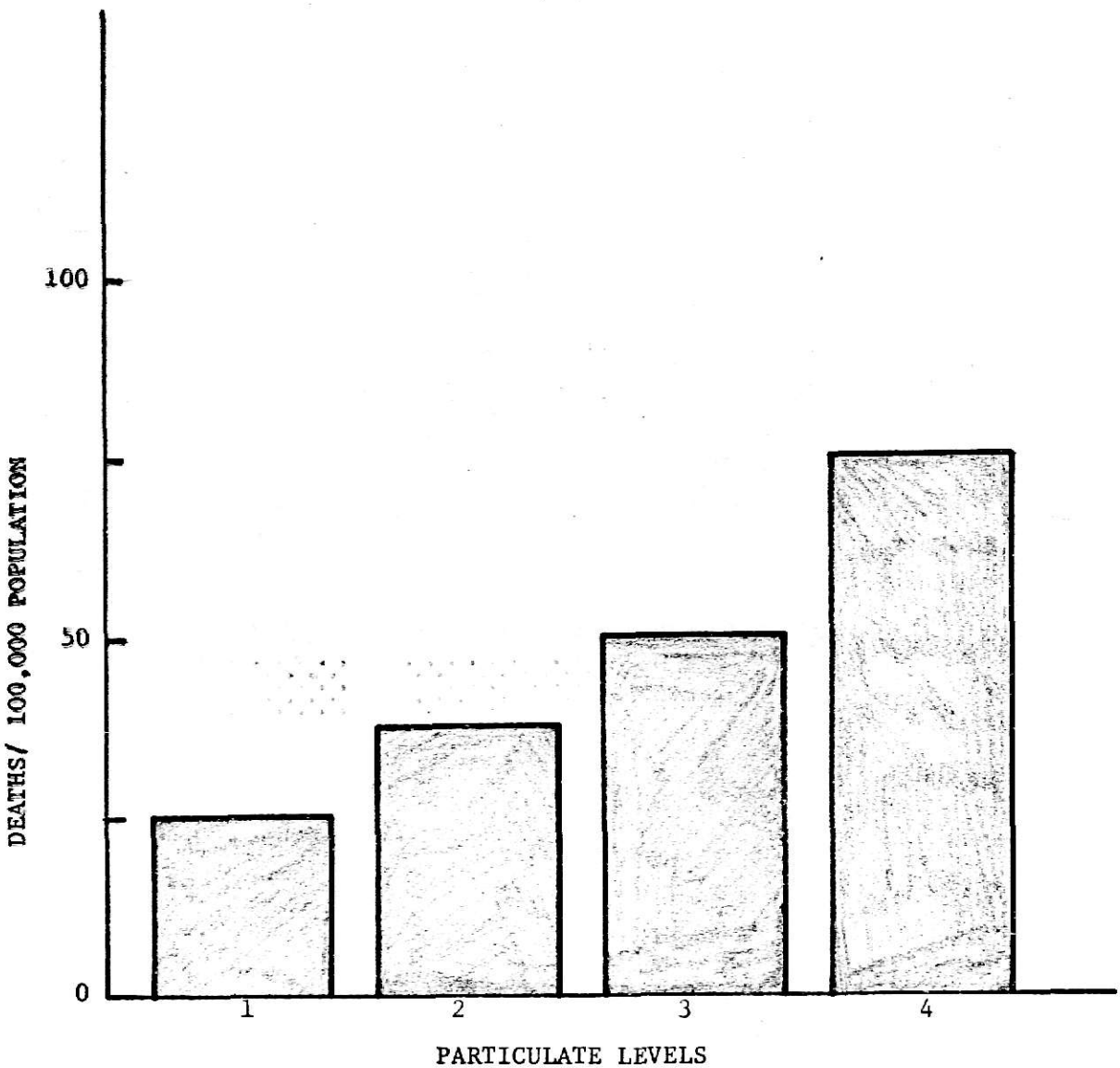


Fig. 5.4 Average annual death rate from gastric cancer. (Fig. 14.10, Ref. 1).

as its occurance in principle population centers of the state. Similarly, vegetation damage proved to be the first evidence that a photochemical pollution problem was developing in Denver in 1953, and along the east coast in 1956 and 1957. Additional surveys by competent observers now indicates that the problem is present in some 31 other states in the union.

The severity of the injury varies with the pollutant, the concentration, duration of exposure and plant species. Generally two types of visible injury may be noted: (1) Acute injury in which markings on the leaves of susceptible plants are quite characteristic and may result in death of cells or tissues. Such injury occurs when the rate of absorption of gas exceeds capacity of tissues to oxidize, reduce, respire, or translocate the pollutant. (2) Chronic injury which is usually not characteristic wherein there is a chlorisis or yellowing of leaf tissue and usually no death of cells.

A third and not very visible effect of pollution on plants, is suppression of growth. This occurs when the plant does not grow as well or yield as much product of good quality. Growth suppression in the absence of visible symptoms occurs when the rate of absorption of the gas is such as to result in alterations in photosynthesis and respiration, interference with enzyme activity, and changes in cell wall permeability.
Modes of Pollution Attack: - Gases usually enter plants through the stomata on the leaves or stems, however, they can become dissolved in water on the leaves or enter through the roots from the soil. Gases are usually absorbed into the mesophyll area of the leaves (Fig. 5.5) [1]. Different species of plants vary considerably in their susceptibility to injury by gaseous pollutants, the difference being due to the different rates of absorption of the gas by leaves.

Factors which cause stomata to open more and adequate ground moisture and nutrients, high humidity, moderate temperatures, moderate sun intensity and increased CO_2 concentration. The stomata close when there is excessive sun intensity, high temperatures, dry conditions and darkness. Gaseous pollutants effects on plants vary depending on pollutant type, pollutant concentration, length of exposure and time of day of exposure.

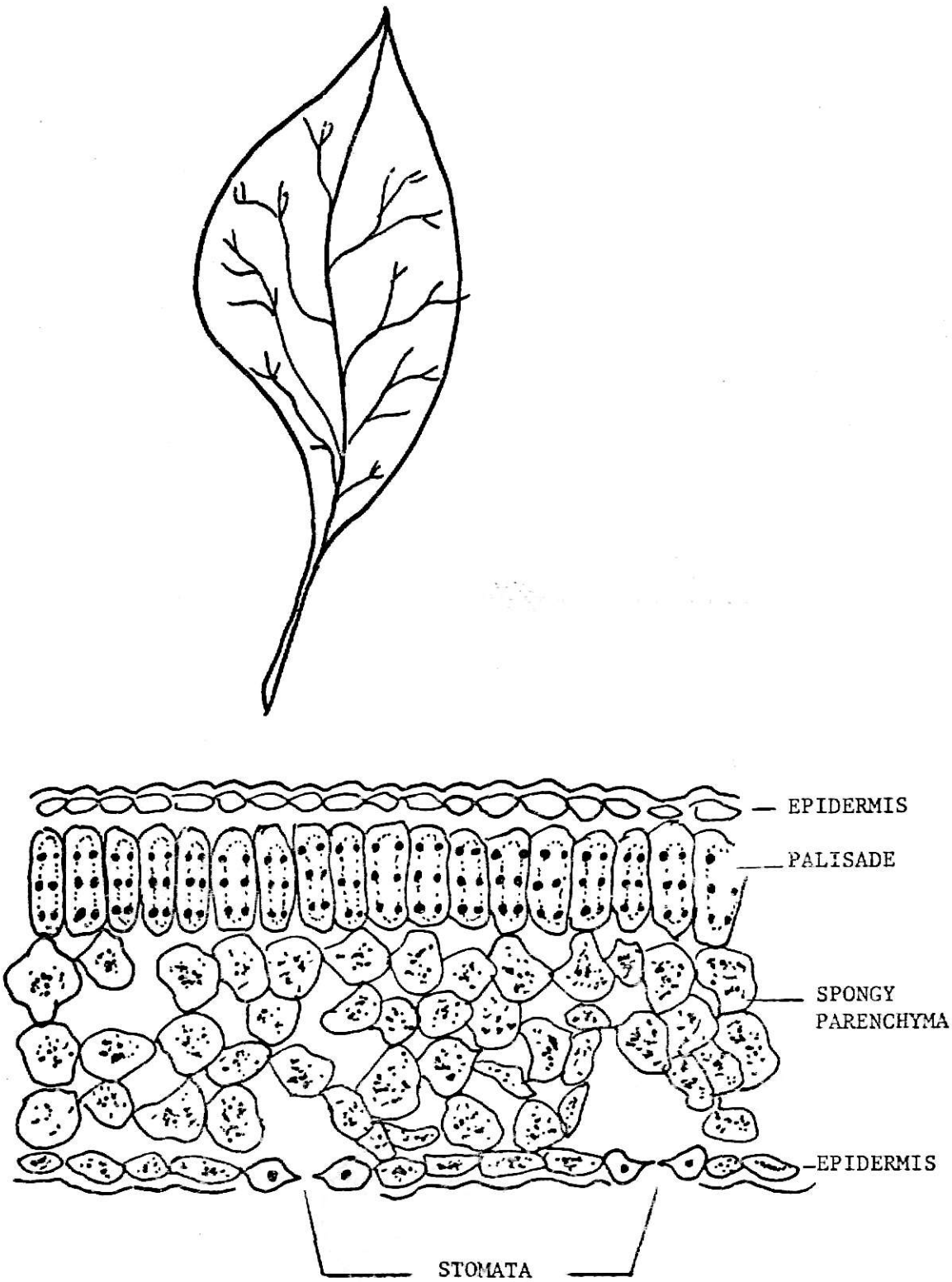


Fig. 5.5 A leaf and its internal tissue.

(Fig. 13.1, Ref. 1).

Particulate type air pollutants such as ash, dirt and grit, land on top of leaves. They do not enter the leaf but may damage it by mechanical abrasion of the surface of the leaf. Particualte matter can also block out sunlight and thereby reduce the foodmaking ability of the plant.

Air pollution damage to plants resulting from the pollution in a particular area is not confined to the immediate locale. Effect on trees, for instance, in California are noticed over eighty miles from the metropolitan region.

Very rough estimates of annual dollar losses from direct effects of air pollution in California have been assessed at from ten to twelve million dollars (1969) and from indirect losses at another $100 million. Most recently, the council on Environmental Quality, in its second annual report (1971) suggested a cost figure of 4.9 billion dollar due to damage of materials and vegetation.

On the following page the effects of specific pollutants is given in a tabular form (Table 5.4).

GLOBAL EFFECTS

One could define three major global effects from air pollution [1]. These are,

1. The green house effect.
2. The effect of particulates.
3. The effect of climate change from man's massive use and dissipation of energy.

Before going into a discussion of the above three effects, let us look into the trends in past temperature changes and the various phenomenon being discussed these days.

There has been a net warming change of $0.6^{\circ}C$ from 1880 to 1940 decade and a net cooling of $0.3^{\circ}C$ since then. The point here is that although such small incremental or decremental changes of temperature may be overlooked by a layman, however, to a metereologist these would be of big concern. Calculations by sellers show that a decrease of 5% in solar constant would be sufficient to start another ice age. This corresponds to a $4^{\circ}C$ temperature change, which means that temperature changes of $0.3-0.6^{\circ}C$ should be cautiously noted [16].

*TABLE 5.4

Pollutant	Dose	Effect	Specific Cases
Ozone	Mild	Flecks on upper surface, premature aging, suppressed growth.	0.06 ppm for 3-4 hr damages alfalfa, white pine. Ponderosa pine badly damaged in S. California.
	Severe	Collapse of leaf, necrosis and bleaching.	
PAN Peroxyacyl Nitrates	Mild	Bronzing of lower leaf surface and suppressed growth.	0.03 ppm acute damage to sensitive plants: spinach romaine lettuce, certain flowers.
SO_2	Mild	Interveinal chlorotic bleaching of leaves.	1 pp, of fumigation tims causes damage to alfalfa, cotton, barley. 0.3 to 0.5 ppm for several days on sensitive plants causes chronic injury.
	Severe	Necrosis interveinal areas and skeletonized leaves	
Ethylene	Mild	Epinasty, leaf abscission	0.1 ppm for several hours affected tomatoes and pepper plants. Flowers affected at 0.1 ppm, ie orchids, carnation after a few hours.
NO_2	Mild	Suppressed growth, leaf bleaching	0.5 ppm for 10-12 days suppressed growth on pinto beans and tomatoes. Navel orange yield greatly reduced at 0.25 ppm for 240 days 0.5-1 ppm for 35 days.
Flourides	Cumulative effect so 1 ppb can be significant	Necrosis at leaf tim	Gladioli, peaches, and grapes are particularly sensitive

*Table 13.1, Ref. [1].

The various phenomenon which could be discussed at this stage are,

i) The behaviour of CO_2 in causing a temperature rise in global temperature, as a result of gradual build up.

ii) The behaviour of particulate build up in decreasing the global temperature.

iii) Could certain feedback mechanisms be activated causing acute climate change.

a.) Ice has a high reflectivity for solar radiation. If temperature rise occurs and some of the ice cap melt, it would result in decreased reflectivity and hence a continued heating trend could result.

b.) The converse could also be true, with increased ice caps due to increasing reflectivity, hence a cooling trend.

c.) There is a CO_2 balance between the oceans and atmosphere. The solubility of CO_2 decreases with rising temperature, with increasing temperature more CO_2 would be ejected out of the oceans, causing even higher temperatures, and vice versa.

Now we will discuss the three major effects;

1. The Greenhouse Effect: We know that sun radiates as a black body at a temperature of $6000^{o}K$ (approximately) and the solar radiation is therefore concentrated in the ultra violet, visible, and near infrared wave length ranges.

According to Wein's law;

$$\lambda_{max} = 0.5 \text{ (for solar radiation)}$$

However, earth radiates with a temperature of $255^{o}K$ and consequently with a $\lambda_{max} = 11$ (approx).

Coming back to carbon dioxide, of the total amount of CO_2 generated thru various processes, half of it is absorbed by oceans and the remaining half dumped into the atmosphere. Since CO_2 is an absorber of radiation in the infrared, particularly in the range 12-18μ,it acts to put a lid on radiation from the earth to space. Incoming solar radiation is essentially uneffected. The net effect is of warming.

In the following table it is quite clear.

TABLE 5.5*

Change of CO_2 content (ppm)	Fixed absolute humidity		Fixed relative humidity	
	Average cloudiness	Clear	Average cloudiness	Clear
300-150	-1.25	-1.30	-2.28	-2.80
300-600	+1.33	+1.36	+2.36	+2.92

2. The Effect of Particulates: Particulates scatter and absorb both solar and terrestrial radiation. Thus they effect the heat balance of the earth. Furthermore they act as nuclei for the condensation of water vapor and thus play a role in cloud formation. The effect of pollutant particles on initiating and controlling precipitation is been discussed these days.

The particulates scatter the solar radiation in the forward as well as backward direction, the effect of backscatter is to increase the reflectivity of the atmosphere. Also particulates reduce the terrestrial radiation to space and absorb some solar radiation. Which effect is dominant depends upon the size, shape and composition of the particulates. The general belief these days is that the particulates have a cooling effect. However, it remains to be independently verified.

3. The Effect of Dissipation of Heat: Energy release occurs both through the evaporation of water vapor and the direct heating of the air. As, a result of this cities are usually warmer, rainier, and foggier than their nonurban surroundings.

We quote here an abstract of an article by Hanna and Swisher, [17]

"If the present global rate of increase in energy consumption-approximately 5% per annum -should persist for another century and half, man's dissipation then would be equal to 10% of the solar energy absorbed over the entire surface of the globe, or one third of the solar energy absorbed over the land. Simple calculations suggest a corresponding mean global temperature increase of about $13^{\circ}F$."

The present day energy consumption is 0.02 Kilo langley/year

*Table 2.2, Ref. [1].

(1 langley = 1 cal/cm^2) averaged over all continents: Increase of energy dissipation has been noted as 4% annually, which points to the fact that a stage could be approached when there could be so much energy dissipation that it could balance the incoming solar radiation, which would mean that the climate will primarily become a function of man's activity.

CHAPTER 6

CONTROLS

CRANK CASE EMISSION CONTROL

Since 1963, the emissions from crankcases of new automobiles have been essentially zero. Prior to that time, any gasoline or exhaust vapors that blew by the piston rings during the pistons rings during the compression stroke and into the crankcase where vaporized and emitted along with the oil droplets from the road draft tube into the atmosphere. Estimated value of hydrocarbon emission in this fashion was 3.15 g/mile.

In the basic blowby control system, the road draft tube is replaced by a tube leading to a flow modulating or positive crankcase ventilating valve which is connected to the intake manifold below the carburetor [18]. The intake manifold vacuum draws the blowby gases and crankcase ventilation air (from the air cleaner) into the engine induction system. The control valve is spring loaded against manifold vacuum, so that the flow increases as the manifold vacuum decreases. Maximum flow occurs at low vacuum, high speed high power engine conditions.

A typical system is shown in the Figure 6.1. Such systems incorporate an orifice to restrict flow in the intake manifold connection so that almost all emissions are drawn through this route at speeds upto about 35 mph. at road load. Above this value air cleaner suction takes effect ensuring adequate ventilation under all conditions.

This system depends on the operation of the ventilation valve for automatic metering of gas flow from crankcase to inlet manifold. A typical design is shown in the Figure 6.2. Such a valve incorporates a fixed orifice at highest vacuum while a variable area orifice (annulus) is additionally provided by spring action when manifold vacuum falls. Furthermore, such a valve must serve as an antibackfire valve isolating the crankcase immediately when a pressure wave arises.

A later design (shown in the Figure 6.3) incorporates a self cleaning plunger to avoid clogging the ventilation tube. Such valves were found to provide satisfactory flow characteristics while maintaining adequate crankcase ventilation at all driving modes.

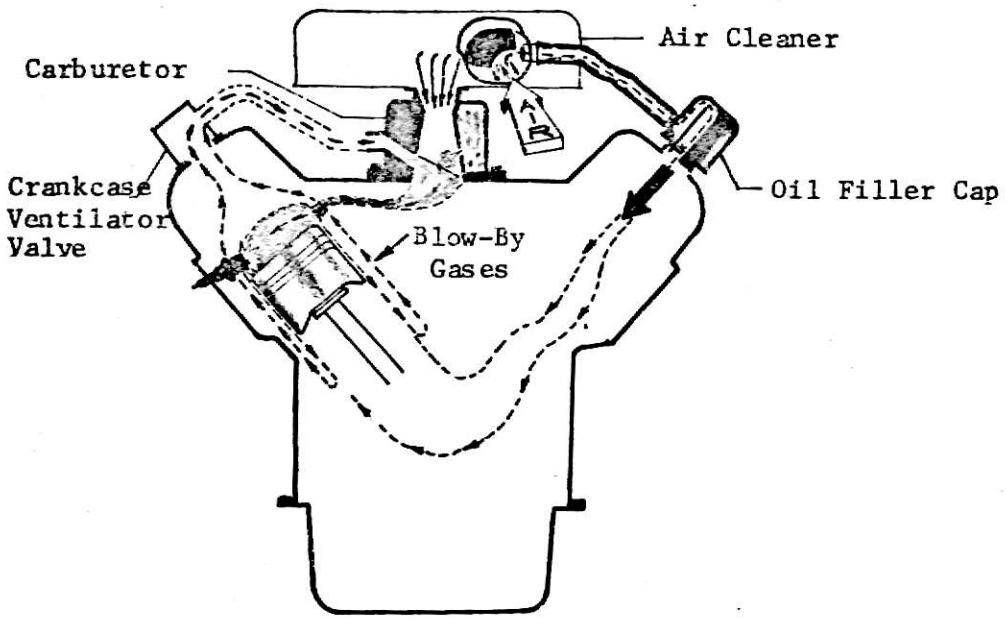


Fig. 6.1 Crankcase Ventilation Control System. (Fig. 23, Ref. [18]).

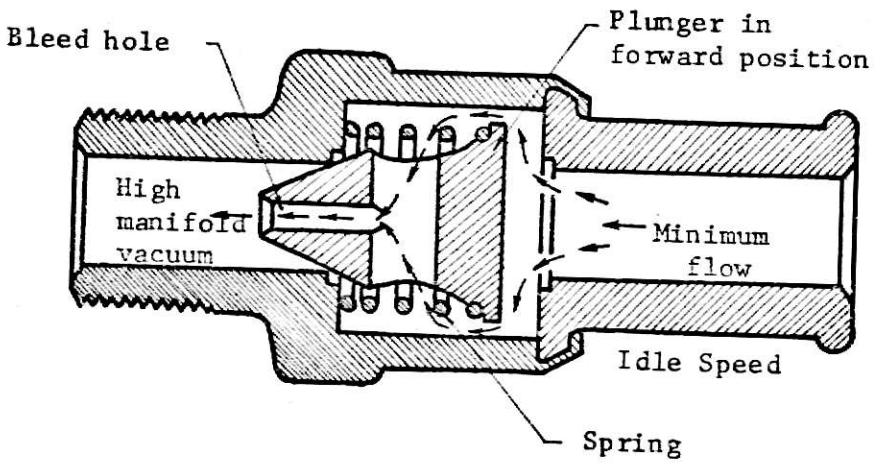


Fig. 6.2 Crankcase ventilation valve. (Fig. 20, Ref. [18]).

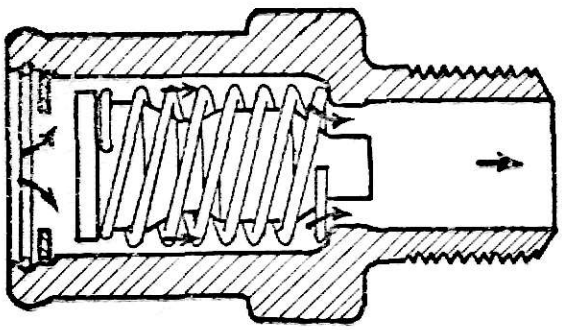
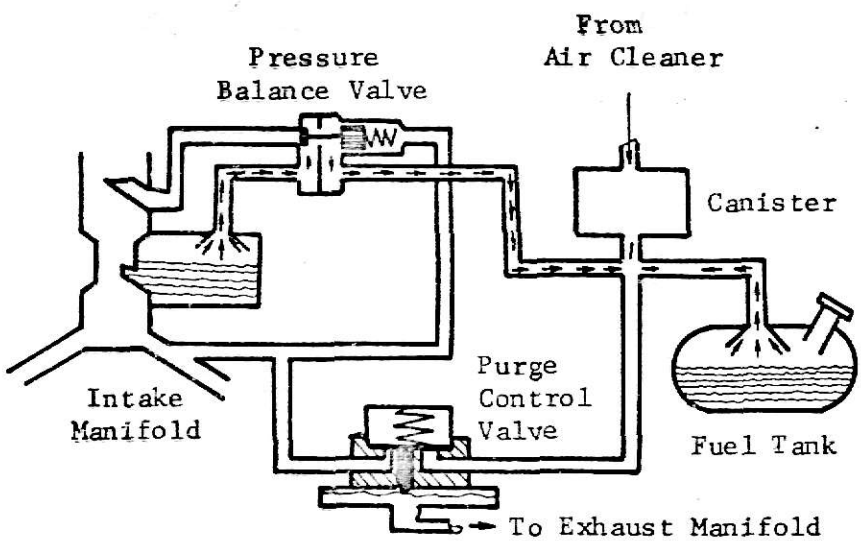


Fig. 6.3 Self-cleaning Crankcase Venilation Control Valve. Movement of Loose-fitting Plunger Tends to Keep Port Free From Deposits. (Fig. 21, Ref. [18]).



HOT SOAK CONDITION HYDROCARBON VAPORS

Fig. 6.4 Basic Evaporative Loss Control Device - Hot Soak Condition. (Fig. 26, Ref. [18]).

CARBURETOR AND FUEL TANK EVAPORATIVE EMISSIONS CONTROLS

Evaporative control systems are designed to virtually eliminate the hydrocarbon vapors emitted by the carburetor and fuel tank during both running and hot soak. 1972 standards were 4g/day.

Two storage systems are used. One is a canister containing activated charcoal located in the engine compartment, and the other is a system which uses the crankcase to store the vapors.

i) The basic EVAPORATIVE LOSS CONTROL DEVICE (ELCD): This device is based upon the adsorption in charcoal as shown in figure 6.4.

Three essential components are involved: the adsorbent canister, a pressure-balancing valve, and a purge control valve. The canister traps hydrocarbon vapors at any parts of the engine cycle when they cannot be fed into the engine. They must then be retained until they can be released to the intake manifold [18].

It consists of a bed of suitably sized charcoal held between retaining screens.

The function of the pressure-balancing valve is twofold (a) during engine operation to maintain metering pressures in the carburetor at high design levels so as to prevent interference with its normal effectiveness. (b) while the engine is shut down to close all external vents and route hydrocarbon vapors to the reservoir canister.

The pressure balancing valve is actuated by intake manifold vacuum against a spring which closes the normal route for the carbureted mixture immediately when this vacuum falls to zero.

In contrast the purge-control valve is actuated by exhaust back pressure. When unseated by this pressure the canister is directly connected with the intake manifold. Air is drawn through the canister, picking up hydrocarbon vapors and going forward directly to the engine under the influence of the manifold vacuum. The purge-control valve is so designed that the stripping of the canister is precisely phased to engine operating mode, the quantity of stripped hydrocarbon-air mixture being kept in step with engine since this is exponentially related to the exhaust backpressure actuating the valve.

Activated charcoal can, on a recycle basis store 30-35 g fuel per 100 g charcoal without breakthrough. Typically 700-800 g charcoal are used in a vehicle system which is adequate unless a high volatility fuel is used. Often a volatility limit of 10 psi RVP (Reid Vapor Pressure) or less is recommended for optimum system performance.
(1) An alternate scheme uses the crankcase to store the vapors. The figure below shows the routes of hydrocarbon vapors during shut down and hot soak. When the engine is restarted these vapors are drawn in to the engine by the inlet manifold vacuum.

The overall effect of the controls is a considerable reduction in pollution.

Other means of containing evaporative emissions are under active consideration. These include means of draining the float chamber to the fuel tank on switch-off, evaporation from the latter being controlled. An electric pump is then required to refill the carburetor at switch on. Fuel tank insulation to reduce heat absorption has been suggested but would be of limited advantage where long hours of day time parking is experienced.

Although a number of devices for control of automotive emissions have been and are being developed, they could be broadly divided into two main groups;

1. Treatment of exhaust after it leaves the engine, and
2. Modification of the engine and its controlled variables so that less emissions are produced.

EXHAUST TREATMENT DEVICES

Thermal Reactors: One of the methods used in production to reduce hydrocarbon and carbon monoxide emissions is air injection into the exhaust system. To achieve a high degree of exhaust system oxidation of HC and CO a high exhaust temperature coupled with sufficient oxygen and residence time to complete the combustion is needed. If a flame is established, the heat generated by the combustion of CO and HC keeps the reaction going [23].

In designing a thermal reactor two points should be considered i) Good mixing ii) Fast warm-up. A reactor has been developed, which is called RAM (Rapid Action Manifold)

An ideal reactor consists of a well section and a plug-flow section (shown in the fig. 6.5). The first section mixes the CO and HC with air, and provides ignition. The second section provides the time and maintains the temperature to complete the combustion.

The RAM consists of an 8 in OD torus made of 2 in stainless steel tubing. Connecting arms lead to the exhaust from on side of the engine to the torus. The gases flow around the torus and exit through a slot into a central plenum and then into the exhaust pipe, the slot is positioned so that the gases must flow at least half-way around the torus before they can leave, and such that a portion of circulating gases goes all the way around to mix with the entering engine exhaust. The back mixing serves to initiate reaction in the incoming gases and ensure that the injected air is mixed in uniformly. The air is injected into each engine exhaust port and is aimed toward the valve. Most of the thermal reaction takes place as the gases swirl through the reactor. Any CO or HC which is not burned in the reactor have an opportunity to react in the exhaust pipe after it is heated.

The flame holders act to stabilize a flame at the outlet of engine exhaust ports, during startup, when the engine is choked. As the gases flow past the grid, they curl around it, forming eddies or recirculation zones in which combustion takes place. These small sheltered zones then serve to ignite the mainstream. Without flame holders, the flame would tend to oscillate periodically with pulsing flow and go out periodically.

The results of RAM are shown in Table 6.1.

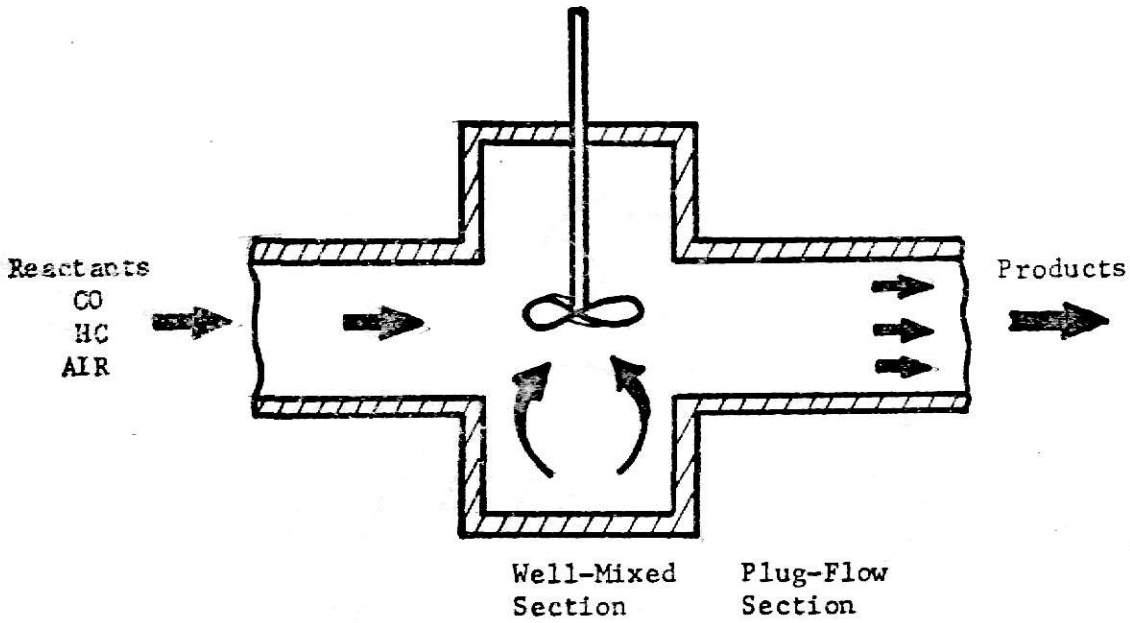


Fig. 6.5 Ideal Thermal Reactor. (Fig. 1, Ref. 23).

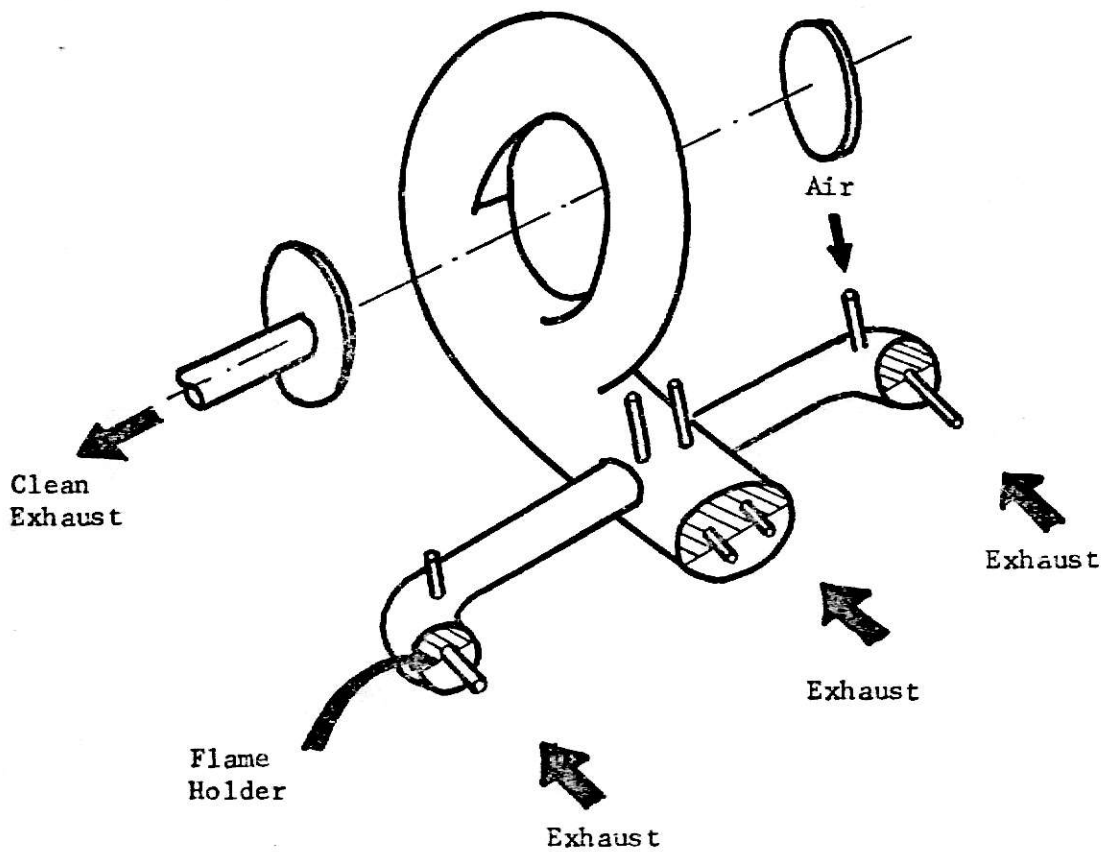


Fig. 6.6 RAM Reactor, Model 1. (Fig. 2, Ref. 23).

TABLE 6.1*

	RAM Results	Modified RAM Results
Emissions:		
gm/mile, CO	3.7	5.2
HC	0.08	0.07
NO_x	0.72	1.89
% Fuel economy debit;		
City driving	22.4	16.9
Turnpike	17.4	9.5
Operating temperature-maximum after the choke is off		
deg F	1950	1750

In modified RAM, the engine was operated at leaner mixture to improve fuel economy, while still maintaining reasonable NO_x emissions.

CATALYSTS: Catalysts are chiefly used for the reduction of NO_x emissions. Of the several catalyst systems proposed for automotive controls for emissions, the dual bed system (shown in Fig. 6.7) appears to have the most potential for meeting low emission standards. This system consists of a bed of NO_x reduction catalyst over which the reactions occur, followed by a bed of oxidation and catalyst over which another set of reactions occur [24].

The reactions are as follows,

Reduction:

$$NO + CO = \frac{1}{2} N_2 + CO_2$$

$$NO + H_2 = \frac{1}{2} N_2 + H_2O$$

Oxidation:

$$CO + \frac{1}{2} O_2 = CO_2$$

$$\text{Hydrocarbons} + O_2 = CO_2 + H_2O$$

To provide reducing conditions in the NO_x reduction catalyst bed, the vehicle engine is operated on the fuel rich side of stoichiometric (standard A/F = 14.7). These conditions will produce a net reducing exhaust. Air is injected between beds to change exhaust composition from net reducing to net oxidizing. The following criteria was developed for NO_x reduction catalyst use in dual bed catalyst systems:

*Fig. 9, Ref [23].

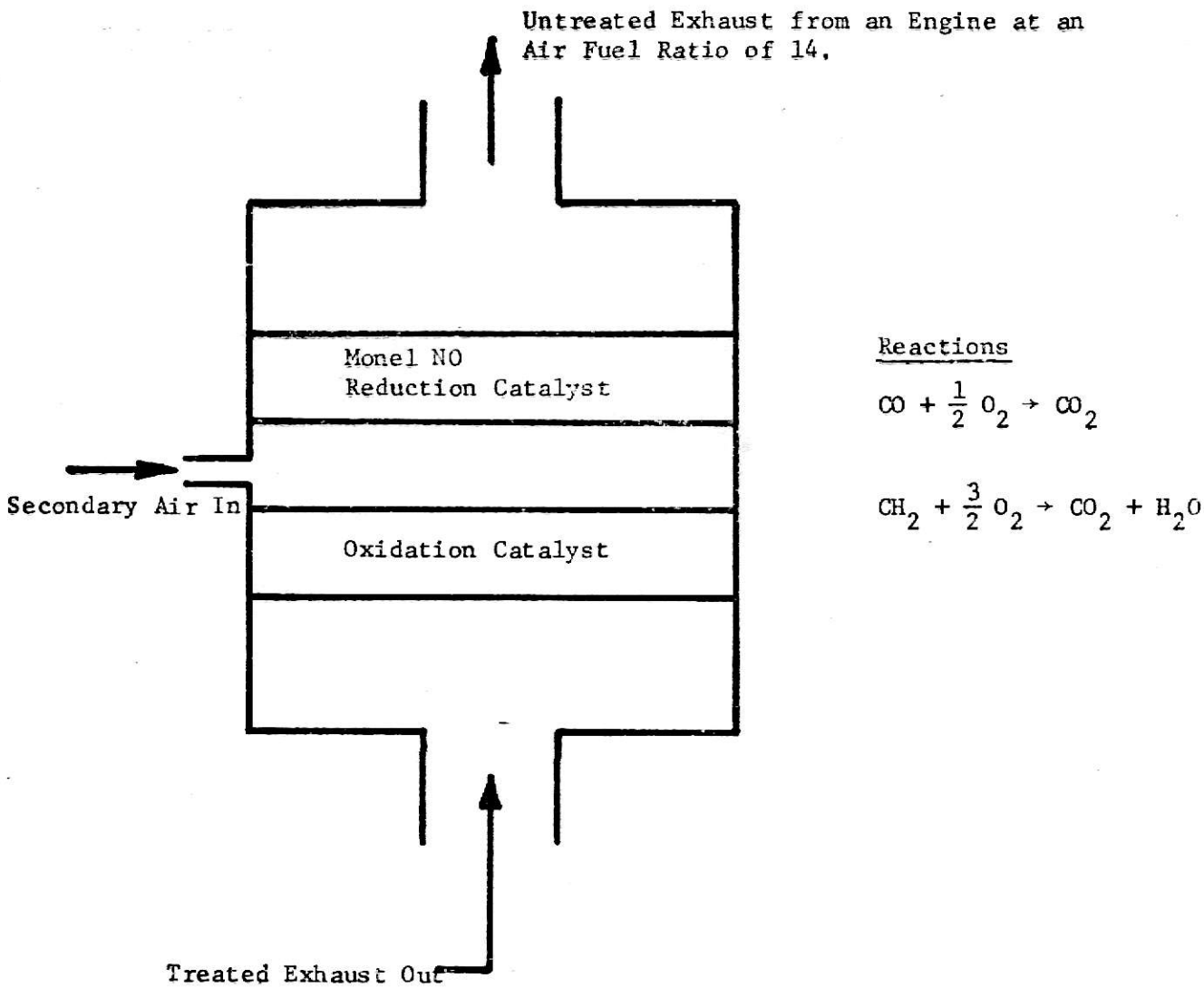


Fig. 6.7 Dual Bed Catalyst System. (Fig. 1, Ref. 24).

1. High reactivity; that is, ability to remove 90% or more of the NO_x in exhaust at 1300°F.
2. Good temperature resistence, that is, ability to withstand temperatures upto 1800°F.
3. High metal content.
4. Economic Feasibility, that is, a combination of low initial cost, good life under actual automotive conditions, and sufficient ability of active competition to supply 10,000,000 vehicles/year.

The summary drawn is Nickel-Copper alloys have been found to be extremely active NO_x reduction catalysts. At temperatures above 1300°F and under net reducing conditions, Monel will catalyse the removal of 90% or more of NO in auto exhaust. On unleaded fuel, monel catalyst have shown good chemical activity for as long as 31,000 miles.

TABLE 6.2*

Performance of Monel as a single bed catalyst

	NO_x,ppm	HC,ppm	CO %
Without Catalyst:	1200	200-150	2.0
With Catalyst:	160	105	0.9

More and more research is been done in this area, one such developed system uses Monel-Platinum. The chips like shape of Monel was changed to unitary structure which improved the strength and maintenance of low pressure drop, NO_x emissions as low as 0.8 grams/mile were obtained. The following fig. 6.8(A-C) shows the performance of various catalysts [25].

A certain catalyst "C" was developed by Union Oil Co. of California [26]. This catalyst was found to be far superior to the Cu-Ni and Pt-NI preparations, the results of experiments conducted on this catalyst were found to be very encouraging.

The catalyst was found to be very resistive to lead and sulfur dioxide poisoning.

*Table 3, Ref. [25].

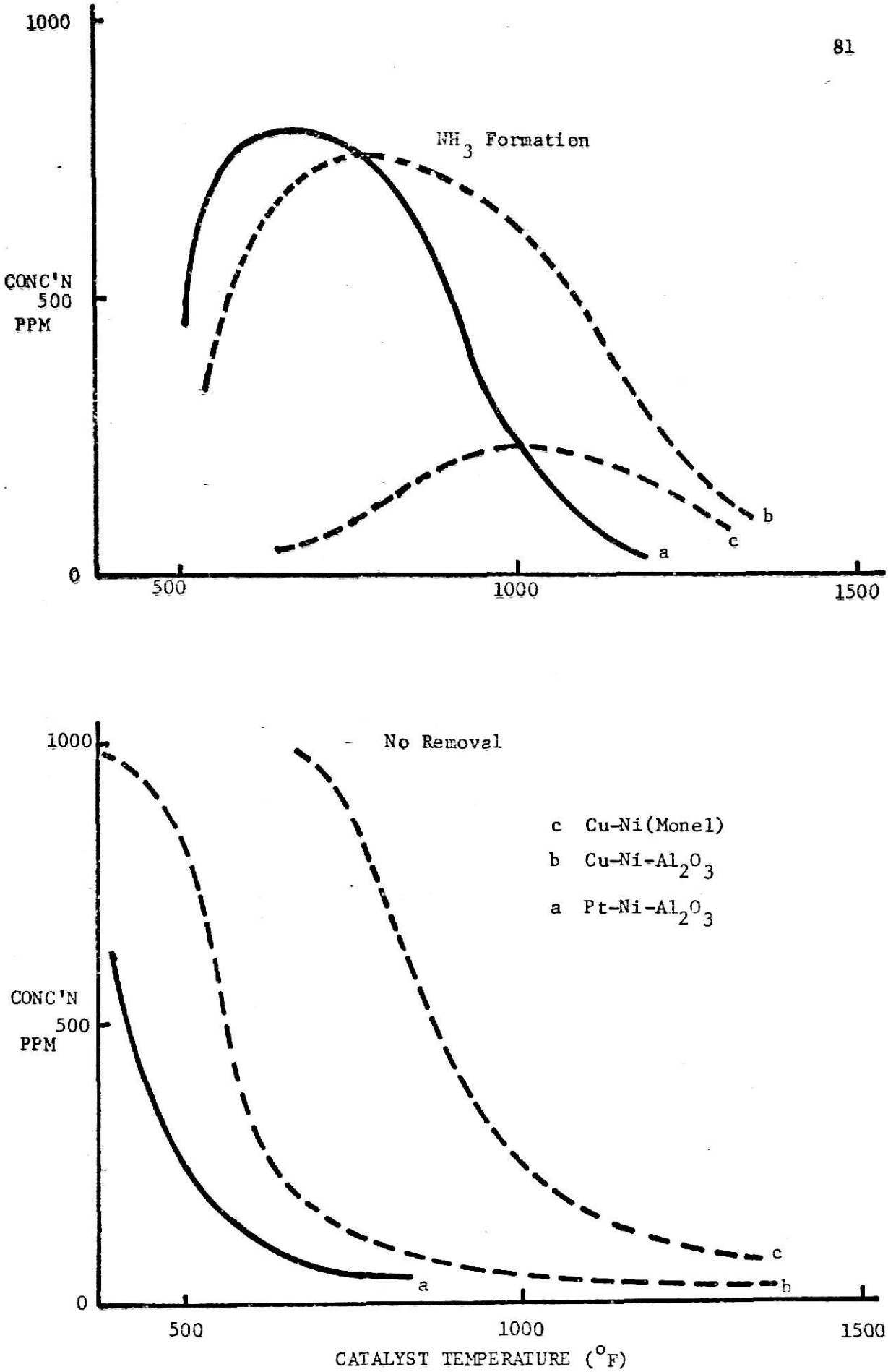


Fig. 6.8(A) Ammonia Formation and NO REmoval Activities for Various Catalysts. (Fig. C, Ref. 25).

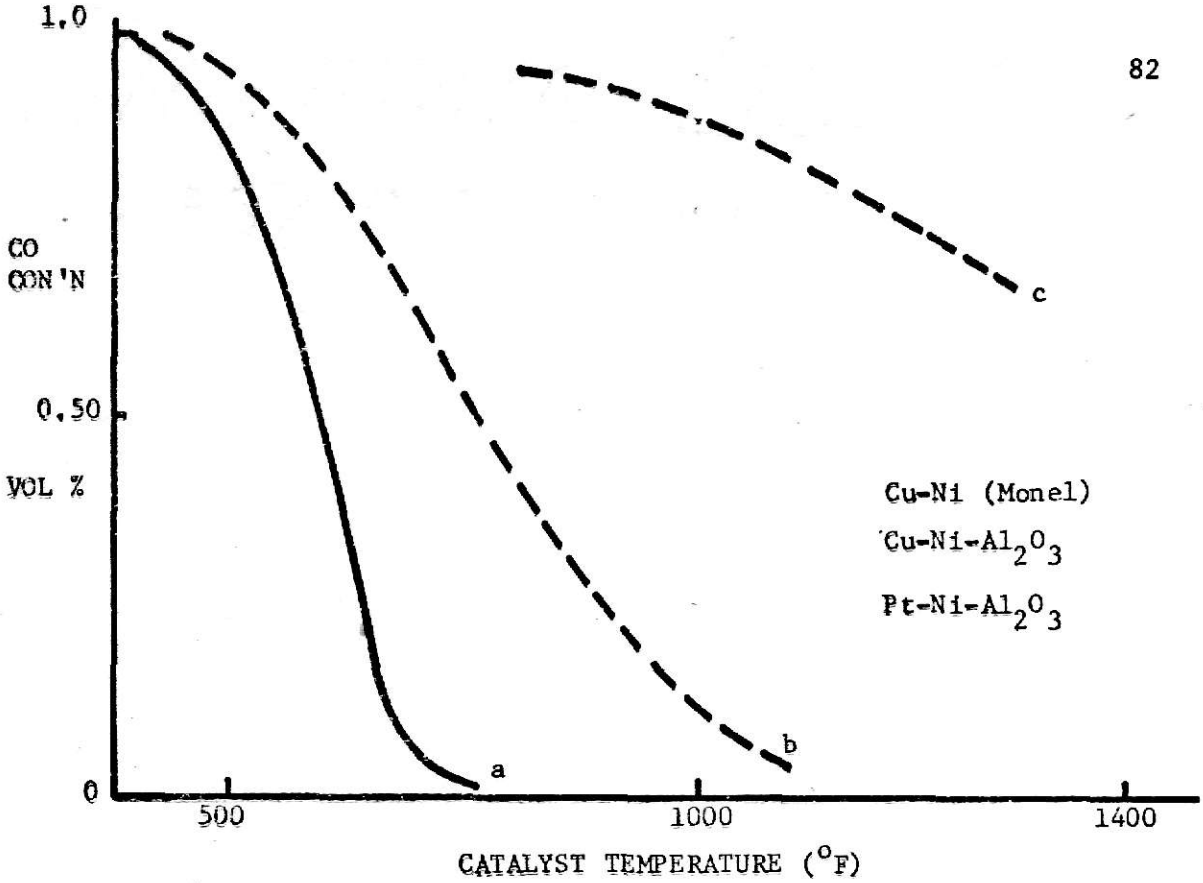


Fig. 6.8(B) CO Oxidation Activity for Various Catalysts (Fig. D, Ref. 25).

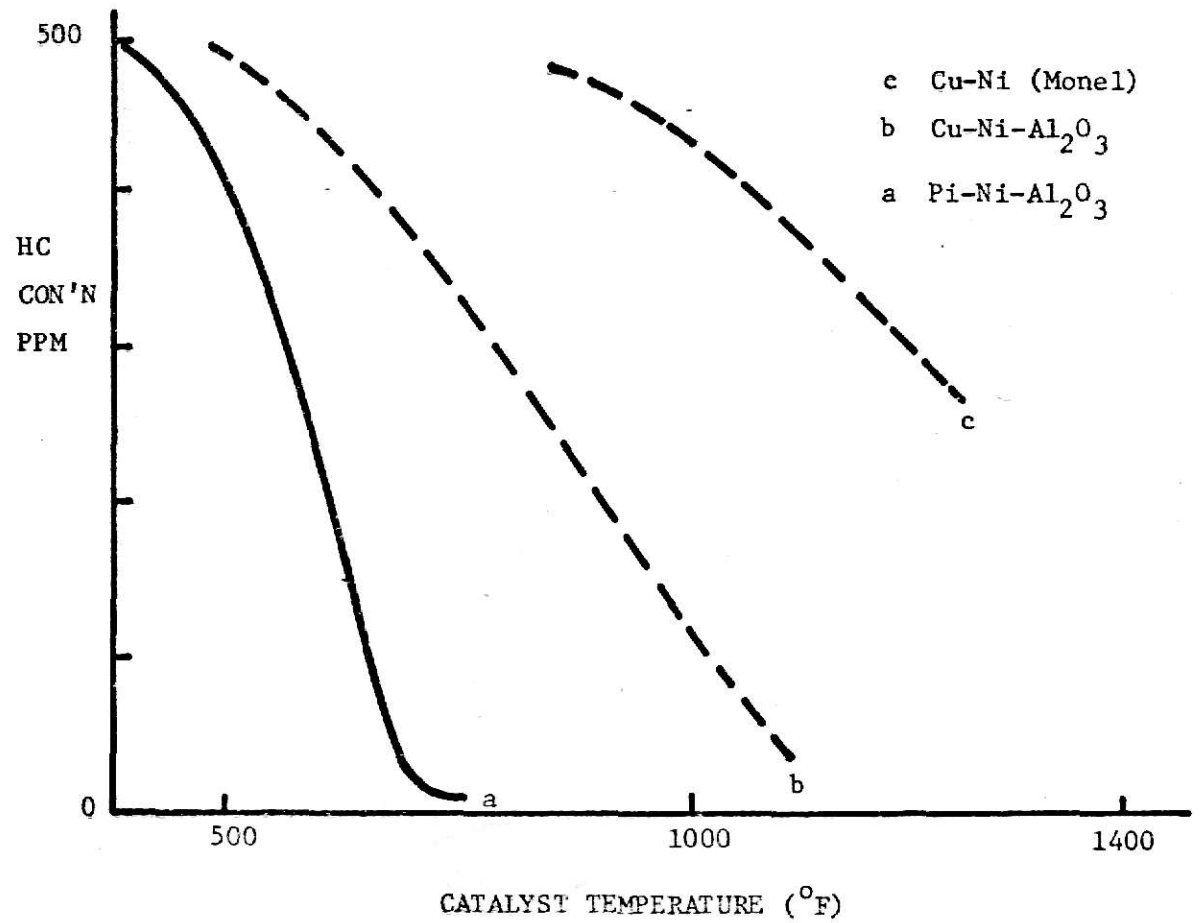


Fig. 6.8(C) HC Oxidation Activity for Various Catalysts. (Fig. E, Ref. 25).

Inlet Manifold Water Injection: It has been hypothesized that NO is very rapidly formed during combustion. Subsequently, during the expansion process, NO remains fixed in concentration and is therefore finally exhausted in quantities corresponding to those of its high temperature formation [27].

The Figures 6.9-6.11 show the influence of temperature and pressure on equilibrium nitric oxide concentration. In all cases it is observed that decreasing combustion temperature tend to yield rapidly decreasing NO concentration. This suggests the control of NO emissions by any means which would tend to reduce the peak combustion temperature of engine cycle.

Among possible methods for achieving such temperature reductions is the dilution of fuel air-mixture entering the engine with a relatively inert or non-combustible substance. In this manner, the molar energy density of the combustible charge is effectively reduced.

One of the methods is the injection of non-combustible liquid phase substance with the gas-phase charge into the engine induction system. Ideally the liquid phase substance selected should undergo significant vaporization only during the compression and combustion processes following closing of the inlet valve. One substance suitable for this purpose is water, and that is because of its following properties;

1. Relatively low vapor pressure at normal induction system pressure.
2. High Latent heat of vaporization.
3. Low boiling point relative to max. engine cycle temperature.

The influence of water injection on calculated flame temperatures is presented in the following fig. 6.12 for a number of fuel-air equivalence ratios, and the influence of water injection on NO concentration is also shown in fig. 6.13-6.14 for inlet manifold pressure of 14.7 psia and 8 psia. NO concentration are presented in terms of percent reduction from the value obtained with no water injection.

The theoretical influence of water injection on both indicated mean effective pressure and indicated specific fuel consumption has been determined and the results obtained show that a minor increase in mep and a slight decrease in isfc occurred.

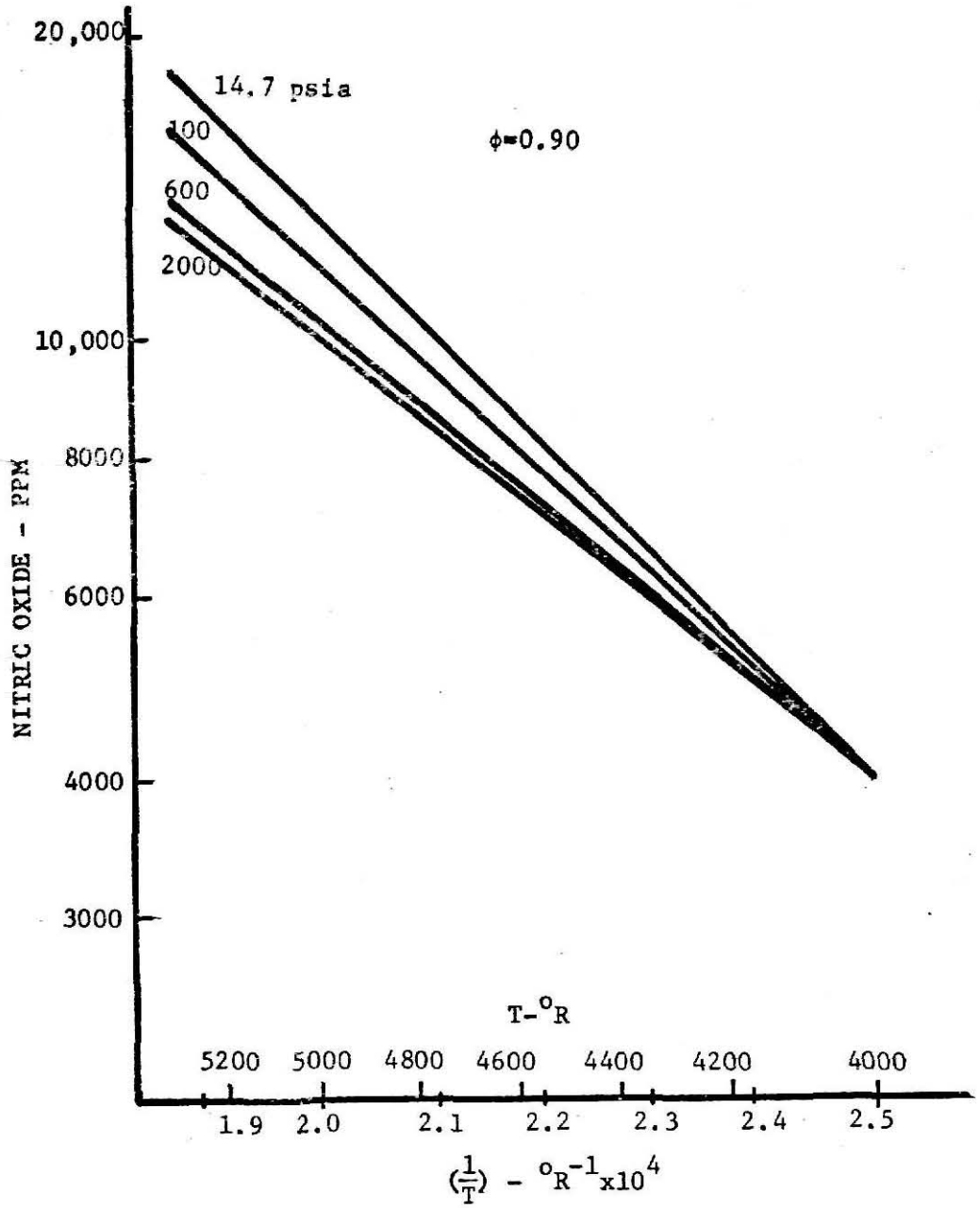


Fig. 6.9 Influence of Temperature on Chemical Equilibrium Nitric Oxide Concentration: Equivalence Ratio 0.9:
(Fig. 2, Ref. 27).

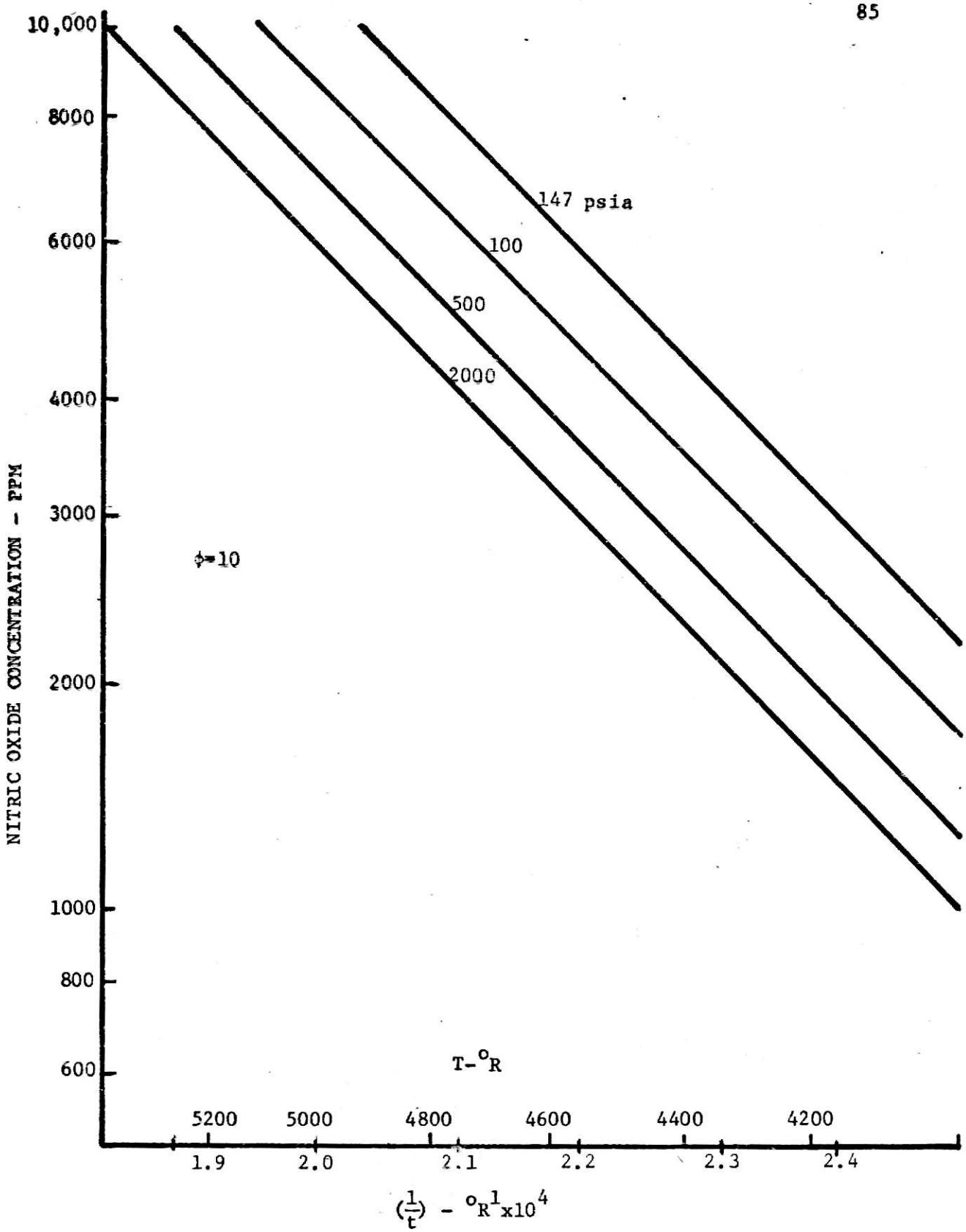


Fig. 6.10 Influence of Temperature on Chemical Equilibrium Nitric Oxide Concentration: Equivalence Ration 1.0: (Fig. 3, Ref. 27).

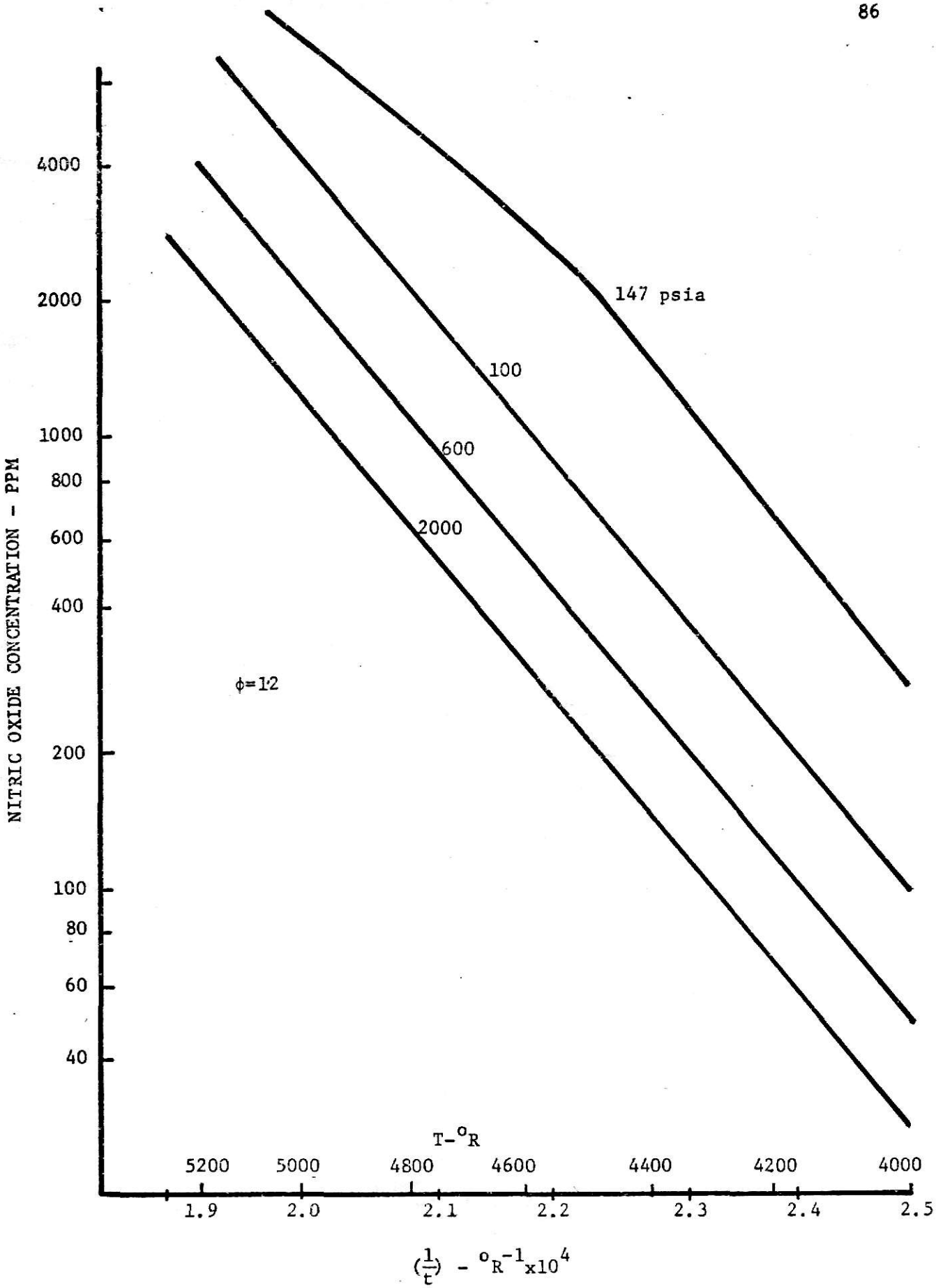


Fig. 6.11 Influence of Temperature on Chemical Equilibrium Nitric Oxide Concentration: Equivalence Ratio 1.2: (Fig. 4, Ref. 27).

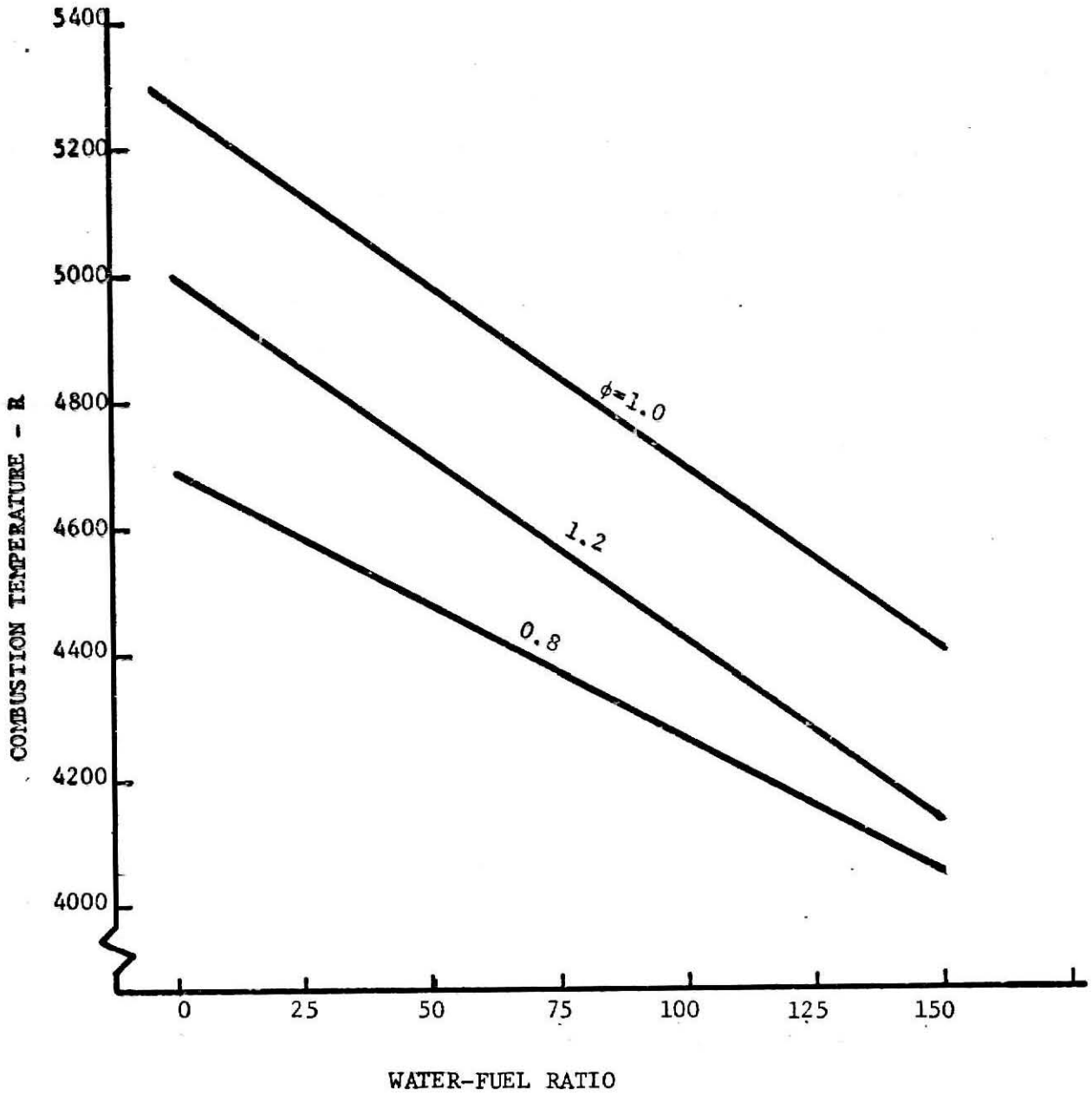


Fig. 6.12 Influence of Water Injection on Theoretical Equilibrium Flame Temperatures for Isooctone (Fig. 6, Ref. 27).

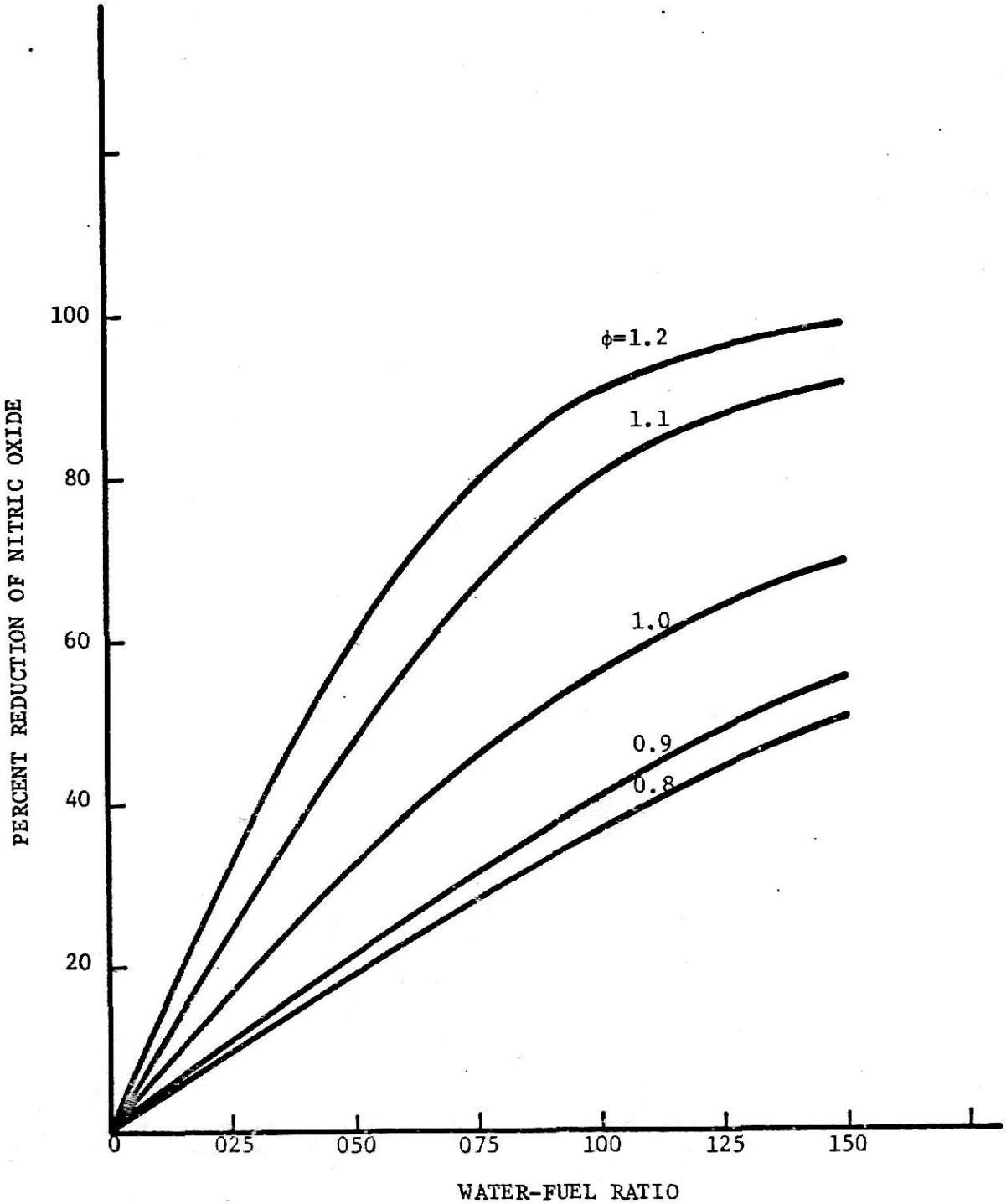


Fig. 6.13 Influence of Water Injection on Theoretical Nitric Oxide Emissions: Compression Ratio - 8: 1: Inlet Manifold Pressure - 14.7 psia. (Fig. 8, Ref. 27).

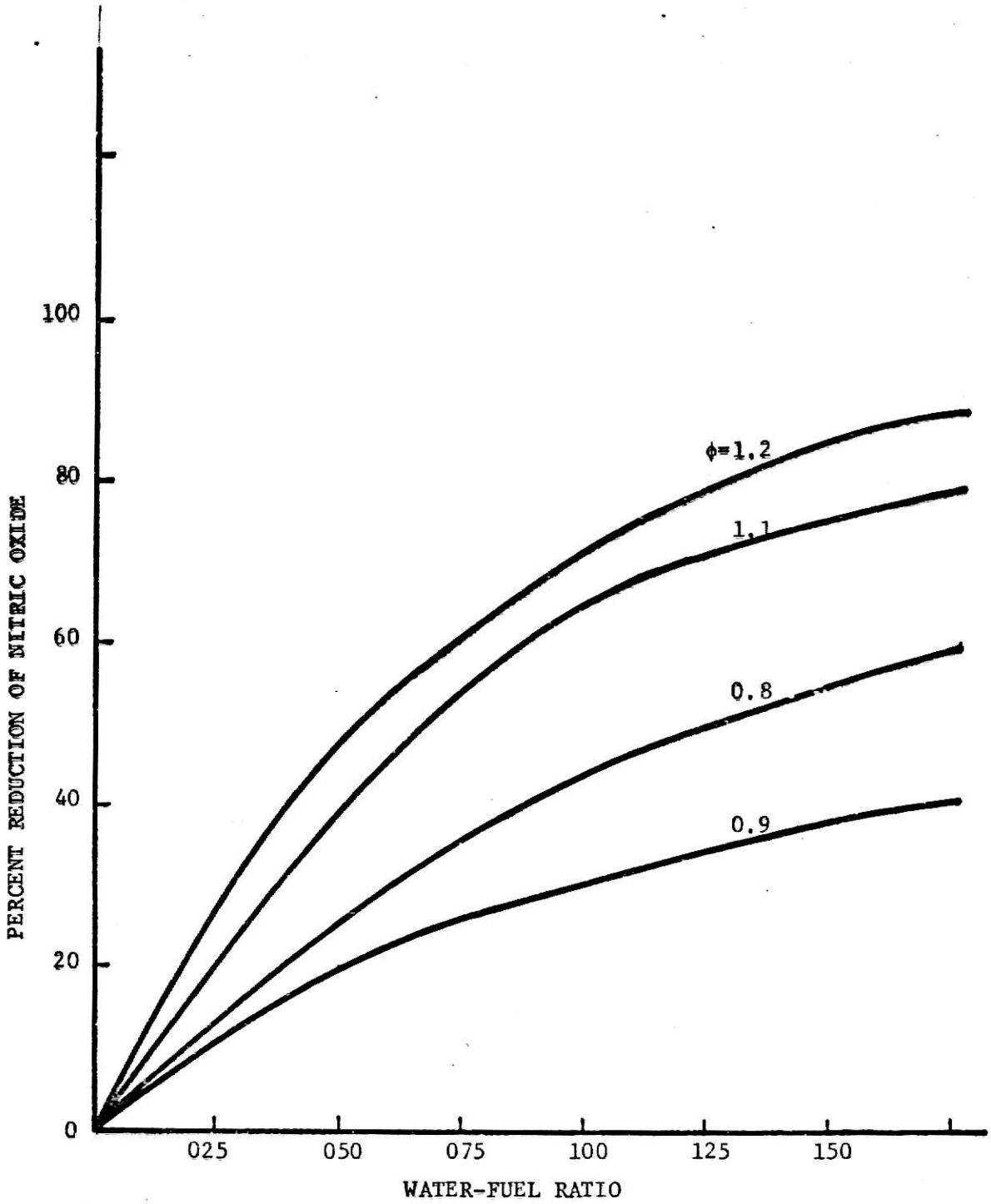


Fig. 6.14 Influence of Water Injection on Theoretical Nitric Oxide Emissions; Compression Ratio - 8: 1: Inlet Manifold Pressure - 8 psi. (Fig. 9, Ref. 27).

A diagram showing the experimental system is shown in fig. 6.15. It consists of an induction pipe carburetor, water injection nozzle and water injection control system.

The experimentally observed influence of water injection on NO emmissions is shown in fig. 6.16. It is evident that water injection was effective in reducing NO at all fuel-air ratios considered.

Gases Used As Diluents: Similar experiments conducted by General Motors laboratory, for the estimation of NO reductions by various gases used as diluents, such as CO_2, N_2, He_2, Argon, steam and other exhaust gases were individually added to the intake charge of a propane fueled, single cylinder engine operated at constant speed and load. The gases with higher specific heats gave larger reductions in NO. The following results were obtained. Fig. 6.17 [28].

Exhaust Gas Recirculation: EGR is a promising method for the reduction of NO. In this system exhaust is recirculated often from the crossover, directly into the intake manifold. The fig. 6.18 shows one method. Here two tubes recirculate exhaust gas from the cross over to each side of the manifold. Good cylinder to cylinder distribution of gas is essential for maximum benefit. At chemically correct fuel air ratio, 70% NO reduction can be obtained with 20% recycle. Theoretically this depreciates only 3% fuel economy. The following fig. 6.19 shows NO reduction [29].

However, a more sophisticated system developed is shown in Fig. 6.20 [30]. To provide more cooling of the recycle gas before it entered the carburetor, several extra feet of tubing (some of it finned) were used in the recycle line. In addition a large hole was cut in the vertical plate beside the radiator to permit a good flow of cooling air past the recycle tube. The recycle line maintained a continuous slope back to the tail pipe so any moisture condensed will drain back to tail pipe and muffler. The cooled recycle gas next passed through the flow limiting orifice contained in the flange of the shut-off valve. Through this vacuum operated valve, through the flow meter, past a thermocouple and into the recycle plate in the carburetor. To provide maximum versitility the off/on recycle valve was controlled by electric switches inside the car and on the accelerator link. These switches controlled a three way solenoid valve which either fed high

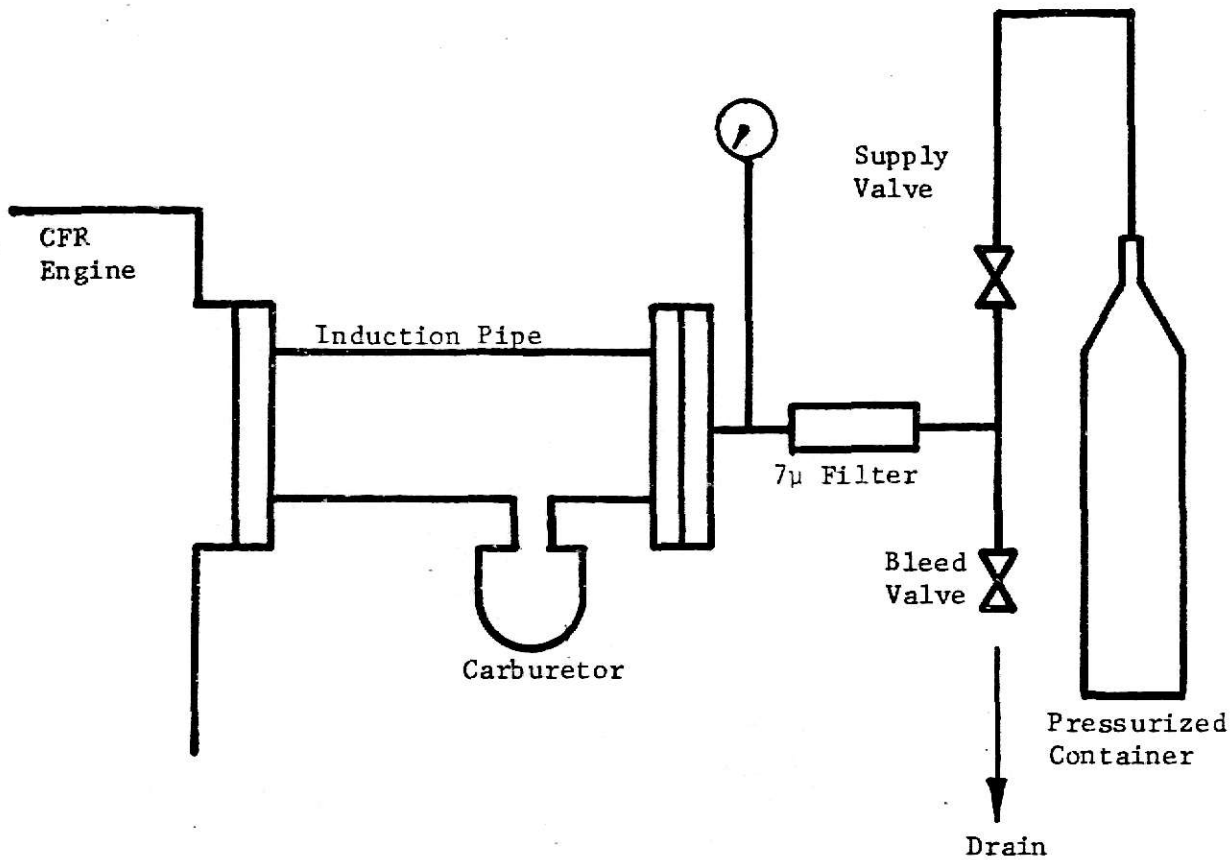


Fig. 6.15 Experimental Water Injection System Used with CFR Engine. (Fig. 15, Ref. 27).

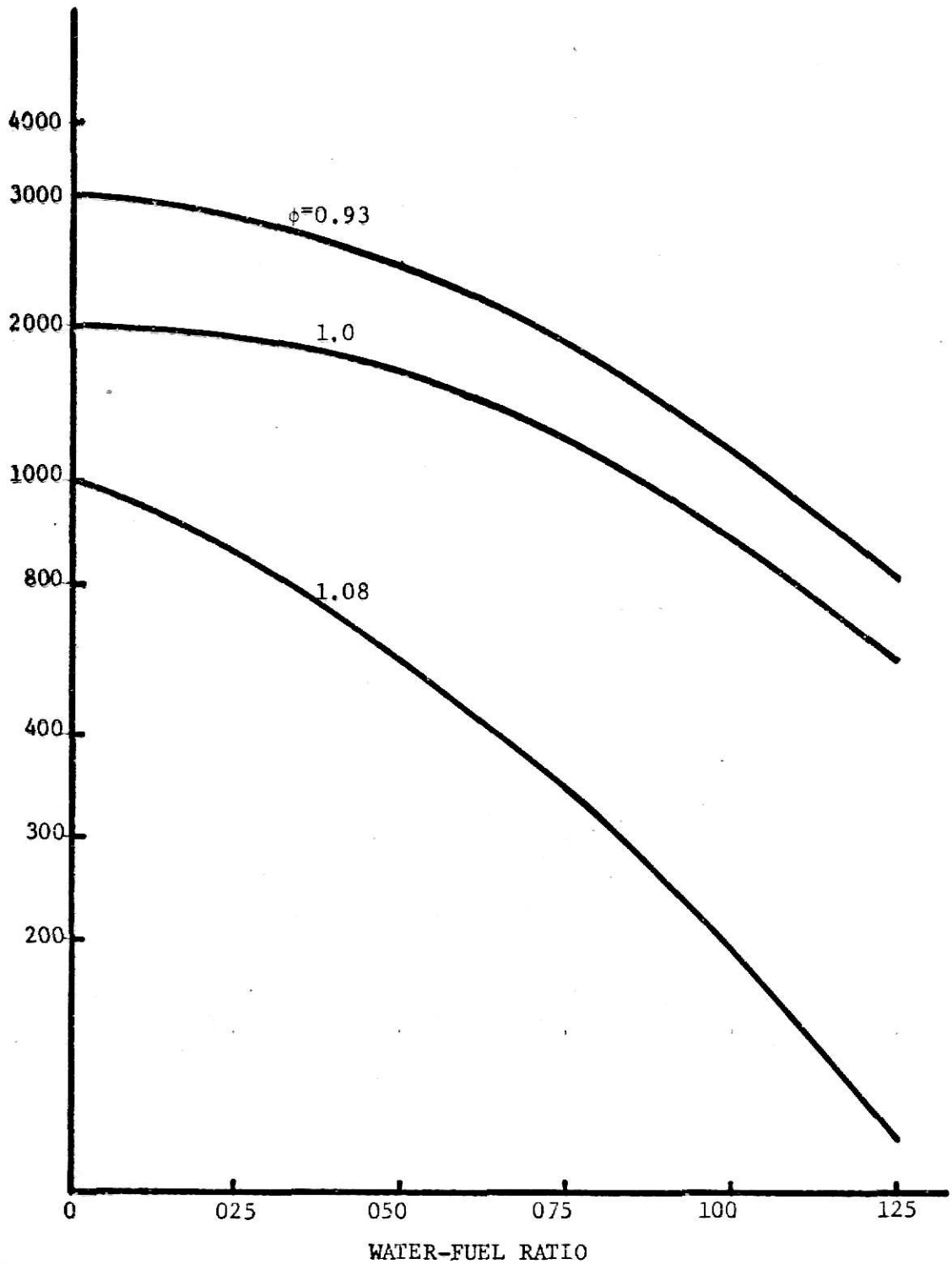


Fig. 6.16 Experimentally Determined Influence of Water Injection on Nitric Oxide Emissions: Inlet Manifold Pressure 14.7 psia: Compression Ratio - 8.5:1: Ignition - 28 deg btdc.

(Fig. 16, Ref. 27).

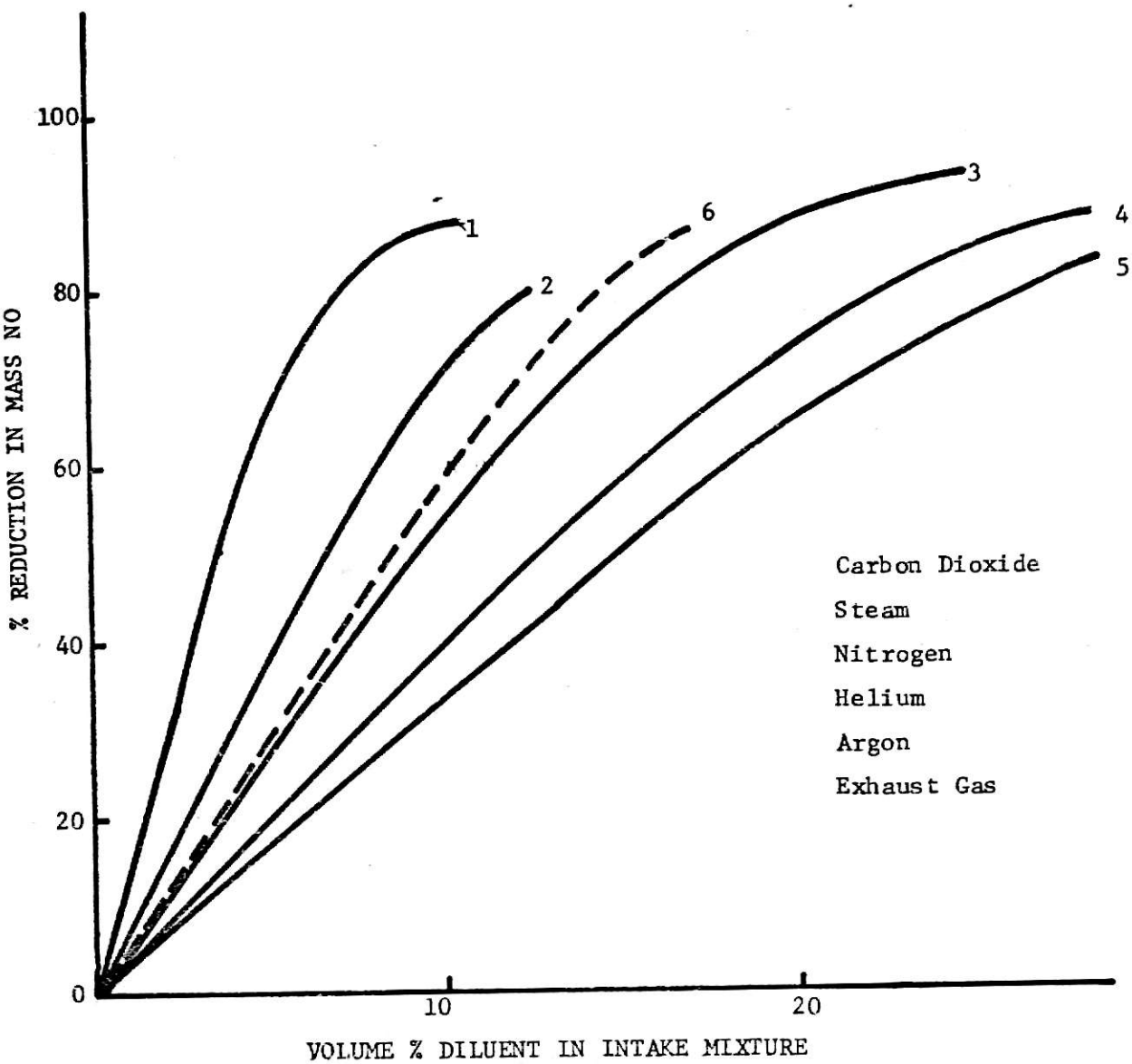


Fig. 6.17 Percentage Reductions in Mass NO Emissions with Various Diluents . (Fig. 4, Ref. 28).

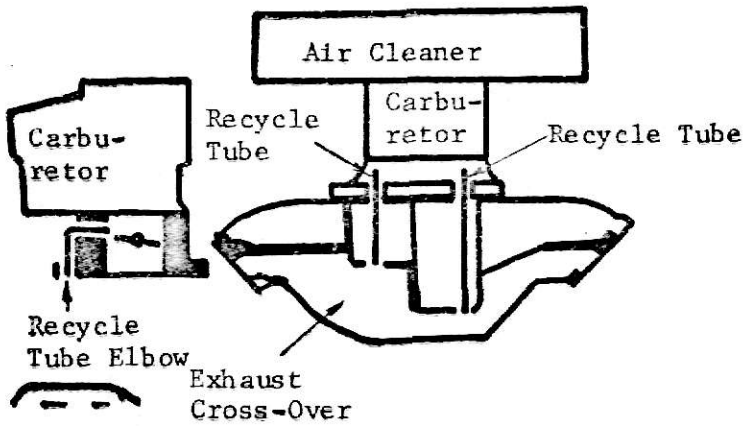


Fig. .18 Carburetor Recycle System. (Fig. 7.8, Ref. 3).

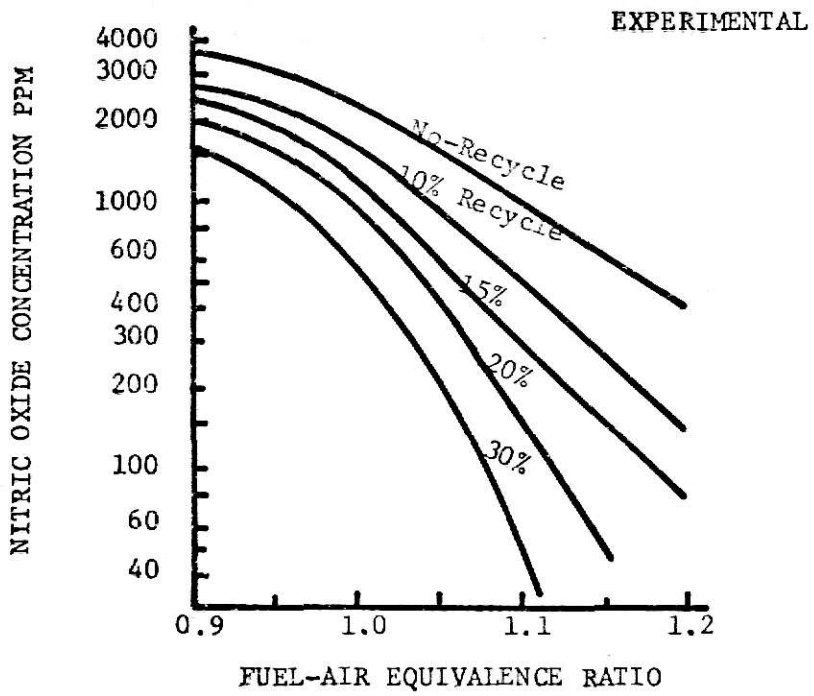


Fig. 6.19 Variation of Exhaust Nitric Oxide with Fuel-air Equivalence Ration. (Fig. 7.9a, Ref. 3).

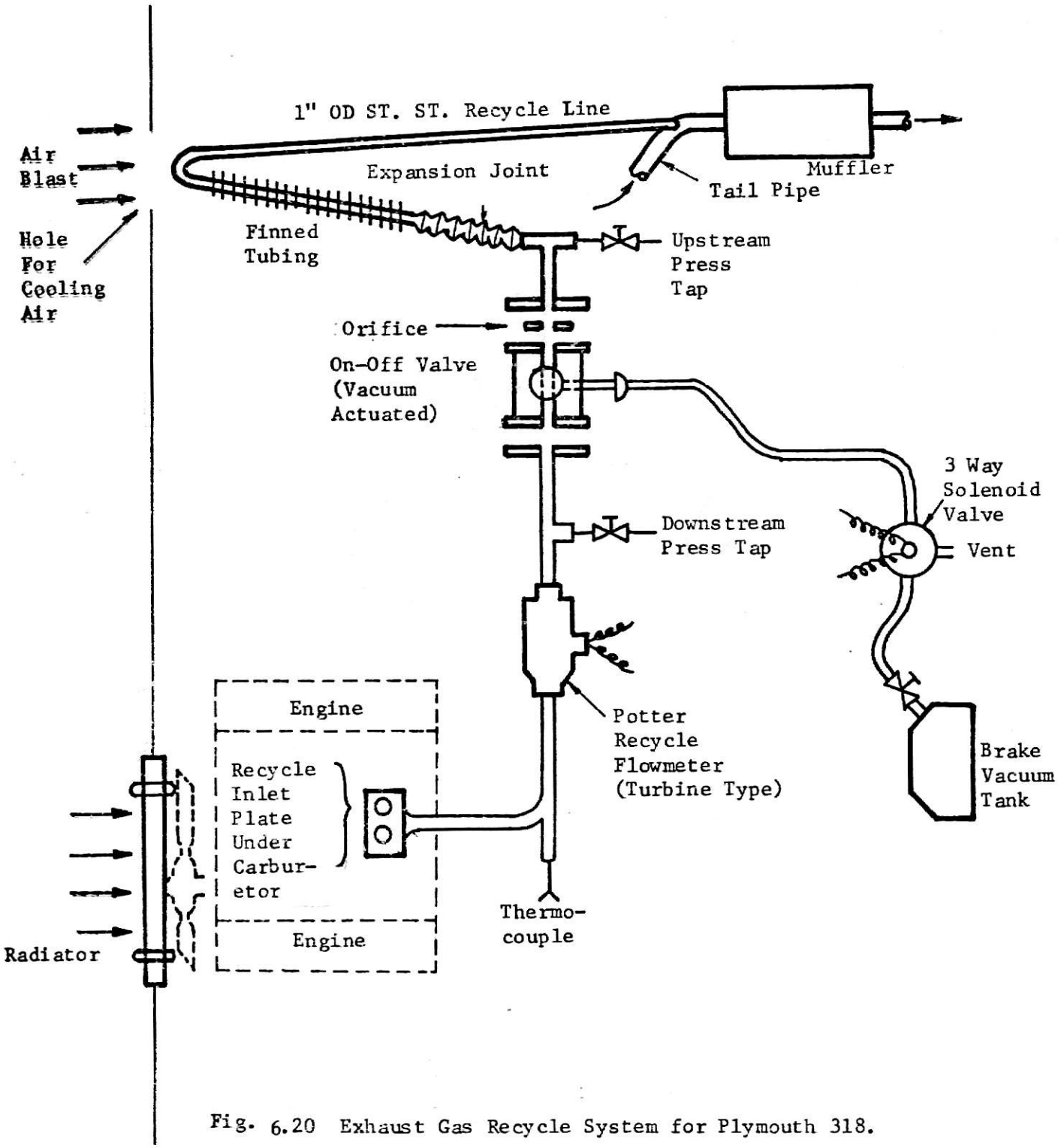


Fig. 6.20 Exhaust Gas Recycle System for Plymouth 318.

(Fig. 2, Ref. 30).

vacuum (from the brake reservoir) or bled atmospheric air into the operating diaphram of the recycle valve. The switches on the accelerator linkage could be adjusted to turn-off the recycle during periods of idle or wide open throttle, this was designated automatic operation. The switches inside permitted the operator to select either automatic or no recycle or continuous recycle. This allows instantaneous switching on the board.

ENGINE MODIFICATIONS

In this section the various engine modifications which help keep the emissions low as well as better designs for a minimal of emissions will be discussed.

Air-Fuel Ratio and Spark Timing: The influence of air/fuel ratio and spark timing on the concentration of NO in exhaust gases has been investigated at different engine speeds and manifold pressures. One example of the results is shown in the fig. 6.21 [31]. At a given fixed spark timing peak concentration of NO appears at an air/fuel ratio leaner than stoichiometric and skirts of the curves spread to both sides of the lean and rich air/fuel ratios but descend rapidly on rich side. As the spark timing is advanced, the air/fuel ratio at the peak of the curves moves to the leaner side. At an air/fuel ratio near 10:1, the concentration level is below 150 ppm as a result of low combustion peak temperatures and shortage of oxygen.

Higher Combustion Surface Temperatures: Increased surface temperatures of the combustion chamber caused lower exhaust hydrocarbon concentration [32]. Hydrocarbon concentration fell 0.35-0.58 ppm (C_6) for each degree farenheit temperature increase depending on the engine speed and intake manifold depression. Combustion surface temperatures may be increased by increasing coolant temperature or by using higher proportion of ethylene glycol in the coolant. A total reduction of 43% in hydrocarbon was achieved when H.P increased from 2-13 IHP.

Spark Timing: Delaying or retarding the spark event requires more throttle opening to maintain speed and causes higher gas temperatures, resulting in lesser hydrocarbon emissions [33].

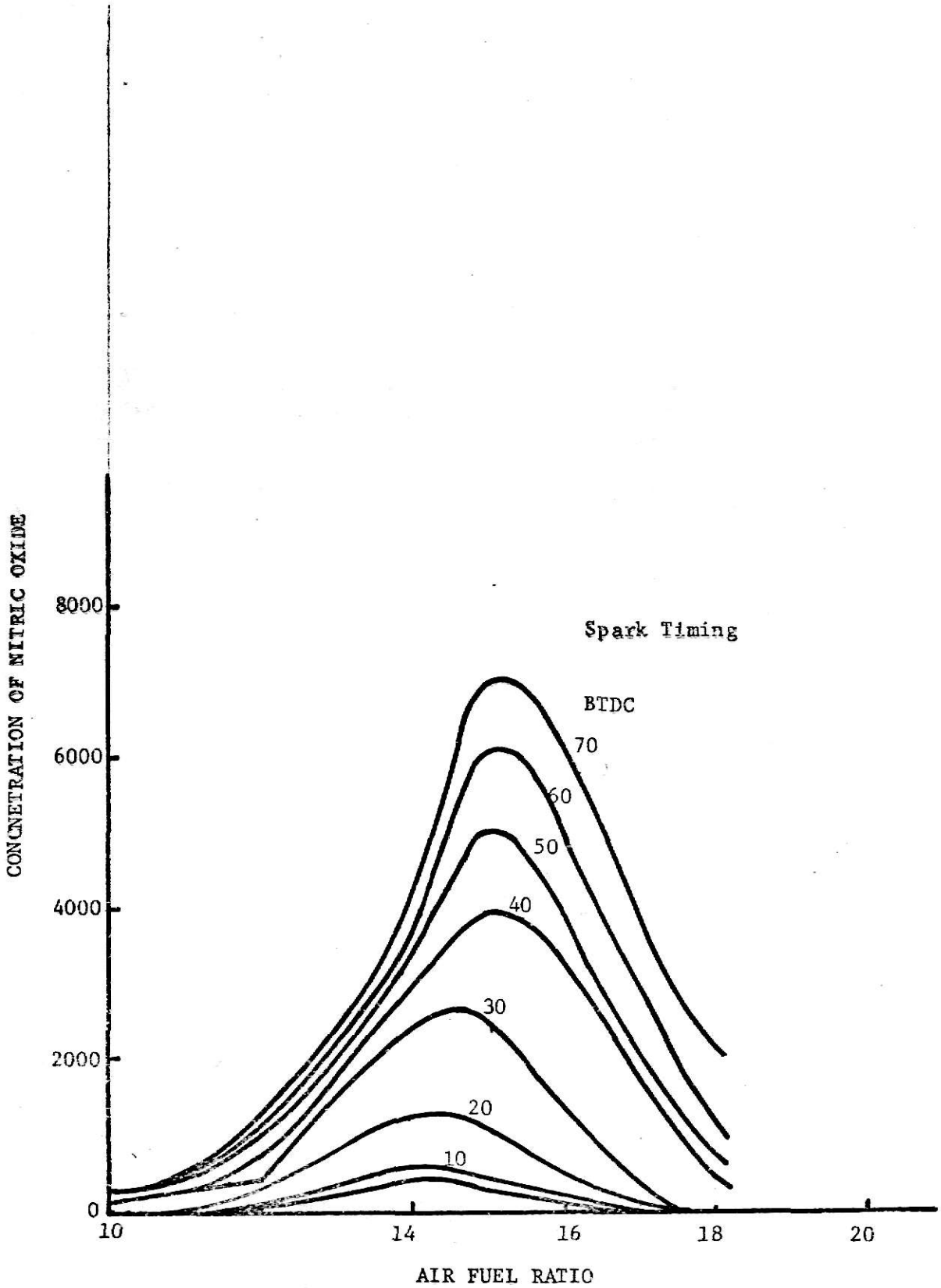


Fig. 6.21 Effect of Air/Fuel Ratio (Engine A, Manifold Pressure 20.45 In. Hg. 2000 rpm). (Fig. 3a, Ref. 31).

Ported spark: Some engines are equipped with "ported" spark advance. The Fig. 6.22 shows that the distributor spark advance vacuum is obtained from a drilled passage in the throttle bore, located above the closed throttle blade. This port does not communicate with manifold vacuum at closed throttle such as idle and deceleration. Without vacuum, the spark timing remains retarded. As the throttle is opened, the blade passes the port and exposes the opening to intake manifold vacuum.

Temperature Controlled Spark: Most engines have the spark advance further controlled by the transmission so that retarded spark timing is retained until the transmission shifts into higher gear. With automatic transmissions, high gear is sensed with a pressure sensitive switch in the clutch oil pressure circuit, while manual transmissions employe a switch on the shift linkage. The switch opens in high gear [33].

Homogenous Charge: A fuel-air mixture generator is used to supply a premixed homogenous gasoline air mixture, and the cylinder to cylinder variation of fuel/air ratio were almost eliminated, the results reported are encouraging, with the premixed charge, the vehicle could be run on an extremely lean air-fuel mixture, (at an A/F ratio of 22.5:1, at good driveability) CO and NO_x emissions were 2.7 and 0.4 grams/mile. However, variation in HC emissions was scarcely affected [34].

Air from a compressor and gasoline vapor from a flash boiler are both metered to give a flowing mixture of desired strength, at a rate greater than the engine will need. The engine has no carburetor and its intake system is connected to the generator. It still has a throttle. Before the engine is started, all the mixture is fed to and consumed by a large burner. When the engine is started and is running, regardless of the mode of operation it simply draws from the supply of mixture what is dictated by the throttle plate position and the engine speed at any instant. Excess mixture is consumed in the burner. Fig. 6.23.

Electronic Fuel Injection System: A computer controlled fuel injection system that eliminates the carburetor has been developed. Air is sucked in during the intake stroke and the gasoline is then injected directly into the intake manifold by an injector valve. The key element is the computer, a collection of transistors, diodes, resistors, and capacitors [35]

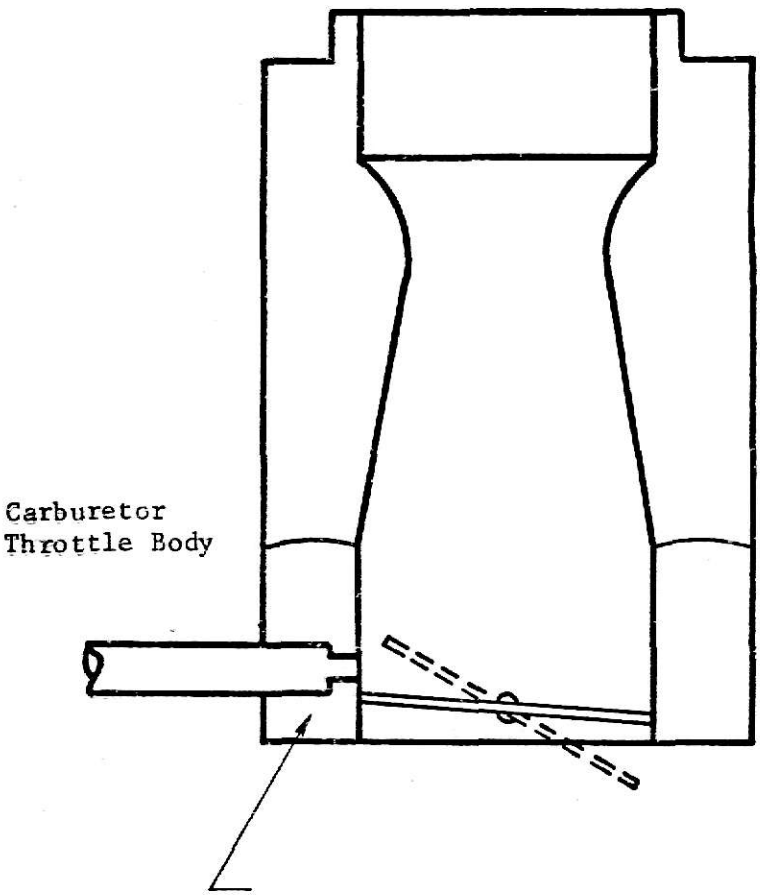


Fig. 6.22 Location of Vacuum Port for "Ported" Spark Advance.

[Fig. 3, Ref. 33].

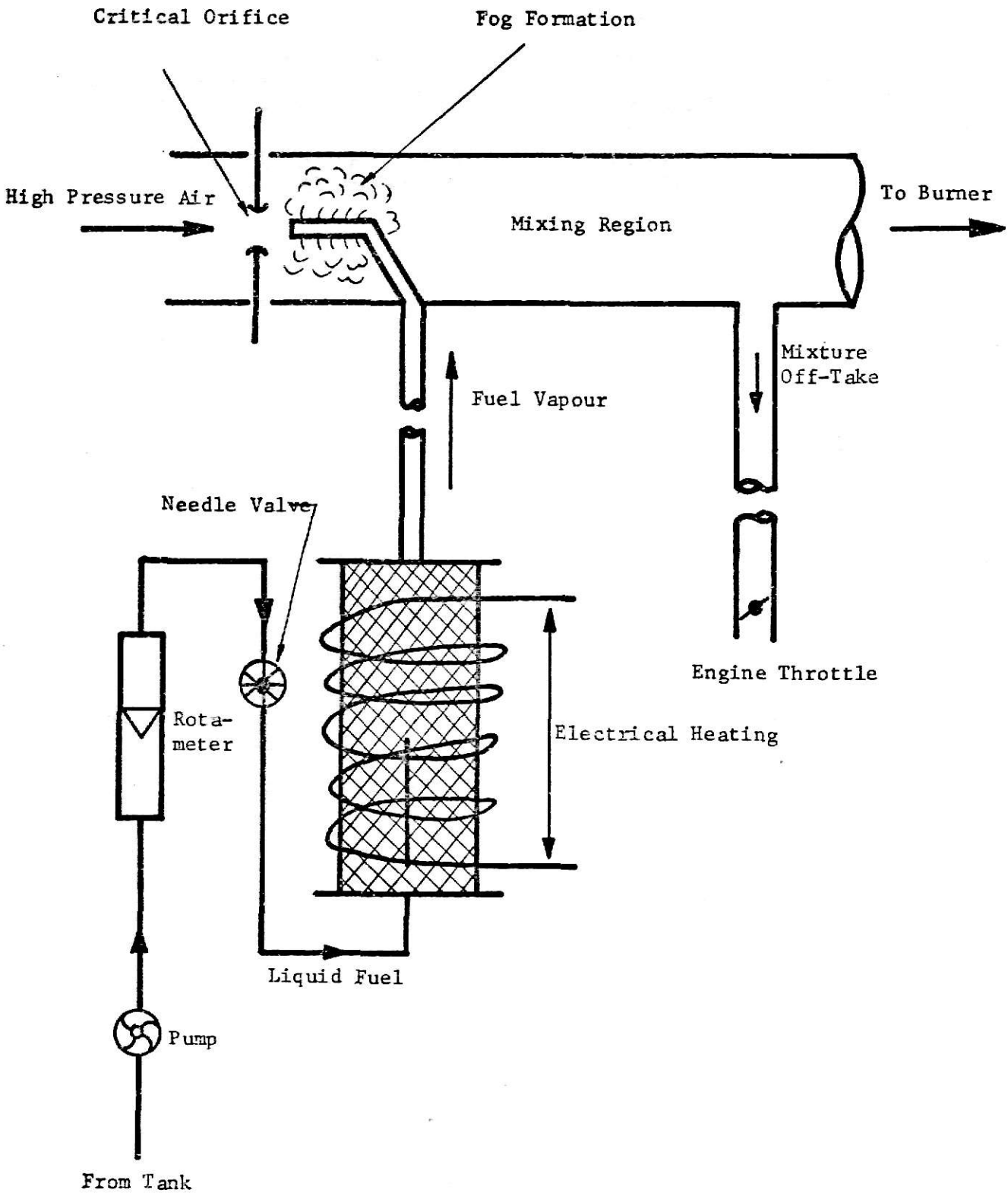


Fig. 6.23 Schematic Layout of Mixture Generator. (Fig. 2, Ref. 34).

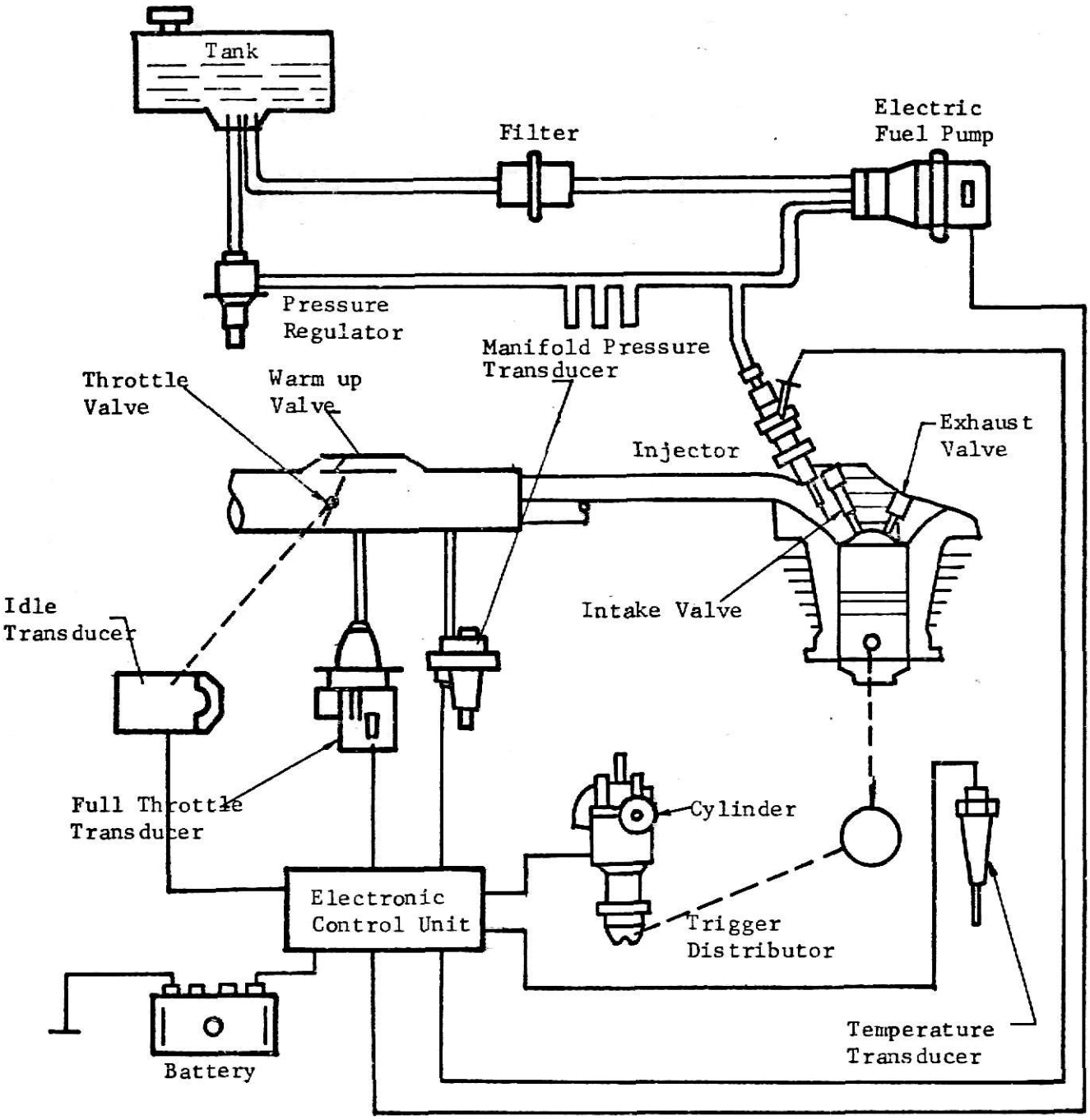


Fig. 6.24 Schematic of Bosch System Above Shows the Various Lines that Feed Information to the Electronic Computer, and Their Relationship. (Fig. from Ref. 35).

that precisely meters the fuel to the engine. The goal is to burn the exact amount of fuel needed at the moment, thereby reducing hydrocarbon and carbon monoxide emissions.

The computer directs the event of length of opening of injector valve, based on the information-engine speed, pressure, and temperature and relayed to it by engine mounted sensors.

The emissions reduced were considerable the following values were obtained for hydrocarbon and carbon monoxide emissions;

CO 0.3%

HC 180 ppm.

Changes In Valve Timing: Advancing the intake valve opening or the exhaust valve closing time can also be another method for HC and NO_x reduction in exhaust emissions. It appears that such changes in valve timing reduce NO_x by internal recirculation and HC are reduced by selective retention of HC rich quench gases [36].

The figures 6.25-6.26 showing HC and NO_x emissions as a function of intake valve opening and exhaust valve closing are presented here.

It is concluded that HC reduced by 25% and NO_x by 38% at 46° btdc intake valve opening. Similarly, with exhaust valve closing HC reduced by 25% at 22° btdc and NO_x decreased by 45% for full exhaust valve closing advance.

Variable Cam Timing: Automatic variation of I.C. Engine valve timing in response to load and speed is an effective technique for reducing emissions of oxides of nitrogen and unburned hydrocarbons. The variation employed is cam advance, which causes part of the exhaust gases normally expelled near the end of the exhaust stroke to be retained and mixed with the fresh air/ fuel mixture during the following inlet stroke. Part of the unburned Hc normally emitted are contained in these recirculated end of stroke gases, and are oxidized further by re-exposure to combustion. The peak flame temperature is reduced by the diluent and the formation of NO_{2x} is suppressed.

A prototype vehicle equipped with an automatic cam advance shows the following results [37].

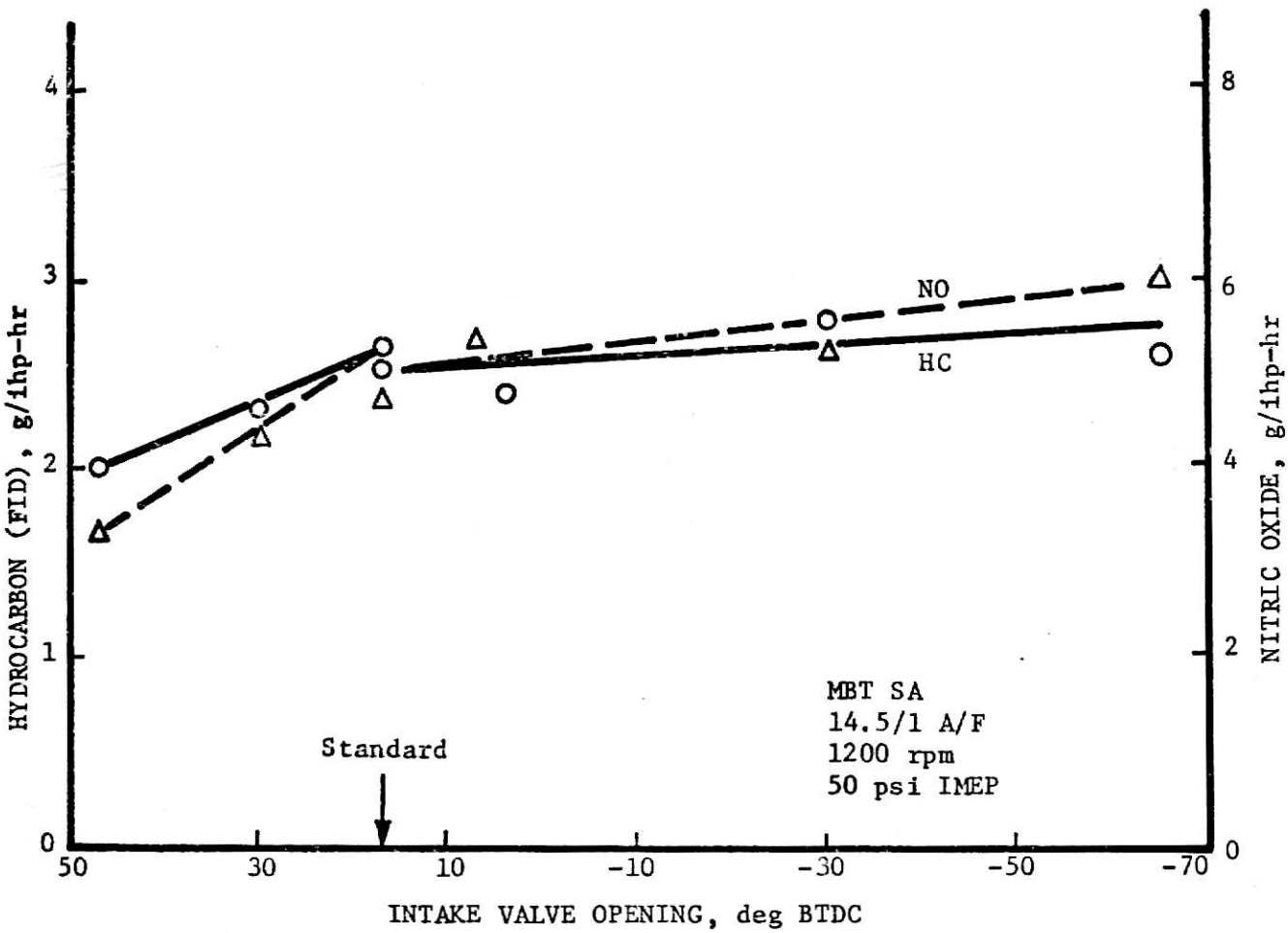


Fig. 6.25 Intake Valve Opening Time can be Varied to Reduce Hydrocarbon and NO Emissions. (Fig. 1, Ref. 36).

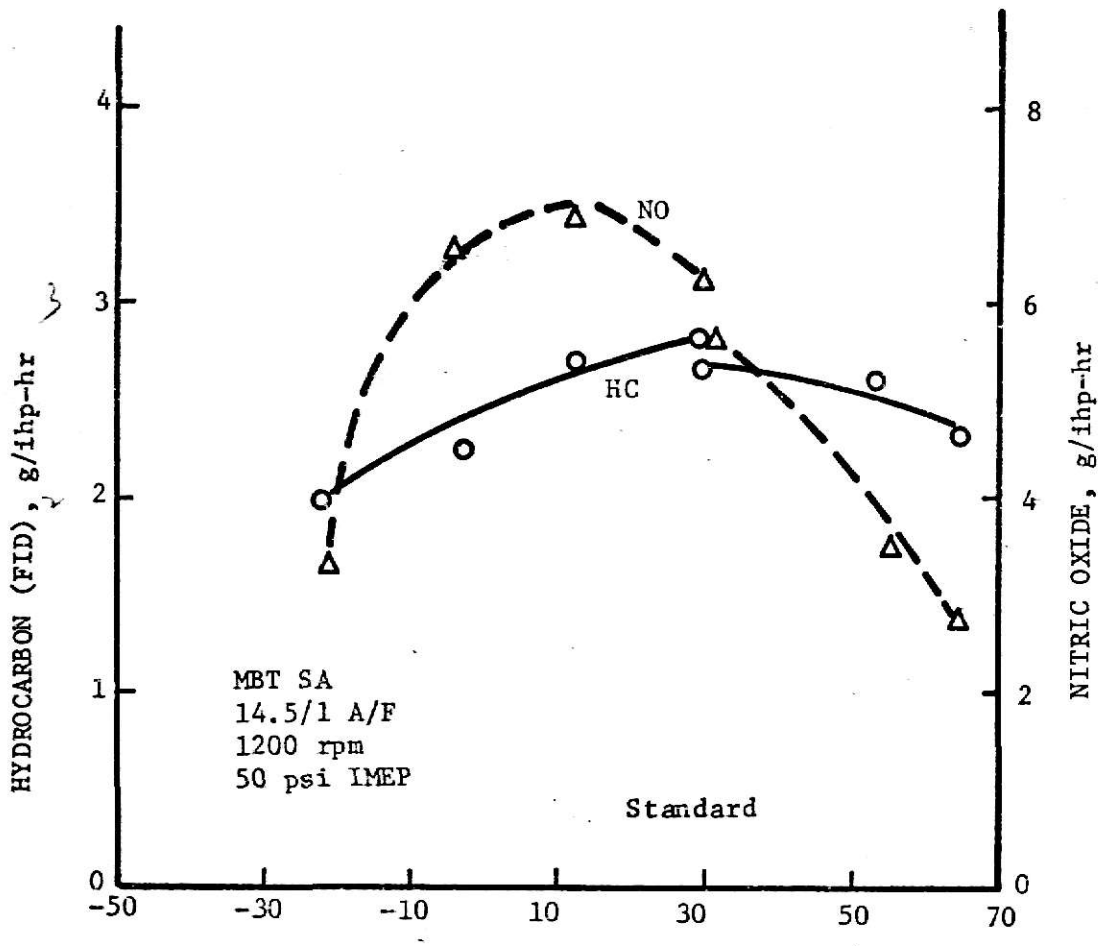


Fig. 6.26 Intake Valve Opening Time can be Varied to Reduce Hydrocarbon and NO Emissions. (Fig. 5, Ref. 36).

TABLE 6.3*

Test Results

Test Description	Result without cam advance at 16:1 A/F ratio	Result with cam advance	% difference
Cold start 1970 California test			
Unburned HC	197	134	32
NO_x	1010	363	64
Carbon monoxide	1.02%	0.85%	16.5
Gas Mileage			
City Schedule	14.1 mpg	13.5 mpg	4.25
Highway Schedule	16.2 "	14.9 "	8.03

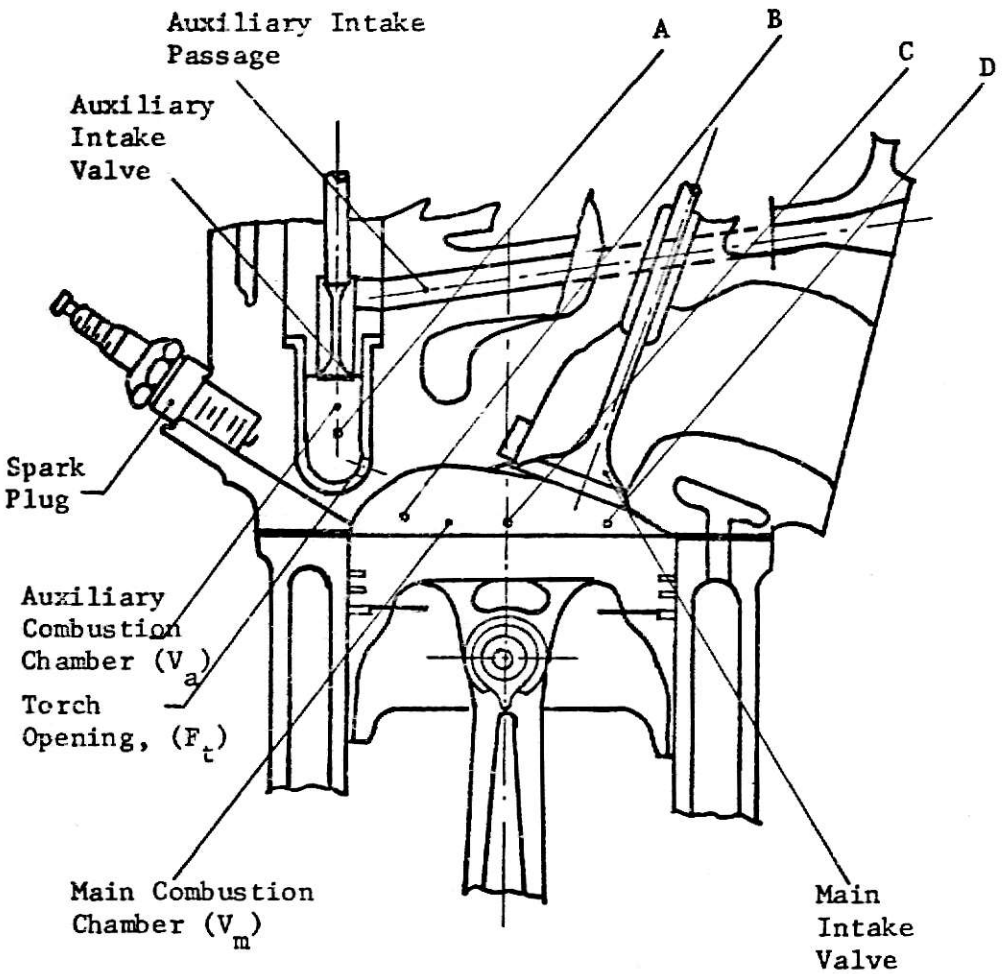
Before concluding the chapter the Honda CVCC engine will be discussed from the emission reduction point of view.

HONDA CVCC ENGINE: The Honda CVCC (Compound Vortex, Controlled Combustion) engine develops a stratified charge to produce stable combustion of an overall lean mixture. By controlling fuel mixtures supplied to the main and auxiliary chambers, and by geometrical combustion chamber design, the mixture formed immediately before ignition is such as to result in low CO, HC and NO_x emissions [38].

The auxiliary combustion chamber is located where the spark plug is installed in a conventional engine. There is a special carburetor just to supply auxiliary chamber with a rich mixture, along with a separate intake passage and a separate intake valve to control the mixture supply timing. The auxiliary chamber is connected through a torch opening to the main combustion chamber.

First on suction stroke of the intake valves for both the main and auxiliary chambers open, and a very rich and fairly lean mixture is supplied to auxiliary and main chambers respectively. Of the mixture supplied to the auxiliary chamber, however a controlled amount flows through the torch opening into the main chamber, where it mixes with a portion of the very lean mixture supplied to main chamber.

* (Table from Ref. 37).



A,B,C,D: Gas Sampling Positions
A,B : Measuring Positions of Combustion Gas Temperature

Fig. 6.27 CVCC Engine Showing Gas Sampling and Temperature Measuring Positions. (Fig. 1, Ref. 38).

During the compression stroke, reverse process takes place and richness of auxiliary mixture is reduced to assure ignition.

The figs 6.30 shows a comparison of emissions by a CVCC engine with that of a conventional engine of same size, and in the table below are compared Exhaust emissions and fuel economy for different cars with and without Honda CVCC engine.

TABLE 6.4 *

	Type	Engine displacement in^3	Exhaust Emissions, g/mile CO	HC	NO_x	Fuel Economy mile/gal.
Honda Civic with manual transmission	CVCC	91	2.42	0.24	1.38	25.5
	CVCC	119	2.12	0.18	0.89	22.1
GM Vega with manual transmission	Original	140	10.6	2.13	3.80	17.2
	CVCC	140	2.62	0.26	1.16	18.9
Chevrolet Impala with automatic transmission	Original	350	19.33	1.56	2.42	10.5
	CVCC	350	2.88	0.27	1.72	10.5

*Table 2, Ref. [38].

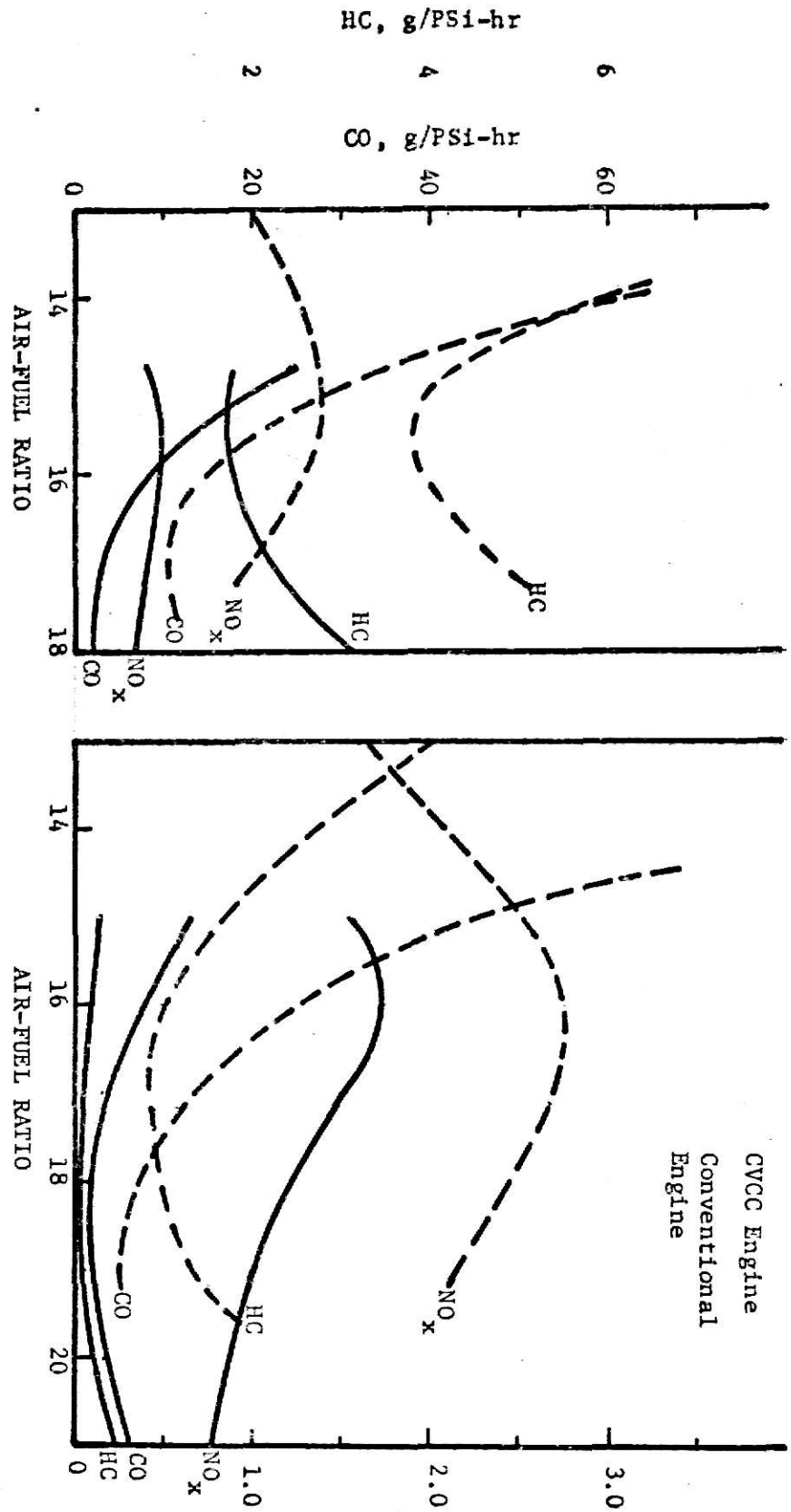


Fig. 6.28 Exhaust Gas Emissions of CVCC Engine and Conventional Engine. A: At Idling, isfc = 410 g/PSi-hr. B: At 50 mph, isfc = 220 g/PSi-hr. (Fig. 2, Ref. 38).

CHAPTER 7

FUTURE PROSPECTS

1. Alternative Fuels

Within the near future, only three types of gaseous fuels can be seriously considered as alternatives to gasoline for powering motor vehicles. (i) Liquified petroleum gas (LPG), (ii) Compressed natural gas (CNG), and (iii) Liquified natural gas (LNG). These fuels are inherently cleaner burning (produce fewer heavy hydrocarbons) than gasoline owing to their lower molecular weight and carbon content [39]. In addition, gaseous fuels ignite more rapidly and the combustion process proceeds more rapidly and more nearly to completion leaving less unburned fuel in the exhaust stream. Similar levels of emission reductions result from conversion to either LPG or natural gas (LNG or CNG).

Modification to gaseous fuel requires the installation of a special carburetor, special fuel tanks (pressure tanks for LPG and CNG, cryogenic tanks for LNG), pressure regulating devices, shut off valves, and fuel lines. Costs of simple conversion of the existing vehicles to those of gaseous fueled vehicles have been estimated. The costs for CNG or LPG range from $350 to $500, while conversion to LNG may cost from $800 to $1000.

Liquified Petroleum Gas (LPG):

Liquified Petroleum Gas, commonly referred to as Propane, is a mixture consisting mostly of propane and butane, with vapor pressures ranging from 300 to 300 pounds per square inch at normal ground level atmospheric temperatures. Due to its economic advantages, LPG can be very well used as motor vehicle fuel; as a matter of fact LPG has been in use to propel approximately 300,000 vehicles. The table below gives the breakdown figures for the LPG powered vehicles.

TABLE 7.1*

Industrial fork-lift trucks	46.8%
Farm tractors	25.0%
Buses and trucks	15.6%
Stationary engines	8.4%
Automobiles	2.9%
Truck refrigeration units	1.3%

* Page 2-2, Ref. [39].

LPG can be transported in compressed liquid form by truck trailers and delivered to pressure storage tanks. Handling procedures are well known and relatively safe. Limited quantities of LPG are available in urban areas throughout the country. The travel range of typical LPG vehicles designed for street use is approximately 220 miles.

Natural Gas:

Natural gas consisting primarily of methane may be used in compressed (CNG) form requiring heavy wall, high pressure fuel tanks. High pressures (from 1000-2000 pounds per square inch) are necessary to store sufficient CNG for reasonable travel range. This in turn necessitates a compressor at refueling points in order to boost local gas distribution pressures. Although natural gas is relatively safe from a flammability point of view, the high pressure required may constitute a significant hazard in case of breakage or disconnection of fuel lines or fittings. Approximately 2,000 experimental vehicles currently use compressed natural gas and a typical travel range is 70 miles.

Liquified natural gas (LNG) is currently being experimentally tested in approximately 200 vehicles. Unlike compressed natural gas, LNG must be transported from special storage facilities or liquification plants to refueling locations by LNG trucks. The liquid is then transferred to cryogenic vehicle storage tanks. There is currently no satisfactory odorant for LNG and therefore leakage could be hazardous. A typical travel range for LNG vehicles is 240 miles.

Emissions from Gasoline and Gaseous Fueled Vehicles

Accurate estimates of the emission reduction potential from simple conversion are not possible with present empirical data. These data are extremely limited and are based on a variety of different analytical test procedures and driving cycles. Moreover, the emission reductions achieved in each case are highly dependent on the specific engine type, conversion equipment, and engine adjustments. In order to achieve the maximum emission reduction it is necessary to detune the engine from manufacturers specifications. For these reasons, reported test results vary considerably and do not permit accurate predictions for in use

vehicle populations. Available data on individual vehicles however, do show that significant emission reductions can be realized by converting pre-1975 cars to gaseous fuels.

To help compare the reductions achieved, the Federal emission standards are also listed in Table 7.2.

TABLE 7.2*

Federal Emission Standards for Light-Duty Vehicles

(1976)

Carbon monoxide	3.40 grams/mile
Hydrocarbons	0.41 grams/mile
Nitrogen Oxides	0.41 grams/mile

TABLE 7.3+

Exhaust Emission Data From EPA For Gaseous Fueled Vehicles

Vehicle	Fuel	Emissions in g/mile HC	CO	NO_x
Converted 1968 Buick 350	LPG	3.5	4.7	8.9
Stock 1968 Buick 350		1.9	29.6	4.0
Converted 1969 Ford 351	LPG	3.1	7.3	8.6
Stock 1969 Ford 351		7.4	37.8	5.2
Converted 1968 Ford 302	LPG	2.4	4.2	1.8
Stock 1968 Ford 302		3.1	28.5	3.6
4 Converted 1969 Chrysler 318s	LPG	2.4	7.2	2.9
Stock 1969 Chrysler 318		3.4	30.5	3.6
2 Converted 1969 Rambler 343s	LPG	3.0	15.4	2.6
Stock 1969 Rambler 343		3.0	31.5	3.1
Converted 1969 Ford 429	LPG	1.3	4.0	1.9
10 Converted 1970 Ford 350s	LPG	0.69	1.8	2.6
10 Stock 1970 Ford 250s		3.70	16.0	9.4
10 Converted 1970 Rebel 232s	LPG	0.51	3.9	3.1
10 Stock 1970 Rebel 232s		2.70	22.1	6.9
2 Converted 1968 Chevrolet 230s	CNG	0.54	9.5	—
2 Stock 1968 Chevrolet 230s		3.70	58.2	--
2 Converted 1969 Ford 250s	CNG	0.46	7.8	--
2 Stock 1969 Ford 250s		2.60	25.3	--

*Table 2-1, Ref. [40].

+Table 2-2, Ref. [40].

Table 7.4 provides the information which readily shows the benefit of conversion to gaseous fuel.

Maximum Feasible Emission Reductions From Conversion to Gaseous Fuels Expressed as a Percentage of Total Motor Vehicle Emissions

The table below is for the city of New York.

TABLE 7.4*

Extent of conversion	Carbon monoxide emission reduction
Borough of Manhattan	
Conversion of all fleet and non-fleet medallion taxicabs in the 1975 Manhattan taxi population.	
Assuming 85.3% reduction from converted fleet vehicles and 90.6% reduction from non-fleet vehicles.	8.8%
Assuming 60% reduction from converted fleet and non-fleet vehicles.	6.0%
Conversion of all fleet medallion taxicabs in the 1975 Manhattan taxi population.	
Assuming 85.3% reduction from converted fleet vehicles.	5.4%
Assuming 60% reduction from converted fleet vehicles.	3.8%
Mid Town Manhattan Central Business District	
Conversion of all fleet and non-fleet vehicles, medallion taxicabs in the 1975 Midtown Manhattan Central Business District taxi population.	
Assuming 85.3% reduction from converted fleet vehicles and 90.6% reduction from converted non-fleet vehicles.	27.1%

Refers to reductions expressed as a % of emissions from all motor vehicles in Borough of Manhattan and Midtown CBD respectively.

*Table (2-7), Ref. [39].

TABLE 7.4 (continued)

Extent of conversion	Carbon monoxide emission reduction[1]
Mid Town Manhattan Central Business District	
Assuming 60% reduction from converted fleet and non-fleet vehicles.	18.5%
Conversion of all fleet medallion taxicabs in the 1975 Midtown Manhattan Central Business District taxi population.	
Assuming 85.3% reduction from converted fleet vehicles.	15.3%
Assuming 60% reduction from converted fleet vehicles.	10.8%

TRAFFIC FLOW TECHNIQUES

Traffic flow techniques refer to those traffic engineering measures that have as their principal objective a reduction in delays, idling periods and stops and starts which, in turn, would tend to increase average vehicle speeds on the existing street systems [40].

To assess the imact on air quality from various traffic flow measures, one needs to understand the relationship of speed on emissions. The results of experiments conduced on five vehicles, four controlled and one uncontrolled are shown in Figs. 7.1 - 7.3.

It is clear that while HC and CO emissions decrease with increasing speed, NO_x emissions increased at higher speeds. This partly due to higher compression ratios found in post 1966 controlled vehicles.

Measures to achieve emission reduction through improved traffic flow fall into two categories: Construction of new major traffic facilities (freeways, expressways, and major arterial linkages) and operational improvements to existing streets and highways.

Major facility construction normally enables significant increases in vehicle speed, but also tends to increase a travel demand. Consequently, a strategy to reduce a travel demand should be coupled with programs providing negative incentives or restrictions on driving. But over a short range of time the air quality impacts of new traffic facilities can be assumed positive.

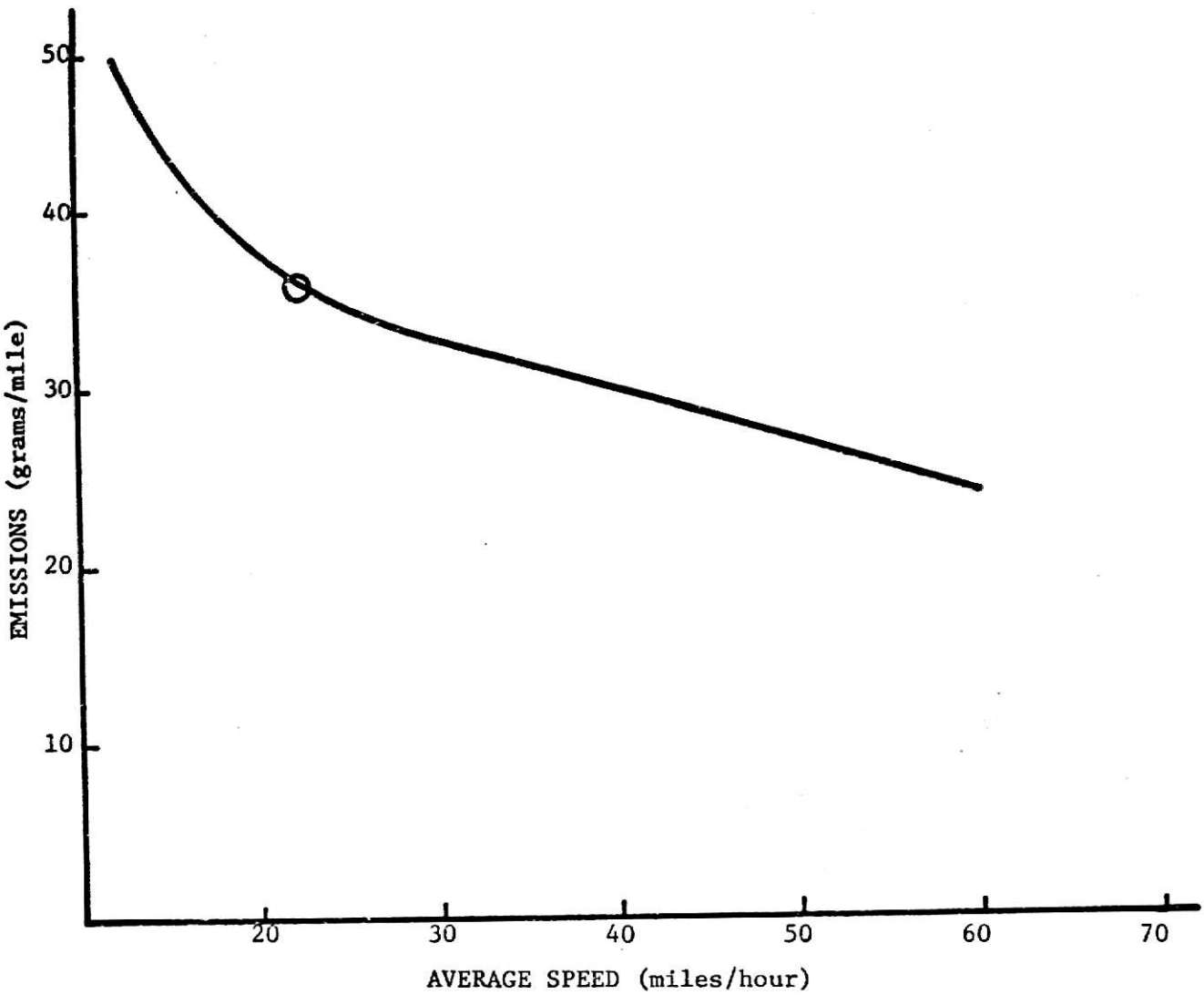


Fig. 7.1 Average Speed vs. Average Emissions (Carbon Monoxide).
(Fig. 6.1, Ref. 40).

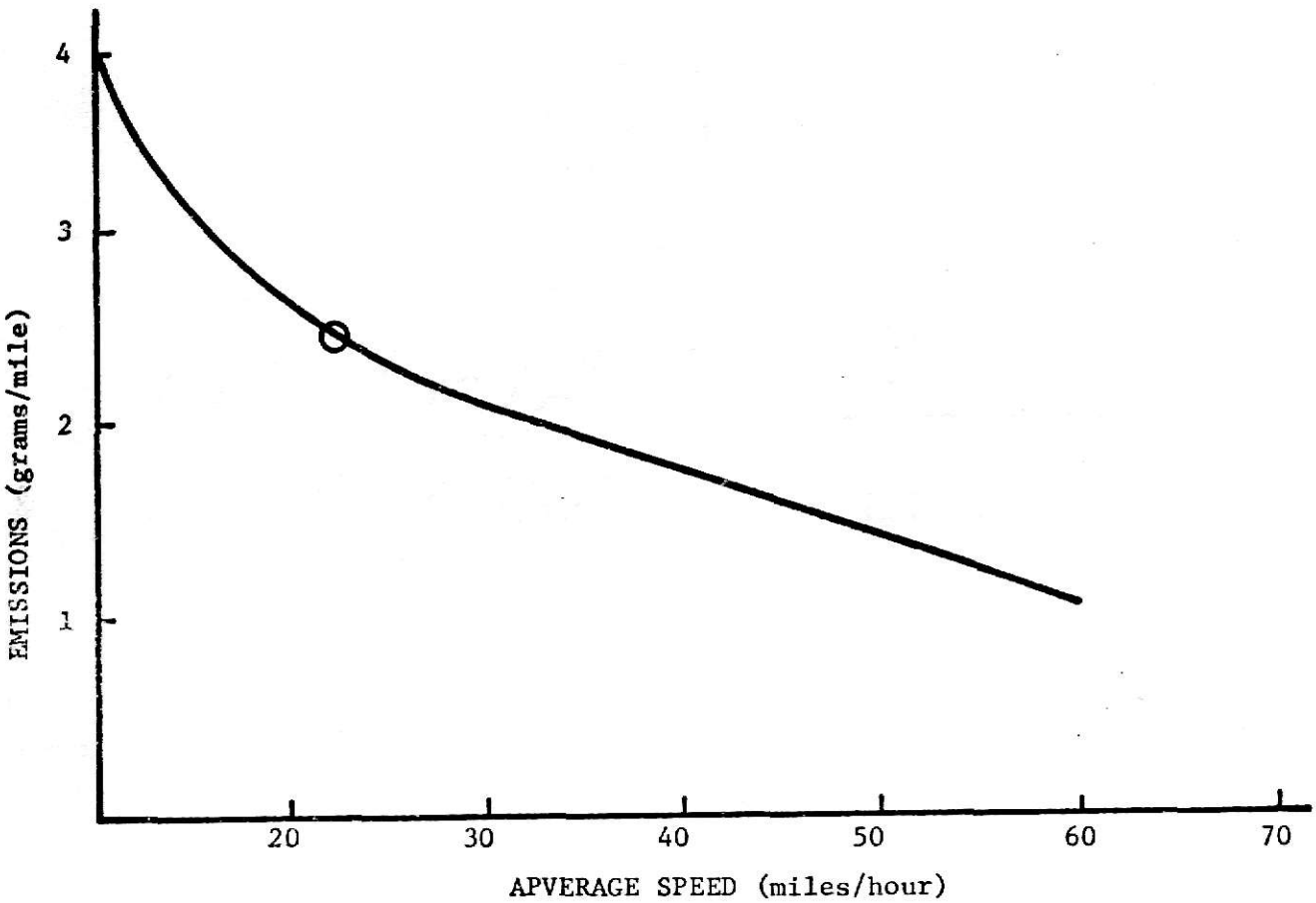


Fig. 7.2 Average Speed vs. Average Emissions (Hydrocarbons).

(Fig. 6.2, Ref. 40).

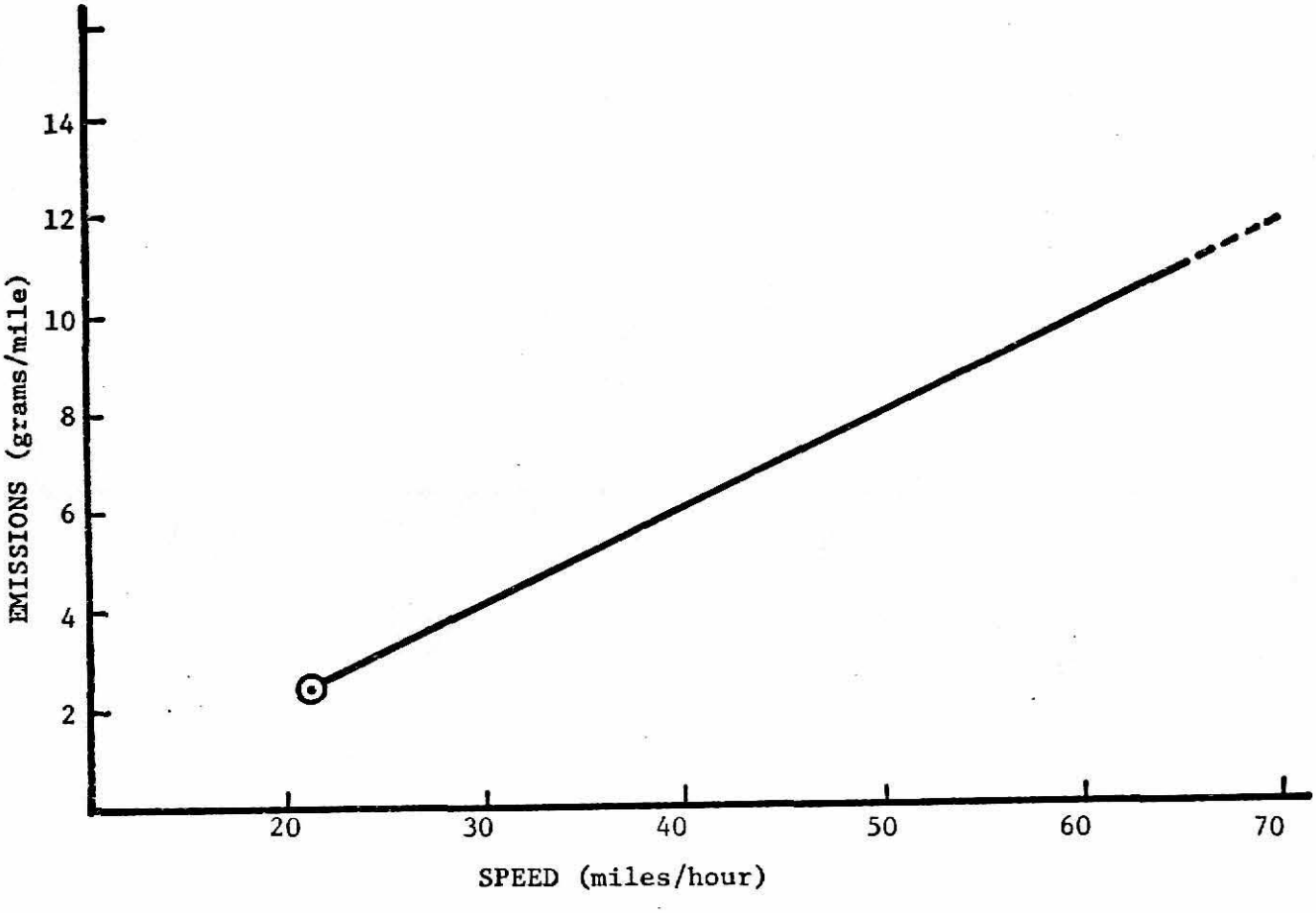


Fig. 7.3 Average Speed vs. Average Emissions (Nitric Oxide).

(Fig. 6.3, Ref. 40).

Operational improvements may be divided as; freeway improvements such as ramp metering and removal of bottlenecks, surface street improvements such as area wide signal system integration, intersection chanellisation, minor widening of streets and intersection approaches, one way systems etc etc.

In many downtown areas, loading and unloading of commercial vehicles impedes traffic flow. One effective measure to lessen the immediate problem is peak hour restriction on such operations. The long range solution is the establishment of off-street loading facilities.

Traffic flow is frequently interrupted by pedestrian movements. Pedestrian/vehicle conflicts can be minimized by special controls, creation of pedestrian malls and grade separated pedestrian traffic from vehicular traffic.

Signalization also forms an effective means of traffic flow techniques and as such this will be discussed in a sub-section.

Signalization:

Traffic signals are one of the most important measures to improve traffic flow. One recent study of eleven experiments with signal controls (five involving single intersections and six involving coordination of signals on arterials or in networks) concluded that; [39]
The signal system of a downtown area is the most important of all the control media available. Very minor changes of signal timing produced large improvements to traffic flow. Many other types of improvements should be considered subservient to the needs of the signal system. Among these are restrictions to parking at intersection approaches, locations of bus stops provision of separate left turn lanes, mandatory lane use, and chanellization, all of which, at least to some degree, are involved in optimizing the signal system. The availability to organize successfully progressions depends largely on the reductions of frictions by use of these other control media.

The conventional practice of signal systems was based upon estimates of flow, historical data, and averages and observations. Given the requirement that cross-traffic on city streets be accomodated, the potential for improvements with a modern control signal system is substantial.

In one large city where computer controlled traffic signal timing tests were conducted, reductions in travel time ranged from 26 to 39 percent and reductions in number of stops ranged from 60 to 86 percent. In another city, network delays were reduced by 14 percent and the probability of a vehicle being stopped was reduced by 17 percent. In a medium sized city, delays were reduced by 18 percent and peak hour average speeds were increased between 10 and 15 mph [41].

To summarize the effect of the potential of traffic flow techniques, we quote the specific cases below;

A project was implemented for a computer controlled, fully interconnected signal system in downtown Spokane, Washington to be completed by 1975. It is estimated that a 2 mph increase in average speeds will result. It is also estimated that the emission reduction would be from 3.7 to 6.2 percent [42].

In Newark, resulting from improved signal progression travel speeds increased from 9.8 to 121.6 percent. In Louisville, the increased speeds ranged from 0.7 percent to 24.3 percent.

In Kansas City, Missouri, an improved signal timing program (SIGOP) produced 18.5 percent fewer stops and increased speeds by 12.2 percent.

The following results were reported by the Stanford Research Institute on increased travel efficiency by computerized traffic signal systems:

New York	20-40% reduction in travel time.
London	9% reduction in journey time.
Toronto	8 to 37% reduction in delay.
Glasgow	12% reduction in journey time.
San Jose	10 to 12% reduction in delay.

Work Schedule Changes

Spreading journey-to-work traffic over the peak hours could contribute significantly to reducing motor vehicle emissions in cities. During the peak hours vehicle speeds are heavily brought down and engine operating efficiency is further reduced by idling and stop-and-go-traffic.

Figure 7.4 shows the variation of traffic density of people starting for work in Manhattan, NY central business district.

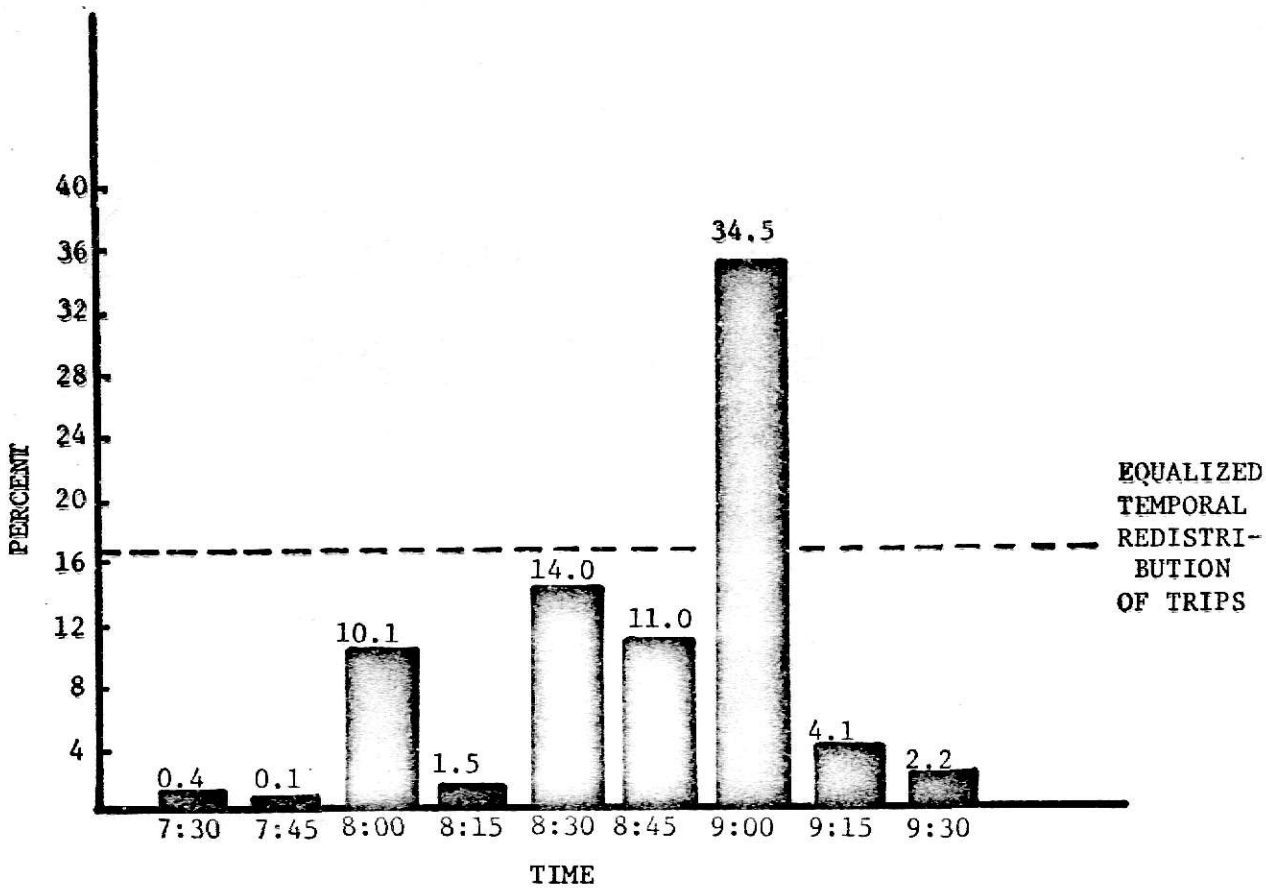


Fig. 7.4 Estimated Percents of People Starting Work in Manhattan CBD. (Fig. 7-6, Ref. 39).

It can be seen that a total of 82.9% of work force starts between 7:30 and 9:30 a.m., with high traffic densities at 9:00, 8:30, 8:45, and 8:00 a.m. Distribution of this traffic uniformly over the five-hour time intervals would make optimal use from a pollution control standpoint. This is shown by the dotted line which represents 16.6% in each one half hour.

In addition to improving traffic flows, another strategy, that is a 4-day work week could contribute to reducing motor vehicular emissions in another important way, i.e. by reducing total work trips.

A variety of 4-day work week arrangements are possible as shown in the following table.

*TABLE 7.5

Possible Arrangements of a 4-Day Week

4-Day Employee work schedule	Percent of Employees on 4-day working a given day					
	M	Tu	W	Th	F	S
1. Equally rotated	80	80	80	80	80	
2. $\frac{1}{2}$ M-Th; $\frac{1}{2}$ Tu-F	50	100	100	100	50	
3. Equally rotated M-S	67	67	67	67	67	67
4. $\frac{1}{3}$ M-Th; $\frac{1}{3}$ Tu-F; $\frac{1}{3}$ W-S	33	67	100	100	67	33
5. $\frac{1}{2}$ M-Th; $\frac{1}{2}$ W-S	50	50	100	100	50	50

In an attempt to quantify these reductions, a recent study was made on the impact of the 4-day week on Los Angeles freeway travel during the peak hours. The findings are tabulated in Tables 7.6 and 7.7.

*Table 7-2, Ref. [39] .

*TABLE 7.6

Weekly Impact of 4-day Work Week on Conditions
At a Freeway Bottleneck

	Weekly Work Schedule Percent Working on Day Shown						15 Minute Periods Demand Exceeds Capacity	Excess Demand Over Capacity (Vehicles)	Reduction From Current Conditions (%)
	M	T	W	T	F	S			
1.	80	80	80	80	80	0	15	2885	68
2.	50	100	100	100	50	0	28	4011	56
3.	67	67	67	67	67	67	12	2484	73
4.	33	67	100	100	67	33	22	3328	63
5.	50	50	100	100	50	50	24	3298	64

+TABLE 7.7

Daily Impact of 4-day Work Week on Conditions
At a Freeway Bottleneck

Percent of 4-Day Employees Working	Number of 15 Minute Period Demand Exceeds Capacity	Excess Demand Over Capacity (Vehicles)	Reduction from Current Conditions (%)
100	8	1,181	33
80	3	577	69
67	2	414	77
50	2	234	87
33	1	69	99

*Table 7-4, Ref. [39].

+Table 7-3, Ref. [39].

Alternative Modes of Transportation

The alternative modes of transportation systems may be classified as mass transit systems, (rail and bus systems), car pools and people movers.

i) Rapid transit system: These are rapid rail systems which are particularly suited for line haul high density corridors in heavily populated areas. Passenger capacities of these systems range from 30,000 to 60,000 persons per hour for each track [39].

Examples of this type of system are the Bay Area Rapid Transit System (BART) in San Fransisco, and Metro in Washington D.C. However conversion to such a system requires long term planning and may take years to overcome the hurdles such as requirement of rights of way because of legal, technical and political difficulties. However, the construction of the existing systems appears to be promising in the short term. Rail ridership of the existing facilities may be increased with measures such as 1. Reducing Fares 2. Increasing comfort cleanliness and safety. 3. Increasing service frequency. 4. Providing park'n ride at the rail stations. and 5. Improving Fare collection.

ii) Bus Systems: Bus systems present a promising area for improvement of public transportation. As a matter of fact 70% of Transit Service travellers make use of bus. Ample passengers attraction could be gained by various means, such as follows; [43]

A deduction of fare from 40 cents to 15 cents in bus fares in Atlanta reduced the automobile population of 20,000 from the roads more than half of them in peak commuting hours.

A no fare zone bus program in Seattle increased the ridership by 56%. This program costs the city $64,000 a year but reduces the air pollution considerably.

Tulsa reduced bus fares to 25 cents with the result that the ridership increased by 50%.

Bus service may also be enhanced by; 1. Exclusive bus lanes 2. Bus priority systems and 3. A variety of operational and service improvements.

iii) Car Pools: Car pools may be defined as the shared use of private passenger cars especially for the journey-to work. Encouragement of car pooling may take the form of tax relief or rebates, eligibility to use otherwise restricted lanes, preferences or reduced prices for parking bridge or tunnel tolls and improved information (e.g. a computerized car pool information service to facilitate formation of car pools).

Car pools have high potential for alleviating congestion at peak hours. An average occupancy of 1.5 riders has been observed for most American cities and downtown areas. Increasing this to 2.0 would create a 25% reduction in traffic [39].

The following figure shows the Average Automobile Occupancy rate vs percent reduction in total daily VMT (vehicular miles travelled).

People movers: People movers may be defined as grade-separated systems of small dimensions operating at moderate to low speeds with continuing access to the service at frequently spaced stations. Capacities will range from 2,000 to over 10,000 riders in the hours.

The principal role of people movers is to move large volumes of people to and from transportation facilities and to provide distribution routes in and around central business districts [39].

Other Strategies

1. Inspection & Maintenance: Inspection/Maintenance approaches reduce emissions from in-use motor vehicles by insuring that the auto population is maintained in a manner sufficient to keep emission to a minimum. This approach is generally implemented by requiring regular mandatory maintenance. It has been demonstrated that significant emission reduction can be achieved by the proper servicing of the vehicle population [40].

In the state of California, several inspection programs have been proposed, for instance:

A large number of people mover concepts have been proposed and several are currently in use. A typical system would consist of small (i.e., one or two passenger capacity with room for parcels) automatically controlled capsules. Passengers using the system would enter the capsule at one of many sidings and push a start button. The capsule would be automatically merged into main line traffic. Deceleration would be done automatically when the capsule is turned into a riding.

i) The certificate of compliance: This includes a sequence of operations which involve inspection and servicing of crankcase devices and exhaust emission control systems. The detailed procedure is specified in a handbook of the Department of Consumer Affairs.

ii) The Idle inspection: is performed by operating the vehicle at idle and analyzing a sample of exhaust to determine pollutant levels.

iii) The Diognostic Inspection: The vehicle is operated on a chassis dynamometer and engine analysis equipment, the vehicles exceeding the established limits are diognized by diognostician and then repaired.

iv) The annual adjustment and maintenance procedure: is a mandatory maintenance program in which the vehicle is repaired and adjusted to prescribed specifications prior to test, adjustments are made according to specified procedure.

Retrofit Systems: Exhaust control systems for retrofit on most 1968 cars have been developed by various auto manufacturers and generally follow a somewhat similar approach (combining modifications and adjustments to the carburetor, distributor and the vacuum advance and installation of a retrofit device) [40].

For the whole nation as a whole, pre-controlled vehicles (pre-68) will account for approximately 17 percent of the vehicle miles travelled in 1975, at which time a 25% reduction for these vehicles would yield an aggregate reduction in carbon monoxide of 5.7%.

The following table shows the costs and effect of retrofit control measures.

TABLE 7.8*

Retrofit Control Measures

	Installed Cost	Average Reduction per Vehicle HC	CO	NO_x
Pre-controlled Vehicles				
Lean Idle Air/Fuel Ratio Adjustment and Vacuum Spark Advance Disconnect	$ 20	25%	9%	23%
Oxidizing Catalytic Converter and Vacuum Spark Advance Disconnect	195	68%	63%	48%
Air Bleed to Intake Manifold	60	21%	58%	0%
Exhaust Gas Recirculation and Vacuum Spark Advance Disconnect	110	12%	31%	48%
Controlled Vehicles				
Oxidizing Catalytic Converter	$175	50%	50%	0%
Exhaust Gas Recirculation	90	0%	0%	40%

*Table 4.4, Ref. [40].

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AUTOMOBILE GENERATED

AIR POLLUTION

by

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The purpose of this report is to discuss the causes and effects of auto generated air pollution, the instrumentation and Federal Test Procedures involved, the controls which may be feasible and the future prospects.

Out of the many pollutors, emphasis is put on the major three gases, carbon monoxide, hydrocarbons and oxides of nitrogen.

Engine exhaust system discharge comprises a major part of the air pollutants, which are the result of automotive emission. Another important emission path is through the engine crankcase.

Emission also comes from evaporation of gasoline from the tank and from the carburetor.

The harmful effects of air pollution due to automotive emission on human health, animal life and vegetation are discussed. Effects upon global climate is also discussed.

The instrumentation needed for the correct measurement of the various pollutants and the Federal Test Procedures are also discussed.

The various controls which would be effective are discussed under the subheadings of controls for carburetor and fuel tank evaporations, controls for crankcase emissions and controls for exhaust pipe.

The last chapter contributes to the future prospects of this problem. Various means of reducing air pollution other than the present controls are discussed.

The potential of mass transit is emphasized, also discussed are traffic flow techniques, staggering work hours and alternative fuels.