

EMISSION CONTROL DEVICES FOR CONVENTIONAL
INTERNAL COMBUSTION ENGINE DESIGNS AND THEIR
IMPLICATIONS FOR OXIDANT CONTROL STRATEGIES

by

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Most of my comments today will be based upon the National Academy of Sciences study which has just recently been completed. There are at least two other people here who have been closely associated with that study, Professor Newhall, University of Wisconsin, recently of Chevron Research, who will be the second speaker, and Dr. Benson of Stanford Research Institute, who was one of the committee members on that study.

There has been some confusion about the National Academy of Sciences study, since there have been several recently in the automotive emissions area. The one which appeared in September, 1974, by the Costs/Benefit Panel received a great deal of publicity, some of it somewhat negative. I would encourage you to read all four volumes of that report. It does contain a lot of good information. It did deal with a very fuzzy subject, that of benefits vs. costs of air pollution control and, therefore, was not as precise as some would like. The report which has recently been completed (the volumes were released last week) is called the Report by the Committee on Motor Vehicle Emissions. Because the interest is high, I'll take a moment to tell you how to get a copy. Request the Report by the Committee on Motor Vehicle Emissions by writing to the National Academy of Sciences, specifically the Commission on Sociotechnical Systems, National Research Council, 2101 Constitution Avenue, Washington, DC 20418.

Some of you may have received copies already; those who contributed to the study should have received copies by this time.

One thing that has become apparent during the first day of this meeting and was even reflected by the previous speaker, is that there remain a lot of unknowns, a lot of questions that seem to me should have been answered in the last ten years. In spite of the uncertainties about the cause/effect relationships between emission sources and photochemical smog, the decision, fortunately, has been made to go ahead and control the smog anyway. The general conclusion has been that air pollution is reduced by reducing the emission of air pollutants and an aggressive automobile emission control program has been initiated, although it has been delayed several times, and the results have not come as rapidly as one would have hoped. With the 1975 automobiles, there is indeed a substantial reduction in hydrocarbon and CO emissions; this impact should now begin to be felt over the next 10 years as these vehicles replace those already on the road.

The costs of these emissions controls are large, somewhere between one and five billion dollars per year. The costs are large, especially in comparison with the investment that has been made in fundamental research to understand the nature of the air pollution problem. I would like to discuss several points: First, I would like to say a few words on the background of the automotive engine emissions controls; then I would like to give my assessment of the 1975 California vehicle and its emission control system--just what its strong points and problems are; and, finally, I will try to identify what the critical problem areas are now in automotive emissions controls.

I believe it is important to remind you that the automobile engine was developed over the last 50 years with goals in mind which had nothing to do

with air pollution. As a consequence, we have an automobile engine which is a low-cost production item, has a high power-to-weight ratio, has turned out to be a reliable, relatively low maintenance, very durable device, and in some cases even the fuel economy is not so bad. Then, after the fact, it was decided that this engine should be made to be low emitting. Therefore, it is not too surprising that the approach of the automobile industry has been to modify this engine, in which they have a great deal of confidence and know how to build inexpensively, as little as possible. The control approaches therefore have been minor modifications to the engine and have now focused upon processing the exhaust. This, to my thinking, as an engineer, is not a good approach. But, objectively, if one judges simply on the basis of whether emissions are controlled or not, has worked out quite well. I do not think we can be too critical of the add-on catalyst technology if it works. The evidence now suggests that it is going to work, that it is probably cost effective, and that the automobile industry probably deserves more credit than they are receiving for the job they've done in developing the oxidation catalyst for the automobile engine. What I'm saying is, the add-on approach is not necessarily all that bad.

Again, to give some general perspective on how one might approach automotive emission controls and how we arrived where we are, I'd like to discuss Figure 1, which points out several approaches to controlling emissions from the automobile engine. These are:

- 1) preparation of the air fuel mixture, which has received only minor attention by the auto industry;
- 2) modification of the engine itself, the combustion process, which is not very evident in the 1975 automobiles, but will be the subject of Dr. Newhall's presentation, and

3) the general field of exhaust treatment, where most of the effort has been placed by the U. S. auto industry.

I would like to emphasize that the first area, the whole matter of mixture control, that is, either improving the present carburetor or replacing it with a better mixture control system, is perhaps the single technological area which has been most overlooked by the automobile industry. The engine requires a well metered fuel-to-air mixture over a wide variety of operating conditions, that is, good cycle-to-cycle and cylinder-to-cylinder control. The present systems simply do not do that. It is also evident that the mixture control system must operate with varying ambient conditions of pressure and temperature. The present systems do not do that adequately. There are promising developments in improvement of mixture control systems, both carbureted and fuel injection, which do not appear to be under really aggressive development by the automobile industry. One should question why this is not occurring.

I will skip the area of combustion modification because that really comes under the new generation of engines. The combustion modification is an important approach, and will be discussed by the next speaker.

The area of exhaust system treatment, the third area, is the one about which you've seen the most. We early saw the use of air injection and then improved air injection with thermal reactors. Now we're seeing oxidation catalysts on essentially 100% of the U. S. cars sold in California. There are yet other possibilities for exhaust treatment: for the control of oxides of nitrogen based upon reduction catalysts, or what is known as threeway catalysts, another variation of the reduction catalyst, and possibly also the use of particulate traps as a way of keeping lead in gasoline if that proves a desirable thing to do (which does not appear to be the case).

What about the 1975 California car? Most of you probably have enough interest in this vehicle that you've tried to figure out just what it does. But in case some of you have not been able to straighten its operation out, let me tell you, as best I understand, what the 1975 California car is. The cars from Detroit are 100% catalyst equipped. There may be an exception sneaking through here and there, but it looks like it is 100%. These are equipped with oxidation catalysts in a variety of configurations and sizes, the major difference being the pellet system which is used by General Motors versus the monolith system which has been used by Ford and Chrysler. The pellet system appears to be better than the monolithic system, but it is not so obvious that there are huge differences between the two now. The catalysts come in a variety of sizes; they are connected to the engine in different ways; sometimes there are two catalysts, sometimes a single catalyst (the single catalyst being on the 4 and 6-cylinder engines). Some of the 8-cylinder engines have two catalysts, some of them have one catalyst. All California cars have all of the exhaust going through catalysts. This is not true of some of the Federal cars in which some of the exhaust goes through catalysts and some does not.

Ninety percent of the California cars probably will have air pumps. Practically all the cars from Detroit have electronic ignition systems which produce more energetic sparks and more reliable ignition. The exhaust gas recirculation (EGR) systems appear to have been improved somewhat over 1974 but not as much as one would have hoped. There were some early designs of EGR systems which were fully proportional, sophisticated systems. These do not appear to have come into final certification so that there still is room for further improvement of the EGR system. The emissions levels in certification of these vehicles are extremely low

(Table I). Just how the automobile industry selects the emission levels at which they tune their vehicles has been of great interest. The hydrocarbon and CO levels in certification (with deterioration factors applied--so this is the effective emissions of the certification vehicles at the end of 50,000 miles) are approximately one-half the California standards. The oxides of nitrogen emissions are approximately two-thirds of the California standards. This "safety factor" is put in by the automobile industry to allow for differences between the certification vehicles and the production vehicles to ensure that they did not get into a situation of recall of production vehicles which would be very expensive.

There appears to have been a great deal of sophistication developed by the automobile industry in being able to tune their vehicles to specific emission levels. General Motors appears to have done better tuning than the other manufacturers. This leads to the rather interesting result that a significant number of the 1975 California vehicles meet the 1977 emission standards (Table II); that is, approximately 10% of the U. S. cars certified for California already meet the 1977 emission standards. This does not mean to say that the industry could immediately put all of their production into such vehicles and meet the 1977 emission standards, because of a concern about the "safety factor" for the certification versus production vehicles. Thirty-four percent of the foreign vehicles certified for 1975 in California meet the 1977 emission standards. The 1977 emission standards are 0.41 g/m hydrocarbons, 3.4 g/m carbon monoxide, and 2.0 g/m oxides of nitrogen. This does confirm that the oxidation catalysts are a more than adequate technology for meeting the 1977 emission standards and only minor refinements and adjustments to those systems are required to go ahead with the 1977 emission standards. There are some other arguments against this optimistic viewpoint, and I'll deal with those later.

There is a great uniformity in the designs which the U. S. manufacturers have selected for the 1975 California vehicles. For those of you who do not live in California, about 80% of the vehicles in the rest of the country will be catalyst equipped. General Motors is going with 100% catalysts, apparently to realize the fuel economy benefit of their system which more than pays for the cost of the catalyst system. We have the very interesting situation that the more stringent 1975 emission standards have not only reduced the emissions of the 1975 vehicles with respect to the 1973-1974 vehicles, but have also reduced the cost of operating the car and have improved fuel economy. The idea that emissions control and fuel economy and economical operation are always one at odds with the other, is simply not true. Compared to the previous year's vehicles, the more stringent emissions standards of 1975 have brought improvements to fuel economy because they forced the introduction of more advanced technology. The fuel savings which have been realized produce a net decrease in operational costs over the lifetime of the car. This is not to say that pollution control doesn't cost something. If you were to compare the 1975 vehicle with a completely uncontrolled vehicle, there would indeed be an incremental cost associated with the 1975 vehicle.

The foreign manufacturers have demonstrated a greater variety of approaches in meeting the 1975 California standards, but again they are producing mostly catalyst equipped vehicles. There is a widespread use of fuel injection by the foreign manufacturers, especially the Europeans, apparently because this is the easiest approach for them and they realize that only a fraction of their production comes to the United States. Volkswagen, for example, apparently has gone to 100% fuel injection on its air cooled engines to be sold in California. Mazda will continue to sell

rotary engine vehicles and thereby be the only rotary engine vehicle manufacturer and marketer in the United States. General Motors' elimination of the rotary engine, stated for reasons of emissions, is probably more influenced by problems with fuel economy, although the two are a bit difficult to separate. Mazda is meeting the 1975 emissions standards and, in fact, can meet the 1977 emission standards. It has not solved its fuel economy difficulties on the 1975 cars; they will do better in 1976. All evidence points to a fuel economy penalty for the rotary engine. Nonetheless, we do have this option available because of the Japanese. Also, the foreign manufacturers are providing us with a small number of diesel engine cars. These are of great interest because of definite fuel economy advantages. The diesel engine vehicles also meet the 1977 emissions standards right now. Also in 1975, we'll see the CVCC engine marketed by Honda.

The costs of the 1975 vehicles over the lifetime of the vehicle are definitely lower than the costs of the 1974 vehicles. The National Academy of Sciences estimate averaged over all vehicles is that in comparison to the 1970 vehicles, the lifetime cost of emission control system, including maintenance and fuel economy costs, is about \$250 per vehicle, greater in 1975 than 1970. Since the 1974 vehicles were about \$500 more expensive, there has been a net saving in going from 1974 to 1975. I think the conclusion we should draw for 1975 is that the auto industry has done a pretty good job in meeting these standards. This is something which they said they couldn't do a few years ago, something which they said that if they could do, it would be much more expensive than it has turned out to be.

The same technology can be applied to 1977 models with no technological difficulty and only slight refinements of the systems. The fuel economy

penalties as estimated by the National Academy of Sciences are small, 3% or less, in going to the 1977 standards. This estimate does assume further advancements by the auto industry to improve fuel economy--primarily improved exhaust gas recirculation systems. It is unfortunate that this issue of fuel economy has become so mixed up with the air pollution question, because the two are only slightly related. If one is really concerned about fuel economy, and there isn't too much evidence that the auto industry or the American public really is too concerned right now, there is only one way to have a drastic effect on fuel economy and that is to decrease the vehicle weight. Until that is done, with gains on the order of 50% or more, to worry about 3 or 5% differences in fuel economy related to emission control systems, is simply to focus upon the wrong issue.

Now, what are the problem areas? What remains to be done? The problems certainly aren't over with the introduction of the 1975 vehicles.

Problem Area Number One: Field performance. What is going to happen to these vehicles when they get into actual service? Past experience with the 1971 through 1973 vehicles has been rather poor, in that EPA and California surveillance data show that these vehicles are not meeting the standards. Many of them did not meet the standards when they were new. The situation in general is getting worse, at least for CO and hydrocarbons, that is, with time the emission levels of CO and hydrocarbons for the 1971 through 1973 vehicles is degrading. There is no in-service experience of this sort with the 1975 vehicles yet. The certification data look quite promising, but the test procedures, especially for durability, are not the same as what occurs in actual use. It is generally stated that the actual use situation for the catalysts will be more severe than the EPA test procedure. A larger number of cold starts are involved in actual use than in the EPA test procedure and thermal cycling will probably have an

adverse effect on the lifetime of the catalyst. This is not so obvious. It is also likely that the higher temperature duty cycle in actual use will improve the performance of the catalyst in that it will help to regenerate the catalyst through the removal of contaminants, as long as one does not get into an overheat situation. The National Academy of Sciences' estimate was that the number of catalyst failures in the first 50,000 miles would be on the order of about 7%. That's a very difficult number to estimate in the absence of any real data. A 7% failure still leaves a net gain in emissions control, even if nothing is done about this failure. This points to the problem of what happens after 50,000 miles. The EPA certification procedure and control program only addresses the first 50,000 miles. The second 50,000 miles or slightly less for the average car, is the responsibility of the states. Unfortunately, there seems to be very little progress in the area of mandatory inspection and maintenance--very little thought being given to whether the replacement of the catalyst at 50,000 miles, if it has failed, is going to be required, and how that is going to be brought about. The area of field performance remains a major problem area, one which obviously needs to be monitored, as the California Air Resources Board has been doing in the past, but probably even more carefully because the unknowns are higher with the catalyst systems.

Problem Area Number Two: Evaporative hydrocarbons from automobiles.

It was identified at least 18 months ago that the evaporative emission control systems are not working, that the evaporative emissions are on the order of 10 times greater than generally thought. In the Los Angeles area, cars which are supposed to be under good evaporative emissions controls are emitting approximately 1.9 grams per mile of hydrocarbons through evaporation. This apparently has to do with the test procedure used.

The EPA is pursuing this. The California Air Resources Board does have some consideration going on for this, but it appears that the level of activity in resolving this problem is simply not adequate. If we are to go ahead to 0.4 of a gram per mile exhaust emissions standards for hydrocarbons, then it just doesn't make sense to let 1.9 grams per mile equivalent escape through evaporative sources.

Problem Area Number Three: What about the secondary effects of the catalyst control systems? Specifically, this is the sulfate emissions problem, and I really do not know the answer to that. Our appraisal is that it is not going to be an immediate problem, so we can find out what the problem is in time to solve it. The way to solve it now, since the automobile industry is committed to catalysts and it is unreasonable to expect that they will reverse that technology in any short period of time, is take the sulfur out of the gasoline. The cost of removing sulfur from gasoline is apparently less than one cent per gallon. Therefore, if it becomes necessary to be concerned with sulfate emissions, the way to meet the problem is to take the sulfur out of gasoline. Obviously, sulfate emissions need to be monitored very carefully to see what happens. The final appraisal is certainly not now available. Another secondary effect of the catalysts is the introduction of significant quantities of platinum into an environment where it hasn't existed before. Not only through exhaust emissions, which appear to be small, but also through the disposal problem of the catalytic reactors. Since the quantity of platinum involved is quite small, the argument is sometimes used that platinum does not represent much of a problem. The fact that the amount of platinum in the catalyst is so small may also mean that it's not economical to recover it. This is probably unfortunate because then the disposal of these catalysts

becomes important. I will not speak to the medical issues because I am not qualified. The evidence is that the platinum will be emitted in a form which does not enter into biological cycles--but this is no assurance that it couldn't later be transformed in such a form. What is obviously needed is a very careful monitoring program which, hopefully, was started before the catalysts were put into service. If it wasn't, then it should be started today.

Problem Area Number Four. NO_x control. The big problem with NO_x control is that nobody seems to know or to be willing to establish what the emission control level should be. It is essential that this be tied down rapidly and that it be fixed for a relatively long period of time, because the NO_x level is going to have a very important effect upon the development of advanced engine technology. The 2.0 g/m level has been attained in California with some loss of fuel economy through the use of EGR and it is not unreasonable, in our estimation, to go to 1.5 grams per mile with very little loss in fuel economy. To go to 0.4 gram per mile with present technology requires the use of one of two catalytic systems, either the reduction catalyst in tandem with the oxidation catalyst or what is known as the three-way catalyst. Both of these systems require technological gains. The state of development appears to be roughly that of the oxidation catalyst two years ago. The auto industry will probably say that it is not quite that advanced, but that if it were required to go to 0.4 gram per mile in 1978 that it could be done. With the catalyst systems, the fuel economy penalties would not be great, in fact, the improvement to the engine which would be required to make the system work would again probably even allow a slight improvement in fuel economy. What the 0.4 gram per mile NO_x catalyst system would appear to do, however, is to

eliminate the possibility of the introduction of stratified charge engines, both the CVCC and the direct injection system, and also diesel engines. It is in the context of the advantages of these advanced engines to meet emission standards with improved fuel economy that one should be very cautious about the 0.4 gram/mile oxides of nitrogen standards for automobiles. My own personal opinion is that the number should not be that stringent, that a number of 1 or 1.5 g/m is appropriate. Such a level would require advancements but would not incur great penalties.

Other items which I view as problem areas are less technically involved and therefore require fewer comments.

- Nonregulated pollutants--again, this is a matter of keeping track of particulates, aldehydes, hydrocarbon composition, to make certain that important pollutants are not being overlooked, or that emission control systems are not increasing the output of some of these pollutants.
- Fuel economy. The pressures of fuel economy are going to be used as arguments against going ahead with emissions control. Mostly, these two can be resolved simultaneously. We should simply ask the automobile industry to work harder at this.
- Final problem area: New fuels. Again, it does not appear that the introduction of new fuels will come about as an emissions control approach, but that they may be introduced because of the changing fuel availability patterns and the energy crisis. These fuels should be watched carefully for their impact upon emissions. This does appear to be an area in which a great deal of study is going on at the present time. It is one problem area, perhaps, in which the amount of work being done is adequate to the problem which is involved.

In summary, then, the appraisal of the 1975 systems is that they are a big advancement; they will be a lot better than most of us thought, and that we should give the automobile industry credit for the job they've done in coming up with their emissions control systems.

With that boost for the auto industry, which I'm very unaccustomed to, I'll entertain your questions.

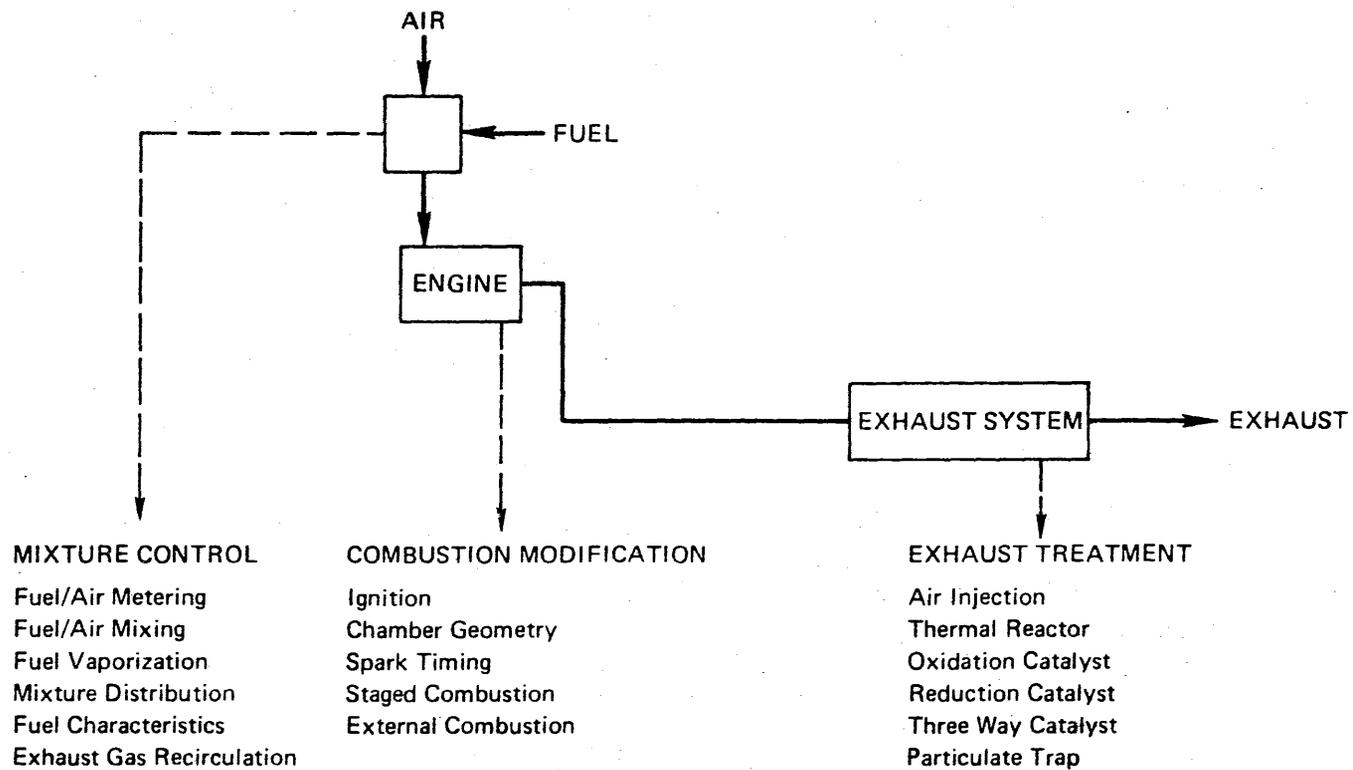


FIGURE 1. Approaches to the Control of Engine Emissions.

TABLE I
 Average Emissions of 1975 Certification Vehicles
 (As Corrected Using the 50,000-Mile Deterioration Factor)

	Emissions in g/mi			Fraction of Standard		
	HC	CO	NO _x	HC	CO	NO _x
Federal 1975						
AMC	0.65	6.7	2.5	0.43	0.45	0.80
Chrysler	0.74	7.7	2.5	0.49	0.51	0.82
Ford	0.81	9.2	2.4	0.54	0.61	0.78
GM	0.83	8.0	2.3	0.55	0.53	0.74
Weighted Average*	0.80	8.2	2.4	0.53	0.55	0.76
California 1975						
AMC	0.42	4.9	1.7	0.47	0.54	0.87
Chrysler	0.48	6.1	1.6	0.53	0.67	0.82
Ford	0.52	5.6	1.3	0.58	0.62	0.67
GM	0.65	5.5	1.6	0.72	0.61	0.82
Weighted Average*	0.58	5.6	1.6	0.64	0.62	0.78

*Weighted average assumes the following market shares: AMC, 3%; Chrysler, 16%; Ford, 27%; and GM, 54%.

TABLE II

Total Number of Vehicles Certified for California 1975 Standard
and the Number (and percentage) of These Able to Meet
Certain More Stringent Standards

Manufacturer	Calif. 1975 0.9/9.0/2.0		Federal 1977 0.4/3.4/2.0		Hypothesized 0.4/9.0/2.0		Hypothesized 0.9/3.4/2.0	
	no.	(%)	no.	(%)	no.	(%)	no.	(%)
AMC	16	(100)	1	(6)	6	(38)	3	(19)
Chrysler	21	(100)	2	(9)	7	(33)	0	(0)
Ford	26	(100)	4	(15)	4	(15)	5	(19)
GM	46	(100)	1	(2)	4	(9)	5	(11)
Foreign	62	(100)	21	(34)	38	(61)	28	(45)

CURRENT STATUS OF ALTERNATIVE AUTOMOBILE ENGINE TECHNOLOGY

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1.0 Introduction and
General Background

1.1 General

The term "stratified charge engine" has been used for many years in connection with a variety of unconventional engine combustion systems. Common to nearly all such systems is the combustion of fuel-air mixtures having a significant gradation or stratification in fuel concentration within the engine combustion chamber. Hence the term "stratified charge." Historically the objective of stratified charge engine designs has been to permit spark ignition engine operation with average or overall fuel-air ratios lean beyond the ignition limits of conventional combustion systems. The advantages of this type of operation will be enumerated shortly. Attempts at achieving this objective date back to the first or second decade of this century.¹

More recently, the stratified charge engine has been recognized as a potential means for control of vehicle pollutant emissions with minimum loss of fuel economy. As a consequence, the various stratified charge concepts have been the focus of renewed interest.

1.2 Advantages and Disadvantages of Lean Mixture Operation

Fuel-lean combustion as achieved in a number of the stratified charge engine designs receiving current attention has both advantages and disadvantages when considered from the combined standpoints of emissions control, vehicle performance, and fuel economy.

Advantages of lean mixture operation include the following:

- Excess oxygen contained in lean mixture combustion gases helps to promote complete oxidation of hydrocarbons (HC) and carbon monoxide (CO) both in the engine cylinder and in the exhaust system.
- Lean mixture combustion results in reduced peak engine cycle temperatures and can, therefore, yield lowered nitrogen oxide (NO_x) emissions.
- Thermodynamic properties of lean mixture combustion products are favorable from the standpoint of engine cycle thermal efficiency (reduced extent of dissociation and higher effective specific heats ratio).
- Lean mixture operation can reduce or eliminate the need for air throttling as a means of engine load control. The consequent reduction in pumping losses can result in significantly improved part load fuel economy.

Disadvantages of lean mixture operation include the following:

- Relatively low combustion gas temperatures during the engine cycle expansion and exhaust processes are inherent in lean mixture operation. As a consequence, hydrocarbon oxidation reactions are retarded; and unburned hydrocarbon exhaust emissions can be excessive.
- Engine modifications aimed at raising exhaust temperatures for improved HC emissions control (retarded ignition timing, lowered compression ratio, protracted combustion) necessarily impair engine fuel economy.
- If lean mixture operation is to be maintained over the entire engine load range, maximum power output and, hence, vehicle performance are significantly impaired.
- Lean mixture exhaust gases are not amenable to treatment by existing reducing catalysts for NO_x emissions control.
- Lean mixture combustion if not carefully controlled can result in formation of undesirable odorant materials that appear in significant concentrations in the engine exhaust. Diesel exhaust odor is typical of this problem and is thought to derive from lean mixture regions of the combustion chamber.

- Measures required for control of NO_x emissions to low levels (as example EGR) can accentuate the above HC and odorant emissions problems.

Successful development of the several stratified charge engine designs now receiving serious attention will depend very much on the balance that can be achieved among the foregoing favorable and unfavorable features of lean combustion. This balance will, of course, depend ultimately on the standards or goals that are set for emissions control, fuel economy, vehicle performance, and cost. Of particular importance are the relationships between three factors - UBHC emissions, NO_x emissions, and fuel economy.

1.3 Stratified Charge Engine Concepts

Charge stratification permitting lean mixture operation has been achieved in a number of ways using differing concepts and design configurations.

Irrespective of the means used for achieving charge stratification, two distinct types of combustion process can be identified. One approach involves ignition of a small and localized quantity of flammable mixture which in turn serves to ignite a much larger quantity of adjoining or surrounding fuel-lean mixture - too lean for ignition under normal circumstances. Requisite mixture stratification has been achieved

in several different ways ranging from use of fuel injection directly into "open" combustion chambers to use of dual combustion chambers divided physically into rich and lean mixture regions. Under most operating conditions, the overall or average fuel-air ratio is fuel-lean; and the advantages enumerated above for lean operation can be realized.

A second approach involves timed staging of the combustion process. An initial rich mixture stage in which major combustion reactions are completed is followed by rapid mixing of rich mixture combustion products with an excess of air. Mixing and the resultant temperature reduction can, in principle, occur so rapidly that minimum opportunity for NO formation exists; and, as a consequence, NO_x emissions are low. Sufficient excess air is made available to encourage complete oxidation of hydrocarbons and CO in the engine cylinder and exhaust system. The staged combustion concept has been specifically exploited in so-called divided-chamber or large volume prechamber engine designs. But it will be seen that staging is also inherent to some degree in other types of stratified charge engines.

The foregoing would indicate that stratified charge engines can be categorized either as "lean burn" engines or "staged combustion" engines. In reality, the division between concepts is not so clear cut. Many engines encompass features of both concepts.

1.4 Scope of This Report

During the past several years, a large number of engine designs falling into the broad category of stratified charge engines have been proposed. Many of these have been evaluated by competent organizations and have been found lacking in one or a number of important areas. A much smaller number of stratified charge engine designs have shown promise for improved emissions control and fuel economy with acceptable performance, durability, and production feasibility. These are currently receiving intensive research and/or development efforts by major organizations - both domestic and foreign.

The purpose of this report is not to enumerate and describe the many variations of stratified charge engine design that have been proposed in recent years. Rather, it is intended to focus on those engines that are receiving serious development efforts and for which a reasonably large and sound body of experimental data has evolved. It is hoped that this approach will lead to a reliable appraisal of the potential for stratified charge engine systems.

2.0 Open-Chamber Stratified Charge Engines

2.1 General

From the standpoint of mechanical design, stratified charge engines can be conveniently divided into two types: open-chamber and dual-chamber. The open-chamber stratified charge engine has a long history of research interest. Those engines

reaching the most advanced stages of development are probably the Ford-programmed combustion process (PROCO)^{2,3} and Texaco's controlled combustion process (TCCS).^{4,5} Both engines employ a combination of inlet air swirl and direct timed combustion chamber fuel injection to achieve a local fuel-rich ignitable mixture near the point of ignition. For both engines the overall mixture ratio under most operating conditions is fuel lean.

Aside from these general design features that are common to the two engines, details of their respective engine cycle processes are quite different; and these differences reflect strongly in comparisons of engine performance and emissions characteristics.

2.2 The Ford PROCO Engine

2.2.1 Description

The Ford PROCO engine is an outgrowth of a stratified charge development program initiated by Ford in the late 1950's. The development objective at that time was an engine having diesel-like fuel economy but with performance, noise levels, and driveability comparable to those of conventional engines. In the 1960's, objectives were broadened to include exhaust emissions control.

A recent developmental version of the PROCO engine is shown in Figure 2-1. Fuel is injected directly into the combustion chamber during the compression stroke resulting in vaporization and formation of a rich mixture cloud or kernel in the immediate

vicinity of the spark plug(s). A flame initiated in this rich mixture region propagates outwardly to the increasingly fuel-lean regions of the chamber. At the same time, high air swirl velocities resulting from special orientation of the air inlet system help to promote rapid mixing of fuel-rich combustion products with excess air contained in the lean region. Air swirl is augmented by the "squish" action of the piston as it approaches the combustion chamber roof at the end of the compression stroke. The effect of rapid mixing can be viewed as promoting a second stage of combustion in which rich mixture zone products mix with air contained in lean regions. Charge stratification permits operation with very lean fuel-air mixtures with attendant fuel economy and emissions advantages. In addition, charge stratification and direct fuel injection permit use of high compression ratios with gasolines of moderate octane quality - again giving a substantial fuel economy advantage.

Present engine operation includes enrichment under maximum power demand conditions to mixture ratios richer than stoichiometric. Performance, therefore, closely matches that of conventionally powered vehicles.

Nearly all PROCO development plans at the present time include use of oxidizing catalysts for HC emissions control. For a given HC emissions standard, oxidizing catalysts permit use of leaner air-fuel ratios (lower exhaust temperatures)

together with fuel injection and ignition timing characteristics optimized for improved fuel economy.

2.2.2 Emissions and Fuel Economy

Figure 2-2 is a plot of PROCO vehicle fuel economy versus NO_x emissions based on the Federal CVS-CH test procedure. Also included are corresponding HC and CO emissions levels. Only the most recent test data have been plotted since these are most representative of current program directions and also reflect most accurately current emphasis on improved vehicle fuel economy.^{6,7} For comparison purposes, average fuel economies for 1974 production vehicles weighing 4500 pounds and 5000 pounds have been plotted.⁸ (The CVS-C values reported in Reference 8 have been adjusted by 5% to obtain estimated CVS-CH values.)

Data points to the left, on Figure 2-2, at the 0.4 g/mile NO_x level, represent efforts to achieve statutory 1977 emissions levels.⁶ While the NO_x target of 0.4 g/mile was met, the requisite use of exhaust gas recirculation (EGR) resulted in HC emissions above the statutory level.

A redefined NO_x target of 2 g/mile has resulted in the recent data points appearing in the upper right hand region of Figure 2-2.⁷ The HC and CO emissions values listed are without exhaust oxidation catalysts. Assuming catalyst conversion efficiencies of 50-60% at the end of 50,000 miles of operation, HC and CO levels will approach but not meet

statutory levels. It is clear that excellent fuel economies have been obtained at the indicated levels of emissions control - some 40% to 45% improved relative to 1974 production vehicle averages for the same weight class.

The cross-hatched horizontal band appearing across the upper part of Figure 2-2 represents the reductions in NO_x emissions achievable with use of EGR if HC emissions are unrestricted. The statutory 0.4 g/mile level can apparently be achieved with this engine with little or no loss of fuel economy but with significant increases in HC emissions. The HC increase is ascribed to the quenching effect of EGR in lean-mixture regions of the combustion chamber.

2.2.3 Fuel Requirements

Current PROC0 engines operated with 11:1 compression ratio yield a significant fuel economy advantage over conventional production engines at current compression ratios. According to Ford engineers, the PROC0 engine at this compression ratio is satisfied by typical full-boiling commercial gasolines of 91 RON rating. Conventional engines are limited to compression ratios of about 8:1 and possibly less for operation on similar fuels.

Results of preliminary experiments indicate that the PROC0 engine may be less sensitive to fuel volatility than conventional engines - an important factor in flexibility from the standpoint of the fuel supplier.

2.2.4 Present Status

Present development objectives are two-fold:

- Develop calibrations for alternate emissions target levels carefully defining the fuel economy potential associated with each level of emissions control.
- Convert engine and auxiliary systems to designs feasible for high volume production.

2.3 The Texaco TCCS Stratified Charge Engine

2.3.1 General Description

Like the Ford PROCO engine, Texaco's TCCS system involves coordinated air swirl and direct combustion chamber fuel injection to achieve charge stratification. Inlet port-induced cylinder air swirl rates typically approach ten times the rotational engine speed. A sectional view of the TCCS combustion chamber is shown in Figure 2-3.

Unlike the PROCO engine, fuel injection in the TCCS engine begins very late in the compression stroke - just before the desired time of ignition. As shown in Figure 2-4, the first portion of fuel injected is immediately swept by the swirling air into the spark plug region where ignition occurs and a flame front is established. The continuing stream of injected fuel mixes with swirling air and is swept into the flame region. In many respects, the Texaco process resembles the

spray burning typical of diesel combustion with the difference that ignition is achieved by energy from an electric spark rather than by high compression temperatures. The Texaco engine, like the diesel engine, does not have a significant fuel octane requirement. Further, use of positive spark ignition obviates fuel cetane requirements characteristic of diesel engines. The resultant flexibility of the TCCS engine regarding fuel requirements is a significant attribute.

In contrast to the TCCS system, Ford's PROCOS system employs relatively early injection, vaporization, and mixing of fuel with air. The combustion process more closely resembles the premixed flame propagation typical of conventional gasoline engines. The PROCOS engine, therefore, has a definite fuel octane requirement and cannot be considered a multifuel system.

The TCCS engine operates with high compression ratios and with little or no inlet air throttling except at idle conditions. As a consequence, fuel economy is excellent--both at full load and under part load operating conditions.

2.3.2 Exhaust Emissions and Fuel Economy

Low exhaust temperatures characteristic of the TCCS system have necessitated use of exhaust oxidation catalysts for control of HC emissions to low levels. All recent development

programs have, therefore, included use of exhaust oxidation catalysts; and most of the data reported here represent tests with catalysts installed or with engines tuned for use with catalysts.

Figures 2-5 and 2-6 present fuel economy data at several exhaust emissions levels for two vehicles--a U.S. Army M-151 vehicle with naturally aspirated 4-cylinder TCCS conversion and a Plymouth Cricket with turbocharged 4-cylinder TCCS engine.^{9,10} Turbocharging has been used to advantage to increase maximum power output. Also plotted in these figures are average fuel economies for 1974 production vehicles of similar weight.⁸

When optimized for maximum fuel economy, the TCCS vehicles can meet NO_x levels of about 2 g/mile. It should be noted that these are relatively lightweight vehicles and that increasing vehicle weight to the 4000-5000 pound level could result in significantly increased NO_x emissions. Figures 2-5 and 2-6 both show that engine modifications for reduced NO_x levels including retarded combustion timing, EGR, and increased exhaust back pressure result in substantial fuel economy penalties.

For the naturally aspirated engine, reducing NO_x emissions from the 2 g/mile level to 0.4 g/mile incurred a fuel economy penalty of 20%. Reducing NO_x from the turbocharged

engine from 1.5 g/mile to 0.4 g/mile gave a 25% fuel economy penalty. Fuel economies for both engines appear to decrease uniformly as NO_x emissions are lowered.

For the current TCCS systems, most of the fuel economy penalty associated with emissions control can be ascribed to control of NO_x emissions; although several of the measures used for NO_x control (retarded combustion timing and increased exhaust back pressure) also help to reduce HC emissions. HC and CO emissions are effectively controlled with oxidation catalysts resulting in relatively minor reductions in engine efficiency.

2.3.3 TCCS Fuel Requirements

The TCCS engine is unique among current stratified charge systems in its multifuel capability. Successful operation with a number of fuels ranging from gasoline to No. 2 diesel

Table 2-I

Emissions and Fuel Economy of Turbocharged
TCCS Engine-Powered Vehicle¹

Fuel	Emissions g/Mile ²			Fuel Economy, mpg ²
	HC	CO	NO _x	
Gasoline	0.33	1.04	0.61	19.7
JP-4	0.26	1.09	0.50	20.2
100-600	0.14	0.72	0.59	21.3
No. 2 Diesel	0.27	1.14	0.60	23.0

¹M-151 vehicle, 8 degrees combustion retard, 16% light load EGR, two catalysts (Ref. 10).

²CVS-CH, 2750 pounds inertia weight.

has been demonstrated. Table 2-I lists emissions levels and fuel economies obtained with a turbocharged TCCS-powered M-151 vehicle when operated on each of four different fuels.¹⁰ These fuels encompass wide ranges in gravity, volatility, octane number, and cetane level as shown in Table 2-II.

Table 2-II
Fuel Specifications for
TCCS Emissions Tests (Reference 10)

	Gasoline	100-600	JP-4	No. 2 Diesel
Gravity, °API	58.8	48.6	54.1	36.9
Sulfur, %	-	0.12	0.020	0.065
<u>Distillation, °F</u>				
IBP	86	110	136	390
10%	124	170	230	435
50%	233	358	314	508
90%	342	544	459	562
EP	388	615	505	594
TEL, g/Gal.	0.024	0.002	-	-
Research Octane	91.2	57	-	-
Cetane No.	-	35.6	-	48.9

Generally, the emissions levels were little affected by the wide variations in fuel properties. Vehicle fuel economy varied in proportion to fuel energy content.

As stated above, the TCCS engine is unique in its multifuel capability. The results of Tables 2-I and 2-II demonstrate that the engine has neither significant fuel octane nor cetane requirements and further that it can tolerate

wide variations in fuel volatility. The flexibility offered by this type of system could be of major importance in future years.

2.3.4 Durability, Performance, Production Readiness

Emissions control system durability has been demonstrated by mileage accumulation tests. Ignition system service is more severe than for conventional engines due to heterogeneity of the fuel-air mixture and also to the high compression ratios involved. The ignition system has been the subject of intensive development, and significant progress in system reliability has been made.

A preproduction prototype engine employing the TCCS process is now being developed by the Hercules Division of White Motors Corporation, under contract to the U.S. Army Tank Automotive Command. Southwest Research Institute will conduct reliability tests on the White-developed engines when installed in Military vehicles.

3.0 Small Volume Prechamber Engines (3-Valve Prechamber Engines, Jet Ignition Engines, Torch Ignition Engines)

3.1 General

A number of designs achieve charge stratification through division of the combustion region into two adjacent chambers. The emissions reduction potential for two types of dual-chamber engines has been demonstrated. First, in a design traditionally called the "prechamber engine," a small auxiliary

or ignition chamber equipped with a spark plug communicates with the much larger main combustion chamber located in the space above the piston (Figure 3-1). The prechamber, which typically contains 5-15% of the total combustion volume, is supplied with a small quantity of fuel-rich ignitable fuel-air mixture while a large quantity of very lean and normally unignitable mixture is applied to the main chamber above the piston. Expansion of high temperature flame products from the prechamber leads to ignition and burning of the lean main chamber fuel-air charge. Ignition and combustion in the lean main chamber region are promoted both by the high temperatures of prechamber gases and by the mixing that accompanies the jet-like motion of prechamber products into the main chamber.

Operation with lean overall mixtures tends to limit peak combustion temperatures, thus minimizing the formation of nitric oxide. Further, lean mixture combustion products contain sufficient oxygen for complete oxidation of HC and CO in the engine cylinder and exhaust system.

It should be reemphasized here that a traditional problem with lean mixture engines has been low exhaust temperatures which tend to quench HC oxidation reactions leading to excessive emissions.

Control of HC emissions to low levels requires a retarded or slowly developing combustion process. The consequent extension of heat release into late portions of the engine cycle

tends to raise exhaust gas temperatures, thus promoting complete oxidation of hydrocarbons and carbon monoxide.

3.2 Historical Background and Current Status

3.2.1 Early Development Objectives and Engine Designs

The prechamber stratified charge engine has existed in various forms for many years. Early work by Ricardo¹ indicated that the engine could perform very efficiently within a limited range of carefully controlled operating conditions. Both fuel-injected and carbureted prechamber engines have been built. A fuel-injected design initially conceived by Brodersen¹¹ was the subject of extensive study at the University of Rochester for nearly a decade.^{12,13} Unfortunately, the University of Rochester work was undertaken prior to widespread recognition of the automobile emissions problem; and, as a consequence, emissions characteristics of the Brodersen engine were not determined. Another prechamber engine receiving attention in the early 1960's is that conceived by R. M. Heintz¹⁴. The objectives of this design were reduced HC emissions, increased fuel economy, and more flexible fuel requirements.

Experiments with a prechamber engine design called "the torch ignition engine" were reported in the U.S.S.R. by Nilov¹⁵ and later by Kerimov and Mekhtier.¹⁶ This designation refers to the torchlike jet of hot combustion gases issuing

from the precombustion chamber upon ignition. In a recent publication,¹⁷ Varshaoski et al. have presented emissions data obtained with a torch ignition engine. These data show significant pollutant reductions relative to conventional engines; however, their interpretation in terms of requirements based on the Federal emissions test procedure is not clear.

3.2.2 Current Developments

A carbureted three-valve prechamber engine, the Honda CVCC system, has received considerable recent attention as a potential low emissions power plant.¹⁸ This system is illustrated in Figure 3-2. Honda's current design employs a conventional engine block and piston assembly. Only the cylinder head and fuel inlet system differ from current automotive practice. Each cylinder is equipped with a small precombustion chamber communicating by means of an orifice with the main combustion chamber situated above the piston. A small inlet valve is located in each prechamber. Larger inlet and exhaust valves typical of conventional automotive practice are located in the main combustion chamber. Proper proportioning of fuel-air mixture between prechamber and main chamber is achieved by a combination of throttle control and appropriate inlet valve timing. A relatively slow and uniform burning process giving rise to elevated combustion temperatures late in the expansion stroke and during the exhaust process is achieved. High temperatures in this part of the engine cycle are necessary to promote complete

oxidation of HC and CO. It should be noted that these elevated exhaust temperatures are necessarily obtained at the expense of a fuel economy penalty.

To reduce HC and CO emissions to required levels, it has been necessary for Honda to employ specially designed inlet and exhaust systems. Supply of extremely rich fuel-air mixtures to the precombustion chambers requires extensive inlet manifold heating to provide adequate fuel vaporization. This is accomplished with a heat exchange system between inlet and exhaust streams.

To promote maximum oxidation of HC and CO in the lean mixture CVCC engine exhaust gases, it has been necessary to conserve as much exhaust heat as possible and also to increase exhaust manifold residence time. This has been done by using a relatively large exhaust manifold fitted with an internal heat shield or liner to minimize heat losses. In addition, the exhaust ports are equipped with thin metallic liners to minimize loss of heat from exhaust gases to the cylinder head casting.

Engines similar in concept to the Honda CVCC system are under development by other companies including Toyota and Nissan in Japan and General Motors and Ford in the United States.

Honda presently markets a CVCC-powered vehicle in Japan and plans U.S. introduction in 1975. Other manufacturers including General Motors and Ford in the U.S. have stated

that CVCC-type engines could be manufactured for use in limited numbers of vehicles by as early as 1977 or 1978.

3.3 Emissions and Fuel Economy with CVCC-Type Engines

3.3.1 Recent Emissions Test Results

Results of emissions tests with the Honda engine have been very promising. The emissions levels shown in Table 3-I are typical and demonstrate that the Honda engine can meet statutory 1975-1976 HC and CO standards and can approach the statutory 1976 NO_x standard.¹⁹ Of particular importance, durability of this system appears excellent as evidenced by the high mileage emissions levels reported in Table 3-I. Any deterioration of emissions after 50,000 miles of engine operation was slight and apparently insignificant.

Table 3-I

Honda Compound Vortex-Controlled Combustion-Powered Vehicle¹ Emissions

	Emissions, ² g/Mile			Fuel Economy, mpg	
				1975 FTP	1972 FTP
	HC	CO	NO _x		
Low Mileage Car ³ No. 3652	0.18	2.12	0.89	22.1	21.0
50,000-Mile Car ⁴ No. 2034	0.24	1.75	0.65	21.3	19.8
1976 Standards	0.41	3.4	2.0	-	-
1977 Standards	0.41	3.4	0.4	-	-

¹Honda Civic vehicles.

²1975 CVS C-H procedure with 2000-lb inertia weight.

³Average of five tests.

⁴Average of four tests.

Recently, the EPA has tested a larger vehicle converted to the Honda system.²⁰ This vehicle, a 1973 Chevrolet Impala with a 350-CID V-8 engine, was equipped with cylinder heads and induction system built by Honda. The vehicle met the present 1976 interim Federal emissions standards though NO_x levels were substantially higher than for the much lighter weight Honda Civic vehicles.

Results of development tests conducted by General Motors are shown in Table 3-II.²¹ These tests involved a 5000-pound Chevrolet Impala with stratified charge engine conversion. HC and CO emissions were below 1977 statutory limits, while NO_x emissions ranged from 1.5 to 2 g/mile. Average CVS-CH fuel economy was 11.2 miles per gallon.

Table 3-II

Emissions and Fuel Economy for
Chevrolet Impala Stratified
Charge Engine Conversion (Ref. 21)

Test	Exhaust Emissions, g/Mile ¹			Fuel Economy, mpg
	HC	CO	NO _x	
1	0.20	2.5	1.7	10.8
2	0.26	2.9	1.5	11.7
3	0.20	3.1	1.9	11.4
4	0.29	3.2	1.6	10.9
5	0.18	2.8	1.9	11.1
Average	0.23	2.9	1.7	11.2

¹CVS-CH, 5000-lb inertia weight.

3.3.2 HC Control Has a Significant Impact on Fuel Economy

In Figure 3-3, fuel economy data for several levels of hydrocarbon emissions from CVCC-type stratified charge engines are plotted.^{22,23,24} At the 1 g/mile HC level, stratified charge engine fuel economy appears better than the average fuel economy for 1973-74 production vehicles of equivalent weight. Reduction of HC emissions below the 1-gram level necessitates lowered compression ratios and/or retarded ignition timing with a consequent loss of efficiency. For the light-weight (2000-pound) vehicles the 0.4 g/mile HC emissions standard can be met with a fuel economy of 25 mpg, a level approximately equal to the average of 1973 production vehicles in this weight class.⁸ For heavier cars, the HC emissions versus fuel economy trade-off appears less favorable. A fuel economy penalty of 10% relative to 1974 production vehicles in the 2750-pound weight class is required to meet the statutory 0.4 g/mile HC level.

3.3.3 Effect of NO_x Emissions Control on Fuel Economy

Data showing the effect of NO_x emissions control appear in Figure 3-4.²² These data are based on modifications of a Honda CVCC-powered Civic vehicle (2000-pound test weight) to meet increasingly stringent NO_x standards ranging from 1.2 g/mile to as low as 0.3 g/mile. For all tests, HC and CO emissions are within the statutory 1977 standards.

NO_x control as shown in Figure 3-4 has been effected by use of exhaust gas recirculation in combination with retarded

ignition timing. It is clear that control of NO_x emissions to levels below 1 to 1.5 g/mile results in significant fuel economy penalties. The penalty increases uniformly as NO_x emissions are reduced and appears to be 25% or more as the 0.4 g/mile NO_x level is approached.

It should be emphasized that the data of Figure 3-4 apply specifically to a 2000-pound vehicle. With increased vehicle weight, NO_x emissions control becomes more difficult and the fuel economy penalty more severe. The effect of vehicle weight on NO_x emissions is apparent when comparing the data of Table 3-I for 2000-pound vehicles with that of Table 3-II for a 5000-pound vehicle. While HC and CO emissions for the two vehicles are roughly comparable, there is over a factor of two difference in average NO_x emissions.

3.4 Fuel Requirements

To meet present and future U.S. emissions control standards, compression ratio and maximum ignition advance are limited by HC emissions control rather than by the octane quality of existing gasolines. CVCC engines tuned to meet 1975 California emissions standards appear to be easily satisfied with presently available 91 RON commercial unleaded gasolines.

CVCC engines are lead tolerant and have completed emissions certification test programs using leaded gasolines. However, with the low octane requirement of the CVCC engine as noted above, the economic benefits of lead antiknock compounds are not realized.

It is possible that fuel volatility characteristics may be of importance in relation to vaporization within the high temperature fuel-rich regions of the prechamber cup, inlet port, and prechamber inlet manifold. However, experimental data on this question do not appear to be available at present.

4.0 Divided-Chamber Staged Combustion Engines (Large-Volume Prechamber Engines, Fuel-Injected Blind Prechamber Engines)

4.1 General

Dual-chamber engines of a type often called "divided-chamber" or "large-volume prechamber" engines employ a two-stage combustion process. Here initial rich mixture combustion and heat release (first stage of combustion) are followed by rapid dilution of combustion products with relatively low temperature air (second stage of combustion). The object of this engine design is to effect the transition from overall rich combustion products to overall lean products with sufficient speed that time is not available for formation of significant quantities of NO. During the second low temperature lean stage of combustion, oxidation of HC and CO goes to completion.

An experimental divided-chamber engine design that has been built and tested is represented schematically in Figure 4-1.^{25,26} A dividing orifice (3) separates the primary combustion chamber (1) from the secondary combustion chamber (2), which includes the cylinder volume above the piston top. A fuel injector (4) supplies fuel to the primary chamber only.

Injection timing is arranged such that fuel continuously mixes with air entering the primary chamber during the compression stroke. At the end of compression, as the piston nears its top center position, the primary chamber contains an ignitable fuel-air mixture while the secondary chamber adjacent to the piston top contains only air. Following ignition of the primary chamber mixture by a spark plug (6) located near the dividing orifice, high temperature rich mixture combustion products expand rapidly into and mix with the relatively cool air contained in the secondary chamber. The resulting dilution of combustion products with attendant temperature reduction rapidly suppresses formation of NO. At the same time, the presence of excess air in the secondary chamber tends to promote complete oxidation of HC and CO.

4.2 Exhaust Emissions and Fuel Economy

Results of limited research conducted both by university and industrial laboratories indicate that NO_x reductions of as much as 80-95% relative to conventional engines are possible with the divided-chamber staged combustion process. Typical experimentally determined NO_x emissions levels are presented in Figure 4-2.²⁷ Here NO_x emissions for two different divided-chamber configurations are compared with typical emissions levels for conventional uncontrolled automobile engines. The volume ratio, β , appearing as a parameter in Figure 4-2, represents the fraction of total combustion volume contained in the primary chamber. For β values approaching

0.5 or lower, NO_x emissions reach extremely low levels. However, maximum power output capability for a given engine size decreases with decreasing β values. Optimum primary chamber volume must ultimately represent a compromise between low emissions levels and desired maximum power output.

HC and particularly CO emissions from the divided-chamber engine are substantially lower than conventional engine levels. However, further detailed work with combustion chamber geometries and fuel injection systems will be necessary to fully evaluate the potential for reduction of these emissions.

Recent tests by Ford Motor Company show that the large volume prechamber engine may be capable of better HC emissions control and fuel economy than their PROCOCO engine. This is shown by the laboratory engine test comparison of Table 4-I¹⁹

Table 4-I

Single-Cylinder Low Emissions
Engine Tests

Engine	NO _x Reduction Method	Emissions, g/l hp-Hr			Fuel Economy, Lb/l hp-Hr
		NO _x	HC	CO	
PROCOCO	EGR	1.0	3.0	13.0	0.377
Divided Chamber	None	1.0	0.4	2.5	0.378
PROCOCO	EGR	0.5	4.0	14.0	0.383
Divided Chamber	None	0.5	0.75	3.3	0.377

Fuel injection spray characteristics are critical to control of HC emissions from this type of engine, and Ford's success in this regard is probably due in part to use of the already highly developed PROCOC-gasoline injection system. Figure 4-3 is a cutaway view of Ford's adaptation of a 400-CID V-8 engine to the divided-chamber system.²⁸

Volkswagen (VW) has recently published results of a program aimed at development of a large volume prechamber engine.²⁹ In the Volkswagen adaptation, the primary chamber which comprises about 30% of the total clearance volume is fueled by a direct, timed injection system; and auxiliary fuel for high power output conditions is supplied to the cylinder region by a carburetor.

Table 4-II presents emissions data for both air-cooled and water-cooled versions of VW's divided-chamber engine.³⁰ Emissions levels, while quite low, do not meet the ultimate 1978 statutory U.S. standards.

Table 4-II

Volkswagen Large Volume
Prechamber Engine Emissions

Engine	Exhaust Emissions, g/Mile ¹			Engine Specifications
	HC	CO	NO _x	
1.6-Liter Air-Cooled	2.0	5.0	0.9	8.4:1 compression ratio, prechamber volume 28% of total clearance volume, conventional exhaust manifold, direct prechamber fuel injection
2.0-Liter Water-Cooled	1.0	4.0	1.0	9:1 compression ratio, prechamber volume 28% of total clearance volume, simple exhaust manifold reactor, direct prechamber fuel injection

¹CVS C-H.

Toyota also has experimented with a large volume prechamber engine using direct prechamber fuel injection and has reported emissions levels comparable to those of Table 4-II.³¹

4.3 Problem Areas

A number of major problems inherent in the large volume prechamber engine remain to be solved.

These problems include the following:

- Fuel injection spray characteristics are critically important to achieving acceptable HC emissions. The feasibility of producing a satisfactory injection system has not been established.

- Combustion noise due to high turbulence levels and, hence, high rates of heat release and pressure rise in the prechamber can be excessive. It has been shown that the noise level can be modified through careful chamber design and combustion event timing.
- If the engine is operated with prechamber fuel injection as the sole fuel source, maximum engine power output is limited. This might be overcome by auxiliary carburetion of the air inlet for maximum power demand or possibly by turbocharging. Either approach adds to system complexity.
- The engine is characterized by low exhaust temperatures typical of most lean mixture engines.

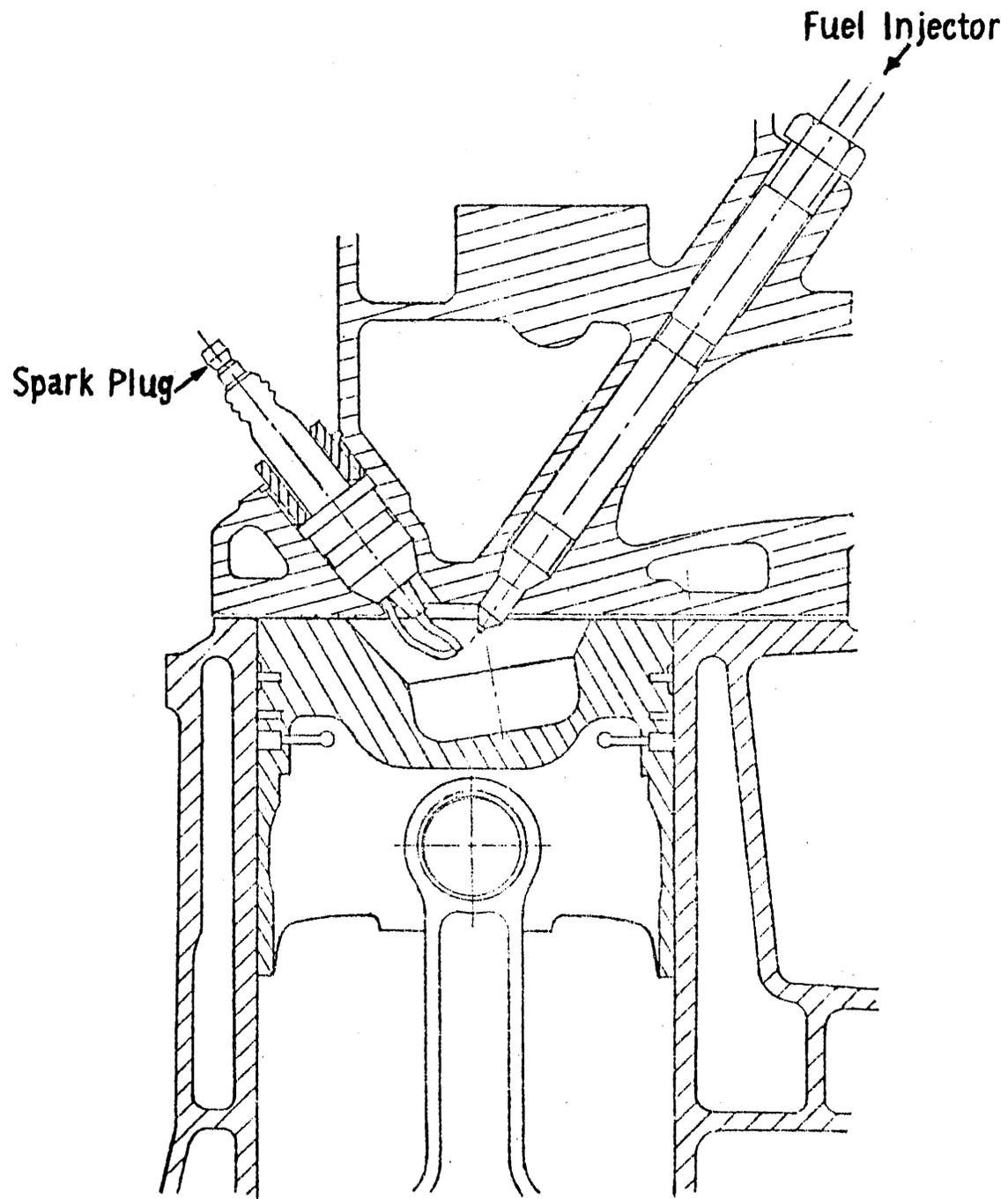
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Fig. 2-1 FORD PROCO ENGINE



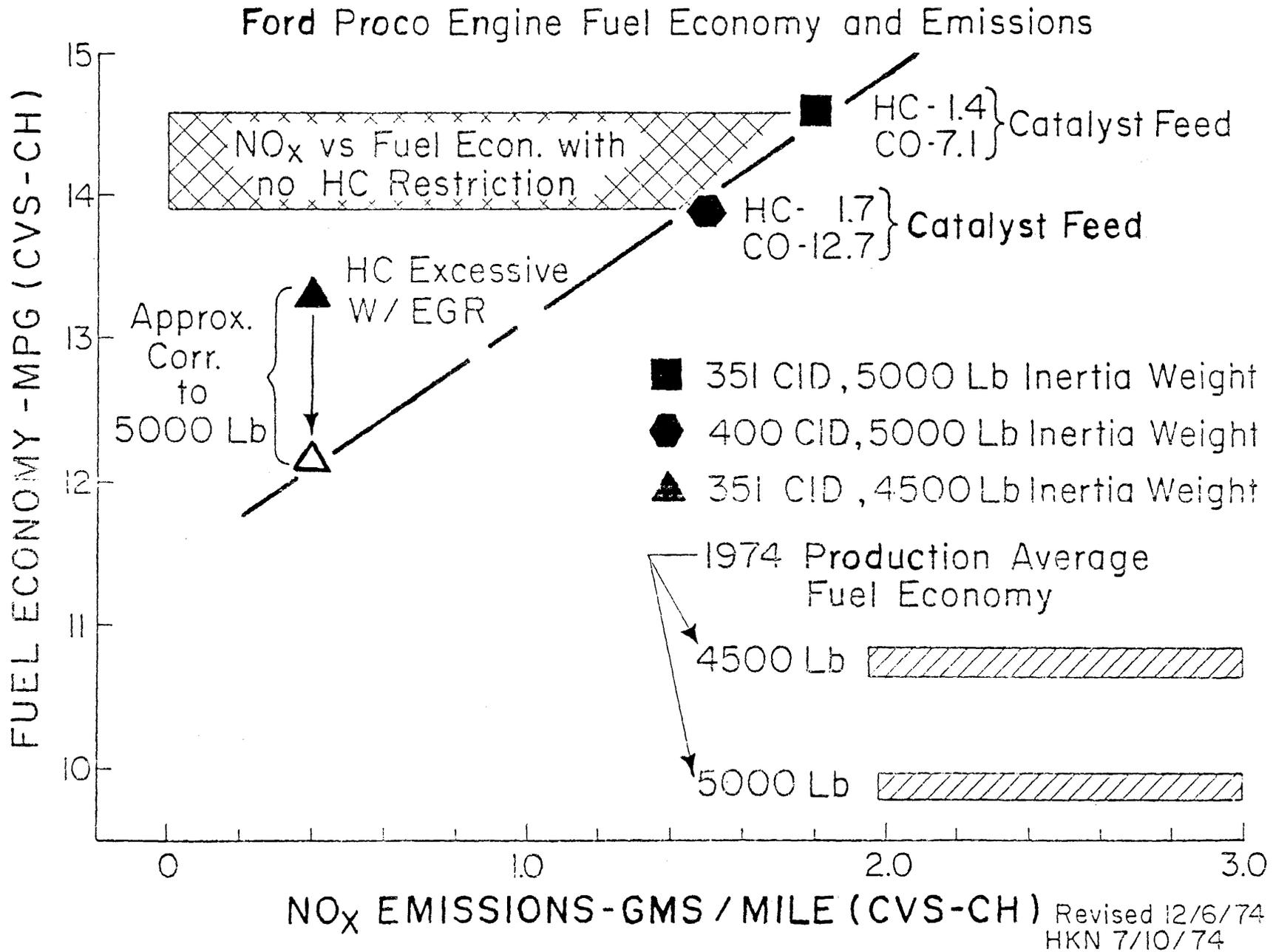


Fig. 2-2

Texaco TCCS Engine

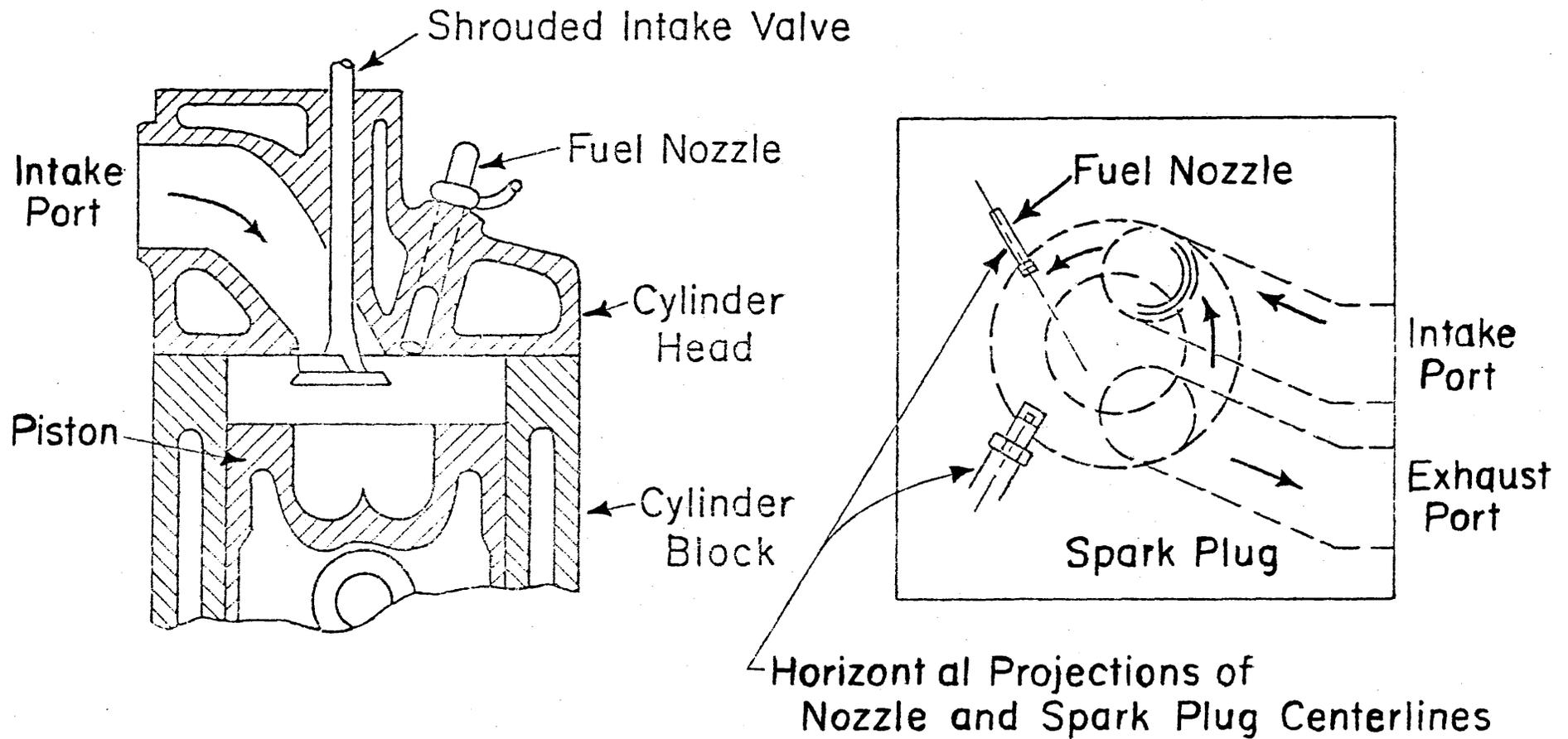
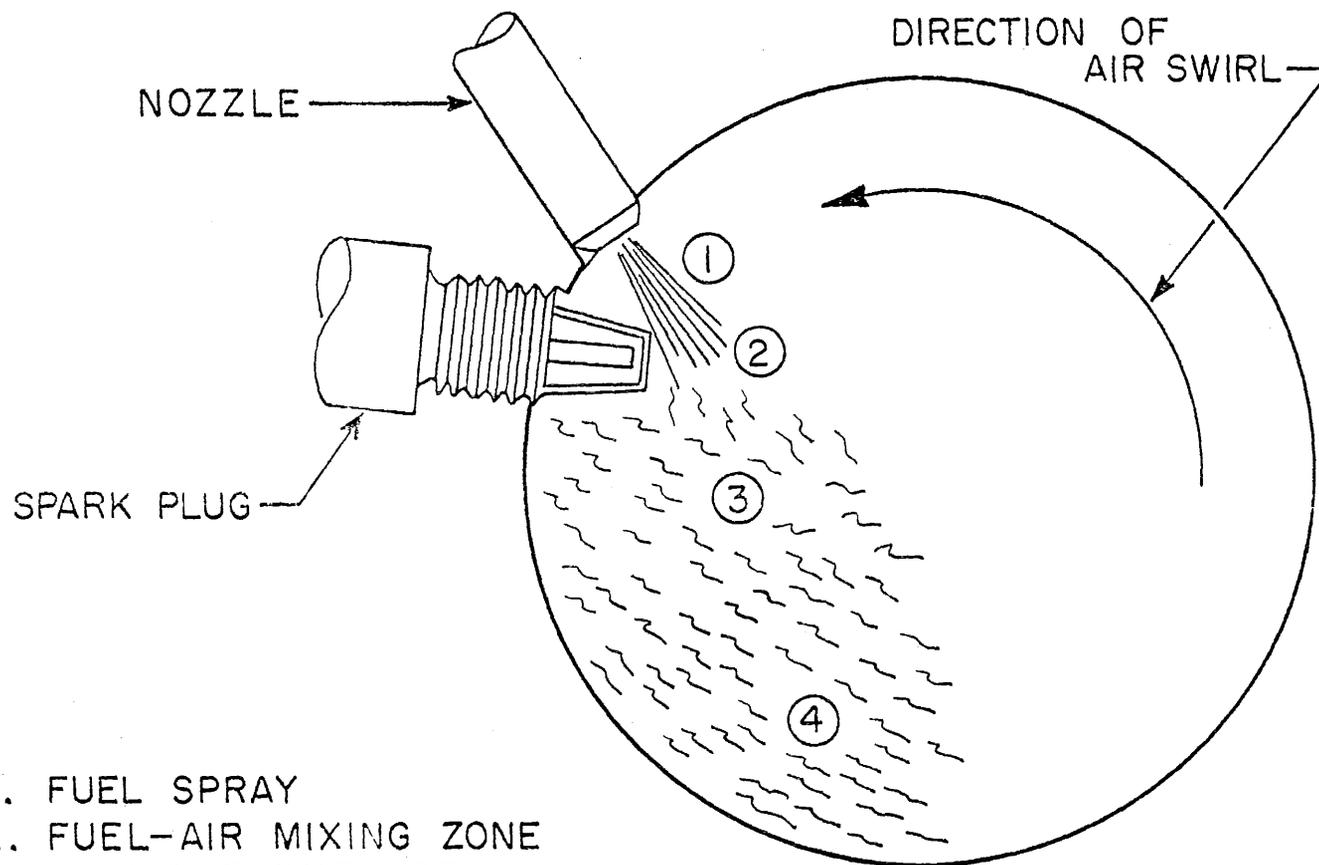


Fig. 2-3

OPEN CHAMBER TYPE STRATIFIED CHARGE ENGINE



- 1. FUEL SPRAY
- 2. FUEL-AIR MIXING ZONE
- 3. FLAME FRONT AREA
- 4. COMBUSTION PRODUCTS

TCCS COMBUSTION SYSTEM

Fig. 2-4

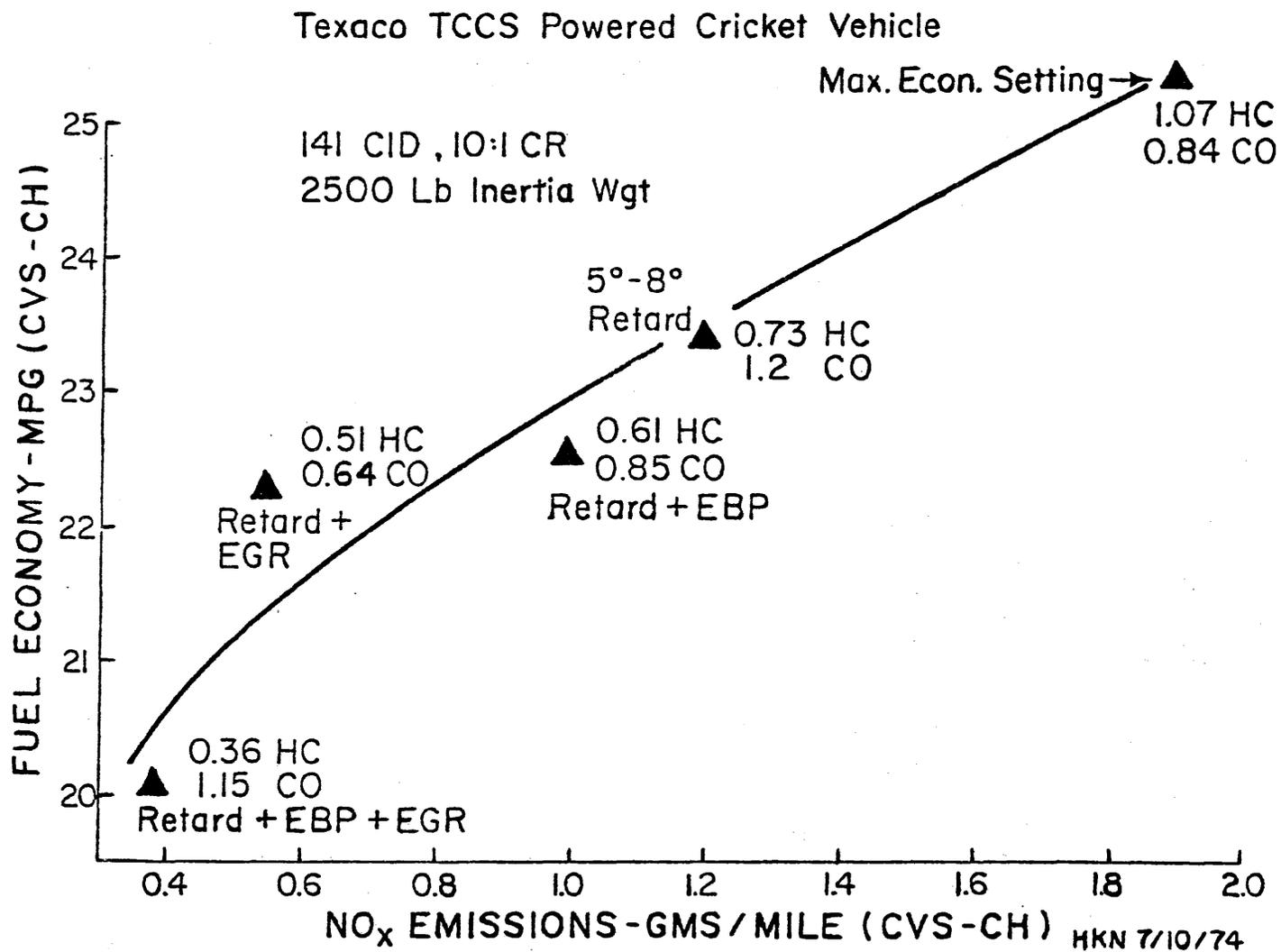


Fig. 2-5

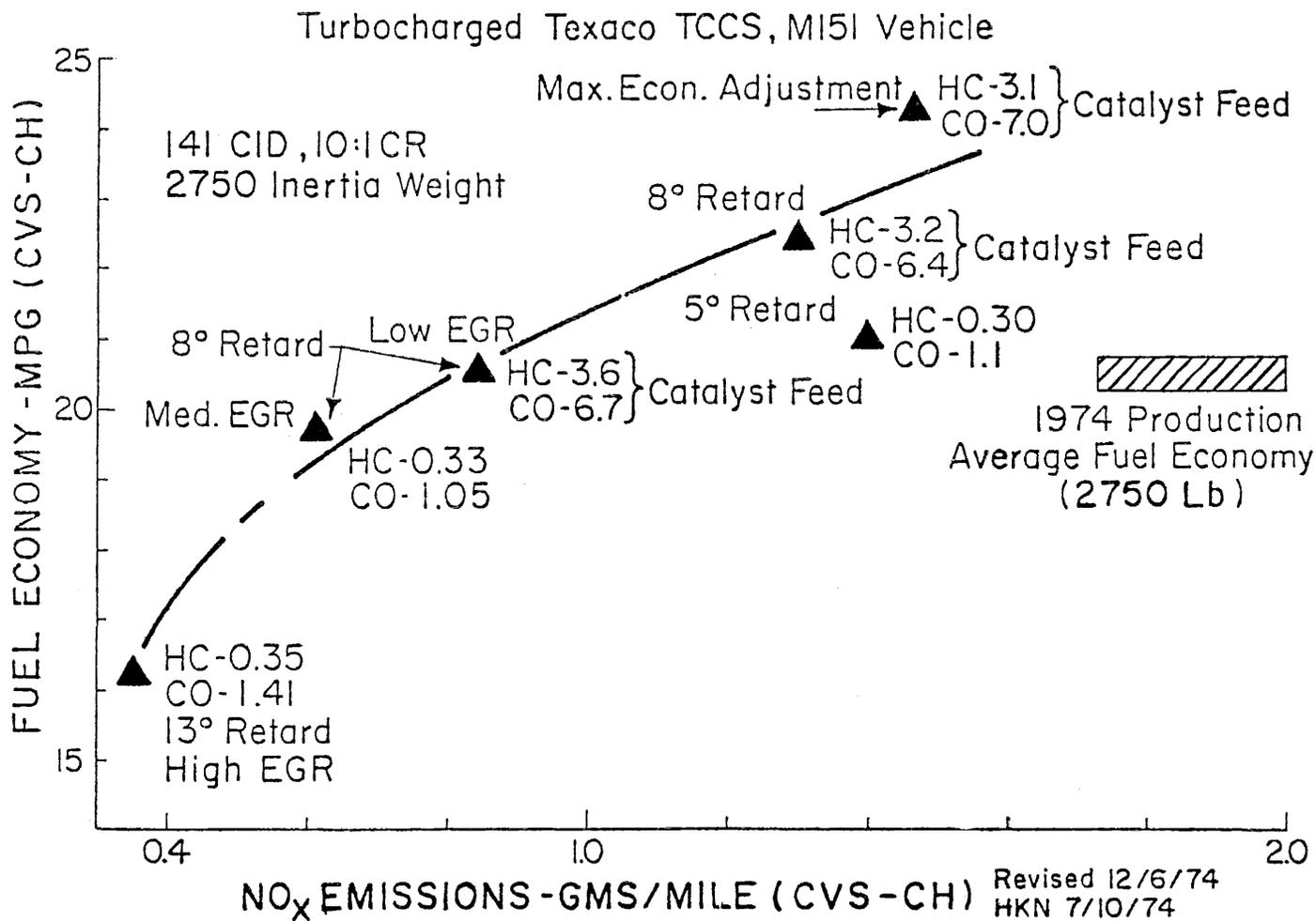
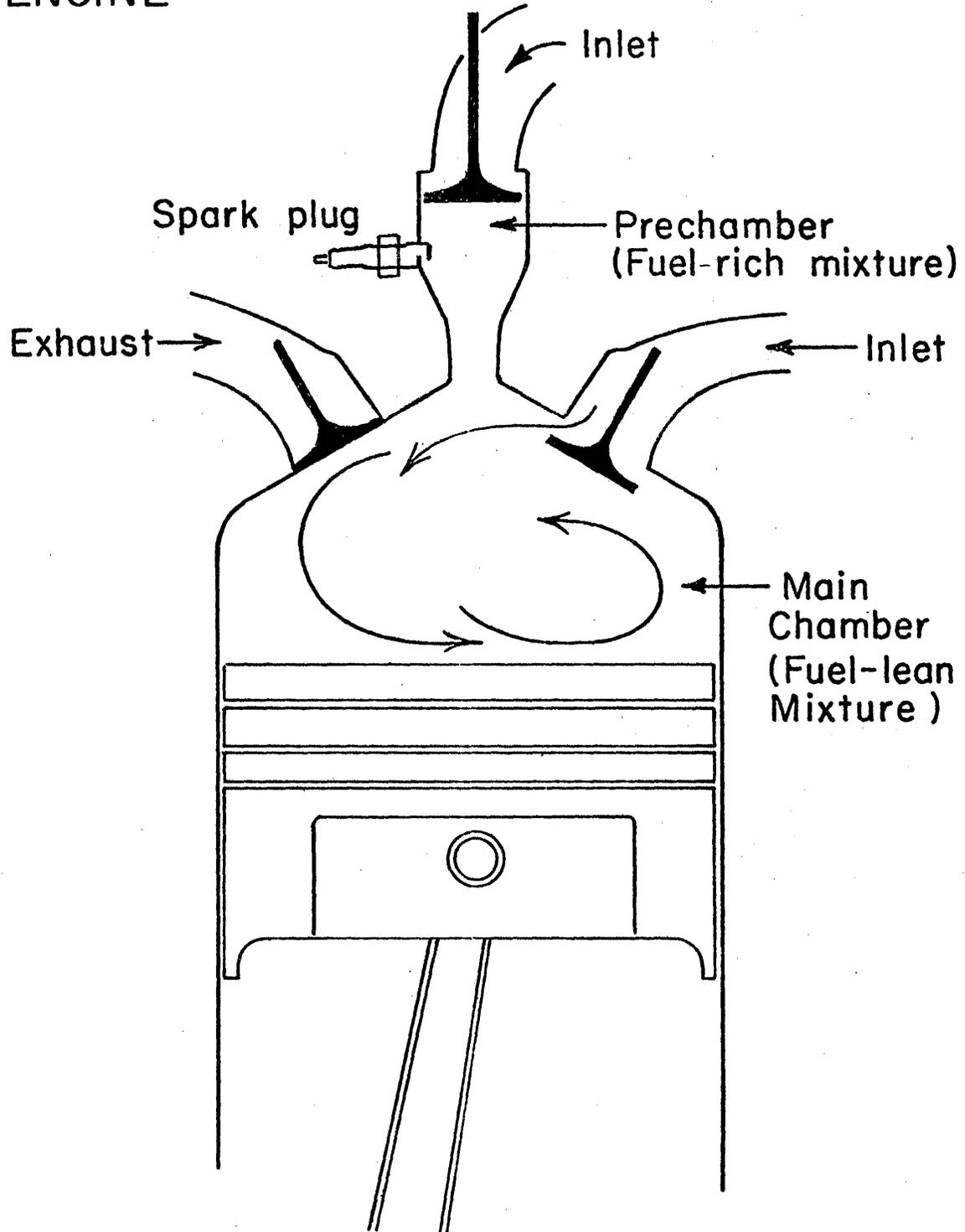


Fig. 2-6

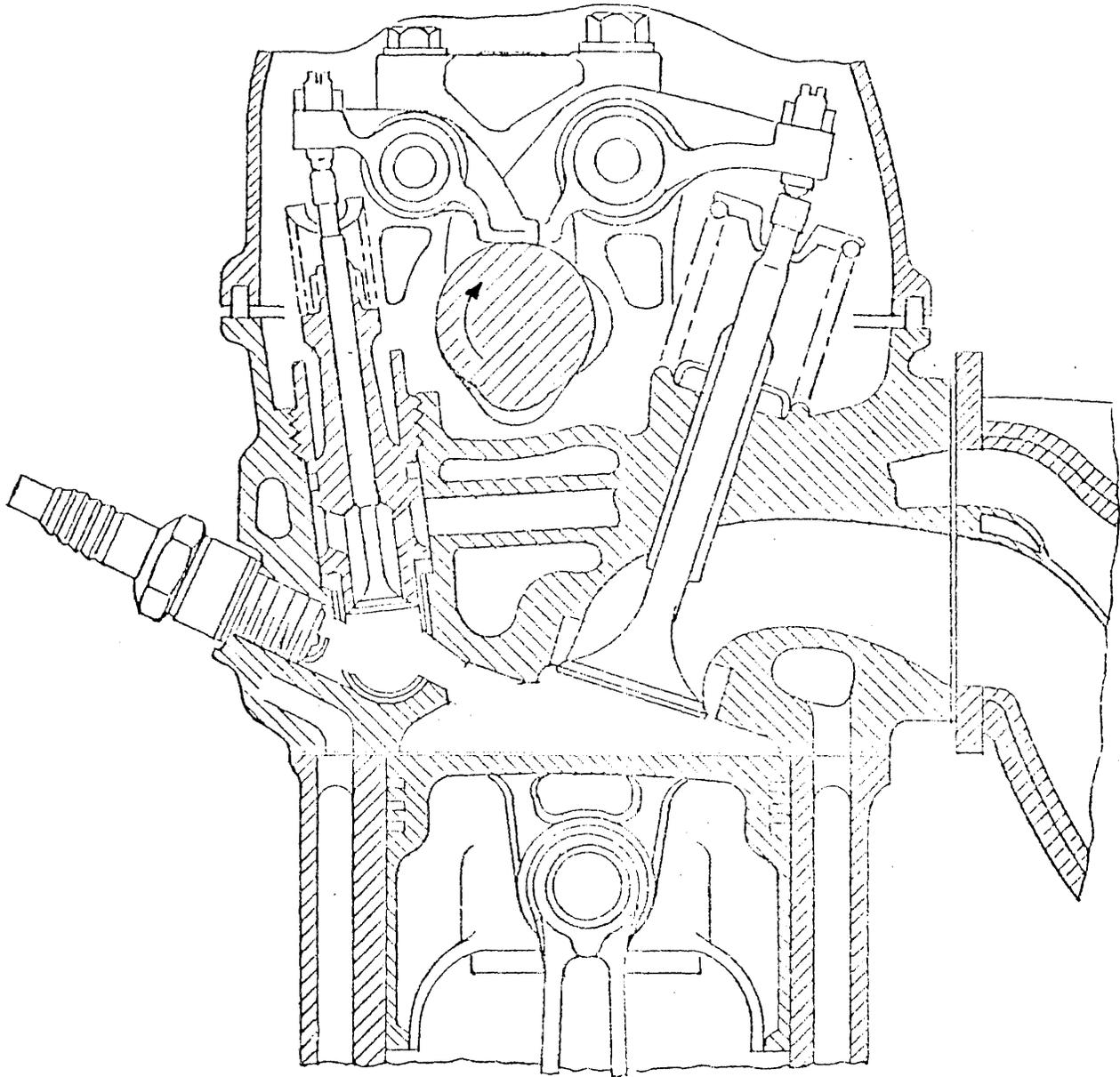
Fig. 3-1

PRECHAMBER TYPE STRATIFIED CHARGE ENGINE



HONDA CVCC ENGINE CONCEPT

Fig. 3-2 Honda CVCC Engine



Fuel Economy vs HC Emissions for 3-Valve Prechamber Engines

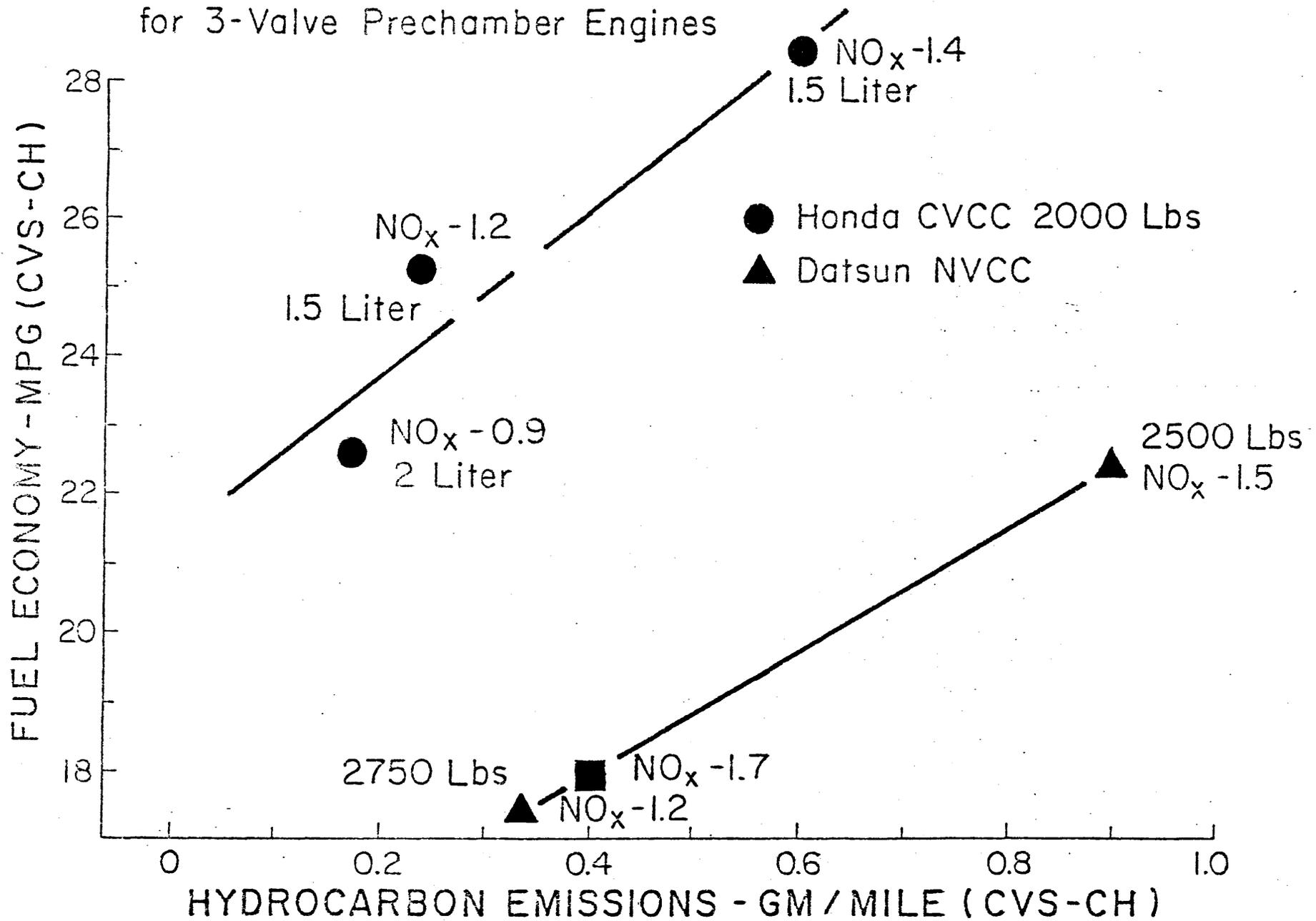


Fig. 3-3

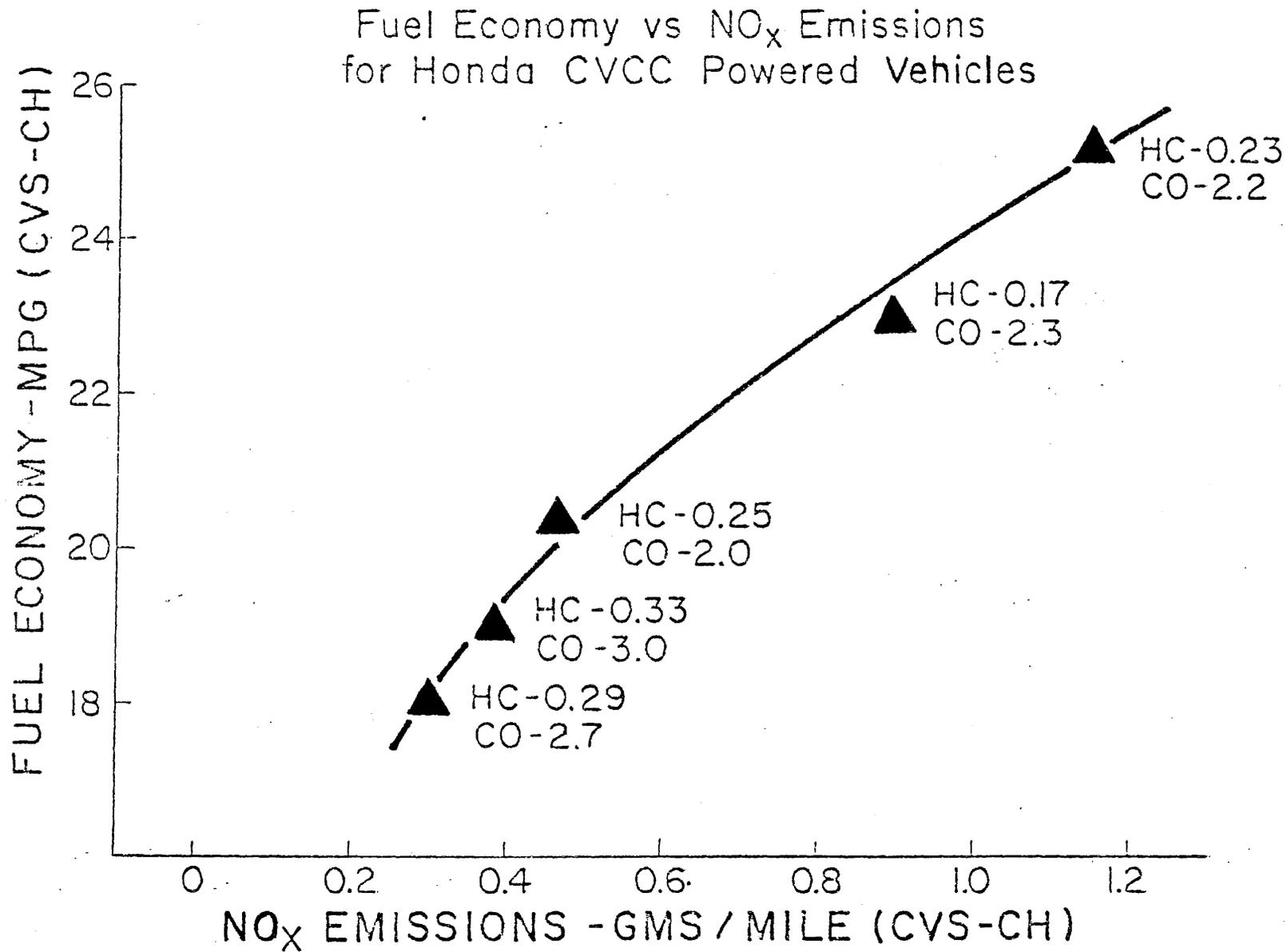


Fig. 3-4

Fig. 4-1 Divided Chamber Engine

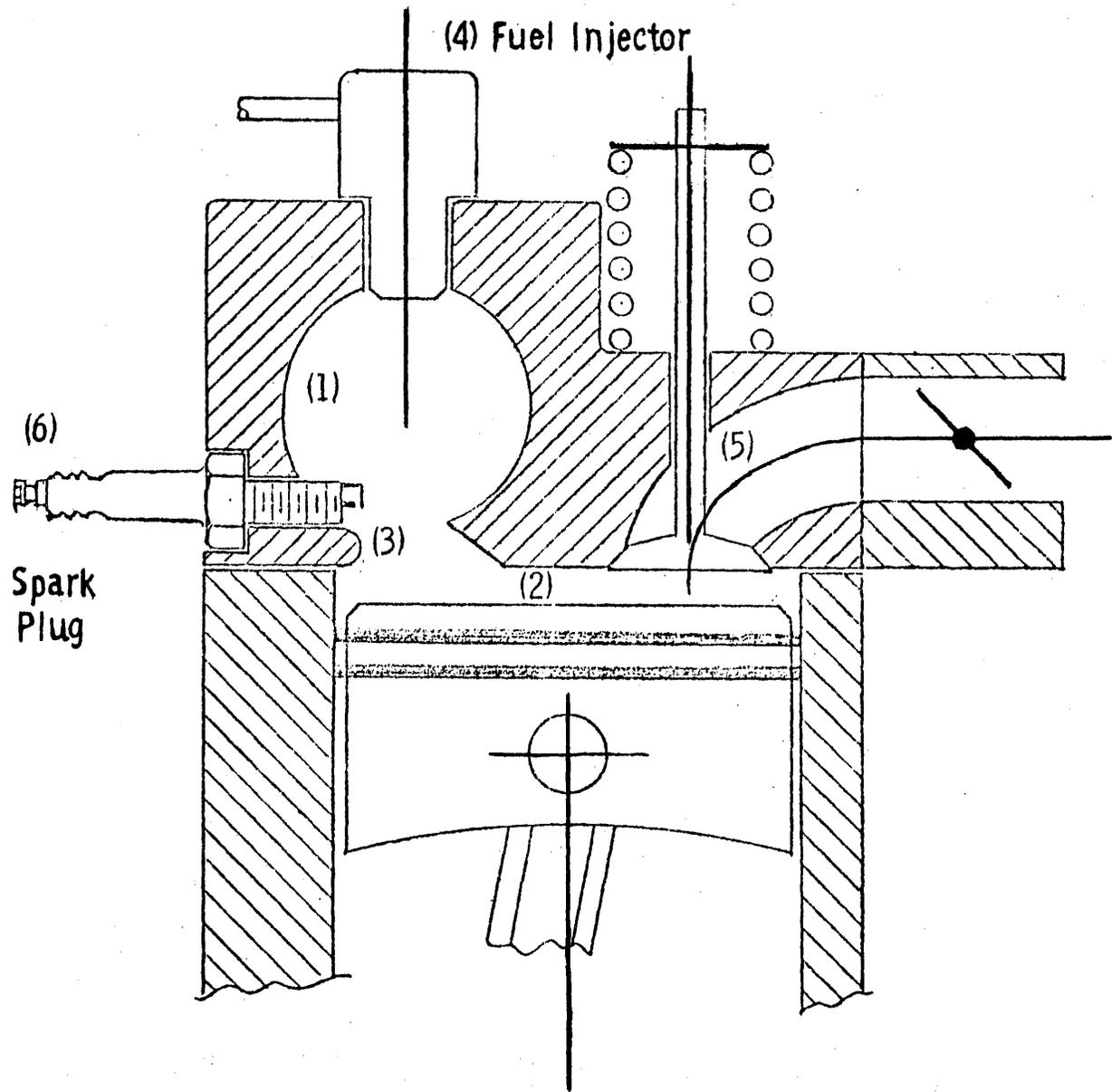
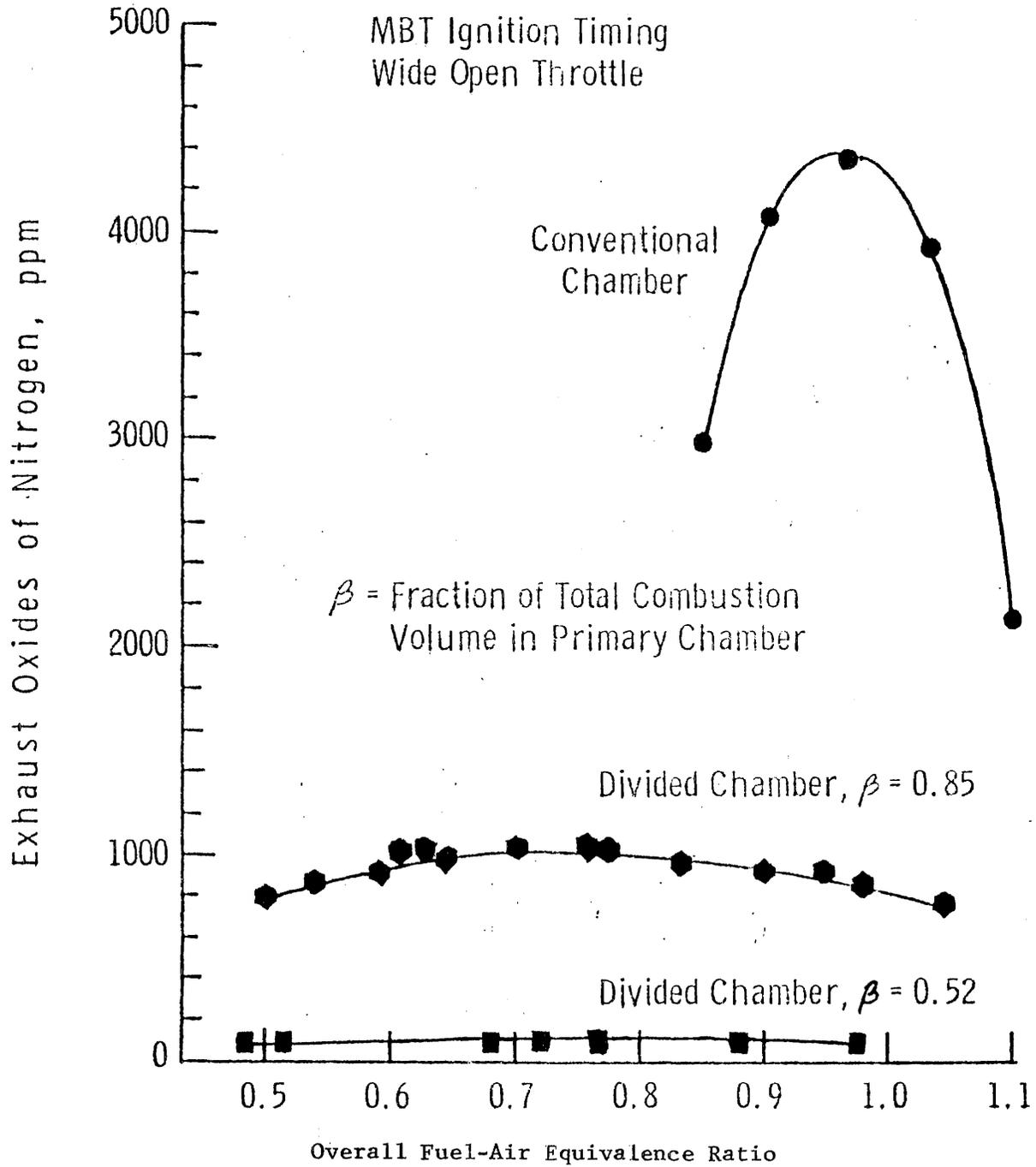


Fig. 4-2

COMPARISON OF CONVENTIONAL AND
DIVIDED COMBUSTION CHAMBER NO_x EMISSIONS



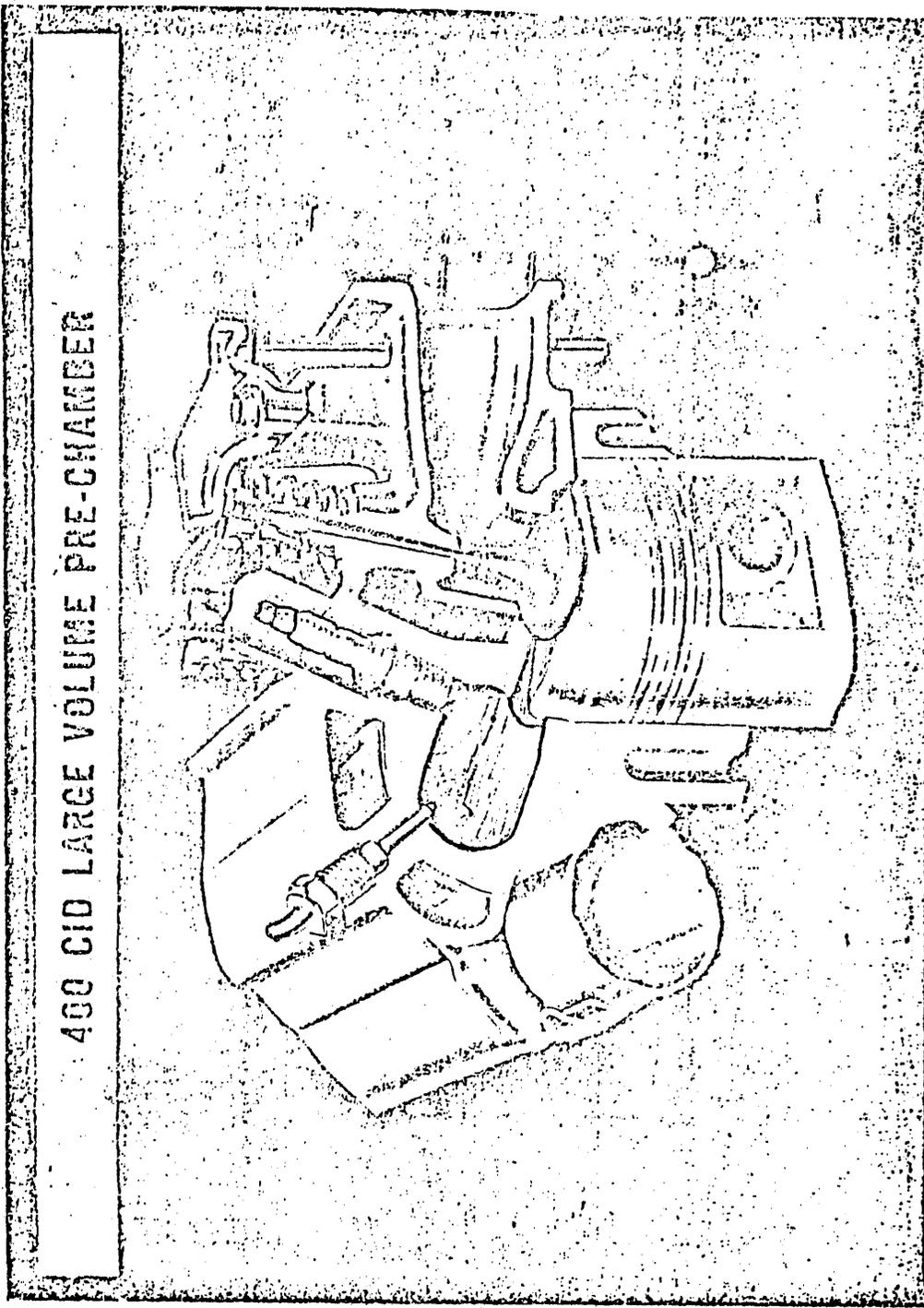


Fig. 4-3

AIRBORNE SURVEYS IN URBAN AIR BASINS:
IMPLICATIONS FOR MODEL DEVELOPMENT

by

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I would like to make several points today. First, ozone is basically a regional, long-range problem. There is a lot of long range ozone transport and this transport is a normal occurrence. The second point is that ozone is stable in the absence of scavengers; Junge mentions in his book that the residence time of ozone in the troposphere is on the order of a month. Third, vertical variations in concentration and ventilation rate are very important in modeling atmospheres such as Los Angeles. Layers aloft are ventilated down to the surface on occasion, and surface pollutants are ventilated up mountain slopes, as Jim Edinger has pointed out before, and often ventilated out of the basin in upper winds. Fourth, the day to day carry over of pollutants from one day to the next is a very important consideration in the Los Angeles Basin. Finally, there is a definite background level of ozone. The geophysical literature says it's about 0.02 to 0.03 ppm in various parts of the world. We've seen data varying from 0.03 to 0.05 ppm. The difference may be due to calibration differences. In any case, numbers like 0.05 are pretty substantial background levels for ozone.

I am going to illustrate the points listed above with some data from Los Angeles Basin. The data were collected during a two-year study funded by the Air Resources Board; some of the analyses were funded by EPA. The study examined the three dimensional distribution of pollutants in the Los Angeles Basin, using airborne sampling systems. Coinvestigators on the project were Dr. Ted Smith and Warren White of Meteorology Research, Inc. (MRI).

The first slide shows one of the aircraft we used. It's a Cessna 205 which had sampling inlets on the side of the aircraft. Figure 2 shows the instrument system on the inside of the aircraft. We were measuring nitrogen oxides, ozone, scattering coefficient with a nephelometer, condensation nuclei, carbon monoxide, and meteorological parameters such as temperature, humidity, turbulence. Altitude and position were also measured.

Figure 4 shows that the typical sampling pattern was a series of spirals from the top of the mixing layer over an airport virtually to ground level; then we would climb up to the next point on the route and spiral down again. We had three routes (A, B, C, Figure 3) that we would fly. We had two aircraft and we would fly two of these three routes three times a day, any given day that we could. The day I will be talking about, September 25, 1973, we flew what was called the Riverside route, (C), and the Los Angeles route (A). The 25th of July, 1973, you might remember, was the day before the federal office buildings were closed in the area here because of smog.

Figure 5 shows the surface streamlines at 0300 Pacific Standard Time, about 4 o'clock in the morning daylight time on July 25. This streamline analysis points out the morning stagnation conditions which are a very normal occurrence in the Los Angeles Basin. You start out with very light winds, quite variable, maybe a slight off shore flow early in the morning. On this particular day this kind of situation extended well into midday. The sea breeze did not really pick up until up around noon. When you have this kind of a situation and a low radiation inversion at night, you have a long period of accumulation of pollutants all over the Basin, especially in the prime source area, the southwest portion of the Basin.

Figure 6 shows the streamline pattern at 1600--4:00 oclock in the afternoon, same day; sea breezes develop and with them a transport pattern that carries pollutants up to the northeast and out toward the eastern portion of the Basin. This is a very regular pattern which we see day after day. On July 25, 1973, it was a little bit exaggerated. The sea breeze was held off for awhile, started a bit late, and so there was a very long period of accumulation in the southwest area and then transport across the Basin.

Figure 7 is an average streamline pattern at 1600 Pacific Daylight Time on low inversion days for August 1970. It is included to show that the pattern shown before is very typical. Flow starts in the western portion of the Basin, and goes right across to the eastern portion. This is using surface data. There is a very high average wind velocity in Ontario, about 13 miles per hour, and 23 mph in Riverside. This is the average for the whole month of August, at 1600 PDT on low inversion days. There is a considerable amount of transport across the Basin, starting relatively slowly in the morning and accelerating in the afternoon.

Figure 8 shows a verticle cross section of the scattering coefficient. The darker areas indicate higher levels of particulates. Scattering coefficient is inversely proportional to visibility. In the crosshatched area, visibility is less than about 3 miles. In plotting altitude versus distance inland from the coast you have Santa Monica (SMO) on the coast, El Monte (EMT) Pomona (BRA), Rialto (RIA), Redlands (RED). The lower broken line is surface ground level. The heavy dashed line is the base of the subsidence inversion that occurred on the two days during this episode. The middle line is the base of the marine inversion. There is a large area over in the western portion of the Basin where emissions accumulate for much of the day. At

midday, the sea breeze has just started ventilating the Santa Monica area. The layer between the inversions is a layer aloft which is fairly well separated from the surface layer. Ozone concentrations, for instance, in the layer aloft were on the order of 0.4, 0.5 ppm, using the ARB calibration method. Down in the surface layer they were quite a bit lower in the morning due to scavenging.

Figure 9 shows that by afternoon, the sea breeze starts and you get kind of a clean air front. Sea breeze starts ventilating the whole Basin, the stuff that was over in the west is transported eastward, and at approximately Brackett (BRA) at 1700 PDT there is a clean air front. The high concentrations that were over Los Angeles earlier are now centered near Upland (CAB). The numbers shown over CAB are data taken from a vertical profile spiral over Upland at about 1600. That turns out to be the time when there was the worst ozone concentration of the day in the Basin and it did occur at Upland. It could well be a result of the very polluted mass from the western Basin being transported over the Upland area. The layer aloft has been a bit undercut by the sea breeze and some of the polluted mass has been around possibly as long as the night before. There has been very little transport in the area aloft; ozone concentrations are still very high.

Figure 10 shows a trajectory analysis of the air arriving at Upland at 1600 since that was the worst time of the day at Upland. We developed a trajectory envelope using surface wind data and winds aloft, so the air arriving at Upland at 1600 started out somewhere back within this envelope, for example at 11:30 PDT. We did not go earlier than 11:30 because the winds were pretty much light and variable before that. The air that arrives at Upland at 1600 has been over the western portion of the Basin for much of

the morning and quite a bit of the evening before. Thus, there is a very long period of accumulation and then a transport, a pulsing effect where you have pollutants moved across the Basin.

Figure 11 is an isopleth map of surface ozone concentrations. Again, all data are corrected to agree with the ARB calibration method. Again you can see that for the hours between 1600 and 1700, using surface data, the Upland area has the highest surface ozone concentrations, about 0.63 ppm. The western area has been well ventilated by the sea breezes, and it is cleaned out. The transport is actually pretty much perpendicular to the isopleth line just about like that.

Figure 12 is a vertical profile taken over Upland, Cable Airport, at roughly the time of maximum ozone concentration, 1636 PDT. We are plotting pollutant concentration on the x-axis versus altitude in meters (since it was done for an EPA report). Surface level at Upland is a little over 400 meters; the "Z" line is ozone. Ozone concentration within the surface mixing layer is pegged on the instrument at somewhat above 0.5 ppm. Above the surface mixing layer it drops off considerably and eventually get down to background. The "T" line is temperature, and you can see the subsidence inversion on this day is very nicely documented here, and provides a very strong trap in that area. The "B" line is the scattering coefficient, inversely proportional to visibility. Within the surface mixing layer, visibility is on the order of 3 miles or less, while up above the surface mixing layer, just a few hundred feet difference, visibilities get up to 60 or 80 miles. The "X" is condensation nuclei, the measure of the very fine particles below about 0.10 micron. It is a measure of quite fresh emissions. If you have a high condensation nuclei count, there are very fresh combustion emissions. If you have

an aged air mass, the condensation nuclei coagulate and the count decreases considerably. You can see that there are still some fresh emissions within this surface layer as well. But up above the surface mixing layer all the pollutant indicators decrease considerably.

Figure 13 is the same type of vertical profile taken over El Monte, which is on the western side of the sea breeze front. The sea breeze front has passed El Monte at this time, almost 1700 PDT, and again there are distinct differences between the mass below the mixing layer within the sea breeze front, (below 400 meters), the marine inversion (400 to 800 meters) and the subsidence inversion. The subsidence inversion occurs at about 800 meters and there is an old layer of very polluted stuff aloft. The surface concentrations are lower because of the ventilation by the sea breeze. Condensation nuclei count ("X" line) within the surface layer is quite high. There are still fresh emissions in the El Monte area. The "Z" line is ozone, about 0.2 ppm within the surface layer (200 m), but it is 0.5 ppm up above the surface mixing layer. The scattering coefficient ("B" line) is very similar; it is lower at the surface and increases to a visibility equivalent of less than 3 miles above the surface mixing layer. The condensation nuclei count is high in the lower portion of this (e.g. at 600 m) but decreases considerably above. This portion of the upper layer (600 m) has been around at least all morning, and condensation nuclei have been scattered from the area. The portion of the upper layer below 600 m has probably just recently been undercut by the sea breeze, and there are still some condensation nuclei left in it.

Figure 14 illustrates a different method of looking at the flushing problems in the Basin. We have tried to develop an objective criteria based on ground level ozone to show the cleansing of the basin, using the time of

arrival of clean air. We determine the time when the ozone concentrations drop by a factor of two at any given point. The 1600 line means that between 1500 and 1700 the ozone concentration at that point dropped a factor of two. This sort of isopleth chart of when the clean air arrives agrees quite well with the trajectory analyses, although the numbers are a little bit behind the trajectory analyses for the polluted air. Figure 14 again shows the transport process that takes place across the Basin, which is ventilated from west to east. At 1900, some of the fresh ocean air finally gets out to Redlands.

In Figure 15, in order to put this whole flux problem into some perspective, we looked at the numbers, the actual amount of ozone flux across the basin. We calculated the mean trajectory from Torrance towards Redlands, using the surface and upper air data. We looked at the flux from the western basin to the eastern basin, basically from Los Angeles and Orange Counties to Riverside and San Bernardino Counties. This is a calculation made at 1700 PDT. We used the winds aloft from Chino as well as the vertical profiles taken at Pomona and Corona. Averaging the ozone concentration throughout the mixing layer and multiplying by an average wind speed, we arrive at a number of 185 metric tons per hour being transported directly from one side of the Basin to the other. If you look at this in terms of actual concentration in the eastern Basin, and assume that the flow was constant for about an hour, it is enough to fill up the box shown in Figure 15 to 0.25 ppm ozone, which exceeds the air quality standard by a factor of three (using the ARB calibration method). Thus, there is a very significant transport of ozone or ozone precursors from one portion of the Basin to the other side of the Basin. One thing to mention, though, is that the concentration would not be kept up on a

steady state basis because the transport is a result of the pulsing effect I mentioned earlier. There is a lot of accumulation in the western Basin, and these accumulated pollutants are then transported across the Basin. This kind of transport did take place in a couple hours, because we also have measurements from 1500 PDT which give us similar flux numbers.

Figure 16 is a trajectory envelope similar to Figure 10 calculated for Upland at 1600, for the air arriving at Redlands about 6:00 o'clock in the afternoon. I wanted to include this trajectory envelope to show that the problem is not really simple. You cannot say that the air at Redlands came from Long Beach, per se. The air at Redlands, if you look at the whole envelope of possible trajectories, using upper air data as well as surface data, could have come from anywhere between Downtown Los Angeles and over the Pacific Ocean south of Long Beach.

Another thing to recognize is that the wind actually changes direction slightly as you go up and down through the mixing layer and the mixing layer is exactly what it implies. There is mixing within the mixing layer, so if you begin with a parcel of air near the surface, this parcel may move to the top of the mixing layer and go one direction for awhile; it then may go back down to the bottom of the mixing layer, and move in another direction for awhile. The ratio of the length scales indicates mixing layer depths of 1500 or 2000 ft., and distances on the order of 70 miles. This makes it very difficult for tetroons to follow an air trajectory, because they do not go up and down. They stay at one altitude and in one wind regime, and yet the wind regimes are different at different altitudes, and the air is continually mixed up and down through this layer. You can often see this on time lapse photographs.

The question is where does the pollutant mass go after Redlands. Figure 17 is a repeat of Jim Pitts' slide from yesterday, and it is data for the same day that we did our analysis. It shows the ozone peaks, starting at Pomona and Riverside, and on July 25, 1973 eventually getting out to Palm Springs, so there is quite a bit of long-range transport. The ozone is stable at 8:00 or 9:00 o'clock at night. There still are ozone concentrations of 0.2 ppm; it hasn't dissipated even at the surface. Ozone does dilute as the mass moves. Other calculations we did were integrations through the mixing layer of various pollutants, such as ozone and CO, along with trajectories that we measured. These integrations show just what the ground data show in Figure 17. The concentrations increase through the western portion of the Basin, and then show a decrease through the eastern portion of the Basin. CO tends to decrease faster than the ozone, indicating a continued production of ozone further east.

Figure 18 is a streamline chart on a larger area map for the 16th of August, 1973. It shows the typical streamline patterns that occur for ventilation from the Basin. By mid-afternoon there is flow out through the major passes, to the north, and towards Palm Springs (PSP). On this particular day we had data from Arrowhead showing that the air mass from the Basin does indeed get up there.

Figure 19 shows a vertical profile over Arrowhead early in the morning, 16 August, 1973, at a time when there was a north wind. Ozone level was about 0.05 ppm, the scattering coefficient was quite low, on the order of probably 60 miles visibility or so. Figure 20 is a vertical profile again over Arrowhead late that afternoon when the winds had switched. There is a flow from the Los Angeles Basin into the Arrowhead area; thus, one sees a

vertical profile that shows a distinct increase near the surface in both the ozone and the scattering coefficient, and in the condensation nuclei. Above that you have fairly clean air. The top of the polluted level is just about the top of the mixing level over the Basin.

I want to leave the transport now, and discuss the complicated vertical structure that can occur. If you want to try to model something, try this one for instance. Figure 21 is a vertical profile over Brackett Airport, Pomona, about 8:30 in the morning on 26 July, 1973, which is the day after the episode shown earlier. A bit of interpretation shows how complicated this can be. If one looks at the temperature profile, it would be very difficult to pick out a mixing layer; there's a little inversion here, another inversion there, several more up here. After looking at hundreds of these profiles, though, you can start interpreting them. What is happening is that there is a surface mixing layer at about 500 m. In this layer, there is a high condensation nuclei ("X" line) count due to morning traffic. The San Bernardino freeway is quite close to Brackett, there is a relatively high nitrogen oxide count about 0.2 ppm and the b-scat is fairly high. Ozone ("Z") within the surface layer, however, at this time is quite low. The layer between 500 m and 700 m turns out to be the Fontana complex plume. Note the very high b-scat level, it is below 3 miles visibility; the plume is very visible, especially at this time of the morning when it is fairly stable. There is a high nitrogen oxide level, (800 m) a high condensation nuclei level, and again a deficit of ozone. Above this layer (800 m) you have stuff that has been left all night, very low condensation nuclei indicating a very aged air mass, ozone concentrations about 0.16 ppm, b-scat of about 0.4. It has been around all night and not yet had a chance to mix down within the

surface layer. In fact, one good way of determining the surface mixing layer early in the morning and at night is to look for the ozone deficit. Another thing to mention is that wind reversals occurred for each of these three layers. The winds were fairly light and westerly at the surface, slightly easterly in the 500 m - 700 m layer and westerly above 800 m. There is a complicated situation early in the morning, but the main problem is that by the middle of the day there is good surface heating, and the pollutants have all been entrained and mixed down to the ground; so in order to model what happens on the second or third day of an episode, you must be able to look at both old pollutants as well as fresh emissions. And you need to account for ozone that is actually transported down to the surface from layers aloft.

The next slide is a photograph (not included), which is another example of some layers aloft. This is due to upslope flow as explained by Jim Edinger in his publications. The mountains are heated during the day, in turn heating the air and making it buoyant; there is upslope flow to a point where the heating cannot overcome the subsidence inversion, and the stuff comes right out from the mountains and spreads out over the Basin. The pollutants can stay up there if the winds aloft are very light and on the subsequent day will be re-entrained to the surface. On the other hand, if there are winds aloft different from those in the surface mixing layer or the wind velocity aloft is high, there can be a very substantial ventilation process for the Basin. Pollutants can be ventilated up the slope and blown away in the upper winds. In the case of the entire July 25th episode, winds aloft were quite light and these upper layers remained.

Figure 22 is a vertical profile of one of those upslope flow conditions, in the same location shown in the photograph, but on a different day. Again

there is a relatively high surface concentration of about 0.3 ppm of ozone ("Z" line), a layer of clean air between 900 to 1100 m, and then high concentrations of ozone again above 1100 m. It has gone up the slopes of the mountains and then come back out. Concentrations in the 1100 to 1300 m area are just slightly lower than they were at 600 to 800 m area. Notice, however, that the condensation nuclei count ("X" line) is quite a bit lower, mainly because the stuff is much more aged above the 1000 m level than it is down below 900 m.

Figure 23 shows the stability of ozone, the fact that it can stay around all night long. This is a vertical profile taken over Riverside about 2200 PDT, 10:00 o'clock at night. Above the surface mixing layer (600 m) there are ozone concentrations of about 0.15 ppm ("Z" line). Within the surface mixing layer (below 500 m), ozone is completely scavenged, decreasing to zero. The nitrogen oxides within this surface layer are being contained, and are around 0.1 ppm from fresh emissions that occurred during the evening. Condensation nuclei near the surface are very high. The temperature profile is very stable. You have a surface based radiation inversion, which is a little strange looking for a radiation inversion; nevertheless it is quite stable. There is a definite restriction of the mixing--a very difficult time getting air from below 500 m to above 500 m. The ozone that exists in the 700 m range is in air where the reactions have virtually gone to completion, and is very stable. All the profiles on this night changed very little; the ozone peak stays there. High concentrations stay around.

Figure 24 is a cross section across the urban plume of the City of St. Louis. I wanted to show that this occurrence is not limited to Los Angeles. We have seen ozone formation and transport in other urban plumes. These data

were taken during a project sponsored by EPA in conjunction with R. Husar of Washington University and William Wilson of EPA. The dark line on this is the ozone concentration across the urban plume, perpendicular to plume. The dashed line is the scattering coefficient. The power plant plume is parallel to the urban plume. The data on the left were taken 35 kilometers down wind about 11:00 o'clock in the morning. The ozone concentration increases slightly to 0.05 ppm in the urban plume; there is a deficit of O_3 in the power plant plume. In the same urban plume, same conditions, 1500 CDT, two hours later, further downwind, there has been substantial increase in the ozone in the urban plume itself. The b-scat is very similar to what it was before but the ozone is now increased quite substantially, except in the power plant plume where there is a strong deficit of ozone due to scavenging by nitrogen oxides. So the formation and transport of ozone and ozone precursors in urban plumes is a regular occurrence that happens in more places than Los Angeles and, as Bob Neligan showed this morning, it can happen over quite a bit longer distances than we are showing here.

To summarize the conclusions as they affect model development, first, once ozone is formed, in the absence of scavengers ozone is a very stable compound. It remains for long periods of time. It can be transported for very long distances. Ozone is a regional problem which cannot be controlled on a local basis. To have effective ozone control one must have a regional control strategy and probably regional type air pollution districts.

A second conclusion is that the vertical distribution of pollutants can be highly complex and models have to include more than just a simple well-mixed surface layer.

A third conclusion is that layers aloft can persist over night and can be re-entrained within the surface mixing layer on subsequent days; models should be able to account for old pollution as well as fresh emissions. Also pollutant accumulation and transport can have distinct diurnal patterns that are strongly dependent on the meteorology. Models should be time dependent and should start at the beginning of the accumulation period. In other words, models ought to be able to run for 24 or 48 hours if they have to. In this case, in Los Angeles, there is often an accumulation of pollutants which starts in one portion of the Basin at midnight and continues through the next morning even before it starts to be transported.

As far as recommendations go, in many areas a lot of ambient data has been collected, and in some cases the data are actually ahead of some of the models, so I think a research program is needed in developing models that will account for this vertical structure and the day to day carry over, and the models need to be extended to cover longer distances. In addition, more smog chamber work is going to be needed in looking at the effects of carry over and mixing old pollutants with fresh emissions. How people go about this, I leave to the modelers and the smog chamber people. They know more about that than I do.

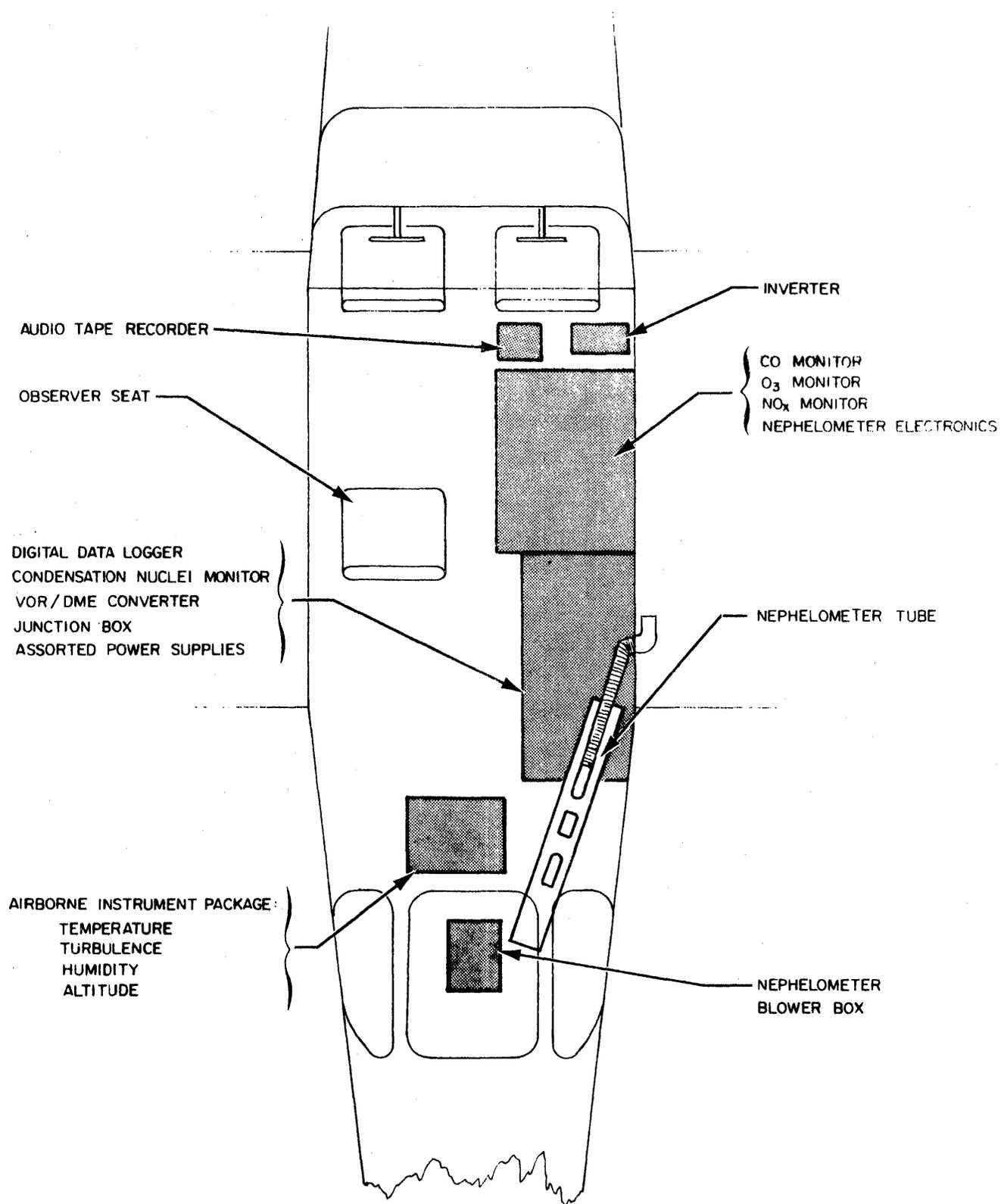


Figure 2. Instrumentation Layout for Cessna 205

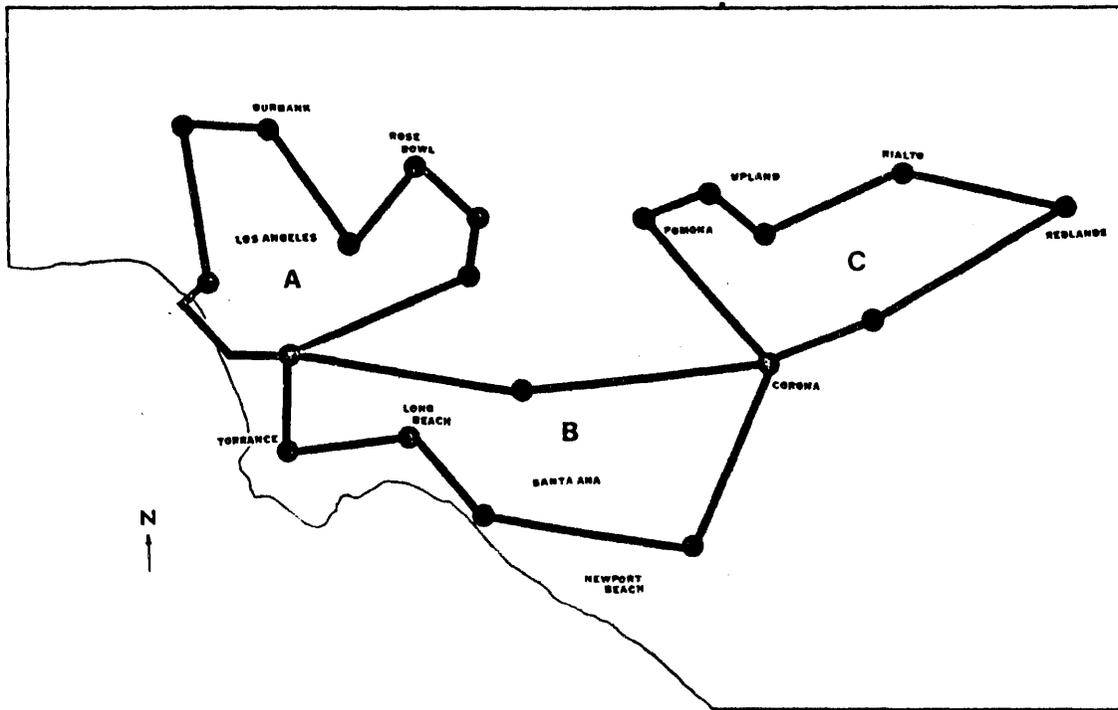


Figure 3. Airborne Sampling Routes in the Los Angeles Basin

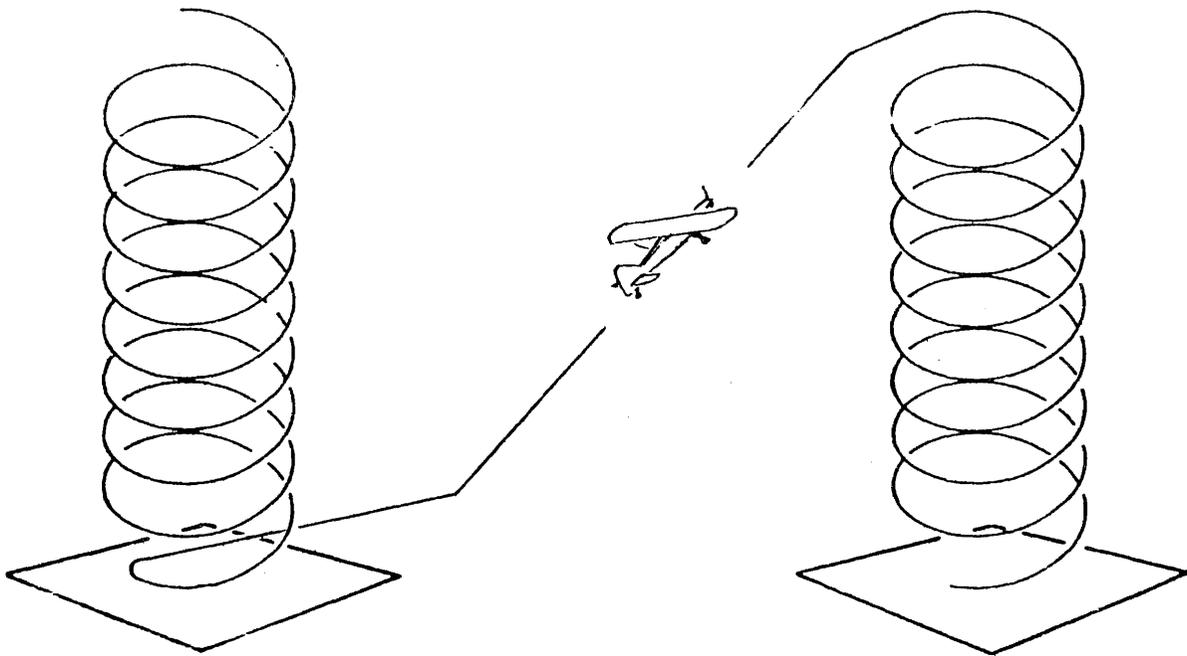


Figure 4. Vertical Profile Flight Path

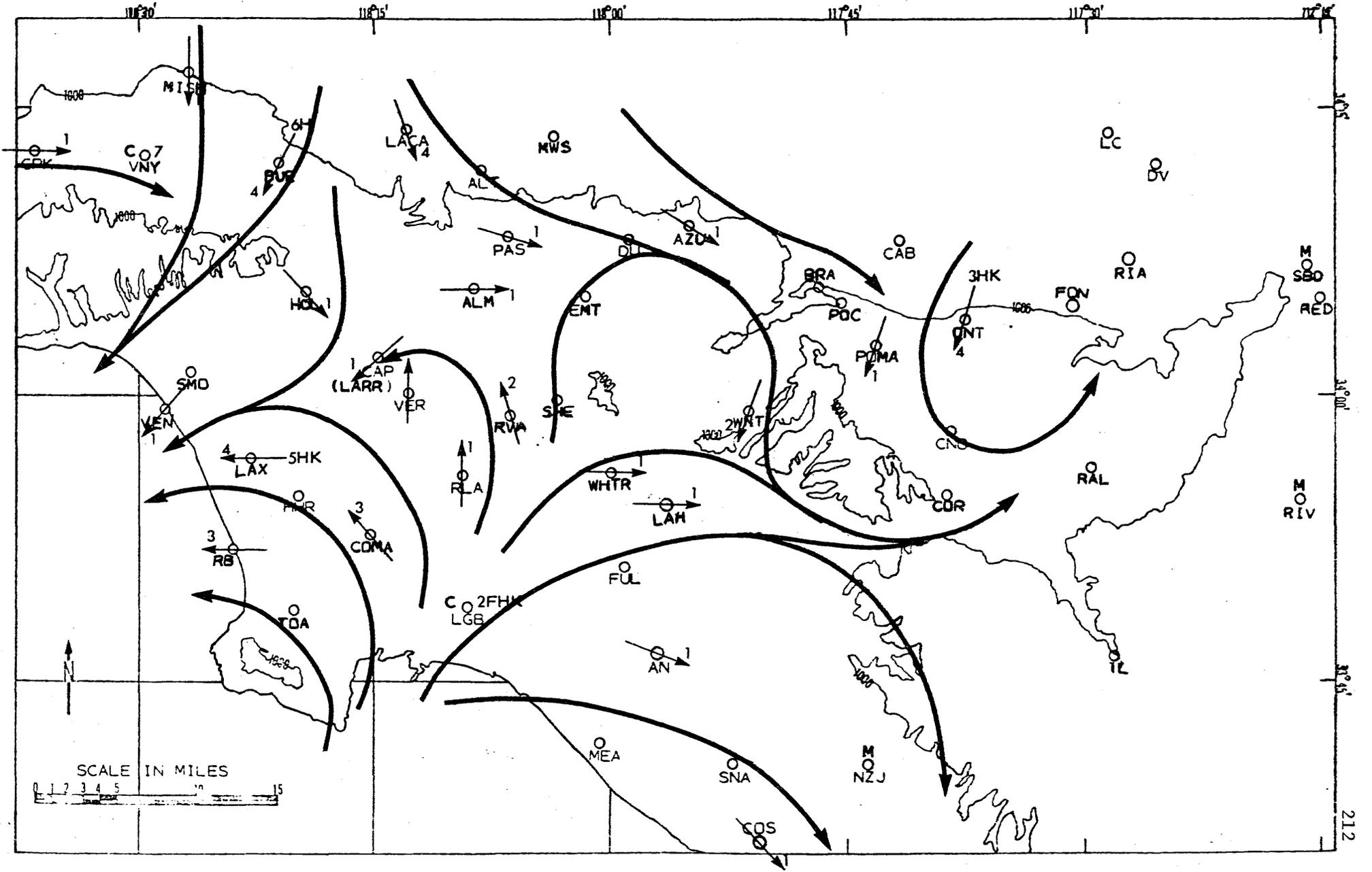


Figure 5. SURFACE STREAMLINE ANALYSIS - 0300 PST
25 July 1973

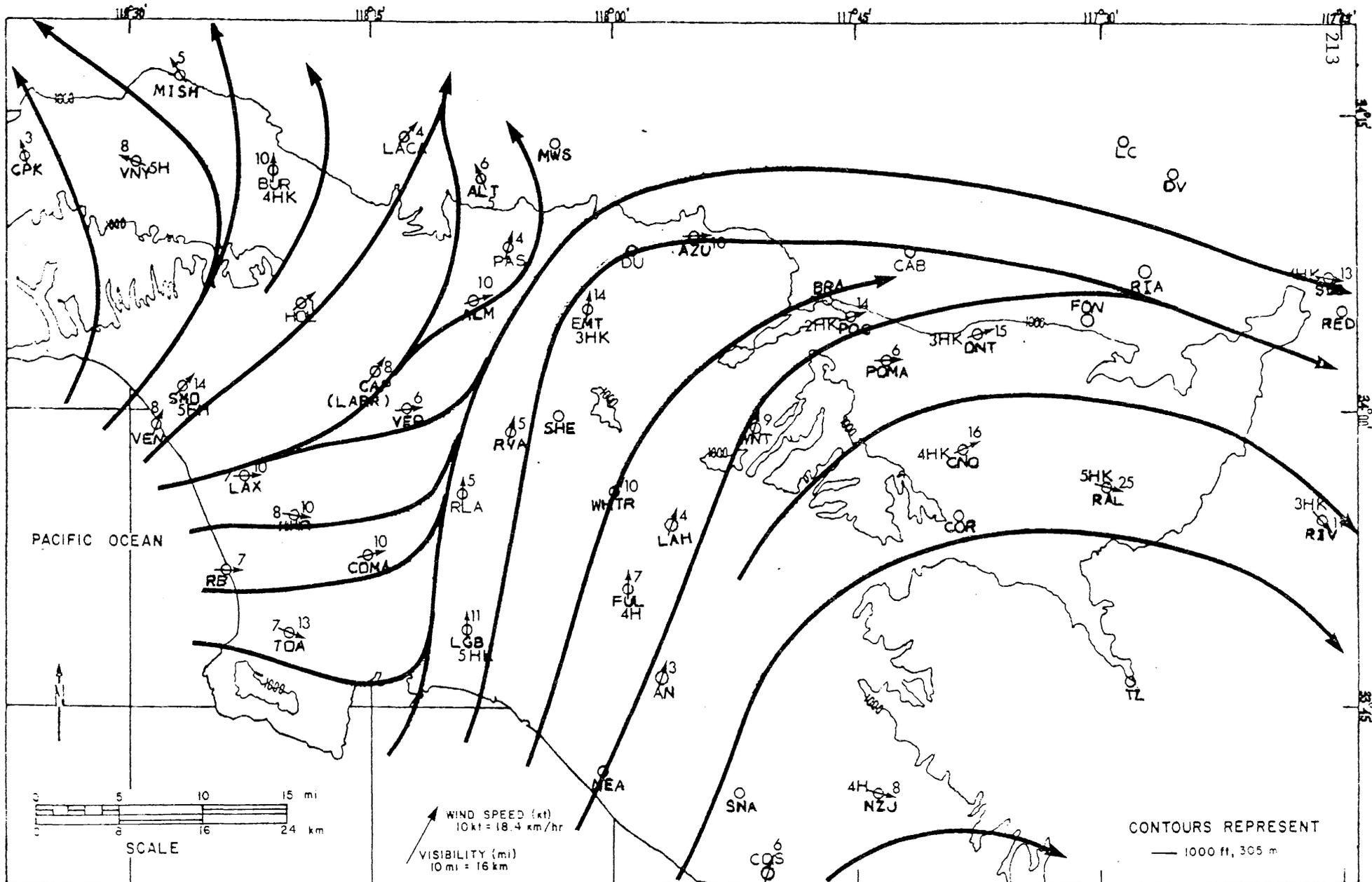


Figure 6. SURFACE WIND STREAMLINES - 1600 PDT, JULY 25, 1973

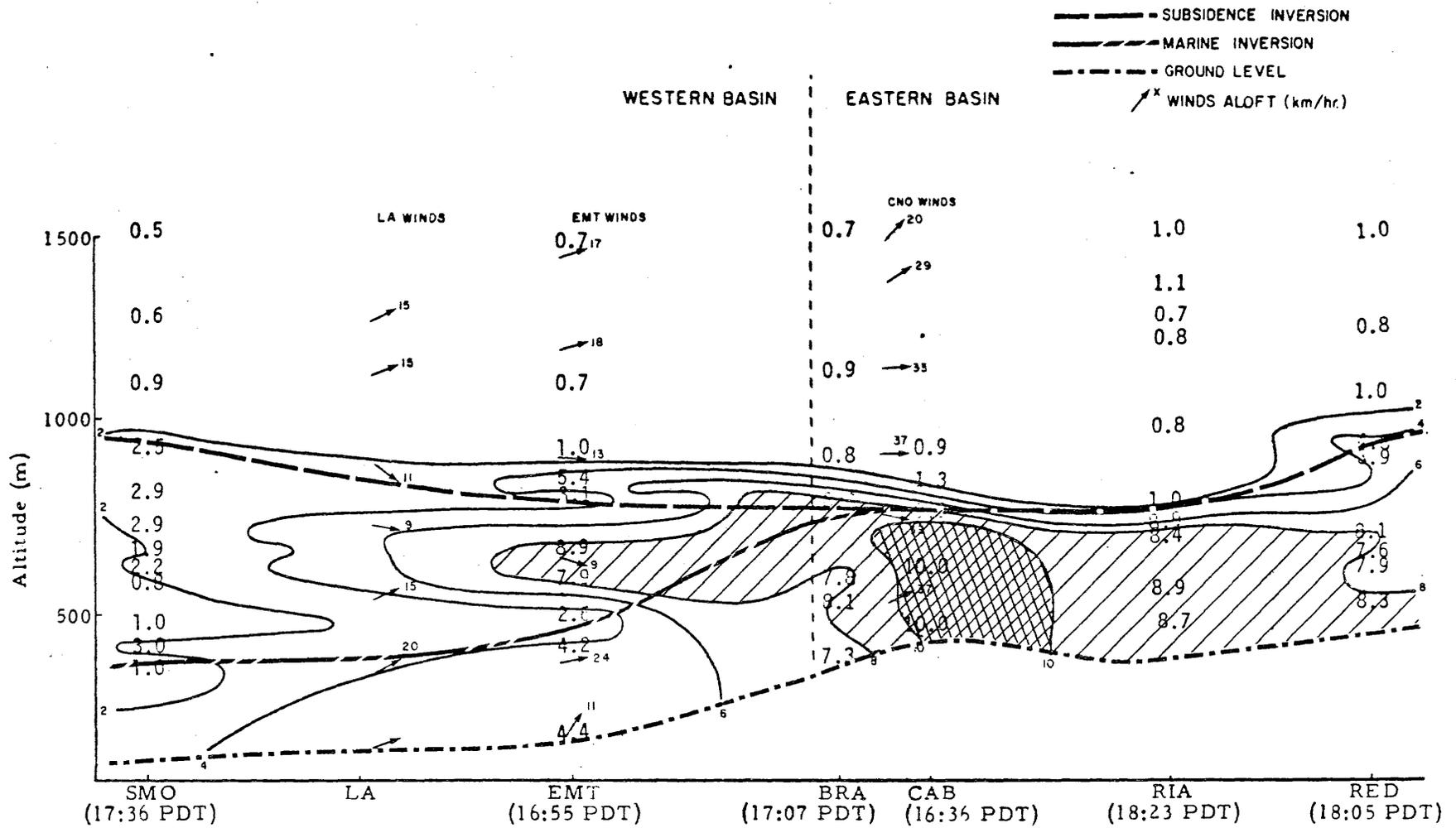


Figure 9. VERTICAL CROSS-SECTION OF b_{scat} FOR AFTERNOON OF JULY 25, 1973
(Units are $10^{-4} m^{-1}$.)

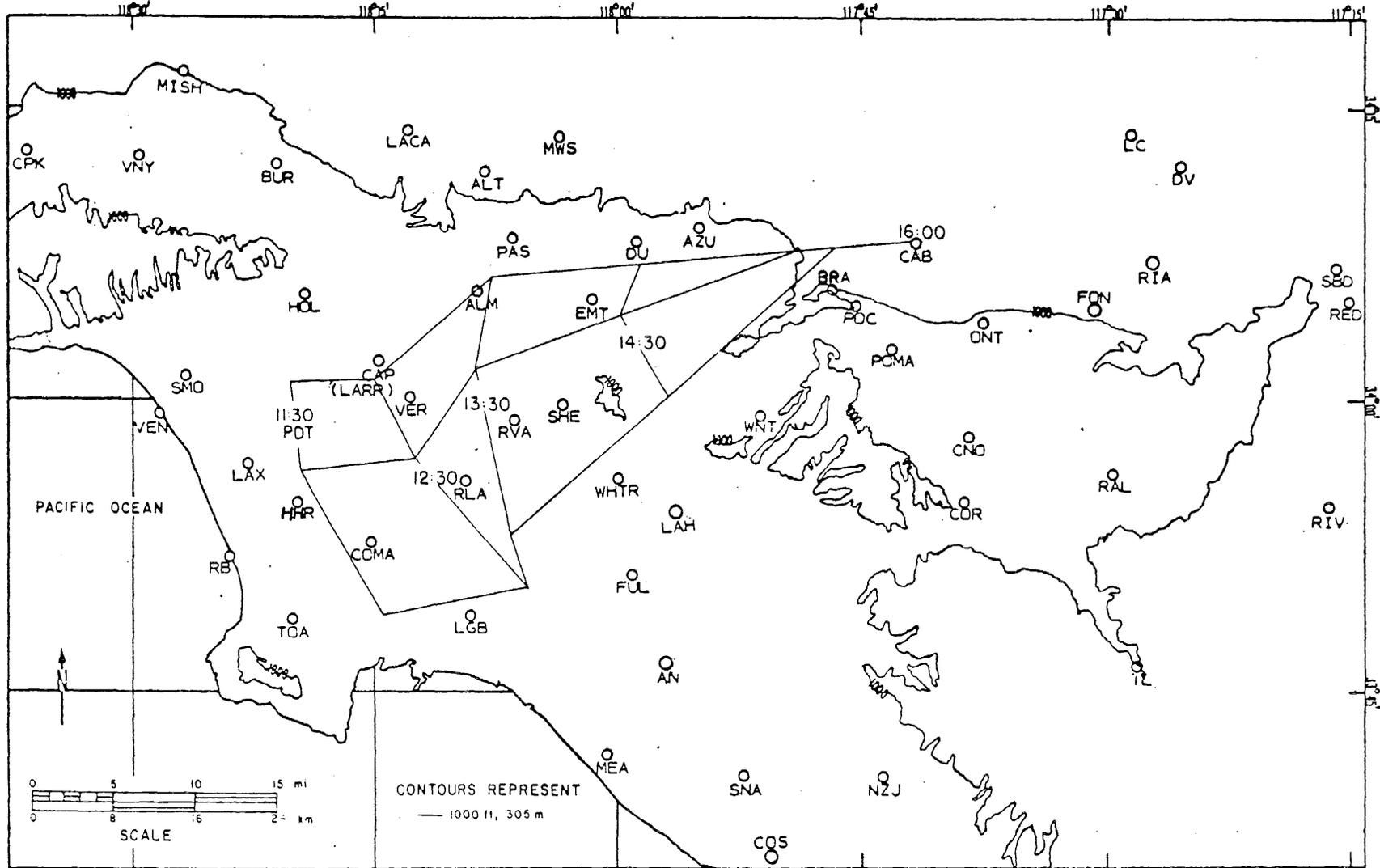


Figure 10. TRAJECTORY ENVELOPE FOR AIR ARRIVING AT CABLE AIRPORT (UPLAND) 1600 PDT, JULY 25, 1973

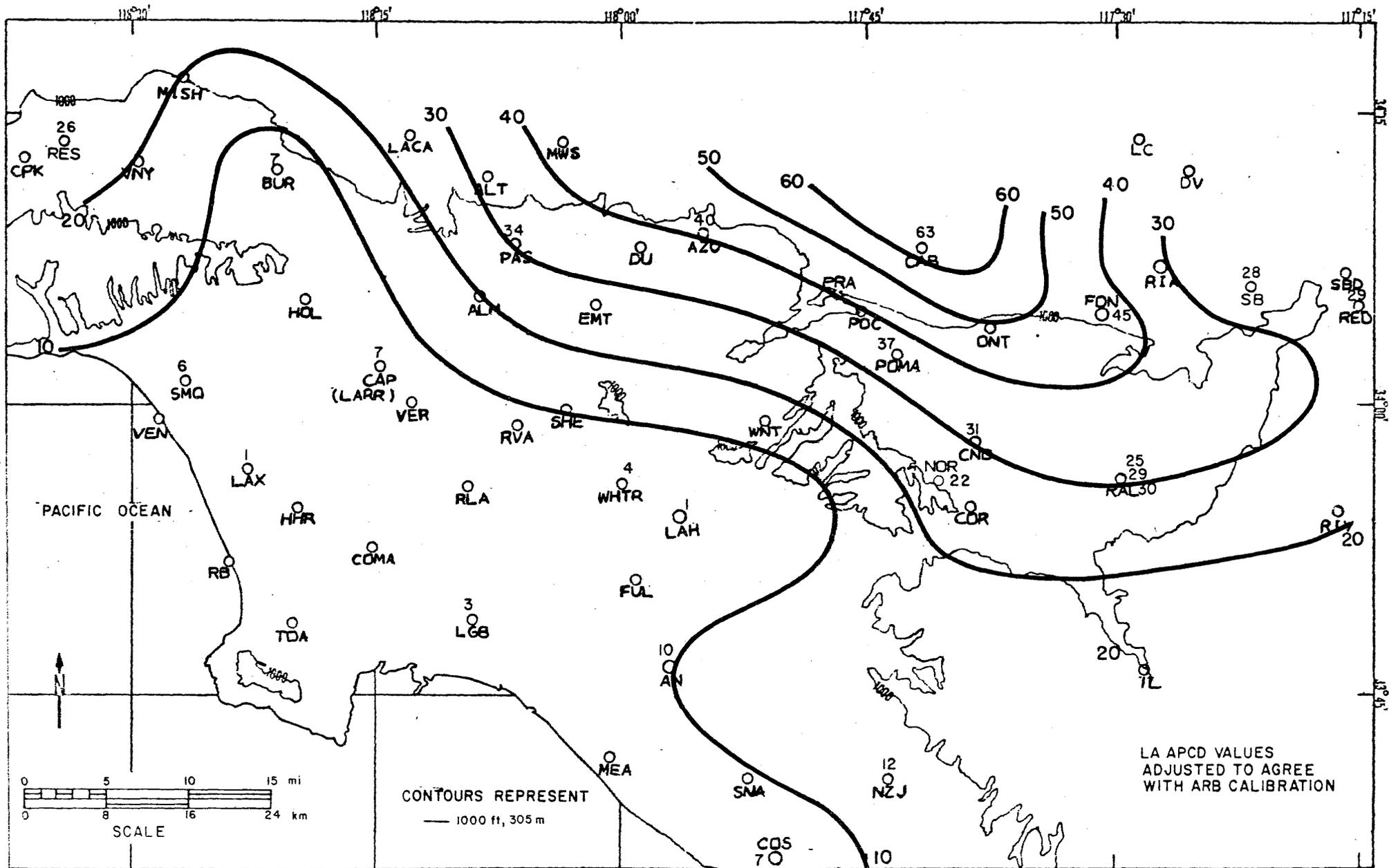


Figure 11. SURFACE OZONE CONCENTRATIONS (pphm), 1600-1700 PDT, JULY 25, 1973

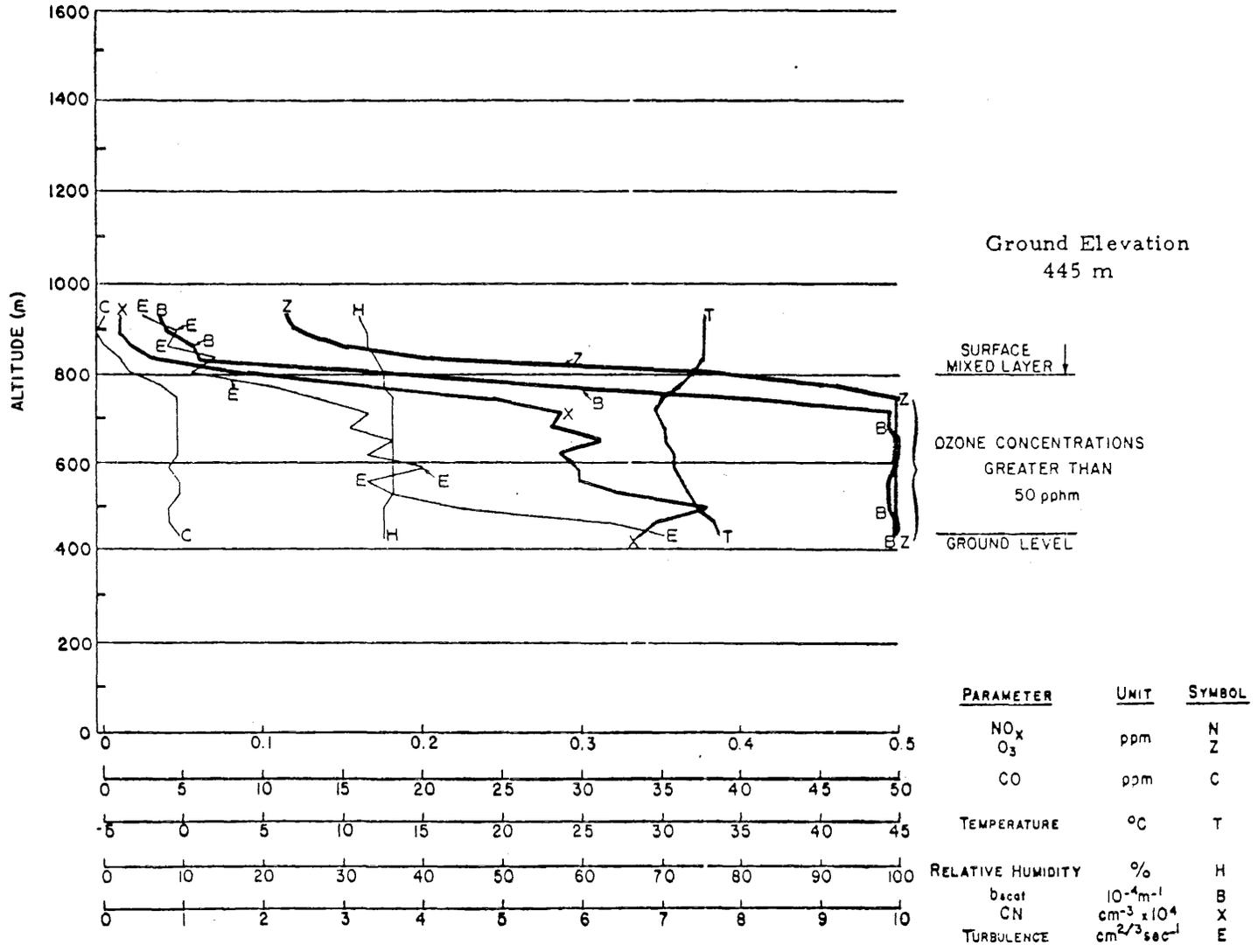


Figure 12. VERTICAL PROFILE OVER CABLE (CAB)
JULY 25, 1973, 1636 PDT

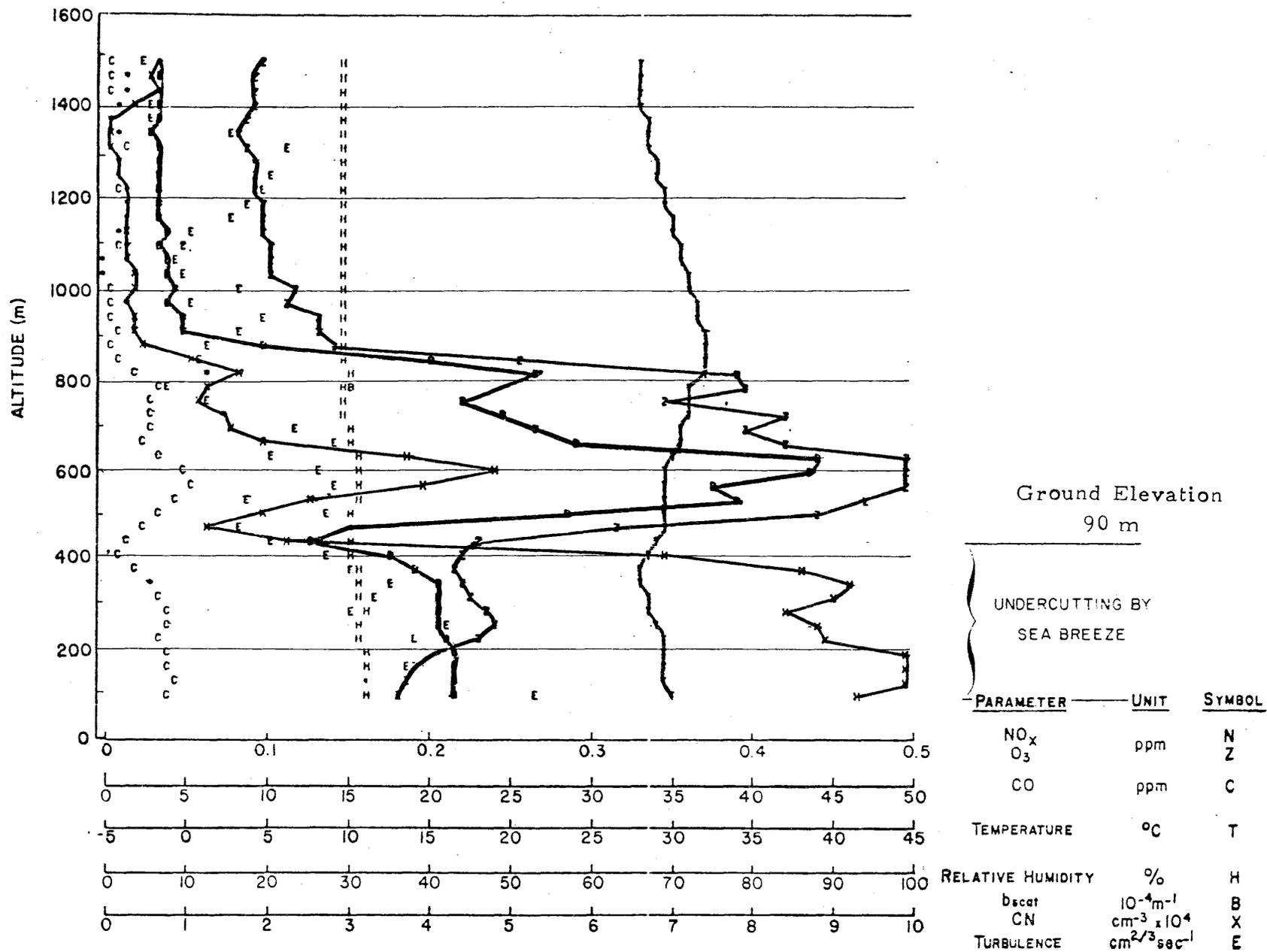


Figure 13. VERTICAL PROFILE AT EL MONTE (EMT)
JULY 25, 1971, 1656 PDT, SHOWING UNDERCUTTING
BY THE SEA BREEZE

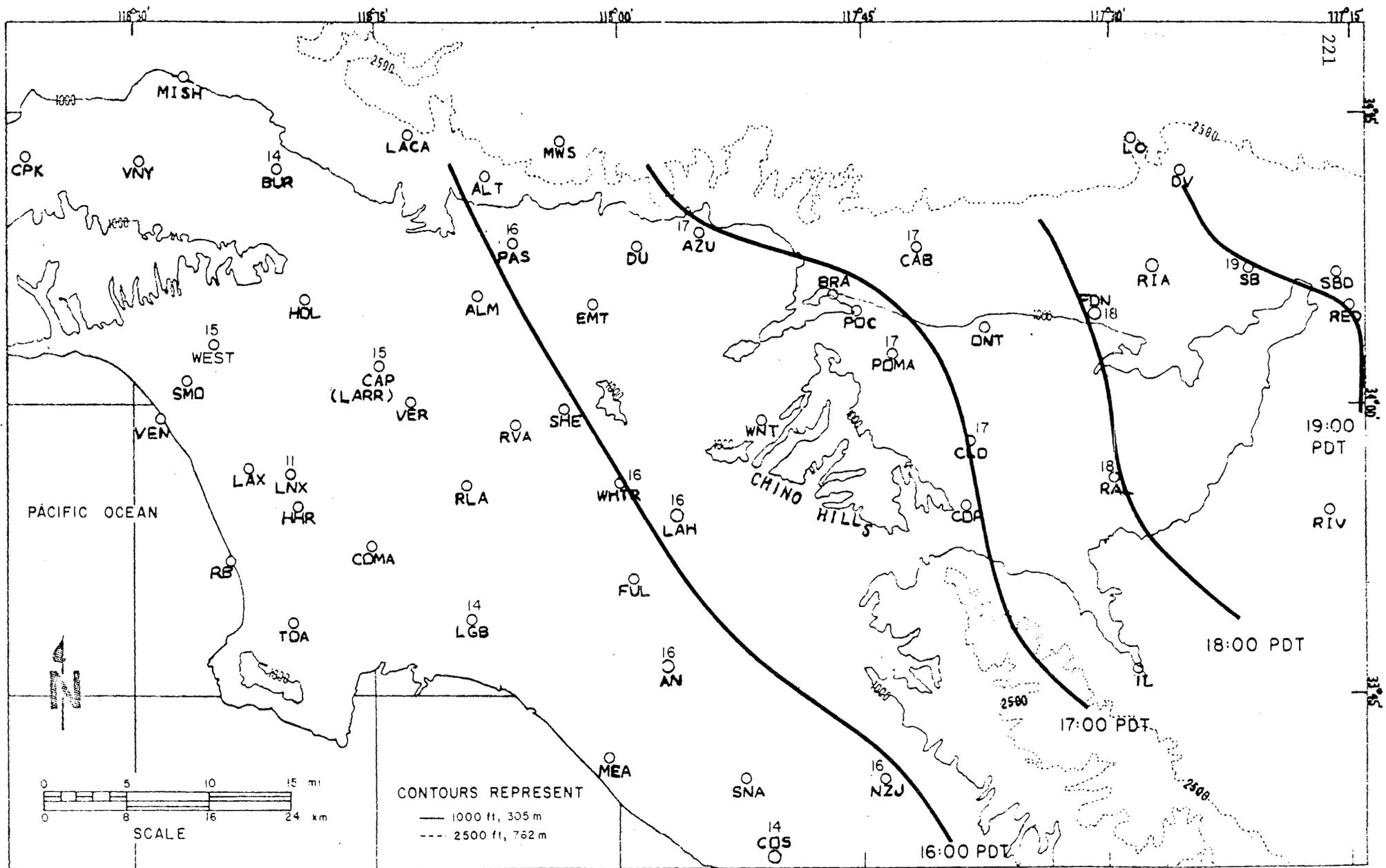


Figure 14. APPROXIMATE TIME (PDT) OF ARRIVAL OF SEA BREEZE, JULY 25, 1973
 (Objective criterion based on ground level ozone concentrations.)

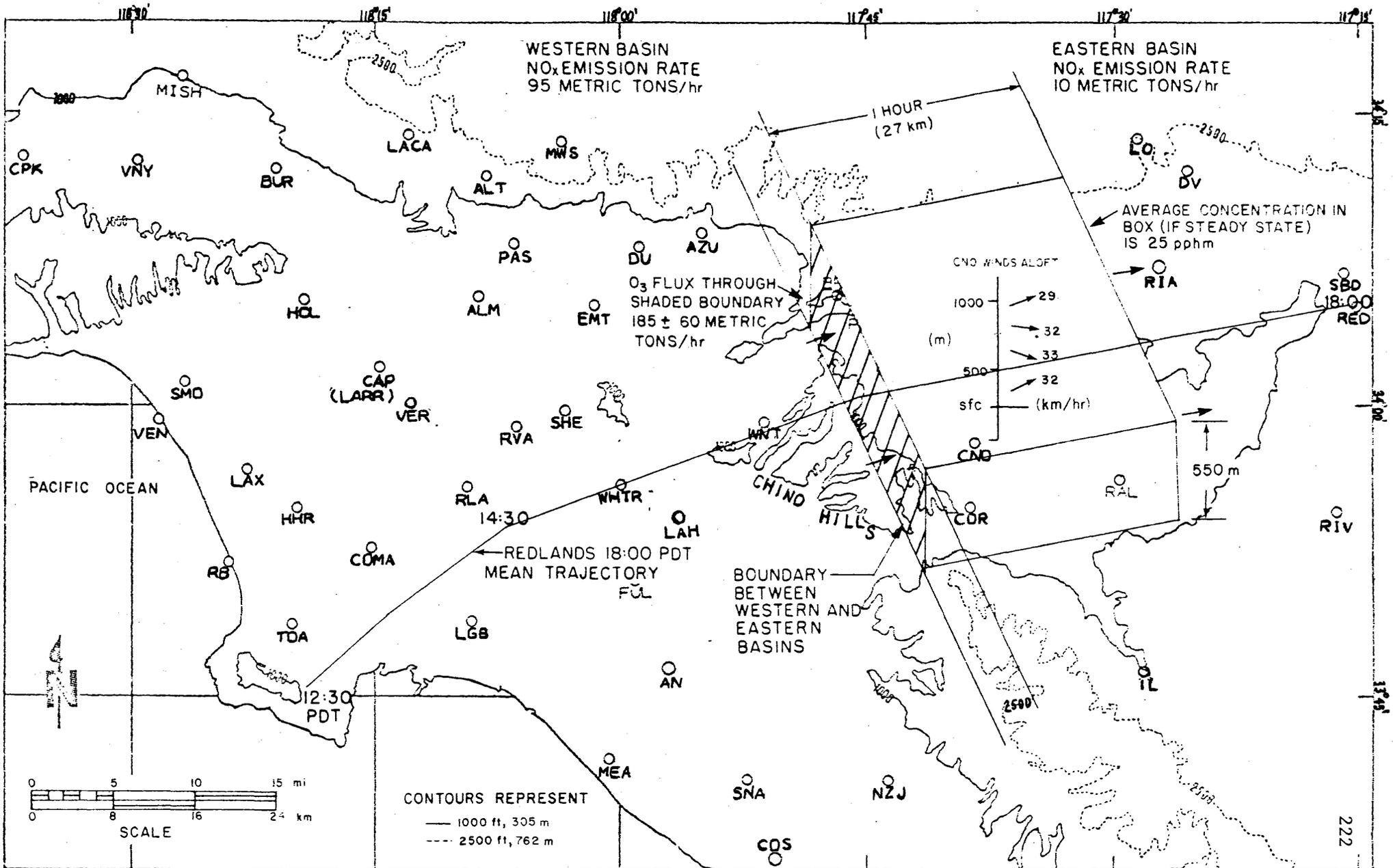


Figure 15. ESTIMATED OZONE FLUX FROM WESTERN TO EASTERN BASIN, JULY 25, 1973 1700 PDT

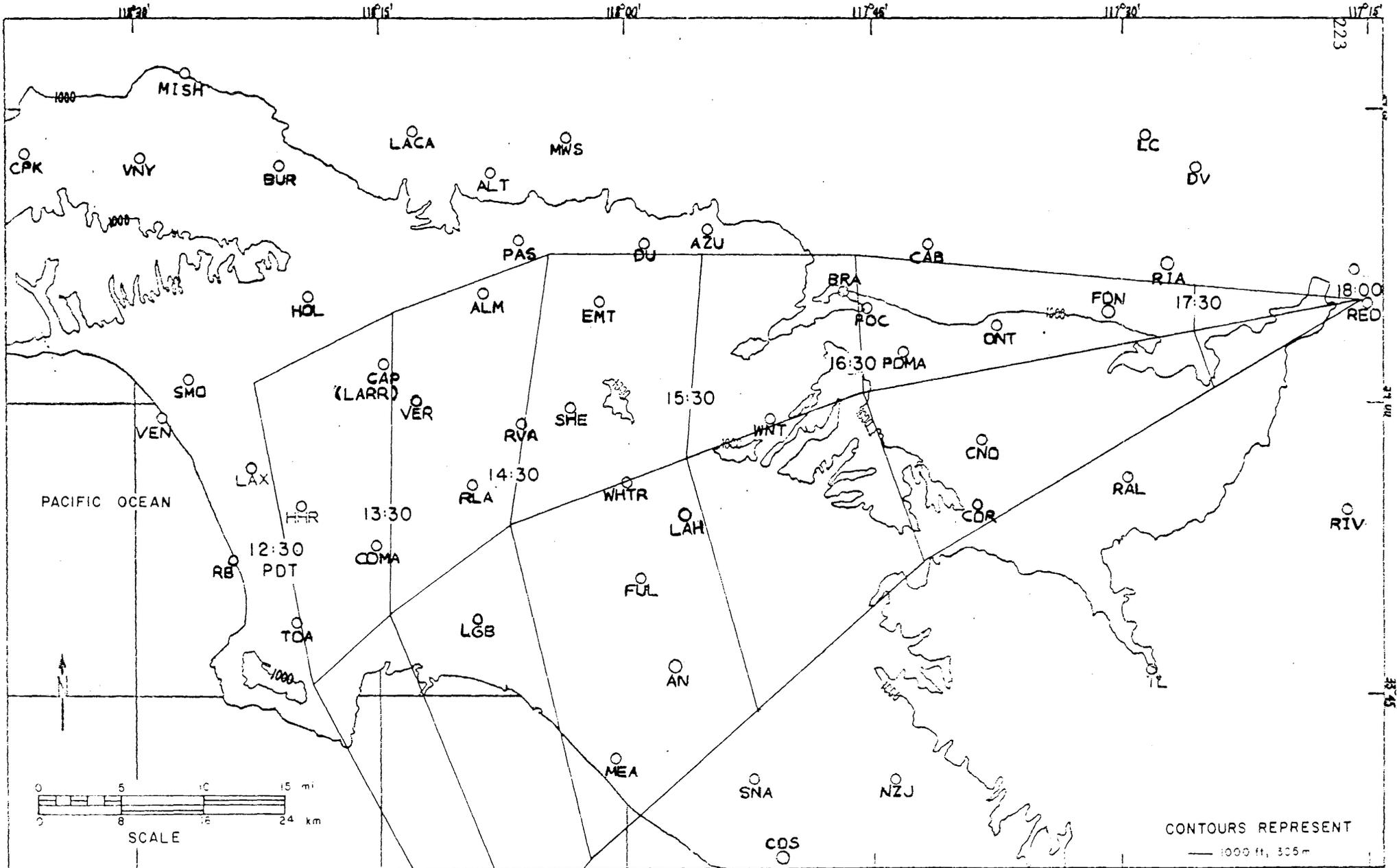


Figure 16. TRAJECTORY ENVELOPE FOR AIR ARRIVING OVER REDLANDS AT 1800 PDT, JULY 25, 1973

JULY 25, 1973

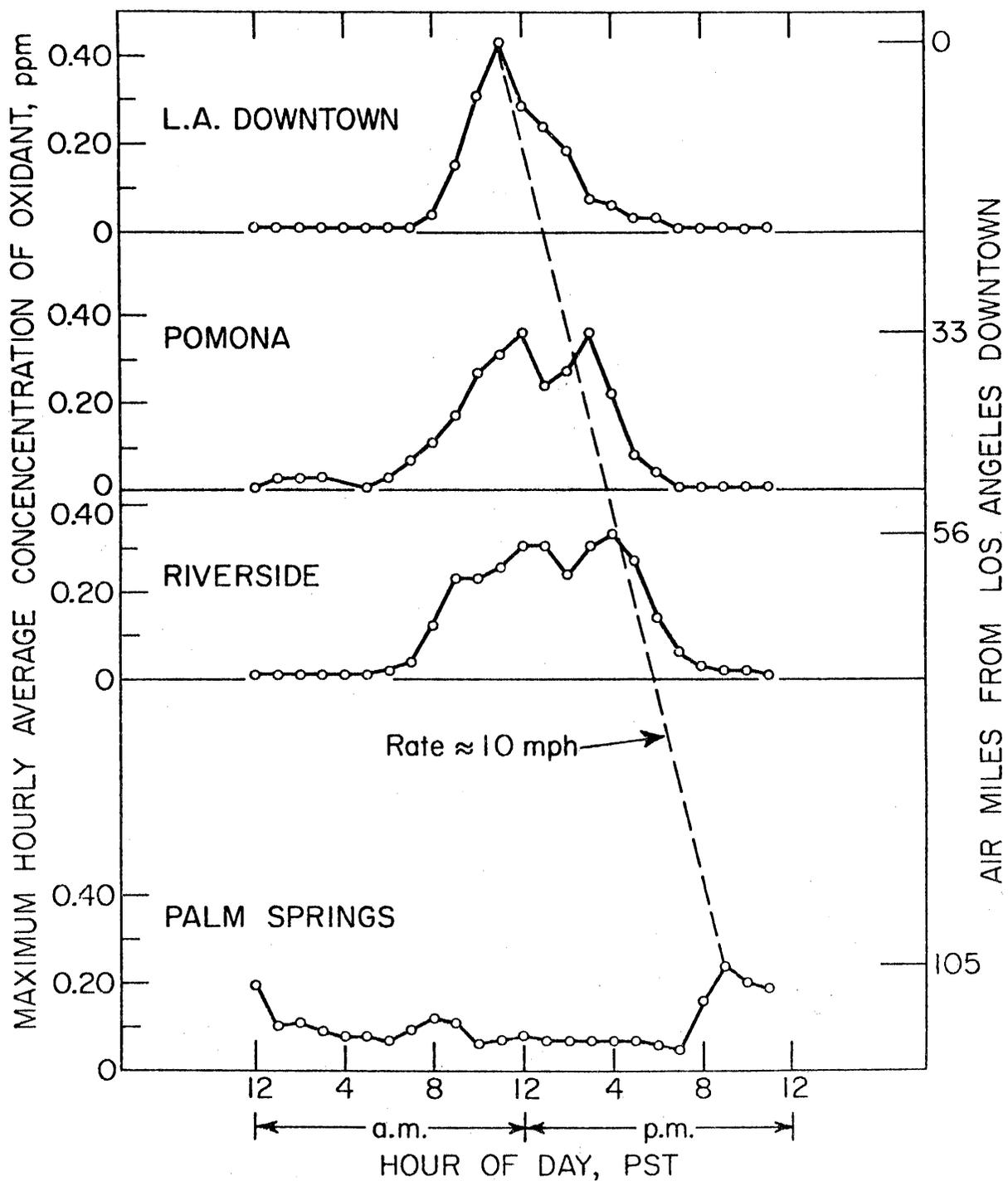
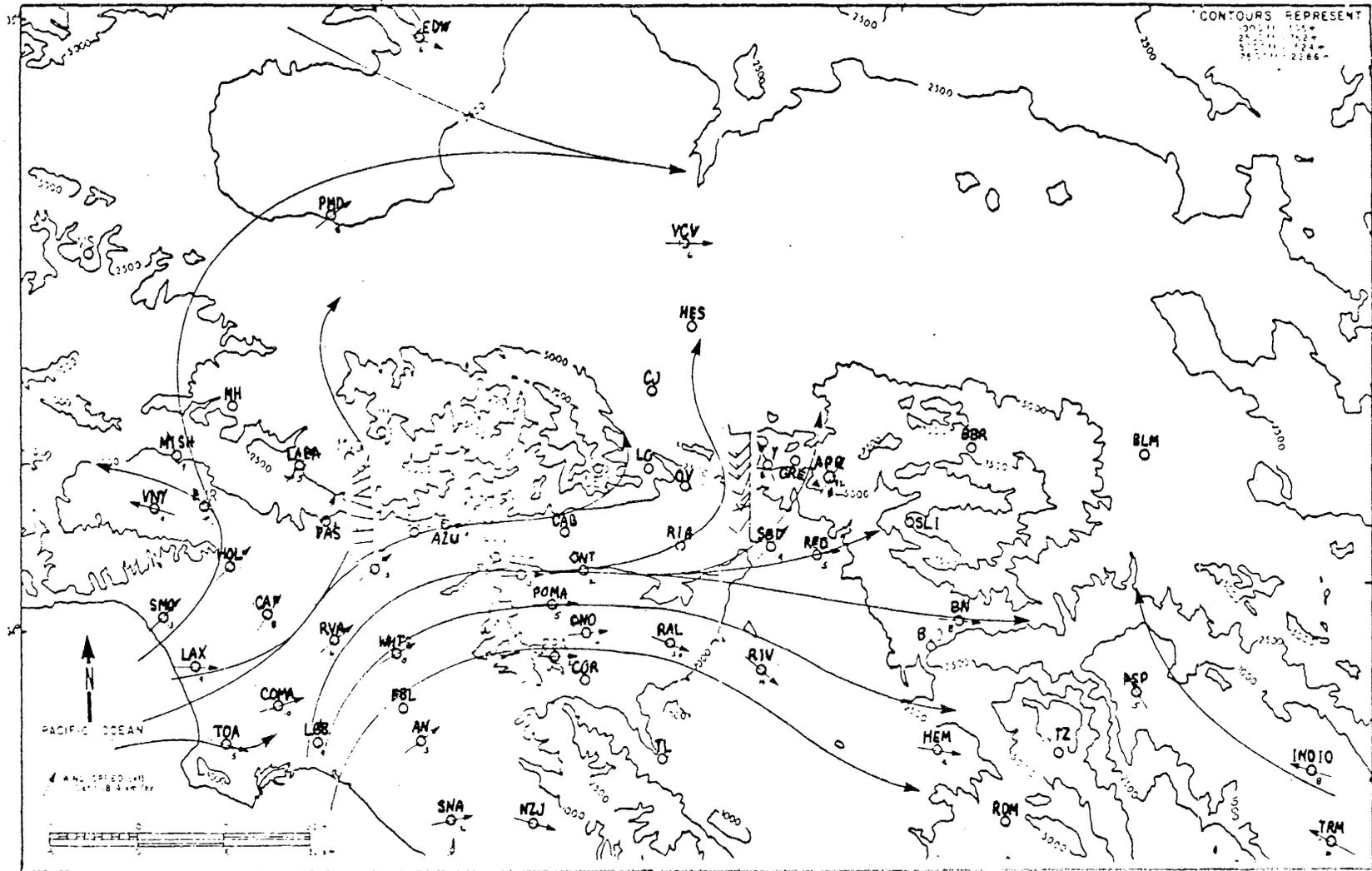


Figure 17. Diurnal variation July 25, 1973, of oxidant concentrations at air monitoring stations at Los Angeles Downtown, Pomona, Riverside, and Palm Springs, California. Values are corrected data: Los Angeles Downtown and Pomona x 1.1 and Riverside and Palm Springs x 0.8.



- ◆ Skyforest
- ▲ Strawberry Mt. Lookout

Figure 18. STREAMLINES FOR 1600 PDT on 8/16/73

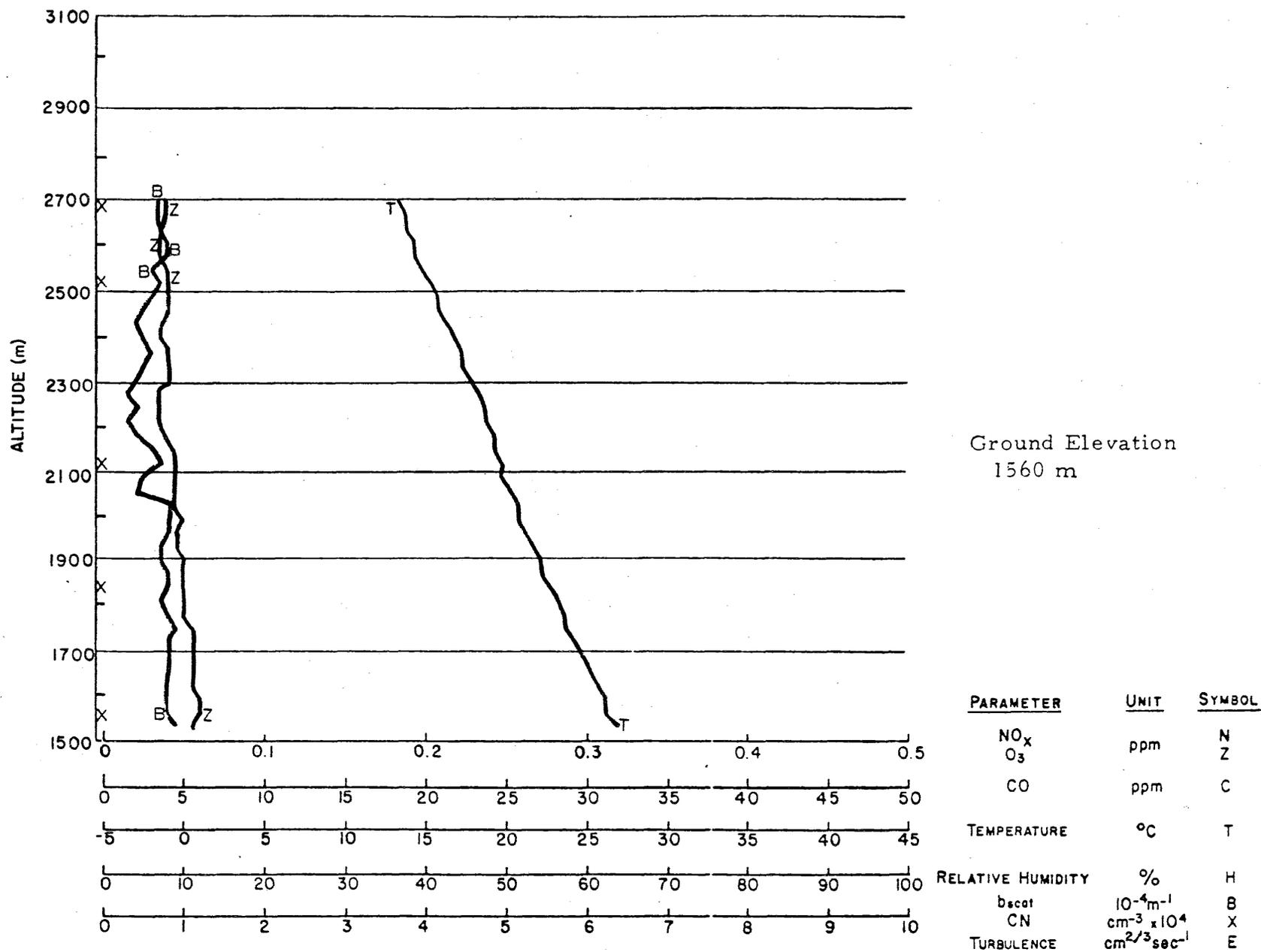


Figure 19. VERTICAL PROFILE OVER ARROWHEAD (ARR) AUGUST 16, 1973, 9:39 PDT

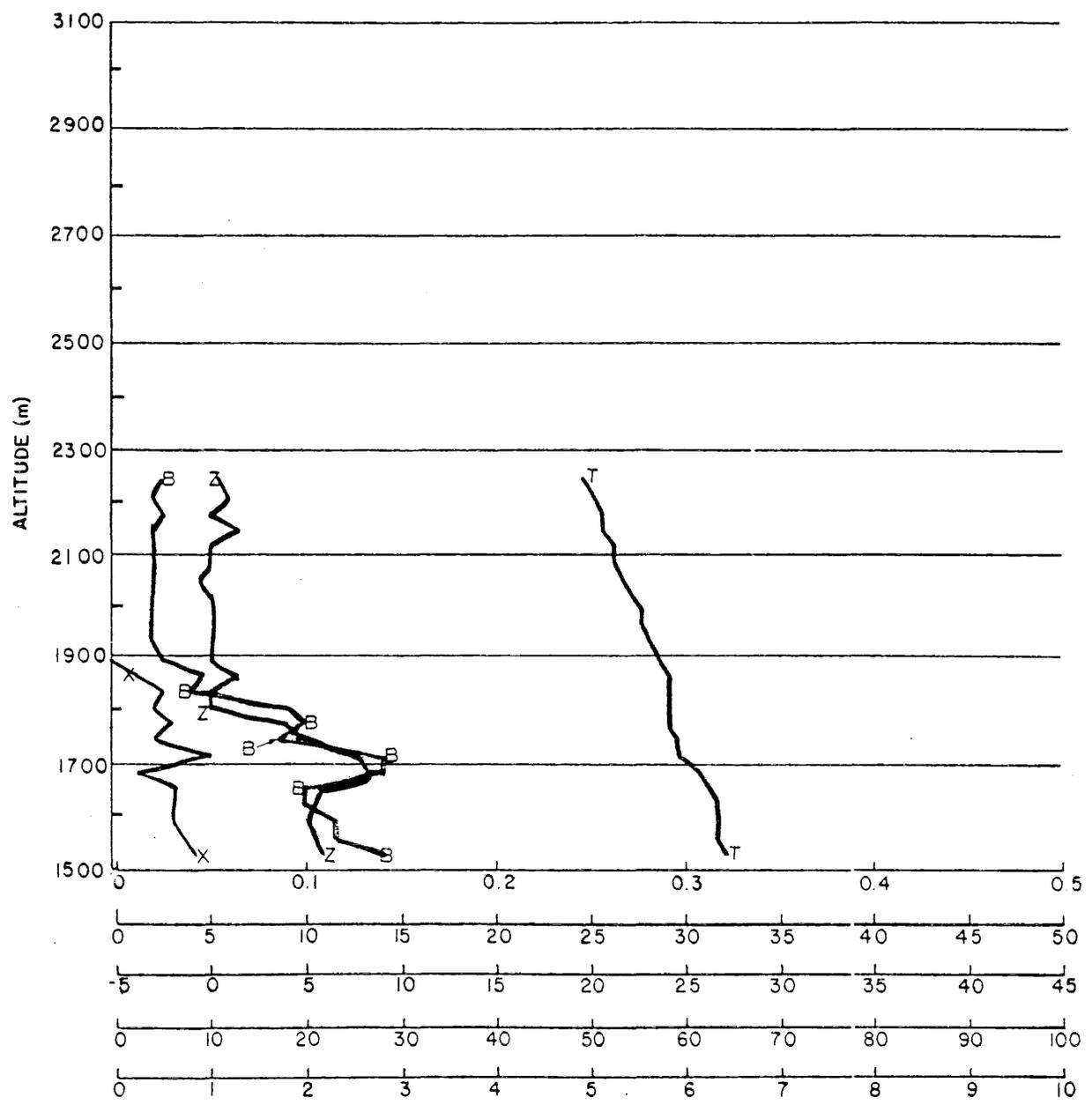
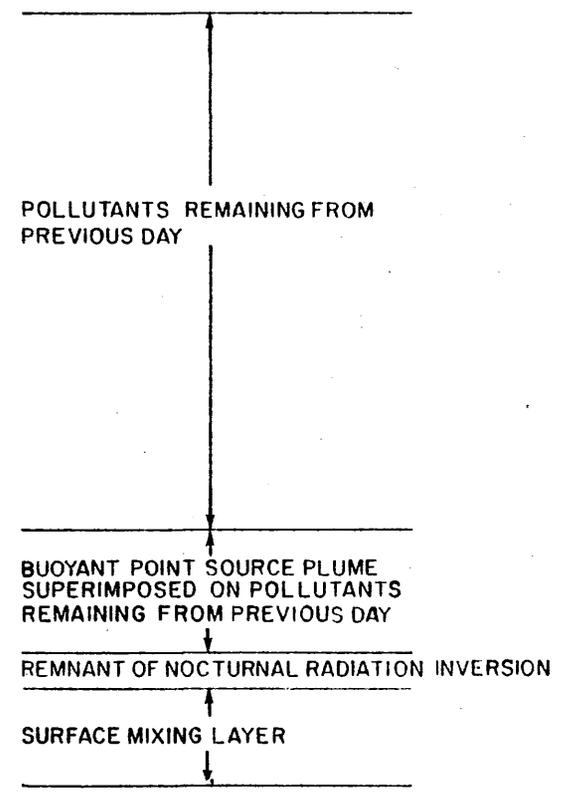
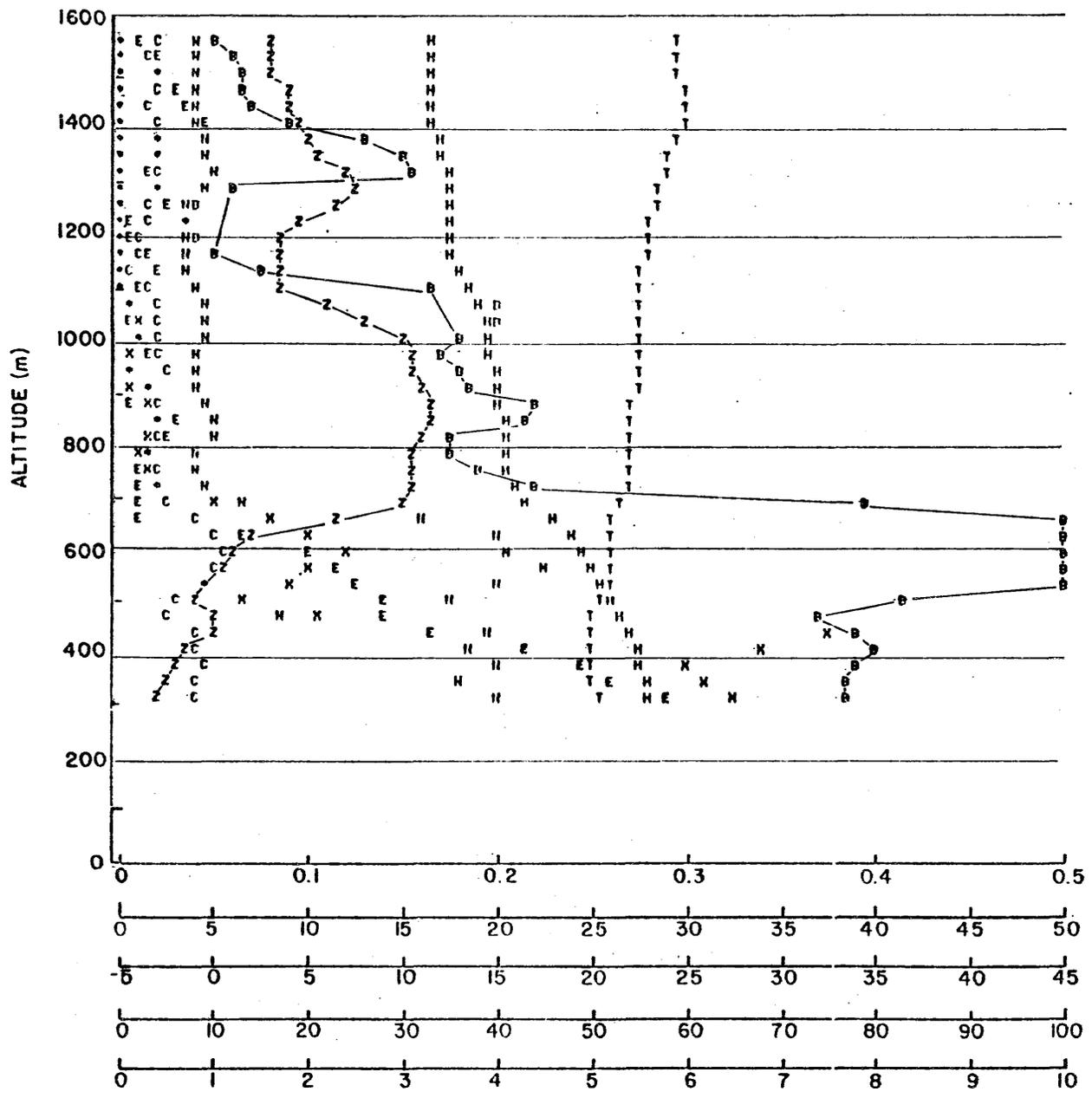


Figure 20. VERTICAL PROFILE OVER ARROWHEAD (ARR)
AUGUST 16, 1973 16:45 PDT



Ground Elevation 305 m

PARAMETER	UNIT	SYMBOL
NO _x	ppm	N
O ₃	ppm	Z
CO	ppm	C
TEMPERATURE	°C	T
RELATIVE HUMIDITY	%	H
Discat	10 ⁻⁴ m ⁻¹	B
CN	cm ⁻³ × 10 ⁴	X
TURBULENCE	cm ^{2/3} sec ⁻¹	E

Figure 21. VERTICAL PROFILE OVER BRACKETT (BRA) JULY 26, 1973, 0825 PDT SHOWING BUOYANT PLUME AND UNDERCUTTING BY RADIATION INVERSION

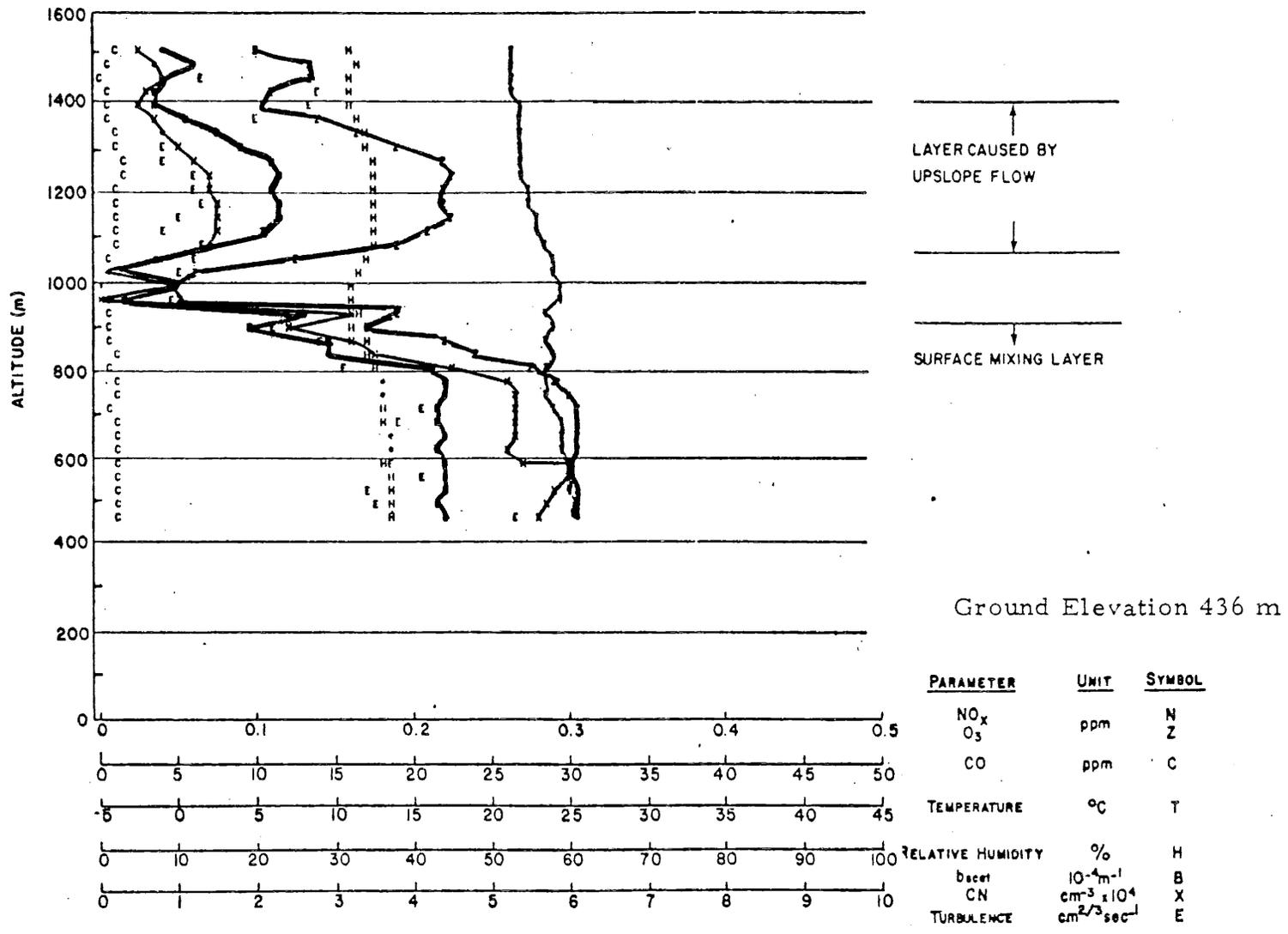


Figure 22. VERTICAL PROFILE AT RIALTO (RIA) JULY 19, 1973, 1738 PDT, SHOWING LAYER CAUSED BY UPSLOPE FLOW

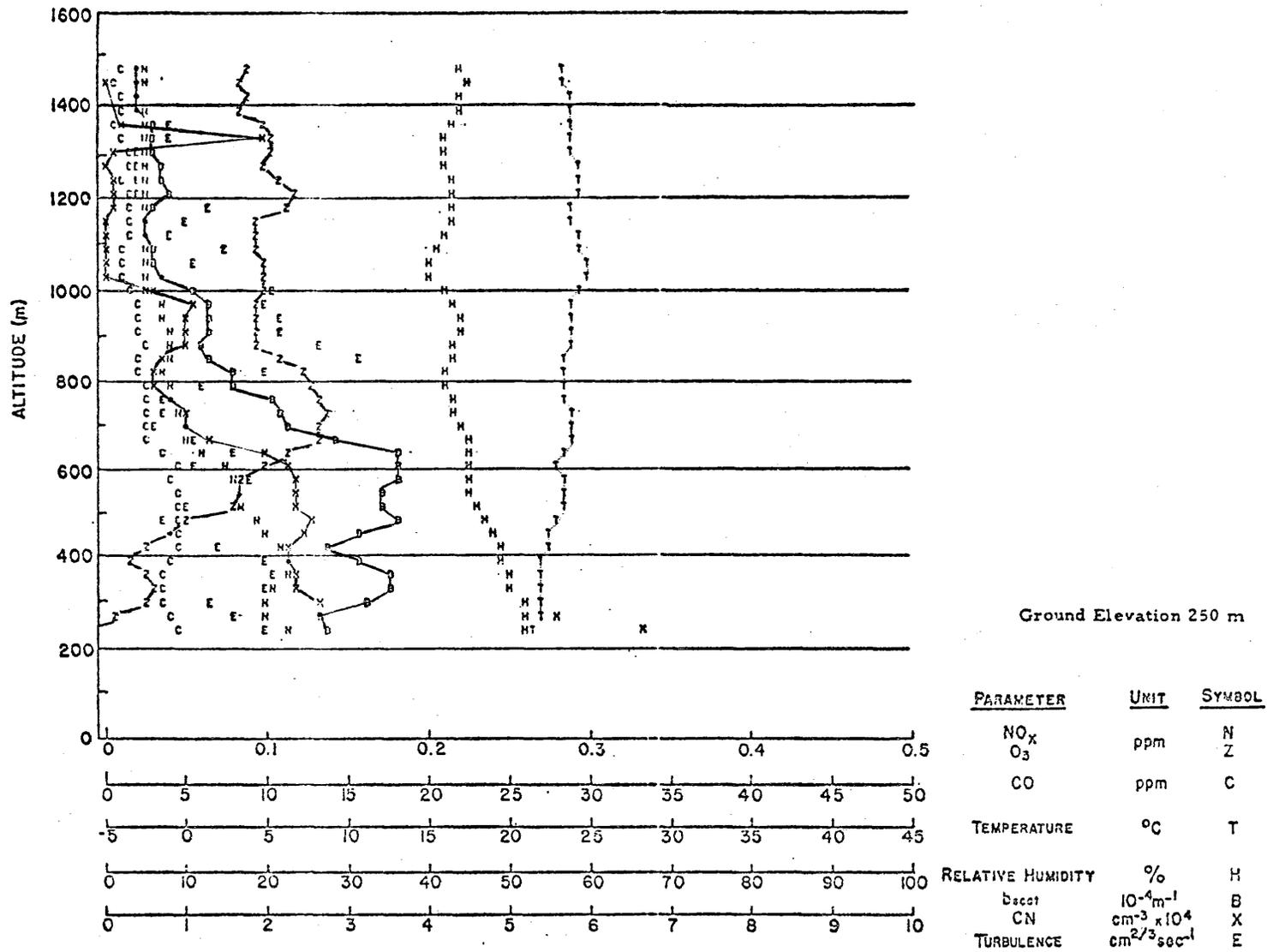
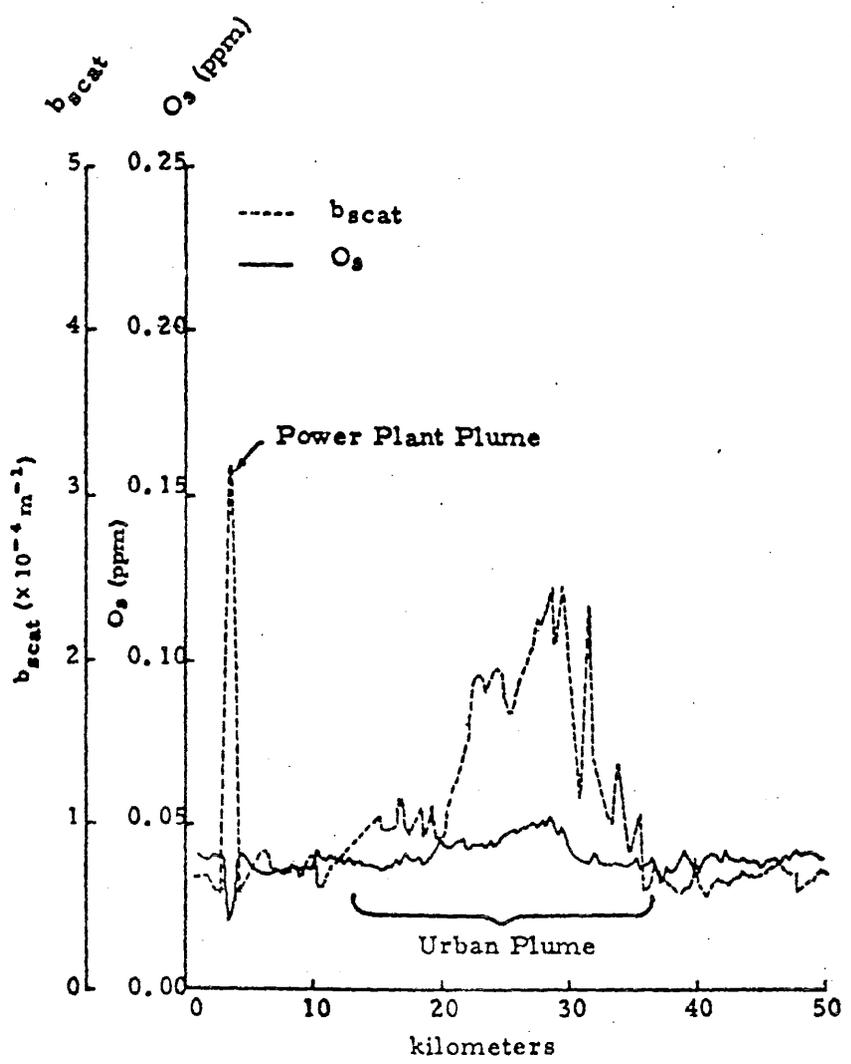
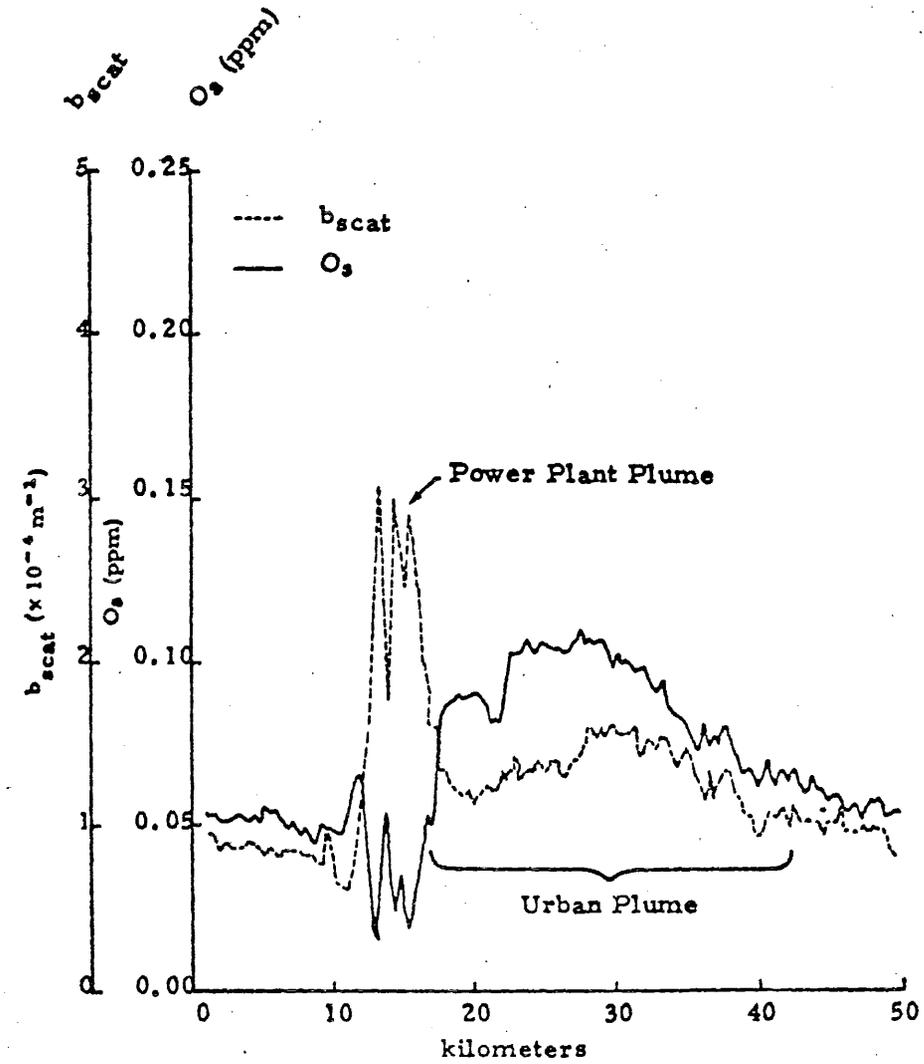


Figure 23. VERTICAL PROFILE OVER RIVERSIDE (RAL)
 JULY 26, 1973, 2239 PDT



Traverse at 750 m msl 35 km Downwind (SW) of Arch - St. Louis, Mo. 1117 - 1137 CDT



Traverse at 750 m msl 46 km Downwind (SW) of Arch - St. Louis, Mo. 1530 - 1549 CDT

Figure 24.

RELATIVE CONTRIBUTIONS OF STATIONARY AND MOBILE SOURCES TO OXIDANT FORMATION IN LOS ANGELES COUNTY: IMPLICATIONS FOR CONTROL STRATEGIES

by

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Introduction

The type of air pollution problem characteristic of the west coast of the United States, and particularly of Southern California, has come to be known as photochemical smog because it is the result of sunlight-energized atmospheric reactions involving oxides of nitrogen and reactive hydrocarbons. Its manifestations--eye irritation, reduced visibility, damage to vegetation, and accumulation of abnormally high concentrations of ozone, or oxidant, --are by now, well known. In fact, the occurrence of high levels of oxidant, which consists almost entirely of ozone, has become the primary indicator for the presence and relative severity of photochemical smog.

During the 25 years since photochemical smog in Los Angeles County was first identified, an extensive program has been underway for control of the responsible contaminant emissions. Initially, during the 1950's these programs concentrated on controlling emissions of hydrocarbons from the stationary sources of this contaminant. In the early 60's, programs for the control of hydrocarbon emissions from motor vehicles in California were begun. An exhaust emission control program for hydrocarbons and carbon monoxide from new vehicles was begun in 1966. Control of oxides of nitrogen emissions from motor vehicles began in 1971.

As a result of the overall control program, by 1974, emissions of reactive hydrocarbons from stationary sources have been reduced 70% from uncontrolled levels, and about the same percentage from mobile sources. Oxides of nitrogen emissions

from stationary sources have been reduced about 53% while emissions from mobile sources are still about 7% above uncontrolled levels, due to the increase in NO_x from 1966-1970 models. Additional controls already planned for the future will, by 1980, achieve reductions of reactive hydrocarbons from stationary sources of about 87% from uncontrolled levels and from mobile sources, about 93%. By 1980, emissions of oxides of nitrogen from stationary sources will have been reduced 53%, and from mobile sources 63% from uncontrolled levels. The past, present, and projected emissions of these contaminants are shown in Figure 1.

Although compliance with the air quality standards has not yet been achieved-- and is not likely before 1980--the results of these programs have been reflected rather predictably in changes in certain of the manifestations of photochemical smog. For example, eye irritation is less frequent and less severe, and in some areas is rarely felt at all any more and damage to vegetation has been markedly reduced. Ozone (or oxidant) concentrations have been decreasing in Southern California coastal areas since 1964; in areas 10-15 miles from the coast, since 1966; and in inland areas 40-60 miles from the coast, since 1970 or 1971, as shown on Figures 2 and 3. All of these positive effects have occurred despite the continuing growth of the area, indicating that the control programs are gradually achieving their purpose-- a return to clean air.

This improvement is also refutation of the so-called "Big Box" concept which assumes that the total daily emissions in a given area are somehow uniformly distributed throughout that area--regardless of its size or of known facts about the meteorology of the area or the spatial and temporal distribution of its emissions--

and of control strategies based on that concept. And, since the improvement in air quality refutes the control strategies based on reductions in total emissions, it thus confirms the value of more recent control strategies which emphasize control of motor vehicle emissions and use of a source-effect area concept.

Following is a brief listing of the evidence we intend to present as supporting our views on just what control strategy is appropriate:

- Examination of relative contributions of HC and NO_x from stationary and mobile sources demonstrates that motor vehicles are the overwhelming source of both contaminants.
- Observation of air monitoring data shows that the effects of photochemical smog are not uniformly distributed throughout the county.
- Study of the meteorology of L. A. County shows consistent paths of transport for various air parcels, and consistent relationships between the areas most seriously affected by photochemical smog and high oxidant concentrations and certain other areas.
- The upwind areas are found to be source areas--the downwind areas--effect areas.
- Central L. A. is found to be the predominant source area for the effect area in which the highest oxidant levels in the SCAB consistently occur.
- The predominant source of emissions in this source area is found to be motor vehicles.
- Central L. A. has the highest traffic density.
- Both primary and secondary contaminant concentrations reflect the effects of the new motor vehicle control program in a predictable fashion.
- A strategy based upon these findings is gradually being verified by atmospheric oxidant data.

The Evidence that Motor Vehicle Emissions Are the Principal Source of Oxidant

As seen from Figure 1, at the present time, the total daily emissions of HC and NO_x from all sources in Los Angeles County are primarily due to the motor vehicle. The problem now is to find the spatial and temporal representation of emissions which, when examined in the light of the known meteorology and geography of the Los Angeles region, best describes the source of emissions responsible for the highest observed oxidant readings.

In the "rollback" models used by EPA and others the basin is treated as a "big box" with uniformly distributed emissions, and peak oxidant is considered to be proportional to total basinwide hydrocarbon emissions.

The fact is that the emitted contaminants from which the smog is formed, and the effects which characterize that smog, are not evenly distributed throughout the Los Angeles Basin; in other words, the basin area under the inversion is not one large box filled to all corners with homogeneously distributed air contaminants and photochemical smog.

Refutation of "Big Box" Myth

Examination of atmospheric contaminant concentrations refutes the "big box" concept. It is found, for example, that concentrations of directly emitted contaminants measured at a particular sampling site reflect the emissions within a rather limited area around that site. For this reason, contaminant concentration levels vary from one location to another and each has a characteristic daily pattern which reflects the daily pattern of emissions in that area.

The "big box" concept is further refuted by the fact that peak concentrations of carbon monoxide and oxides of nitrogen in areas of high traffic density were fairly static prior to 1966. Thus, they did not reflect the 45-50 per cent growth in motor vehicle registrations and gasoline consumption which occurred in Los Angeles County between 1955 and 1965 and which caused comparable increases in total daily emissions of such vehicle-related contaminants. This demonstrates that growth was outward, rather than upward, so that a larger area of the County began to be affected by photochemical smog, but no area experienced smog of greater severity than that originally affected by smog formed from the vehicular emissions which accumulated each weekday in central Los Angeles and were transported later that day to the San Gabriel Valley.

Meteorological Evidence

To verify the geographical dependence of emissions and resulting atmospheric concentrations, let us examine the meteorology of these large areas of Southern California. Both the County and the Basin have many meteorological sub-regions in which the patterns of wind speed and direction may be similar, but within which the patterns of air transport are parallel with those of adjacent sub-regions and the respective air parcels do not ever meet or join.

The characteristic patterns of inversion height, and wind speed and direction in these sub-regions, and their patterns of vehicular emissions, together have created a network of source areas--those in which the reactant contaminants accumulate in the morning and begin to react--and related receptor areas--those to which the products, and associated effects, of the photochemical reactions of the contaminants originally emitted in the source areas, are carried by the late morning and

afternoon winds (sea breeze).

Wind-flow patterns show that characteristic patterns of transport for related source area-effect area combinations are separate and parallel, not mixing or joining. Each source area has its own "reactor pipeline" to its own effect area or areas.

To illustrate this source area-effect area relationship, the typical flow of polluted air from downtown Los Angeles to Pasadena was selected as a "worst case" situation for in-depth examination. Figure 4 shows that the air in downtown Los Angeles on the morning of smoggy days moves directly from the central area to Pasadena.

Vehicular traffic is the predominant emission source in both downtown Los Angeles and Pasadena. Thus, the air in each locality should contain CO. Also, since oxidant would form in the air parcel moving from Los Angeles to Pasadena, oxidant levels would be expected to be higher in Pasadena than in downtown Los Angeles.

Figure 5 shows these relationships for the period 1960-1972. The atmospheric CO level is similar for the two areas, while oxidant levels were higher in Pasadena than in Los Angeles throughout this time period. This demonstrates that a significant amount of oxidant formed in the air as it moved to Pasadena containing both the unreactive CO and the photochemical reactants for producing oxidant. Both CO and oxidant show a marked downward trend in each locality since 1965, which emphasizes the effect of vehicle exhaust controls and the correlation between the localities.

On a day which is favorable to the formation and accumulation of photochemical smog, a contaminated air parcel normally originates during the 6-9 a. m. period on a weekday from an area of dense traffic, centered just south and west of Downtown Los Angeles. It is oxidant generated within that air parcel which usually affects Central Los Angeles and the West San Gabriel Valley area around Pasadena.

The traffic area in which this smog had its origin is about the most dense in Los Angeles County, and has been so for the past 25-30 years. No area has a higher "effective density" than this. Using carbon monoxide, which is almost entirely attributable to motor vehicles, as an indicator of such emissions, it is found that the concentrations of emitted vehicular contaminants measured in Central Los Angeles during the past 15 years confirms both this lack of change in "effective density" and the absence of any area of any greater "effective density" when local differences in inversion are acknowledged.

This area, the "Central Source Area" is depicted in Figure 4. The size and shape of the Central Source Area was chosen to be large enough to reduce to an insignificant level any diffusion or transport into this area from any externally generated reactants. This conclusion is based in part on the trajectory studies previously referenced, as well as an analysis of the diffusion and transport parameters for the area.

The Central Source Area has been identified as that geographical region which contributes essentially all of the primary contaminant emissions giving rise to the high atmospheric oxidant levels in the West San Gabriel Valley. The proportion of emissions in the CSA due to motor vehicles and that due to stationary sources is shown in Table 1. For the County as a whole about 80 per cent of (6-9) AM reactive hydrocarbons are due to motor vehicle emissions and this figure rises to 90 per cent for the CSA. The same conclusion applies to NO_x emissions. The Central Source Area contains the greatest density of vehicle traffic in the County and thus the greatest density of source emissions. Thus it appears that the source area with the highest density of emissions during the critical (6-9) AM period is responsible for the highest afternoon oxidant levels observed in Los Angeles County and in the South Coast Air Basin. These highest oxidant levels are consistently observed to occur in the San Gabriel Valley. This is true whether the LAAPCD or the ARB oxidant calibration procedure is used.

Further, the atmospheric concentrations of the primary pollutants can be identified as originating primarily from the motor vehicle and they reflect the effects of the motor vehicle emission control program. A vehicular source area can be identified by its atmospheric levels of CO and NO_x . Figure 6 compares measured atmospheric levels with calculated atmospheric levels for CO, NO_x and the CO/ NO_x ratio in the downtown area.

REACTIVE HYDROCARBON EMISSIONS

(6-9) AM

1970

SOURCE	LOS ANGELES COUNTY		CENTRAL SOURCE AREA	
	TONS	PER CENT	TONS	PER CENT
Mobile*	126.0	81.3	13.5	91.2
Stationary	29.0	18.7	1.3	8.8
<hr/>				
Total	155.0	100.0	14.8	100.0

*By 7-Mode, Gallonage

The calculated values shown in Figure 6 were derived from a baseline survey of 1100 vehicles and continued surveillance tests, both using the California 7-Mode test cycle. The baseline survey showed that motor vehicles without exhaust control systems had average exhaust emissions concentrations of 3.4 per cent CO and 1000 parts per million of NO_x. Baseline emissions data apply to 1965 and earlier model vehicles, and surveillance data to 1966 and later models.

Since it can be concluded from calculations and observations that the dilution of auto exhaust emissions in the atmosphere on a smoggy day in Los Angeles is approximately 1000 to 1, the calculated values for CO and NO_x prior to 1965 are 34 ppm CO and 1 ppm NO_x. After 1965, the changing effect of controlled vehicles in the total vehicle population is reflected in the calculated values.

CO and NO_x values measured in the atmosphere are also shown in Figure 6 and confirm the values calculated entirely as diluted vehicular emissions. NO_x concentrations measured in the atmosphere tend to be consistently a little lower than the calculated values, probably because photochemical reactions remove some NO_x from the system.

The data for CO and NO_x, calculated and measured, show that emissions in downtown Los Angeles originate almost exclusively from motor vehicles and that atmospheric concentrations there reflect the average emissions from a representative vehicle population.

The ARB has recently published a report entitled "A Trend Study of Two Indicator Hydrocarbons in the South Coast Air Basin". Acetylene was used as a

specific indicator of automobile exhaust emissions and it was found to have declined in concentration in the Los Angeles atmosphere at an annual rate of 12.5 per cent since 1970. To quote from this report, "The California implementation plan requires an annual average reduction in these emissions (reactive organic compounds) of 166 tons per day, or 11.1% of the 1970 tonnage per year. The per cent reductions in the acetylene levels at Los Angeles and Azusa are greater than required by the implementation plan. Since acetylene is almost entirely associated with auto exhaust, this demonstrates that the motor vehicle emission control program is achieving its purpose."

To summarize at this point it has been demonstrated that high oxidant values are due to motor vehicular emissions of NO_x and HC because:

NO_x and HC are the principal reactants in the oxidant formation process and they originate primarily from motor vehicle emissions; and

The highest oxidant values are recorded in effect areas that receive air from source areas where motor vehicles are clearly identified as the dominant source of NO_x and HC.

Future Control Strategy

The APCD strategy for achieving and maintaining the oxidant air quality standard is based upon the fact that high oxidant values are due to motor vehicle emissions of hydrocarbons and nitrogen oxides. This strategy is as follows:

1. Both Hydrocarbon and Nitrogen Oxides Emissions Must Be Considered To Achieve the Federal Oxidant Standard

There is wide agreement that NO_x and HC are the principal reactants in the oxidant formation process, and that vehicular emissions are a major source of NO_x , HC and CO.

2. Effective Regulation of Atmospheric Concentrations of Both HC and NO_x , and of the Ratio Between Them, is necessary for Attainment of the Federal Air Quality Standard for Oxidant

Based on the abundance of available experimental evidence, it is our firm position that the most rational approach to solving the photochemical oxidant smog problem in the South Coast Air Basin (SCAB) is to control the quantities of emissions from motor vehicles of both smog precursors--HC and NO_x --their resulting atmospheric concentrations, and the ratios between both contaminants which will result from these controls.

We are also convinced that the oxidant and nitrogen dioxide air quality standards can and will be met, not by 1975 or 1977, but by the early 1980's if the emission control program as originally outlined by California, or a slight modification of it proposed by the District, is followed and enforced. This should also provide for continued compliance with these air quality standards, at least through 1990.

It will also allow time for a reappraisal in about 1978 of the whole situation relative to the ultimate emission standards required, and the best approach to their implementation.

Calculation of the degree of control necessary to attain the air quality standards for oxidant and nitrogen dioxide involves indirect, complex methods aimed at determining the degree of control of the primary contaminants directly emitted by automobiles.

The following evidence supports our proposed solution to the problem in terms of both the atmospheric concentrations of the oxidant precursors, NO_x and HC; the ratio between them, as reflected in their exhaust emission standards; and the resulting atmospheric concentrations of oxidant which comply with the air quality standards.

Chamber Results and Projections to the Atmosphere

The importance of environmental chamber work cannot be minimized; the need for, and direction of, the whole emission control program was based initially on the results of chamber experiments. In order to understand the importance to air quality of achieving both the correct low quantities of emissions and the right ratio, we can present several graphic portrayals of analyses of experimental laboratory work, together with their relationship to past, present and future air quality, in terms of both morning primary reactant concentrations, during the morning traffic peak, and the equivalent emissions which would produce them.

Figure 7 shows maximum ozone levels that were obtained by irradiating varying amounts of auto exhaust hydrocarbons and oxides of nitrogen in an environmental chamber. The corresponding ozone levels, then, can be found for any combination of HC and NO_x concentrations. Thus, high ozone is produced with high "emissions" of both hydrocarbons and oxides of nitrogen and low oxidant is formed with low emissions. However, either low NO_x or low HC "emissions" can also produce low oxidant--graphic and clear evidence of the importance of the NO_x/HC ratio in ozone formation. Furthermore, each and every possible combination of values for NO_x and HC has, then, a corresponding characteristic maximum chamber ozone concentration.

Using this graph, we can estimate what ozone levels would result if certain atmospheric mixtures of NO_x and HC could be injected into the chamber and irradiated. Such estimates were made for 1960 and 1965, using atmospheric data. The points labeled "1960" and "65" show the location of the highest levels of both HC and NO_x found in the air in those years, in Downtown Los Angeles (DOLA) area during the 6-9 AM traffic peak.

It has been demonstrated, by use of CO and NO_x data and CO/ NO_x ratios, how well the characteristics of vehicle emissions are reflected in the atmosphere. We know what emissions from the "average vehicle" were then, in 1960-1965, both for HC and NO_x , so that we can mathematically relate emissions to atmospheric concentrations for those years; and so for future years also, knowing or calculating only what the characteristic emissions will be from the average vehicle.

The NO_x concentrations stayed about the same from 1960 through 1965 because average vehicle emissions of that contaminant did not change during that time! Mobile source emissions can be shown to have contributed essentially all of this observed result. However, blowby controls did reduce emissions of HC, and the concentrations dropped accordingly. In 1965, the last year before exhaust controls, the point "65" indicates where we were then, in terms of maximum ozone formation to be expected in a chamber with the highest HC and NO_x concentrations found in the air that year. Levels of ozone actually measured in the atmosphere, however, are higher than those shown on the graph for high NO_x and HC concentrations, for those years up to the present.

The strategy to meet the oxidant standard is obvious--get atmospheric NO_x and HC concentrations out of the area on the chart that produces high ozone levels, and put them in the areas with the lowest levels. This can only be done by implementing appropriate emission standards.

As can be seen, that did not happen between 1965 and 1970 because manufacturers used controls on new cars in California which, while causing a decrease in HC, (and CO) allowed a large increase in NO_x emissions. Thus, the "path" line of the atmosphere on the chart goes up from 65 and diagonally to the left, passing through an area of higher ozone "levels". The atmospheric concentrations of oxidant predictably increased during the years 1967 and 1968. By 1970 they dropped to lower levels--back to about the same as in 1965--exactly as predicted by the model! The approximate location of the point for 1970 (70) was both predicted, on the basis of

the "mathematical model", and confirmed by atmospheric measurements of Downtown Los Angeles, morning, summertime, NO_x and calculated HC values.

Again, it should be pointed out that those points show the highest possible concentrations of NO_x and HC. Years with less restrictive weather conditions (for accumulating high primary contaminant levels) would cause lower measured maximum NO_x and HC levels, but the calculations would still yield the points shown. Thus, we are taking the most pessimistic view.

Future Projections

In 1973 we were at about the point labeled '73, and ozone levels were beginning to drop as expected. It should be emphasized that ozone values plotted on this graph are for the chamber only - not the atmosphere. The future path, the points '74 and on to '90, represents our estimate of future atmospheric levels of NO_x and HC expected if the exhaust emission standards are just met. While that is optimistic, it is all we really can do since performance of future vehicle models is unknown. We will achieve maximum ozone levels at or below the standard by about 1980-1985. This will only be true, however, if cars in compliance with the California interim standards for HC and NO_x continue to be added to the vehicle population at the normal rate. These standards provide the optimum ratio of NO_x to HC necessary to provide the nitric oxide (NO) needed for the reaction that removes from the air both oxidant formed photochemically and oxidant which occurs as natural background which alone may cause the standard to be exceeded. This ratio is about 1 1/2 or 2 parts NO_x to 1 part HC.

The optimum NO_x/HC ratio is a key element in the APCD strategy, but will require a finite time for its attainment. Replacement of older cars by newer ones equipped to meet the most stringent standards is the only reasonable mechanism which can change it. VMT reduction proposed as a prime strategy by EPA, cannot change this critical ratio which is a basic characteristic of the "population" at any given time.

Validation of the District's Control Strategy

Figure 8 compares: (1) future "chamber" oxidant levels, based upon the future maximum concentrations of HC and NO_x we expect each year with the California control program; (2) calculated "atmospheric" concentrations, using our chamber-to-atmosphere empirical translation; and (3) actual measured atmospheric oxidant maxima. This clearly sets forth the relationship among these three factors.

The chamber concentrations (lower curve) are the lowest values shown. The actual atmospheric data (points connected by heavy dotted and solid lines) vary considerably from year to year partly because of the vagaries of the weather. In all cases, the atmospheric oxidant values are higher than the chamber values because of the addition of vehicle emissions as the air parcel travels from source to receptor areas. The calculated atmospheric data (thin dashed and solid curves) are shown to be the highest, generally exceeding or equalling the actual measured data and, of course, always exceeding the chamber data. Thus, the model paints the most pessimistic picture possible. It can be seen that by about 1980-1985 atmospheric levels should be at or below the Federal air quality standard of 0.08 ppm oxidant.

3. Motor Vehicle Exhaust Control is the Only Requirement for Achieving the Oxidant Standard by 1980.

We can show that the existing motor vehicle control program has resulted in a significant reduction of oxidant concentrations in the air.

The foregoing material explained the relationship between vehicular emissions in source areas and the high oxidant levels measured in effect areas. This relationship is exemplified by the downward trend of oxidant levels in the atmosphere and by the similar year-by-year trends of NO_x and HC emissions from the average motor vehicle. A projection of these vehicle emissions factors shows that the associated maximum oxidant level in the atmosphere will meet the oxidant standard by about 1980-1985.

Figure 9 compares, by year, the number of days that the oxidant air quality standard was exceeded in three separate areas with the average NO_x and HC emissions per vehicle mile. To comply with the air quality regulations the number of days that this standard is exceeded must be reduced to one per year.

The lines plotted on Figure 9 show that a definite relationship exists between the emissions from the average motor vehicle and the number of days each year that the oxidant concentration in the air exceeds the "clean air" standard.

The oxidant trendlines for downtown Los Angeles, Pasadena and Azusa are all downward and the slopes are about the same. This similarity is logical because the process that results in the suppression of oxidant accumulation simply has been displaced from one area to another. This was a unique, one time situation because of the increase in NO_x between 1966 and 1971. After 1971 all areas are down. Thus,

the same conclusion is reached: that the oxidant standard will be met in the 1980's whether air quality data or vehicle emissions trends are projected.

This outlook is based on the APCD's belief that future growth in both the Los Angeles area and SCAB will not create any locality with a traffic density greater than any traffic density in the area to date. For the past 25 years, the area around downtown Los Angeles has been the area of maximum traffic density, and therefore the emissions source area responsible for the maximum effect area measurements.

It is assumed that the traffic density in any future source area will be no greater than the traffic density in downtown Los Angeles. Thus, since the vehicular emissions control program will achieve and maintain the air quality standards in areas affected by vehicular emissions from downtown Los Angeles, it will also achieve and maintain them for any area of SCAB.

Summary , Conclusions and Recommendations

In conclusion, we have shown that a source and effect area analysis of emissions and resulting oxidant is a more reasonable and accurate representation of the Los Angeles area for air quality analysis than gross integration methods such as the big box technique. It has been shown that motor vehicles are the major, and almost sole, contributor to the primary HC and NO_x emissions in the downtown source area, which results in the high oxidant levels in the San Gabriel Valley, in fact the highest in SCAB. An air quality model and vehicle emissions control strategy has been suggested to meet the oxidant standard by mid-1980's.

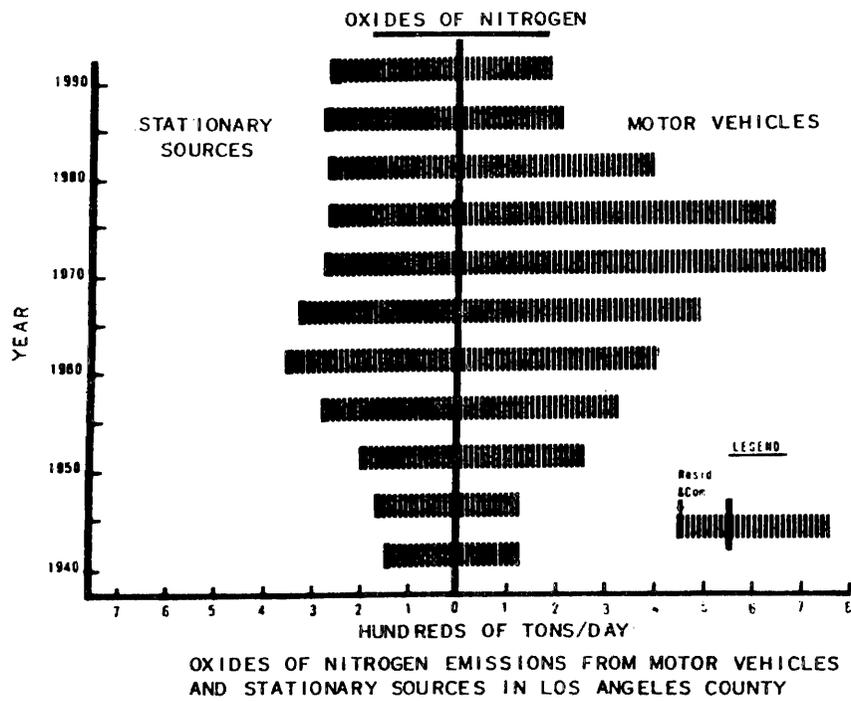
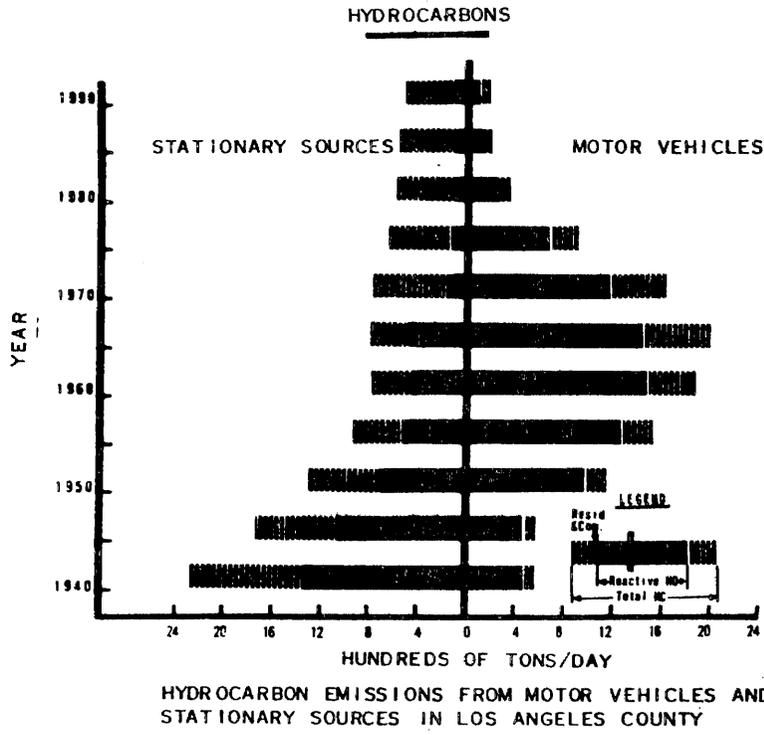
We have shown that:

- Only by adjusting the ratio of NO_x/HC in the motor vehicle emissions to permit accumulation of sufficient atmospheric NO to scavenge the normal atmospheric background oxidant can the standard be attained.
- The APCD strategy which provides for implementation of the present California interim emissions standards for NO_x , HC and CO for new motor vehicles in California, beginning with the 1975 model vehicles, will result in compliance with the CO, NO_2 and oxidant air quality standards by the mid 1980's, and will maintain this compliance until 1990, and possibly longer.
- The effectiveness of the present California motor vehicle control program is easily demonstrable, using air quality data from several areas in Los Angeles County, 1960-1973.
- To assure achievement and maintenance of the air quality goals as now predicted, there must be periodic assessments of the effectiveness of the motor vehicle control program, followed by corrective actions, if necessary.

What has been accomplished thus far is significant, but much more remains to be done so that the best possible representation of emissions and resulting air quality may be available for use in this air basin. A much better emission inventory defining the spatial and temporal distribution of both mobile and stationary sources is needed. Better stationary source information is needed to evaluate the local effects of these emissions. Further detailed studies are needed to establish the

true relationship between emissions data from vehicle test cycles and the actual operation of vehicles; neither the 7-mode nor the CVS procedure provides a true representation of actual vehicle operation. Further tracer studies to assess the transport and dilution of mobile and stationary source emissions from selected source areas are also needed.

FIGURE 1



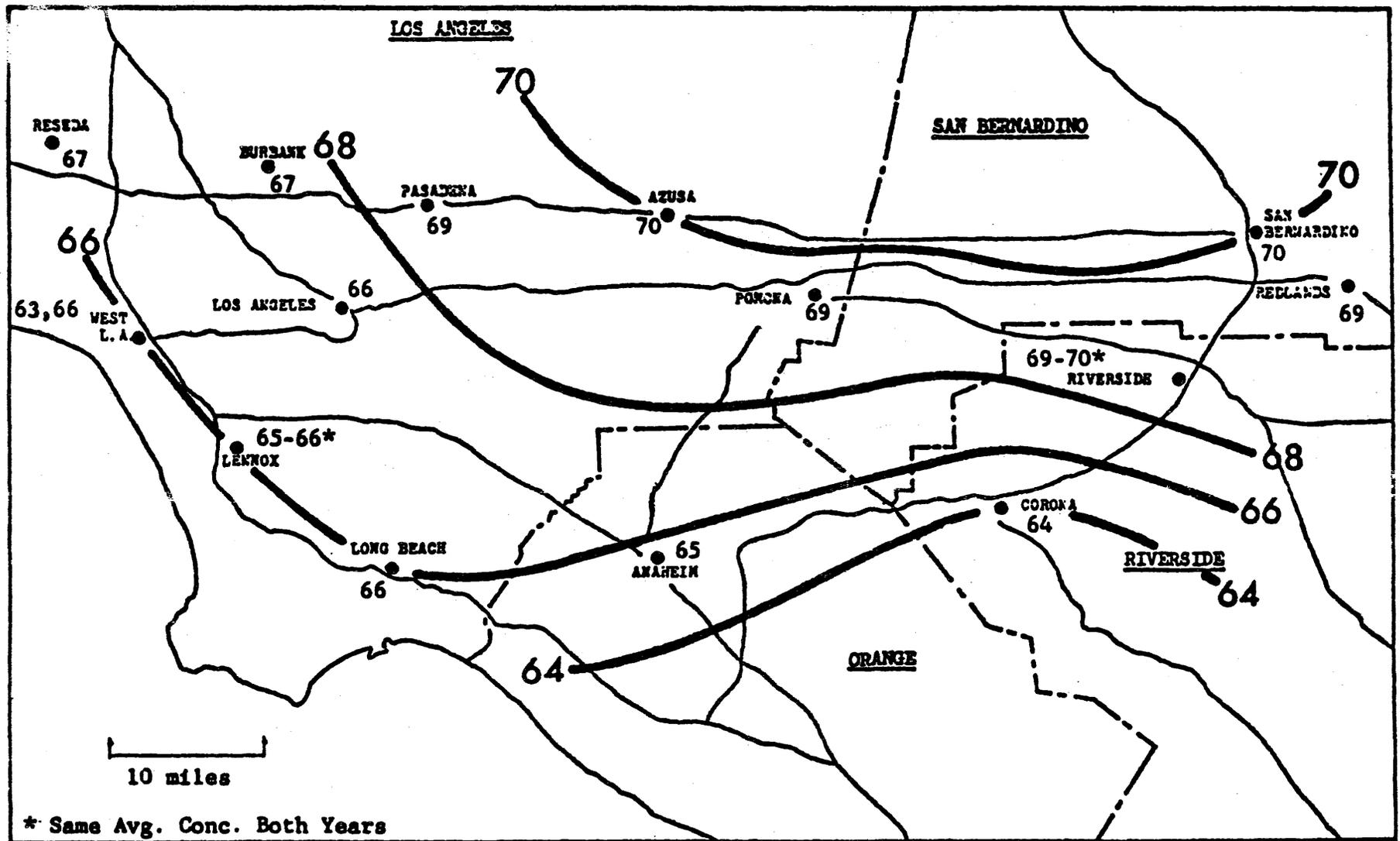


Figure 2

YEAR OF HIGHEST OXIDANT CONCENTRATIONS

Highest Average of Daily Maximum One-Hour Concentrations

During July, August & September, 1963-1972

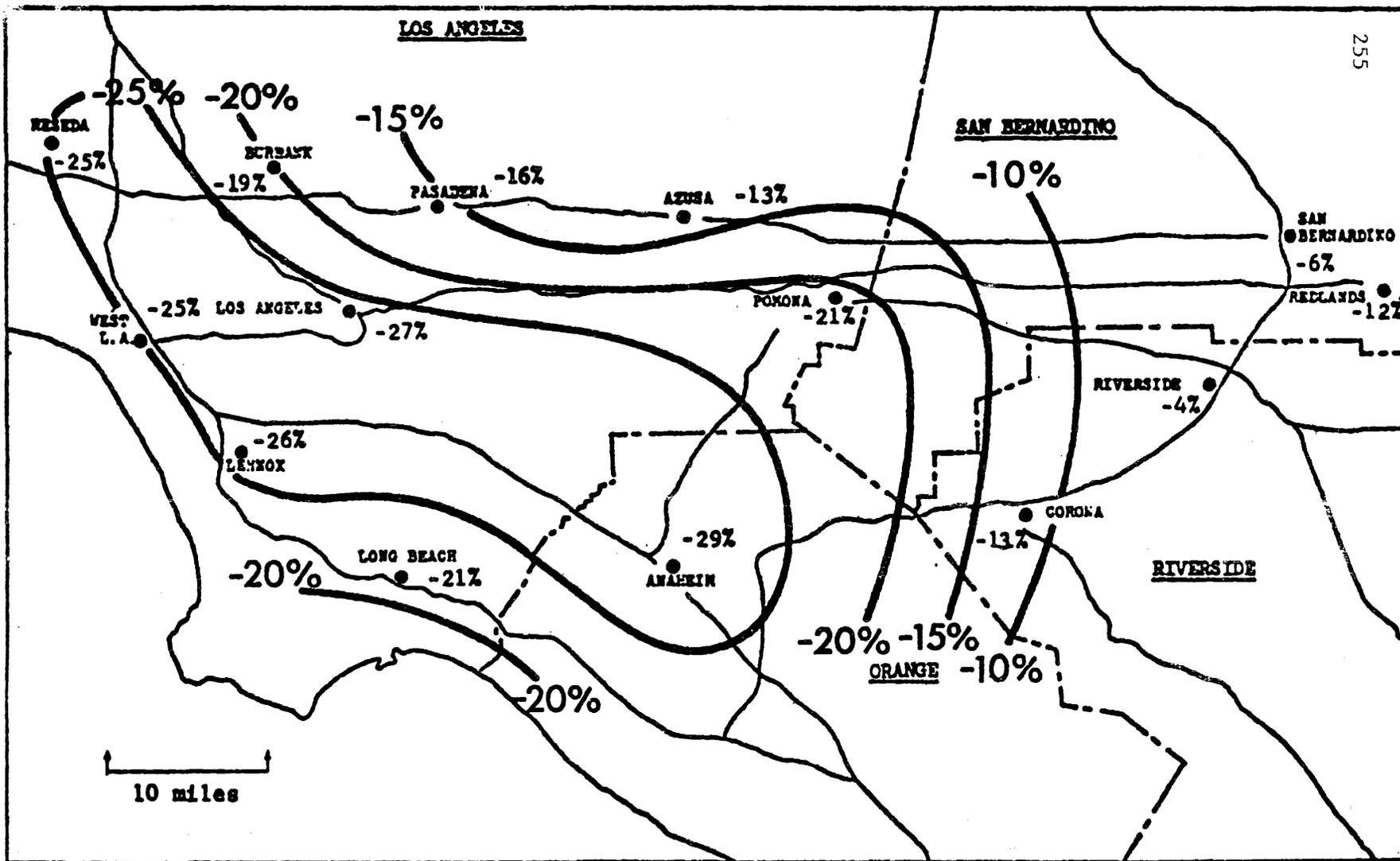


Figure 3

CHANGE OF OXIDANT CONCENTRATIONS

Percent Change from the Highest Three-Year Average to the 1970-72 Average
Of Daily Maximum One-Hour Concentrations for July, August & September

Source: Air Resources Board

FIGURE 4 TYPICAL FLOW OF POLLUTED AIR PARCELS ORIGINATING AT DIFFERENT LOCATIONS IN THE LOS ANGELES BASIN - STARTING 0900 PST.

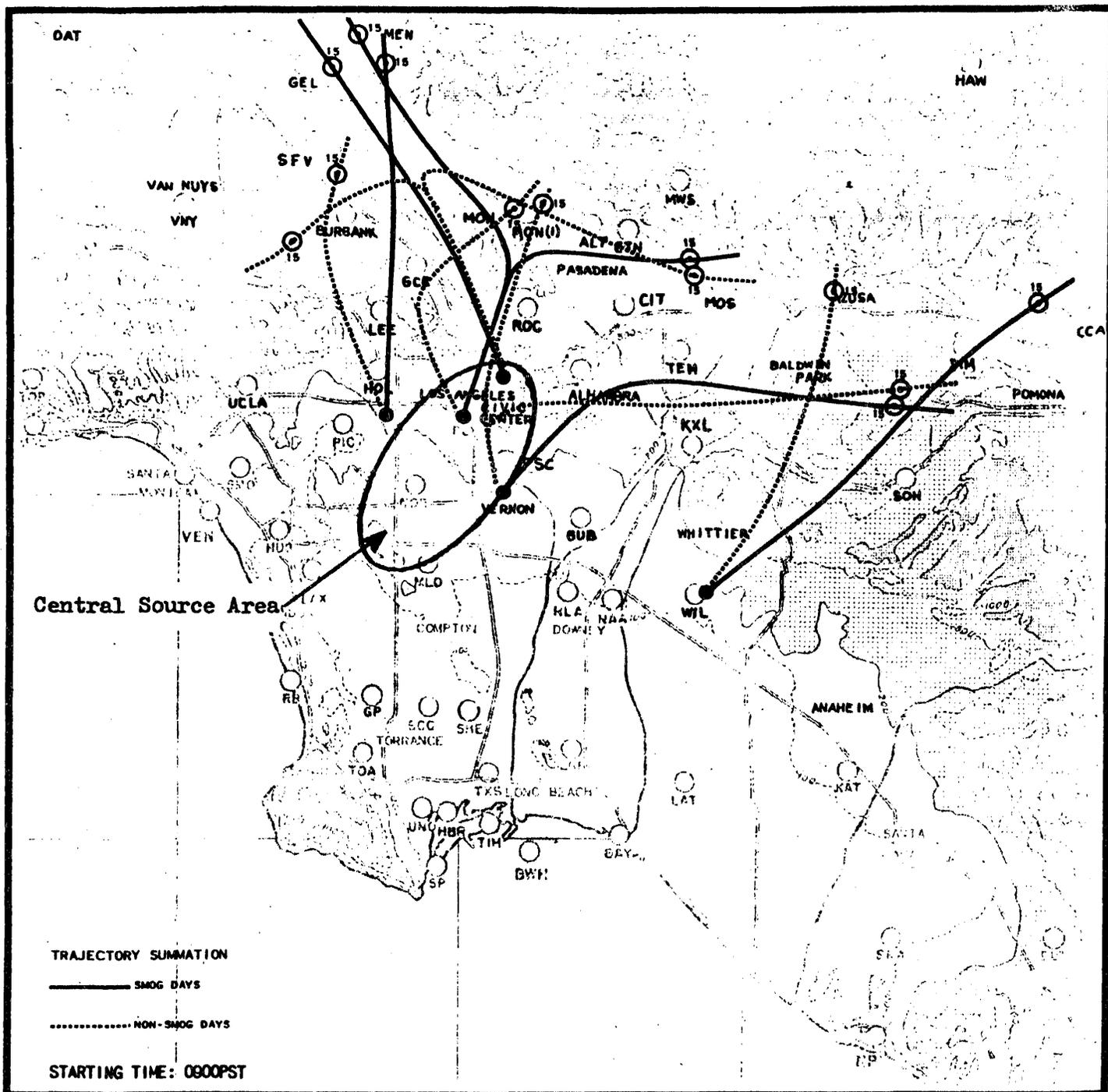


FIGURE 5 ATMOSPHERIC CONCENTRATIONS* OF CARBON MONOXIDE AND OXIDANT IN DOWNTOWN LOS ANGELES (SOURCE AREA) AND PASADENA (EFFECT AREA) 1960-1972

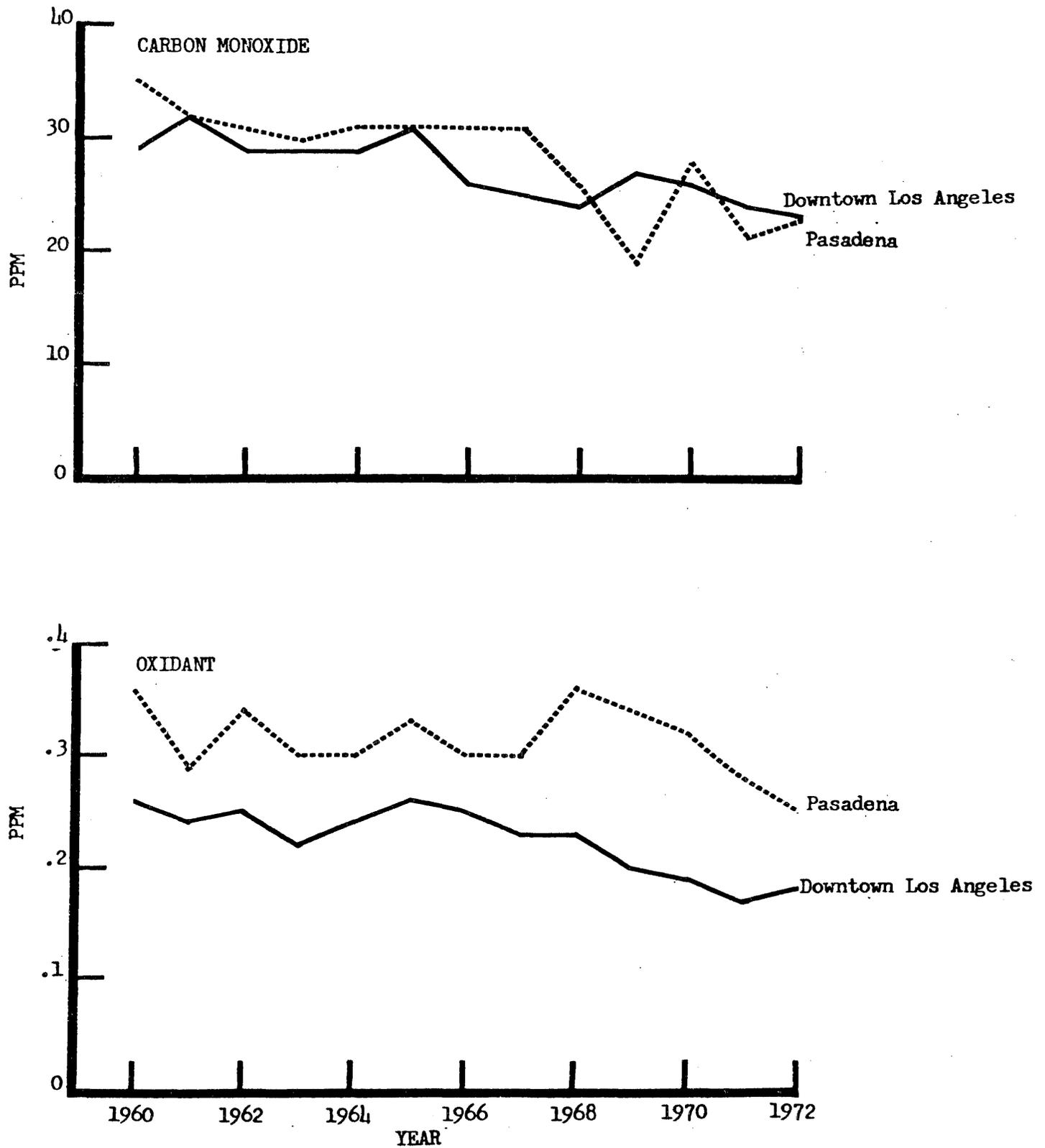
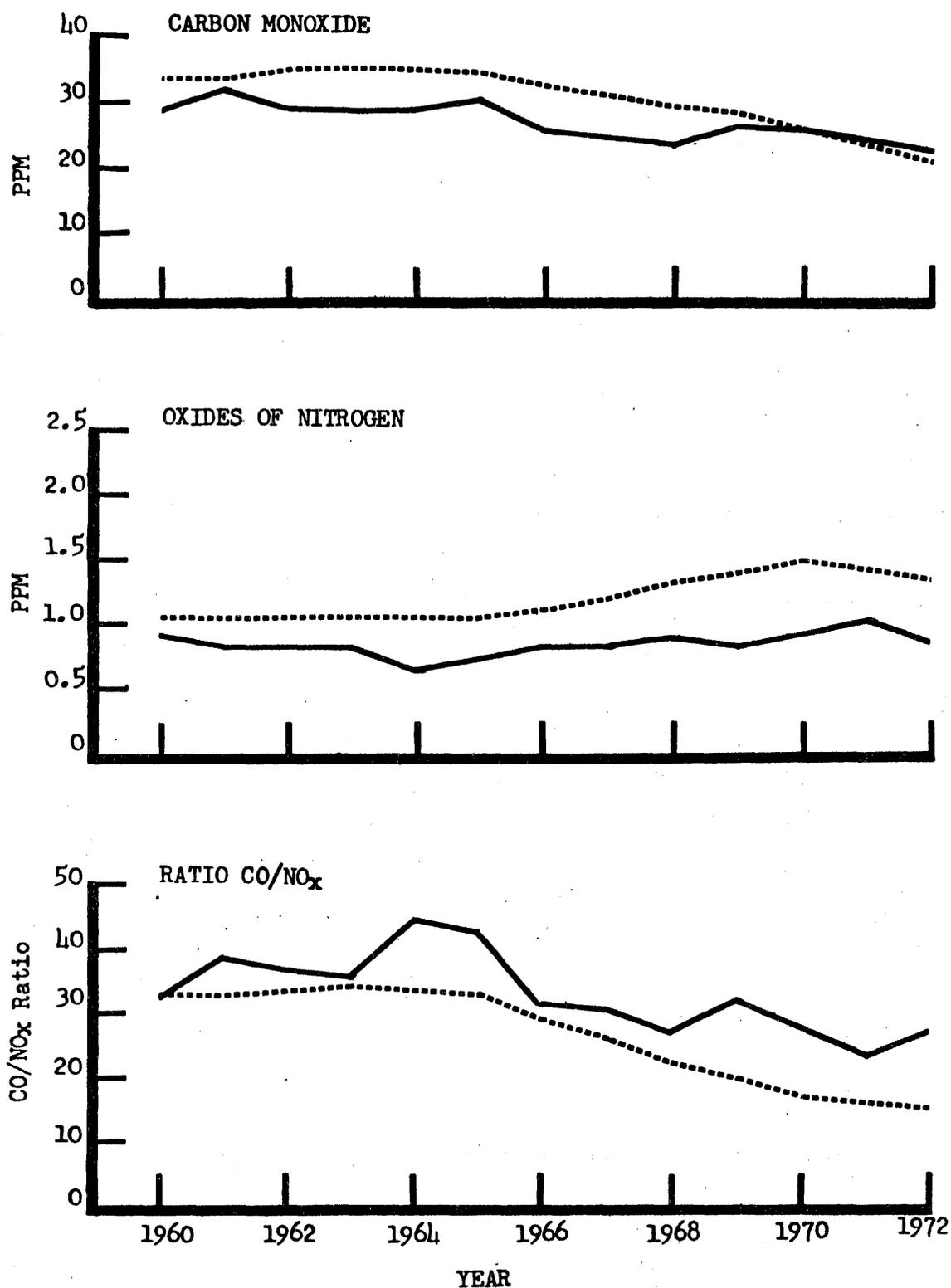


FIGURE 6 COMPARISON OF CALCULATED AND MEASURED ATMOSPHERIC CONCENTRATIONS OF CARBON MONOXIDE AND OXIDES OF NITROGEN IN DOWNTOWN LOS ANGELES 1960-1972



— Measured-Downtown Los Angeles (90th percentile of daily instantaneous maxima)
 Calculated - Average vehicle emissions - Present control program

FIGURE 7 EFFECT OF CALIFORNIA'S AUTO EXHAUST CONTROL PROGRAM ON MAXIMUM CHAMBER OZONE CONCENTRATION.

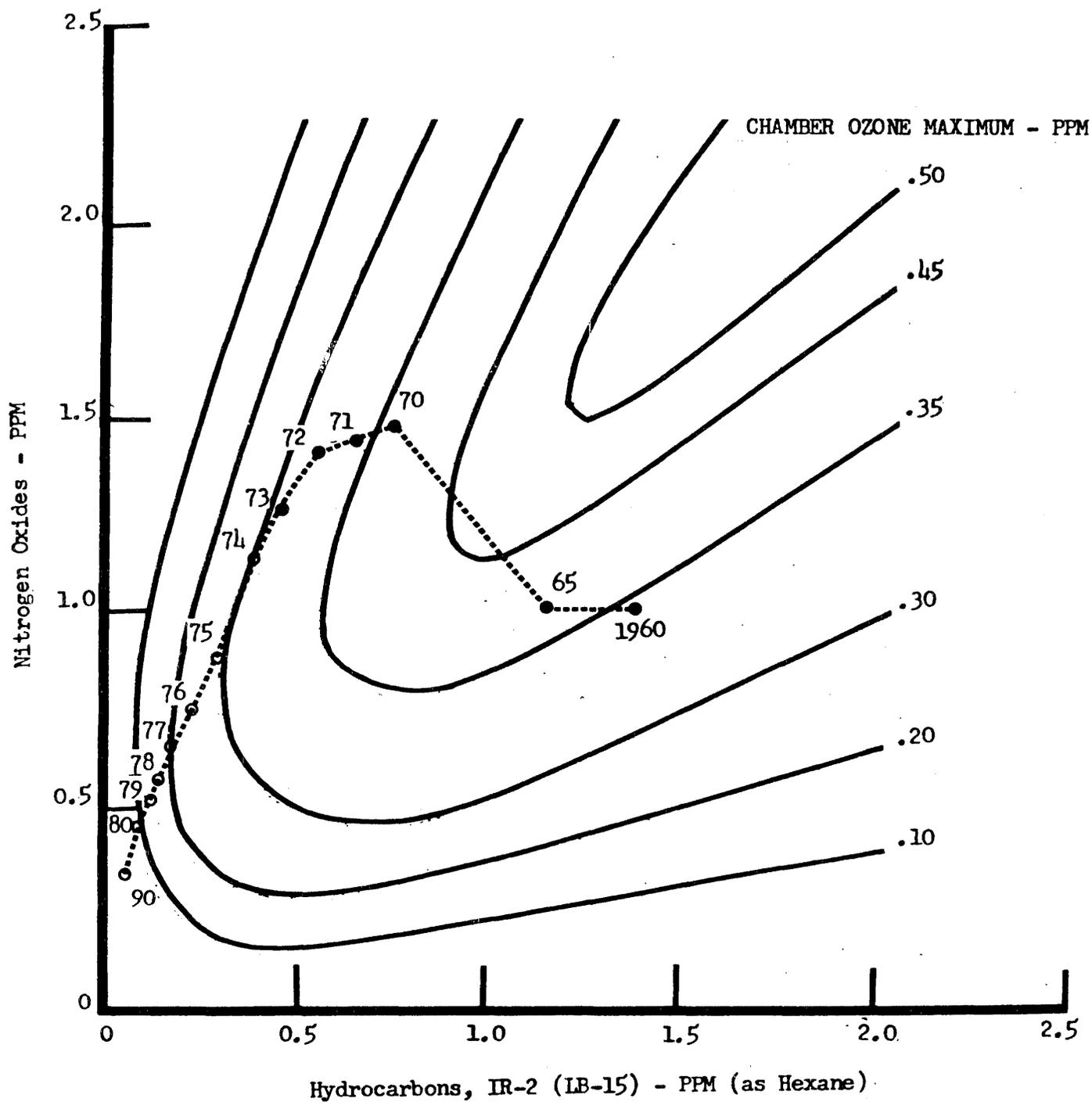
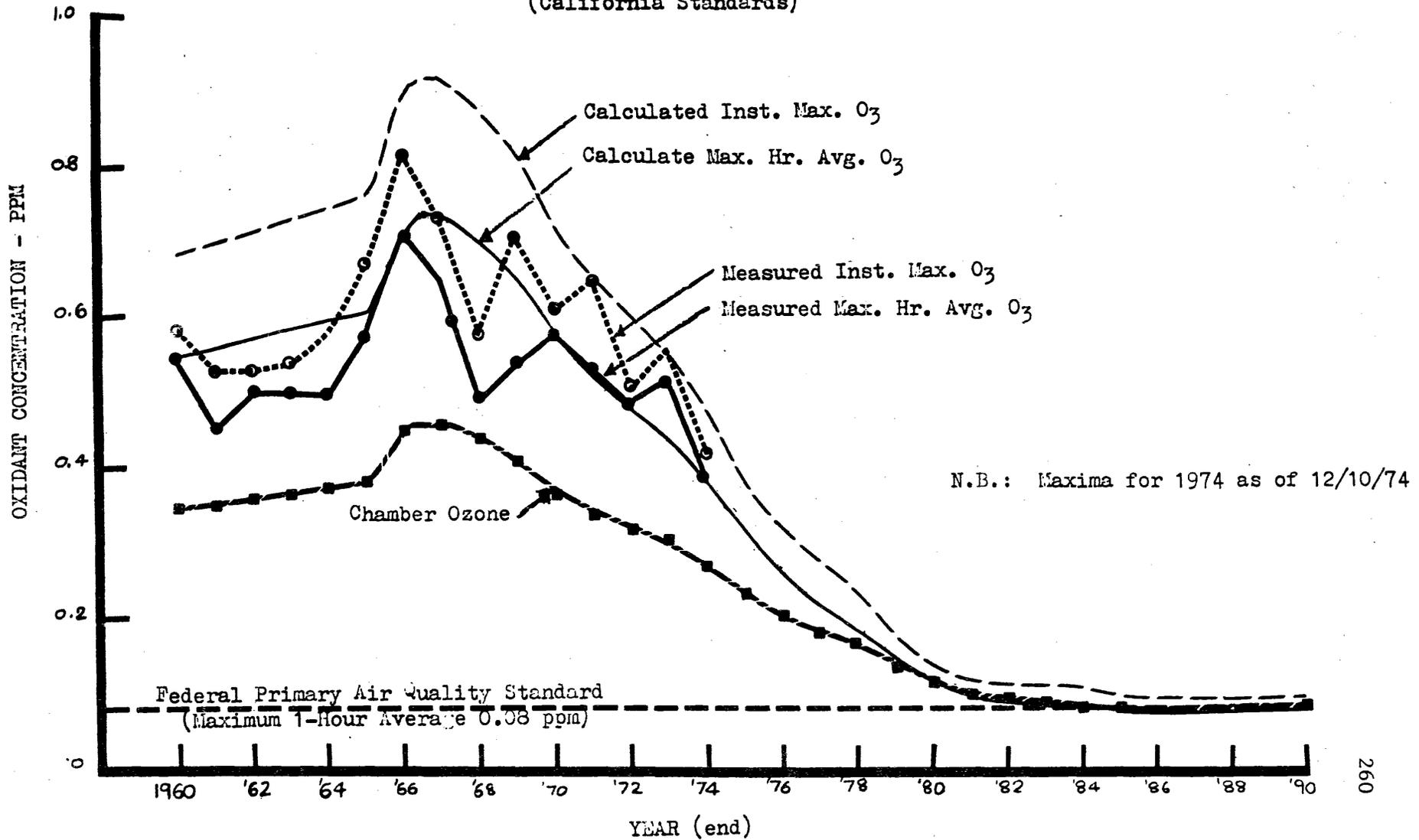


Figure 8
 Calculated Maximum Levels, Instantaneous and Hourly Average,
 of Atmospheric Oxidant Compared to Measured Los Angeles County
 Maxima-with Projections to 1990
 (California Standards)



261
 FIGURE 9 COMPARISON OF ATMOSPHERIC OXIDANT TRENDS WITH AVERAGE NO_x AND
 HC EMISSIONS (Grams per Mile from Average Vehicle)

