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EPA

# The Role of Ozone Precursors in Tropospheric Ozone Formation and Control

## A Report to Congress

# THE ROLE OF OZONE PRECURSORS IN TROPOSPHERIC OZONE FORMATION AND CONTROL

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U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

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## SECTION 1 - INTRODUCTION

### 1.1 1990 Clean Air Act Requirements

This Report responds to the requirements of Section 185B of the 1990 Clean Air Act Amendments (CAAA). In this section, the Act requires that "The Administrator, in conjunction with the National Academy of Sciences, shall conduct a study on the role of ozone precursors in tropospheric ozone formation and control." Specifically, the Act requires that the EPA submit a Report to Congress that addresses the following topics:

1. the roles of oxides of nitrogen (NOx) and volatile organic compounds (VOC) emissions reductions,
2. the extent to which NOx reductions may contribute (or be counterproductive) to achieving attainment in different nonattainment areas,
3. the sensitivity of ozone to control of NOx,
4. the availability and extent of controls for NOx,
5. the role of biogenic VOC emissions, and
6. the basic information required for air quality models.

Findings from this Report must be considered in cases where the Administrator makes determinations regarding the applicability of Section 182(f) requirements for stationary source NOx control in approving State Plan provisions. Section 182(f)(3) also provides that a person may petition EPA for such determinations only after the final Report is submitted to Congress.

### 1.2 Report Structure - roles of NAS and EPA

The National Academy of Sciences (NAS) report entitled Rethinking the Ozone Problem in Urban and Regional Air Pollution is a comprehensive review of the science underlying the topics listed under Section 185B, and should be considered as an integral part of this 185B Report. The NAS report is included as Attachment 1 of this Report. Attachment 2 is an EPA report addressing the availability and extent of NOx controls, a topic not addressed in the NAS report. A draft 185B Report was subject to a 30-day public review and comment period. Attachment 3 includes a summary of public comments and EPA responses. For clarification, the complete Report including the three attachments is referred to herein as either the "Joint Report" or the "185B Report."

The Environmental Protection Agency (EPA) urged development of the NAS study in 1987 and provided partial funding from 1989 through 1991. Other sponsors included the Department of Energy with additional support from the American Petroleum Institute and the Motor Vehicle Manufacturers Association. The study was conducted by the Committee on Tropospheric Ozone Formation and Measurement established in 1989 by the Board on Environmental Studies and Toxicology of the National Research Council (NRC) in collaboration with the NRC's Board on Environmental Sciences and Climate. The Committee's members are experts in the fields of atmospheric chemistry, measurement, mathematical modeling, meteorology, exposure assessment, air-pollution engineering, and environmental policy. The Committee's report was released in December, 1991.

The remaining sections of this Report include:

Section 2 - Providing an EPA overview of key ozone control strategy issues, emphasizing the NOx issues listed in Section 185B of the CAA;

Section 3 - Providing EPA perspectives on the ten main NAS findings in Attachment 1 (i.e., the NAS report); and

Section 4 - Providing a summary of Attachment 2, the NOx control technology report.

# SECTION 2 - KEY OZONE CONTROL STRATEGY ISSUES

## 2.1 Background

Tropospheric[1] ozone pollution, which occurs at ground level and is the major component of ground-level summertime "smog," remains an important environmental and health concern despite nearly 20 years of regulatory efforts. Based on data collected from 1988-1990, roughly 100 metropolitan areas were classified nonattainment (40 CFR, part 81) of the ozone National Ambient Air Quality Standard (NAAQS).

Ozone is a "secondary" pollutant formed in the atmosphere by reactions of volatile organic compounds (VOCs) and oxides of nitrogen (NOx) in the presence of sunlight. Carbon monoxide (CO) also plays a role in the formation of ozone. Major sources of VOCs include exhaust and evaporative emissions from motor vehicles, emissions from solvent use and emissions from the chemical and petroleum industries. In addition, there is now a heightened appreciation of the importance of VOCs emitted by vegetation (biogenic emissions). NOx and CO come mainly from combustion; major sources include motor vehicles and electricity generating stations.

Formation of ozone in the atmosphere involves complex nonlinear processes, adding to the difficulty of identifying effective control strategies. Scientific knowledge continues to evolve at a rapid pace. Recent scientific information has resulted in increased focus on the role of reducing NOx emissions in lowering ozone concentrations. Previous scientific studies and air pollution control programs emphasized VOC reductions as the primary approach to ozone control. The following EPA perspectives identify two key components (strategy selection; modeling and data bases) which must be addressed in resolving the tropospheric ozone problem.

## 2.2 Ozone Precursor Control Strategies

### 2.2.1 Evolving Perspective on NOx and VOC controls

Previous ozone precursor control programs emphasized VOC reductions to achieve the ozone NAAQS. The best available scientific evidence at the time suggested that VOC reductions were preferred in most instances. The VOC control approach was reinforced by the fact that NOx reductions could in some cases increase ozone.

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[1]The term "tropospheric ozone" refers to ozone occurring from ground level through the first several kilometers of the atmosphere and is not to be confused with high altitude (i.e., roughly 15 - 30 km) "stratospheric ozone."

Several recent studies discussed in this Joint Report indicate that NOx controls may lead to greater ozone benefits than previously thought. This apparent shift coincides with improved data bases and modeling techniques that provide the analytical means to evaluate the effectiveness of ozone precursor control strategies. Particularly noteworthy is the important role of biogenic emissions in control strategy calculations. This emerging knowledge combined with the recognition that significant numbers of ozone nonattainment areas remain, implies a need for using sophisticated approaches to develop effective control strategies.

### 2.2.2 Need for Area-Specific Analyses

While the recent shift in attention toward NOx control may be justified, a synthesis of findings from all studies suggests that a nationally based control approach - - whether NOx-only or VOC-only or combined VOC + NOx - - is not likely to be an efficient means for reducing ozone everywhere. The problem is complex and ozone response to precursor control can vary greatly with each area. The following facts present a simplified description of how ozone responds to changes in VOC or NOx:

NOx change

- ozone levels initially can increase or decrease with respect to NOx controls.
- However, in cases where ozone might initially increase in response to small NOx reductions, ozone levels eventually will decline if NOx levels are reduced more substantially.

VOC change

- VOC reductions generally reduce ozone, although conditions exist where the degree of reduction can be minimal.
- ozone levels rarely increase when VOC is reduced.

The body of knowledge based on over 20 years of research and applied studies (Attachment 1) further suggests:

1. NOx controls generally are more effective than VOC control in areas where ambient VOC/NOx ratios are relatively large. For example, rural areas and small to moderate sized urban areas in the eastern U.S. generally are characterized by such ratios.
2. VOC controls generally are more effective than NOx controls in areas where ambient VOC/NOx ratios are

relatively small. For example, the central core sections of large urban areas (New York and Los Angeles) generally are characterized by such ratios.

3. From the perspective of simple smog chamber experiments, combined VOC and NOx reductions are as a rule less effective than reducing either one alone. In the real world, however, the complexity of geographical and temporal variations in meteorology, source composition, and control feasibility often make combined VOC and NOx control the option of choice.

4. Ambient data bases generally are not available to adequately characterize these VOC/NOx ratios, which can vary substantially with space and time in an urban area and its surroundings.

5. Ambient VOC/NOx ratios are influenced by emissions, pollutant inflow from surrounding areas, transformation through atmospheric chemical reactions, deposition, and given the non-uniformity of sources in urban areas and surrounding regions, by meteorology also.

6. Ozone response to precursor changes is influenced by meteorology and can exhibit day-specific responses.

7. Gridded photochemical air quality simulation models provide the most comprehensive treatment of processes responsible for ozone formation and provide a means for estimating changes in ozone due to hypothesized VOC and NOx reductions.

8. High quality emissions, air quality and meteorological data bases are critical for deriving credible model conclusions.

As one proceeds from a central-city location downwind to the suburban and rural fringes, a gradual change from relatively low to high VOC/NOx ratios occurs. This pattern arises, in part, from a greater concentration of NOx emissions sources (e.g., automobile exhaust and various commercial and industrial activities) in central-core regions and attendant influences associated with relatively faster depletion of NOx during downwind transport. Thus, when NOx reductions are applied in large urban areas, greater ozone reductions are likely to be seen several kilometers downwind of the central urban-core, relative to the central-core. This is so, because NOx availability becomes the limiting factor in further ozone production when the VOC/NOx ratio is high.

This highly generalized spatial response pattern has important implications for population exposure to ozone arising from NOx controls, and for the long-distance transport of ozone. Conclusions based on just an analysis of peak hourly ozone may not always apply to other important measures such as total population exposed to high concentrations of ozone. Certain modeling studies have suggested that NOx controls result in less reduction of total ozone exposure relative to VOC controls in the New York City and Los Angeles airsheds. However, NOx controls appear to have a greater effect than do VOC controls in reducing downwind ozone, thereby lowering the ozone transported to downwind metropolitan areas. Thus, upwind NOx controls may result in a reduction of ozone precursor controls needed in the downwind location.

These observations indicate that comprehensive, objective analyses should be applied to specific areas to determine an effective ozone precursor control strategy. Such analyses need to consider both the regional and smaller urban-scale implications. Furthermore, multiday, area-specific application of gridded photochemical models supported by the best available data bases is the preferred method for developing and evaluating such strategies. This reasoning is consistent with that recommended by the NAS report:

> "Application of grid-based air quality models to various cities and regions shows that the relative effectiveness of controls of volatile organic compounds (VOCs) and oxides of nitrogen (NOx) in ozone abatement varies widely.....These cities share an ozone problem, but differ widely in the relative contributions of anthropogenic VOCs and NOx and biogenic emissions. As a result, the optimal set of controls relying on VOCs, NOx, or, most likely, reductions of both, will vary from one place to the next."

## 2.3 Supporting Data Bases and Air Quality Modeling

### 2.3.1 Description of the issue

Development and implementation of effective control strategies relies on air quality models and supporting data. The NAS report raises the following concerns regarding the adequacy of data bases and modeling used to date in formulating and verifying ozone precursor control programs:

1. models need to be subjected to careful, comprehensive evaluations;

2. emission inventories, particularly mobile source components, have underestimated VOC emissions, a problem of consequence both in evaluating and in applying models;

3. biogenic emissions must be better defined, for the same reasons, and included in strategy assessment;

4. ambient air monitoring networks have not provided adequate feedback information on effectiveness of control programs, or corroboration of emission inventories;

5. gridded photochemical models should be used in strategy development; and

6. air quality, emissions, and meteorological data bases used to drive and evaluate models need improvement.

It is clear that, as the NAS report suggests, past emission inventories understated VOC emissions. This probably was one of the reasons that NOx controls were not adequately integrated into past air quality management programs. Emissions are crucially important inputs to current photochemical grid models, and less important, but nevertheless still significant, inputs to the earlier used EKMA model. If emissions estimates understate VOCs relative to NOx, the models will wrongly give greater weight to VOC control in reducing ozone. Failure to consider the role of biogenic VOC emissions exacerbated this problem. Furthermore, a more comprehensive ambient measurement network could have provided basic reality checks needed to implement mid-course corrections. Greater confidence will result if analyses based on both ambient data and models suggest similar control pathways.

### 2.3.2 Dealing with the technical issues

The EPA has been sustaining a program development and research effort to improve data bases and model systems. Reflecting those needs, Congress added substantial new requirements in the 1990 CAAA to foster improvements in data bases and model applications.

Air Quality Modeling. The EPA has developed an integrated application program for urban and regional scale gridded photochemical modeling. Two major modeling initiatives were undertaken by EPA in the late 1980s and early 1990s to foster use of advanced gridded photochemical models in the SIP process: (a) development of application capability to apply the Regional Oxidant Model (ROM) and (b) updating and documenting the Urban Airshed Model (UAM) to make it more accessible for use by State agencies. The ROM provides simulated boundary air quality concentrations needed to drive the finer scale UAM. These boundary concentrations for current year model exercises would be especially difficult and expensive to characterize through ambient measurements, and impossible for projected future modeling years[2]. This program is consistent with the NAS recommendation and Title I CAA mandates for the use of gridded photochemical models in the more seriously polluted ozone nonattainment areas to demonstrate that control strategies will result in attainment of the ozone NAAQS. Virtually every metropolitan area required by the Act to conduct grid modeling has progressed through the initial model setup phases or has plans in place to meet the regulatory modeling requirements. This is a considerable achievement considering that prior to the 1990 amendments most gridded photochemical model applications were directed toward research objectives. However, EPA's ROM and UAM models have yet to be subjected to the comprehensive evaluations needed to produce high accuracy and precision in model predictions. Such evaluation efforts require large blocks of funds that could not be accommodated to date in the Agency's limited research budgets. Innovative and cooperative efforts between public and private sectors must be implemented to meet this need.

Emission inventories and biogenics. EPA has accelerated and enhanced the process of upgrading the inventory process by:

1. continued improvement of mobile source emission factor models, including better evaporative/running loss factors and accounting of emissions not included under standard EPA Federal Test Procedures (FTP).

2. substantial increase in funding to improve

[2]Regulatory model applications include a "current" year evaluation based on observed data and a "future" year assessment of impacts of planned emission control strategies on ozone.

emission inventories,

3. designation of SIP emission inventories as high priority for EPA Regional Office and State implementation programs,

4. requiring inclusion of biogenic emissions in gridded photochemical model attainment demonstrations,

5. developing state-of-the-art biogenic emissions models and supporting research efforts on improved biogenic emission estimates, and

6. establishing the Emissions Inventory Branch (EIB) in 1991 within the Office of Air Quality Planning and Standards (OAQPS) to centralize coordination of inventory activities, and establishing the Joint Emissions Inventory Oversight Group (JEIOG) in 1990 between EPA's Office of Research and Development and the Office of Air and Radiation to develop research programs and guidance on high priority inventory issues.

Air Quality Monitoring. The NAS has pointed out that past air quality management efforts did not place enough emphasis on monitoring as a "feedback" mechanism for determining how well control strategies were implemented. Air quality models are excellent control strategy design tools which incorporate the necessary physical and chemical processes to make objective air quality assessments in the uncertain future. Despite the best efforts and intentions, control programs are not always implemented as planned, or are as effective as desired. Also, the models and supporting data bases are not perfect. Therefore, subsequent ambient monitoring of ozone precursors is needed to provide assurance that planned reductions are actually occurring and effecting air quality improvements, and to support future analyses to identify appropriate adjustments to control programs. These modeling and data collection efforts used to develop, assess and check control strategies are embodied in the existing State Implementation Plan (SIP) process.

Section 182(c) of the CAA contains requirements for enhanced ozone monitoring. The EPA has proposed regulations and attendant guidance in 1992 pursuant to this section which would establish a network of Photochemical Assessment Monitoring Stations (PAMS) in the 23 areas classified as serious or above. The enhanced ozone monitoring program is a concerted effort by the EPA and State and local air agencies to address data deficiencies, including those identified by the NAS. PAMS data are intended to support:

1. better assessments of ambient ozone and precursor concentrations,
2. corroboration of ozone precursor emission inventories,
3. ozone model applications, and
4. tracking progress of control programs.

Research to Improve Ozone Strategies

The initiatives outlined above are important steps toward upgrading emissions and monitoring data bases and regulatory models. Nevertheless, additional intensive data collection and model application efforts beyond these initiatives will be needed. Furthermore, additional development of more robust models which improve the treatment of meteorological and chemical reaction processes is needed. The advances in our knowledge of atmospheric chemistry must continue to address uncertainties in areas that have not been fully tested (e.g., natural and aromatic VOC emissions effects, and future-year projected atmospheres arising from the planned implementation of emission strategies). Strong commitments must be made to ensure decisive improvements in emissions and monitoring data bases, which are the foundation for developing and assessing success of ozone precursor control strategies. A strong supporting research effort is needed to improve the modeling and monitoring tools which are the basis of all application efforts.

## SECTION 3.0 - EPA PERSPECTIVES ON THE NAS FINDINGS

The National Academy of Sciences (NAS) produced ten findings in the Executive Summary of their report entitled Rethinking the Ozone Problem in Urban and Regional Air Pollution (Attachment 1). These NAS findings and recommendations are reproduced below and combined with the following EPA responses.

### 3.1 Ozone in the United States

#### 3.1.1 NAS finding

Despite the major regulatory and pollution-control programs of the past 20 years, efforts to attain the National Ambient Air Quality Standard for ozone largely have failed.

#### 3.1.2 NAS discussion

Since passage of the 1970 Clean Air Act amendments, extensive efforts to control ozone have failed three times to meet legislated deadlines for complying with the ozone NAAQS. Congress set 1975 as the first deadline, but 2 years after this deadline, many areas were still in violation of the NAAQS. The 1977 amendments to the Clean Air Act extended the deadline for compliance until 1982 and allowed certain areas that could not meet the 1982 deadline until 1987. For 1987, however, more than 60 areas still exceeded the NAAQS; the following year, the number of areas exceeding the NAAQS jumped to 101. In 1990, 98 areas were in violation of the NAAQS.

EPA has reported a trend toward lower nationwide average ozone concentrations from 1980 through 1989, with anomalously high concentrations in 1983 and 1988. Ozone concentrations were much lower in 1989 than in 1988, possibly the lowest of the decade. However, since the trend analysis covers only a 10-year period, the high concentrations in 1983 and 1988 cannot be assumed to be true anomalies, nor can the lower concentrations in 1989 be assumed to be evidence of progress. It is likely that meteorological fluctuations are largely responsible for the highs in 1983 and 1988 and the low in 1989. Meteorological variability and its effect on ozone make it difficult to determine from year to year whether changes in ozone concentrations result from fluctuations in the weather or from reductions in the emissions of precursors of ozone. However, it is clear that progress toward nationwide attainment of the ozone NAAQS has been extremely slow at best, in spite of the substantial regulatory programs and control efforts of the past 20 years.

### 3.1.3 EPA comment

Air quality data clearly attest to a current situation where a number of U.S. metropolitan areas are nonattainment with respect to ozone. In large measure, the 1990 amendments to the Clean Air Act (CAA) were motivated by the extent of nonattainment in the U.S. Although many areas remain nonattainment, analysis of 1980-1991 ozone data (EPA, 1992) suggests a downward trend in peak ozone values. Furthermore, this trend coincides with a period of substantial population and economic growth throughout the 1980s. In the absence of effective emission control programs, the demographic growth would have led to increased emissions and attendant increases in ozone. Thus, considerable "progress" has been achieved by averting increases in ozone concentrations in the face of demographic factors which would otherwise worsen ozone levels.

In recognizing the current extent of ozone pollution, perhaps the most important message is that the ozone problem is complex and historically has been extremely difficult to solve with state-of-the-art scientific knowledge and technologies. The knowledge-base concerning ozone continues to evolve rapidly and provides added insight on methods to counter ozone pollution. To improve our chances of solving the ozone problem, existing air quality programs must be flexible enough to enable adoption of evolving knowledge and emerging methods. Similarly, air programs must incorporate the extended vision and patience required to realize long-term air quality improvements which are functions of future, uncertain values of economic, technological and meteorological variables. Finally, new research and control initiatives need to be undertaken.

## 3.2 Ozone Trends

### 3.2.1 NAS finding

The principal measure currently used to assess ozone trends (i.e., the second-highest daily maximum 1-hour concentration in a given year) is highly sensitive to meteorological fluctuations and is not a reliable measure of progress in reducing ozone over several years for a given area.

### 3.2.2 NAS recommendation

More statistically robust methods should be developed to assist in tracking progress in reducing ozone. Such methods should account for the effects of meteorological fluctuations and other relevant factors.

### 3.2.3 EPA comment

The EPA's annual ozone trend assessments focus on statistical measures closely related to the health-based National Ambient Air Quality Standards (NAAQS) in order to provide a convenient frame of reference for the results. The ozone NAAQS requires that the average number of days with hourly maximum ozone concentrations above 0.12 ppm not be more than one per year. Thus, the annual second highest daily maximum (SHDM) value is used as an ozone trend statistic. This does place an emphasis on peak values, which can be influenced by year-to-year variations in meteorology. The EPA's trend reports have highlighted this point, particularly with respect to the effect of hot summer weather on ozone (EPA, 1991a).

The EPA recognizes the need for additional trend statistics that may be less influenced by year-to-year meteorological fluctuations. Such statistics could be useful indicators of long-term progress and the EPA will continue to encourage their development. At the same time, the EPA strongly supports the NAS caution that these alternatives "should not be mere statistical entities." Analyses must communicate trends relevant for the health based NAAQS. Trends in the quality of the air that people actually breathe can not be discounted in favor of trends in hypothetical air quality that would have occurred under normalized meteorological conditions.

The use of statistical approaches which normalize effects of meteorological influences are useful for developing insight on the relation between ozone and emission trends. This, in turn, would provide a clearer view of long-term changes of health-and environmentally-related measures. Indeed, if the trends were adjusted to consider the strong meteorological influence generated by a hot, dry 1988 summer, as well as effects in other years with less conducive meteorology, different conclusions might be reached concerning the rate of progress in reducing ozone.

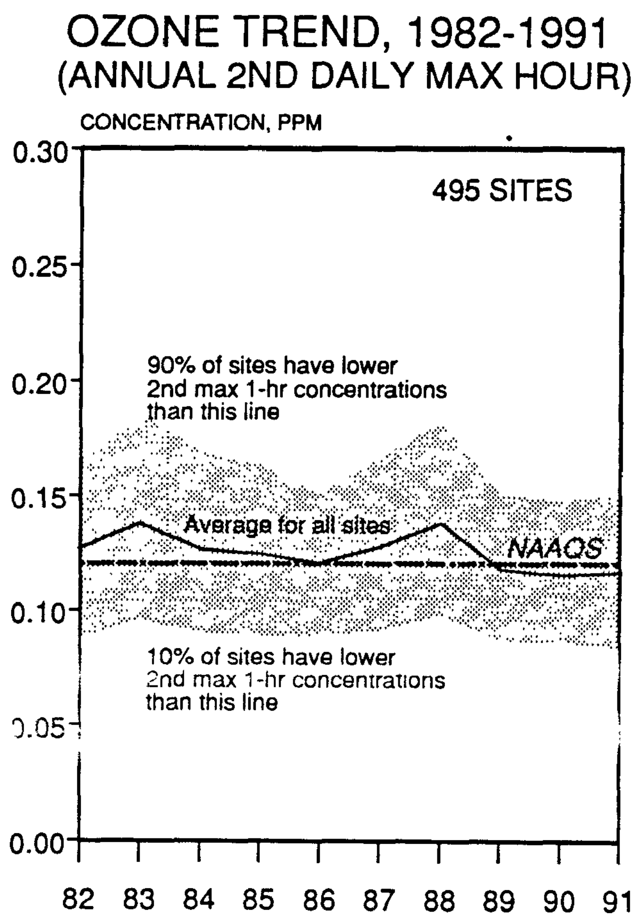
The EPA has initiated a program (Cox and Chu, 1991) to investigate techniques for adjusting ozone trends for meteorological influences, to address concerns regarding the apparent lack of robustness exhibited by extreme value indicators such as the second highest daily maximum. One of the methods being studied is a statistical model in which the frequency distribution of ozone concentrations is described as a function of meteorological parameters such as temperature and wind speed. The statistical model includes a trend component such that long-term changes in ozone can be determined that are less dependent on annual changes in meteorological conditions. The model has been applied in approximately 25 urban areas using monitored ozone data collected over the past decade. The results show promise in that adjusted ozone trend statistics are relatively smooth compared with the unadjusted ozone data. The EPA is seeking to review and expand the technical basis for the methodology under a cooperative agreement with the National Institute of Statistical Sciences (NISS). Under this agreement, the NISS also will examine more sophisticated statistical models that would treat both spatial and temporal components of meteorological/ozone behavior. Expectations of definitive results from this work must be tempered by the fact that the usable ozone record is not much greater than a decade; certainly less than optimal for such a study.

Separate programs are under development which explicitly address progress in emissions reductions and the relationships among emissions, meteorology and air quality. Data from the developing enhanced ozone monitoring program (discussed in Section 3.6) potentially will address many of the issues raised by the NAS; tracking ozone precursor emissions trends is one of several program objectives.

The NAS committee did not address the definition of the ozone NAAQS. However, the NAS did raise concerns that are relevant to the definition and use of ozone design values. Most of the planning, control strategy development, implementation and verification elements of the State Implementation Planning (SIP) process are based on the ozone design values for specific metropolitan areas. For example, classification status of ozone nonattainment areas is based on ozone design values. Given the importance of ozone design values in developing and assessing ozone strategies, the EPA is conducting an Ozone Design Value study as required by Section 183(g) of the 1990 CAA to determine if a different and/or additional ozone statistic should be incorporated in the planning process.

In summary, existing reporting procedures of the ozone trends data provide a view of air quality metrics which closely reflect the current 1-hour ozone standard. However, the second highest daily maximum is a difficult metric to use for assessing long-term trends. The EPA is developing and encouraging the use of statistical procedures which attempt to isolate meteorological influences on ozone trends and facilitate interpretation of long term underlying trends.

Ozone trends data from 1982 through 1991 are shown below. The recent trends suggest improvement relative to 1988. The 1989-1991 period is too brief to provide conclusive evidence that control programs are responsible for the downward trend. Meteorological influences are not extracted form the trends data.



## 3.3 State Implementation Planning

### 3.3.1 NAS finding

The State Implementation Plan (SIP) process, outlined in the Clean Air Act for developing and implementing ozone reduction strategies, is fundamentally sound in principle but is seriously flawed in practice because of the lack of adequate verification programs.

### 3.3.2 NAS recommendation

Reliable methods for monitoring progress in reducing emissions of VOCs and $NO_x$ must be established to verify directly regulatory compliance and the effectiveness associated with mandated emission controls.

### 3.3.3 EPA comment

The SIP process was developed to determine the level of emissions controls required to meet the NAAQS and ensure implementation and enforcement of those controls. The 1977 CAAA required that the NAAQS for ozone be met by 1982, with extensions for certain areas to 1987. Since a number of ozone nonattainment areas remain, aspects of the SIP process have been criticized. The NAS found that the basic SIP approach consisting of strategy development, implementation and enforcement elements was sound. However, the SIP process was weakened by the lack of an adequate verification component. A major issue here is the scope of efforts to track changes in ozone precursor emissions and related ambient concentrations and the effectiveness of control measures in reducing precursors and, ultimately, ozone.

Section 182(c)(1) of the 1990 CAA addresses the need for ambient verification and mandates promulgation of enhanced ozone monitoring regulations. A principal objective of developing an enhanced monitoring program is corroboration of emission trends through measurements of ozone precursor concentrations (VOCs and NOx). [A more complete description of this program is included in Section 3.6.]

Briefly, previous VOC and NOx monitoring programs were designed principally to support trajectory modeling analyses and to characterize ambient pollutant trends in major urban centers. As such, measurements focused on VOC and NOx concentrations observed between 6 - 9 AM on weekdays, and typically were taken at downtown sites. A more comprehensive set of measurements is needed to provide an independent means of verifying that emissions reductions required by a control strategy are, in fact, occurring at levels specified in the SIP. Furthermore, the measurements should be capable of explaining measured trends in VOC and NOx which are inconsistent with expectations accompanying a control strategy.

To meet such an objective, VOC and NOx measurements are needed at several locations within a nonattainment area several times a day. Also, VOC measurements need to be resolved into individual compounds and meteorological data collected in order to associate specific source categories with ambient data. In addition to providing data for these basic verification needs, enhanced monitoring program networks serve other related SIP functions. The measurements may provide a means for refining emission estimates, supporting ozone model applications and tracking future air quality and emissions trends. Recognizing that the PAMS are intended to serve multiple needs and the significance of ambient data in the SIP process, careful assessments of the contemplated PAMS program must be conducted to insure that the program is capable of meeting prescribed goals.

A PAMS network will be phased-in over time once the program is promulgated. Regulations and guidance for establishing an enhanced monitoring system are being set and forthcoming data are not expected until after 1994. The monitoring program will provide a feedback/verification mechanism for post-1994 SIP revisions with attainment targets in the 1999-2010 timeframe. However, the air quality modeling needed to design initial control strategies will be completed before November, 1994 and, consequently, will not benefit from the enhanced ozone monitoring data.

In addition to verification through ambient monitoring, it is important to track emissions reductions. Past SIPs have assumed that regulatory programs for stationary sources would be implemented with full effectiveness, achieving all of the intended emission reductions at all times. The EPA's rule-effectiveness policy (1989) requires SIPs to reflect more realistic emission reduction scenarios and encourages States to evaluate actual reductions and incorporate that information into the SIP.

### 3.4 Anthropogenic VOC Emissions

#### 3.4.1 NAS finding

Current emissions inventories significantly underestimate anthropogenic emissions of VOCs. As a result, past ozone control strategies may have been misdirected.

#### 3.4.2 NAS recommendation

The methods and protocols used to develop inventories of ozone precursor emissions must be reviewed and revised. Independent tests, including monitoring of ambient VOCs, should be used by government agencies to assess whether emissions are indeed as they are represented by emissions inventories.

#### 3.4.3 EPA comment

The NAS raises important concerns shared by the EPA regarding the adequacy of past emission inventories. Illustrating the seriousness of this subject is the recent understanding that mobile source VOC emissions may have been underestimated by a factor as high as 2 or more. Emission inventories need to be improved. The EPA acknowledges that past inventories have understated VOC and CO emissions due to limitations of data and methodologies. In addition to the studies cited by the NAS, more recent analyses (Baugues, 1991; Fujita et al., 1992) generally support the conclusion that historical anthropogenic emission estimates have been understated.

The precise extent to which various source categories have been understated is not clear, and adequate data currently are not available to revise the emissions models or estimates. The most likely suspects are mobile source emissions (including non-road mobile source emissions), commercial/consumer solvents, and point source emissions (caused by inappropriate rule effectiveness assumptions, poorly-characterized fugitive emissions, and emissions from sources emitting less than prescribed cutoff limits such as 100 tons/year, which historically have not received adequate attention). Shortcomings in emissions estimates have arisen from incomplete scientific understanding and inadequate emphasis on inventory studies.

The 1990 CAAA put a much higher premium on accurate inventory compilations than has been true formerly. As noted in Section 2, the EPA has accelerated and enhanced its efforts at upgrading the inventory process and has directed increased support to States to assist them in utilizing available new findings in State Implementation Plans due in 1993.

1. Continued improvement of mobile source emission factor models.

Concerns about mobile source emission factor models have provided an ongoing feedback mechanism to improve existing techniques for several years. Mobile source models are upgraded periodically to reflect new findings on evaporative and exhaust emission components in addition to incorporating changes stemming from combustion technology in new automobiles. Mobile source models are generated from emission testing of in-use vehicles using a driving cycle typical of urban driving. However, this driving cycle may be inadequate in characterizing the full spectrum of vehicle driving patterns of individual operators such as heavy acceleration rates. Transient rapid acceleration events may cause order of magnitude increases in exhaust emissions for short periods of time. The EPA is evaluating whether other driving modes should be added to this cycle. Several other factors such as accounting for frequency of cold and hot starts, high-emitting older vehicles, use of average speeds for model inputs, determining traffic flow patterns and other parameterization considerations present formidable challenges. Ambient studies which measure emissions over characteristic traffic areas may provide useful enhancements to mobile source emissions modeling methods. Meanwhile, the EPA has field research programs underway focusing on driving cycle effects and better characterization of higher mileage and earlier vintage vehicles.

In addition to improving highway vehicle emission estimates, attention must be directed toward nonroad vehicle emissions (e.g., diesel engines in large construction operations). A recent study (EPA, 1991b) suggests that nonroad vehicle emissions potentially constitute a significant portion of total vehicle emissions. Accordingly, methodologies are being developed to provide more accurate estimates of the nonroad emissions component.

2. Designation of emission inventories as high priority for EPA and State and local programs.

Emission inventories form the basis for several air quality programs. The effort to develop the 1985 National Acid Precipitation Assessment Program (NAPAP) Emission Inventory proved successful in providing an adequate inventory of $SO_2$ and NOx emissions from large point sources for the acid rain program. A focus is now on the SIP emission inventories for ozone nonattainment areas. The EPA has issued several volumes (EPA, 1991 c-g) of Emission Inventory guidance procedures and held national workshops on preparing inventories. States were required to submit inventories by November, 1992.

Steps to upgrade these inventories above previous inventories include: focus on quality assurance/quality control, procedures for developing biogenic emissions estimates, guidance to develop future year emission estimates and vehicle miles travelled (VMT), improved mobile source models reflecting current research, training workshops for applying mobile source models, electronic submittal of inventories to allow for consistency checking, and the availability of a direct State assistance system. Considerable fundamental research/testing is being applied to improve accuracy of stationary source emission factors, mobile emission procedures, uninventoried sources, and other emission inventory methodology needs (e.g., continuous emissions monitoring for VOCs, Fourier transform infrared (FTIR) integrated measurements for fugitive releases including speciation, and real-time episodic data on emissions).

As noted in Section 3.6, major objectives of the new enhanced ozone monitoring program include verification of inventories and the tracking of inventory changes. This objective is a central concern shared by the NAS and the EPA. Emissions are difficult to estimate, and monitoring checks are needed to affirm the adequacy of estimation procedures, or uncover as yet unknown systematic errors in the inventory process. Accordingly, strong support for an expansion of the enhanced monitoring program should be fostered to develop a responsive monitoring system which complements the inventory process.

3. Establishing a Emissions Inventory Branch (EIB) and a Joint Emissions Inventory Oversight Group (JEIOG).

The EIB resides in the OAQPS and consolidates all OAQPS inventory activities into a single program function. Initially, the EIB has taken steps to enhance the consistency and quality control aspects of the inventory process. Recently, several workshops have been conducted and guidance developed to assist States in producing improved inventories.

The JEIOG is a multi-discipline effort structured to develop consistency among the EPA's various research and operation arms and incorporate the latest research and technical efforts in the inventory process. JEIOG members have identified a number of pressing inventory-related needs and have attempted to prioritize these in terms of their widespread applicability and impact on program needs. Work has begun to address several of the highest priority issues. These include uncertainty assessment, estimation techniques for emissions from natural sources, emission factor development, field validation of area source methodologies, resolution of the difference between emissions inventories and ambient measurements, methods for improving estimates of automotive activity levels, and other tasks.

Past ozone precursor control approaches have relied on the best science available. More recent developments on the role of biogenic emissions and the understatement of anthropogenic emissions in control strategy analyses cast uncertainty on past control strategy approaches. The current approach to developing strategies includes (1) enhancement of the ambient data bases used to design and check the progress of strategies, (2) a focus on improving emission inventories, and (3) regional and local application of the most comprehensive and defensible air quality models. While the above efforts constitute an important step toward improvement, other important needs have yet to be addressed. A need exists for research-grade emission inventory data bases for at least two (south and northeast) nonattainment areas for use in evaluating existing and future ozone models and emission inventory protocols. Reliable emission inventory and accompanying monitoring data are needed not only for the early morning hours (6-9 AM), but also for mid-day hours when the highly uncertain and perhaps critically important biogenic and auto evaporative VOC emissions occur at peak levels.

## 3.5 Biogenic VOC Emissions

### 3.5.1 NAS finding

The combination of biogenic VOCs with anthropogenic $NO_x$ can have a significant effect on photochemical ozone formation in urban and rural regions of the United States.

### 3.5.2 NAS recommendation

In the future, emissions of biogenic VOCs must be more adequately assessed to provide a baseline from which the effectiveness of ozone control strategies can be estimated before such strategies are applied for a specific urban core or larger regions. Ambient measurements of concentrations and emission rates are needed to improve the accuracy of biogenic VOC inventories.

### 3.5.3 EPA comment

Throughout the late 1970s and mid-1980s there was a consensus (Altshuller, 1983) in the scientific community that, while natural emissions may be quite large, they did not play a significant role in ozone formation and precursor control assessments. This consensus can be attributed to 1) a focus on modeling large urban areas where anthropogenic VOCs dominate[1], 2) a failure to properly account for rural ozone formation and transport of ozone and precursors, and 3) the large uncertainties in biogenic emission rates[2]. Consequently, biogenic emissions were not included in air quality modeling analyses.

Chameides et al. (1988) illustrated the need for considering biogenic emissions when assessing the effectiveness of emission reduction strategies. That work and other similar follow up studies (Scheffe et al., 1990) showed that for Atlanta, Georgia, VOC control requirements increase by as much as 50% when model simulations incorporate biogenics, relative to simulations without biogenics. The primary reason for this finding was that after anthropogenic VOCs were reduced substantially in the simulations, ozone became much more sensitive to further changes in VOCs. Thus, adding biogenics at this point produced significant differences in predicted ozone. Recognizing that biogenic emissions have important implications on ozone precursor

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[1] Although biogenics probably represent over half of all (anthropogenic and natural) VOC emissions on a continental basis, it is important to point out that in most central urban cores, anthropogenic VOC emissions constitute the larger fraction.

[2] Uncertainty ranges of +/- a factor of three typically are associated with biogenic emission estimates.

control programs and must be considered in ozone modeling analyses, the EPA expanded both the 5-City UAM (Morris et al., 1990; EPA, 1990a) and Regional Ozone Modeling for NorthEast Transport (ROMNET) (EPA, 1991h) studies to verify with grid modeling and test the geographic robustness of the Chameides et al. findings. As a result of those efforts, the EPA's gridded photochemical modeling policy (EPA, 1991i) now requires incorporation of biogenic emissions.

Model simulations based on the EPA's 5-City UAM study also suggested that NOx control is more effective in reducing ozone than VOC control for Atlanta (Scheffe et al., 1990), an effect linked to consideration of biogenics. [The NOx implications from biogenics are addressed in Section 3.8.] Initially, the EPA reacted cautiously to these findings by acknowledging that biogenics may indeed be important in areas, such as Atlanta, characterized by a large biogenics component and predominantly residential demographics. Following the Atlanta studies, results from the EPA's ROMNET study suggested that the importance of biogenics extended beyond the southeast into much of the northeastern U.S. as well.

Based on these and other studies, the EPA agrees with NAS findings stating that biogenic emissions are a significant component of total VOC loading to the atmosphere. Biogenic emissions can influence both direction (i.e., VOC or NOx) and extent of required emissions controls and, therefore, are necessary inputs to regulatory model applications which assess various ozone mitigation strategies.

To address the large uncertainty attendant with biogenic emission estimates (a factor of at least +/- 3 typically is associated with biogenic emission estimates), the Biogenic Emissions Inventory System (BEIS) (Pierce and Waldruff, 1991) has been modified to incorporate latest model developments and improve mapping resolution of vegetation groups emitting biogenics. The BEIS is the EPA's recommended model to develop biogenic inputs for ozone air quality models, which are used to assess the effectiveness of emission control strategies.

The Southern Oxidant Study (SOS), a comprehensive air quality and modeling effort designed to determine, among other things, the relation between biogenic emissions and ozone formation is funded partly by the EPA. The SOS is motivated, in part, by the uncertainty and acknowledged importance of biogenic emissions. Use of ambient data collection and analysis techniques forms the major thrust in attempting to shed additional insight on the role of biogenics in ozone generation. Although the SOS contains a significant natural emissions component, the difficulties associated with characterizing biogenic emissions will require additional efforts to improve emissions measurement techniques for natural systems. The JEIOG is funding additional research work to update the national landuse/biomass data base, improve methodologies for making environmental corrections of emissions rates (i.e., biogenic emissions are functions of temperature and sunlight intensity), and reevaluating the existing biogenic emission factors.

## 3.6 Ambient Air Quality Measurements

### 3.6.1 NAS finding

Ambient air quality measurements now being performed are inadequate to elucidate the chemistry of atmospheric VOCs or to assess the contributions of different sources to individual concentrations of these compounds.

### 3.6.2 NAS recommendation

New measurement strategies that incorporate more accurate and precise measurements of the individual trace compounds involved in ozone chemistry should be developed to advance understanding of the formation of high concentrations of ozone in the United States and to verify estimates of VOC and $NO_x$ emissions.

### 3.6.3 EPA comment

Past ambient data bases have not provided enough information to fully characterize an area's ozone problem. As noted elsewhere in this report, air quality measurements are of value for several reasons: understanding ozone formation processes, providing feedback on the SIP process, verifying both emissions estimates and effectiveness of emission reduction programs, and providing support for model application efforts. The linkage with emissions is particularly noteworthy, as discussed in Sections 3.3 and 3.4, and worth restating here: Had an effective ambient data collection been in place, it may have been possible to (1) determine that anthropogenic emissions were understated, and (2) effect an attendant shift in control strategy emphasis.

Recent and ongoing studies like the Southern Oxidant Study (SOS) rely strongly on the use of ambient measurements to assist in the development of effective control strategies, and enhance our predictive modeling efforts. Given all the uncertainties in the modeling process (emissions, meteorology, chemistry, growth forecasting, etc.), ambient data provide basic reality checks on our predictive efforts. The EPA in partnership with State and local Air agencies is developing a national program to enhance ambient data bases. This enhanced ozone monitoring program should address several data deficient areas identified by the NAS. A brief review of the previous nationally-based ozone precursor monitoring program followed by discussion of the new enhanced ozone monitoring program provides insight into the motivation for expanding ambient data collection efforts.

Implementation of the previous Non-Methane Organic Compound (NMOC) network was partially motivated by Empirical Kinetic Modeling Approach (EKMA) data needs. The EKMA relies heavily on measured air quality data to drive model simulations. Partly as a consequence of the modeling requirement for monitoring data, the first nationally-based VOC (the more descriptive term "NMOC" is used rather than VOC) monitoring program was established.

The design of the NMOC monitoring networks which supported EKMA analyses (i.e., unspeciated ambient data collected from 6:00 A.M. - 9:00 A.M. in nonattainment central business districts) did not provide continuous year-to-year data at given locations. Thus, the NAS concludes (Attachment 1) that the NMOC data base did not provide (1) explanations for continued and frequent ozone exceedances beyond 1987, or (2) an adequate ambient data monitoring system to serve as a feedback mechanism to track progress towards attainment and make midcourse corrections as needed.

Following completion of the regulations and attendant guidance proposed in 1992 on the enhanced ozone monitoring program, a network of Photochemical Assessment Monitoring Stations (PAMS) will be phased in over several years. Such a program is mandated by Section 182(c)(1) of the CAA. The enhanced ozone monitoring program will require States to establish PAMS as part of their SIP ambient air monitoring networks in nonattainment areas classified serious, severe, or extreme. Each affected State air pollution control agency (or local delegated agency) would install an array of additional monitors to gather data on ozone, NOx, VOCs (speciated, including aldehydes) and meteorological parameters. Such stations would be positioned to sample upwind and downwind (rural/suburban fringe areas) and at central urban locations. Sampling frequency at certain sites would allow for the development of diurnal patterns in observed concentration profiles.

However, routine measurements of the sort envisioned for PAMS will not provide all of the data needed to completely characterize air quality. In particular, the PAMS data are not expected to provide the array of trace atmospheric measurements recommended by the NAS, or the intensive set of measurements needed to drive and evaluate gridded photochemical models. Furthermore, the PAMS locations are limited to highly polluted areas; yet we have seen that rural/regional effects are important factors in understanding ozone formation and control.

Data to be collected from the PAMS network will not meet all concerns raised by the NAS. Other programs directed at specific locations will be needed to address shortcomings associated with nationally-based, routine efforts. Implementation of well-designed, intensive field studies conducted at specific areas over a 2 - 6 week period of probable ozone conducive weather are needed to enhance the PAMS and other data bases. Such studies, when combined with sophisticated model applications, provide valuable insight on ozone cause-effect phenomena and reduce the uncertainty in conclusions regarding the effectiveness of emission control strategies. These field studies are expensive and take time to design, execute and produce results. Several are needed covering the non-compliance areas. Priority areas include the northeast corridor and the Texas-Louisiana coastal region (Houston, Beaumont, Port Arthur, Baton Rouge). Case examples and additional discussion on intensive studies are provided in the following section on air quality modeling.

## 3.7 Air Quality Models

### 3.7.1 NAS finding

Although three-dimensional or grid-based ozone air-quality models are currently the best available for representing the chemical and physical processes of ozone formation, the models contain important uncertainties about chemical mechanisms, wind-field modeling, and removal processes. Moreover, important uncertainties in input data, such as emissions inventory data, must be considered when using such models to project the effects of future emissions controls.

### 3.7.2 NAS recommendation

Air-quality models are essential in predicting the anticipated effects of proposed emissions controls on ambient ozone concentrations. Therefore, the effects of uncertainties on model predictions, such as uncertainties in the emissions inventory and in the chemistry incorporated in the models, must be elucidated as completely as possible. Predictions of the effects of future VOC and $NO_x$ controls should be accompanied by carefully designed studies of the sensitivity of model results to these uncertainties.

### 3.7.3 EPA comment

While advocating the use of gridded photochemical models as the principal planning tool for developing ozone precursor emission reduction strategies, the NAS report presents important caveats associated with model applications: (1) the model's description of physical and chemical processes is not perfect, (2) many current data bases which will be used to drive and evaluate model applications do not contain the desired level of spatial, temporal and compositional resolution, and (3) uncertainty in the model estimates is not treated explicitly in regulatory applications. This last caveat falls under the general subject of "The use of models in the regulatory process." In addressing these issues, it is important not to lose sight of the primary NAS conclusion that grid-based photochemical models are the best available tools for assessing ozone mitigating strategies.

**Model processes and components**: The EPA encourages a systematic program to incorporate improvements to the models reflecting new scientific findings and efficient computational methods as they become available. Two major modeling initiatives were undertaken by the EPA in the late 1980s and early 1990s to foster use of advanced gridded photochemical models in the SIP process: (a) development of the application capability to apply the Regional

Oxidant model (ROM) and (b) updating and documenting the Urban Airshed Model (UAM) to make it more accessible for use by State agencies. Recognizing that ozone often persists for several days and is transported over large distances, the Regional Ozone Modeling for Northeast Transport (ROMNET) project was initiated in 1987. In addition to providing valuable information for assessing region-wide emission control strategies, the ROMNET project also produced interfacing software for generating inputs to the UAM for future SIP applications. This ROM-UAM linkage should provide a consistent basis for supplying current and future year boundary conditions for UAM (boundary conditions are an especially difficult, but important, set of model inputs which must be specified in using the UAM). The EPA's Regional Oxidant Modeling program has grown to include a significant applications component to complement the research and development focus. Capability now exists to provide ROM-generated information for use in urban attainment demonstrations east of 99 W longitude. This covers almost all serious or more severely polluted areas outside of California.

Recognizing that gridded photochemical modeling is the preferred tool for understanding ozone problems and assessing effectiveness of precursor controls, several UAM initiatives were undertaken by the EPA in the late 1980s: the 5-City UAM study (EPA, 1990a), placing the upgraded UAM into the public domain, development of the UAM User's Guides (EPA, 1990b) and guidance for regulatory application (EPA, 1991i). The 5-City UAM study provided useful information on emerging policy issues such as alternative fuels, biogenic emissions, and the relative effectiveness of VOC and NOx controls. Perhaps more significantly, the 5-City UAM study served as a precursor for future UAM SIP applications as the project emphasized control strategy evaluations and included a technology transfer component to train participating States to operate the UAM.

In 1990 the EPA released an updated version of the UAM to the public domain, reflecting numerous advances in photochemistry and numerical solution techniques which emerged during the 1980s. An extensive multi-volume UAM User's Manual was prepared to facilitate operation of the UAM. Guidance on regulatory application of the UAM released in 1991 should foster national consistency among UAM applications. Several efforts are underway to improve pre and postprocessing UAM capabilities and train the States in applying the model.

The 1990 CAA requires the use of gridded models in many nonattainment areas, and over the last three years the EPA has positioned itself and the States to address this mandate with the aforementioned ROM and UAM efforts. The NAS reminds us, however, that current methods are not without flaws and that regulatory approaches should incorporate advances as they become operational. Accordingly, the continuation and enhancement of research and application efforts addressing the following areas are needed:

1. improving the ability of chemical mechanisms to characterize biogenic (and anthropogenic) processes and treat future, expected changes in the mix of atmospheric pollutants;

2. integrating day-specific emissions estimates, including direct emissions measurements, into emissions models which develop inputs to air quality models;

3. integration of prognostic meteorological models capable of characterizing complex flow phenomena into air quality modeling;

4. development of computationally efficient, bi-directional, variable grid systems offering high spatial resolution and broad geographical coverage;

5. development of plume-in-grid modeling techniques to more rigorously treat major point source plumes in regional and urban ozone models; and

6. evaluation of models using special, research-grade ambient monitoring and emission inventory data bases.

Applications of more advanced modeling methods such as variable grid approaches and prognostic meteorological models which have the capability of characterizing complex flow phenomena are encouraged. The Lake Michigan Ozone Study (LMOS), funded partially by the EPA, is applying such techniques. Although significant advances have occurred over the last decade, further improvements in the basic chemical mechanism, emissions and meteorological components and solution techniques must be made in gridded photochemical systems. A strengthened commitment to research in these areas is required. Balancing the desire to use the best tools while fostering national consistency will continue to pose challenges to regulatory programs.

**Model Data Bases and Regulatory Application:** Concerns about the adequacy of available data bases, as well as the topographical and meteorological complexity of certain areas, have motivated several intensive field studies to support ongoing modeling efforts; the South Coast Air Quality Study, San Joaquin Valley Study, Lake Michigan Ozone Study, Baton Rouge Study, and the Southern Oxidant Study (SOS) are examples. A similar effort is being initiated in the Texas and Louisiana Gulf Coast. Data base adequacy concerns remain, and additional efforts clearly are desirable and to be encouraged in other areas. However, practical constraints of time and resources preclude requiring multi-million dollar field efforts in all cases. Avenues of funding should be explored for this support. Consideration should be given to increased public sector appropriations, and the establishment of partnerships among industry, academia and government research and regulatory components. The Baton Rouge application and the SOS program are excellent examples of a cooperative venture among government, industry, and academia. Most pressing among such new programs needed, is one addressing the ozone problem in the northeast.

The 5-city UAM study identified difficulties associated with using routinely available data bases; however, the study also suggested that in some areas routine data bases could support model applications. The NAS recommendation that minimum aerometric data bases be established for model applications was considered when national guidance for applying the UAM (EPA, 1991i) was developed. However, the disparate area-specific requirements for data bases preclude setting of generalized minimum data base criteria. Furthermore, the CAA provisions requiring SIP submittals with model attainment demonstrations for serious and above as well as for certain moderate ozone nonattainment areas are due by November, 1994. To meet that deadline, modeling should be near completion in the late 1993 timeframe. This timing does not allow for planning and implementation of specific field studies to support modeling. However, most urban scale model applications in this immediate round of SIP demonstrations will benefit from supporting ROM applications to generate boundary value concentrations, as discussed above. For future applications (i.e., post 1994), the PAMS program will enhance routine aerometric data bases and assist in evaluating model performance and development of model inputs. However, enhancements to the twice daily, routinely collected National Weather Service/Federal Aviation Association (NWS/FAA) vertical profiles of wind speed and direction and temperature are recommended for those areas performing grid modeling. Due to the spatial and temporal sparseness of the NWS/FAA data, the urban-scale three-dimensional gridded model applications often contain significant uncertainties in their meteorological fields.

This discussion on supporting data bases underlies a fundamental concern about uncertainty in model predictions. As the richness of support data increases, uncertainty in both model inputs and subsequent predictions decreases. The EPA's guidance on regulatory application of the UAM incorporates several NAS recommendations including: (1) the use of multiple meteorological episodes to test emission strategies, (2) model diagnostic and performance evaluations, (3) expansion of domains and (4) execution of multi-day, as opposed to single day, simulation periods. However, the guidance does not prescribe criteria for establishing minimum data bases, nor require a formal report on uncertainty. Model simulations conducted to define the more sensitive parameters are useful starting points for quantifying uncertainty and designing complementary field efforts. These data issues are best addressed on a case by case basis, because metropolitan areas exhibit varying climatological, topographical and demographic features leading to different data priorities.

Concerns about the richness of existing model support data are motivation for implementing data enhancement programs. However, such concerns should not be the basis for circumventing or delaying the modeling analysis required to determine ozone precursor control requirements. In fact, extensive model simulations should help in planning the type, number and siting of additional monitors for enhanced monitoring networks. While sparse data bases hinder the use of the air quality models in a highly deterministic manner, their use for directional guidance on precursor control programs is certainly indicated. Precise determination of specific control requirements from air quality models is probably beyond the reach of the models at present, given the lean and error-prone data bases that are often used. However, models are critical for structuring and guiding control strategy development when used with flexibility and reality checks on the interpretation of modeling results.

Although the models and supporting data bases are not capable of yielding high precision control strategy requirements, they remain the most objective tools available for driving control strategy decisions. Models provide the best planning approach for air quality management at the present time. Consequently, the EPA requires use of models in the attainment demonstration process. Nevertheless, the long-term goal should be to enhance data bases and the modeling science to improve our basis for control measure decisions.

In addition to data base considerations underlying model exercises, the gridded models provide analytical capabilities that have not been completely tapped. Model analyses can be expanded to explore multifaceted questions coupling air quality, population exposure, and economic considerations. Intermediate years between the current baseline and future attainment years can be modeled to gain a sense of progress and incorporate "relative speed toward improvement" as a factor in developing emission control strategies. Air quality metrics of interest can be expanded to include averaging times greater than 1 hour, net domain and selected sub-domain spatial effects, and population exposure. Also, other pollutants and processes such as formaldehyde, peroxy acetyl nitrate (PAN), nitric acid, and nitrate deposition can be incorporated in model analyses. This expanded use of gridded models potentially can produce the information needed to explore a wide spectrum of existing and emerging issues. The vehicle for developing such information is underway, as we progress through the initial stages of applying complex models on a routine basis.

### 3.8 VOC versus NOx Control

#### 3.8.1 NAS finding

State-of-the-art air-quality models and improved knowledge of the ambient concentrations of VOCs and $NO_x$ indicate that $NO_x$ control is necessary for effective reduction of ozone in many areas of the United States.

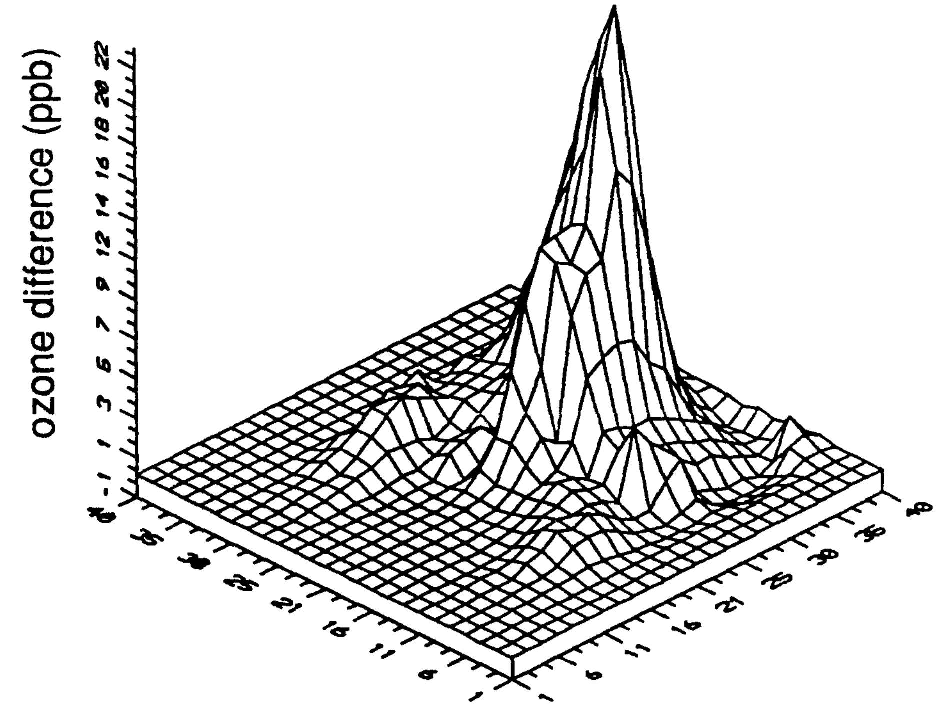
#### 3.8.2 NAS recommendation

To substantially reduce ozone concentrations in many urban, suburban, and rural areas of the United States, the control of $NO_x$ emissions will probably be necessary in addition to, or instead of, the control of VOCs.

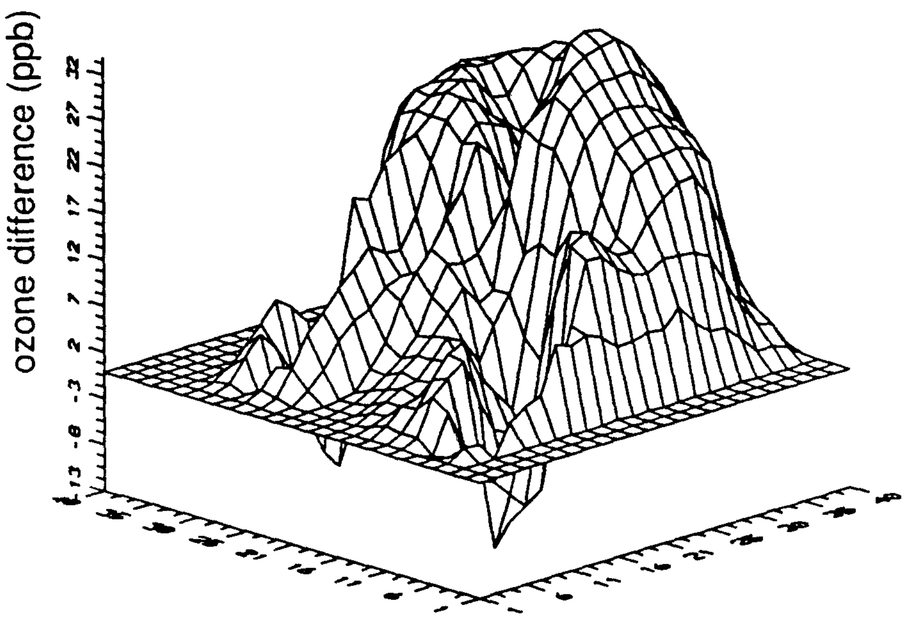
#### 3.8.3 EPA comment

The EPA agrees that NOx controls in addition to or instead of VOCs are likely to reduce ozone in many areas. However, in certain cases NOx controls might not be effective in reducing ozone. Possible exceptions are not necessarily limited to New York and Los Angeles urban cores. Application of gridded photochemical models on a case by case basis is required to determine the efficacy of NOx controls, because the ozone response to precursor reductions is area specific. The following Urban Airshed Model (UAM) and Regional Oxidant Model (ROM) modeling studies support the general assertion that NOx controls (1) may be beneficial in many places (e.g., Atlanta and several parts of the northeastern U.S.) and (2) might not be effective in reducing ozone in other areas (e.g., Dallas-Fort Worth and New York). [The following UAM applications for Atlanta and Dallas-Fort Worth are based on the 5-City UAM study (EPA, 1990a) and are provided to illustrate that ozone response to controls of VOCs or NOx is area-specific. The five-city study investigated the feasibility of low-cost UAM applications, and modeling results are to be viewed for illustration only. A more complete analysis examining several sets of meteorological conditions and more closely scrutinized data bases are required for SIPs or a demonstration under Section 182(f).]

Figures 3-1 through 3-4 illustrate somewhat contrasting ozone responses from VOC and NOx controls for specific days in Atlanta and Dallas-Fort Worth. Figures 3-1 and 3-2 depict relative benefits of VOC and NOx control, respectively, to the base case (i.e., zero control) throughout the Atlanta domain. VOC controls show limited benefits restricted to the center of the Atlanta domain (Fig. 3-1); whereas NOx controls show more widespread and more pronounced reductions in peak ozone predictions throughout most of the domain (Fig. 3-2). The Dallas-Fort Worth results show greater peak ozone reductions for VOC controls (Fig. 3-3), and several areas which exhibit ozone

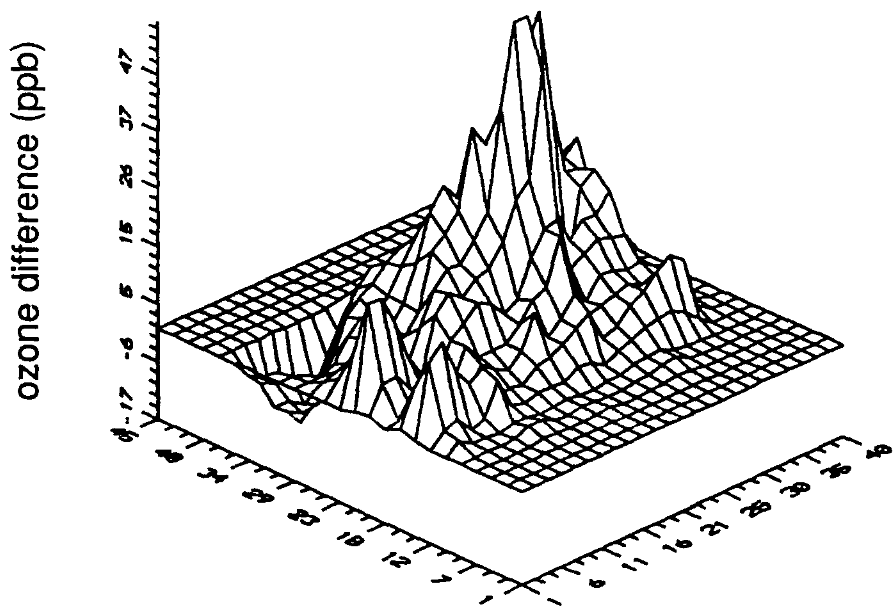



Atlanta domain: base case - 60% VOC control (6/4/84)

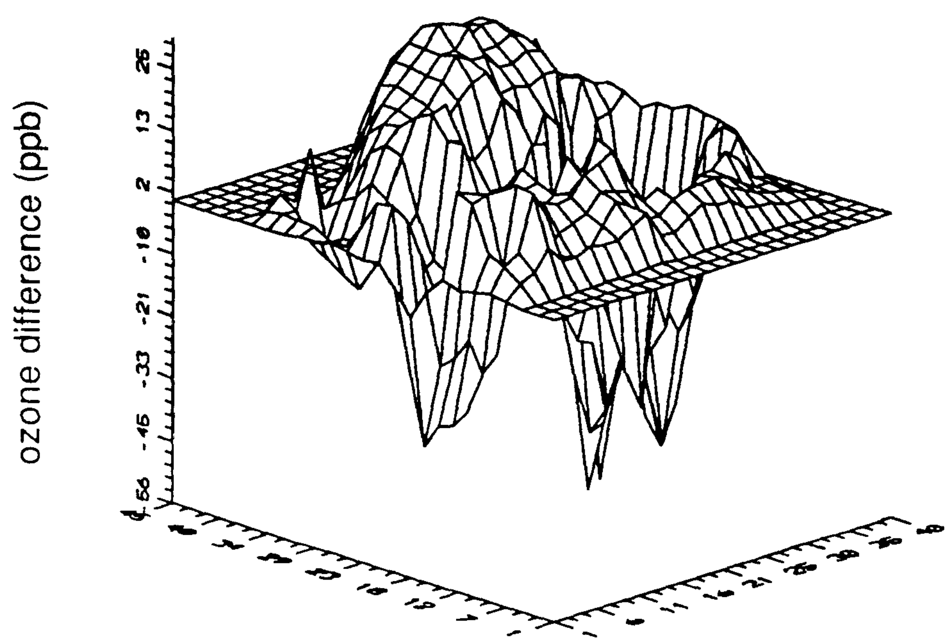



Atlanta domain: base case minus 60% NOx control

**Figures 3-1 (top) and 3-2.** Peak ozone difference plots for Atlanta showing impacts from 60% VOC and NOx control. Positive and negative values reflect ozone reductions and increases, respectively, from the base case. The modeling domain consists of a 40 by 40 array of 4 km grid cells.




Dallas-Fort Worth domain: 1995 base case - 60% ROG control




Dallas-Fort Worth domain: 1995 base case - 60% NOx control

**Figures 3-3 (top) and 3-4.** Peak ozone difference plots Dallas-Fort Worth showing impacts from 60% VOC and NOx control. Plus and minus values reflect ozone reductions and increases, respectively, from the base case. The modeling domain consists of a 40 by 45 array of 5 km grid cells.

increases due to NOx controls (Fig. 3-4).

The ROMNET study (EPA, 1991h) extended the limited number of model simulations which considered biogenics and explicitly compared effects of strategies emphasizing NOx controls with those emphasizing reductions in VOC. Some of the important relevant ROMNET findings include:

1. NOx controls show greater reductions in peak-ozone throughout most of the ROMNET domain, relative to VOC controls,

2. NOx controls increase peak ozone in certain areas of the New York City CMSA, and

3. VOC controls are effective in reducing New York City CMSA peak ozone,

4. the benefits of NOx controls increase as longer ozone averaging times (e.g., 8 hours) are used as the analysis metric, and

5. conclusions regarding relative benefits of NOx or VOC controls show day-to-day variations for the Baltimore - Washington D.C. area.

The ROMNET study suggests that NOx controls also are beneficial in areas outside the southeast U.S. The results showed rather clear benefits of NOx controls in rural/semi-rural northeast regions. Furthermore, the benefits may extend beyond the rural regions since net ozone flowing into cities (i.e., transported ozone) is reduced. In light of the NAS assertion that anthropogenic VOC emissions have been understated, the ROMNET results could be interpreted as over-optimistic with respect to the beneficial impacts of VOC controls.

The evidence from these and other studies suggests that analysis of NOx benefits is best conducted through photochemical grid modeling, a view supported by the NAS. Less rigorous approaches are not advised. The EPA investigated the feasibility and acceptability of applying relatively inexpensive screening techniques (Langstaff and Scheffe, 1991) to the needs of the NOx/VOC control issue. Those techniques appeared to generate more questions than they answered and therefore were not adopted. The prevailing opinion of a spectrum of government, academic and industrial groups is that photochemical grid modeling is needed to fully address the NOx issue.

These ROM studies, while highly significant, do not provide complete evidence on the relative efficacies of the VOC control and NOx control approaches to attainment. First, the ROMNET study was not designed to address this latter objective. It was intended instead to determine how best to use currently available VOC control and NOx control technologies for ozone reduction. Thus, relative impacts of VOC and NOx controls were derived for only few levels of control and extrapolation of results to other levels is known not to be valid. Clearly, additional ROM runs are needed for different levels of VOC and NOx controls before the relative efficacies of the VOC and NOx control approaches can be assured reliably. Second, questions are raised because ROM's spatial resolution is too coarse for adequate simulations of ozone on the urban scale. The NOx emission sources are spread across too large a volume in the regional model to properly treat the urban scale atmospheric chemistry. In general, the regional model will cause lower VOC/NOx ratios in the grid cells containing urban areas by introducing NOx emissions in areas that do not, in reality, contain emission sources. This effect, as well as the understated-VOC-emissions problem, biases the ROM results in favor of VOC control over an exaggerated spatial extent. On the other hand, for those areas in the urban complex directly affected by NOx plumes, the regional model dilutes the NOx emissions through too large a volume, thereby raising the ratio compared to what is really occurring in the plume's vicinity. Finally, the ROM studies have focused on the northeast U.S. Comparable studies in other Regions are also needed before a national picture can emerge regarding the relative effectiveness of VOC and NOx controls. Of all these issues, emission inventory accuracy is probably the most important one, and it is imperative that the issue be resolved <u>before</u> it can be determined whether NOx control is indeed as beneficial as the existing evidence suggests and NAS supports.

The statutory requirement to conduct photochemical grid modeling is accomplished through the SIP process. All ozone nonattainment areas classified as "serious" or above and interstate moderate areas are required to submit an attainment demonstration based on gridded photochemical modeling as part of the SIP submittal due in November, 1994.

In addition, the grid-based modeling results are amenable to a wide spectrum of time, spatial, demographic, and economic analyses. Thus, assessments of various control strategies can include consideration of population exposure impacts. Consideration of population exposure effects arising from NOx control measures may be critical because NOx controls, unless very large, can increase ozone in certain locations, and decrease ozone in other locations within a broad area. Further, the relative impacts on population exposure arising from VOC or NOx controls may be area specific, rather than exhibiting any general trend favoring a unilateral precursor control approach.

The important conclusion from this analysis is that, as pointed out by NAS and agreed by EPA, the latest evidence suggests that the ozone precursor control effort should focus on

NOx controls in many areas. The development and implementation of control programs should not be hindered by a bias favoring one control direction over another. This is extremely significant because it raises questions regarding the effectiveness of the VOC and NOx control programs mandated by the current CAA. Because of these implications and the fact that the evidence, as explained above, has limitations, it is imperative that more responsive modeling studies of highly polluted areas addressing the specific issue of relative effectiveness of VOC and NOx controls receive immediate and highest priority.

## 3.9 Alternative Fuels for Motor Vehicles

### 3.9.1 NAS finding

The use of alternative fuels has the potential to improve air quality, especially in urban areas. However, the extent of the improvement that might result is uncertain and will vary depending on the location and on the fuels used. Alternative fuel use, alone, will not solve ozone problems nationwide. Moreover, it will not necessarily alleviate the most critical problem associated with motor vehicle emissions—increased emissions as in-use vehicles age.

### 3.9.2 NAS recommendation

Because there is uncertainty about the degree to which alternative fuels would reduce ozone, requiring the widespread use of any specific fuel would be premature. An exception may be electric vehicles, which can lead to substantial reductions in all ozone precursor emissions. Coordinated emissions measurement and modeling studies should be used to determine which fuels will work best to control formation of ozone.

### 3.9.3 EPA comment

Motor vehicle emissions constitute roughly 35% of all man-made VOC and NOx emissions, and 65% of total CO emissions. Clearly, efforts towards reducing reactive VOC and CO[3] emissions from this major group of emission sources should yield air quality benefits. The term "alternative fuels" is interpreted broadly in this section to include, among others, alcohols and alcohol/gasoline blends (e.g., methanol and ethanol), reformulated gasoline, natural gas, liquified petroleum gas, hydrogen or electricity. Several documents describing the expected air quality benefits from certain alternative fuels are available (EPA, 1988; EPA, 1989; EPA, 1990 c,d,e).

Alternative fuel programs represent one facet of an array of CAAA programs designed to reduce ozone and air toxics pollution. In particular, the CAAA require the introduction of clean fuel vehicles in (1) centrally fueled fleets in over 20 areas and (2) a pilot program for California where these vehicles must specifically be designed to meet stricter tailpipe emission standards regardless of what clean fuel is used. Also, the CAAA require introduction of reformulated gasoline. A subset of nine of the worst ozone nonattainment areas are required to have reformulated gasoline programs in 1995. Reformulated gasoline

[3]Carbon monoxide (CO) plays an important role in ozone formation and reductions of CO generally lead to reductions in ozone.

use would be required in all gasoline vehicles in these areas. The reformulated fuel program mandates a 15% VOC and toxics reduction by 1995 and at least a 20% reduction in 2000, relative to baseline gasoline use (CAAA, Section 219).

The following assessment clarifies the benefits to be expected from use of alternative fuels in highly polluted areas. The assessment is based on current evidence on the role of the VOC/NOx ratio factor, relative importance of auto emissions in current and future atmospheres, and on effectiveness of current or targeted emission control technologies.

Most alternative fuel programs currently are expected to result in reduced amounts and/or reactivities of VOC emissions. Fuel programs mandated by the CAA do not require NOx reductions although, based on current knowledge, NOx reductions may be possible. The VOC reductions from the CAAA alternative fuels programs are expected to produce ozone benefits in urban areas with relatively low VOC/NOx ratios and lesser benefits in rural areas and cities with high VOC/NOx ratios. Benefits in future years are not easy to predict because of uncertainties in growth of vehicle miles travelled which may vary widely among cities. Ozone reductions associated with auto vehicle-based emission controls will stabilize once new standards are fully phased in. Reductions associated with fuel modification will diminish as the older technology cars that are most responsive to these modifications leave the fleet. The beneficial effect of VOC emission reductions on ozone air quality should increase as the VOC/NOx ratios diminish due to implementation of future auto emission standards and other regulations that are in place.

Of the alternative fuels contemplated for future use, the reformulated gasoline is the only one for which widespread introduction is required. VOC reductions are expected to reduce ozone in the nine areas where reformulated fuels are required. Auto/Oil Air Quality Improvement Research Program (AQIRP) data clearly support the potential of gasoline reformulation to abate ozone. Since the CAAA require only that NOx emissions with reformulated gasolines be no greater than that with conventional gasolines, less ozone benefit would be expected in areas where ozone reduction requires reduced NOx emission. However, recent data suggests there may be NOx side benefits from changes in gasoline composition (such as reducing fuel sulfur levels) to achieve VOC reductions. Also, the EPA has general authority for establishing NOx reduction requirements. Most other alternative fuel programs (e.g., fleet programs, California Clean Car Pilot, etc.) are, at least initially, relatively small. Although these programs merely allow for compliance via alternative fuels rather than specifically requiring them, they may add an economic advantage to alternative fuels. The intrinsic cleanliness of electric, compressed natural gas, and alcohol fuels (with respect to evaporative emissions) could provide greater benefits than standard gasoline if emission control devices fail.

In considering the potential for ozone abatement with alternative fuels, it is important to recognize that today's literature simply provides a "snapshot in time". The AQIRP reformulated gasoline activities have focused on VOC, toxics, and CO reduction. The data frequently show NOx reductions as well when certain fuel parameters are changed as they will be with gasoline reformulations. Thus, it is recognized that there exist possibilities with alternative fuels for reductions of both VOC and NOx that do not exist with gasoline. For example, the relatively high octane characteristics of several alternative fuels provide greater possibilities for manipulation of spark timing to manage NOx emissions; many of the alternative fuels provide the possibility for leaner engine combustion and a new regime of associated catalyst technologies; alcohol fuels typically have lower peak combustion temperatures than gasolines, favoring lower NOx emissions; and many of the alternative fuels have naturally lower sulfur levels providing for improved long term catalyst performance (and lower NOx). Because the alternative vehicle-fuel technologies may have different emission control approaches, their durabilities with mileage accumulation in consumer fleets may be different. NOx emissions can be reduced by alternative modal manipulation of engine air/fuel ratio, spark timing, valve timing, etc., and change in fuel composition. Also, stratified charge engines, which are more feasible with alcohol fuels than with gasoline, can have significant lower NOx. Some work with CNG and alcohol fueled vehicles already show newly developed engines with low NOx compared to conventional gasoline or diesel engines. These, clearly, are areas for focus of future alternative fuels research.

In summary, alternative fuels can be part of an ensemble of contributions from several programs that are needed to make significant progress in abating ozone pollution.

## 3.10 A Research Program on Tropospheric Ozone

### 3.10.1 NAS finding

Progress toward reducing ozone concentrations in the United States has been severely hampered by the lack of a coordinated national research program directed at elucidating the chemical, physical, and meteorological processes that control ozone formation and concentrations over North America.

### 3.10.2 NAS recommendation

A coherent and focused national program should be established for the study of tropospheric ozone and related aspects of air quality in North America. This program should include coordinated field measurements, laboratory studies, and numerical modeling that will lead to a better predictive capability. In particular, the program should elucidate the response of ambient ozone concentrations to possible regulatory actions or to natural changes in atmospheric composition or climate. To avoid conflict between the long-term planning essential for scientific research and the immediacy of requirements imposed on regulatory agencies, the research program should be managed independently from the EPA office that develops regulations under the Clean Air Act and from other government offices that develop regulations. The research program must have a long-term commitment to fund research on tropospheric ozone. The direction and goals of this fundamental research program should not be subjected to short-term perturbations or other influences arising from ongoing debates over policy strategies and regulatory issues. The program should also be broadly based to draw on the best atmospheric scientists available in the nation's academic, government, industrial, and contract research laboratories. Further, the national program should foster international exchange and scientific evaluations of global tropospheric ozone and its importance in atmospheric chemistry and climate change. The recommended tropospheric ozone research program should be carefully coordinated with the Global Tropospheric Chemistry Program currently funded and coordinated by the National Science Foundation (NSF) and with corresponding global change programs in the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the Department of Energy (DOE), and other agencies.

### 3.10.3 EPA comment

The NAS finding that a coordinated national research program is crucially needed was fully endorsed by the Agency and a commitment was made to commence implementation immediately. The EPA has begun a serious public/private sector research coordination effort for base programs; and has completed a joint effort to identify and plan needed additional tropospheric ozone research. EPA, in conjunction with the National Oceanic and Atmospheric Administration (NOAA) and the Electric Power Research Institute (EPRI), has convened an executive level Research Cooperators Group representing 45 major organizations. This group of executives has met twice in the past year to explore research needs, priorities, and opportunities for cooperation, and will continue to do so.

During the last half of 1992, the EPA convened a working group of 140 senior scientists representing a cross-section of disciplines and public and private organizations to design a national research initiative. They produced the "Coordinated North American Research Strategy for Tropospheric Ozone." In it is a strategic framework for the 43 research questions and 139 corresponding research projects which must be undertaken to produce the key scientific information needed to effectively address the ozone problem. The strategy offers alternative options for conducting research on a range of priority issues that will cost from $600 million to $1 billion in new resources over the next 10 years. Clearly, no one organization can supply this level of funding. Cooperation from the participating public and private organizations is key to the success of the research strategy.

Many organizations have worked to establish highest priorities for the research program. The next step is to secure funding partnerships, through a combination of government and private funding, to begin as much of the priority research as possible. EPA has asked that the NAS/NRC extend the function of its 185B Committee on Tropospheric Ozone Formation and Measurement to serve in an advisory and peer review capacity in setting up the coordinated national research program.

Progress towards achieving ozone attainment has been hampered by numerous factors which all relate to the evolutionary nature of atmospheric chemistry and a scarcity of observational data to check and correct our predictive methods and control implementation programs. The system in place within EPA for planning, conducting and evaluating research provides for soliciting and utilizing input from the users of the research products, but also from the scientific community at large. Periodic peer reviews of EPA research plans and work are conducted to provide sufficient input from outside scientists to ensure maximum credibility and scientific merit of EPA's ozone research program. The principal focus within EPA's Office of Research and Development is on advancing the science; relevance of the research effort to the regulatory programs also is considered.

The achievements of EPA's research program demonstrate an effective effort based on efficient use of limited research budgets. The EPA conducted or supported most of the basic chemistry and smog chamber studies leading to development of chemical mechanism models which are the framework for past and current ozone research and regulatory efforts. Large scale efforts to develop photochemical models (such as the UAM, ROM, and RADM) for ozone air quality were initiated and sustained by EPA. Similarly, EPA research lead to various ozone-related pollutant measurement and characterization techniques: chromatographic analysis of ambient organics, remote sensing methods for ozone and for ozone precursor emissions, and reactivity-characterization of organic pollutants. In addition, EPA research played a major role in measuring and characterizing emissions from natural, stationary and mobile sources. These and other accomplishments have been recognized by NAS, as reflected by the frequent use of EPA studies as a basis for the NAS findings.

Despite past scientific advances, gaps and uncertainties in knowledge and controversial issues hamper progress toward ozone control. Significant challenges remain due to the complexity of the physical and chemical processes underlying ozone formation and control, as well as the difficulty and cost involved in obtaining reliable and sufficient ambient monitoring and emissions data.

The EPA agrees in concept with all NAS recommendations for new, needed research; such recommendations repeatedly have been submitted by EPA researchers. Research needs clearly must be prioritized to effectively utilize available resources. EPA's current planning efforts include prioritizing tasks emerging from the list of NAS recommendations. Most NAS recommendations were motivated by the fact that the historically high emphasis on VOC controls, rather than NOx, was partly responsible for the current nonattainment status of several areas. The solution of this problem is not a simple redirection of the control effort everywhere. Current belief is that control of VOC will continue to be the most effective approach to ozone reduction in some areas, as NOx control or combined VOC+NOx controls would be in others. Key to development of successful ozone control strategies is the availability of reliable area-specific evidence on the relative efficacies of the VOC control and NOx control approaches. Accordingly, the development of such evidence for assessing effectiveness of ozone precursor control strategies is one of the most important objectives receiving highest priority in the Agency's ozone research effort.

Research programs designed to improve model and data base systems to develop optimum ozone strategies are under way within the EPA. Observations-Based Modeling (OBM) methods are being developed within the Southern Oxidants Study (SOS) -- a large field/modeling research program on the photochemical ozone problems in the Southeast. OBM methods can assess the relative benefits of VOC and NOx controls. Since OBMs are driven by ambient measurements, they complement the emissions driven grid models and potentially offer strong corroborative support for control strategy assessments. The OBM development program was initiated in 1991 and, assuming current rate of progress continues, is expected to provide usable methods and conclusive strategy-related evidence for the South by the late 1990's.

The EPA's base research program continues to develop and refine the Emission-Based Modeling (EBM) methods required by the Clean Air Act. Doubt exists regarding the credibility of predictions based on previous EBM applications. This credibility problem is due to uncertainties both in the models and in the requisite emission inventory (EI), air quality and meteorological inputs for operating EBM's. On-going EPA research programs and plans address these uncertainties, and improvements are expected to be achieved in the future. The EPA plans to conduct extensive field, laboratory, emission inventory and modeling studies that would result in EBMs and associated emission inventories that could be used with confidence to improve ozone strategies for southern cities as part of the SOS. Such efforts, contingent on expected levels of resources, are targeted for completion by 1998 and would be conducted in cooperation with other Federal and state government agencies and private research institutions. An analogous program for northern cities is planned for the early 2000's.

Emission inventory research, supported also by the utilities, auto and oil industries and other governmental agencies, is focused on improving estimates for three areas of greatest uncertainty: natural sources, mobile sources, and large numbers of area-wide sources. Estimation protocols will be developed for these sources with subsequent field validation of emission rates. The validated methods will be used to develop improved emissions inputs for the EBMs by the late 1990's. Establishment and operation of a first PAMS network in the mid-1990's is expected to provide aerometric data to partially support model evaluations and applications. Enhancement of the PAMS capability through other intensive programs to fully meet the modeling needs is not anticipated until several years later.

The EPA plans provide for sustaining a development program expected to produce the following new generation air quality concepts by the mid-1990's: (1) Models-3 system of catalogued EBMs, (2) OBMs, (3) chemical mechanisms for ozone with improved treatment of biogenic and anthropogenic VOC's, particularly in the low VOC, $NO_x$ concentration area, and (4) mechanistic concepts such as the Australian GRS mechanism. These projected accomplishments will be of partial use in the 1999 round of SIP revisions, and of full use in subsequent rounds.

The NAS also offered recommendations concerning the management of the EPA's research programs. The comments on interaction between the research and regulatory components of EPA and on utilization of outside scientific talent have been addressed above. The EPA agrees with NAS on the need to foster international exchange on ozone science, and has been pursuing such exchanges with Europe, Canada, Mexico, Japan, and Australia. Environmental Agreements with Germany, Mexico and Japan have facilitated several interactions. The EPA has been an active participant in interagency cooperative activities within the Federal Government, including membership in the Federal Coordinating Committee on Science, Engineering and Technology, ties to the NRC Committee on Atmospheric Chemistry, and interagency agreements with NOAA, NSF, DOE, NASA, and DOC/NIST. Clearly, a well managed research program, closely coordinated with other ozone research programs within and outside the Federal Government and the country, is a prerequisite to efficient use of the resources available to obtain, disseminate, and utilize the scientific information needed.

## SECTION 4 - OVERVIEW OF NOX CONTROL TECHNOLOGIES[1]

### 4.1 Introduction

Nearly all anthropogenic NOx emissions produced from stationary or mobile sources result from combustion of fossil fuels (Figure 4.1). Combustion-derived NOx is formed through two mechanisms, thermal NOx and fuel-bound NOx. Thermal NOx occurs at high flame temperatures through oxidation of molecular nitrogen in air and is the principal component from fuels which contain little or no nitrogen (e.g., natural gas or distillate oil). Fuel NOx occurs through oxidation of nitrogen species contained in the fuel and is the principal component from higher nitrogen fuels such as heavy oil and coal. Noncombustion generated NOx emissions accompany chemical manufacturing processes such as nitric acid and explosives production.

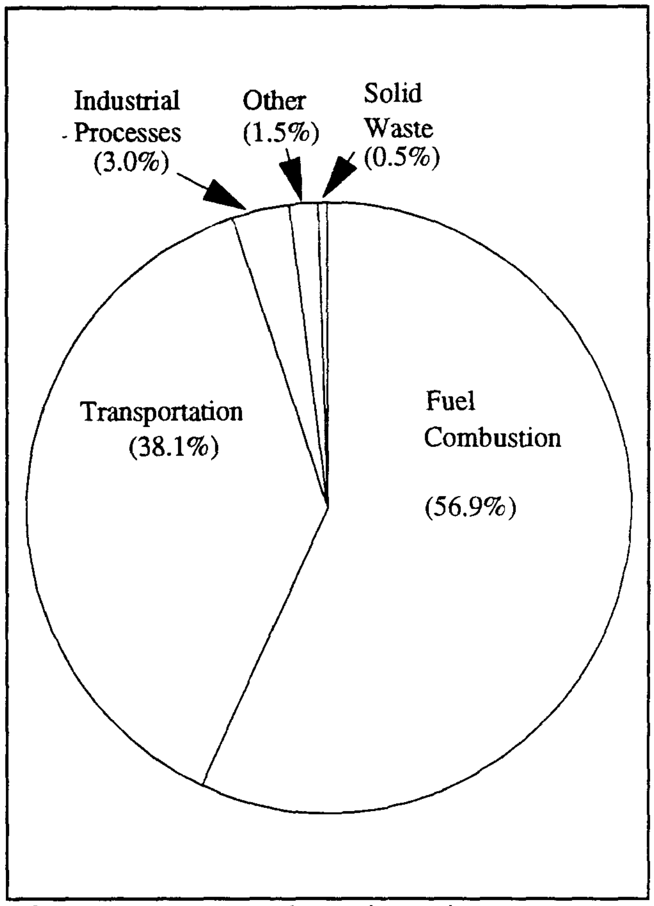



**Figure 4-1.** Distribution of 1990 NOx emissions by major source category. Transportation fraction also reflects fuel combustion. Data taken from EPA, 1991a.

Control techniques. NOx control methods (1) modify the combustion environment so that less thermal and/or fuel NOx is generated, and/or (2) chemically treat flue gas emissions to transform NOx to molecular nitrogen. [Fuel switching is also considered a NOx control technique.] NOx generation is enhanced when high flame temperatures and excessive oxygen are available. Accordingly, combustion-based control

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[1]This section summarizes basic information presented in Attachment 2 on available NOx control technologies for stationary sources, and briefly addresses mobile source control technologies. Since the completion of Attachment 2 in early 1992, several additional Available Control Technology (ACT) documents addressing various NOx control techniques have been published by EPA.

technologies include an array of modifications to operating conditions and burner design which achieve lower temperatures and richer fuel to oxygen ratios (i.e., more fuel relative to available oxygen). Examples of these modifications are low excess air (LEA), staged combustion {overfire air (OFA), biased burner firing (BBF), and burners out of service (BOOS)}, flue gas recirculation (FGR) and steam/water injection cooling. Low-NOx burners (LNB) are burners based on staged combustion principles, which are used in retrofitting operations and new facilities.

Repowering is alternative retrofit approach that involves a basic change in the type of combustion system and extensive modification of the power plant. Two examples of repowering technology are: conversion of the boiler portion of the system from a pulverized coal-fired burner to a fluidized bed combustor; or installation of an integrated gasification combined cycle system (IGCC) requiring the addition of a coal gasifier and a gas turbine power generator. The normal motivation for repowering is to expand generation capacity; however, some systems, especially IGCC, can provide highly effective NOx control.

Flue gas treatment techniques typically are based on the use of ammonia ($NH_3$) or other reductants like urea to reduce NOx to molecular nitrogen. The most common techniques are selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR). Various catalysts used in SCR facilitate ammonia-induced NOx reduction at different temperature ranges and operating conditions. Thus, SCR systems are considered the most effective NOx reduction methods available (Gao et al., 1991); however, they are much more expensive than combustion modificatiion systems. SNCR use is somewhat restricted by temperature dependence and reaction time requirements. Non-selective catalytic reductions (NSCR) do not use ammonia and reduce VOCs and carbon monoxide in addition to NOx. Table 4.1 summarizes basic features of control technologies for stationary sources.

Fuel switching can effect substantial NOx emission reductions by burning a cleaner fuel in the ozone season. For example, the use of natural gas instead of coal could also reduce annual and summertime emissions of sulfur dioxide ($SO_2$), carbon dioxide ($CO_2$), and particulate matter (PM-10). Further, emission reductions of these pollutants may be especially effective in the summer with respect to visibility and PM-10.

Industrial NOx controls often are applied in combination. Multiple modifications of operating conditions, as well as combined combustion modification and flue gas treatment are viable control approaches.

Conditions which favor NOx reduction might reduce operating efficiencies. For example, fossil fuels burn more completely when high temperatures and excessive oxygen prevail. The modest, less expensive techniques which modify operating conditions may be accompanied by attendant efficiency reductions and increased carbon monoxide emissions.

**Table 4.1 Summary of Basic Control Technologies for Reducing NOx from Stationary Sources.**

| Technology | Description |
|---|---|
| **Combustion based** | |
| Low Excess Air (LEA) | provide less than normal air to reduce oxidation through various equipment adjustments |
| Staged Combustion | initial combustion in fuel rich zones followed by leaner zones to complete combustion |
| - overfire air (OFA) | rich burn with additional air at top of normal combustion zone |
| - biased burner firing (BBF) | rich burn at low burner rows with additional air at upper rows |
| - burners out of service (BOOS) | use of "air only" burners with total fuel directed to fewer burners |
| Low-NOx burner (LNB) | installation of new burners incorporating staged design concepts |
| Flue gas recirculation (FGR) | recycling portion of flue gas back to primary combustion zone to lower peak flame temperature and thermal NOx |
| Steam/water injection cooling | induces direct cooling in combustion zone to reduce thermal NOx |

Table 4.1 continued

| | |
|---|---|
| Repowering | replacement of burner/boiler system with a different combustion system |
| - fluidized bed | lower combustion temperatures suppress thermal NOx and design may control fuel NOx |
| - IGCC | coal gasification system may remove fuel nitrogen and low NOx turbine combustor can suppress thermal NOx |
| Fuel Switching | temporary switch to cleaner burning fuel during summer ozone season |
| **Flue Gas Treatment** | |
| Selective Catalytic Reduction (SCR) | ammonia-induced reduction of NOx to $N_2$ aided by a catalyst |
| Nonselective catalytic reduction (NSCR) | reduction of NOx and VOCs by available carbon monoxide aided by a catalyst |
| Selective noncatalytic reduction (SNCR) | ammonia-induced reduction of NOx without a catalyst |

## 4.2 Source category specific control techniques

Principal combustion related stationary sources accounting for roughly 57% of all anthropogenic NOx emissions are utility and industrial boilers, petroleum refinery operations, and natural gas transmission engines (Figure 4-2).

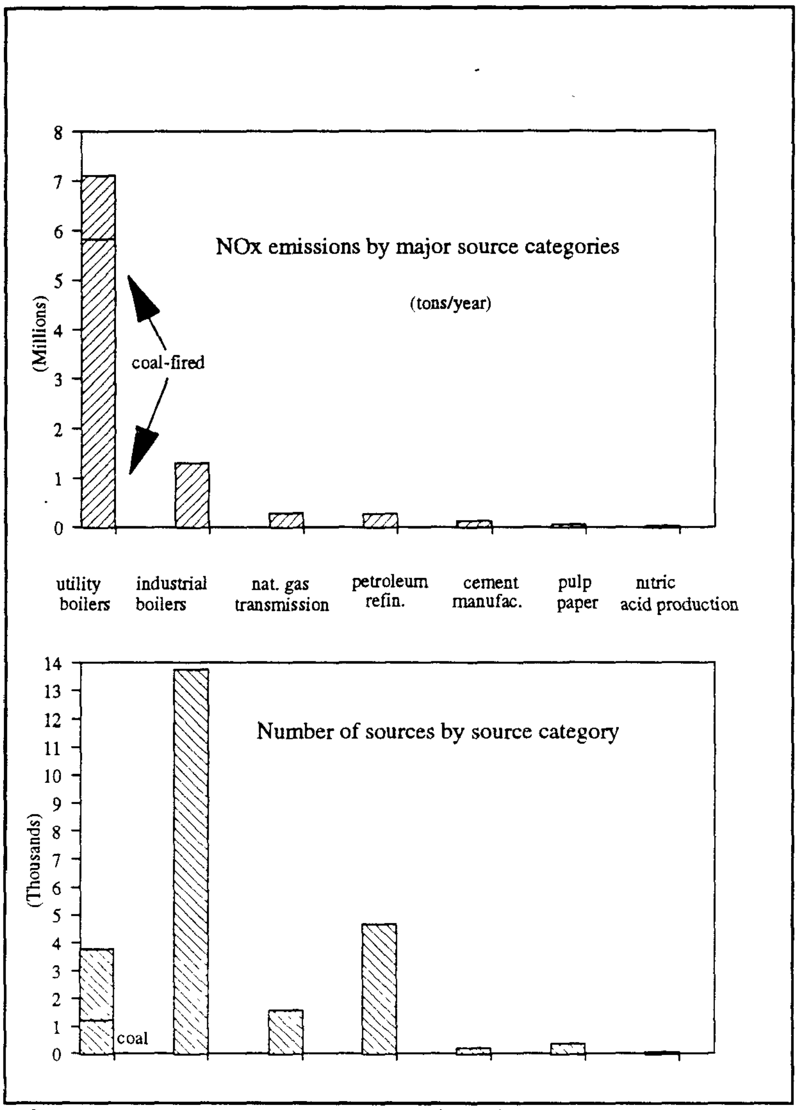


**Figure 4-2.** NOx emissions by source category (above) and source distribution (below) among major stationary sources greater that 100 tons/year. Data based on 1985 NAPAP annualized emissions estimates.

Transportation sources; including passenger cars, gasoline and diesel trucks, off-highway vehicles, and air, rail and marine vessels, account for roughly 38% of all anthropogenic NOx emissions (EPA, 1991a). As discussed above, two basic principles (combustion modification and flue gas treatment) underlie most NOx reduction approaches. Since most NOx emissions are combustion derived, NOx emissions from several of the major source categories discussed below are controlled by similar technologies.

### 4.2.1 Boilers

NOx control approaches for coal-, oil- and gas-fired utility boilers in the United States have focused on combustion modification techniques over the past two decades. Flue gas treatment techniques are more widely applied in Germany and Japan. Low excess air (LEA) is easy to implement in existing and new boilers and is widely applied throughout the U.S.

Coal-fired utility boilers. Generally, LEA is supplemented by other modifications resulting in total control efficiencies for coal-fired boilers ranging from 15 to 60% for various forms of Low NOx Burner Technology (LNBT). When low NOx burners incorporate overfire air, the potential NOx emission reduction can range from 40 to 60%. Several examples of LNB applications are listed in Attachment 2. Repowering technology is being demonstrated at a number of coal-fired utility power plants as part of the Department of Energy (DOE) Clean Coal Technology Program. The potential NOx reductions are projected to range from 50 to 95%, depending on repowering type and specific design. SCR applications are widespread in Japan and Germany, and recent applications have emerged in Austria. U.S. applications have been limited to a few demonstrations. SCR has been applied to more than 100 utility boilers in Japan, and a similar number of SCR units operate in Germany. NOx reductions from 70-90% typically are associated with those applications. Applications of SCR in the United States, which include gas turbines, other industrial combustion sources, and municipal waste combustors, are typically designed for 80 to 90% removal. Two SNCR applications on coal-fired boilers have also been running very successfully on a long term basis since 1989 and 1990.

Oil and gas-fired utility boilers. Similar combustion modification techniques are applied to oil- and gas-fired boilers, although staged combustion modifications (BOOS and BBF) and FGR are more prevalent, relative to coal-fired boilers. General NOx reductions of about 40% are reported for low-cost combustion modifications, and reductions to 60% are associated with LNB systems. Repowering technologies are potentially applicable to this class of equipment as well. Also, full-scale applications of SCR again are limited to Japan and Germany. Certain California based utilities plan to implement SCR systems by the mid-1990's. SCR NOx reduction efficiencies from 75-80% are reported for oil and gas-fired boilers. Limited SNCR applications report NOx control efficiencies of about 50 to 60 percent.

Other boilers. Control technologies applied to smaller scale, industrial, commercial and institutional boilers used in manufacturing processes and heat and electricity generation are similar in extent and efficiencies to those noted for large scale utilities. Fluidized bed combustors may be used for commercial/industrial heat and steam generation; however, these are normally new, not repowered, systems.

### 4.2.2 Stationary Internal combustion (IC) engines

Stationary IC engines which burn natural gas or oil are used in a number of utility, commercial, industrial and municipal operations. IC engines pump natural gas through extensive pipeline networks. Several types of engines and turbines exist, many that are 50 or more years old.

Reciprocal engines. Combustion-based control technologies include pre-ignition chamber combustion, ignition timing retardation, air/fuel mixture adjustment, and exhaust gas recirculation (EGR). NOx reductions range from 20 to 80% depending on engine type and applied control technology.

SCR applications in the U.S. have been limited largely to natural gas-fired engines in California with NOx reductions approaching 90%. SCR has been applied to gas- and oil-fired IC engines in Japan and Germany. Non-selective catalytic reduction (NSCR) has been demonstrated to achieve 90% NOx reductions (in addition to attendant VOC and CO reductions) on numerous tests performed on rich-burning units in California.

Turbines. Water/steam injection cooling frequently is applied to gas- and oil-fired turbines resulting in NOx reductions from 70 to 85 percent. Various combustion modification techniques are also applied to turbines. SCR is used on over 70 turbines in the U.S. to supplement reductions from steam/water injection or combustion modifications. NOx reductions as high as 90% have been reported.

### 4.2.3 Industrial processes involving combustion

Petroleum refining and chemical process heaters. Process heaters are used extensively in a range of refining processes (e.g., distillation, thermal cracking, and coking) and other chemical operations. Commonly applied combustion controls are based around automated LEA and low-NOx burner installations. LNB induced NOx reductions range from 40 - 70 percent. SCR is applicable to numerous processes and has been installed on more than 9 refinery process heaters in California, resulting in NOx reductions up to 90 percent. SNCR also has been installed on several refinery process heaters in California with NOx reductions ranging from 35 to 70 percent.

Metallurgical processes. Several processes including pelletizing, sintering, coke ovens, blast furnaces, heat treating and finishing produce NOx emissions in the iron and steel industry. Control applications for these operations appear to be limited to furnace overhaul and LEA, with NOx reductions ranging from 20 to 70 percent.

Cement manufacturing. Combustion modifications have been applied to certain cement kilns. Applications have not been widespread and NOx reductions of about 15 - 30% have been reported.

### 4.2.4 Noncombustion industrial processes.

Nitric acid plants are the largest noncombustion generated source of NOx emissions. Emissions can be controlled on new plants through advanced process design features such as high inlet pressure absorption columns or strong acid applications. Existing plants must rely on flue gas treatment techniques including extended absorption, SCR and NSCR. Extended absorption typically is used in retrofit applications by adding a second absorption tower in series with the primary tower. NOx reductions of about 95% have been reported. SCR is used extensively in Japan and Europe. Three U.S. plants apply SCR with a reported NOx reduction of 97 percent for one plant. European facilities exhibit NOx reductions from 44 to 87 percent.

Three of the four U.S. adipic acid plants apply extended absorption or thermal reduction to reduce NOx emissions from 81 to 86 percent. Information concerning existing controls on explosive manufacturing plants is limited.

### 4.2.5 Motor vehicles

The EPA's control programs for VOC from mobile sources are highly visible and well known: vehicle standards, fuel volatility, reformulated gasoline, etc. The EPA also is implementing a number of programs to reduce motor vehicle NOx emissions under Title II. Use of reformulated gasoline is required to result in no NOx increase; in practice, some reductions of NOx are expected. Also, Tier I standards for light duty vehicle NOx emissions have been implemented for 1994, and final rulemaking requiring enhanced inspection/maintenance programs for a number of areas include a NOx reduction requirement. The EPA implemented stricter NOx standards for heavy duty diesels effective with the 1991 model year; NOx standards for these engines are even lower for the 1998 model year. Finally, the EPA plans to propose standards to control NOx from new non-road diesels over 50 horsepower.

Motor vehicle NOx from gasoline engines is reduced catalytically by the 3-way catalyst system with feedback control to monitor and control the air:fuel mixture with an oxygen sensor. The feedback control results in stoichiometric operation which allows NOx to be reduced to nitrogen (this can occur only with stoichiometric or rich mixtures; excess air prevents catalytic NOx reduction) while VOCs and CO are oxidized to $H_2O$ and $CO_2$ (which can occur with stoichiometric or lean mixtures). Exhaust gas recirculation also reduces motor vehicle NOx but frequently is not necessary with the 3-way catalyst. NOx is controlled from diesel engines by modifications of the combustion chamber and injection timing.

Just as with gasoline, vehicle NOx levels with alternative fuels, such as 85-100% methanol, 85-100% ethanol, and Compressed Natural Gas (CNG), are dependent upon engine design and calibration as well as emission control design. Peak combustion flame temperature is lower with alcohol and CNG fuels than with gasoline which leads to lower NOx. However, other factors such as engine calibration (e.g., very lean air:fuel ratio, advanced ignition timing, high compression ratio) with these fuels also affects NOx. Vehicles or engines using alternative fuels would have to meet the same NOx standards as those using gasoline (or diesel) fuel. While most data suggest little overall change in NOx emissions with alcohol fuels and a potential for increase with CNG, this work generally has focused on minor adaptations of engines designed for gasoline, with no priority for NOx control. Recent work on more fundamentally optimized concepts shows vehicles can be designed for low NOx with alcohols or CNG. Also, it is important that available data suggests heavy-duty engines with alternative fuels could have lower NOx than heavy-duty diesel engines.

Transformation to clean fuels such as electrified vehicles produce zero vehicle NOx emissions. However, increased electricity would need to be generated in order to support electrified motor vehicle fleets. Some argue (Gao et al., 1991) that a massive move to electric vehicles could result in reduced utility NOx emissions since the increased power demand would force construction of new, efficient, high capacity power plants to replace certain existing plants.

## 4.3 Summary

NOx control technologies for a variety of utility, industrial, commercial and other sources involve some form of combustion modification and/or flue gas treatment or fuel switch. Table 4-1 summarizes the more common control approaches. Combustion modifications and low-NOx burners producing NOx reduction efficiencies from 15-60 percent have been the prevalent control approaches on major U.S. utilities, which represent the majority of stationary source NOx emissions. Repowering technology, which is being demonstrated for coal-fired utility systems, offers the potential for NOx control from 50-95%. More advanced and highly efficient SCR applications are widely used in Japan and Germany with NOx reductions from 70 - 90% or more. Similar NOx control technologies and attendant efficiencies are installed on a multitude of other U.S. manufacturing and chemical industry processes. However, advanced SCR and SNCR are applied more widely in the chemical industry (limited mostly to select California sites) than in the utility industry. Fuel switching approaches during the summer ozone season provide various environmental benefits in addition to seasonal NOx reduction.

Combustion modification technologies that result in NOx reductions can decrease operating efficiency and increase other emissions, particularly carbon monoxide. Repowering is projected to permit expanded capacity and/or increased generation efficiency; however, a full assessment of the environmental impacts of the demonstration system has not been completed. SCR is extremely effective in reducing NOx emissions but carries large associated capital and operating and maintenance costs, relative to combustion modifications. Both the effectiveness and required maintenance of all technologies depend on several factors, principally the type of source on which control is applied. Accordingly, careful formulation of recommended technologies must consider source type and specific unit characteristics.

## SECTION 5.0 - SUMMARY

This report provides an assessment of the most significant issues affecting tropospheric ozone pollution and their implications for regulatory programs. In addition, the report presents findings from the NAS report entitled RETHINKING THE OZONE PROBLEM IN URBAN AND REGIONAL AIR POLLUTION. The EPA perspectives are then provided on how those findings relate to previous and existing programs, and the implications they hold for developing NOx and VOC control strategies. Reductions in NOx and VOC emissions are likely to reduce ozone in many areas. However, the latest evidence suggests that NOx controls will be more effective than VOC controls in many areas. Ozone response to reductions to VOC or NOx varies from one area to another. Consequently, control strategy development should be made on a case-by-case basis through application of gridded photochemical models. The EPA plans on requiring such applications, based on the best available data, to meet certain CAAA requirements.

The NAS has questioned the adequacy of existing data bases to support modeling analyses which are used to design optimal NOx and VOC emission reduction strategies. The EPA has recognized many of the same concerns identified by the NAS, and initial efforts are underway to correct expected deficiencies. These efforts include (1) a greater emphasis on compilation of high quality emission inventories, (2) development of an enhanced ozone and precursor monitoring system to characterize ambient concentrations and track progress of emissions control implementation programs, and (3) use of gridded photochemical modeling for SIP planning.

Despite these initial efforts, several concerns remain which pose significant challenges to both research and regulatory programs:

1. Current air quality and meteorological monitoring networks and emission inventories may not provide sufficiently comprehensive data sets to reduce the uncertainty associated with applying photochemical gridded models. The EPA believes that the models will provide accurate directional indications of the relative effectiveness of NOx or VOC control, but the level of confidence in the precision of control level estimates generated by the models is compromised by deficiencies in current routine data bases.

2. Avenues of support for designing and implementing research grade laboratory and field studies to fully address the serious concerns raised by the NAS have not been identified. Aggressive and innovative approaches fostering private and public sector partnerships are needed to (1) ensure adequate support of new research,

(2) develop concurrence on the interpretation of current techniques and (3) improve confidence of future applications.

3. Current programs do not account for model uncertainty. This inadequacy is serious considering the costliness of emission control programs. Techniques to consider model uncertainty should be developed as they will provide important information for decision makers and assist in defining needed research efforts for model and monitoring improvements.

Following is a synopsis of 11 key findings. The first ten of these are NAS findings followed by EPA's response in italics. The eleventh finding on NOx control technology was not addressed by the NAS:

1. Ozone in the United States - Ozone remains a widespread and important problem despite repeated abatement programs. *EPA agrees that ozone reduction efforts have not achieved previous goals and that new research and control initiatives will have to be undertaken.*

2. Ozone Trends - The metric used to identify ozone trends by the EPA is highly influenced by meteorology and unreliable as a measure of progress. *The trends analysis tracks a key indicator relevant to human and welfare impacts. Other methods designed to account for meteorological influence on ozone concentrations are being investigated and encouraged by the EPA.*

3. State Implementation Planning - While sound in design, the SIP process is flawed in practice by the lack of an adequate verification program. *A new monitoring program which is designed to track progress towards attainment, reductions in emissions, and provide information needed to make mid-course adjustments is under development to make the SIP process more complete. The PAMS program is facing substantial challenges which will require increased support to successfully fulfill those objectives.*

4. Anthropogenic VOC Emissions - Emission inventories understate anthropogenic VOCs. This may lead to incorrect development of control strategies. *EPA has accelerated and enhanced its efforts to improve data and emission estimation techniques to develop an accurate nationwide VOC and NOx inventory. Additional efforts are needed; particularly pressing is the need for a true research level inventory addressing episodic conditions to further improve the inventory process beyond ongoing efforts.*

5. Biogenic VOC Emissions - Biogenic emissions have significant impacts on ozone formation. *The NAS confirms EPA findings. Based on recent studies, EPA requires that biogenics*

*be included in photochemical grid model applications including those which assess the effectiveness of emission control strategies. The large uncertainty in biogenic emission estimates demands that a high priority be placed on characterizing natural emissions.*

6. Ambient Air Quality Measurements - Routine measurements do not elucidate relevant chemical processes needed to assess source contributions. *A new monitoring program mandated by the CAA is under development as an initial step toward applying advanced monitoring methods routinely in key areas. However, support for additional methods research and data acquisition is required to address issues raised by the NAS, particularly the need for monitoring low-level NOx in rural environments.*

7. Air-Quality Models - Grid models are preferred control strategy assessment tools; however, parts of the model structure and supporting data bases (particularly emissions) contain important areas of uncertainty. Lacking pertinent information, the EPA has not considered model uncertainties in development of emission control programs. The *EPA requires use of the best available models and data bases within practical resource and time constraints. Both the NAS and EPA agree that research to reduce model uncertainties has immediate and highest priority.*

8. VOC versus NOx control - NOx control is necessary for effective reduction of ozone in many areas, and more NOx control should be emphasized than is allowed under current EPA strategy. *NOx control is expected to provide ozone reductions in many areas. Area-specific and regional analyses using photochemical grid models, as required under the 1990 CAA for more seriously polluted ozone nonattainment areas, will be used to assess the effectiveness of control strategies. Such objective analyses should not be biased toward any single precursor.*

9. Alternative Fuels for Motor Vehicles - The CAA requires widespread use of reformulated gasoline and will likely lead to limited use of other clean fuels in large urban areas with serious ozone problems. The NAS concluded that alternative fuels by themselves will not solve the ozone problem. *VOC reductions from the reformulated gasoline program are expected to reduce ozone in the nine areas where reformulated fuels are required. There also is the potential for NOx reductions with the use of reformulated fuel, as well as other alternative fuels such as alcohols and CNG.*

10. A Research Program on Tropospheric Ozone - A coordinated national research program is needed. *The EPA agrees with the NAS's assessment of the national research effort. The NAS made numerous recommendations for specific new research needed. The EPA has commenced implementation of such recommendations, starting with a major cooperative, planning effort with other*

*Federal agencies, industry and academia to develop a national, coordinated research program.*

11. <u>Availability and Extent of NOx Control</u> -

Stationary Sources - *Combustion modifications are used extensively in the U.S., relative to flue gas treatment techniques which are more widely applied in Japan and Germany.*

*Mobile Sources - The EPA has a wide variety of programs underway to reduce mobile source NOx. These include stricter Tier I standards for passenger cars and light duty trucks. Also, stricter NOx standards are required for heavy duty diesel engines, and enhanced vehicle inspection and maintenance programs have been promulgated that will result in NOx benefits from in-use vehicles. Finally, the EPA plans to propose non-road emission standards for NOx reductions for diesels over 50 HP.*

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16. ABSTRACT


This Report is the main component of the CAA Section 185B Report to Congress. The Report addresses the technical issues underlying the development of effective ozone precursor strateies, and provides EPA responses to the National Academy of Sciences report entitled, Rethinking the Ozone Problem in Urban and Regional Air Pollution.


17. KEY WORDS AND DOCUMENT ANALYSIS

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