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Automobile Emissions — A Study in Environmental Benefits versus Technological Costs

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SOCIETY OF AUTOMOTIVE ENGINEERS, INC.

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THE PROBLEM of air pollution has existed ever since our ancestors sat coughing around a smoky fire in a recessed cave. In fact, there probably never was an unpolluted atmosphere, since decaying vegetation and animal matter, forest fires, dust storms, volcanoes, and other natural phenomena surely have emitted gaseous and particulate matter ever since the world began. Fortunately, our atmosphere is continually being cleansed by natural means—for example, removal of particulates by settling and by precipitation and consumption of carbon dioxide by growing plants. Thus, from the beginning of the world the condition and concentration of many of the components of our atmosphere has been influenced (and perhaps determined) by the relative rate of these additions and removals.

In the past the rate of these additions has been determined primarily by natural events. Consequently, over most of geological time the condition of the atmosphere has not changed rapidly, except for major isolated events such as volcanic eruptions, etc. Inside the last century, however, man-caused atmospheric additions have become increasingly important—possibly even to the extent of almost determining the trace constituents of the atmosphere in many places. The increase in man-caused additions has resulted from dramatic increases in both population and industrialization in the past few centuries.

Fig. 1 (1)* shows the population increase as a plot of population versus time—note the logarithmic scale as well as the extrapolation to the year 2000. The number of "contributors" to the atmosphere is increasing at an increasing rate! At the same time, especially in the United States but also in the world as a whole, the "contribution" per person has also increased dramatically. Fig. 2 presents a plot made by Magill (2) showing one "contribution" criteria: energy consumption per capita in the United States as a function of time. Fig. 3 shows the energy consumption for the world as a whole (3). You will recognize, of course, that energy production "contributes" to atmospheric pollution both directly and indirectly. Not only are our number of "contributors" increasing dramatically, our "contribution" per person to the atmosphere is increasing dramatically also.

As a result of these trends, there is well-founded concern—and considerable evidence—that these dramatic increases in man-caused additions to our atmosphere are markedly chang-

*Numbers in parentheses designate References at end of paper.

ABSTRACT

Recent increase in man-caused additions to the atmosphere are markedly changing its quality. With rising population, these additions will increase in the future. This paper discusses the magnitude of the overall problem in relation to mass rate balances for particulate matter, carbon dioxide, nitrogen oxides, sulfur dioxide, lead, and hydrocarbons. Pollution from automobiles is then discussed specifically, along with some possible solutions (both with the existing reciprocating engine and alternate power sources), the effect of controls, and the long-term reduction of emissions.

Methods of cooperation between government, manufacturers, and the public are suggested.

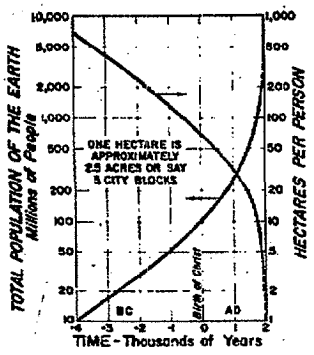

Fig. 1 - Population growth

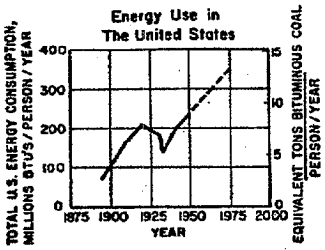

Fig. 2 - Energy use per capita in United States, 1875-1975

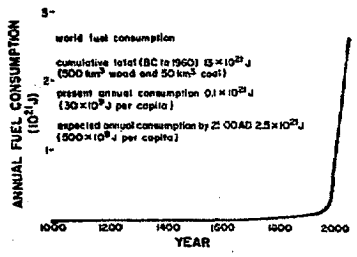

Fig. 3 - Annual fuel consumption for world

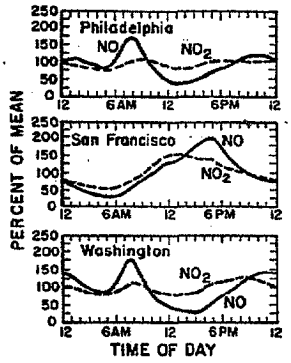

Fig. 4 - Diurnal variation patterns of NO_x

ing its quality. This concern is highlighted by evidence such as recurrent "photochemical smog" in Los Angeles, the deaths of 4000 people as a result of the 1952 London Fog, or 20 people in the small town of Donora, Pa., in 1948, the "Yokohama asthma" experienced by American Troops stationed in Japan after World War II, and the rapid growth in the phenomena of lung deterioration called emphysema.

About 20% of the energy consumed in the United States is used in automobiles (3). Thus, the automobile has been, and is, still under severe attack as a "polluter." Some people feel the criticism is too harsh and that significant advances have been made (4); others feel that the situation is urgent and immediate action is required (5). However, we, as automobile engineers, should not be too discouraged, for it has been shown that pigeons (6) also contribute significantly to airborne particulate matter in New York City. In any event, we, as engineers concerned with technical and technological feasibilities and relative costs, have a special interest and role to play in the problem of air pollution—so let's try to assess the magnitude and urgency of the problem. After having done this, let's next look at the automobile as a source of pollution and what can and is being done about it.

AIR POLLUTION—URGENCY AND MAGNITUDE OF PROBLEM

Air pollution is a very complex problem and much of the data required for realistic evaluation are missing. First of all, air pollution varies with time at a fixed point (both daily and annually) and has long-term trends as well. Furthermore, these trends may vary with time in a different way at different locations as shown in Fig. 4 (7). Thus, one must be concerned with the maximum value of a pollutant as well as time and space averages. At the same time, at the low concentrations found in the atmosphere, the effects of many pollutants on health is not well established.

Fundamentally, there is a conflict today between man's technological and biological needs and because of insufficient data, judgments and evaluations are involved.

MASS RATE BALANCES - Our atmosphere—like any life-sustaining environment—is self-cleansing with contaminants continually entering and leaving the atmosphere. Thus, the concentration of many of our pollutants is affected by the mass rate of addition and removals; in a simple sort of way it is like a pail of water with a hole in it—under steady-state conditions the level of water is determined by the rate of addition and removal of water, but during times of change the size of the pail is of interest also. Let us then look at the mass of the pollutant in our atmosphere as well as the mass rate of additions to and removal from the atmosphere.

In looking at the mass rate of additions, we recognize that they can arise from natural or from man-caused events. However, the rate of removal is primarily due to natural events. Since man-caused events are of fairly recent origin, we will particularly note the relative size of the man-caused additions in comparison with the size of the natural additions.

On a global basis, the total mass of the earth's atmosphere is estimated as 5.7×10^{15} tons of major components plus selected trace constituents as shown in Table 1. However, my friends in meteorology tell me that the rate of atmospheric mixing between the northern and southern hemisphere is very

Table 1 - Mass and Lifetime of Selected Atmospheric Constituents

Lifetime		Mass in Entire Atmosphere, tons X 10^{15}	Approx. Mass in 30-60 deg Atmosphere, tons X 10^{15}	Approx. Mass in Los Angeles Basin, tons X 10^{10}
	N_2	4.25	0.55	2.66
	O_2	1.3	0.17	0.82
		tons X 10^9	tons X 10^9	tons X 10^4
Years	CO_2	2800	–	–
Years	CO	0.6	–	4
Days	NO_x	0.009	0.002	1
Years	CH_4	5	–	–
		tons X 10^7	tons X 10^7	tons X 10^4
Days to years	Particulate matter	15.5	3	0.6
Days	SO_2	0.25	0.05	0.3

slow, in fact, they suggest that the portion of the atmosphere lying roughly between 30-60° N latitude and below 30,000 ft (a little less than 20% of the total)* be considered as an isolated system except for very long times. Table 1 also shows the order of magnitude of lifetime in the atmosphere of selected trace constituents. It seems logical to consider the 30-60° N portion of the atmosphere as a system for those constituents having a lifetime measured in days and the entire atmosphere for those measured in years.

Aside from obtaining the numbers, determining mass rate additions to the atmosphere poses problems. Much of the world's industry is located in the 30-60° region of the northern hemisphere; consequently, much of the man-caused additions probably originate within this section of the atmosphere even though they are normally given on a world-wide basis. However, natural additions and removals correspond more nearly to a worldwide basis. Some of the contaminants originating over the ocean may be entirely destroyed over the ocean and thus have but little effect on mankind. Very little precision is claimed for any of the numbers shown in the mass rate balances.

It will be impractical to identify the source of every estimate. The Air Conservation Commission (8), Sittig (9), Jaffee (10), Magill (2), National Conference on Air Pollution (53), Erikksson (11), Kehoe (12), Stopps (13), California Department of Public Health (14), U. S. Department of Health, Education and Welfare (15), Hovey (16), Altshuler (17) Robinson (18), as well as many other sources, have been used.

PARTICULATE MATTER - Natural events, such as meteoric dust, volcanic eruptions, dust storms, natural fires, etc., all contribute to particulate matter. However, human activities contribute directly to particulate pollution and may cause increased natural event particulate pollution.

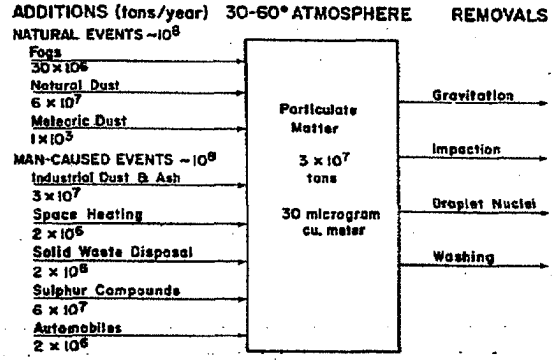

Fig. 5 - Mass rate balance for particulate matter

Fig. 5 presents a mass rate balance for particulate matter. The inclusion of the gas sulfur dioxide in the particulate mass balance needs explanation. A large percentage of the sulfur dioxide in the air oxidizes to sulfur trioxide which forms sulfuric acid mist. The sulfuric acid in the aerosols reacts with other materials in the air and forms, among other things, ammonium and calcium sulfate. The available evidence suggests that a substantial portion of the atmospheric sulfur dioxide is directly neutralized by ammonia, calcite dust, or one of the many other airborne alkalies and is then rapidly oxidized to the corresponding sulfates (19). Fog is included as a matter of interest rather than concern with it as a pollutant.

Fig. 5 indicates that the man-caused additions are approximately equal to the natural additions and that both are larger than the mass in the atmosphere. This is in agreement with the estimate of Junge (20) that the mean life time of particulates varies from a few days to a few years depending on particle size.

*As will become more evident later on, mass rate additions are known with very little precision. In fact, in some cases, they are really estimates. We will indicate this lack of precision by rounding of numbers.

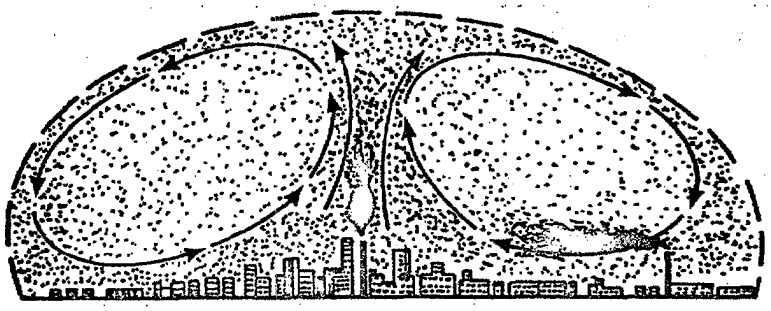

Fig. 6 - Self-contained dust dome of a large industrial city showing how air circulation patterns intensify air pollution

Remembering that the Los Angeles basin is not a fixed-mass atmospheric system (but nevertheless assuming a fixed-mass system), it is interesting to compare mass rates for that area. It is estimated (21) that there are 170,000 tons per year of particulate matter (including sulfur dioxide) descending upon the Los Angeles area per year. The mass of dust in the air over Los Angeles is estimated at 6000 tons, that is, the annual mass input rate is some 30 times the mass in the atmosphere.

There is considerable evidence that suggests that the density of particulate matter is increased over industrial areas by a self-contained dust dome as postulated by Bryson (22) and illustrated in Fig. 6. All the evidence indicates that only urban areas 6 miles or more in diameter have circulation patterns that sustain a dust dome. The dust dome is caused by the energy released by fossil and nuclear fuels in a city, by the increased absorption of solar radiation, and by the decreased energy going into evaporation because the land is covered by pavement rather than vegetation. All of these combine to cause a chimney effect over the city with consequent air inflows as shown in Fig. 6.

Particulate matter has the obvious effects of decreasing visibility and increasing soiling and corrosion. From a health standpoint, it is estimated that an individual breathes about 1 mg suspended matter per day during times of heavy pollution (23). The larger particles are undoubtedly collected by the mucous lining, but the smaller particles usually reach the deeper structure of the lungs.

There is also considerable concern that increased particulate concentrations in the atmosphere may cause significant weather modifications. Bryson (24) has made the plot shown in Fig. 7 illustrating the changes in CO_2 concentration and dust concentration from 1880 to 1960. He suggests that the data indicate that since 1930 the increase of dust has begun to dominate the carbon dioxide effect, terminating the warming period and producing a decline in world temperatures.

To summarize, man-caused particulate mass rates are beginning to be of the same order of magnitude of those caused by natural events and on an annual basis both are larger than the storage in the atmosphere.

CARBON DIOXIDE - Carbon dioxide is not normally considered as a pollutant—it is essential for plant life. There has, however, been increasing concern about its potential for modifying our climate (25) by modifying the energy balance of the

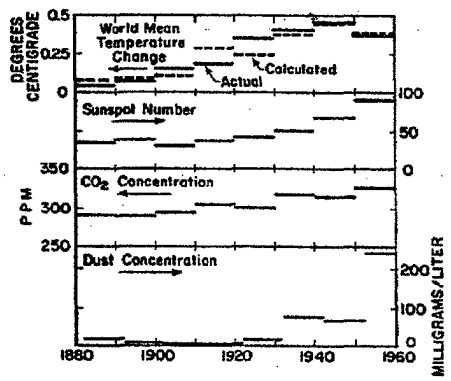

Fig. 7 - Changes in dust concentration, CO_2 concentration and world temperature with time.

earth, that is, the greenhouse effect. Reasons for this are shown in Fig. 7 where the rising mean temperatures correspond to rising CO_2 concentrations—and rising sunspot number also!

Fig. 8 presents comparative data on tonnages of CO_2 involved. Note the logarithmic scale. The total amount of CO_2 added to date by combustion is not large: say, 10-15% of that present in the atmosphere. It does appear, however, that approximately one-half of the CO_2 added by combustion is currently being stored in the atmosphere. Since the total CO_2 that could be added, if all fossil reserves were burned, is some 5-10 times the CO_2 in the atmosphere, there is an ultimate potential for significant changes of the atmospheric concentration of CO_2.

Fig. 9 shows a mass rate balance for CO_2. The primary source of CO_2 from natural events is decay of organic material, although respiration amounts are large and will increase as the population increases. Note that combustion is the primary source of man-caused CO_2 and that the natural and man-caused amounts are of the same order of magnitude.

One big removal source is, of course, photosynthesis by plants. Another big source is the ocean, but absorption rate data are lacking. The potential is there—the ocean could hold some 50 times the amount of the CO_2 in the atmosphere.

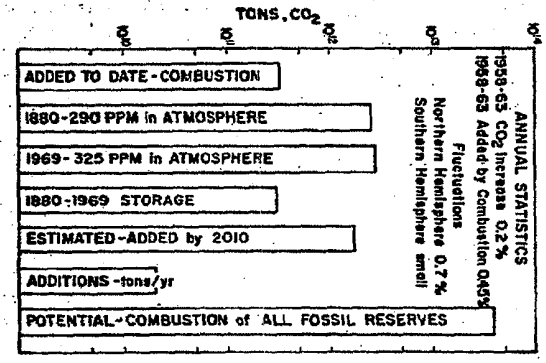

Fig. 8 - Tons of CO_2 in and added to atmosphere

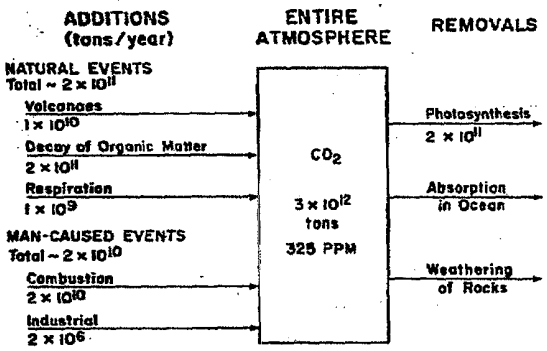

Fig. 9 - Mass rate balance for CO_2

However, the oceans circulate slowly (26) and CO_2 can be stored (and released) by carbonates (27) in the sea water. Thus, the best estimates are that the CO_2 concentration will continue to increase and could become large enough to cause climatic changes.

CARBON MONOXIDE - Aside from CO_2, carbon monoxide is the most abundant and widely distributed pollutant. Very little CO is due to natural events, almost all is from man-caused events. Approximately 90% of man-caused CO is from automobiles. Thus, it is not surprising that the correlation between carbon monoxide and traffic is excellent, as shown in Fig. 10 (28). However, some carbon monoxide does come from natural events such as marsh gas, coal mines, seed germination, lightning storms, injured vegetation, forest fires, etc. (10).

Destruction of carbon monoxide is almost entirely by natural events, all poorly understood and possibly unknown. Jaffe (10) states, "The removal process or processes cannot, at the present time, be identified with certainty." The duration of CO in the atmosphere is equally uncertain and has been estimated as low as 0.3 years (20) and as high as 5 years (29).

An estimated mass rate balance is shown in Fig. 11 for carbon monoxide. Because of the uncertainties, no mass rate of destruction is shown. The mass rate additions are beginning to approach the order of magnitude of the mass in the atmosphere.

On a local basis the figures are even more striking. In Los

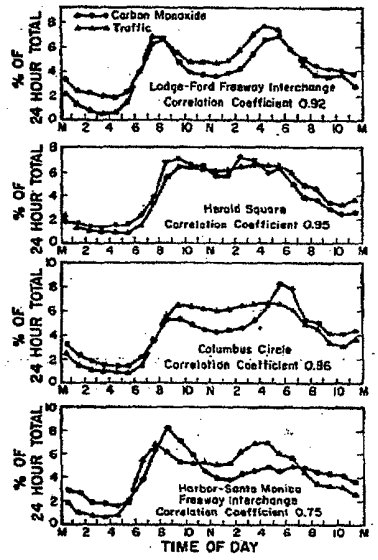

Fig. 10 - Correlation between carbon monoxide concentration and traffic patterns during day

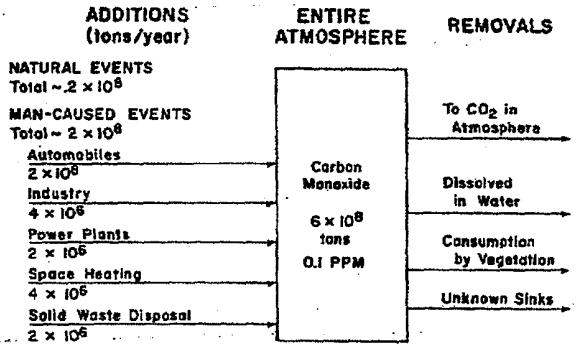

Fig. 11 - Mass rate balance for CO

Angeles, for example, about 4×10^6 tons per year of CO are added to the atmosphere (21). If the Los Angeles basin is again assumed to be a closed system (during temperature inversions, this might be a better assumption than first thought) the Los Angeles atmosphere would have of the order of magnitude of 4×10^4 tons of CO in it, that is, the annual additions would be some 100 times the mass of the carbon monoxide in the Los Angeles atmosphere. The Air Conservation Commission (8) found that in Los Angeles the time-and-space-averaged concentration of carbon monoxide increased from about 7 ppm to about 11 ppm from 1957 to 1963, which is not surprising even considering that Los Angeles is not a closed system. Since 1966, when control devices on automobiles were instituted, the concentration of CO in Los Angeles has been slowly dropping (30).

Let us next look at carbon monoxide from a health standpoint. Carbon monoxide is dangerous because it has a strong affinity for hemoglobin, which carries oxygen to body tissues. Thus the effect of carbon monoxide is to deprive the body tis-

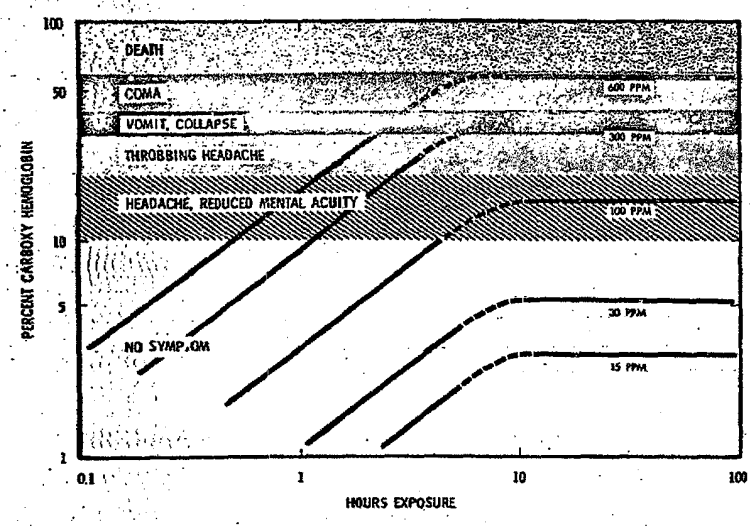

Fig. 12 - Effect of CO concentration and time on carboxy hemoglobin

sues of oxygen. Most American scientists believe that carbon monoxide is not a cumulative poison (31), with the blood being cleared of about half of the carbon monoxide in 3-4 hr for healthy subjects. However, some of our European colleagues (32) feel its effects may be cumulative and not completely reversible.

The effects of carbon monoxide involve both concentration and time. The effects are best shown as a plot of percent carboxy hemoglobin versus time as shown in Fig. 12 (33). For comparison, the highest average of recent carbon monoxide measurements in urban areas (28) was 38 ppm for 1 hr, 27 ppm for 8 hr, and 17 for 24 hr. None of these concentrations should give noticeable effects according to Fig. 12. However, short-term concentrations considerably higher than these have been reported numerous times and places. For example, concentrations in moving vehicles (34) of as high as 75 ppm for periods of at least 5 min with a median of 60 ppm were found. Also some people would feel that Fig. 12 is too conservative. For example, the California Department of Public Health (35) indicated that exposure of 30 ppm for 8 hr may be a serious risk to the health of sensitive people.

To summarize, carbon monoxide is primarily a man-caused pollutant, the removal mechanism is not known, present concentrations are clearly not a hazard to healthy people and probably in only a few cases present a health hazard to sensitive people. In addition, many people, when smoking, voluntarily expose themselves to levels many orders of magnitude (42,000 ppm) higher than those under discussion (36).

OXIDES OF NITROGEN - In addition to the molecular nitrogen found in the air, nitrogen is present as NO, NO_2, NH_3, N_2O, N_2O_4, N_2O_5, and possibly other nitrogen compounds. However, of all of these compounds the only pollutants that are significantly man-caused are NO and NO_2. Thus, we shall limit our attention to the so-called oxides of nitrogen.

It should be realized, however, that these two oxides of nitrogen represent only a small fraction of the total circulation of nitrogen compounds. For example, the mass rates of NH_3 circulation are some 10 times those of the two oxides of nitrogen.

Nitric oxide is formed at high combustion temperatures with the exact amount primarily dependent upon the temperature, oxygen concentration, and time. In the atmosphere nitric oxide reacts with oxygen and is rapidly converted to nitrogen dioxide. This reaction can be greatly accelerated by the presence of sunlight and organic material in the air.

Most atmospheric determinations of oxides of nitrogen combine together nitric oxide and nitrogen dioxide and designate the combination as NO_x. Typical urban atmospheric concentrations range 0.02-0.9 ppm (37), although concentrations as high as 3.9 ppm have been recorded in Los Angeles. By way of comparison, tobacco smoke contains 250 ppm (31, 36).

In addition to causing a reduction in atmospheric visibility, nitrogen dioxide also has an affinity for hemoglobin. However, because it forms acid in the lungs, it is considerably more toxic than carbon monoxide for the same concentrations. For example, a tentative standard of 5 ppm for an 8 hr working day has been set and some people think this is too high.

A mass rate balance for oxides of nitrogen is shown in Fig. 13. The natural event addition of 2×10^8 tons, by biological reactions, was justified by Robinson (18) as necessary to have a reasonable residence time in the atmosphere. This amount is surprisingly large with respect to man-caused additions and is quite large with respect to the mass in the atmosphere. This gives mass rate additions some 100 times the mass in the atmosphere.

A local mass rate balance around Los Angeles (using our inaccurate closed-system assumption) gives a different picture. The concentration in the Los Angeles atmosphere is some 100 times higher than the world average, giving a mass in the Los Angeles atmosphere of 1×10^4 tons—this is about the same as the natural event biological reaction contributions (assuming uniform distribution). On the other hand, if the man-caused oxides of nitrogen were uniformly produced throughout the

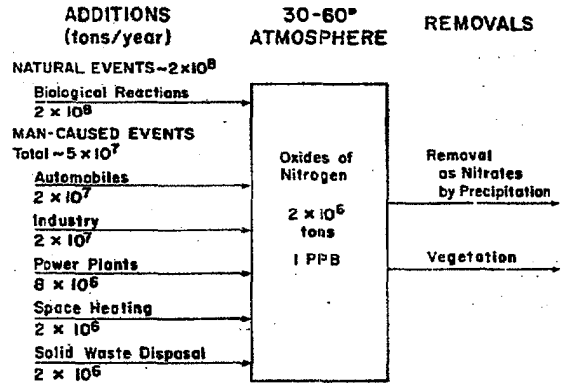

Fig. 13 - Mass rate balance for NO_x

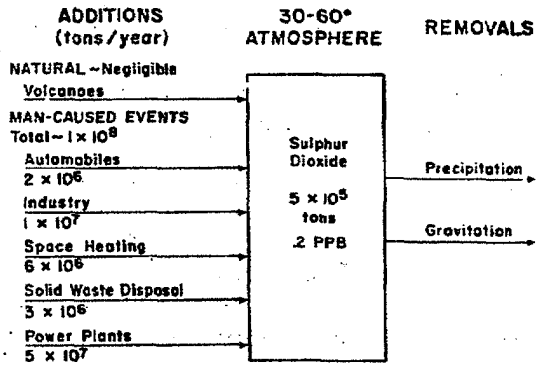

Fig. 14 - Mass rate balance for SO_2

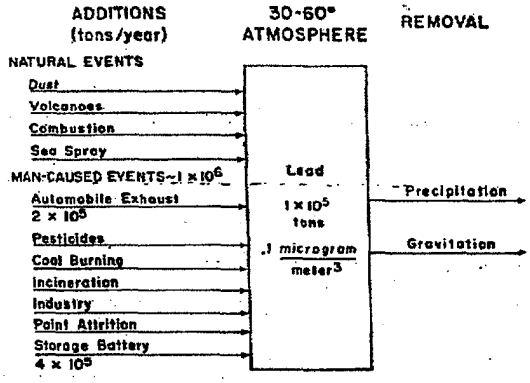

Fig. 15 - Mass rate balance for lead

world, there should only be some 3×10^2 tons/year produced in Los Angeles—in actuality there are 3.5×10^5 tons/year (21) produced in Los Angeles—a factor of approximately 1000. It is not surprising that the concentrations of oxides of nitrogen are higher in Los Angeles than the average concentration for the world.

In summary, on a global basis it appears that man is contributing but little to the concentrations of oxides of nitrogen. However, on a local basis where man-caused contributions are grouped together, concentrations can be hundreds of times greater than the average atmospheric concentration, giving severe local problems.

SULFUR DIOXIDE - Atmospheric sulfur is primarily in three forms: SO_2, H_2S, and sulfates. H_2S comes primarily from natural sources; SO_2 comes primarily from man-caused events; the sulfates come primarily from sea spray and from oxidation of SO_2. Thus we shall consider only SO_2, even though it represents only a small fraction of the mass rate of the total sulfur mass rate balance.

It should be appreciated, however, that the great majority of the sulfur in the atmosphere comes from natural sources. For example, estimates of amounts from natural sources ranging from 75% (8) to as high as 89% (11) of total sulfur mass rates have been given.

Fig. 14 presents a mass rate balance for SO_2. It is estimated that 70% of SO_2 comes from the combustion of coal. It is clear from Fig. 14 that mass rates are high with respect to the mass in the atmosphere.

With regard to health, the peaks of SO_2 concentrations rarely exceed 11 ppm (38)—this is about the bottom of the range frequently used for health observations in the laboratory. For example, a concentration of 0.6 ppm will produce no detectable response in healthy human beings; most people can detect 5 ppm and most people find 10 ppm quite unpleasant. Note that concentrations up to 3.2 ppm have been measured in industrial sections of cities that use a great deal of solid fuel (37). In addition, there is considerable doubt as to the accuracy of the measuring instruments used for sulfur dioxide (38). The situation is further complicated by the interaction and increased toxicity, insofar as health is concerned, when sulfur dioxide, high air temperature, high air humidity, aerosols, etc., are simultaneously present.

In summary, the available evidence indicates to me that on a global basis man-caused contributions are not of concern. On a local basis, however, severe problems have existed and will undoubtedly continue to exist in the future.

LEAD - Lead is one of the most widely used of metals, with storage batteries being the largest consumer. It is this widespread use that makes evaluation of lead as an atmospheric pollutant very difficult.

A schematic mass rate balance for lead is shown in Fig. 15, but few numbers are given. In the first place, I was unable to find reasonable estimates. Also, as will be explained later, as I studied the problem more I was not too certain the numbers would be meaningful anyway.

Concern with atmospheric lead arises primarily from its use as a gasoline additive. Tests have shown fairly conclusively that lead concentrations in the urban atmosphere (as well as carbon monoxide concentrations) follow traffic density patterns (39). The reason for this is shown in Fig. 16. Fig. 16 shows that approximately 70% of the lead used in your car is emitted from the tail pipe with 30% settling almost immediately to the ground and the other 40% becoming airborne and causing concern.

Airborne lead and its effect on human beings must be con-

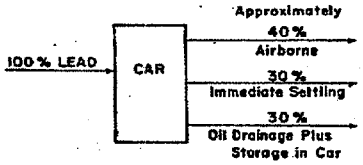

Fig. 16 - Schematic lead balance for an automobile

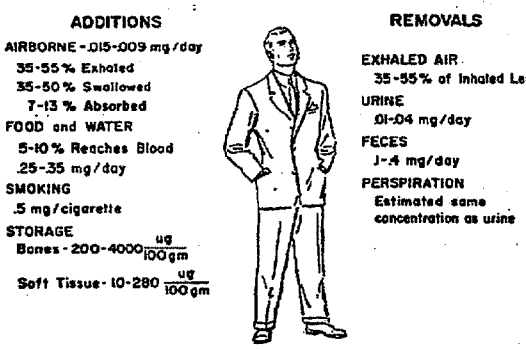

Fig. 17 - Mass rate balance for lead for an individual

sidered in the proper context, however. Fig. 17 shows an approximate mass rate for a human being. Inspection of Fig. 17 shows that the airborne lead is small in mass in comparison with that taken in via food and water, but that a higher percentage of the airborne lead reaches the blood. It appears that the body has over a period of time, adapted to certain lead levels determined primarily by "natural" events and that the airborne lead from automobiles is an addition to this relatively large quantity. There is general agreement that there is no evidence to date of ill effects due to the present levels of lead in the air.

HYDROCARBONS - Hydrocarbons are known to be a participant in photochemical smog and suspected as a contributor to cancer. Smog was reported in Los Angeles during the days of its early exploration by the white man. Also, it has been inferred (57) that "The nature and concentration of organic vapors of an atmosphere are among the prime determinants of its sensory quality of freshness." Thus, it seems certain that natural events contribure significantly to "air quality" insofar as hydrocarbons are concerned. It must be remembered, of course, that the term hydrocarbon covers literally hundreds of compounds as opposed to previously discussed pollutants. It should also be realized that particulate matter may contain hydrocarbons.

Fig. 18 summarizes the data that were found. Methane is the largest single source—it is thought to come primarily from bacterial decomposition which as a source seems relatively stable with time. Methane also has a relatively long lifetime. Vegetation contributes hydrocarbons also. The automobile is the biggest single contributor to man-caused hydrocarbon pollution, although the contribution of incinerators is surprisingly large. Man-caused events are not large with respect to methane emissions, but they are large with respect to natural sources of heavier hydrocarbons. In addition, in areas where photochemical air pollution is a serious problem, the

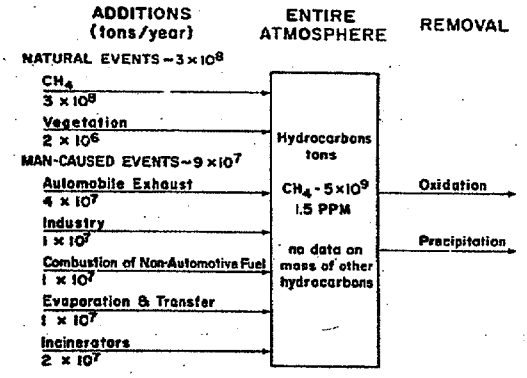

Fig. 18 - Mass rate balance for hydrocarbons

major concern is with the reactive hydrocarbons rather than simply total hydrocarbon emission.

AIR POLLUTION FROM AUTOMOBILES

I hope that I have convinced you in the previous discussion that air pollution is a current problem and that you either as an individual or a professional engineer, will be concerned with the problem and its solution. In addition, we automotive engineers have a special interest and contribution to make since our product is a major contributor to the problem.

Table 2 presents a summary of air pollution from all sources in the United States in 1966. Note that the automobile contributed about 60% of the total mass of air pollutants. Table 3 shows how this 60% was distributed between the different pollutants. Let us look at the source in the automobile of these different pollutants.

One obvious source is blowby past the rings. This source was estimated as containing from 25-33% of the contaminants (40, 41). However, all cars in the United States are equipped with PCV valves and thus this source has been fairly well eliminated—at least in well-maintained vehicles (42).

Fig. 19 presents information showing the realtive magnitude of emissions from the carburetor, gas tank, and exhaust. The source of emissions from the tank and carburetor are fairly obvious and plans for their control are well underway, so let's concentrate on understanding the source of the emissions in the exhaust. It should be realized that the exhaust contaminants have both quantity (Fig. 19) and quality (Fig. 20); that is, smog forming potential. By either standard, the exhaust is by far the largest contributor.

OXIDES OF NITROGEN - Fig. 21 (43) shows a plot of NO concentration versus the extent of expansion of the products of combustion in the cylinder. The curves shown are for different equivalence ratios and show the NO concentration that would be present if thermodynamic equilibrium were maintained during expansion. Also shown on the curves are measured exhaust levels of NO concentration at two different equivalence ratios. It is clear from Fig. 21 that the measured levels correspond more nearly to the NO concentrations present at the beginning of expansion, rather than the NO concen-

Table 2 - Total United States Air Pollution, 1966

Source	10^6 tons/year	% of Total
Industry	23	16.8
Powerplants	20	14.1
Motor vehicles	86	60.6
Space heating	8	5.6
Refuse disposal	5	3.5

Table3 - Motor Vehicle Pollution

Pollutant	10^6 tons/year
Carbon monoxide	66.0
Oxides of nitrogen	6.0
Hydrocarbons	12.0
Sulfur oxides	1.0
Lead compounds	0.19
Particulates	1.0

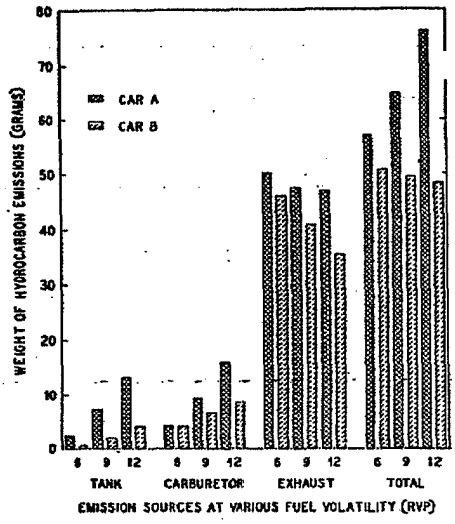

Fig. 19 - Relative magnitude of mass of emissions from a car

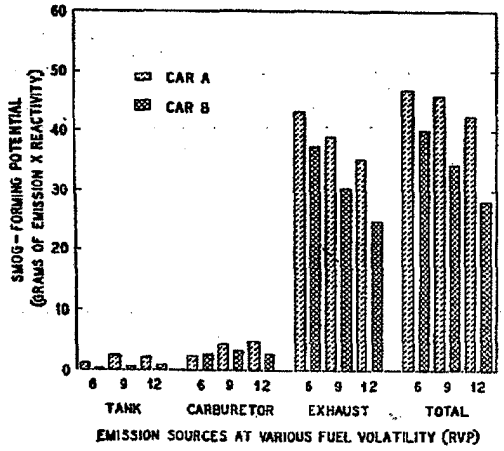

Fig. 20 - Relative magnitude of smog-forming potential of emissions from a car

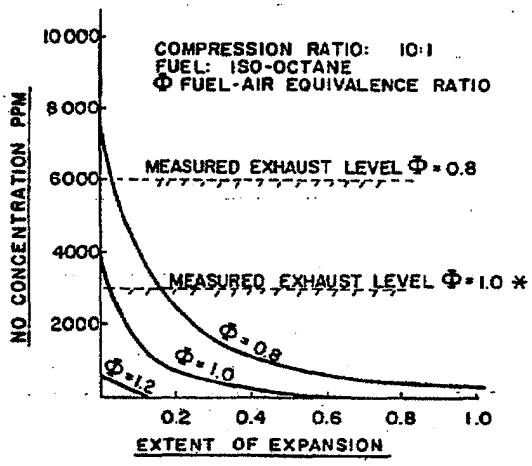

Fig. 21 - Variation of equilibrium NO concentration throughout expansion

tration at the end of expansion. In other words, apparently there is nonequilibrium during expansion insofar as NO is concerned. One concludes from this that the NO concentration measured in the exhaust should correlate reasonably well with the peak cycle temperature, recognizing that the peak temperature varies with location in the combustion chamber.

Fig. 22 shows a plot of peak cycle temperature versus spark advance as measured experimentally. Also plotted in Fig. 22 are exhaust NO concentrations in parts per million as a function of spark advance (NO data from Ref. 44). The NO concentrations at approximately stoichometric air-fuel ratios follow the same trend as the peak temperature curve. The lower set of data in the figure are for a rich mixture—they do not follow the same trend as the peak temperature curve.

If the NO is primarily related to peak combustion temperature (and to air-fuel ratio as will be shown later), it may be in-

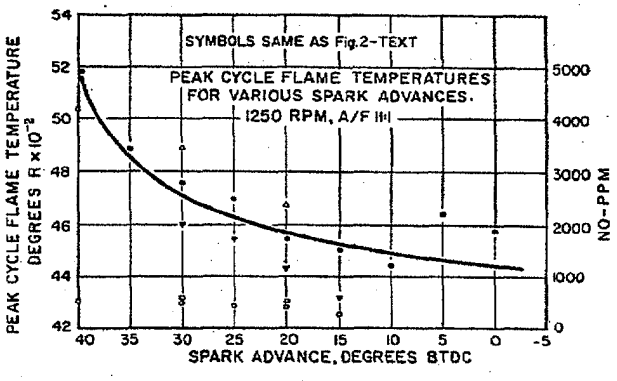

Fig. 22 - Correlation between peak cycle temperature and NO concentration

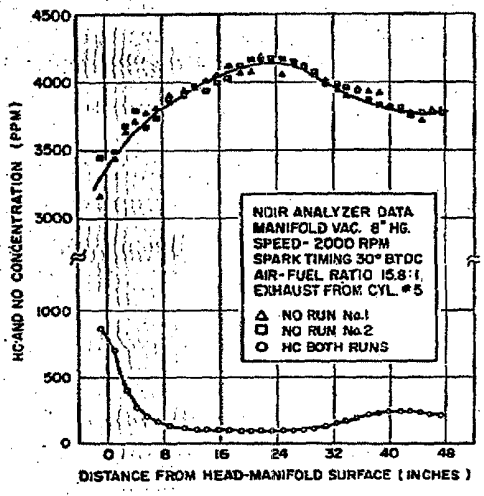

Fig. 23 - NO and HC concentration profile of exhaust from cylinder

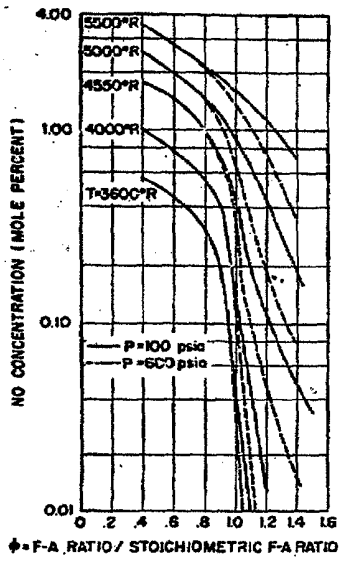

Fig. 24 - Calculated NO concentration versus equivalence ratio

ferred that it is formed primarily in the bulk gases as opposed to being formed in a quench zone next to the cold combustion chamber walls. This deduction is confirmed by the data shown in Fig. 23 (44) where both NO and hydrocarbon concentrations are plotted as a function of distance from the head-manifold surface, that is, as distance downstream from the exhaust valve. For three-quarters of the cycle there is no flow in the exhaust line. When exhaust does occur, the first gases to come out will be those adjacent to the exhaust valve, which in turn will be followed by the large bulk of the gases, which in turn will be followed by the quench zone gases scraped from the cylinder walls as the piston moves up on the exhaust stroke. If the deduction that the NO is formed primarily in the bulk gases is correct, the concentration of NO as a function of distance down the exhaust pipe should increase, reach a maximum, and then decrease. Thus, the data shown in Fig. 23 are in agreement with the hypothesis that NO is formed in the bulk gases.

Inasmuch as the NO does seem to be formed in the bulk gases and at nearly the peak cycle temperature, let us next see how under equilibrium conditions the NO concentration varies with temperature, pressure, and fuel-air ratio. Fig. 24 (45) presents a plot resulting from equilibrium calculations. It shows NO concentration versus equivalence ratio with lines of constant temperature at two different pressures. A rich mixture is shown in Fig. 24 as abscissa values greater than 1.0 and a lean mixture as abscissa values less than 1.0. Following a line of constant temperature, NO increases rapidly as we go from rich to lean. This occurs because of the increased oxygen concentration. As one would expect, NO increases rapidly with temperature at a given fuel-air ratio. It can also be seen in Fig. 24 that pressure has a significant effect on NO concentration at rich mixtures, but very little effect at lean mixtures. For rich mixtures an increase in pressure decreases the amount of NO formed under equilibrium conditions.

Fig. 25 presents a summary of experimentally measured NO concentrations for both spark ignition and diesel engines. In

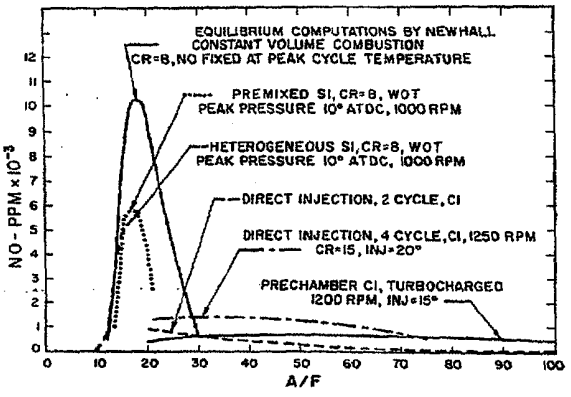

Fig. 25 - NO concentration versus air-fuel ratio

Fig. 25 NO concentration is plotted as a function of air-fuel ratio. The first curve in Fig. 25 is a computed curve showing the amount of NO that would be present in the exhaust if an ideal, constant volume cycle were followed and if the NO concentration in the exhaust was that formed at top-center, that is, at the peak cycle temperature. It can be seen that for this situation NO reaches a maximum at an air-fuel ratio of around 18 or 19.

Two experimental curves for spark-ignition engines are shown. Both curves were taken with the spark timing adjusted as the air-fuel ratio was changed so that the peak pressure always occurred at 10 deg atc. The reason for doing this is that in the engine, peak temperature changes with a change in air-fuel ratio for two reasons. In the first place, peak temperature will change with a change in air-fuel ratio because of more or less excess air to be heated up, just as in a burner. However, in the engine, in addition the flame speed varies with a change in air-fuel ratio and, as a consequence, peak pressure will occur

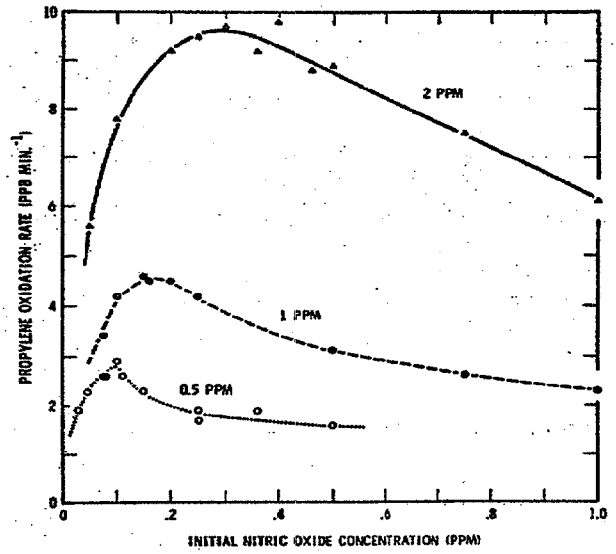

Fig. 26 - Effect of atmospheric nitric oxide concentration on hydrocarbon oxidation

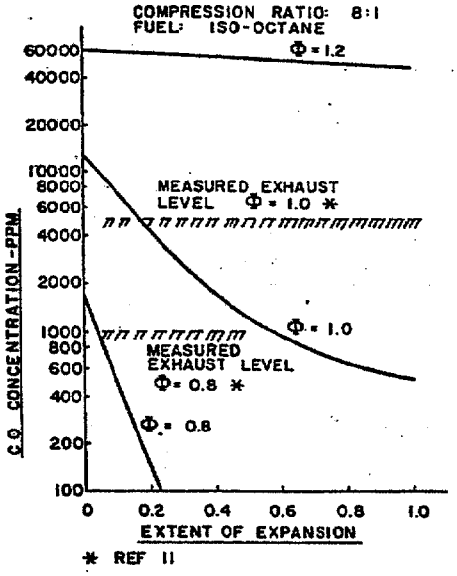

Fig. 27 - Variation of theoretical CO concentration throughout expansion

at different cylinder volumes with a consequent change in peak temperature. One of the curves is for a premixed mixture and the other curve is for a heterogeneous mixture such as is undoubtedly present in a practical multicylinder spark-ignition engine.

In comparing the two curves (premixed versus heterogeneous) it can be seen that the heterogeneous mixture has higher NO concentrations than does the premixed mixture. This can be explained by the nonlinear averaging that occurs. For example, if the average mixture was rich (say an air-fuel ratio of 12), the heterogeneous mixture would have local air-fuel ratios both richer and leaner than 12. The richer mixtures would contribute but little NO, while the lean mixtures would contribute significantly greater amounts of NO. Thus, on the average, the amount of NO would be larger than that obtained with a premixed mixture.

A similar explanation can be given for the diesel data shown in Fig. 25. It is believed that even though the overall mixture is quite lean in diesel engines, combustion actually takes place at an air-fuel ratio richer than stoichometric. Thus, the measured NO concentrations would correspond to the air-fuel ratio at which combustion took place rather than the overall air-fuel ratio. This explanation is consistent with the data shown in Fig. 25.

After consideration of all of the data presented, it can be concluded that the recombination reactions which destroy NO have relatively slow reaction rates. The four most important destruction reactions are:

1. $NO + M = N + O + M.$
2. $NO + N = N_2 + O.$
3. $NO + O = O_2 + N.$
4. $NO + NO = N_2O + O = N_2 + O_2.$

Of these four reactions, number 1 is the slowest, while numbers 2 and 3 are the fastest. All of them are quite slow, thus explaining the fact that very little recombination takes place during expansion.

Before leaving the subject of NO, it should be mentioned that NO is considered to take part in the destruction of hydrocarbons and may be necessary for the elimination of hydrocarbons from the atmosphere. This is shown in Fig. 26 (46) where the rate of propylene oxidation is plotted as a function of NO concentration for different initial concentrations of propylene. It can be seen that the rate of destruction of propylene is related to the NO concentration.

CARBON MONOXIDE - The next partially oxidized product I wish to talk about is carbon monoxide. In an attempt to deduce where and how carbon monoxide is formed, the results of theoretical computations are presented in Fig. 27 (43). Fig. 27 shows CO concentration as a function of the extent of expansion of the gases for an ideal cycle for three different equivalence ratios. Experimentally measured exhaust gas concentrations of CO are shown for two equivalence ratios. Again, the data show that the measured concentrations of CO correspond more nearly to the equilibrium concentrations of CO at peak cycle temperature than those existing at the end of expansion. Thus, as in the case of NO, we deduce that CO is formed in the bulk gases and in part, at least, as a result of frozen equilibrium, that is, a slow rate of destruction of some of the products. Fig. 28 is a summary plot of calculated and experimental data showing mole percent CO versus air-fuel ratio. The upper solid curve is the CO concentration that would be computed at the peak cycle temperature of an ideal constant volume cycle. The lower solid curve is the computed concentration, assuming equilibrium during the expansion to 1400 R. The experimental data points were taken holding the peak pressure constant at 10 deg atc so that any tempera-

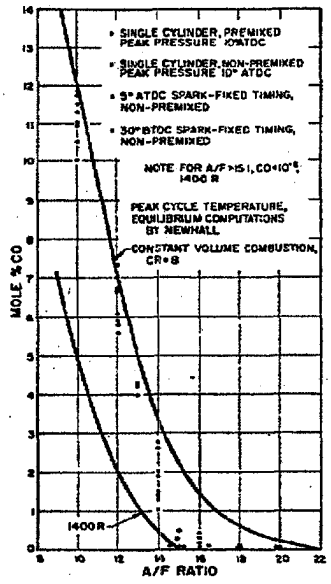

Fig. 28 - CO concentration versus air-fuel ratio

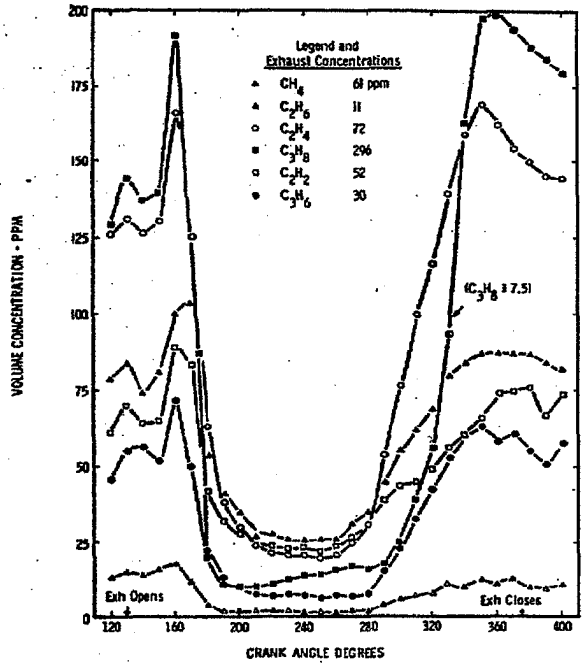

Fig. 29 - Variation in HC concentration during exhaust stroke

ture variations that took place were due to the air-fuel ratio effects directly, rather than to variations in flame speed. Fig. 28 clearly shows that, particularly at rich mixtures, measured concentrations of CO are closer to the peak cycle concentrations than to those existing if equilibrium occurred all during the expansion process.

Interestingly enough, as one approaches stoichometric or leaner mixtures, it appears that measured concentrations of CO more nearly approach the concentrations that would be expected if equilibrium occurred during all of the expansion process. As a matter of interest, Newhall (47) has set up a model of the expansion process using 30 reaction rate equations. He predicts the same trend as is shown in Fig. 28, that is, CO is further from equilibrium at rich mixtures.

Since we do apparently have nonequilibrium insofar as the concentration of CO is concerned during the expansion process, let us look at the destruction reactions involved. The primary destruction reaction for CO is:

$$CO + OH = CO_2 + H$$

This reaction is in equilibrium, that is, its reaction rate is relatively rapid. It appears that the CO concentration is high because the atomic hydrogen concentrations are high, that is, the rate of destruction of hydrogen appears to be low. The two reactions that cause hydrogen destruction are:

1. $H + H = H_2$
2. $H + OH = H_2O$

Apparently we have a peculiar situation where the CO concentrations are high because the atomic hydrogen concentrations are high.

HYDROCARBONS - Turning next to hydrocarbons in the exhuast, theoretical computations show that no hydrocarbons should exist if the system is in thermodynamic equilibrium. Thus it is believed that they are formed in the quench area, that is, in the cold zone immediately adjacent to the cold combustion chamber walls. This hypothesis is confirmed by data shown in Fig. 29 (48) showing hydrocarbon concentration as a function of the time in the cycle. The bulk gases will be exhausted primarily during the middle portion of the exhaust period. During this time, it is experimentally observed that the hydrocarbon concentration is low. On the other hand, the first and last part of the exhaust process which is primarily when the quench gases are being exhausted shows high concentration of hydrocarbons. Fig. 23 would also confirm this deduction.

Fig. 30 (48) shows engine data also confirming the quench theory. To obtain the data shown in Fig. 30, a sampling valve was used at different flow rates. The thought here is that at very low rates only the quench gases will be drawn through the sampling valve, while at high flow rates one will obtain increasing quantities of the bulk gases. It can be seen in Fig. 30 that at low sampling rates, high hydrocarbon concentrations are obtained, thus supporting the quench theory.

In looking at hydrocarbon data from real engines, however, one must recognize that oxidation does take place in the exhaust process and exhaust system. Fig. 31 (45) shows measured hydrocarbon concentration as a function of spark advance for two different situations. In the first situation, called "exhaust cooling off," a copper cooling coil was placed in the exhaust system adjacent to the exhaust valve. However, no water was passed through the copper cooling coil and the data as shown were obtained. It will be remembered that as the spark is retarded and combustion occurs later in the cycle,

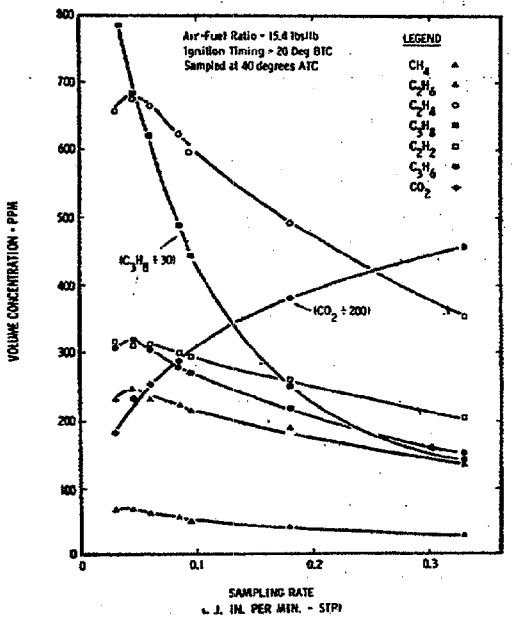

Fig. 30 - Hydrocarbon component concentrations near combustion chamber wall

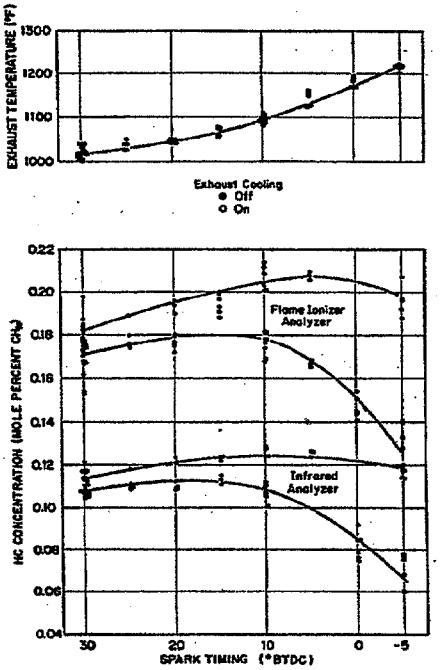

Fig. 31 - Exhaust temperature and HC concentration versus spark timing with and without cooling

there will be an increased quench area and one would anticipate, therefore, an increased concentration of hydrocarbons in the exhaust. However, the data indicate a small increase, followed by a decrease.

The second set of data were taken with the water flowing through the copper cooling coil located immediately adjacent to the exhaust valve. It can be seen in Fig. 31 that the data obtained are more consistent with quench theory; that is, as the spark is retarded, the concentration of hydrocarbons in the exhaust gas increases. From this it can be concluded that there is significant destruction of hydrocarbons in the exhaust system, and that what finally comes out of the exhaust system is the hydrocarbons formed less those destroyed in the exhaust system.

SOLUTIONS TO PROBLEM OF EXHAUST EMISSIONS

RECIPROCATING ENGINES -

Oxides of Nitrogen - Now that I have presented the source of the different emittants from the exhaust of the automobile, what solutions can be found to the problem? Looking first at NO, one obvious solution would be to prevent the formation of NO. One suggested way to do this is to add an inert gas, for example, recycle some of the exhaust. This would decrease the peak cycle temperature without increasing the oxygen concentration.

Another obvious way of preventing the formation of NO is to burn a mixture that is either quite rich or quite lean. Burning a mixture that is quite rich is undesirable in the sense that it increases the amount of CO and unburned hydrocarbons. Looking at the lean side, it is difficult to burn a mixture lean enough to decrease the NO to the desired quantity.

One obvious combination would be to run rich, which would form a considerable amount of unburned hydrocarbons and CO and then destroy the hydrocarbons and CO in the exhaust system. This thought could be expanded to include two-stage combustion with additional air added between stages. Either technique would probably involve sacrifices in fuel consumption.

Another possibility for elimination of NO in the exhaust gases would be to speed up the destruction of NO during the expansion process. This would require a catalyst that would speed up the previously quoted NO reduction reactions so that equilibrium would exist all during the expansion process. While finding such a catalyst is not an impossibility, the author is unaware of any such catalyst.

Yet another possibility is to reduce the NO in the exhaust system. In general, this is difficult because of the slow reduction of NO.

Another possibility is the reduction of peak flame temperatures by retarding the spark. While this procedure is obviously bad from an economy standpoint, it does raise the exhaust gas temperature which helps to destroy hydrocarbons in the exhaust.

Carbon Monoxide - Let us look next at the elimination of carbon monoxide. Again a possible procedure would be to add an inert gas. Preliminary calculations indicate, however, that equilibrium persists during the early portion of the expansion stroke. Consequently, rather large amounts of inert gas would have to be added in order to obtain the needed temperature effect. Thus, the addition of an inert gas does not seem to be a profitable approach.

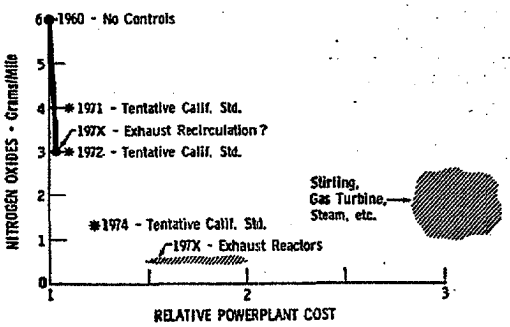

Fig. 32 - Relative cost of reducing NO_x (California vehicles)

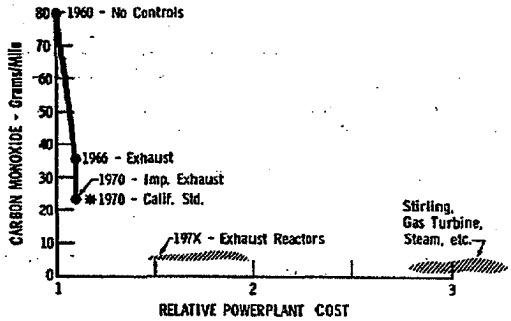

Fig. 33 - Relative cost of reducing CO

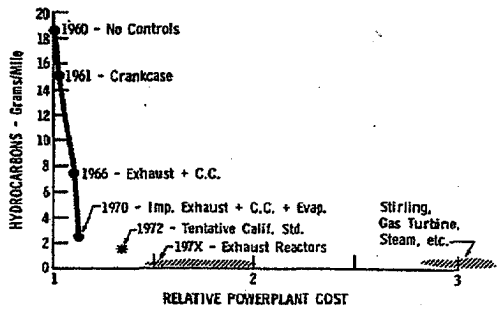

Fig. 34 - Relative cost of reducing HC

As can be seen in Fig. 28, CO is primarily a function of air-fuel ratio. If the engine can operate at a mixture leaner than stoichometric, it would appear that CO could be reduced to manageable levels. Also, as in the case of NO, an equilibrium catalyst might be used to achieve equilibrium all during the expansion process. However, at richer than stoichiometric mixtures CO would still be high. It will be remembered from the previous discussion that the equilibrium catalyst would be needed for the reactions involving the destruction of the hydrogen atom. Again the author knows of no such catalyst.

It is also possible to destroy carbon monoxide in the exhaust system by further oxidation.

Hydrocarbons - Turning next to hydrocarbons in the exhaust, we could in theory minimize their formation by using a stratified charge engine. In a stratified charge engine the area of the quench zone next to the cold combustion chamber wall would be automatically reduced at reduced load. However, a new quench zone at the interface between the combustible mixture and the air would be introduced and there could be considerable mixing with a quenching effect at this interface. Thus most people in the United States feel that a stratified charge engine will not give the required reduction in exhaust gas emissions.

One approach is to complete the oxidation of hydrocarbons in the exhaust. This is the basic approach that is currently being followed in the United States; that is, to increase the rate of exhaust destruction in the exhaust either by increasing the amount of oxygen present in the exhaust, or by maintaining the exhaust at high temperatures with the use of insulated or heat conserving manifolds or by both. In general, retarded spark timing gives a higher exhaust temperature and is being used as a means of increasing exhaust temperatures. Increased engine operating temperatures are an aid to minimizing quench gases and maximizing exhaust temperatures. Combustion chamber design for minimum quench area is now universal.

Competing Power Sources - Since hydrocarbons are thought to be formed in the quench zone, engines which do not "scrape off" the quench zone will undoubtedly have hydrocarbon emissions which are relatively quite low. The situation is not as clearly favorable with regard to carbon monoxide and oxides of nitrogen since they are formed in the bulk gases. It is true that in steady flow combustion there is much more latitude in choice of overall fuel air ratios and consequently a wider choice of solutions.

While there is considerable disagreement as to exact numbers, there is complete agreement that air pollution controls are going to cost money. Figs. 32-34 show the progress already made and estimated costs of additional progress by both reciprocating and other types of engines (33).

EFFECT OF CURRENT AND PROPOSED CONTROLS ON AIR POLLUTION - As our technology has progressed our standards for pollution for automobiles have become more stringent. The extent of progress is shown in Fig. 35 where the estimated emissions from untreated cars is shown as well as the progressive decrease in emittants with time. The decrease in hydrocarbon emission is 85%—in carbon monoxide it is 68%. These are significant reductions, but I suspect the general public does not appreciate the tremendous technical effort required to achieve these reductions or the magnitude of the further effort required to bring about further reductions.

The 1970 and 1971 standards were switched from exhaust concentration standards to a mass-per-vehicle-mile standard. It appears that future standards will continue to use mass per mile. While proposed future standards may become more stringent, they will also probably place more emphasis on startup emissions with other driving cycle modifications aimed at more nearly representing driver patterns.

Fig. 36 presents Heinen's (4) estimate of the present and future situation so far as automotive exhaust emissions in the United States are concerned. The effect of crankcase emission control in the early 1960's is evident as well as the effect of exhaust emission controls in the late 1960's. Fig. 36 emphasizes the time lag between the introduction of a control device

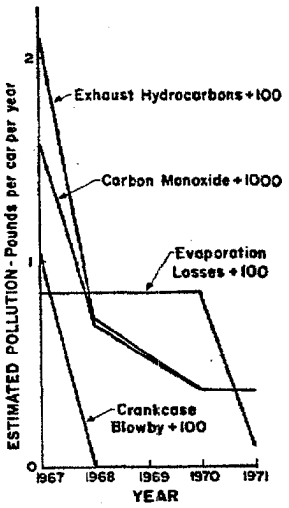

Fig. 35 - Reduction in automotive emissions with time

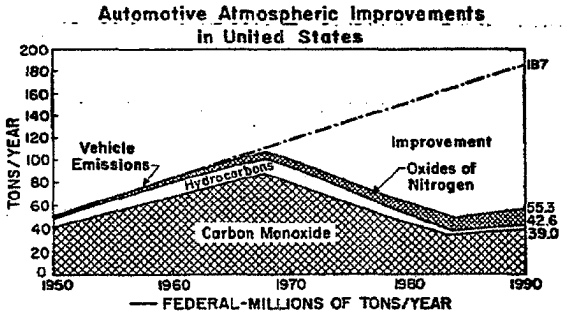

Fig. 36 - Atmospheric improvements in United States as result of automotive emissions control

on new cars and the impact of this control on total emissions because of the many uncontrolled cars on the road.

LONG TERM REDUCTION IN EMISSIONS - Although the general public is probably unaware of its magnitude, much effort has been expended in attempting to reduce pollution from the IC engine below any currently proposed standards. The main thrust of the efforts insofar as hydrocarbons and carbon monoxide are concerned has been either to operate very lean or to keep the exhaust gases hot and complete oxidation in the exhaust system. As an example of a laboratory experiment and clearly not as a technique ready for production, Fig. 37 shows the combined effect of lean mixture, heated exhaust, and the use of back pressure (49). Another laboratory approach is the use of a heat-conserving exhaust manifold (50). Figs. 38-40 show results from this approach which is equally effective when using olefins. There are obvious material problems using this approach.

The above two approaches are only samples of the intensive effort aimed at reducing automotive pollutants. Ultimately, as exemplified by Figs. 32-34, it will be a simple economic question—what is the cost-benefit ratio for further reductions and will adaptations of the IC engine be the most economic

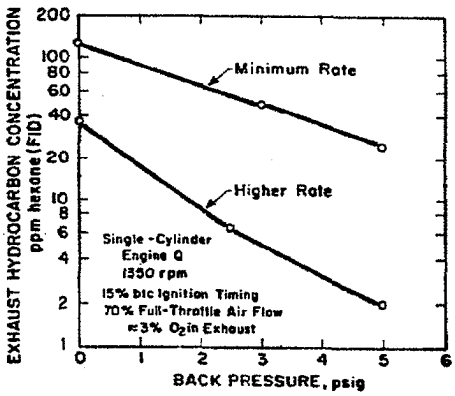

Fig. 37 - Example of reductions in HC obtained in laboratory experiments

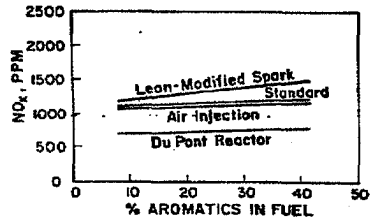

Fig. 38 - Reduction in NO_x using experimental thermactor

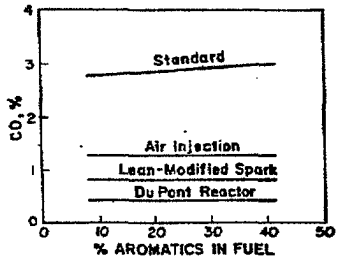

Fig. 39 - Reduction in CO using experimental thermactor

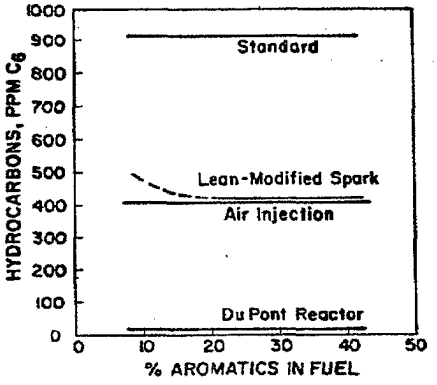

Fig. 40 - Reduction in HC using experimental thermactor

way to achieve these reductions in comparison with steam engines, gas turbines, Stirling engines, batteries, fuel cells, etc.

THE ENGINEER AND AIR POLLUTION

You have now had a brief exposure to the major elements of the problem—projected population growth, atmospheric contaminants, the source of emittants from automobiles, the effect of current and proposed controls and potentialities, and at least order of magnitude cost estimates. At this point, it would be simple for us as engineers to shrug our shoulders, argue that science is morally neutral and return to our computers. However, as stated by Solandt (51), "Even if science is morally neutral, it is then technology or the application of science that raises moral, social and economic issues." As stated in a different way by one of the top United States automotive engineers, "our industry recognizes that the wishes of the individual customer are increasingly in conflict with the needs of society as a whole and that the design of our product is increasingly affected by this conflict." This is clearly the case with pollution—an individual customer will not voluntarily pay extra for a car with emissions control even though the needs of society as a whole may be for emission controls. This conflict between individual and society needs has been present in the behavioral field since Cain and Abel. The conflict between the two is more recent in the technological field, but in my opinion will increase and not decrease in the future. The conflict involves social benefit versus technological costs (52). Thus, we as engineers will be "in the middle," so perhaps we should "get used to it." I think if in the future we are to truly optimize our engineering design we will inevitably be struggling with such decisions, so let's make an attempt at this one.

To assemble our "facts" as I see them:

1. Man-caused additions are, or will be, large in the near future with respect to natural contributions for particulate matter, carbon monoxide, oxides of nitrogen, and nonmethane hydrocarbons. They are adding appreciably, especially on a local basis, to our environmental levels of sulfur dioxide and lead.

2. There are fragmentary data indicating a potential for effects on weather by atmospheric pollutants, expecially CO_2 and particulates.

3. There are no data indicating that pollutants *at present levels* have a deleterious effect on healthy persons. This statement could be questioned in the specific case of NO_x in the Los Angeles basin where levels are sometimes briefly above those recommended by toxicologists. In addition, people voluntarily expose themselves to situations having greater potential effect. Nevertheless, at present levels there is evidence of some deleterious effects on those having marginal health, especially under adverse conditions.

4. Large population growths and nonlinear relationships between population density and pollutants and their effects must be recognized.

5. The automobile provides a significant portion of the man-caused additions of carbon monoxide, oxides of nitrogen, hydrocarbons, and airborne lead.

6. While there is some disagreement as to the exact time it will occur, there is universal agreement that at some time in the future the growth of the automobile population will exceed the effect of present and proposed controls and that if no further action is taken mass rates of addition of pollutants from automobiles will rise again.

7. There is a time lag of 3-5 years from the establishment of probable technological feasibility until a control technique involving significant modifications can be placed in universal mass production.

8. There is an additional time lag of 4-7 years before a sufficient fraction of the car population are equipped with the control device so that noticeable reductions occur.

From these "facts" it seems clear to me that the heavy emphasis placed on solving the emission problem by both manufacturers and government is justified. I would observe that I think the manufacturers would be well advised to do much more in the way of informing the public about the problem, its complexities and what they, the manufacturers, are doing in an attempt to solve the problem.

However, we have still not faced squarely up to the problem—how much should we spend for pollutant control and what should be our standards for air quality? I think the approach suggested by Cassell (38) is sound. He suggests that air pollution control be based on the concept of "the control of pollutant emissions to the greatest degree feasible employing maximum technological capabilities." The statements "feasible" and "maximum technological capability" have built into them continued progress whereas fixed standards are notably difficult to change. Furthermore, if a fixed standard is not feasible for technological or economic reasons, it is not enforced.

However, the urgencies and necessities of the problem must also be taken into account in evaluating the "greatest degree feasible employing maximum technological capabilities." This is illustrated in Fig. 41*. (CO_2 curve from Ref. 55.) You may quarrel with the location of the caution and catastropic regions in Fig. 41, but they clearly exist. In addition to the ideas illustrated by Fig. 41, information on the length of time it will take the atmosphere to clear itself is also needed. Perhaps we should talk about the half life of pollutants! In any event, I think the concept is clear—"the greatest degree feasible employing maximum technological capabilities" must be interpreted differently when you are in the caution or catastropic region as compared to when you are well below the caution region.

The same concept can and should be applied to local situations. For example, Figs. 42 and 43 show data for the Los Angeles basin (56). It is unfortunate that data on "alerts" are not available from 1940 on. It is interesting to speculate whether the very low number of "alerts" for CO in 1968 is truly a result of the downtrend in the CO emitted curve or is a

*This method of plotting was suggested by Dr. N. J. Beck of White Motor Corp.

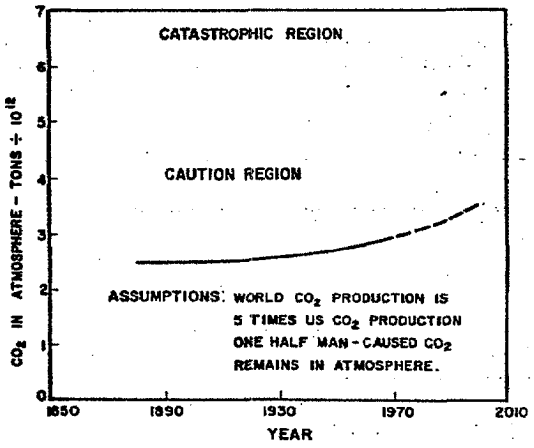

Fig. 41 - Plot of CO_2 on worldwide basis illustrating different control urgencies

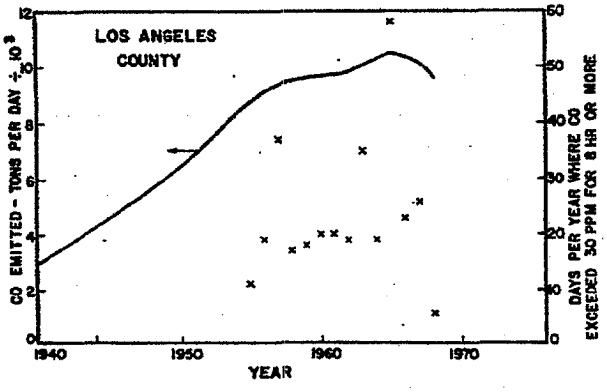

Fig. 42 - Plots of CO in Los Angeles Basin illustrating different control urgencies

result of atmospheric conditions. Again, I think the principle is clear—assuming the alerts represent highly unsatisfactory or dangerous conditions, your interpretation of the "greatest degree feasible employing maximum technological capabilities" becomes more stringent as the number of alerts increase. With this understanding I think it is up to us as professional engineers to see that our engines are controlled to produce "the minimum emissions feasible employing maximum technological capabilities."

Several procedures can be followed in "setting the numbers" that represent "the greatest degree feasible employing maximum technological capabilities." I do not have in mind here the enabling legislation that is probably inevitable and necessary—that is unquestionably a perogative of government. What I have in mind is the process by which reasonable numbers are arrived at which, while they may ultimately be incorporated into legislation, are set initially and primarily to represent "the greatest degree feasible using maximum technological capabilities."

The groups that might be involved in establishing such numbers are (assuming appropriate technical qualifications in all

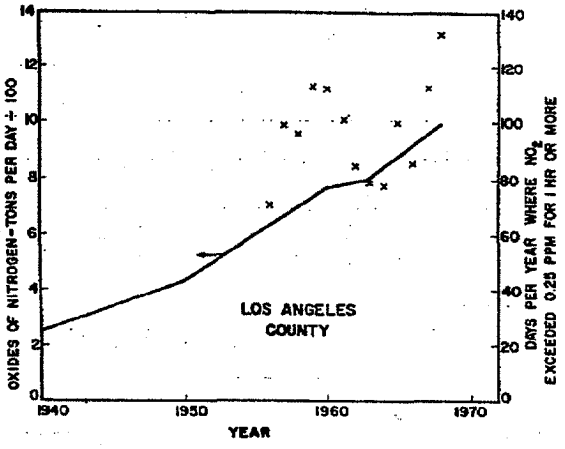

Fig. 43 - Plot of NO in Los Angeles Basin illustrating different control urgencies

cases):

1. Government employees.
2. Advisory groups set up by government officials.
3. Industry groups or associations.
4. Appropriate professional societies.

In considering the problem, it seems axiomatic to me that none of us are unbiased, try as hard as we may. Thus I conclude that an "unbiased" decision is best reached by a widely representative group whose individual bias in total add up to approximately zero and who are individually flexible and honest enough to recognize the possibility of bias and the necessity for compromise. Thus, I would feel that either two or four would have the most potential for reaching unbiased decisions. Personally, I would favor the use of appropriate technical societies—possibly because of my own bias, but more fundamentally because I think this offers the best opportunity for obtaining qualified individuals with the minimum of political and economic pressures. I predict that the procedure followed in the setting of performance level standards for technological matters will markedly influence the type of society we enjoy in the future.

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