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THE SIGNIFICANCE OF NOx EMISSIONS FROM COAL-FIRED POWER PLANTS IN THE MIDDLE TENNESSEE AREA ON TROPOSPHERIC OZONE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Andrea Elizabeth Early

May 1995

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ABSTRACT

This thesis examined the significance of NO_x emissions from power plants on tropospheric ozone in the Middle Tennessee area using the Urban Airshed Model. The modeling domain used covers a 46,000 km^2 rectangle with Nashville, Tennessee located approximately in the center. Located within this area are three coal-fired power plants (Cumberland Steam Plant, Gallatin Steam Plant, and New Johnsonville Steam Plant) which represent the greatest point sources of NO_x emissions within the modeling domain. The emissions are based on a 1990 State Implementation Plan (SIP) inventory that has been backcast to 1988. The emissions, including area, point, mobile, non-road, and biogenic sources were chemically, temporally, and spatially allocated throughout the domain.

The NO_x emissions from the three power plants were reduced by 25%, 50%, 75%, and 100% for two episode dates in 1988 which exceeded the National Ambient Air Quality Standard (NAAQS) for ozone to determine the significance of power plant NO_x emissions on ozone formation. An additional simulation was conducted in which Gallatin's NO_x emissions were reduced by these percentages for a third day in 1988 which also exceeded the NAAQS. The results from this study showed that the maximum ozone that the NO_x emissions from power plants contributed to tropospheric ozone in the Middle

Tennessee Area ranged from 19 to 39 parts per billion (ppb) and was predicted to decrease as the NO_x emissions from the power plants were reduced.

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1. INTRODUCTION

In the past regulations focused on controlling the concentrations of volatile organic compounds (VOCs) emitted from anthropogenic sources for the reduction of tropospheric ozone. This issue has been debated due to the findings which show that the control of nitrogen oxides (NO_x) may be more effective in reducing ozone in the atmosphere.[19] Coal-fired power plants emit the largest amount of point source NO_x in the United States. As a result, the focus for reducing ozone in certain areas of the country has turned to NO_x sources, especially these power plants.[11]

It is evident that the control of NO_x was not a widely accepted method for the reduction of tropospheric ozone when the Clean Air Act Amendments of 1990 were formulated. States which are in violation of the National Ambient Air Quality Standard (NAAQS) for ozone are required by law to reduce volatile organic compounds (VOCs). The target year and extent of these reductions depend on the degree of nonattainment. Although ozone formation has been shown to be a result of reactions involving VOCs, NO_x, and sunlight, initial control strategies established by The Clean Air Act Amendments of 1990 focused more on mandatory VOC reductions and controls than on NO_x. It has since been found that many areas have sufficient natural emissions of VOCs that the areas actually become NO_x-limited. In effect, the ozone

becomes sensitive to reductions in NO_x but not to anthropogenic VOCs. Different parts of the country react differently to reductions in VOC and reductions in NO_x depending on the level of natural emissions.[6]

Nashville Tennessee, a moderate area of ozone nonattainment, is most sensitive to reductions in NO_x emissions, as can be seen from this study. A large portion of the NO_x emissions emitted within this area are from three large power plants: Cumberland Steam Plant, Gallatin Steam Plant, and New Johnsonville Steam Plant. In order to assess the impact that these plants have on ozone concentrations in the Middle Tennessee Area, the Urban Airshed Model (UAM) was used to conduct modeling scenarios in which the NO_x emissions from the plants were altered. The maximum ozone concentrations reductions that resulted from reduced NO_x emissions were analyzed.

The modeling domain used for this study was a 46 by 40 grid that was 46,000 km^2 in area. The grid cells were 5 km on each side, and the domain had 5 vertical layers which varied in height due to hourly variations in meteorological conditions. The emissions used for modeling purposes were based on a 1990 State Implementation Plan (SIP) Inventory for Nashville and the Middle Tennessee Modeling Domain.[28] The emissions were backcast to 1988 to validate the model. These 1988 emissions were the baseline case for this power plant study.

The second section is a review the literature dealing with NO_x control technology for power plants, along with NO_x and ozone chemistry, NO_x regulations, and steam plant technology. Section 3 includes a description of the power plants and days which were modeled and the methods which were used for this study. Section 4 includes an outline and discussions of the ozone concentrations that resulted from modeling. The conclusions drawn from modeling NO_x emissions from power plants in the Middle Tennessee Area are reported in Section 5.

2. LITERATURE REVIEW

Nitrogen oxides (NO_x) are produced in all fossil fuel combustion processes which use air as the oxidant. Even though there are many known oxides of nitrogen, two are most important in the atmosphere, nitric oxide, NO and nitrogen dioxide NO_2.[3] Figure 2-1[1] shows the chemical transformations of NO in the atmosphere. One of the chemical reactions that takes place is the oxidation of NO to NO_2. NO_2 not only contributes to health problems, such as bronchitis and pneumonia, but also contributes to acid rain, smog, and ozone formation.[1] The primary purpose of this literature review is to identify the mechanisms of NO_x formation and control of NO_x emissions from coal-fired power plants. In addition the review includes discussion of the role of power plant emissions in the formation of atmospheric ozone. Modeling efforts concerning the role of NO_x from power plants in ozone production are discussed. Current regulations for NO_x controls are also addressed.

2.1. STEAM PLANT BASICS

In order to understand the formation of NO_x emissions from coal-fired power plants, a basic understanding of steam plant operation must be developed. A schematic showing a coal-fired utility power plant is shown in Figure 2-2[2]. Steam plants produce electricity by using the heat from

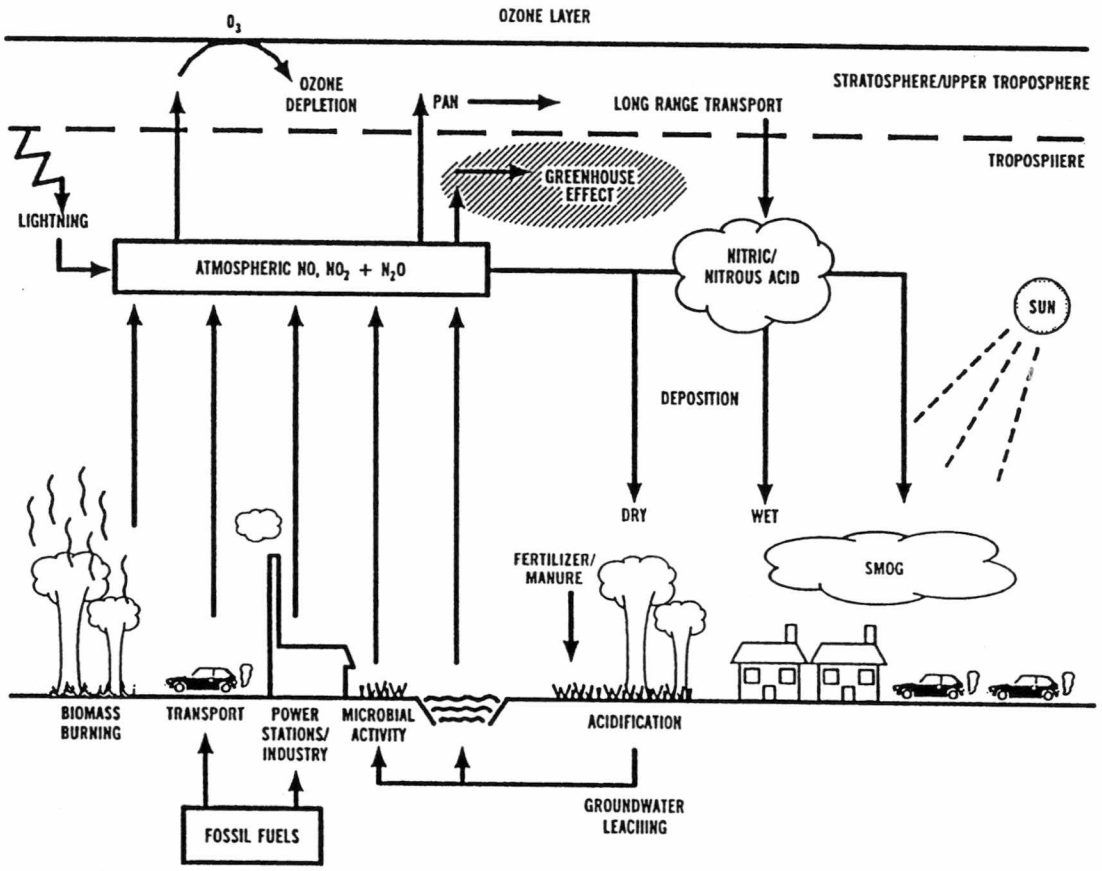


Figure 2-1. Chemical Transformation of NO in the Atmosphere

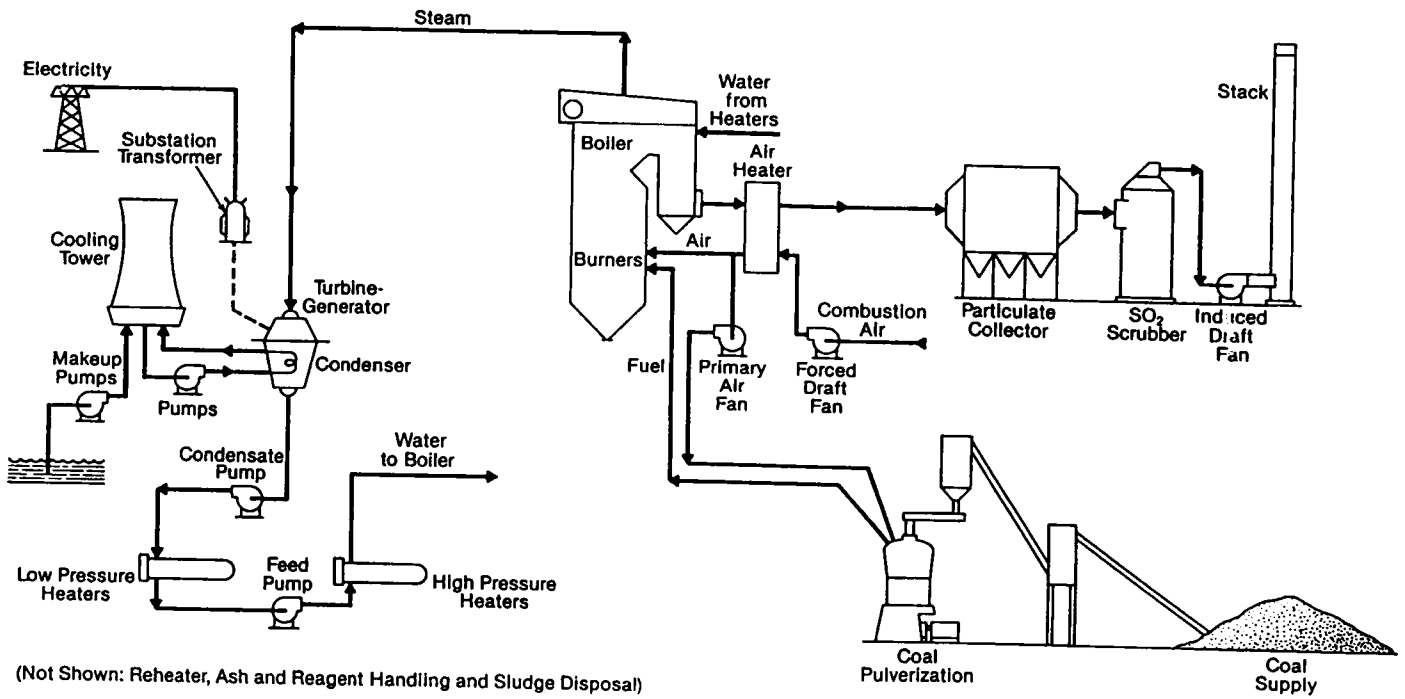


Figure 2-2. Coal-Fired Utility Power Plant Schematic

combustion to heat water above its boiling temperature, eventually producing steam. Coal, either bituminous, subbituminous, or lignite, is the dominant energy source used in the United States for electricity production. This trend is shown in Figure 2-3[2] which gives the breakdown of energy source types used for electricity generation in the US in 1990. It is expected that coal will dominant the role of supplying energy to new, base loaded utility power station boilers.[2]

Coal can be fed to the system in different ways. Pulverizing the coal before burning it provides smaller particle sizes and higher combustion rates.[2] Before being fed through the burners to the combustion chamber where it is fired in suspension, the pulverized coal is usually entrained in the primary air.[20] Cyclone furnaces feed coal grades that are not suited for pulverized coal combustion. Stokers are the third type of coal burning system. They feed fuel onto a grate where it burns with air passing up through it. Of these three coal burning options, pulverized coal is the dominant method used today in large coal-fired boilers.[18]

The two classifications of pulverized coal furnaces are either dry or wet bottom, depending on the ash removal techniques. The dry bottom furnaces use dry ash removal techniques and fire coals with high ash fusion temperatures. The wet bottom furnaces use coals with low ash fusion

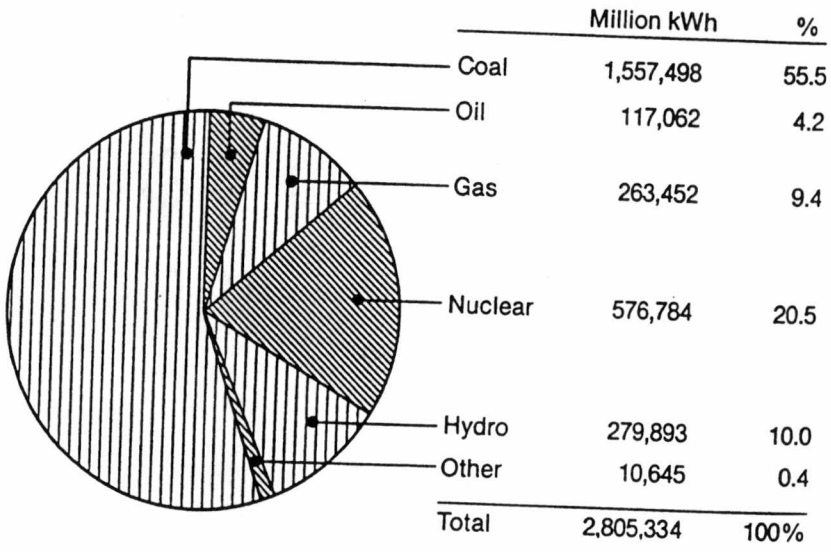


Figure 2-3. U.S. Net Electricity Generation by Energy Source During 1990

temperatures and molten ash is drained from the bottom of the furnace.[20]

The boiler contains the water which under pressure is transformed into steam by the application of heat from the combustion of coal.[18] Included in the boiler are the furnace and burners which play a part in the coal combustion. Four types of burners exist and each is suited for a particular boiler furnace design. The horizontal circular burner is made up of a center tube through which the coal and primary air pass. At the end of the nozzle is a component which is known as a diffuser, which serves to diffuse the primary coal and air into the hot secondary air and also acts as a flame holder. The secondary air enters around the coal nozzle. These burners are known to exceed EPA limits on NO_x emissions because of the high turbulence and short flame.

The second type of burner is the tangential burner. The tangential burners have coal nozzles that have secondary air nozzles above and below it. To control the air to each secondary air compartment, these burners have dampers. These burners are angled so that their center lines are tangent to an imaginary horizontal circle the center of the furnace. A configuration of this type produces a high degree of mixing in the furnace. Connected to a coal nozzle in each of the four corner burners are the pulverizers. The tangential burner design permits the tilting of the burner components, done automatically to control furnace heat

absorption and to maintain superheat and reheat temperatures.

The directional flame burner is the third burner type which is located in a furnace which is in the shape of a venturi. In such a furnace the burners are located below the venturi. The walls at the front and rear of the furnace are inclined downward at 25°. At the neck of the venturi above the burners, overfire air ports are installed.

The coal nozzles are located in the center of the two burner slots. Vanes that can move to deflect air up or down are located in the secondary air slots which are above and below the coal nozzles. These moving vanes shifts the fireball up or down in the furnace. To keep the fire centered in the furnace, opposing burners are connected to the same pulverizer. A diffusion flame with a low NO_x emission is produced from this design.

The fourth type of burner is the vertical or down shot burner, which is used mainly for firing anthracite, coke, or similarly low volatile fuel. Surrounded by a small portion of the secondary air, the primary air and pulverized coal are discharged vertically downward. As the flame descends, the balance of the air required for complete combustion is fed into the flame.

For pulverized coal burners these four principle burners are best suited for a particular boiler furnace design. Straight wall furnaces, or single wall furnaces,

use horizontal circular burners while tangential wall furnaces or corner fired furnaces use tangential burners. The burners used a for a turbo flame furnace are directional flame burners. Vertically fired furnaces use vertical or down shot burners. Figure 2-4[3] shows each of these arrangements. Another burner configuration for pulverized coal furnaces is the horizontally opposed fired furnace.[20]

A burner usually has two zones, a primary and secondary zone. The region in which fuel is injected and ignition occurs is the primary zone. This zone is where the fuel is mixed with a portion of the combustion air, both of which must be evenly distributed. In order for the flame to be maintained inside the primary zone, the velocity in this zone must be below the flame velocity. Combustion is completed in the secondary zone, which is also where the remaining air is mixed with the combustion gases leaving the primary zone.[3]

The placement and number of burners in the boiler is critical in order to avoid flame impingement on the furnace walls. Opposed fired burners tend to provide uniform heat distribution across the furnace which reduces thermal gradients and prevents slagging, thus reducing NO_x emissions and improving combustion efficiency.[2]

The steam that is produced from the heat from combustion process is then converted from heat into mechanical energy by a steam turbine. The steam turbine

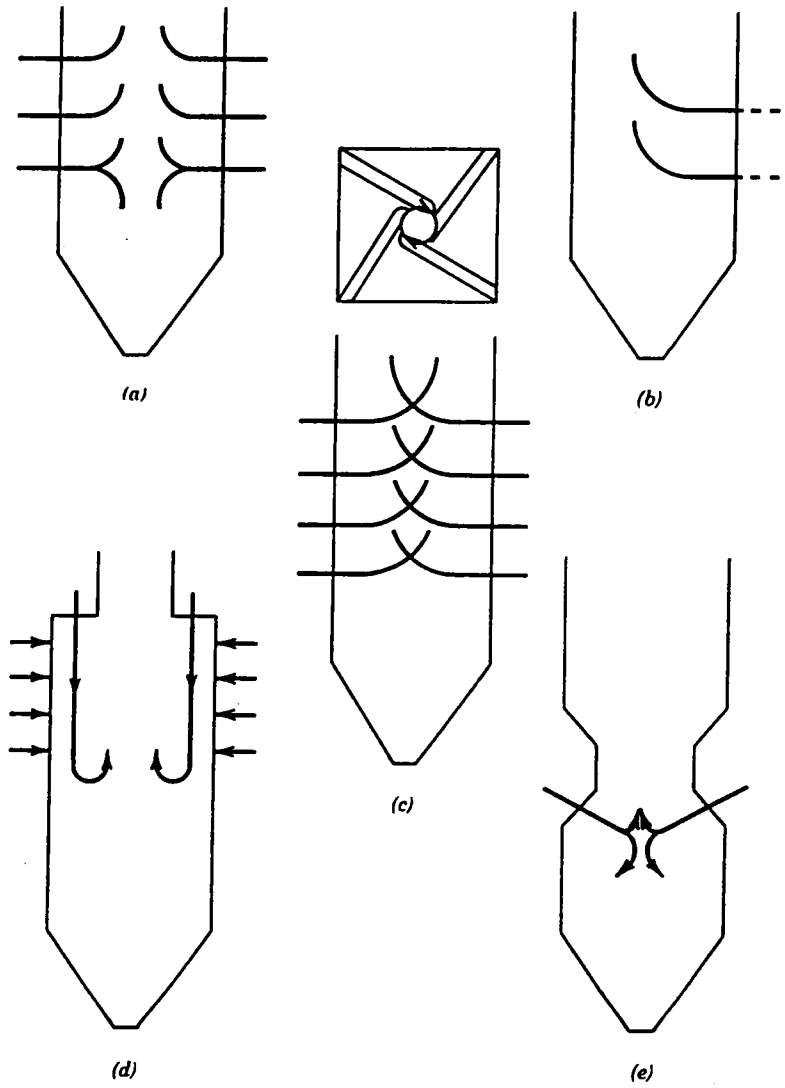


Figure 2-4. Pulverized Coal Burner Types: (a) one-side horizontal, (b) opposed horizontal, (c) tangential, (d) turbo furnace, (e) down shot

supplies the mechanical energy for an electric generator. The generator needs more energy from the turbine as energy demands increase. The amount of steam flow provided to the turbine depends on the demand of electricity.[3]

Figure 2-5[2] shows the typical power plant effluents and emissions. NO_x emissions along with SO_2 and other atmospheric pollutants come from the byproducts of combustion and are released from the power plant through the stack. NO_x emissions arise from the nitrogen compounds in the fuel and molecular nitrogen in the air supplied for combustion. Other factors affect the amount of NO_x emitted from the power plant such as burner arrangement, flame temperature, and stoichiometry. These factors are altered in order to control NO_x emissions.[2] Another consideration in looking at emission controls is fitting the control to suit the current configuration of the power plant. For NO_x controls the furnace type and burner arrangement in the furnace govern which type of combustion modification can be applied for NO_x control.[3]

2.2. NO_x PRODUCTION FROM POWER PLANTS

The primary product of combustion where oxygen and nitrogen are both present is NO which is a colorless, odorless gas that is slightly soluble in water. The reaction that occurs that produces NO is:

$$N_2 + O_2 \rightarrow 2NO.$$

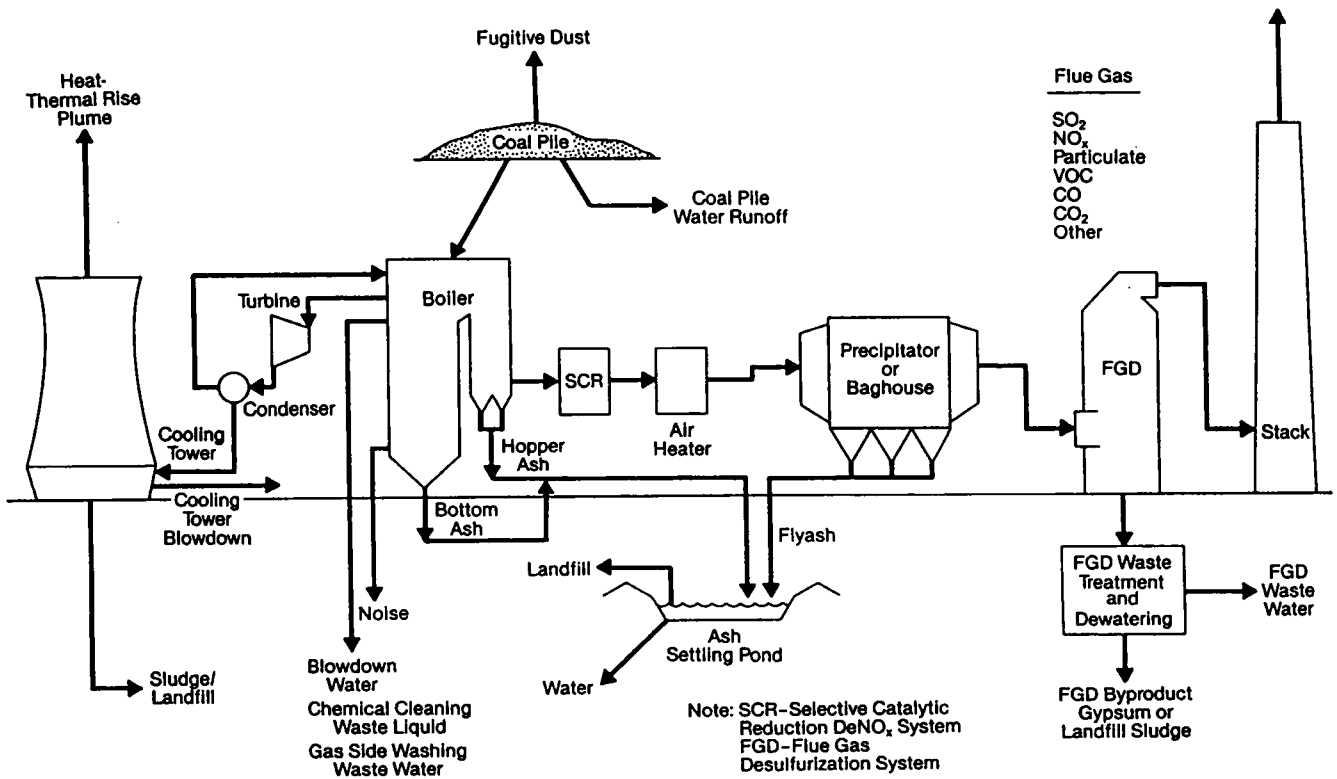


Figure 2-5. Typical Power Plant Effluents and Emissions

The nitrogen in the fuel and the nitrogen present in the air are the sources of nitrogen for this reaction.

Thermodynamic and kinetic rate factors determine the amount of nitric oxide formed during combustion. NO production is influenced by the fuel type and composition, heat and mass transport rates, operating and design variables, and the temperature-time history of the combustion process. The operating variables that determine the nitric oxide emissions formed are flame temperature, excess air and residence time at a given temperature. Figure 2-6[3] shows the uncontrolled NO emissions for various types of boilers. Table 2-1[20] shows NO_x emissions factors for external bituminous and subbituminous coal combustion from AP-42.

There are three different sources of NO_x formation. The first source is fuel nitrogen which is bound within the coal and is the major source of NO_x emissions from nitrogen bearing fuels. Fuel NO_x contributes about 50% of the total uncontrolled emissions when firing residual oil and more than 80% when firing coal. Nitrogen found in these fuels is usually bound to the fuel as part of organic compounds.[2] Fuel nitrogen content in coal ranges from 1% to over 2% and is reported as nitrogen in the final analysis of the coal. Fuel NO_x is released during combustion as N, NH, or CN which can be oxidized to NO_x or recombined to form N_2 molecules.[3]

The rate of mixing of the fuel and air and the local

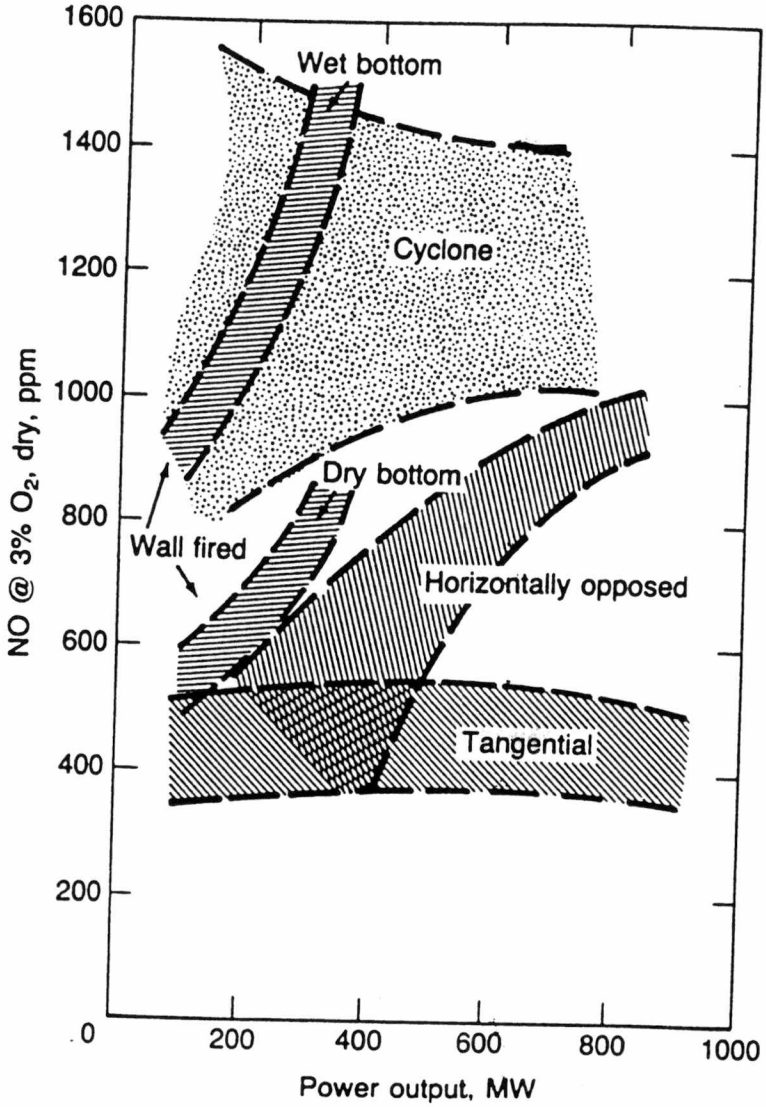


Figure 2-6. Uncontrolled NO Emissions for Various Types of Boilers

Table 2-1. Uncontrolled and Controlled NO_x Emission Factors External Bituminous and Subbituminous Coal Combustion

Firing Configuration	NOx Emission Factor (lb NO_x/ton coal)
Pulverized Coal fired	
Dry Bottom	21 (15 for tangentially fired)
Wet Bottom	34
Cyclone Furnace	37
Spreader Stoker	
Uncontrolled	14
After multiple cyclone	
With fly ash reinjection from multiple cyclone	14
No fly ash reinjection from multiple cyclone	14
Underfeed stoker	
Uncontrolled	9.5
After multiple cyclone	9.5
Handfired units	9.5

oxygen concentration affect the production of fuel NO_x. Local combustion conditions must be controlled in order to control this type of NO_x emissions. Controlling fuel NO_x involves introducing the fuel with a sub-stoichiometric amount of air, creating a "rich" fuel-to-air ratio. Rather than being oxidized to NO_x, the fuel bound nitrogen is then released as molecular nitrogen.[2]

The thermal fixation of molecular nitrogen and oxygen in the combustion air produces thermal NO_x. This thermal fixation is the second mechanism by which NO_x is produced from the combustion process. The availability of oxygen, the furnace temperature, and residence time in the furnace are the factors on which thermal NO_x production is dependent. Figure 2-7[4] shows the effects of these variables on thermal NO_x production.

Thermal NO_x is formed by the dissociation of O_2 to 2 oxygen molecules in the outer flame perimeter where the oxidation of carbon and hydrogen take place.[4] The thermal fixation of molecular nitrogen and oxygen occurs in the combustion air. This NO_x formation, which becomes rapid at gas temperatures of 3000-3600°F, is most sensitive to local flame temperature and, to a lesser extent, to local oxygen concentrations. Thermal NO_x production is maximized at a slightly lean fuel-to-air ratio, in which an excess of available oxygen exists for reaction within the hot flame zone.[5] A model developed by Zeldovich describes thermal NO_x

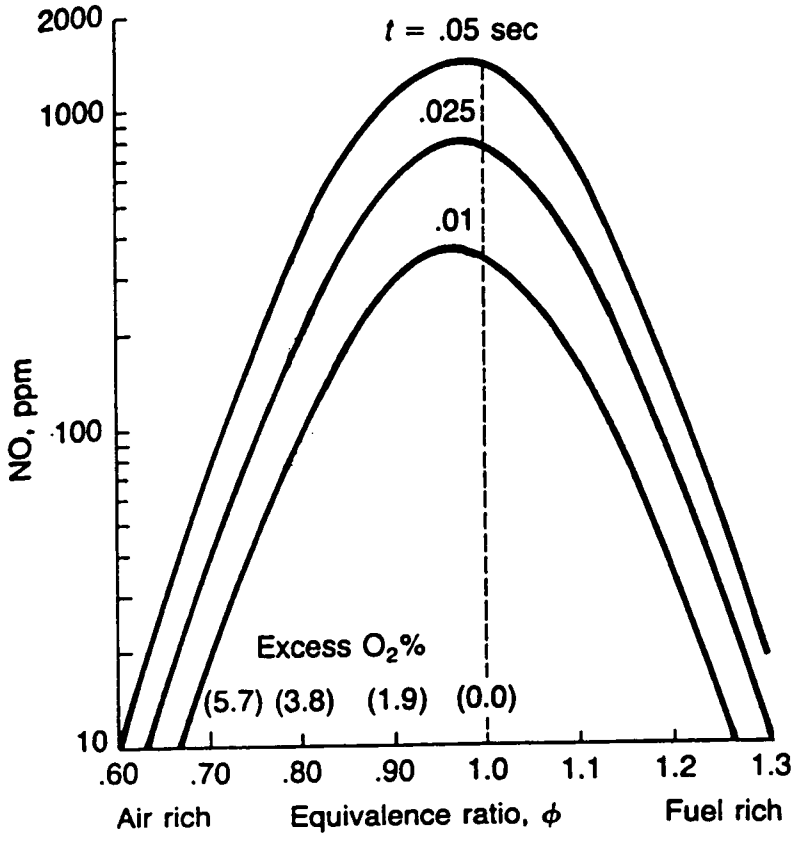


Figure 2-7. NO Versus Fuel Equivalence Ratio and Time

formation with these reactions:

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

The combination of the first two reactions combined produce the resulting reaction:

$$N_2 + O_2 \rightarrow 2NO$$

A reduction in NO_x formation can be achieved by lowering the operating temperature, decreasing the gas residence time, and/or off-stoichiometric fuel-air ratio.[4]

A third type of NO_x emissions is produced by combustion of coal but its contribution to overall NO_x formation is small. These NO_x emissions are called "prompt NO_x" and are formed by the reaction of molecular nitrogen in the combustion air with free hydrocarbon radicals available from the fuel in the combustion zone. These steps can be seen in the following reaction,

$$N_2 + CH \rightarrow HCN + N$$

HCN combines with free OH radicals to form CN which is then oxidized to NO in many intermediate steps. Prompt NO_x has a short lifetime of microseconds.[5]

Figure 2-8[4] shows the distribution of NO between the different formation mechanisms with coal combustion as function of temperature.

2.3. OZONE PRODUCTION AND NO_x

The formation of photochemical smog involves two cycles, the hydrocarbon cycle and the ozone cycle. NO_x plays a part in both of these chemical reactions. NO_x controls the amount of ozone that is produced in the ozone cycle, while the oxidation of NO in the atmosphere is determined by the hydrocarbon reactivity in the hydrocarbon cycle.

The formation of tropospheric ozone can be described by three basic reactions:

$$NO_2 + hv \rightarrow NO + O$$

$$O + O_2 + M \rightarrow O_3 + M$$

$$NO + O_3 \rightarrow NO_2 + O_2$$

The NO_2/NO ratio governs the rate of ozone production. Other species in the atmosphere influence the NO_2/NO ratio if the ozone level is determined by the reaction

$$O + O_2 + M \rightarrow O_3 + M.$$

The NO_2/NO ratio mainly controls the level of ozone in the atmosphere.

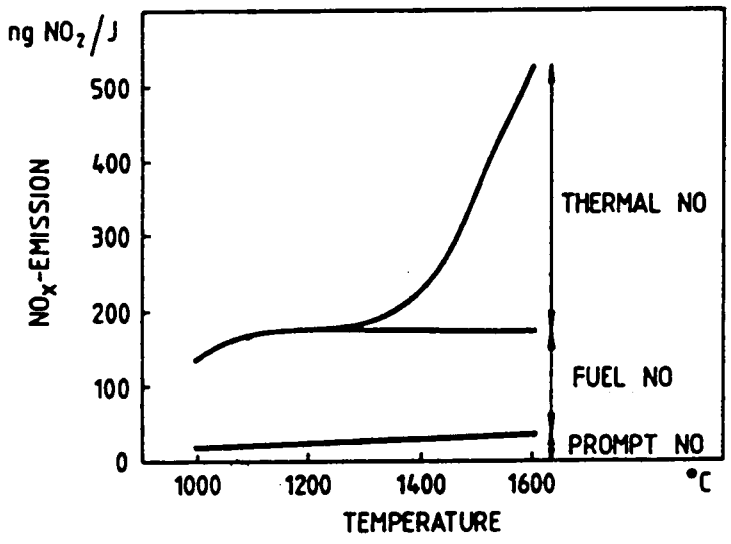


Figure 2-8. Schematic representation of the distribution of the formation of NO between different formation mechanisms when burning coal, as a function of temperature

The conversion of NO to NO_2 comes into play in the hydrocarbon cycle, the second part of the photochemical smog cycle. The ozone isopleth diagrams shown in Figure 2-9[6] describe the relationship between hydrocarbon and nitric oxide emissions. These diagrams are frequently used by EPA in control strategies. The isopleths show the production of ozone as a function of NO_x and hydrocarbons. The figure shows that there are two regions with very different chemical behaviors, one having high VOC/NO_x (>15:1) ratios and the other having low VOC/NO_x ratios (<4:1). With the higher VOC/NO_x ratios, ozone formation increases with increases in NO_x and is, for the most part, insensitive to VOC concentrations. The low VOC/NO_x ratios show an increase in ozone with an increase in VOC concentration and a decrease in ozone with increasing NO_x.

The decrease of ozone due to increases in NO_x can be seen downwind of a power plant. This decrease results from the conversion of emitted NO to NO_2 by the reaction:

$$NO + O_3 \rightarrow NO_2 + O_2.$$

This same reaction affects the NO emissions at night, on cloudy days, or in winter.

Although an ozone reduction seems advantageous environmentally, the ozone reducing reaction produces NO_2, whose chemical properties are similar to ozone. Also, if

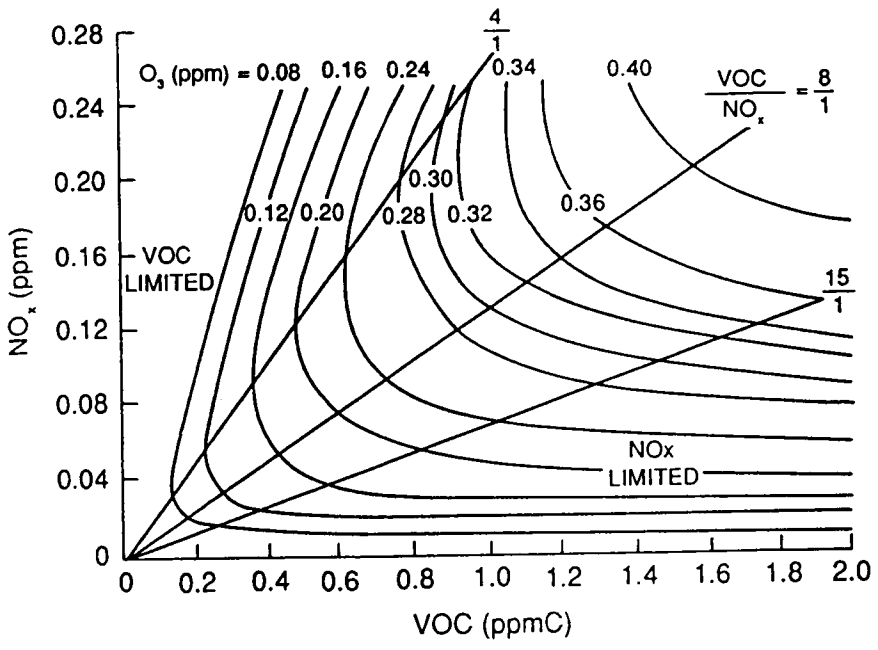


Figure 2-9. Ozone isopleths describing relationship between VOC and NO_x emissions

conditions favor high ozone levels, the ozone consumed in the power plant plume will be replaced and ozone levels will increase moving farther downwind. In a low VOC/NO_x ratio environment increasing NO_x lowers the OH radical concentration thereby slowing the rate of all chemical reactions. This retardation of the reactions means that less ozone is formed but high levels of VOC and NO_x remain in the atmosphere longer.

EPA initially recommended VOC controls as a means of reducing ozone in the atmosphere. Recent studies suggest a need for NO_x controls, in addition to or instead of reductions in hydrocarbons.[19] EPA suggests that the benefits of NO_x reductions must be analyzed through photochemical grid modeling. They recommend that NO_x controls be examined closely since a decrease in NO_x can result in an increase in ozone in certain locations thus population exposure must be examined. EPA concludes that VOC versus NO_x is a location specific issue.[7]

2.4. POWER PLANT URBAN AIRSHED MODELING STUDIES

There exist only a limited number of models that are able to simulate ozone formation due to the complexity of the chemistry involved. The models that do exist include the Reactive Plume Model (RPM), the Urban Airshed Model (UAM), Ozone Isopleths Plotting Mechanism (OZIPM-4) model and variations on the above. UAM studies will be discussed

here.

A modeling study was performed for the Chicago area using UAM in order to assess utility emissions on ozone.[8] Chicago is a "severe" O_3 nonattainment area and is not affected by regional pollutant transport as are most areas of the country. The modeling domain used for this study was a 50 by 50 grid with each cell being 5 km on a side.

The emissions used for the study were 1985 National Acid Precipitation Assessment Program (NAPAP) emissions backcast to July 5-6 1988, a day whose meteorology consisted of a high pressure system which provided sunlight and stagnant conditions to allow pollutant build-up. These emissions were also forecasted to 2010. Wind speed and direction, temperature and relative humidity, surface pressure and cloudiness were obtained from the National Weather Service (NWS) radiosonde and surface stations and from pollution monitoring networks and utility meteorological towers. This data was used to determine mixing heights, inversion levels, water vapor content, and stability. Initial conditions were obtained from EPA's Aerometric Information Retrieval System (AIRS). These concentrations were one-hour average monitoring concentrations for the region and episode. The species used for initial conditions were O_3, NO_x, and CO. Boundary conditions for O_3 were set at 80 ppb.

The results of the study showed that UAM overpredicted

O_3 at night and underpredicted maximum O_3. The authors conclude that the reason for this error in the results was due to the particular values of evening mixing height and initial boundary concentrations. Overall the model performed well in spatially distributing the O_3 concentrations during the day on July 6. The simulated maximum was 159 ppb compared to the observed maximum of 222 ppb. This peak was underpredicted by 28%, and the average monitoring site was underestimated by 19%.[8]

When the utility emissions in this area were completely removed, attainment was not achieved, and air quality only improved by 20-25% even though the power plants contributed approximately 50% of the NO_x emissions. Removal of about half the NO_x emissions showed a reduction in O_3 of about 10%. The Title IV regulations showed little effect on air quality for 2010. It was concluded that VOC emissions were important to the air quality in the Chicago area. An examination of spatial plots of VOC:NO_x concentration ratios showed that the area was mostly VOC limited, and NO_x controls did not harm the air quality in limited areas downwind of the power plants. The authors concluded that controls on utilities may not be cost-effective as even complete removal of the utility emissions did not result in attainment.

This same sort of study is being performed in the Philadelphia and New York areas to assess the contribution

of power plant emissions to ozone. This study is also using UAM as its model but here EPA's Regional Oxidant Model (ROM) was used for boundary conditions. The emissions are based on a 1990 baseline inventory to be backcasted to 1988 and forecasted to 2005.

The episode days chosen are July 2-13, 1988. ROM meteorological data is to be preprocessed through the ROM/UAM interface after which the inputs to UAM will be analyzed. If wind fields seem to be unreasonable, the Diagnostic Wind Model will be examined. The mixing heights to be used are episode-specific estimates calculated using the UAM modeling system and other more advanced techniques.

The purpose of the study is to among other things, apply UAM to Philadelphia and New York nonattainment areas to determine the effect of combining reductions of NO_x from power plants and VOC emissions from other sources on peak ozone levels. Although no results and conclusions were given in this paper, the expectations of the study were to be that the effectiveness of combined VOC and NO_x reductions to ozone was to vary from area to area, from day to day within an area, and from place to place within an area. This combined reduction approach is the prediction that the authors have for successful ozone reduction in this area.[9]

Bandyopadhyay[10] studied the effects of different sources on ozone formation in the troposphere using the UAM in the West Tennessee Area. The modeling domain used was a

20 by 20 grid with cells of 5 km on a side. One source examined was a large NO_x source, a 620 MW TVA power plant that accounted for 28.6% of the total NO_x emissions in this area.

The TVA power plant emissions were removed in order to determine the relative impact of the power plant. This scenario was compared to the base case scenario. The results indicated that the plant contributed 6.2% of the total ozone concentration; however, the maximum contribution of the plant occurred in a grid different than the grid in which the base case maximum occurred. This base case maximum occurred in a grid directly downwind from the monitoring station. Looking at this grid, the plant contributed 9.2% of the total ozone concentration. The removal of this large NO_x source resulted in scavenging of ozone immediately downwind from the power plant. The depletion resulted from a low VOC/NO_x ratio in the plume and also from the nitric oxide emitted from the plant.

Although mobile sources had the greatest effect on ozone formation, the study showed that in that area, ozone formation was more dependent on NO_x emissions rather than VOC emissions. Where NO_x were reduced, ozone reductions were higher that for those case when the VOC concentration was reduced.[10]

2.5. NO_x CONTROL REGULATION

In 1980 electric utilities contributed 30 percent of total NO_x emissions in the United States. In 1990 their contribution rose to account for 38 percent of NO_x emissions. Of this 38 percent of total utility NO_x emissions, 80 percent of these NO_x emissions came from coal-fired plants.[2] Regulations for the control of NO_x emissions from major stationary sources exist in Titles I and IV of the Clean Air Act Amendments (CAAA).

Under Title I of the CAAA, states must apply the same requirements to major stationary sources of NO_x as to those major stationary sources of VOCs. The two provisions that are required are: (1) Reasonably Available Control Technology (RACT) which must be applied to existing major stationary sources and (2) new and modified major stationary sources which must apply the Lowest Achievable Emissions Rate (LEAR) and will obtain offsets prior to operation. RACT means the lowest available limitation that a particular source is capable of meeting by the application of control technology that is reasonably available considering technological and economical feasibility.

The Acid Rain Program is under Title IV of the CAAA. The Acid Rain Nitrogen Oxides Emission Reduction Rule is part of this program and initiates the reduction of nitrogen oxides from utility boilers across the United States. The Title IV regulations use a two part strategy to reduce NO_x

emissions. The first rule sets limitations on Group 1 boilers which are dry bottom wall fired and tangentially fired boilers. Group 2 includes wet bottom wall-fired boilers, cyclones, cell burner technology, and all other boiler types.

Phase I of this program requires NO_x reductions by January 1, 1995. Group 1 boilers under Title IV must reduce NO_x emissions by 1.8 million tons by relying on performance standards, not technology standards, on a boiler by boiler basis. This rule means that the utilities choose the methods of compliance that best suits their needs, hopefully providing flexibility, promoting technology development, and providing opportunities for reducing the cost to control.

The second part of the plan says that by January 1, 1997 EPA will rule whether or not more stringent standards should be established for dry bottom wall-fired or tangentially fired Phase II units. At that time EPA will also establish limitations for Group 2 boilers, which include wet bottom wall-fired boilers, cyclones, boilers using cell-burner technology, and other coal-fired boilers.

There exist five options for compliance under Title IV of CAAA. The first option is a standard emission limitation which states that dry bottom wall-fired boilers must meet the emission rate of 0.5 lb NO_x / million BTU and tangentially fired boilers must meet the emission rate of 0.45 lb NO_x / million BTU[11], which in most cases can be met

through the use of low-NO_x burners in combination with overfire air.[5] Another choice for compliance is averaging the emissions of two or more boilers in order to reduce the overall emissions to that of the standard.

When a utility is unable to meet the standard, it can qualify for a less stringent alternative emission limitation if it uses low NO_x burner technology (LNBT) which includes all commercially available combustion air staging approaches. A fourth option is for Group 1 boilers asking for a 15 month extension from January 1, 1995 to March 31, 1996, but the utility must prove that low NO_x burner technology cannot be installed before January 1, 1995 without interfering with the utility's ability to provide electricity to its customers. The fifth and final option is for a Phase II limitation affected unit with a Group 1 boiler. If these utilities comply with Phase I NO_x emission limits by January 1, 1997, they will be exempt from any revised Phase II emission limitations until 2008.[11]

2.6. NO_x CONTROLS

Controlling NO_x emissions from coal-fired utility boilers can be achieved through precombustion fuel modifications, combustion techniques, or by post combustion flue gas treatment. Figure 2-10[14] shows the development to date of these NO_x control technologies. Not all of these technologies are the most effective for coal-fired utilities

Technology	Developmental status
Pre-combustion techniques	
Fuel switching	Applies mainly to coal-fired units; usually produces only marginal improvement.
Combustion modifications	
Low-excess air firing (LEA)	This marginal technique has been widely practiced for more than a decade.
Burners out of service (BOOS)	This technique has been successful on gas-fired units, but has had poor results on coal.
Fuel biasing	Results similar to BOOS.
Overfire air (OFA)	In use for more than a decade. Very effective in combination with substoichiometric combustion techniques.
Flue gas recirculation (FGR)	This technique suffered difficulties on coal and was withdrawn from the market. It is a viable technique for natural gas.
Low-NO_x burners	Technology is in commercial operation.
Fuel reburning	Reburning with gas (in gas- or coal-fired units) has shown some promise, but is not yet widely commercial. Reburning with coal requires demonstration of coal micronizing technology.
Post-combustion reduction	
Selective non-catalytic reduction	This technique has been demonstrated, but is highly dependent on boiler design and suffers from ambiguous commercial assurances.
Selective catalytic reduction	This technique has been used extensively on coal-fired units for a few years in Japan and Germany, but the first applications to coal-fired boilers are just beginning in the U.S. Reaction to U.S. coals is a concern.
Adsorption/regeneration	
Various combined SO_2/NO_x control techniques	Mitsui's B-F process is in operation overseas; the Clean Coal demonstration of NOXSO is under construction; other technologies await full-scale demonstration.

Source: Fluor Daniel, Inc.

Figure 2-10. NO_x control technologies and their maturation

but are mentioned in this review for completeness. Figure 2-11[14] shows a summary of the performance and cost of some NO_x control technologies. Each of these technologies will be discussed in detail in the following section.

2.6.1. Precombustion Fuel Effects

One NO_x control technology to consider for coal-fired power plants is fuel switching. Coal contains a considerably greater amount of nitrogen than other fuels such as oil; therefore, coal combustion produces the highest amount of NO_x emissions, followed by oil firing and gas. Those boilers with the capability of firing multiple fuels could consider fuel switching as an option for controlling NO_x emissions.[2]

2.6.2. Combustion Modifications

Applications of combustion modification include low excess air (LEA), overfire air, low-NO_x burners, low-NO_x burners with overfire air, burners out of service (BOOS), flue gas recirculation, steam/water injection cooling, and reburning. These techniques lower NO_x emissions by one of the three methods: reduction in peak flame temperature in the combustion zone, reduction in the gas residence time in the high temperature zone, or operating at an off-stoichiometric ratio reducing the amount of excess air present during combustion. The later technique also results

Control technique	Reduction, %	Retrofit cost, $/kW
Miscellaneous combustion modifications	10-30	0-10
Overfire air	20-30	5-15
Flue gas recirculation	20-50	4-12
Low-NO_x burners	20-40	6-12
Reburning	40-50	30-50
SNCR	20-60	25-50
SCR	60-90	90-180

Source: Fluor Daniel, Inc.

Figure 2-11. NO_x reductions for various NO_x control technologies and their retrofit costs

in a lower flame temperature, enhancing NO_x reduction.[4]

2.6.2.1. Low Excess Air

The theory behind the use of low excess air for the reduction of NO_x emissions from coal-fired boilers involves reducing the total amount of excess air supplied for the combustion process.[12] Because of the resulting decrease in oxygen in flue gas with less excess air, a reduction in the fuel nitrogen conversion to NO_x occurs. Fuel nitrogen is converted to N_2 thus reducing NO_x production. With a decrease in excess air comes an increase in CO emissions and decrease in flame stability. LEA is usually supplemented by some other NO_x control resulting in total control efficiencies for coal-fired boilers of 15 to 60%. These efficiencies apply to various forms of low-NO_x burner technology.[7]

The utility industry originally implemented low excess air (LEA) firing in order to increase thermal efficiency and to reduce stack gas opacity due to acid mist. In fact it is used more as an energy conservation method rather than a NO_x control technique. LEA also has an economic incentive because it results in an increase in fuel efficiency. Most new boilers install LEA as a standard practice, while existing boilers are retrofitting to implement this technology.

Controls that must be installed to implement LEA while

also maintaining air/fuel distribution are: adjustments for air registers, fuel injector positions, and overfire dampers. For closer operator attention that must exist with LEA, continuous oxygen monitoring; accurate, sensitive air and fuel flow controls; and instrumentation for adjusting air flow at various loads must also be installed.[7]

2.6.2.2. Overfire Air

Overfire air (OFA) uses conventional burners that introduce fuel and sub-stoichiometric quantities of combustion air which is primary air. The remaining combustion air, the secondary air, is introduced at approximately a third of the distance down the firebox through overfire air ports. This technology reduces NO_x emissions in two ways. First, the staging of combustion which delays the process results in a cooler flame, thus suppressing thermal NO_x formation. The staging of the combustion air also reduces oxygen concentrations. This causes less mixing of fuel and air in the combustion region where fuel nitrogen is produced; therefore, NO_x formation is reduced.[13] Figure 2-12[4] demonstrates the dependence of NO_x on overfire air flow.

Overfire air ports are also referred to as NO_x ports. As discussed above, these ports reduce a portion of the secondary air and diverts this air to ports which introduce it later in the combustion process. NO_x ports are located

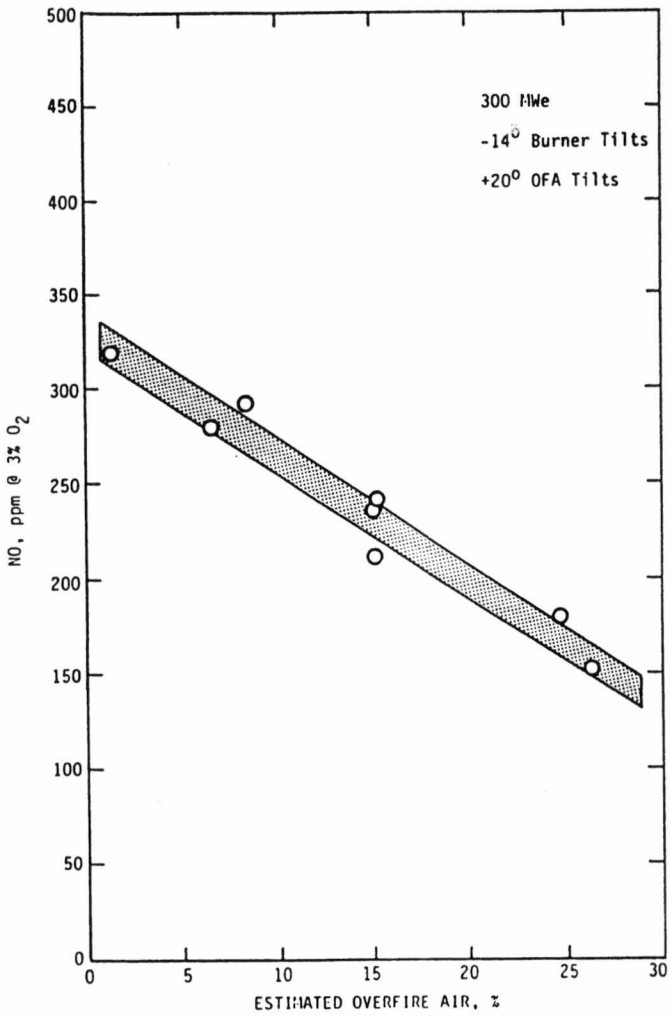


Figure 2-12. NO_x dependence on overfire air flow

close to the burners or at some distance from the burners; however, in most applications they are placed above the burner zone in furnaces arranged for gases to travel upward and out. Figure 2-13[2] illustrates the placement of these ports above the burners.

The use of overfire air (OFA) is a low cost option for reduction in NO_x emissions. After the effective date of federal New Source Performance Standards, most of the U.S. tangential boilers put into service were equipped with OFA. All commercially available systems include some OFA with redesigned low-NO_x coal and air nozzles. In order to retrofit low-NO_x combustion control technology for tangentially fired boilers, overfire air is a must. However, OFA technology is more attractive for new boilers rather than retrofitting existing boilers because of the cost of additional duct work, furnace penetrations, extra fan capacity and physical obstructions that must be incurred retrofitting an existing boiler. Another cost consideration is the potential need for an increase in furnace size to ensure complete combustion. For this reason OFA is more easily implemented on larger units.[7] Alone OFA can reduce NO_x by 30% with 10-20% of the combustion air being staged. The 1991 capital costs for OFA alone is between $5 per kilowatt and $10 per kilowatt.[2]

For the retrofit of existing coal-fired boilers there are two principal design requirements. The first of these

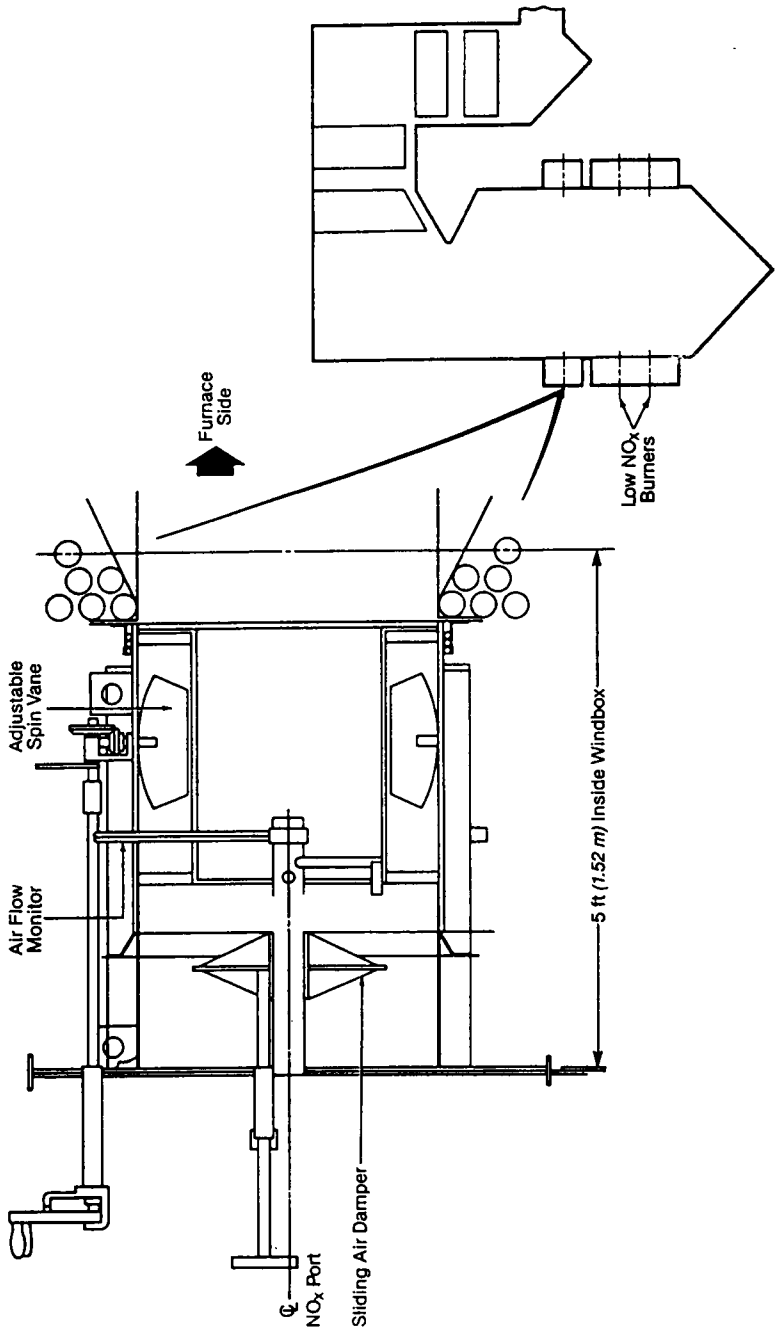


Figure 2-13. Dual zone NO_x port

additions is the provision for adequate furnace volume above the top row of burners which provides sufficient residence time to achieve optimum NO_x reduction performance. Secondly, several ports must be installed to assure high OFA velocity required for good mixing. The penetration of these ports into the furnace can weaken boiler tube panels along with affecting the structural integrity of the furnace.[7]

Operational problems, caused by low primary air flow rate creating incomplete combustion conditions, limit the degree to which staging can occur. Additional excess air may also be required in an OFA system in order to ensure complete combustion. This increase in excess air results in decreased boiler efficiency. The flame is larger with staged combustion and extends further into the furnace. These conditions can lead to flame impingement causing refractory damage and/or tube failures and diminishes the applicability of staging techniques for high heat release ranges. Constraints of the installation of OFA on existing units include the potential for affecting the structural integrity of the furnace as described above. Unburned carbon ash along with carbon monoxide emissions can be increased if >25% excess air is used. This is especially the case with high-rank bituminous coals. The reason for the increase in unburned carbon ash and CO is due to the large portion of the furnace volume that is needed with OFA in order to obtain sufficient separation between first and second stage

combustion. Another disadvantage of OFA retrofit is the issue of waterwall corrosion in high-sulfur coal and oil-fired boilers.

Although OFA is effective for all fuels, there exists an increase in potential furnace tube wastage due to local reducing conditions when firing coal or high-sulfur fuel oil. Also when firing coal in a system with OFA, a greater tendency for slag accumulation in the furnace exists. The reduced airflow to burners reduces the mixing of fuel and air.

2.6.2.3. Low-NO_x Burners

Low NO_x burners were manufactured in the early 1970s for thermal NO_x control. They were mostly designed for utility and industrial boilers and utilize low excess air, off-stoichiometric combustion or flue gas reduction principles. This technology is most useful for medium- or small-size boilers which usually have a few burners.[12] It is now generally accepted that low-NO_x burners (LNB) will be the primary technology for Title IV compliance, however, it has not been accepted whether OFA should be an integral part of the LNB system.[14]

The combustion scheme for low-NO_x burners is shown in Figure 2-14[4]. The pyrolitic zone is formed after the initial combustion zone. Pyrolysis involves the liberation of volatile nitrogenous species. Following this zone is the

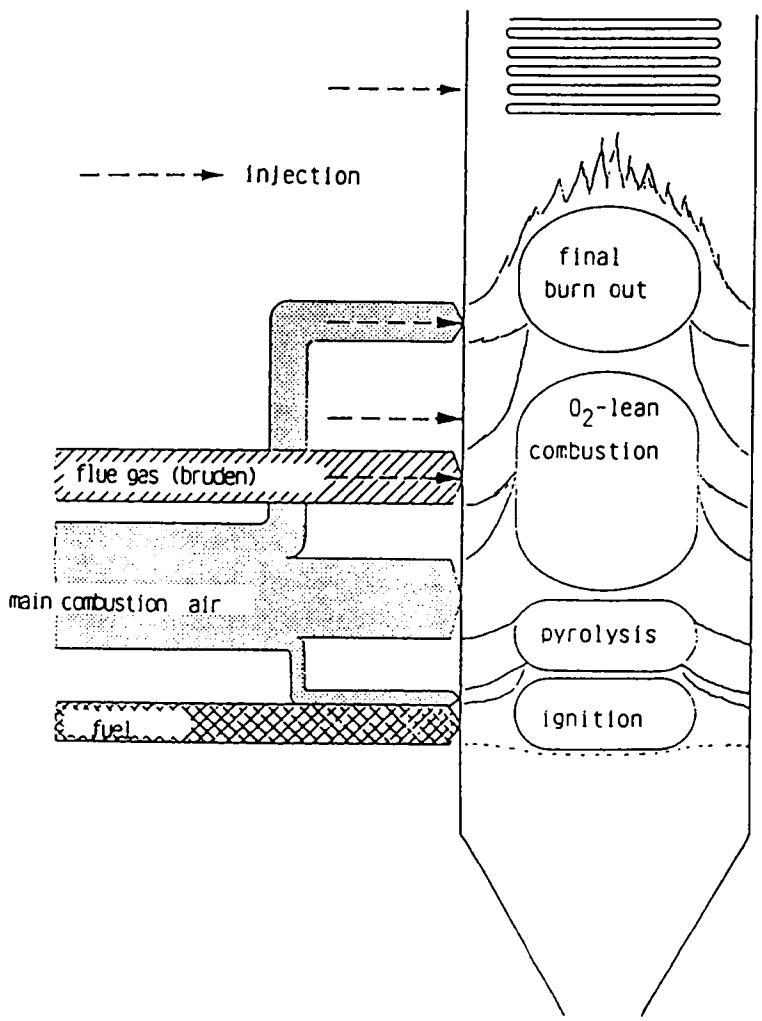


Figure 2-14. Low-NO_x combustion scheme

fuel-rich combustion zone which limits the formation of NO_x. A burnout zone follows in which combustion is allowed to proceed to completion.

The goal of the low-NO_x burner is to achieve a balance between minimum NO_x formation and acceptable combustion of carbon and hydrogen in the fuel.[13] Burner staging delays combustion, reduces flame temperature, and thus reduces NO_x. Low-NO_x burners reduce both fuel and thermal NO_x formation because of the lower peak flame temperature and oxygen concentrations.[15] Low-NO_x burners are only effective on the tangentially- and wall-fired units. The configuration of cyclone furnaces configuration prevents the application of standard low-NO_x burner technology. The design for the low-NO_x burner for the wall-fired unit is shown in Figure 2-15[4] while a comparison of the standard and tangentially fired burners is shown in Figure 2-16[4]. Figure 2-17[11] shows the benefits resulting from LNB retrofits on wall-fired boilers and Figure 2-18[11] shows the same for tangentially-fired units.

Figure 2-19[2] shows the cyclone furnace burner configuration which consists of a cyclone burner connected to a horizontally water-cooled cylindrical chamber. After coal and air are introduced into the chamber by the cyclone burner, large coal particles are forced onto the molten slag layer. This layer is formed on the chamber wall by the cyclonic effect of the injection and is where the combustion

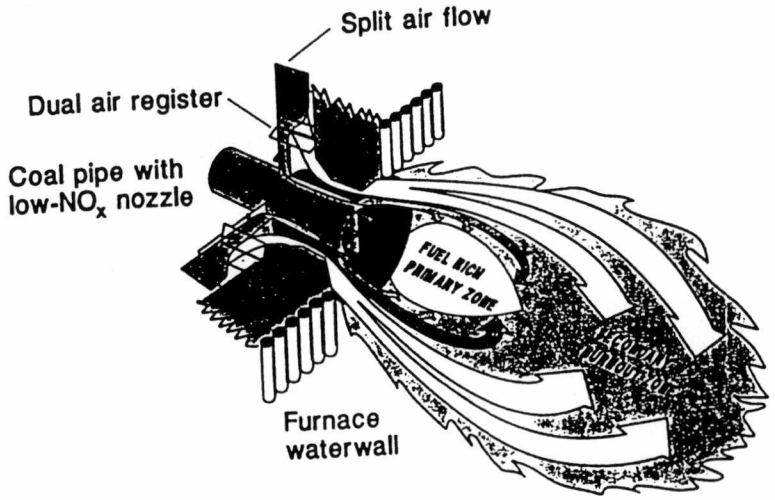


Figure 2-15. Schematic of a Low-NO_x burner for a wall-fired boiler

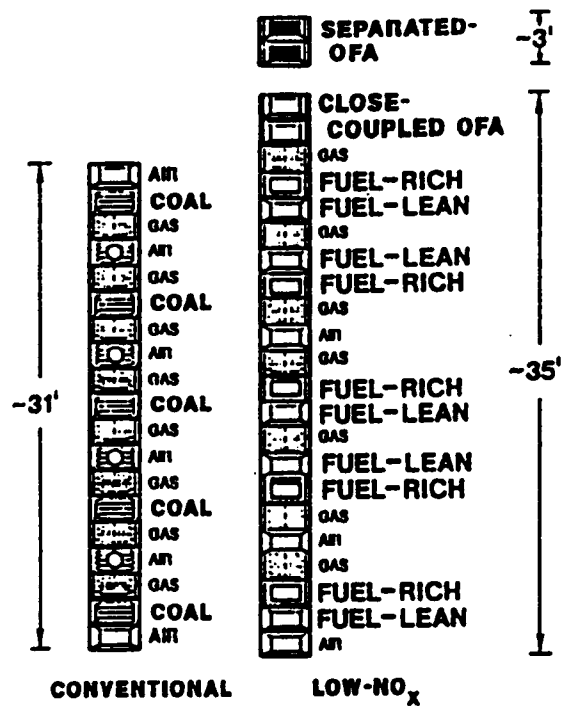


Figure 2-16. Comparison of conventional and PM burner configurations

Plant and unit	Utility	Combustion NO_x control[1]	Average emission reduction (percent)
Campbell Unit 3	Consumers Power	LNB	27
Cherokee Unit 3	Pub. Service Colorado	LNB	33
Colbert Unit 3	TVA	LNB	31
Cottam Unit 4	UK Utility	LNB	38
Drax Unit 6	UK Utility	LNB	51
Duck Creek Unit 1	Central Ill. Lt. Co	LNB	50
Edgewater Unit 4	Ohio Edison	LNB	41
Eggborough Unit 2	UK Utility	LNB	43
Four Corners Unit 3	Arizona Public Service	LNB	51
Gaston Unit 2	Alabama Power	LNB	50
Hammond Unit 4	Georgia Power	LNB	48
Harrison Unit 3	Monongahela Power Co	LNB	50
Homer City Unit 2	Pennsylvania Electric	LNB	65
Hsin-Ta Unit 1	Taiwan Utility	LNB	68
Johnsonville Unit 8	TVA	LNB	48
N. Simpson Unit 5	Black Hills Pwr. & Lt	LNB	58
Pleasants Unit 2	Monongahela Power Co	LNB	59
Quindaro St. Unit 2[2]	KS Bd. Pub. Utilities	LNB	—
Ratcliffe Unit 2	UK Utility	LNB	35
Wabash Unit 5	PSI Energy Inc	LNB	21
Hsin-Ta Unit 1	Taiwan Utility	LNB + OFA	80
Hammond Unit 4	Georgia Power	LNB + OFA	62
Gibson Unit 3	PSI Energy	LNB + OFA	37
Howard Down Unit 10	City of Vineland	LNB + OFA	65
Pleasants Unit 2	Monongahela Power Co	LNB + OFA	68
San Juan Unit 1	NM Public Service	LNB + OFA	65
Wabash Unit 2	PSI Energy Inc	LNB + OFA	58

[1] LNB = Low NO_x burners without overfire air; AOFA = Advanced overfire air; OFA = Overfire air.
[2] Only controlled NO_x emission rates available.

Figure 2-17. LNBT retrofits on wall-fired boilers

Plant and unit	Utility	Combustion NO_x control [1]	Average emission reduction (percent)
Gallatin Unit 4	TVA	LNC 1	8
Hunter Unit 2	Utah Power and Light	LNC 1	31
Fiddlers Ferry Unit 1	UK Utility	LNC 1+	38
Smith Unit 2	Gulf Power	LNC 1+	37
Bowen Unit 4	Georgia Power	LNC 2	31
Cherokee Unit 4	Pub. Service Colorado	LNC 2	37
Eastlake Unit 2	Cleveland Elec. Illum	LNC 2	33
Kingsnorth Unit 2	UK Utility	LNC 2	21
Smith Unit 2	Gulf Power	LNC 2	32
Valmont Unit 5	Pub. Service Colorado	LNC 2	35
Vermillion Unit 2	Illinois Power	LNC 2	29
Wansley Unit 1	Georgia Power	LNC 2	30
Yates Unit 6	Georgia Power	LNC 2	32
Brown Unit 3	Kentucky Utilities	LNC 3	30
Fucina Unit 2	Italian Utility	LNC 3	52
Labadie Unit 4	Union Electric Co	LNC 3	40
Smith Unit 2	Gulf Power	LNC 3	40

[1] LNC 1 = low NO_x coal and air nozzles with close-coupled OFA; LNC 1+ = modified LNC 1 system; LNC 2 = low NO_x coal and air nozzles with separated OFA; LNC 3 = low NO_x coal and air nozzles with close-coupled and separated OFA.

Figure 2-18. LNBT retrofits on tangentially-fired boilers

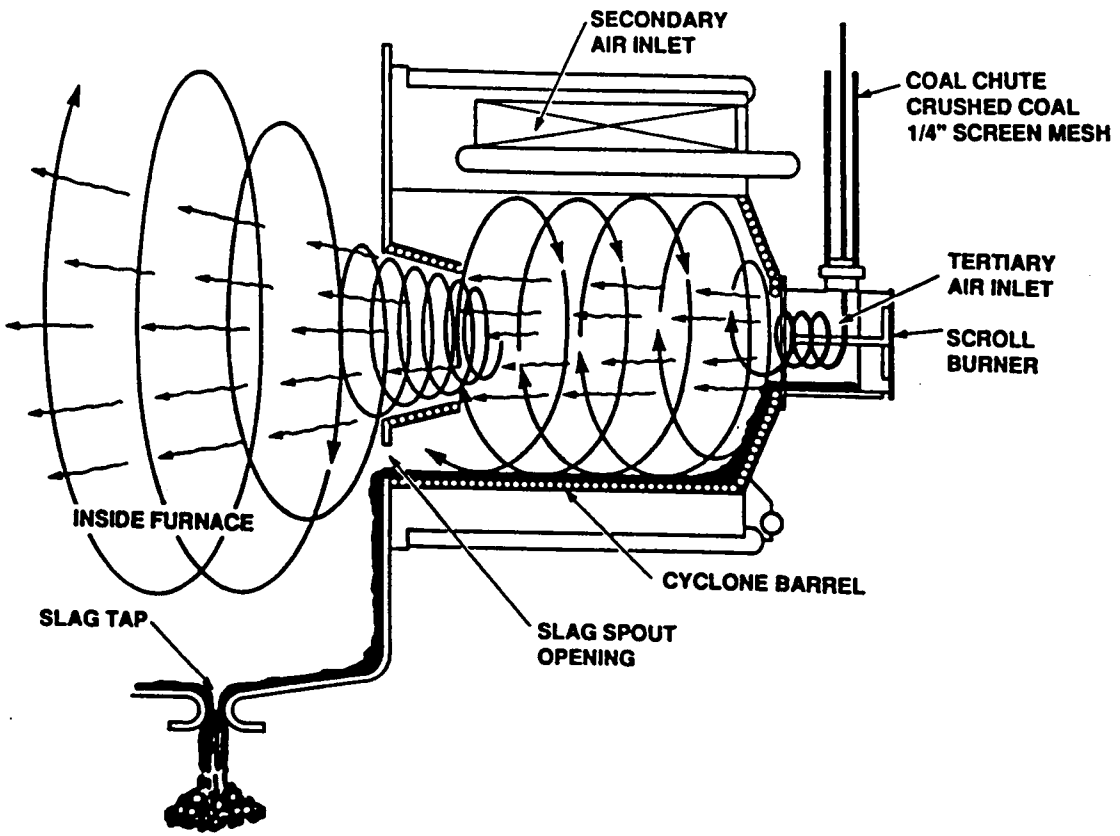


Figure 2-19. Cyclone furnace configuration

of the large coal particles occurs. The finer particles that are held in suspension by the gas stream within the cylindrical chamber are burned in the primary combustion zone. The flue gases and the remaining ash leave the cyclone, at which time they enter the main furnace. Combustion occurs outside the main furnace; therefore, modifying the furnace is not possible making the use of LNBs impossible also. The most effective method for reducing NO_x from cyclone configurations is reburning, which is discussed later in this review.

Babcock and Wilcox developed the dual register burner (DRB) in 1972 for firing pulverized coal. This burner provides two air zones around an axially positioned coal nozzle. A separate register controls each zone. Figure 2-20[2] shows this configuration. A portion of the secondary air is admitted through the inner air zone to help with ignition and flame stability. The rest of the air is passed through the outer air zone and mixed downstream in the flame. A venturi on the burner nozzle disperses the primary air-coal mixture which is then injected into the throat without deflection. A stable flame is produced with a fuel-rich core. This type of unit is used in combination with enlarged furnace combustion zones to reduce thermal NO_x and with a compartmented windbox to better control air distribution. NO_x reductions of 50 to 60% from uncontrolled levels can be achieved which enables its use on new boilers

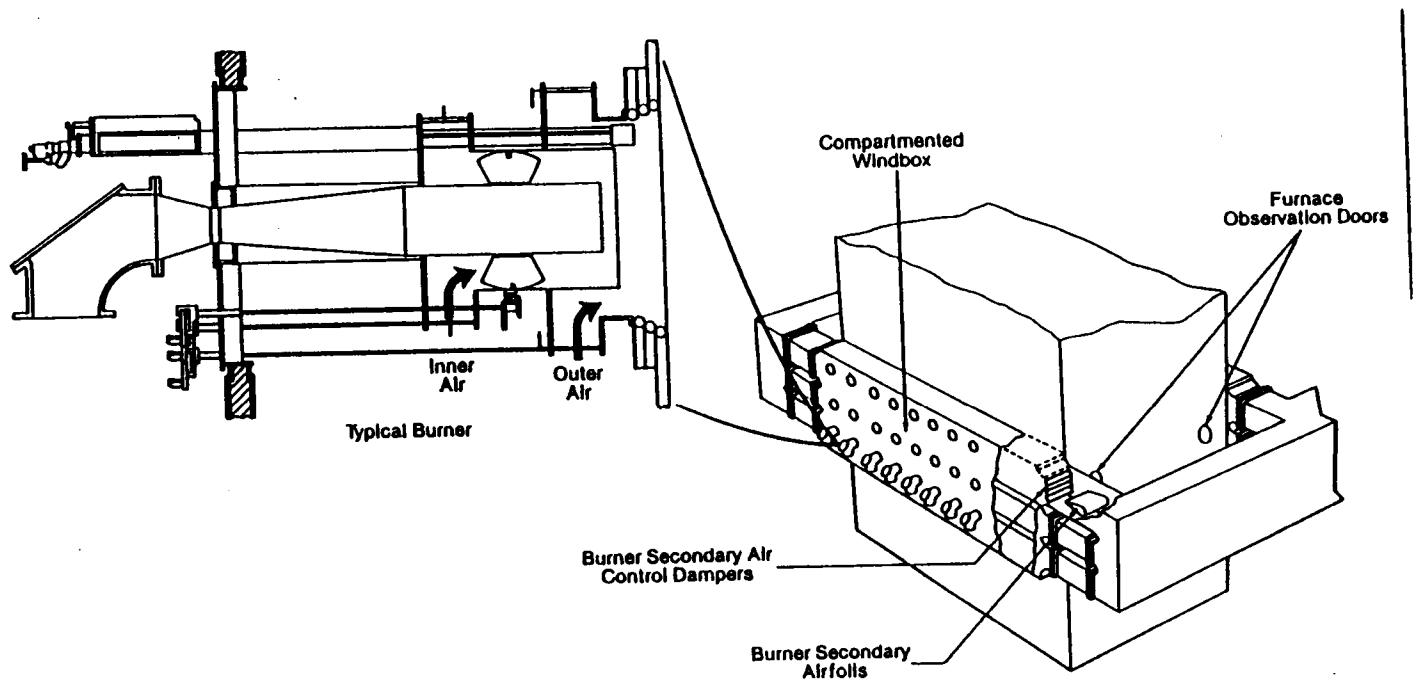


Figure 2-20. Dual register burner and compartmented window

without NO_x ports. NO_x emissions on utility boilers with the DRB are 0.27 to 0.70 lb/10^6 Btu.[2]

An advanced version of the DRB is the dual register XCL burner, called the DRB-XCL™ and shown in Figure 2-21[2]. A sliding disk regulates the air flow to the burner. In the burner barrel is an impact/suction pitot tube grid that measures the secondary air flow which then can be uniformly distributed among all burners by adjusting the disks. The inner and outer air zones are located downstream of the pitot tube grid. Ignition is stabilized by the adjustable vanes in the inner zone, while the outer zone is the main air path. A conical diffuser and flame stabilizing ring in the burner nozzle improve flame stability and reduce NO_x emissions by incorporating fuel staging. Without NO_x ports the DRB-XCL™ reduces NO_x emissions by 50 to 70%.

The flame combustion zones that the burner produces generate rapid heating and high temperatures in the fuel-rich flame core as seen in Figure 2-22[2]. More of coal is burned as volatile matter and a larger portion of the fuel nitrogen is released earlier in the combustion process which leaves less char. NO_x formation is minimized by limiting the available oxygen in the flame core and by generating the reducing species from the volatile material which later can aid in reducing NO_x.

The Low-NO_x Cell™ burner (LNCB) in Figure 2-23[2] is designed to fit existing cell burner locations and reduce

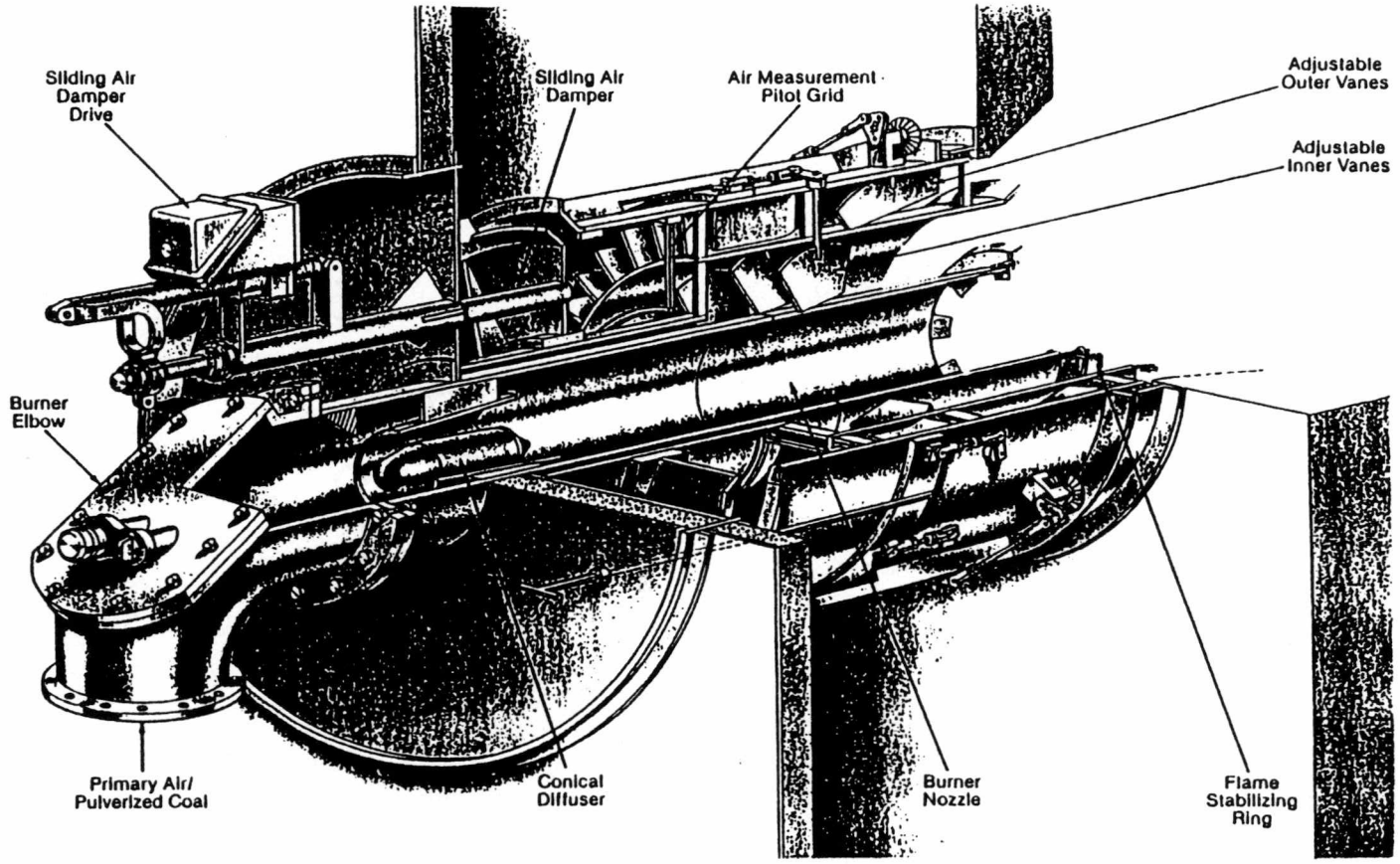


Figure 2-21. DRB-XCL™ low-NO_x burner for pulverized coal firing

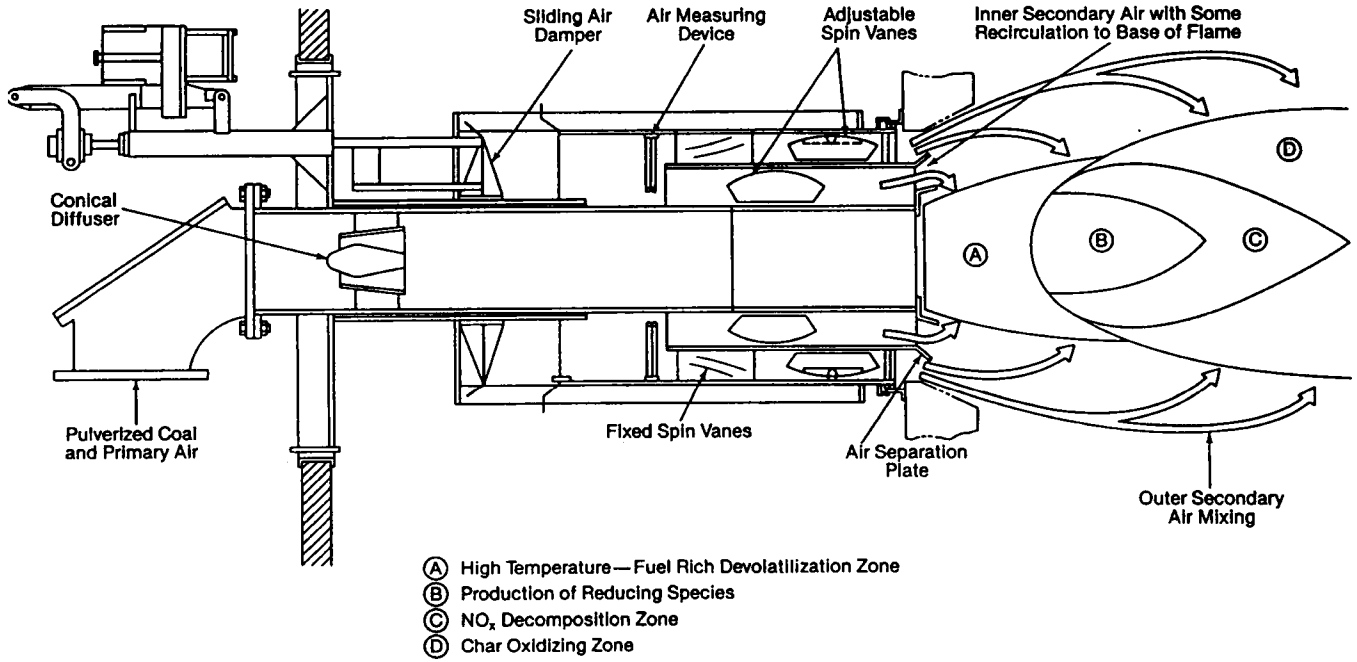


Figure 2-22. DRB-XCL™ low NO_x combustion zones

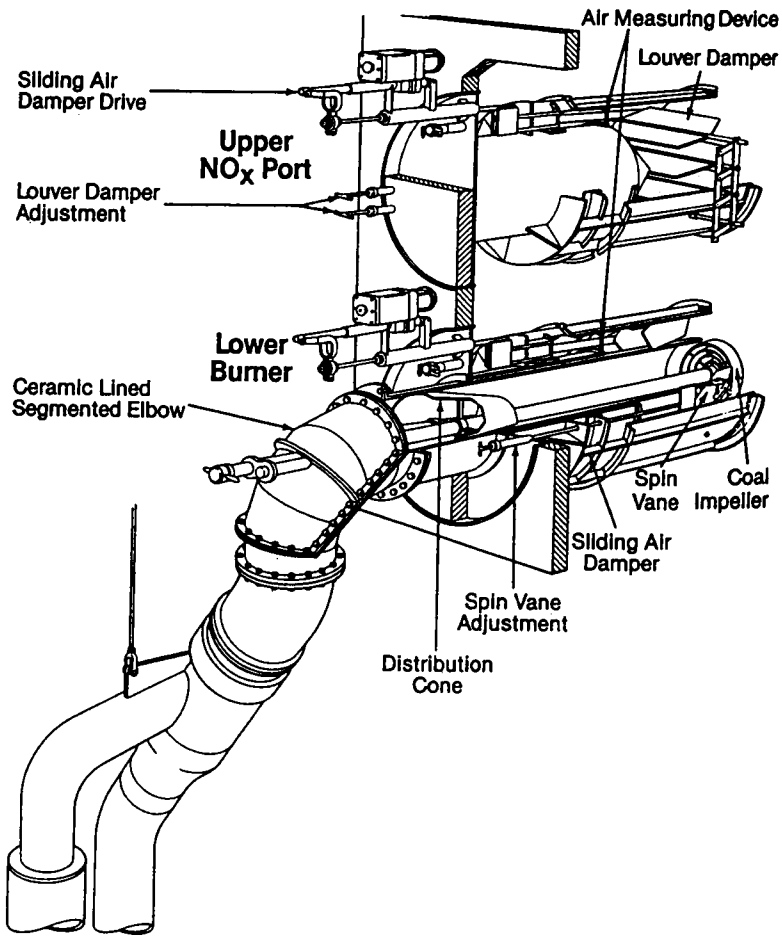


Figure 2-23. Low-NO_x Cell Burner

NO_x. This burner supplies all the coal to the lower burner throat with a portion of the secondary air, while the upper throat serves as an integral NO_x port for each burner location. This upper throat has a sliding disk and pitot tube grid which sets secondary air flow. Vanes in the upper throat also control the mixing of this air into the flame. NO_x emissions can be reduced by 50% with LNCB™ and at the same time maintain combustion efficiency.[2]

The use of overfire air with low-NO_x burners is an effective way of increasing NO_x reductions. Incorporating OFA with low-NO_x burners can achieve NO_x reductions of up to 50%. For OFA with LNBs the capital costs are approximately $15 to $25 per kilowatt.[2]

2.6.2.4. Burners out of Service

Burners out of service (BOOS) involves using only individual burners or rows of burners to admit air. The remaining fuel-admitting or active burners then supply the total fuel demand. These active burners operate under more fuel-rich conditions than normal. The inactive burners emit the remaining air required for combustion.[5] This technique has not been successful on coal-fired units, but has had positive results on gas-fired units[14]. Figure 2-24[5] shows the typical BOOS arrangement for opposed fire units.

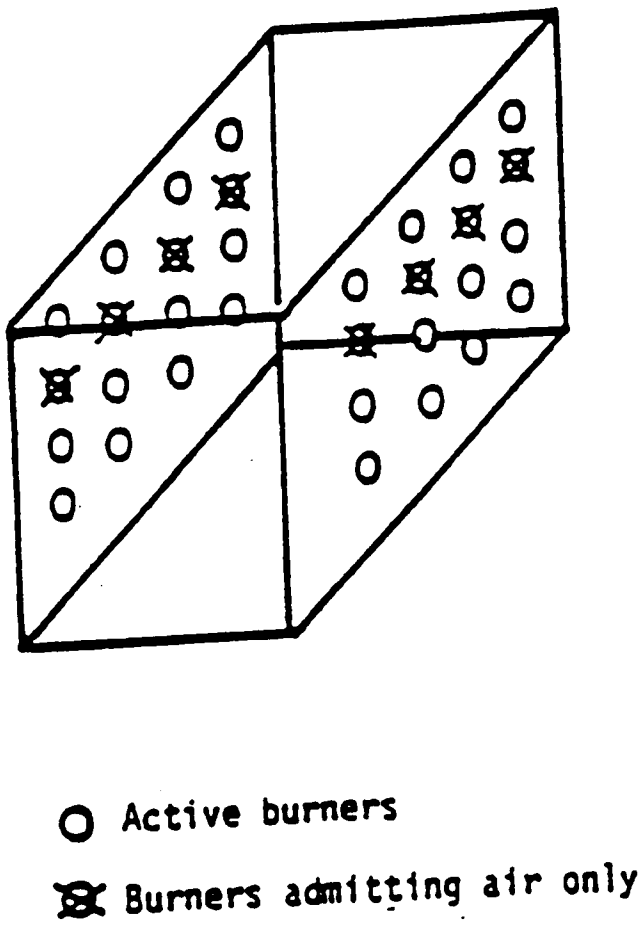


Figure 2-24. Typical BOOS arrangement for opposed-fired units

2.6.2.5. Flue Gas Recirculation

Flue gas recirculation involves recycling a portion of the flue gas to the combustion zone, reducing peak flame temperature and the partial pressure of available oxygen at the burner inlet. When introduced into the combustion zone, the recycled flue gas may be pre-mixed with the combustion air or injected directly into the flame zone. This second option provides more control of the amount and location of the flue gas recirculation.

Because the peak flame temperature and available oxygen is reduced, thermal NO_x is reduced rather than fuel NO_x; therefore, this technique is mainly applicable to gas- and oil-fired boilers. Other disadvantages of FGR include altering of heat distribution and lowering of fuel efficiency. This NO_x reduction method is more adaptable to new designs rather than as a retrofit application.[12]

2.6.2.6. Reburning

Reburning is also referred to as fuel staging. Reburning destroys NO_x after it has been formed by introducing the fuel into the furnace in steps. The majority of the fuel is burned in the furnace at near stoichiometric conditions. When the combustion process is partially complete, the remainder of the fuel is introduced to create a reducing zone which forms hydrocarbon radicals. These radicals strip oxygen from the already formed NO_x

reducing the amount of NO_x present. The rest of the air required for combustion is then introduced. Figure 2-25[4] shows the concept of reburning technology.[4]

Fuel-staged systems can have separate burners or fuel injectors followed by NO_x ports that supply the remainder of the combustion air. Some low-NO_x burners incorporate fuel staging in supplying all the fuel for combustion. NO_x emissions can be reduced 50-70% with such burners.[2]

2.6.3. Post Combustion Techniques

Because combustion modifications are not always possible or do not provide adequate NO_x reductions, additional techniques may be applied downstream of the combustion zone. Two common techniques of this type are selective catalytic reduction (SCR) and selective noncatalytic reduction (SNCR) each of which controls NO_x emissions by reducing NO_x to N_2 and water.

These reactions take place as a result of a chemical agent being injected into the flue gas. The chemical agents most commonly used for such applications are ammonia and urea for SNCR and ammonia for SCR. Anhydrous ammonia (NH_3) is usually used as the reducing agent; however, because of the hazards of storing and handling such a chemical, aqueous ammonia at a 25 - 28% concentration is sometimes used.[2]

Another less common technique for reducing NO_x emissions is nonselective catalytic reduction (NSCR) in

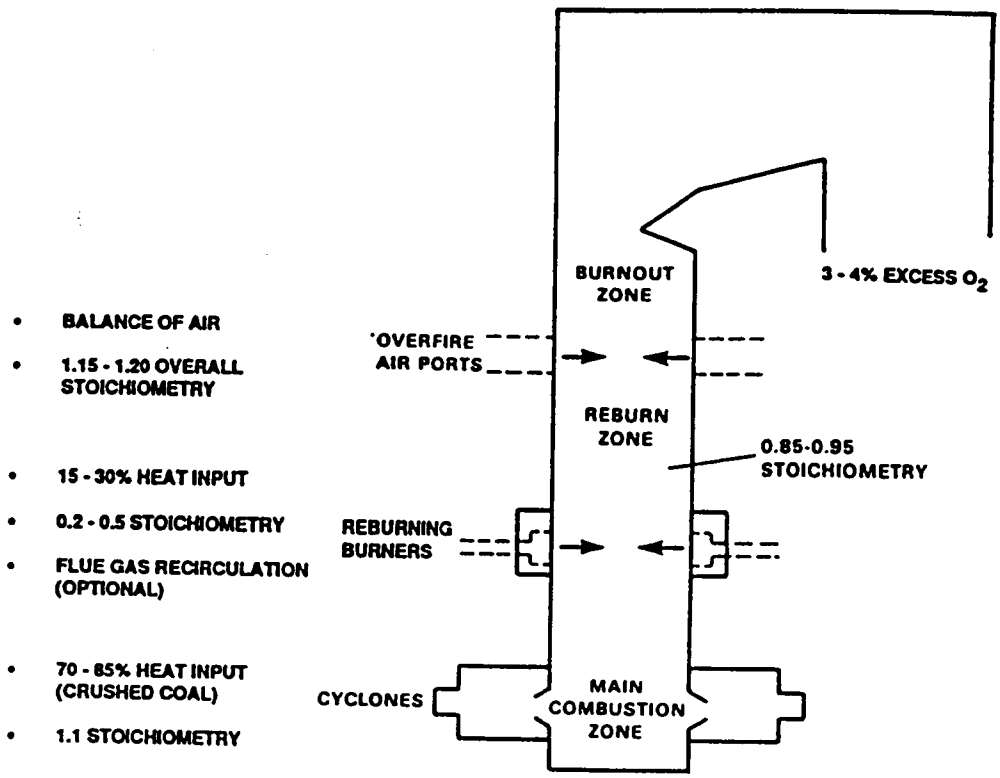


Figure 2-25. Reburning technology

which NO_x and VOCs are reduced by available carbon monoxide aided by a catalyst.[7]

2.6.3.1. Selective Catalytic Reduction

When high efficiencies of 70-90% are required, SCR is the most effective technology for reducing NO_x. Selective catalytic reduction (SCR) technology uses ammonia to reduce flue gas NO_x to N_2 and H_2O in a chemical reduction. Environmental regulations mandate that SCR systems be installed on utility boilers in Japan, Germany, and other European countries. Although the use of SCR technology currently in the United States has been applied mainly to gas turbines, combined cycle systems, and small industrial boilers and process heaters, it is expected that its use will extend to new large installations during the 1990s.[2]

Ammonia is introduced into the flue gas at an optimal temperature range for such reactions[4], which occurs between 675 and 840°F. Although the minimum temperature range varies, it is based on fuel, flue gas specifications, and catalyst formulation. With an increase in the flue gas sulfur dioxide concentration the minimum temperature also increases in order to eliminate the formation of ammonium sulfate salts in the catalyst bed. If operated above the appropriate temperature, many catalyst materials become less effective.[2]

After ammonia injection, NO_x is then reduced to

molecular nitrogen in a separate reactor vessel containing the catalyst. The process of NO_x reduction that occurs once the mixture enters the catalyst is governed by the following reactions:

$$4NO + NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

Figure 2-26[2] shows the SCR process, and Figure 2-27[2] shows the principles of the NO_x removal process for SCR.

Catalysts typically fall into one of three categories: base metal, zeolite, and precious metal. To date base metal catalysts have been the main catalyst type used.[2] This catalyst is usually a mixture of titanium dioxide, vanadium pentoxide, and tungsten trioxide.[4] The disadvantage of the base metal catalyst is its tendency to oxidize SO_2 to SO_3. The SO_3 from this reaction reacts with ammonia slip to form micron-sized ammonium sulfate salts which can lead to a visible plume under certain temperature conditions. This problem can be reduced with proper system design and catalyst formulation.

New to NO_x emission control zeolite catalysts are aluminosilicate materials. They function as the base metal catalysts do, even having the potential as the base metals to oxidize SO_2 to SO_3. An advantage of the zeolites is that they have an operating temperature of 970°F.

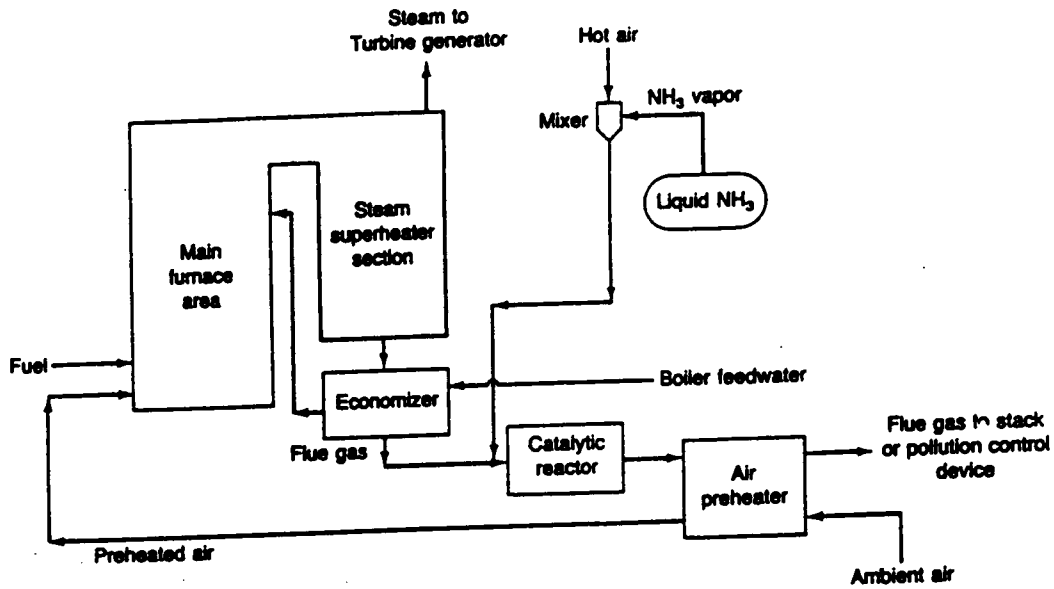


Figure 2-26. Schematic flow diagram for the SCR method for NO_x control

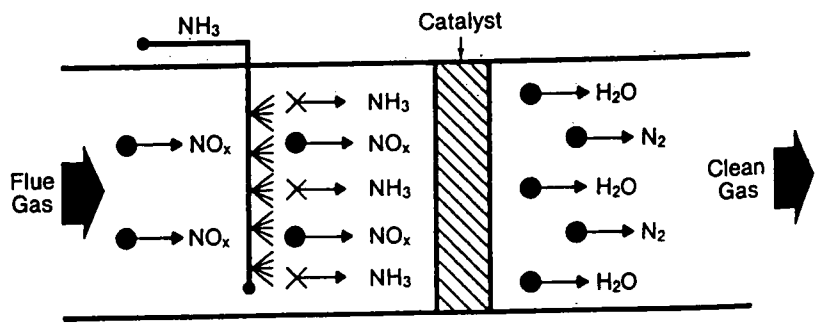


Figure 2-27. Principles of NO_x removal process for SCR

Also a new catalyst in NO_x control is the precious metal catalyst, which is manufactured from platinum and rhodium. Operating temperature and flue gas constituents are important to consider as precious metal catalysts can act as oxidizing catalysts converting CO to CO_2 under certain temperatures. The higher costs and SO_2 to SO_3 oxidation cause these catalysts to be used less often.

Catalysts are manufactured into a catalyst block which is either in parallel plate or honeycomb configuration, each having its own advantages and disadvantages. While the honeycomb configuration requires less reactor volume for a given surface area, the plate type catalyst produces less pressure drop and is less likely to plug or erode when particulate laden flue gas goes through the SCR reactor.[2]

In Japan two different SCR systems have been developed for placing the catalyst into the boiler-flue gas system. The first system is the low dust configuration in which the flue gas particles were removed before the gas entered the SCR. High temperature electrostatic precipitators (ESP) are used on such systems.

Another option for placing SCR is the high dust configuration which is used if the ESP were a low temperature device. The SCR in this case is placed immediately downstream of the boiler outlet. The term, high dust, is used because the catalyst has to operate under the full particulate loading conditions of the boiler flue gas.

A third system was developed by the Germans called a tail-end design. In this configuration part or all of the particulates collected at the ESP are re-introduced into the boiler to slag them for disposal. These systems have the SCR placed downstream of the flue gas desulfurization equipment and are used at power plants which use a slagging or wet bottom boiler. Figure 2-28[16] shows the layout of all three of these systems.

The efficiency of SCR for reducing NO_x depends on the temperature of the flue gas. Other important factors to consider for proper operation are the NO_x concentration, the amount of ammonia and its distribution throughout the flue gas relative to NO_x distribution, the amount of dust in the flue gas, SO_2 concentration in flue gas, the amount and form of flue gas trace material concentrations, and the amount of oxygen present.[1]

2.6.3.2. Selective Noncatalytic Reduction (SNCR)

Two basic selective noncatalytic reduction processes are available. The first is an ammonia based system that has been developed by Exxon, called Thermal DeNOx. The second of these two SNCR systems is a urea-based technology developed under the Electric Power Research Institute (EPRI), called NOxOUT.

Both systems operate off the same principles, by injecting a reducing agent (ammonia or urea) into the NO_x

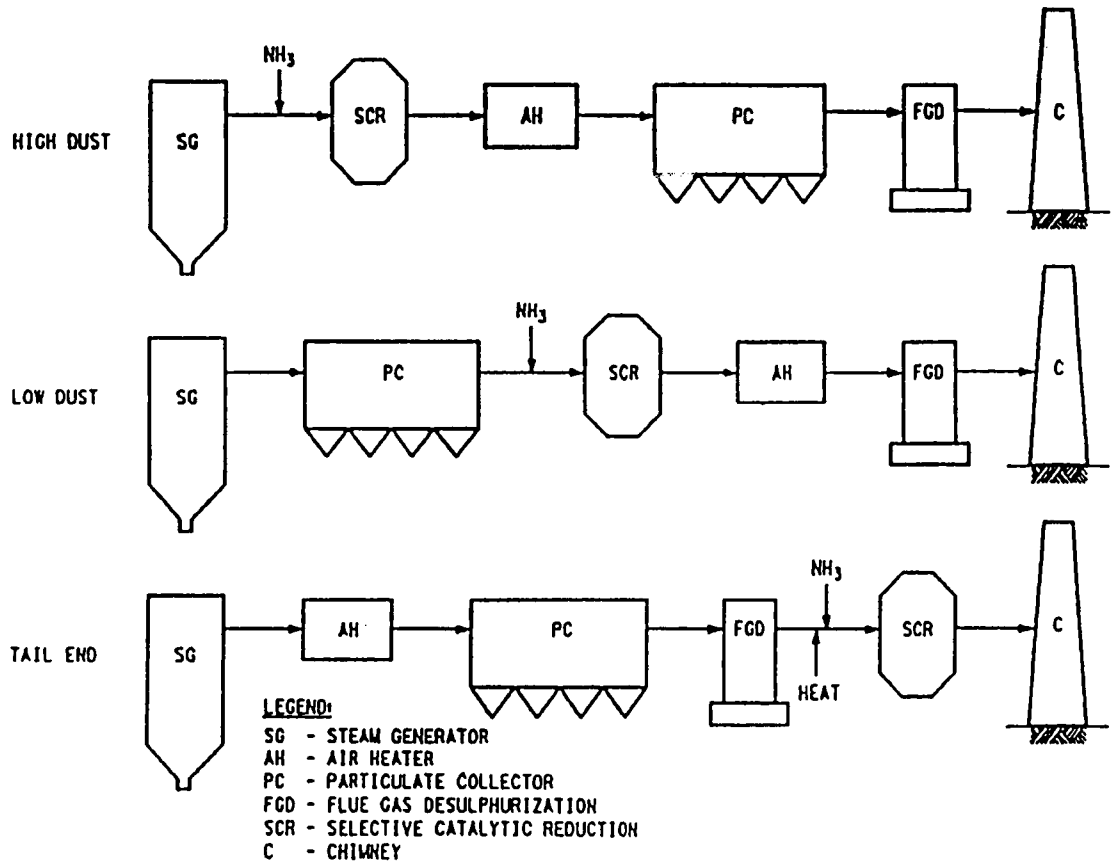


Figure 2-28. Three SCR system layouts

laden flue gas within a certain temperature range. This chemical agent must be properly mixed with the flue gas along with having sufficient residence time in order to have adequate results. The reactions for both processes are:

Ammonia: $4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$

Urea: $2NO + (NH_2)_2CO + 1/2O_2 \rightarrow 2N_2 + 2H_2O + CO_2$

Although temperatures above 1700°F are preferred, the optimal temperature range for both these reactions is 1400 to 2000°F. At temperatures greater than 2000°F, ammonia and urea react with available oxygen to form NO_x. Chemical enhancers, such as hydrogen, are required below 1600°F to assist the reactions.

Storage and handling equipment for the ammonia or urea, equipment for mixing the chemical with the carrier (either compressed air, steam, or water), and the injection equipment make up the SNCR system. The injection system is made up of nozzles located at various elevations on the furnace walls to match the expected flue gas temperature. The supplier provides the number and location of the nozzles based on good reagent distribution within the flue gas.

While ammonia is usually injected into the gas stream in a gaseous state, urea is injected as an aqueous solution. Because the urea is injected in an aqueous form, a longer residence time is required in order to provide sufficient

time for the liquid droplets to vaporize. Ammonia could be injected in an aqueous form; however, as with the aqueous urea solution, a longer residence time would be required.

Excess unreacted ammonia must be treated because as flue gas temperatures increase, unreacted ammonia can react with other combustion species, mainly sulfur trioxide (SO_3), to form ammonium salts. The products of unreacted ammonia and combustion products are ammonium sulfate [$(NH_4)_2SO_4$] and ammonium bisulfate (NH_4HSO_4). While ammonium sulfate is a dry particulate (1 to 3 microns in diameter) that may contribute to plume formation, ammonium bisulfate is highly acidic and sticky and deposit on air heaters contributing to fouling and corrosion.

NO_x reductions of 70% are possible under controlled conditions, but 30-50% reductions in NO_x are usually used in order to minimize reagent consumption and unreacted ammonia carryover.[2] Capital costs are about $10 to $20 per kilowatt but operating costs have not been documented since 1991.[4]

The NOxOUT process has two important features, a low energy consumption of 20-40 KW and the ability to control ammonia slip. This technology can achieve up to 80% NO_x reduction or when combined with other NO_x reduction technologies, can achieve greater than 85% reductions.

NOxOUT has been tested on a full-scale basis on different utilities. After performing a three week demonstration of NOxOUT, Wepco's boiler #4, a 70MW unit,

achieved a NO_x reduction of 60% at an installation cost of $9.00/kW and an annualized use cost of $414/ton NO_x reduced. The New England Power Company (NEPCO) has installed NOxOUT on Units 1, 2, and 3. Unit 2 is a front wall-fired, dry bottom boiler burning bituminous coal with a size of 84 MW. The Unit achieved NO_x reductions of 66%.[21]

Most SNCR systems are seen on smaller municipal waste or biomass fueled boilers. In these systems the proper temperature range is located in the upper furnace, while in large utility units, this optimal temperature window is found in the convection pass cavities making application more difficult, especially in retrofits. Applying SNCR to large utility boilers can achieve 20 to 40% NO_x emission reductions. To incorporate SNCR in new boilers, the boiler convection passage may have to be specially designed with a dedicated open cavity in an optimal temperature window for the reactions to occur as in Figure 2-29[2].

2.6.3.3. Combined SO_2 and NO_x controls

Combined NO_x and SO_2 control systems are at various stages of development and demonstration.[2] Many of the designs have only been tested on a pilot scale. Although several of these technologies exist, a selected few are covered here. The NO_x removal in most cases relies on the same principles and even the same technologies already discussed.

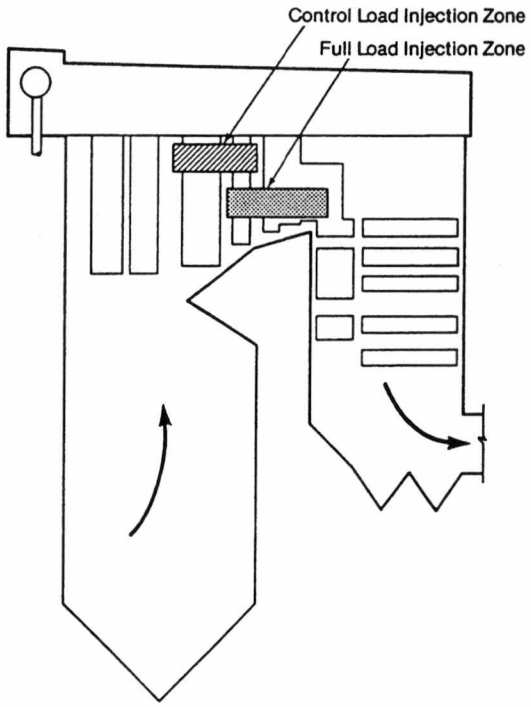


Figure 2-29. Coal-fired utility boiler with SNCR temperature window location at full- and control-load

Flue gas desulfurization systems, wet or dry, can achieve 70 to 90% SO_2 removal while SCR systems are able to achieve NO_x reductions of more than 80%. Integrating these two systems creates a combined SO_2 and NO_x removal into a single unit operation. Such a configuration should minimize waste production or form valuable by-products, along with minimizing energy use especially in the flue gas heating or cooling. This design should consider flexibility to different circumstances in addition to considering the possibility of refitting requirements. High efficiency of SO_2 and NO abatement must be attained while keeping overall costs low.

One such a system that provides all the above options uses a dry process based on regenerable copper-on-alumina sorbent catalyst. At the same time that the copper-on-alumina catalyzes the oxidation of SO_2 to SO_3 which immediately reacts with the sorbent-catalyst to form surface metal-sulphate species, copper ions catalyze the conversion of NO to N_2 in the presence of O_2 and added ammonia. Figure 2-30[1] shows the schematic for the process layout along with the chemicals involved in this system.[1]

Another combined SO_2 and NO_x removal system is a dry injection process that has demonstrated 90% SO_2 removal and 65% NO_x removal. This removal is achieved by the combined injection of hydrated lime and sodium bicarbonate coupled with a low-NO_x burner. The hydrated lime injected into the

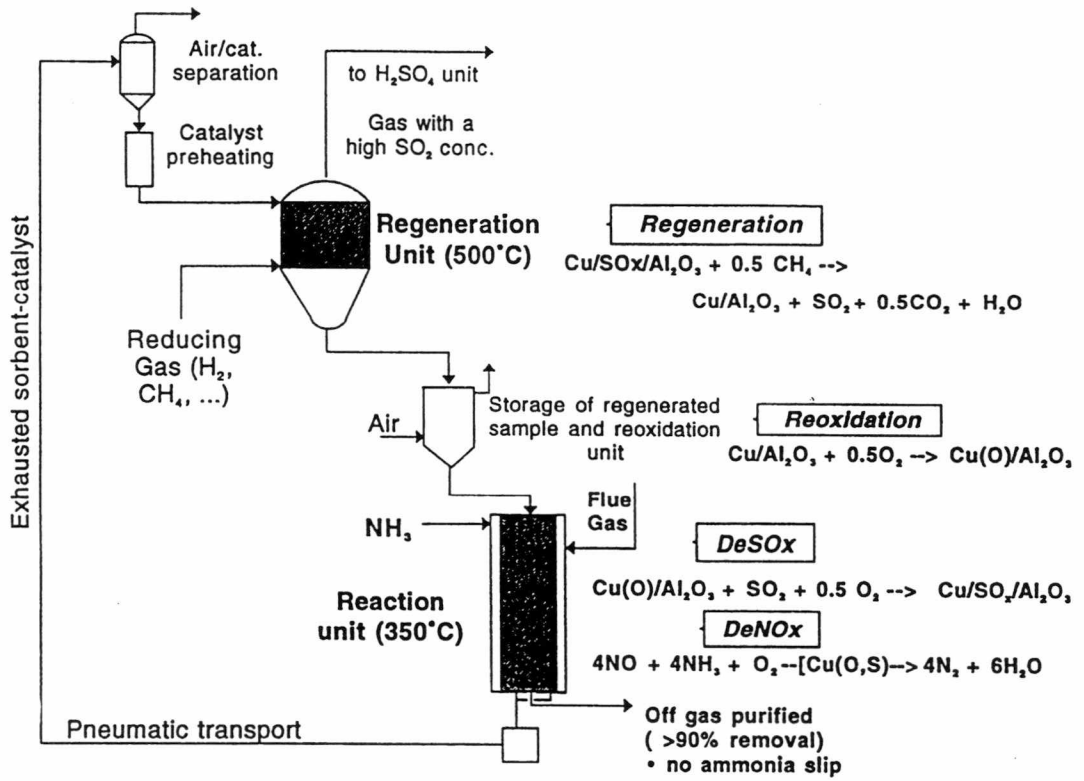


Figure 2-30. Copper-on-alumina sorbent catalyst system (combined SO_2 and NO_x removal system)

economizer captures 80% of the SO_2 after which sodium bicarbonate is injected downstream of the air heater. This second injection raises SO_2 removal to 90% and contributes to NO_x removal. EPRI tested this system and concluded that the process is a suitable low-capital cost retrofit technology with low maintenance requirements. Disposal of sodium-based wastes has been a problem, historically, however, due to the solubility of sodium.[16]

Another combined removal process uses an electron beam for the removal of SO_2 and NO_x in the flue gas of coal-fired boilers. The high energy beam of electrons that is directed into flue gas produces radicals and free atoms that contain oxygen and react with SO_2 and NO_x to form acids. By reacting with an alkali to form solid salts, these acids can be removed. In order to reach high humidity and low temperatures, conditions which enhance the alkali reactions, a lime slurry dryer can be used.

With this type of design, the flue gas passes though a spray dryer, cooling and humidifying the gas. Hydrated lime in the form of fine particulate is then entrained by the gas. Calcium sulfite is formed in the spray dryer where half of the SO_2 reacts with the calcium hydroxide. The gas is then irradiated by an electron beam resulting in the conversion of SO_2 and NO_x to sulfuric and nitric acid. After the gas passes through a fabric filter and reacts with calcium hydroxide, calcium sulfate and nitrate are produced.

The filter removes both these products and the fly ash.

This system has been tested on a pilot scale basis on a 150 MW coal fired boiler at the TVA Shawnee Steam Plant. The test showed that other than radiation dose, inlet SO_2 concentration had the largest effect on E-Beam removal of SO_2 and NO_x. A high inlet concentration of SO_2 promoted NO_x removal but impeded SO_2 removal. With an applied dosage of 1.5 mrad and 1125 ppm inlet SO_2 concentrations, the NO_x removal was 80%. The same applied dosage of 1.5 mrad with 80 ppm SO_2 inlet concentration achieved a NO_x removal of 50%.[17]

The NOXSO process utilizes regenerable, dry adsorption to remove over 95% of SO_2 and NO_x from boiler flue gas. Advantages of this process include the absence of wastewater streams to treat or solid wastes to store, the economical competiveness with conventional flue gas treatment, the reduced amount of space required as compared with conventional flue gas treatments, and the compatibility of the process on any type of fuel.

The process works by having flue gas from the combustion process flow upward through a fluidized bed of NOXSO sorbent beads. Onto these beads SO_2 and NO_x are absorbed. The sorbent is transferred to a sorbent heater to begin the regeneration cycle after the sorbent is saturated with pollutants. NO_x is stripped from the sorbent in the heater. The pollutant is then returned as combustion air to

the furnace and reduced to nitrogen, carbon dioxide, and water.

The sorbent is moved to the regenerator where through a series of chemical reactions, the adsorbed sulfur compounds are removed. The gases that are formed in the regenerator are sent to an off-gas processor where either commercial grade sulfur, sulfuric acid or liquid SO_2 are recovered. The adsorber is returned for reuse after it is cooled in a fluid bed.

The pilot scale plant for the NOXSO process was Ohio Edison's Toronto Power Plant in Toronto, Ohio. The slip stream tested was extracted from either Boiler #10 or #11 and was equivalent to a 5 MW coal-fired power plant. After 6000 hours of operation, the removal efficiency of SO_2 averaged 90%, and the removal efficiency of NO_x averaged 80%. The removal efficiencies of SO_2 and NO_x varied with SO_2 and NO_x concentration in the flue gas, sorbent circulation rate, flue gas flowrate, adsorber bed height, and adsorber temperature.

A full scale commercial demonstration of the NOXSO process is the retrofitting of a 115 MW pulverized coal-fired cyclone boiler. The point at which the process will be tied into the plant if the flue gas ductwork between existing particulate collection devices and the plant stack. Although the NOXSO Process can operate either upstream or downstream of a particulate collection device, the NOXSO

Process for this demonstration project will be placed to minimize the effect on collector performance. This project was to have begun construction in 1993.[22]

3. MODELING METHODOLOGY

In order to determine the effects that power plant NO_x control technologies have on ozone concentrations, the Urban Airshed Model (UAM) was used to model NO_x reductions from power plants in the Middle Tennessee Area. Nashville is a moderate nonattainment area for ozone due to violations in 1988. A 1990 State Implementation Plan (SIP) Inventory[23] was performed by the University of Tennessee for this area. Computer modeling is required for moderate nonattainment areas by the Clean Air Act Amendments to show attainment of the National Ambient Air Quality Standard for ozone by 1996. The 1990 SIP Inventory was first backcast to 1988 for validating the model and was then forecast to 1996 for attainment purposes. The three power plants located in this area are Cumberland Steam Plant, Gallatin Steam Plant, and New Johnsonville Steam Plant. This study on power plants was performed on the 1988 basecase emissions.

The modeling domain, Nashville, and the power plants in this area are shown in Figure 3-1. These power plants emit NO_x due to the combustion of coal. This NO_x reacts with other atmospheric species causing the formation of ozone (see Chapter 2). Although in some parts of the country the reduction of VOC emissions causes a decrease in ozone concentrations, the production of ozone in this area proved to be most sensitive to reductions in NO_x emissions, which can be

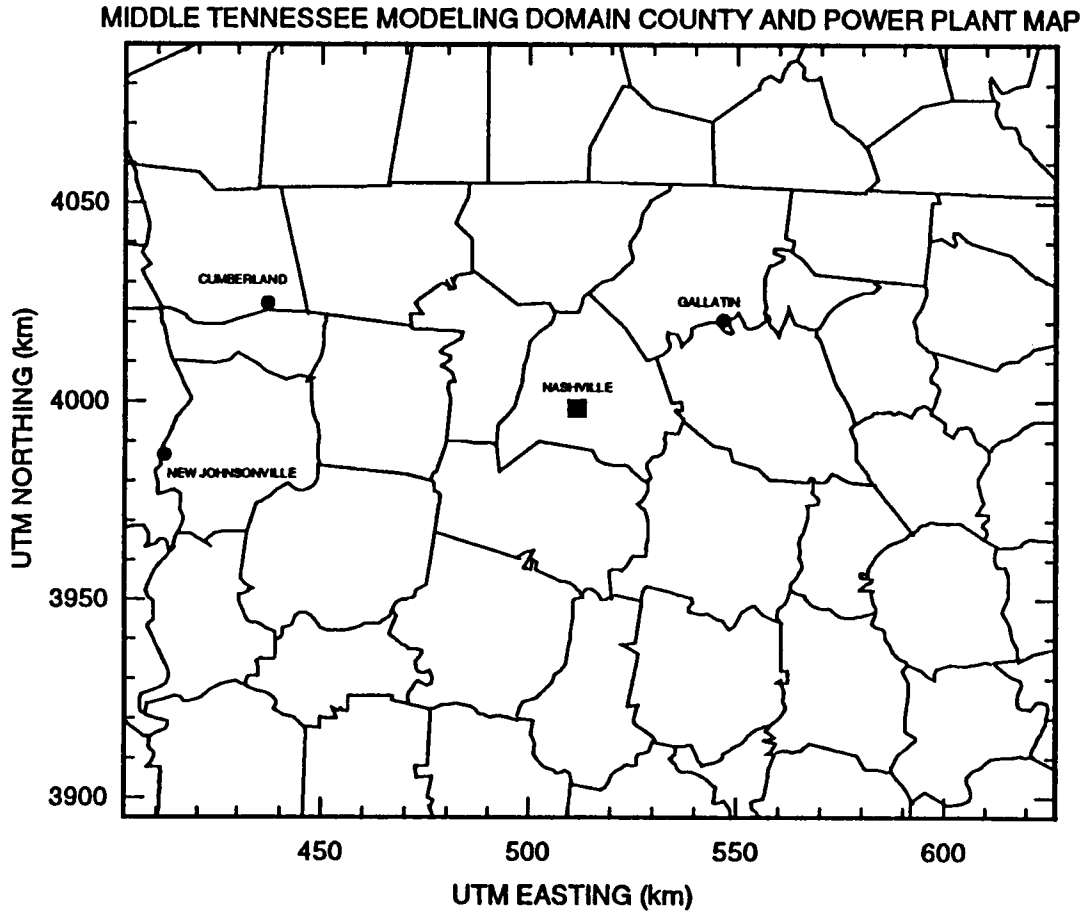


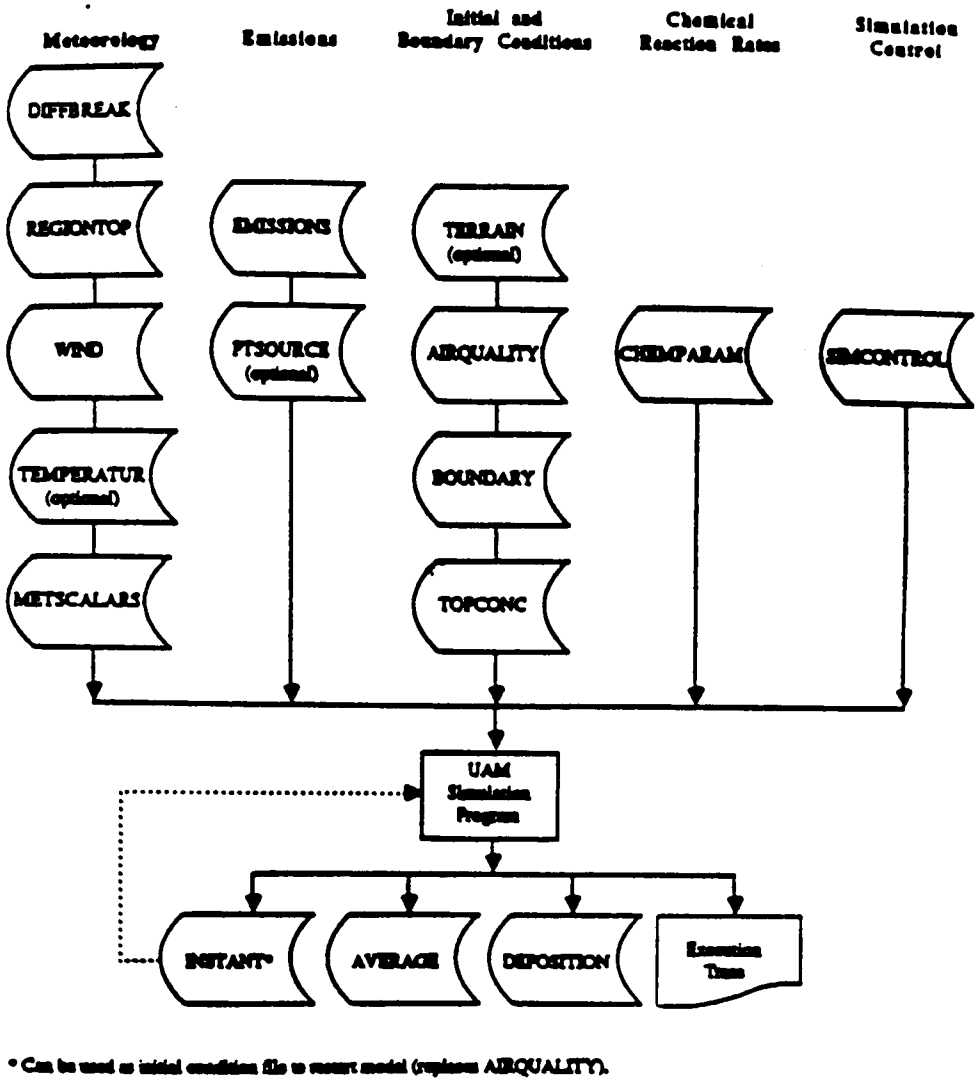
Figure 3-1. Middle Tennessee Modeling Domain and Power Plant Map

seen in the results of this study.

This chapter describes the UAM, model input, model output, and day specific data. The input to UAM consists of 13 binary files all but one of which are created through a preprocessor or a number of preprocessors. UAM gives as output four files. This study involved reducing the amount of NO_x emissions from each of the three power plants for different days in 1988. The predicted ozone concentrations were plotted and analyzed in order to determine the effects of reductions in NO_x on ozone concentrations. The meteorology and emission data for each day, along with information on each of the power plants, are summarized in this chapter.

3.1. URBAN AIRSHED MODEL

The UAM is a three-dimensional photochemical grid model which calculates the concentration of inert and chemically reactive pollutants. The model simulates the physical and chemical processes in the atmosphere that affect pollutant concentrations. The UAM accounts for spatial and temporal variations along with the differences in the speciation of emissions. Figure 3-2 shows a UAM flowchart for the 13 binary files and 4 output files.[24] The input consists of meteorological, emission and air quality data for a particular day or days. The output from the model includes the average and instantaneous concentrations for each averaging period, which is usually an hour. The model also gives as output an



* Can be used as initial conditions file to restart model (replaces AIRQUALITY).

Figure 3-2. Urban Airshed Model program with input and output files

execution trace file and a deposition file.

3.1.1. UAM Input

The input to UAM consists of 13 binary files: Airquality, Boundary, Chemparam, Diffbreak, Emissions, Metscalars, Ptsource, Regiontop, Simcontrol, Temperature, Terrain, Topconc, and Wind. These files are described below along with the preprocessor or preprocessors that created each file and the input to each program. Three types of preprocessors exist: ROM-UAM Interface preprocessors, UAM preprocessors, and Emissions Preprocessor System (EPS2.0) programs. The ROM-UAM programs require Regional Oxidant Model (ROM) data as input. These ROM data were provided by EPA for the dates of interest. ROM data are the results of modeling performed by EPA for certain areas of the country. The input to the ROM modeling runs was a 1985 NAPAP Inventory which was projected to 1990. The purpose of using such data is to develop boundary concentrations which include those sources that are not located in the modeling domain, but whose plumes do become evident in the area during modeling scenarios. The initial EPS2.0 input for point and area sources is a work file downloaded from the Aerometric Information Retrieval System (AIRS). The other EPS2.0 preprocessors require the output from a preceding EPS2.0 program as input.

3.1.1.1. Airquality File

The output from the ROM-UAM Interface program ICONC consists of three binary files which are input to UAM, the Airquality file, the Boundary file, and the Topconc file. These last two files are discussed later in this chapter. The ICONC preprocessor requires as input the ROM concentrations (called the ROM22 file) along with a file containing day specific data (called a "control" file) such as modeling dates, modeling times, and domain coordinates. The program also takes as input the hourly gridded layer 1 heights (called the MF165 file), the gridded terrain elevation data (called the PF119 file), and the diffusion break data (discussed under Section 3.1.1.4. The ROM22, MF165, and PF119 files are all ROM files that were provided by EPA.

The Airquality file provides air quality initial conditions for a UAM scenario. Created from ROM data, these concentrations are day specific and consist of 17 species for the first hour of simulation. The initial conditions are not average concentrations over an hour but the concentrations in the first instant of the hour. The ROM-UAM Interface preprocessor ICONC creates this input file for the first day's simulation. Because two days usually make up a modeling scenario, the second day's initial concentrations are the instantaneous concentrations that are output from the first day's UAM run. The UAM output file containing these instantaneous concentrations is discussed later in this

chapter.

3.1.1.2. Boundary File

The Boundary file consists of lateral boundary concentrations for each hour of the modeling scenario. These concentrations can be set to EPA default values or can be provided in ROM data. The ROM boundary concentrations are emissions that have blown in from outside the modeling domain. The ROM-UAM Interface preprocessor ICONC creates this file for each of the two days for a modeling scenario. ICONC is described in the Section 3.1.1.1. The Boundary file is one of the three binary output files from the ICONC preprocessor.

3.1.1.3. Chemparam File

The Chemparam file provides the model with information on the chemical species characteristics, reaction properties and stoichiometric characteristics. The preprocessor which creates this file is called CPREP, a UAM preprocessor. The information used as input to this program was downloaded from the EPA Bulletin Board. The Chemparam file is not day specific; therefore, the CPREP program was only run one time in order to create the Chemparam file for each modeling scenario. If there is a need to change a characteristic of a chemical species, a change to this input file would be necessary. Otherwise, the Chemparam file remains the same for every modeling scenario.

3.1.1.4. Diffbreak File

The Diffbreak file contains hourly, gridded diffusion break data. Diffusion break refers to the mixing height of the modeling domain. The mixing height is the vertical extent to which turbulent and convective mixing takes place.[25] Creating this file involves running three preprocessors. Kaminski[26] discussed these preprocessors in detail. The RAMMETX program is a UAM preprocessor and is the first step in producing the Diffbreak file. This preprocessor requires five input files, which are: (1) the file containing the "control" information such as modeling dates and domain boundaries, (2) the meteorological data which can be downloaded from the EPA Bulletin Board (SCRAM), (3) the twice daily mixing height values which have been preprocessed by the National Climatic Data Center (NCDC) and can also be downloaded from SCRAM, (4) the file which contains the format statements, which are not day specific, and (5) the file containing a series of random numbers used by the program to calculate random flow vectors, which are also not day specific. The output file from RAMMETX contains the mixing height in meters for each hour.

The ROM-UAM Interface preprocessor PDFSNBK is the next program to run in order to create the Diffbreak file. This preprocessor requires two input files: (1) the output file from RAMMETX with the hourly mixing heights, and (2) the file which contains the "control" parameters for the modeling scenario, such as modeling dates, times, and domain

characteristics.

The output from PDFSNBK is an ASCII file which is then taken to the final step for preparing the Diffbreak file. The last preprocessor is the DFSNBK program which requires as its only input the ASCII file created by PDFSNBK. The DFSNBK program creates two output files, an ASCII and a binary file. Both of these output files contain gridded mixing height values, but the binary file is the only one used as input to UAM. The ASCII file can be used for checking the output for accuracy.

3.1.1.5. Emissions File

This file contains low level emissions, that is, those emissions that are emitted within the first or lowest vertical cell. The preprocessors that create this file are part of the Emissions Preprocessing System (EPS2.0). These preprocessors perform all speciation and also are able to forecast, backcast, and control emissions. The point, area, nonroad mobile, and mobile sources are all preprocessed separately through the EPS2.0 process and at the end are merged together as one binary emissions file that is fed into UAM. The area and nonroad mobile sources are processed in one file, because EPS2.0 considers both of these sources to be area sources.

The point sources were preprocessed through the following EPS2.0 programs in order to create the emission files for the 1988 modeling: PREPNT (point source preprocessing), CNTLEM

(backcasting to 1988), TMPRL (temporal allocation of emissions), CHMSP (chemical speciation of emissions), and GRDEM (spatially allocation of emissions). The area and nonroad mobile sources were preprocessed through the following EPS2.0 programs in order to create the emission files for the 1988 modeling: PREAM (area source preprocessing), CNTLEM, TMPRL, CHMSP, and GRDEM. The output file from GRDEM containing the gridded area and nonroad mobile emissions was then merged with the biogenic emissions from ROM by a ROM-UAM Interface program called IBIOG. The mobile sources were included with the area and nonroad mobile sources until after running PREAM at which time a separate mobile source file was created. The mobile emissions were then processed through CNTLEM, TMPRL, CHMSP, and GRDEM. The three files containing the point, area, mobile, nonroad mobile, and biogenic emissions were then merged at the end into one binary emission file by running the EPS2.0 program MRGUAM. Butala[27] described the above processes in detail, along with the temporal allocation of the emissions. Cawlfield[28] discussed the spatial allocation of the emissions.

3.1.1.6. Metscalars File

The Metscalars file contains meteorological parameters which are assumed to be constant over the entire modeling domain. These parameters include the temperature gradient below the diffusion break, the temperature gradient above the

diffusion break, the exposure class (an integer scale of the near ground-level atmospheric stability due to surface heating or cooling), the NO_2 photolysis rate constant, the average concentration of water, and atmospheric pressure. The creation of this file involves a ROM-UAM Interface program (IMETSCL) and a UAM preprocessor (METSCL).

The input to IMETSCL consists of five files, four of which are ROM data files. These ROM files are (1) the hourly gridded vertical temperature profile (called the PF102 files), (2) the hourly gridded fractional cloud cover data (called the PF117 file), (3) the gridded terrain elevation data (called the PF119 file), and (4) the hourly gridded water vapor concentrations of layer 1 (called the MF174 file). The last input file to IMETSCL contains "control" information, such as modeling dates, times, and domain characteristics.

The output from IMETSCL is a text file which is the input to the UAM preprocessor METSCl. Running this program creates the final Metscalars binary file which is used as input to UAM. METSCL also creates an ASCII file which contains the same data as the binary output but is only used to check for accuracy.

3.1.1.7. Ptsource File

The elevated point source file is created by the UAM preprocessor PTSRCE. This program requires as input an output file from the EPS2.0 processor PSTPNT. PSTPNT takes as input

a binary emissions file that has been temporally and chemically speciated, but not gridded. PSTPNT recognizes the point sources which are emitted into an elevated vertical grid that is higher than the first cell. These point sources were already marked as being elevated in the PREPNT program, which calculates a worst case plume height for each of the point sources. PREPNT then marks those sources which have plume heights greater than the user defined plume height cutoff. The PSTPNT program then takes these files and calculates a realistic plume height for each hour. These elevated emissions are then placed in the appropriate vertical cell.

PTSRCE also requires as input the Diffbreak file, Metscalars file, Regiontop file, Temperature file, and the Wind file. PTSRCE creates a binary, gridded elevated point source emission file that is used as input to UAM. An ASCII file is also provided by the program which can be used for accuracy checks, but is not used for input to UAM.

Since the purpose of this study was to evaluate the effect of changes in NO_x from large power plants, the PSTPNT file was a critical file. It was possible to modify this file to produce the required changes in NO_x which were to be evaluated. Because this file has ungridded point source emissions and the power plants were all elevated sources, altering emissions at this step proved to be the most efficient way to alter elevated emissions. A Fortran program was written to alter the emissions from the PSTPNT output

file. After executing the Fortran program which was used for altering NO_x emissions, PTSRCE was run, creating the elevated binary point source file that was used in UAM.

3.1.1.8. Regiontop File

The Regiontop file contains the heights of the top of the modeling domain, which are the sum of the heights of all five of the vertical cells for each hour and each grid cell. This file is created in two steps. The first preprocessor is a ROM-UAM Interface program, called IREGNTP. This program requires four files as input, which are: (1) the terrain elevation heights (file PF119), (2) the ROM layer 2 heights (called the MF166 file), (3) the ASCII diffbreak file, and (4) the file containing the "control" information.

The output from IREGNTP is two ASCII files, the first of which contains the hourly regiontop values. This file is used with the ASCII diffbreak file for other preprocessors. The second output file from the ROM-UAM Interface program is fed into a UAM preprocessor called REGNTP. This program creates an ASCII and binary file which contain the hourly gridded region top heights. The binary output from REGNTP is used as input to UAM.

3.1.1.9. Simcontrol File

The Simcontrol file contains day specific data for the simulation. These data are much of the same data that are

contained in the headers of the other input files, such as modeling dates, times, and coordinates. Unique to this file, however, are flags which indicate certain characteristics about a modeling scenario, including a flag to indicate whether the optional elevated point source and terrain files are included for a simulation. Also included in the Simcontrol file is a flag indicating if the simulation day is a restart day, which is the second sequential day in a two day modeling scenario. The binary Simcontrol file is usually created by altering the dates, times, and/or flags from an existing ASCII Simcontrol file.

3.1.1.10. Temperature File

The preprocessing required for the production of the binary Temperature file is similar to that required for the Metscalars file, that is, a ROM-UAM Interface preprocessor and a UAM preprocessor are both used. The input to the ROM-UAM Interface program ITMPRTR is a ROM file that contains gridded hourly surface air temperatures (PF103 file) along with a "control" file that gives day specific data. The output from this program is an ASCII file that is used as input to the UAM preprocessor TMPRTR. This preprocessor creates a binary UAM file which contains hourly surface air temperatures that are gridded to the appropriate size for the modeling domain specified in the header information.

3.1.1.11. Terrain File

The Terrain file is optional for a modeling scenario. A flag in the Simcontrol file can be set in order to eliminate the necessity for this file if the data are not available. This file contains surface roughness and land use fractions for each land use category. Terrain data are not day specific for each modeling domain. UAM does require that the header information for each input file be identical; therefore, although the data are not day specific, there must be a terrain file for each day in order for the model to execute appropriately. The ROM-UAM Interface preprocessor ICRETER creates this file. ICRETER requires three input files, which are: (1) the ROM gridded effective surface roughness length values, (2) the ROM gridded land use fractions for each land use category, and (3) the file containing the "control" data. The output from ICRETER is a binary file that is fed into UAM.

3.1.1.12. Topconc File

The Topconc file contains the concentrations which exist at the top of the modeling domain, that is, at the region top. As with the Airquality and Boundary files, the ROM-UAM Interface preprocessor ICONC creates this concentration file. ICONC produces all three of these files simultaneously. The input that ICONC requires is discussed in Section 3.1.1.1.

3.1.1.13. Wind File

The UAM Wind file contains wind fields for each vertical layer of the modeling domain for a 24 hour period for a one day modeling scenario. This file is created by a ROM-UAM Interface program called IWIND. This preprocessor requires six files as input. These input files are: (1) the ROM terrain elevations (file PF119), (2) the ROM layer 1 heights (MF165 file), (3) the ROM layer 1 winds (the PF115 file), (4) the ROM layer 2 heights (the PF114 file), (5) the diffusion break data file, and (6) the region top data file. The output from IWIND is the UAM Wind file. IWIND does not create an ASCII Wind file but displays the ASCII information on the screen as the program is running.

3.1.2. UAM Output

The output from UAM consists of four files, two of which are binary while the other two are formatted files. The following sections describe each of these files.

3.1.2.1. Airquality File

The Airquality file contains binary, gridded instantaneous concentrations for each species for each hour of the simulation. The instantaneous concentrations that occurred in the last hour of the first modeling day are the concentrations that can be fed into a sequential simulation day as the initial first hour concentrations. The second day

in such a scenario is called the restart day.

3.1.2.2. Average File

This file contains binary, gridded average hourly concentrations for 24 species for each hour of the simulation. This file contains those concentrations that were analyzed for this study. This is usually the case due to the fact that the standards that UAM results are compared to are average hourly concentrations. The file was first converted to ASCII and using a Fortran program, the ozone concentrations for each hour were extracted from the file.

3.1.2.3. Deposition File

The Deposition File is a formatted file that contains the amount of each deposited species on the ground in each horizontal grid cell in the modeling domain for each hour of the modeling scenario. This file was not used in this study since the primary focus was on the ambient ozone concentrations.

3.1.2.4. Simulation File

The Simulation file proves most helpful when a model run does not execute properly. The file contains information on when input files were opened and closed, contents of the input files, time steps used, status of the simulation, mass balance summary, and any error messages.

3.2. OTHER INPUT INFORMATION

This section summarizes emission and meteorological data for each day that was modeled. Included in this information are descriptions on each of the three power plants in the Middle Tennessee Modeling Domain.

3.2.1. Power Plant Descriptions

The three power plants that were evaluated for this study were Cumberland Steam Plant, Gallatin Steam Plant, and New Johnsonville Steam Plant. All of these plants, which are located in the Middle Tennessee Area, are coal-fired. Figure 3-1 shows the location of these plants along with the modeling domain, county boundaries, and Nashville, Tennessee. This section gives specific information on each of the plants including size and design configuration. The emissions emitted from each of the plants for each of the modeling days is discussed in the sections that contain day specific data.

3.2.1.1. Cumberland Steam Plant

Cumberland Steam Plant is the largest power plant in this area and is located in Stewart County, Tennessee (see Figure 3-1). The maximum load for each of the two units in this plant is 1300 MW. The plant began operation in early 1970.

The 80 burners in each furnace are arranged in an opposed firing cell configuration. This design is uncommon as

references which described this design were not found. According to reports by TVA, this unique design makes it incapable of installing low-NO_x burners for the reduction of NO_x emissions. The furnaces are of the dry bottom type. The NO_x emission factor for the plant in 1988 was 1.2 lbs NO_x per million Btu. The stack heights for each of the two stacks are 1000 feet. The stack diameter is 31 feet, and the stack temperature is 407 K. The exit velocity for each of these stacks was 106 feet per second.

3.2.1.2. Gallatin Steam Plant

Gallatin Steam Plant is located in Sumner County, Tennessee, near Nashville. Under certain meteorological conditions the power plant plume blows directly over the Nashville urban area. The plant has four units, two of which have loads of 300 MW and the other two having loads of 328 MW. The first unit was put into operation in 1956.

The 64 burners in each of the four units are arranged in a tangentially-fired burning configuration, and the bottom is dry. The emission factor for each the four units in 1988 was 0.6 lbs NO_x per million Btu. TVA has installed low-NO_x burners with overfire air in Unit 4 of the Gallatin Steam Plant[11]. The stack height for two of the stacks is 501 feet and 502 for the other two stacks. The stack diameter for all for stacks is 25 feet. The stack temperature for the 501 feet stacks is 406 K and is 395 K for the 502 feet stacks. The exit velocity for

the 501 feet stacks is 56 feet per second and is 60 feet per second for the 502 feet stacks.

3.2.1.3. New Johnsonville Steam Plant

New Johnsonville Steam Plant is located in Humphreys County, Tennessee and has ten boilers. Four of the ten boilers have maximum loads of 125 MW, another four have maximum loads of 173 MW, and the remaining two units have maximum loads of 147 MW.

Each of the ten units has 16 burners. Six boilers are arranged in a tangentially-fired configuration. The remaining four boilers have the burners in the front-fired configuration. The emission factor for the six tangentially-fired units in 1988 was 0.6 lbs NO_x per million Btu, while the NO_x emission factor from the other four units in 1988 was 0.9 lbs NO_x per million Btu. This plant has plans to install low-NO_x burners by the year 1996. The number and location of these LNBs is unknown.

Nine of the stacks have 600 feet stack heights. The last stack has a height of 400 feet. The nine 600 feet stacks have diameters of 33 feet and an exit velocity of 115 feet per second. The 400 foot stack has a diameter of 14 feet and an extremely high exit velocity of 620 feet per second. The stack temperature for the nine larger stacks is 419 K, and for the last stack the temperature is 424 K.

3.2.2. Day Specific Descriptions

This section briefly describes the meteorological conditions that occurred on each primary modeling day along with information on the emissions for each day. Each of the following days which were used for this study had unique meteorological conditions and fell on different days of the week in the year 1988. The meteorological conditions for all days came from ROM data. The emissions data section includes the loads and NO_x emissions from each of the units of the power plants being modeling on the three days. These 1988 emissions were provided by TVA for modeling purposes. In the analyses conducted in this study, these emissions were reduced by 25%, 50%, 75%, and 100% from the base case emissions. After each NO_x reduction for each plant, a UAM run was conducted. The preceding day for each of these primary modeling days was also initially modeled in order to create initial conditions for the primary modeling day.

3.2.2.1. June 24, 1988

June 23 and June 24 were modeled to determine the impact of the plants on ozone formation for the June 24 episode day. In 1988 June 24 fell on a Friday.

3.2.2.1.1. June 24, 1988: Meteorological Conditions

The ROM winds for June 24 blew from the northwest to the southeast at a speed of approximately 3 meters per second

(m/s). Similar winds with an average wind speed of 3.2 m/s were observed in the previous day. The maximum temperature on June 24, 1988 was 100° F, which occurred at 1 o'clock in the afternoon and also at 2 o'clock in the afternoon. The average temperature for the 24 hour period was 84° F.

3.2.2.1.2. June 24, 1988: Emissions Data

The average hourly loads and NO_x emissions from each boiler in the Cumberland Steam Plant for June 24, 1988 are shown below.

Unit	Load (MW)	NO_x Emissions (lbs/day)
1	1,214	341,383
2	1,222	343,137
Total	2,436	684,520

The average hourly loads and NO_x emissions from each boiler in the Gallatin Steam Plant for June 24, 1988 are shown below.

Unit	Load (MW)	NO_x Emissions (lbs/day)
1	227	30,634
2	225	30,921
3	246	33,006
4	245	32,850
Total	943	127,411

The average hourly loads and NO_x emissions from each

boiler in the New Johnsonville Steam Plant for June 24, 1988 are shown below.

Unit	Load (MW)	NO_x Emissions (lbs/day)
1	93	14,948
2	91	14,753
3	88	14,281
4	95	15,338
5	0	0
6	0	0
7	93	20,650
8	90	20,023
9	92	20,564
10	84	18,804
Total	726	139,361

3.2.2.2. August 1, 1988

July 31 and August 1 were modeled to determine the impact of the plants on ozone formation for the August 1 episode day. In 1988 August 1 fell on a Monday.

3.2.2.2.1. August 1, 1988: Meteorological Conditions

The wind for August 1, 1988 was predominantly from the west to east. At one point in the day, the winds start to blow to the north; however, the power plant plumes have been formed and are still evident in the modeling domain for most of the day. The ROM winds showed a wind speed of

approximately 1.6 meters per second (m/s), almost half of the value observed on of June 24. July 31, 1988, the day before the August 1 simulation, had wind speeds of approximately 2.2 m/s. The maximum temperature on August 1, 1988 was 97° F, which occurred in the period of 3 to 5 p.m. The average temperature for the 24 hour period was 85° F.

3.2.2.2.2. August 1, 1988: Emissions Data

The average hourly loads and NO_x emissions from each boiler in the Cumberland Steam Plant for August 1, 1988 are shown below.

Unit	Load (MW)	NO_x Emissions (lbs/day)
1	1,145	321,569
2	1,242	348,564
Total	2,387	670,133

The average hourly loads and NO_x emissions from each boiler in the Gallatin Steam Plant for August 1, 1988 are shown below.

Unit	Load (MW)	NO_x Emissions (lbs/day)
1	241	32,550
2	238	32,145
3	254	34,114
4	257	34,450
Total	990	133,259

The average hourly loads and NO_x emissions from each boiler in the New Johnsonville Steam Plant for August 1, 1988 are shown below.

Unit	Load (MW)	NO_x Emissions (lbs/day)
1	86	13,952
2	63	10,216
3	94	15,103
4	90	14,497
5	0	0
6	0	0
7	103	22,774
8	96	21,232
9	87	19,431
10	83	18,589
Total	702	122,794

3.2.2.3. August 3, 1988

August 2 and August 3 were modeled to determine the impact of the plants on ozone formation for the August 3 episode day. In 1988 August 3 fell on a Wednesday. Because of wind directions, only one power plant plume, Gallatin Steam Plant, was visible in the modeling domain on this day. The plume blew over the Nashville urban core making it a potentially interesting modeling scenario.

3.2.2.3.1. August 3, 1988: Meteorological Conditions

The wind for August 3, 1988 was predominantly from the east to west. The wind speed for this day averaged 1.8 m/s while the preceding day's wind speeds averaged 16. m/s. The maximum temperature for this day in 1988 was 96° F which occurred at 3 o'clock in the afternoon. The average temperature for the entire day was 78° F.

3.2.2.3.2. August 3, 1988: Emissions Data

As mentioned above, the NO_x emissions from Gallatin Steam Plant were the only emissions altered for August 3, 1988 due to the fact the meteorological conditions were such that the other plumes were transported out of the Middle Tennessee Area.

The average hourly loads and NO_x emissions from each boiler in the Gallatin Steam Plant for August 3, 1988 are shown below.

Unit	Load (MW)	NO_x Emissions (lbs/day)
1	134	18,005
2	219	29,572
3	234	31,423
4	236	31,719
Total	823	110,719

4. RESULTS

This chapter contains the results of the UAM runs that were made for this study in which the effect of NO_x emissions from power plants in the Middle Tennessee Area on ozone formation was analyzed. Discussions concerning the effect of NO_x emissions from power plants on tropospheric ozone are also included in this chapter.

The analysis of the impact of power plants on ozone formation was conducted as follows. First, a base case UAM run was conducted for each episode date in which emissions from all sources were included. (Based on the actual operation of the sources on that date.) Second, a UAM run was then conducted in which power plant NO_x emissions were reduced by a specified percentage reduction (referred to as an NO_x reduction run). The output of each of these two runs consisted of a matrix of 1840 ozone concentrations for the 46 by 40 gridded system (each cell being 5 km on each side) for each of the 24 hours of that day's simulation. A difference matrix was then created by subtracting the paired spatially and temporally allocated values obtained in the NO_x reduction run from those obtained in the base case run. The ozone values found in the difference matrix represented the ozone reduction in ppb which occurred as a result of the specified reduction in NO_x emissions.

Isopleth graphs of predicted ozone concentrations for the

base case runs were then created for each hour of the day to illustrate the variation in ozone throughout the modeling domain. Although hourly graphs were created, only selected maps are shown herein to demonstrate the more important results. Isopleth graphs of the predicted ozone concentrations were also created for the runs in which specified power plant NO_x reductions were made. Finally, isopleth graphs of the difference matrices were created. These later graphs represented the reduction in ozone which occurred as a result of the specified reduction in NO_x emissions.

The following chart shows the maximum ozone concentrations which were predicted in the base case runs for each of the three episode dates, that is, with no reduction in NO_x emissions from the power plants. Also shown in this chart are the ground-level cells in which the maximum ozone concentrations occurred and the time at which they occurred. The ozone concentrations are in parts per billion (ppb), and the location of the maximum ozone concentrations are the UTM (Universal Transverse Mercator) coordinates of the cell within the modeling domain. Figure 3-1 in Chapter 3 shows the UTM coordinates for this modeling domain.

	June 24, 1988	Aug. 1, 1988	Aug 3, 1988
Ozone Conc (ppb)	113	115	132
UTM (Easting)	557	522	497
UTM (Northing)	4085	4020	4005
Time (Hour)	5 p.m.	5 p.m.	4 p.m.

Figure 4-1 is an ozone isopleth plot which shows the predicted ozone concentrations resulting from the June 24, 1988 base case run which included all sources, including all three power plants with no NO_x reduction. Figures 4-2 and 4-3 show the same plots but for August 1, 1988 and August 3, 1988, respectively.

This chapter outlines the results of the UAM modeling conducted for this study. Each section discusses the maximum predicted ozone concentration reductions which were predicted to be achieved based on the hypothetical reduction of NO_x emissions from each individual plant. Also contained in this chapter is a section which includes an overall discussion of the results.

4.1. CUMBERLAND STEAM PLANT

This power plant emits the largest amount of point source NO_x emissions in the modeling domain. UAM runs were conducted for the base case (no reduction) and for the plant's NO_x emissions reduced by 25%, 50%, 75%, and 100% for the episode dates of June 24, 1988 and August 1, 1988. These same reductions were also made in the emissions for June 23, 1988 and July 31, 1988, the days preceding the primary episode day since each UAM run required a two day simulation. Other dates were not modeled since the wind direction on the other dates created plumes which did not disperse into the modeling domain. The following chart shows the maximum ozone

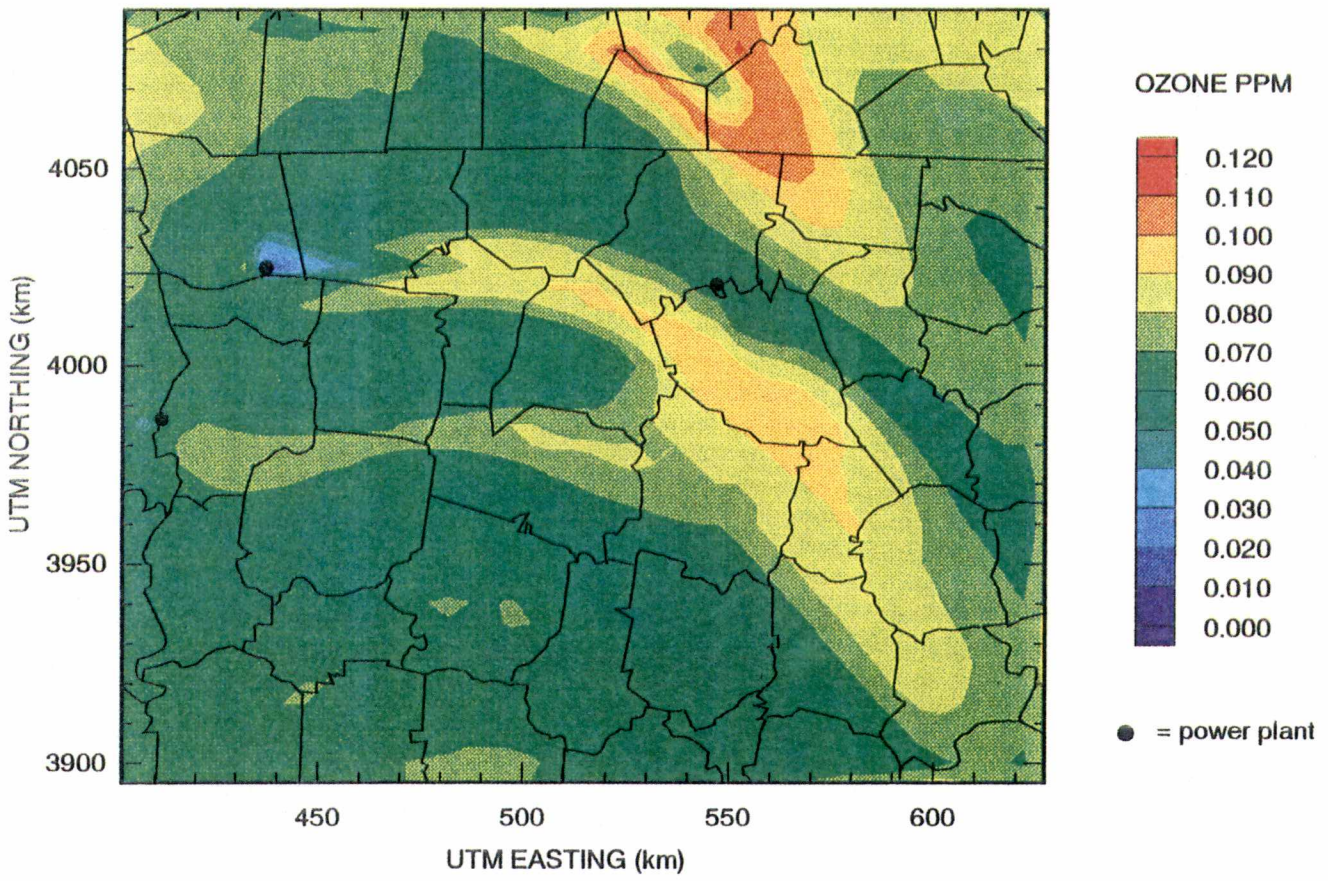


Figure 4-1. UAM simulation with all sources for June 24, 1988
Maximum daily ozone concentration in a cell is 0.113 ppm at 5 p.m.

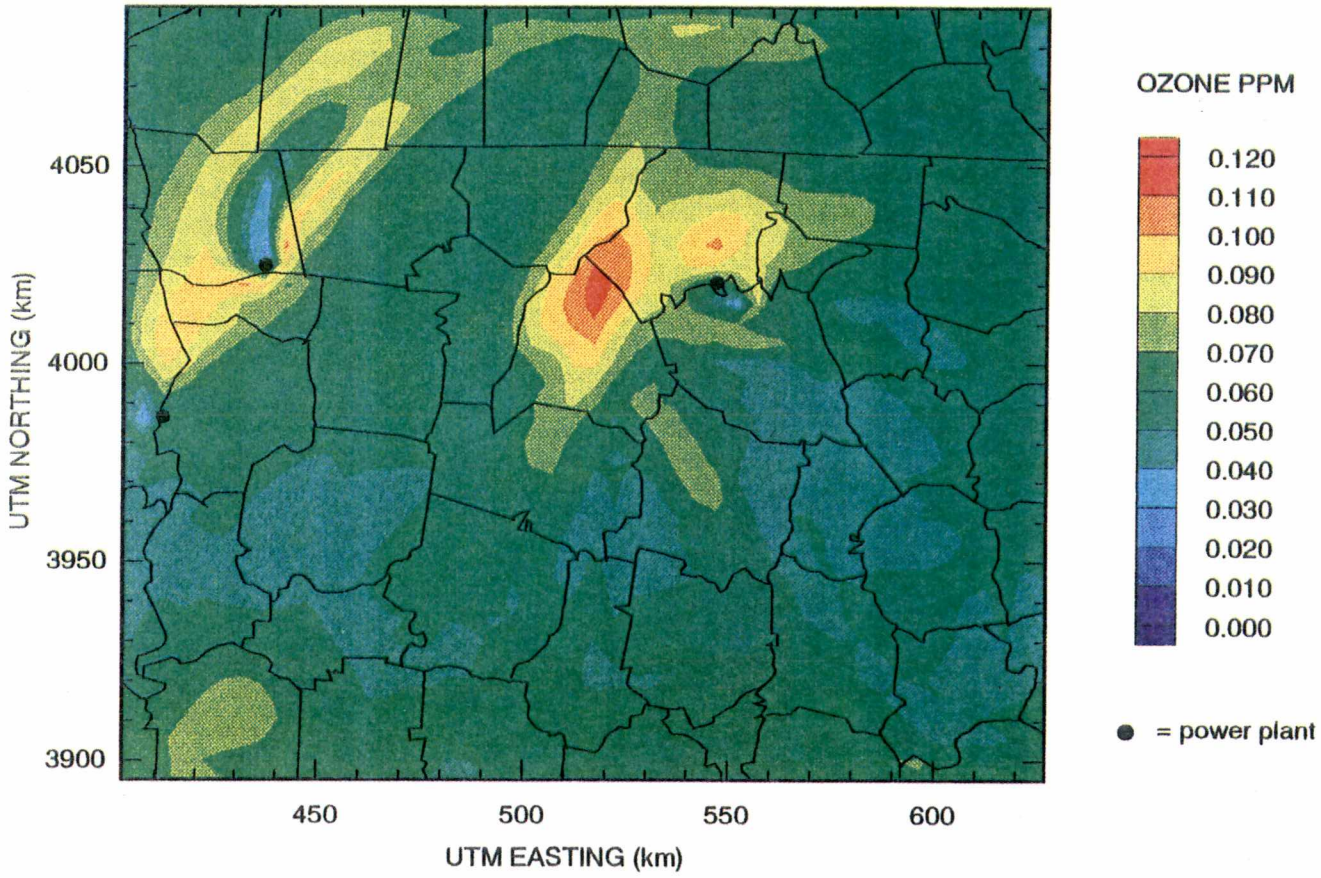


Figure 4-2. UAM simulation with all sources for August 1, 1988
Maximum daily ozone concentration in a cell is 0.115 ppm at 5 p.m.

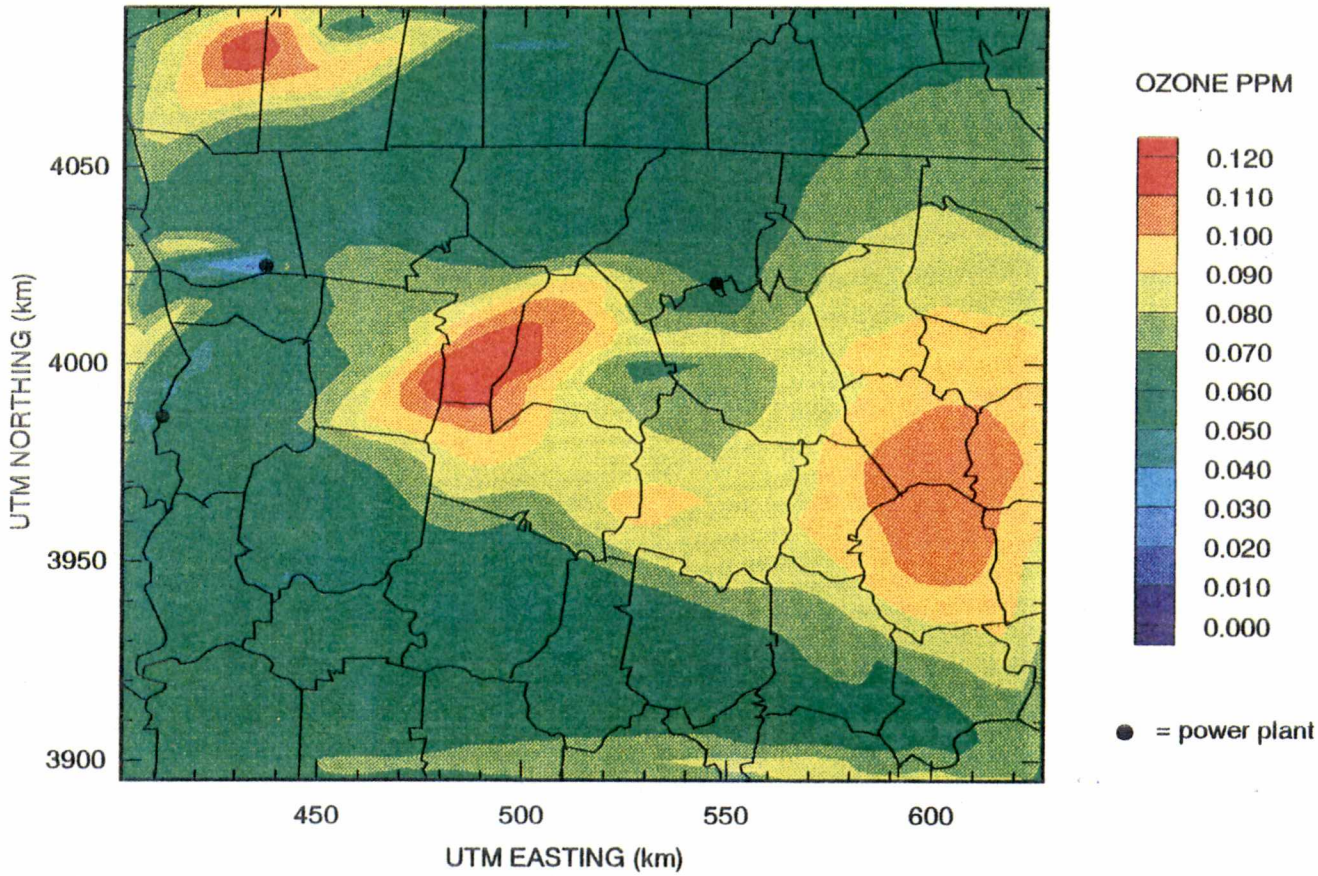


Figure 4-3. UAM simulation with all sources for August 3, 1988
Maximum daily ozone concentration in a cell is 0.132 ppm at 4 p.m.

concentrations which were obtained in the reduction runs for Cumberland Steam Plant. Also contained in the chart are the times and locations of the maximum ozone concentrations for June 24, 1988 and August 1, 1988.

Cumberland Steam Plant

(Maximum Ozone Concentrations Observed in NO_x Reduction Runs)

	June 24, 1988				August 1, 1988			
NO_x Reduction (%)	**25**	**50**	**75**	**100**	**25**	**50**	**75**	**100**
Ozone Conc (ppb)	113	113	113	113	115	115	115	115
UTM (Easting)	557	557	557	557	522	522	522	522
UTM (Northing)	4085	4085	4085	4085	4020	4020	4020	4020
Time (Hour)	5pm	5pm	5pm	5pm	5pm	5pm	5pm	5pm

The second chart summarizes the "maximum ozone concentration reductions" which occurred as a result of the specified NO_x reductions as obtained from the difference matrices described at the beginning of this chapter. This value warrants additional explanation. The difference matrix represents the reduction in ozone concentration in each cell which resulted from a hypothetical reduction in NO_x emissions at the power plant. An evaluation of the 46 by 40 cell matrix (1840 cells) was conducted for each hour of simulation to identify that cell which had the greatest reduction in ozone. This value is referred herein as the "maximum ozone concentration reduction." It is important to note that this analysis identifies the cell which had the highest change in concentration, and is not necessarily at the same location or

at the same hour of the day in which the peak ozone concentration was observed (as shown in Figures 4.1 - 4.3). As such the "maximum ozone concentration reduction" is indicative of the maximum contribution of the power plant. The actual time and location of this value is reported in the chart. The actual maximum contribution of the power plant associated with the peak ozone concentrations (Figures 4.1 - 4.3) may be slightly less than that shown in this analysis.

Based on the results presented in the chart for June 24, it was predicted that a 25% reduction in Cumberland Steam Plant's NO_x emissions would reduce ozone concentrations by 8 ppb, whereas a 100% reduction (or the absence of the source) would have created a 39 ppb reduction. Another way of stating this result would be to state that the power plant's contribution to ozone on June 24, 1988 was predicted to be 39 ppb.

Cumberland Steam Plant

(Maximum Ozone Concentration Reductions from Difference Matrices)

	June 24, 1988				August 1, 1988			
NO_x Reduction (%)	**25**	**50**	**75**	**100**	**25**	**50**	**75**	**100**
Ozone Conc (ppb)	8	18	29	39	6	12	19	26
UTM (Easting)	492	487	487	497	452	462	437	457
UTM (Northing)	4035	4035	4035	4035	4085	4045	4070	4060
Time (Hour)	4pm	4pm	4pm	3pm	9pm	4pm	9pm	4pm

4.1.1. Cumberland Steam Plant: June 24, 1988

The meteorological conditions on this day produced power plant plumes that were clearly evident in the modeling domain when an isopleth map was constructed. In the base case run, the plume from the Cumberland plant was evident (see Figure 4-1), stretching across the modeling domain picking up part of the urban plume along with some of the Gallatin plume. All of the maximum ozone concentrations from the NO_x reduction runs occurred in the same cell and at the same time as the base case June 24 run. It should be noted that all 4 of the June 24 difference matrix maximum ozone concentration reductions for 25%, 50%, 75%, and 100% NO_x reductions, occurred in the same general vicinity; however, none were in the exact same cell as the maximum concentration which was observed in the base case scenario. The maximum ozone concentration reductions in the difference matrix occurred on the outer edges of the Cumberland plume, downwind of the plant. The location of the maximum reduction only moved about 10 km for all of the NO_x reduction runs.

The times at which the maximum ozone concentration reductions occurred in the difference runs were not at 5 p.m., the time at which the maximum ozone concentration occurred for the base case scenario on June 24. The ozone concentrations from the difference matrices at 5 p.m. for the difference runs varied by approximately 2 to 5 ppb from the maximum ozone concentration reductions. The changes in the times of the

maximum ozone concentration reductions from the base case scenario maximums shifted one to two hours.

Figure 4-4 shows the predicted ozone concentration isopleth plot with no NO_x emissions from Cumberland Steam Plant, that is, with a 100% reduction in these emissions. Figure 4-5 is the difference plot showing the relative contribution of Cumberland's NO_x emissions to ozone concentrations. The orange edges on the outer edge of the plume show the maximum ozone concentrations. The difference plot shows zones in which ozone was being depleted near the center of the Cumberland Steam Plant plume due to high NO_x concentrations. It is these areas within the plume that are sensitive to VOC concentrations, whereas the modeling domain as a whole is most sensitive to NO_x emissions. The maximum possible contribution to ozone concentrations occurred on the peripheral edges of the plume.

Figure 4-6 plots the maximum ozone concentration reduction in ppb versus the percentage of reduction of NO_x emissions from Cumberland Steam Plant for June 24, 1988. Again, these values represent the maximum possible ozone reduction which was predicted to occur as a result of reductions in the NO_x emissions from Cumberland. Figure 4-7 shows this same plot, except that the NO_x has been converted to an equivalent pounds per hour of emissions rather than percent. The hourly NO_x emissions reduction in pounds per hour represents the average NO_x reduced per hour for the

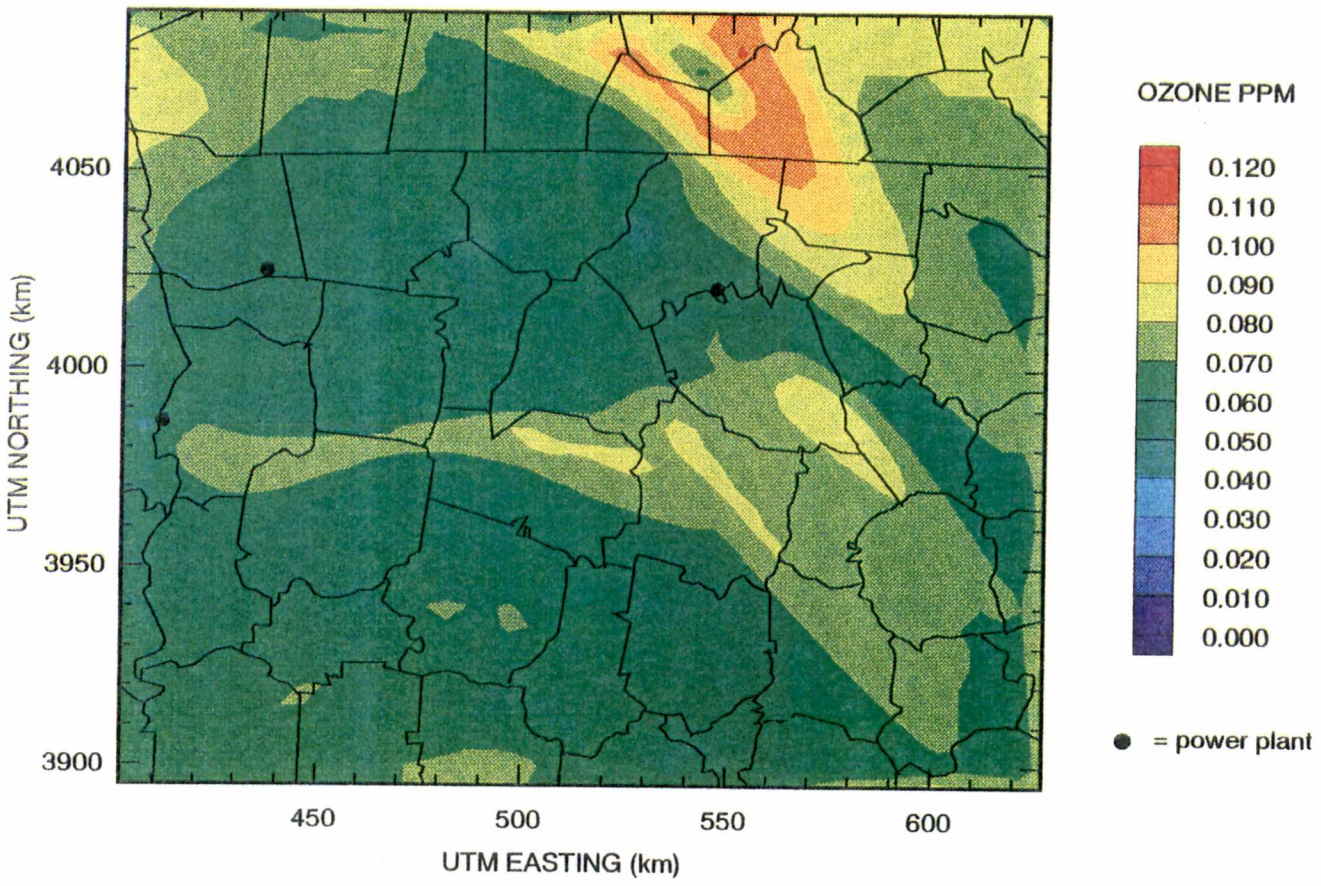


Figure 4-4. UAM simulation without Cumberland's NO_x emissions for June 24, 1988 Maximum daily ozone concentration in a cell is 0.113 ppm at 5 p.m.

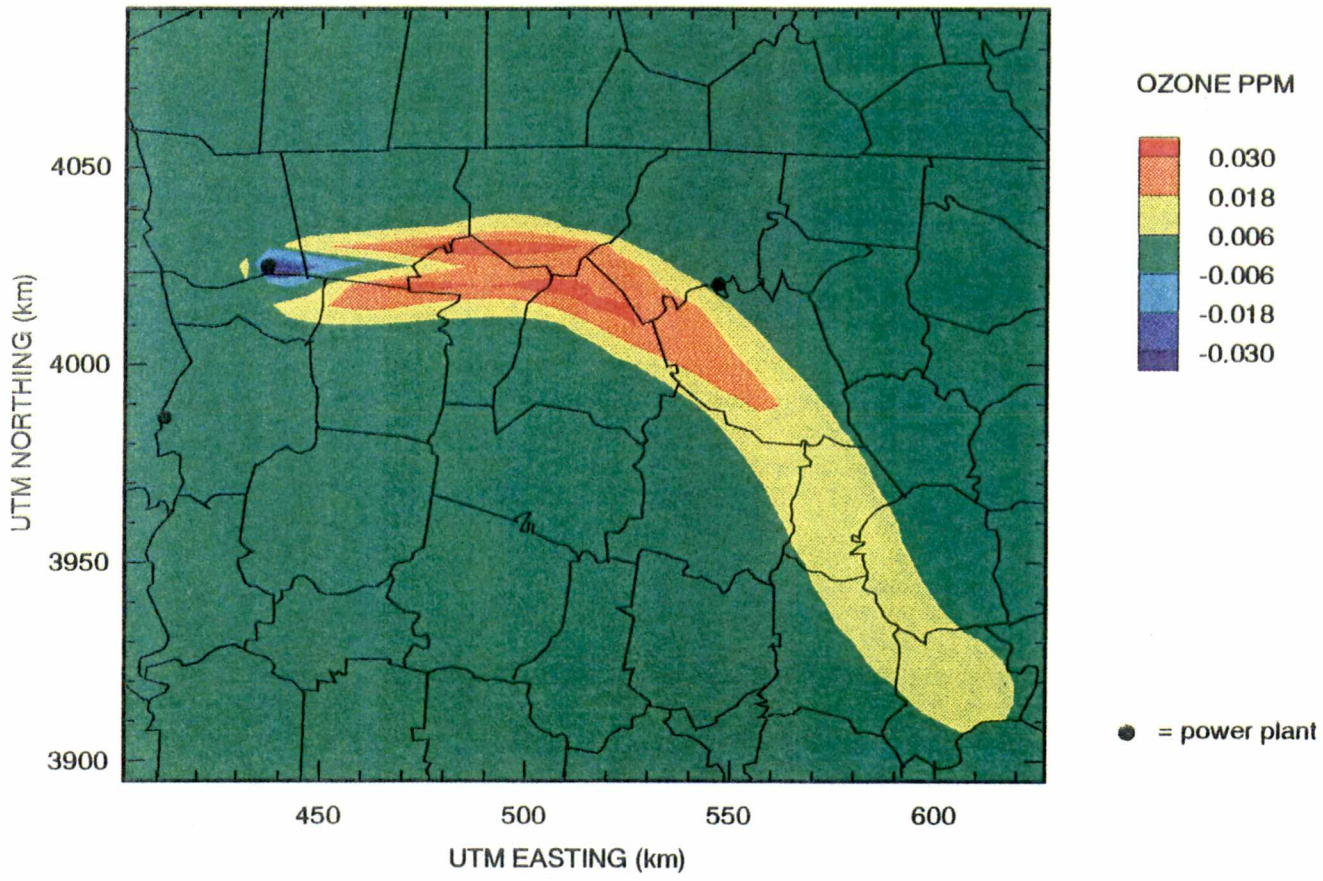


Figure 4-5. UAM Difference Plot of Cumberland's NO_x emissions for June 24, 1988 Maximum ozone concentration is 0.039 ppm at 3 p.m.

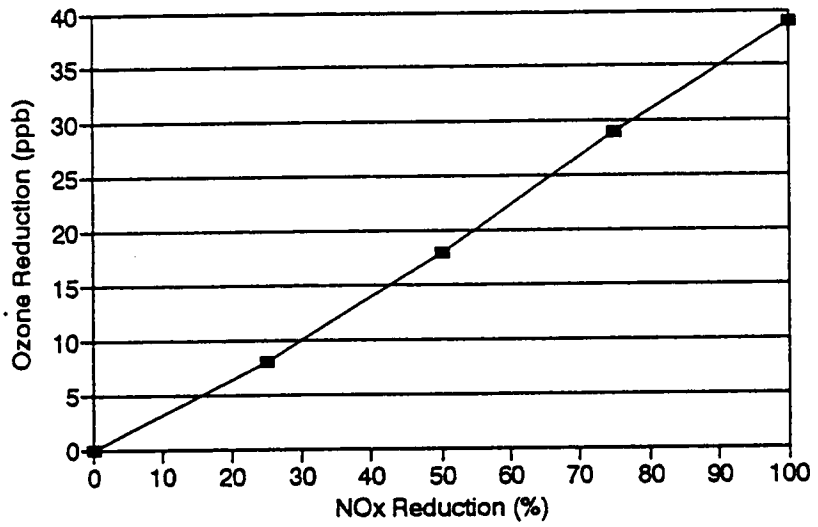


Figure 4-6. Reduction in Ozone Concentration vs. NO_x Reduction for Cumberland June 24, 1988 (% NO_x)

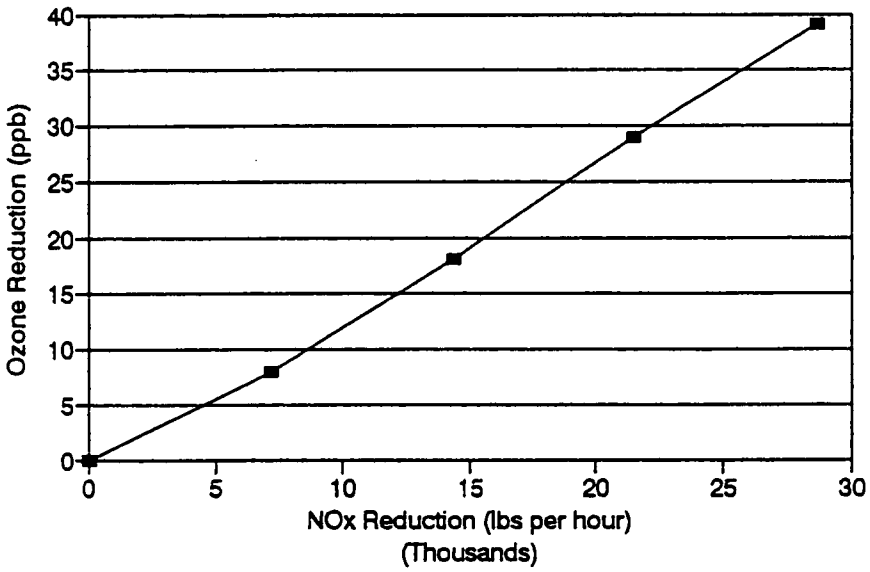


Figure 4-7. Reduction in Ozone Concentration vs. NO_x Reduction for Cumberland June 24, 1988 (pounds per hour NO_x)

immediate 8 hour period that preceded the hour associated with the maximum ozone concentration reduction. A relatively linear relationship was exhibited between NO_x reductions and the associated reduction in ozone due to the power plant in this particular case.

While the above analysis concentrated on the contribution of the Cumberland Steam Plant to ozone formation, it is of interest to note that the predicted maximum concentration in the overall modeling domain did not occur as a result of this power plant. The maximum ozone concentrations in the Middle Tennessee Modeling Domain for all of these NO_x reduction runs remained the same and was located in the northern portion of the domain; it was associated with transport into the domain from sources in Kentucky, north of the modeling domain.

4.1.2. Cumberland Steam Plant: August 1, 1988

Figure 4-8 shows the predicted ozone concentration isopleth plot with no NO_x emissions from Cumberland Steam Plant on August 1, 1988. Figure 4-9 is the difference plot showing the relative contribution of Cumberland's NO_x emissions for August 1, 1988. The meteorology on this day was such that the Cumberland plume stayed within the bounds of the domain for most of the day. The difference plot shows that zones of ozone scavenging occurred in the center of the plume, but not the entire length of the plume.

On August 1, 1988 it was predicted that a 25% reduction

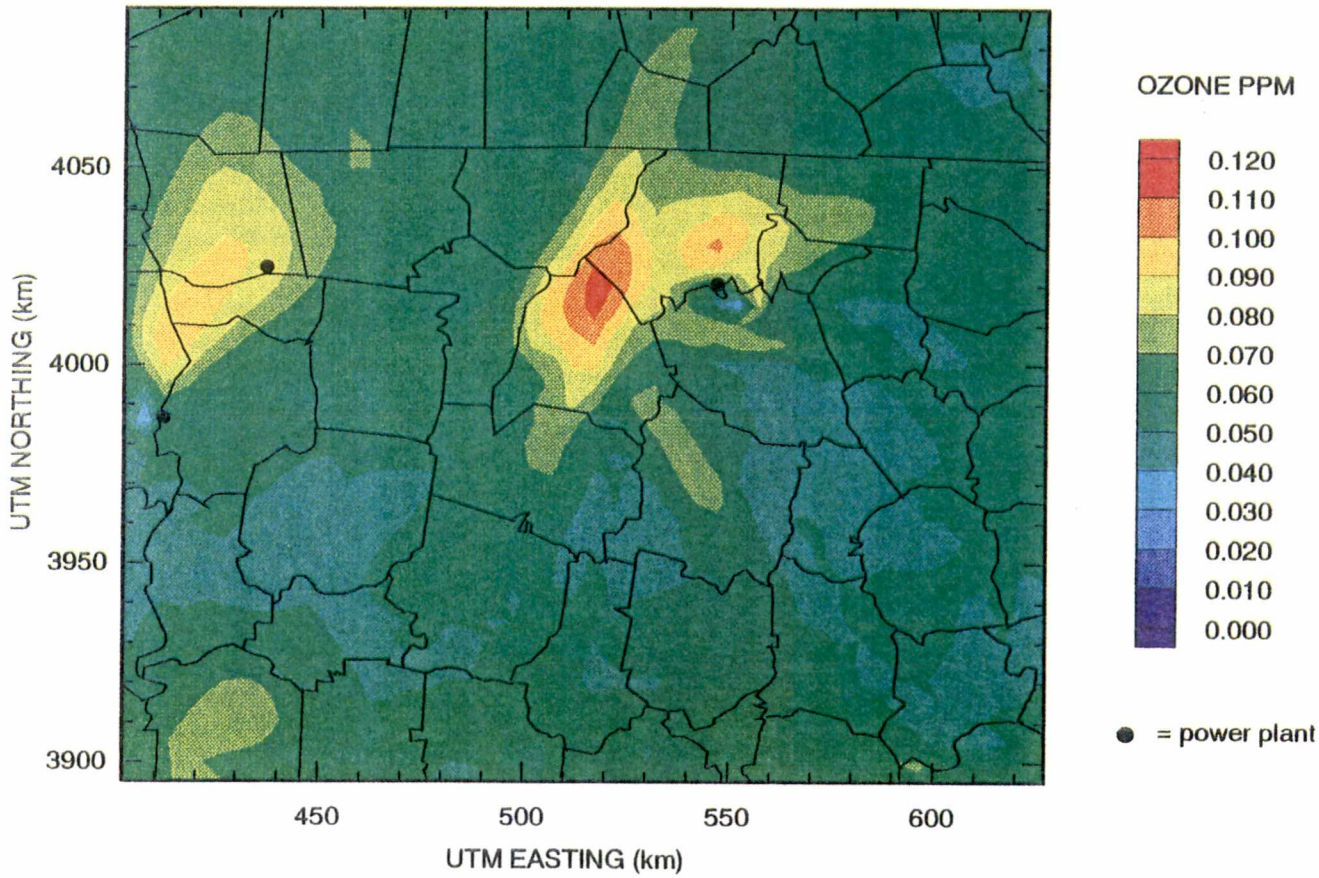


Figure 4-8. UAM simulation without Cumberland's NO_x emissions for August 1, 1988
Maximum daily ozone concentration in a cell is 0.115 ppm at 5 p.m.

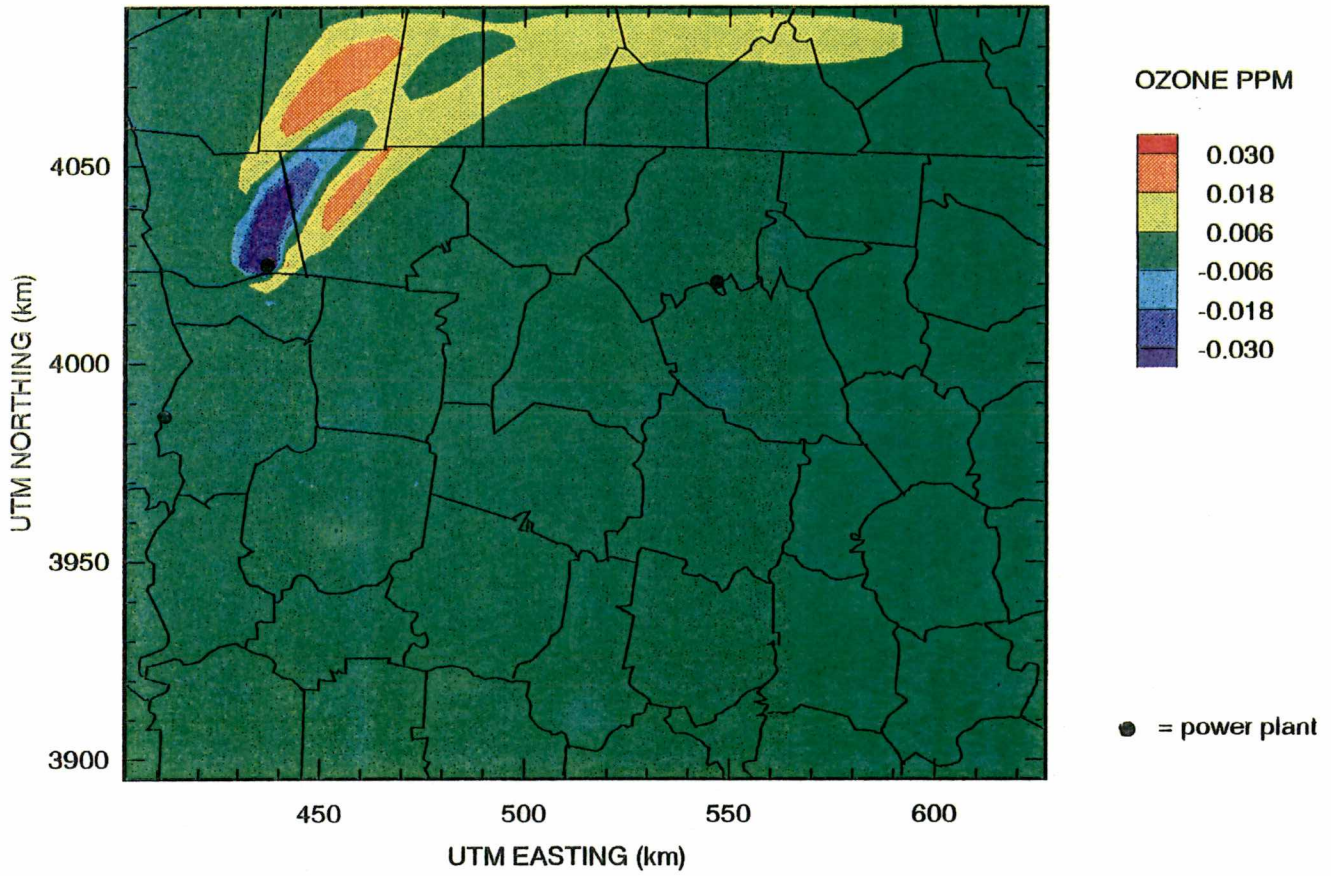


Figure 4-9. UAM Difference Plot of Cumberland's NO_x emissions for August 1, 1988 Maximum ozone concentration is 0.028 ppm at 4 p.m.

in Cumberland Steam Plant's NO_x emissions would reduce ozone concentrations by 6 ppb, whereas a 100% reduction (or absence of the plant) would have created a 26 ppb reduction; therefore, Cumberland Steam Plant's contribution to ozone on August 1, 1988 was predicted to be 26 ppb.

Figures 4-10 and 4-11 plot the maximum ozone concentration reduction in ppb versus the reduction in NO_x emissions from Cumberland. The first graph gives the reduction of NO_x in percent, while the second graph is the same plot except with the NO_x has been converted to an equivalent pounds per hour. As with the June 24 graphs, the hourly NO_x emissions reduction in pounds per hour represent the average NO_x reduced per hour for the immediate 8 hour period that preceded the hour associated with the maximum ozone concentration reduction. A relatively linear relationship was exhibited between NO_x reductions and the associated reduction in ozone due to the power plant in this particular case.

The peak concentrations moved temporally and spatially from the 5 p.m. base case peak ozone concentration on this day. The 50% NO_x difference plot for Cumberland on this day moved to the other side of the outer edges; otherwise, the maximum ozone concentrations in the difference matrix remained downwind of the plant on the outer edges of the plume. Although the shift in the hour in the maximum ozone concentration reductions shifted by one to four hours, the 5

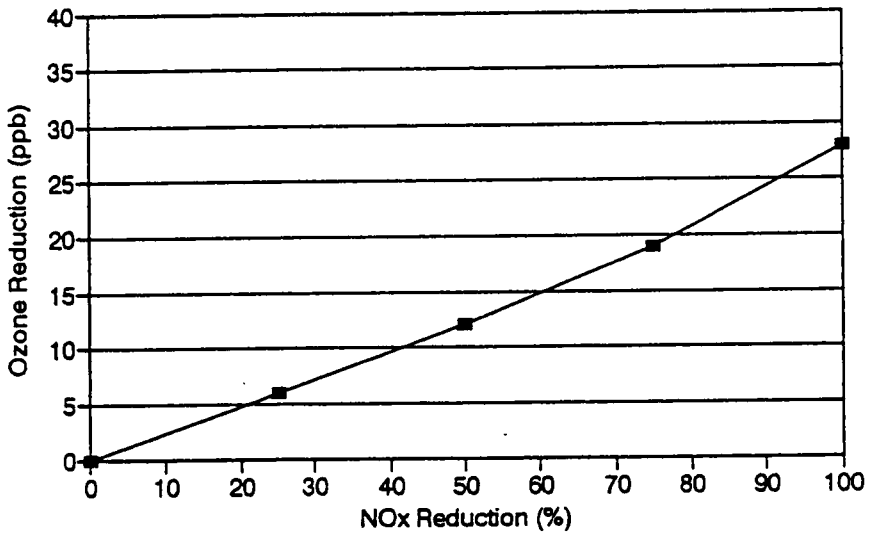


Figure 4-10. Reduction in Ozone Concentration vs. NO_x Reduction for Cumberland August 1, 1988 (% NO_x)

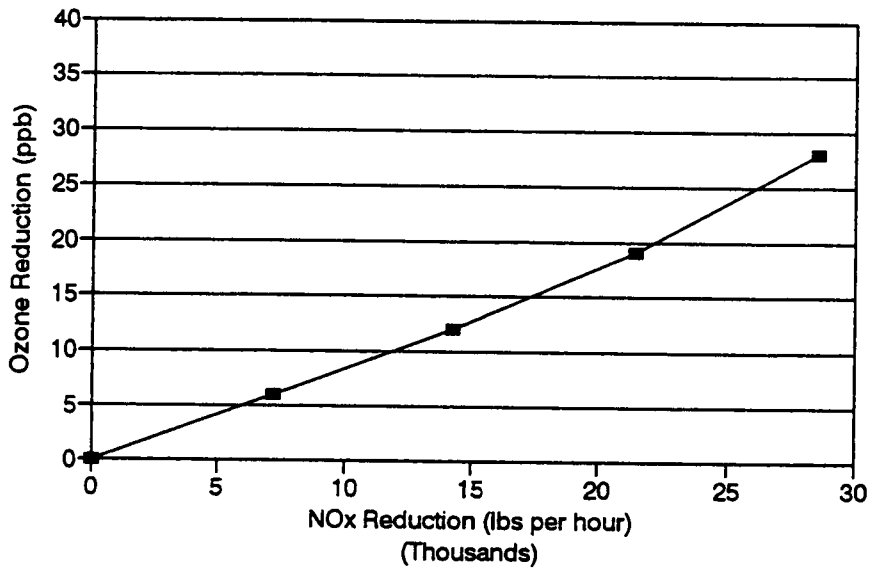


Figure 4-11. Reduction in Ozone Concentration vs. NO_x Reduction for Cumberland August 1, 1988 (pounds per hour NO_x)

p.m. difference matrix concentrations varied by only 1 to 2 ppb from the maximum ozone concentration reductions.

As with the results on June 24, the predicted maximum concentration in the overall modeling domain did not occur as a result of this power plant. The maximum daily ozone concentrations in the Middle Tennessee Modeling Domain for all of these NO_x reduction runs remained the same and was located in the central portion of the domain; it was most likely associated with the urban plume.

4.2. GALLATIN STEAM PLANT

Gallatin Steam Plant is located in Sumner County, Tennessee adjacent to Nashville. This plant's NO_x emissions were reduced by 25%, 50%, 75%, and 100% for June 24, 1988, August 1, 1988, and August 3, 1988. These same reductions were also made in the emissions for June 23, 1988, July 31, 1988, and August 2, 1988, the days preceding the primary episode day since each UAM run required a 2 day simulation.

The following chart shows the maximum ozone concentrations which were obtained in the NO_x reduction runs for Gallatin Steam Plant. Also contained in the chart are the times and locations of the maximum ozone concentrations for June 24, 1988 and August 1, 1988, and August 3, 1988. The August 3 data is in a separate chart following the June 24 and August 1 data chart.

Gallatin Steam Plant

(Maximum Ozone Concentrations Observed in NO_x Reduction Runs)

	June 24, 1988				August 1, 1988			
NO_x Reduction (%)	25	50	75	100	25	50	75	100
Ozone Conc (ppb)	113	113	113	113	115	115	115	115
UTM (Easting)	557	557	557	557	522	522	522	522
UTM (Northing)	4085	4085	4085	4085	4020	4020	4020	4020
Time (Hour)	5pm	5pm	5pm	5pm	5pm	5pm	5pm	5pm

Gallatin Steam Plant (cont.)

(Maximum Ozone Concentrations Observed in NO_x Reduction Runs)

	August 3, 1988			
NO_x Reduction (%)	25	50	75	100
Ozone Conc (ppb)	131	131	129	128
UTM (Easting)	497	497	497	502
UTM (Northing)	4005	4005	4005	4005
Time (Hour)	4pm	4pm	4pm	3pm

The second chart summarizes the maximum ozone concentration reductions which occurred as a result of the specified NO_x reductions as obtained from the difference matrices described at the beginning of this chapter. Based on the results presented in the chart for June 24, it was predicted that a 25% reduction in Gallatin Steam Plant's NO_x emissions would reduce ozone concentrations by 3 ppb, whereas

a 100% reduction (or the absence of Gallatin Steam Plant) would have created a 19 ppb reduction in ozone. Gallatin's contribution to ozone on June 24, 1988 was predicted to be 19 ppb.

Gallatin Steam Plant

(Maximum Ozone Concentration Reductions from Difference Matrices)

	June 24, 1988				August 1, 1988			
NO. Reduction (%)	25	50	75	100	25	50	75	100
Ozone Conc (ppb)	3	6	11	19	7	18	28	36
UTM (Easting)	587	577	577	572	562	562	562	557
UTM (Northing)	3990	4005	4005	4010	4025	4025	4025	4035
Time (Hour)	5pm	3pm	3pm	3pm	5pm	5pm	4pm	4pm

Gallatin Steam Plant (cont.)

(Maximum Ozone Concentration Reductions from Difference Matrices)

	August 3, 1988			
NO. Reduction (%)	25	50	75	100
Ozone Conc (ppb)	5	12	21	34
UTM (Easting)	507	507	532	512
UTM (Northing)	4025	4025	4015	4025
Time (Hour)	5pm	5pm	2pm	5pm

4.2.1. Gallatin Steam Plant: June 24, 1988

Figure 4-12 shows the predicted ozone concentration

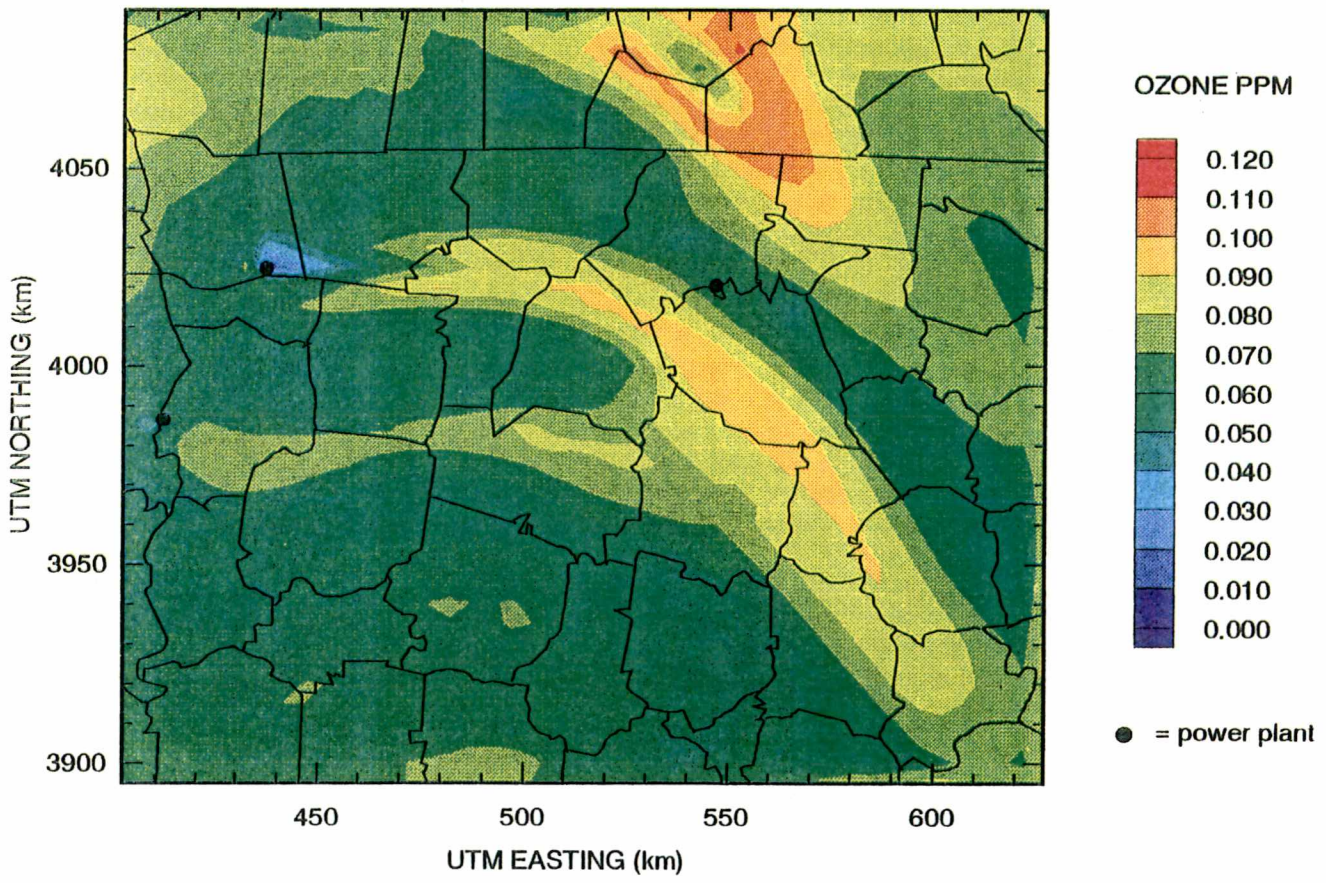


Figure 4-12. UAM simulation without Gallatin's NO_x emissions for June 24, 1988 Maximum daily ozone concentration in a cell is 0.113 ppm at 5 p.m.

isopleth plot without Gallatin's NO_x emissions on June 24, 1988. The maximum ozone concentration for the entire domain was the same as in the base case modeling scenario with all sources included. This maximum not only occurred in the same hour but also in the same location. Figure 4-13 is the difference plot which shows the relative contribution Gallatin's NO_x emissions to ozone concentrations on June 24, 1988. The scavenging that was present in the Cumberland difference plot for this day is not present in the Gallatin plume, because of the fact that Gallatin emits only 20% of the NO_x emissions that Cumberland does.

The maximum ozone concentration reductions from the difference matrices for each of the NO_x reductions remained within 2 hours of the hour associated with the base case maximum ozone concentration (5 p.m.). The 5 p.m. concentrations for these difference matrices only varied by approximately 1 ppb. The location of the maximum ozone concentration reductions obtained from the difference runs were different than those locations of the maximum base case ozone concentrations for June 24, 1988. This difference in location shows that the maximum domain ozone concentration for this day was not due to Gallatin Steam Plant, but was associated with transport into the domain from sources in Kentucky, north of the modeling domain.

Figures 4-14 plots of maximum ozone concentration reduction in ppb versus the percent reduction of NO_x. The

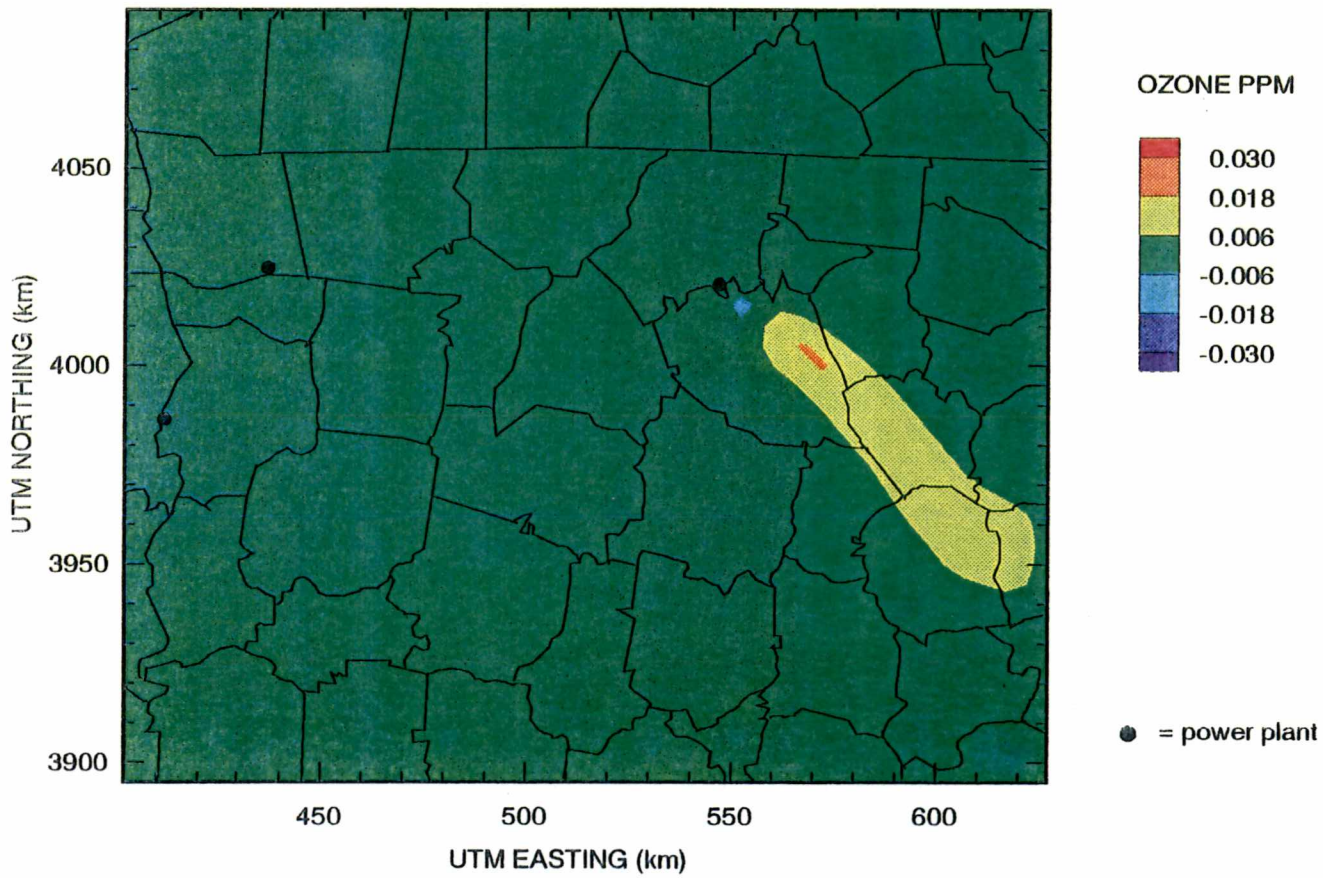


Figure 4-13. UAM Difference Plot of Gallatin's NO_x emissions for June 24, 1988 Maximum ozone concentration is 0.019 ppm at 3 p.m.

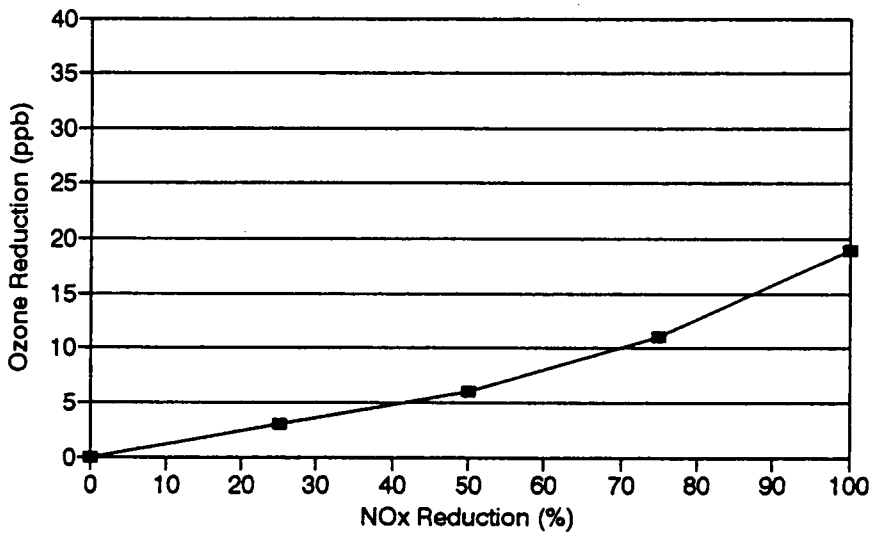


Figure 4-14. Reduction in Ozone Concentration vs. NO_x Reduction for Gallatin June 24, 1988 (% NO_x)

ozone concentrations in these plots are the maximum ozone concentration reductions obtained from the difference matrix for each NO_x reduction. These values represent the maximum ozone concentration reductions which were predicted to occur from a reduction in NO_x emissions from Gallatin Steam Plant. Figure 4-15 shows the same plot as Figure 4-14, except that the NO_x has been converted to an equivalent pounds per hour. The hourly NO_x emissions reduction in tons per hour represents the average NO_x reduced per hour for the immediate 8 hour period that preceded the hour of associated with the maximum ozone concentration reduction.

4.2.2. Gallatin Steam Plant: August 1, 1988

Figure 4-16 shows the predicted ozone concentration isopleth with no NO_x emissions from Gallatin for August 1, 1988. The maximum ozone concentration for the entire domain was the same as in the base case modeling scenario with all sources included. This maximum not only occurred in the same hour but also in the same location. Figure 4-17 is the difference plot which shows the relative contribution that Gallatin's NO_x emissions were predicted to have on ozone concentrations on August 1, 1988. This plume shows some scavenging in the general vicinity of the plant, but has an area of increasing ozone down the plume's centerline. This area of orange in the plot represents the predicted maximum ozone concentration reduction could have resulted from

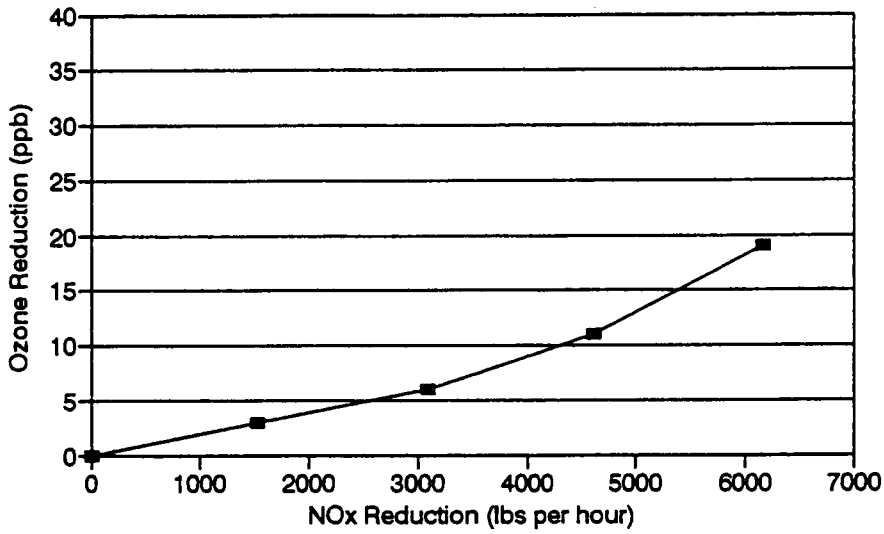


Figure 4-15. Reduction in Ozone Concentration vs. NO_x Reduction for Gallatin June 24, 1988 (pounds per hour NO_x)

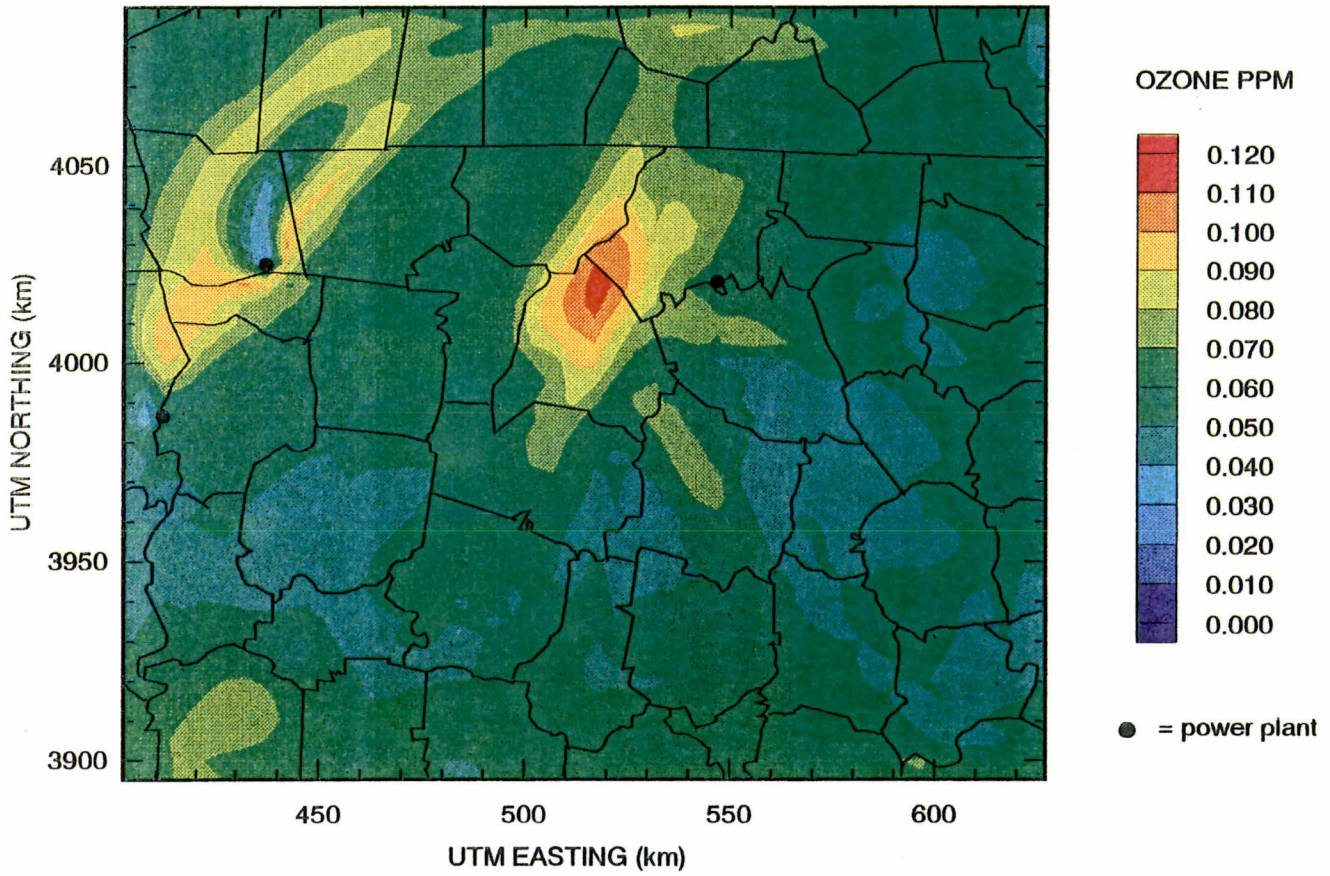


Figure 4-16. UAM simulation without Gallatin's NO_x emissions for August 1, 1988 Maximum daily ozone concentration in a cell is 0.115 ppm at 5 p.m.

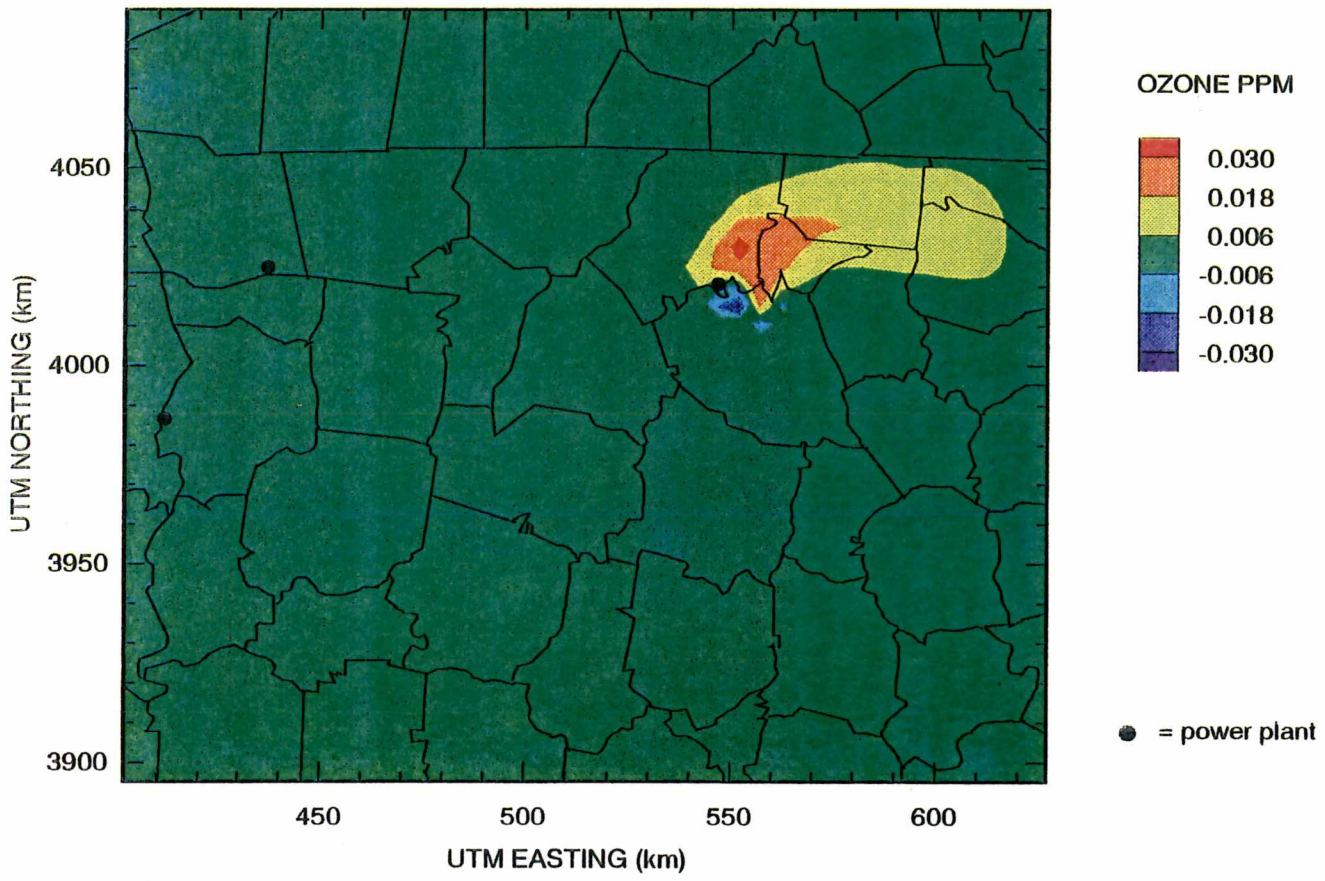


Figure 4-17. UAM Difference Plot of Gallatin's NO_x emissions for August 1, 1988 Maximum ozone concentration is 0.036 ppm at 4 p.m.

removing Gallatin's NO_x emissions.

On August 1, 1988 it was predicted that a 25% reduction in Gallatin Steam Plant's NO_x emissions would have reduced ozone concentrations by 7 ppb, whereas a 100% reduction (or absence of the plant) would have created a 36 ppb reduction. Gallatin Steam Plant's contribution to ozone on August 1, 1988 was predicted to be 36 ppb.

The maximum ozone concentration reductions for each of the NO_x reductions stayed relatively in the same time period. The 25% and 50% difference matrices had maximum ozone concentration reductions at 5 p.m., the hour at which the maximum base case ozone concentration occurred. The maximum ozone concentration reduction for the 75% and 100% difference matrices occurred at 4 p.m. The ozone concentration at 5 p.m. for these last two scenarios varied only by approximately 1 to 3 ppb from the maximum ozone concentration reduction.

Gallatin did not contribute to the maximum daily ozone concentration on August 1, 1988. The maximum base case ozone concentration was located in the central portion of the modeling domain and was most likely caused by the urban plume.

Figures 4-18 and 4-19 show plots of maximum ozone concentration reduction in ppb versus the reduction of NO_x. The first figure has the NO_x reduction in percent, while the second graph is the same plot, except with the NO_x has been converted to an equivalent pounds per hour. The hourly NO_x emissions reduction in tons per hour represents the average

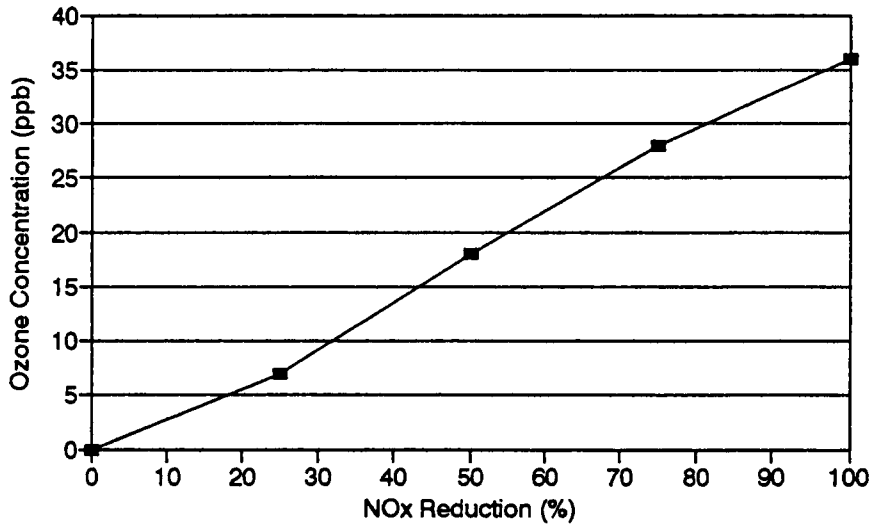


Figure 4-18. Reduction in Ozone Concentration vs. NO_x Reduction for Gallatin August 1, 1988 (% NO_x)

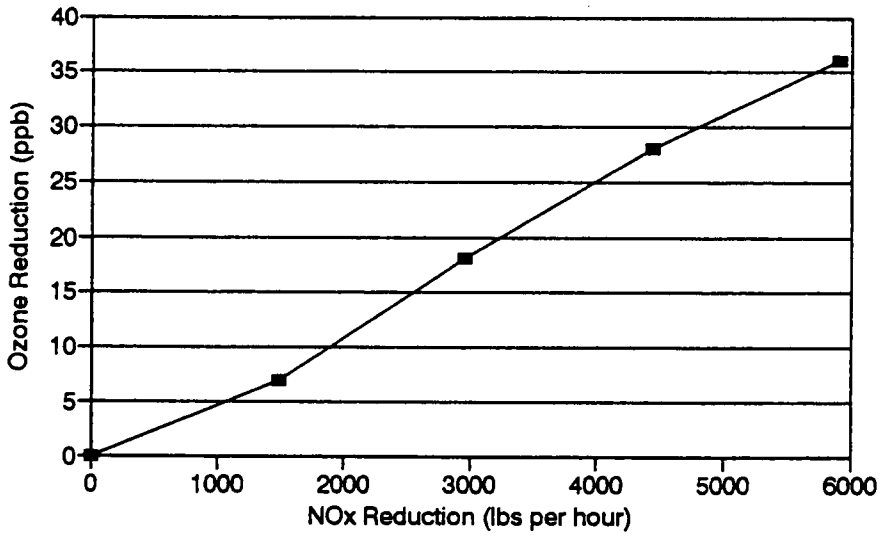


Figure 4-19. Reduction in Ozone Concentration vs. NO_x Reduction for Gallatin August 1, 1988 (pounds per hour NO_x)

NO_x reduced per hour for the immediate 8 hour period that preceded the hour associated with the maximum ozone concentration reduction.

4.2.3. Gallatin Steam Plant: August 3, 1988

Figure 4-20 shows the predicted ozone concentration isopleth plot with no NO_x emissions from Gallatin Steam Plant for August 3, 1988. Unlike the first two episode dates (June 24 and August 1) the maximum ozone concentration for the entire domain changed when the NO_x emissions were reduced for Gallatin Steam Plant. For the 25%, 50% and 75% NO_x reduction runs, the maximum ozone concentration remained in the same cell as the base case scenario maximum ozone concentration, but the concentration itself varied. The maximum predicted ozone concentration was predicted to be reduced by 1 ppb for the 25% and 50% NO_x reduction runs, and predicted to be reduced by 3 ppb for the 75% NO_x reduction runs. The 100% NO_x reduction run predicted a maximum ozone concentration of 128 ppb, a reduction of 4 ppb from the maximum ozone concentration predicted from the base case runs. The location of this maximum ozone concentration moved to the east by 5 km and shifted in time to 3 p.m. from 4 p.m. These results imply that Gallatin's NO_x emissions contributed to the maximum ozone concentration that occurred in the modeling domain for August 3, 1988.

Figure 4-21 is the difference plot which shows the

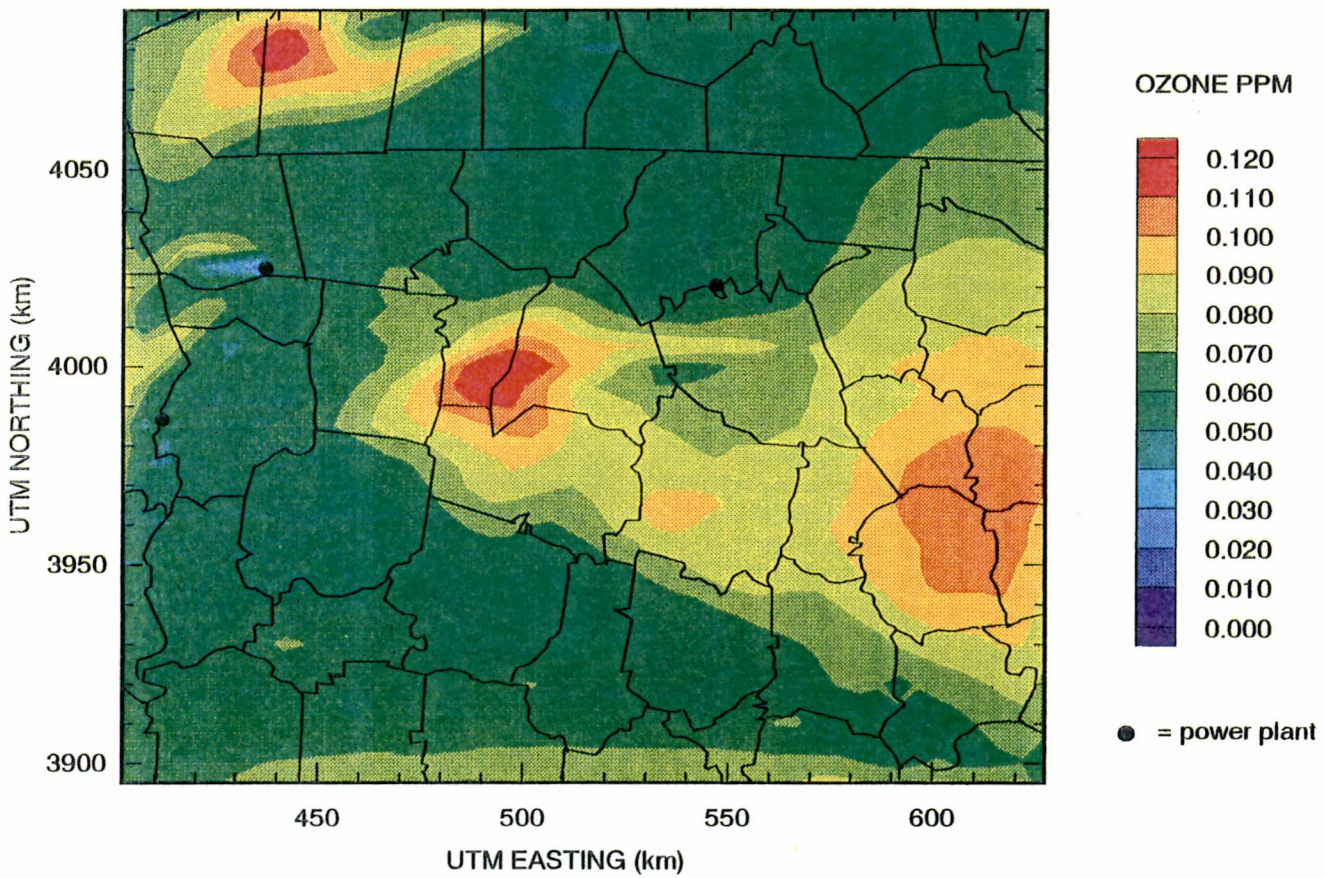


Figure 4-20. UAM simulation without Gallatin's NO_x emissions for August 3, 1988 Maximum daily ozone concentration in a cell is 0.128 ppm at 3 p.m.

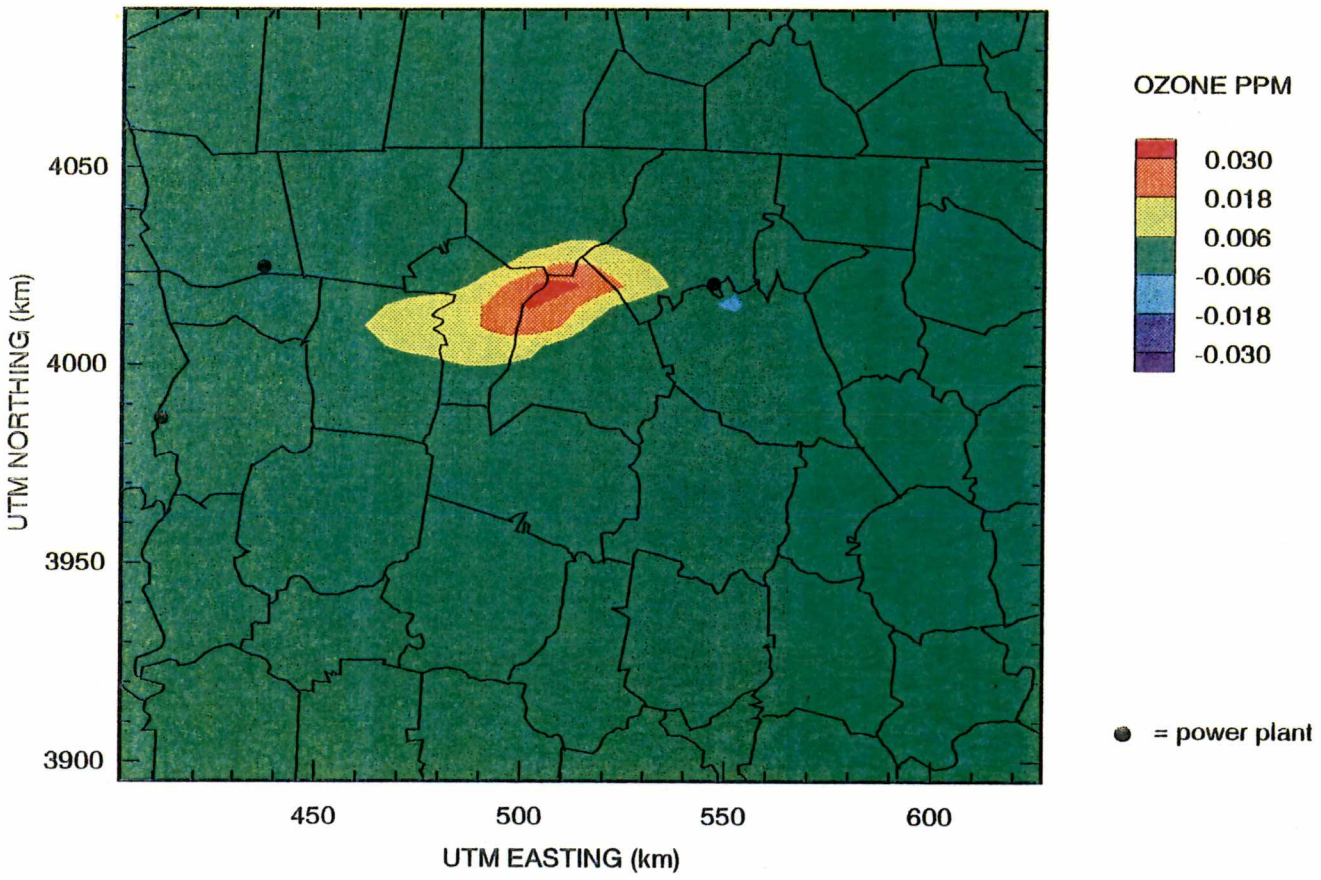


Figure 4-21. UAM Difference Plot of Gallatin's NO_x emissions for August 3, 1988 Maximum ozone concentration is 0.034 ppm at 5 p.m.

relative contribution of Gallatin's NO_x emissions had on ozone concentrations on August 3, 1988. This plume shows no scavenging except for a very small amount around the plant. The time at which the maximum ozone concentration reduction occurred for each of the NO_x reductions differed from the base case and NO_x reduction runs. The maximum ozone concentration reductions for the 25%, 50%, and 100% NO_x reductions were predicted to occur at 5 p.m., while the 75% difference matrix showed a predicted maximum ozone concentration reduction at 2 p.m. The 4 p.m. concentrations (the hour associated with the base case maximum ozone concentration) varied by approximately 1 to 3 ppb from the maximum ozone concentration reductions.

Based on the results presented in the chart at the beginning of Section 4.2, it was predicted that a 25% reduction in Gallatin Steam Plant's NO_x emissions on August 3, 1988 would reduce have ozone concentrations by 5 ppb, whereas a 100% reduction (or the absence of Gallatin Steam Plant) would have created a 34 ppb reduction in ozone. Gallatin's contribution to ozone on June 24, 1988 was predicted to be 34 ppb.

Figures 4-22 and 4-23 show plots of maximum ozone concentration reductions in ppb versus the reduction of NO_x. The first figure has the NO_x reduction in percent, while the second graph is the same plot, except the NO_x has been converted to an equivalent pounds per hour. The hourly NO_x emissions reduction in tons per hour represents the average

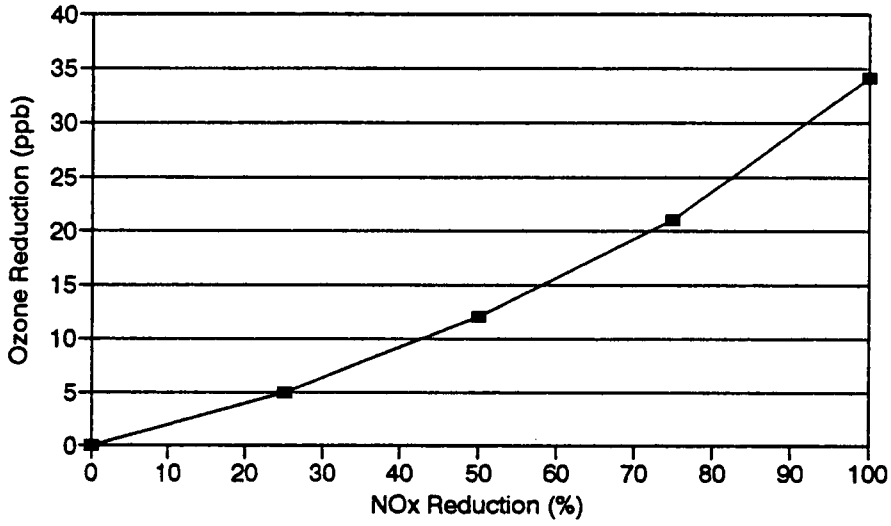


Figure 4-22. Reduction in Ozone Concentration vs. NO_x Reduction for Gallatin August 3, 1988 (% NO_x)

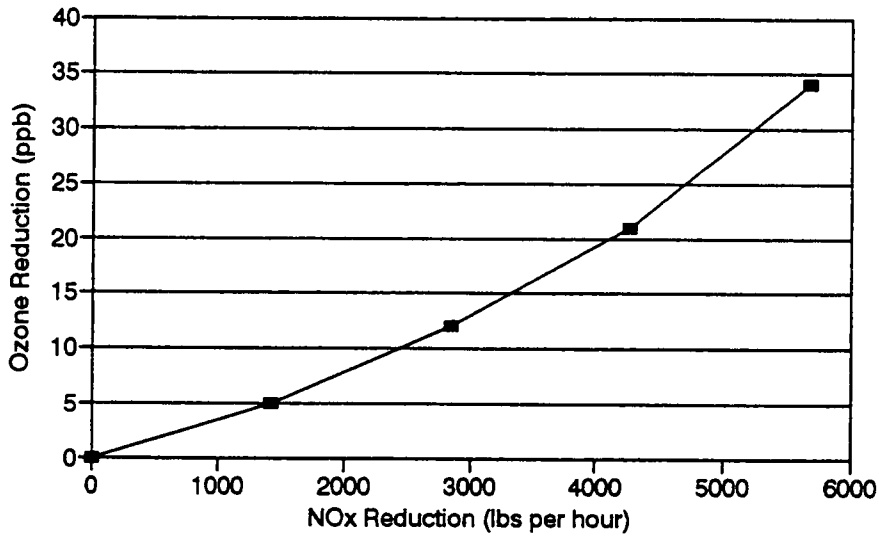


Figure 4-23. Reduction in Ozone Concentration vs. NO_x Reduction for Gallatin August 3, 1988 **(pounds per hour NO_x)**

NO_x reduced per hour for the immediate 8 hour period that preceded the hour associated with the maximum ozone concentration reduction.

4.3. NEW JOHNSONVILLE STEAM PLANT

New Johnsonville Steam Plant is located in Humphreys County, Tennessee on the west side of the modeling domain. This plant's NO_x emissions were reduced by 25%, 50%, 75%, and 100% for June 24, 1988 and August 1, 1988. These same reductions were also made in the emissions for June 23, 1988 and July 31, 1988, the days preceding the primary episode day since each UAM run required a 2 day simulation.

The following chart shows the maximum ozone concentrations which were obtained in the NO_x reduction runs for New Johnsonville Steam Plant. Also contained in this chart are the times and locations of the maximum ozone concentrations for June 24, 1988 and August 1, 1988.

New Johnsonville Steam Plant

(Maximum Ozone Concentrations Observed in NO_x Reduction Runs)

	June 24, 1988				August 1, 1988			
NO_x Reduction (%)	25	50	75	100	25	50	75	100
Ozone Conc (ppb)	113	113	113	113	115	115	115	115
UTM (Easting)	557	557	557	557	522	522	522	522
UTM (Northing)	4085	4085	4085	4085	4020	4020	4020	4020
Time (Hour)	5pm	5pm	5pm	5pm	5pm	5pm	5pm	5pm

The second chart summarizes the maximum ozone concentration reductions which were predicted to occur as a result of the specified NO_x reductions as obtained from the difference matrices described at the beginning of this chapter. Based on the results presented in the chart, it was predicted that a 25% reduction in New Johnsonville Steam Plant's NO_x emissions on June 24, 1988 would have reduced ozone concentrations by 4 ppb, whereas a 100% reduction would have created a 21 ppb reduction. New Johnsonville's contribution to ozone on June 24, 1988 was predicted to be 21 ppb.

New Johnsonville Steam Plant

(Maximum Ozone Concentrations Reductions from Difference Matrices)

	June 24, 1988				August 1, 1988			
NO_x Reduction (%)	25	50	75	100	25	50	75	100
Ozone Conc (ppb)	4	7	13	21	5	10	16	25
UTM (Easting)	457	457	452	447	422	422	422	422
UTM (Northing)	3980	3980	3985	3985	4005	4005	4005	3979
Time (Hour)	4pm	4pm	6pm	6pm	5pm	5pm	5pm	4pm

4.3.1. New Johnsonville Steam Plant: June 24, 1988

Figure 4-24 shows the predicted ozone concentration isopleth plot with no NO_x emissions from New Johnsonville Steam Plant for June 24, 1988, that is, with a 100% reduction

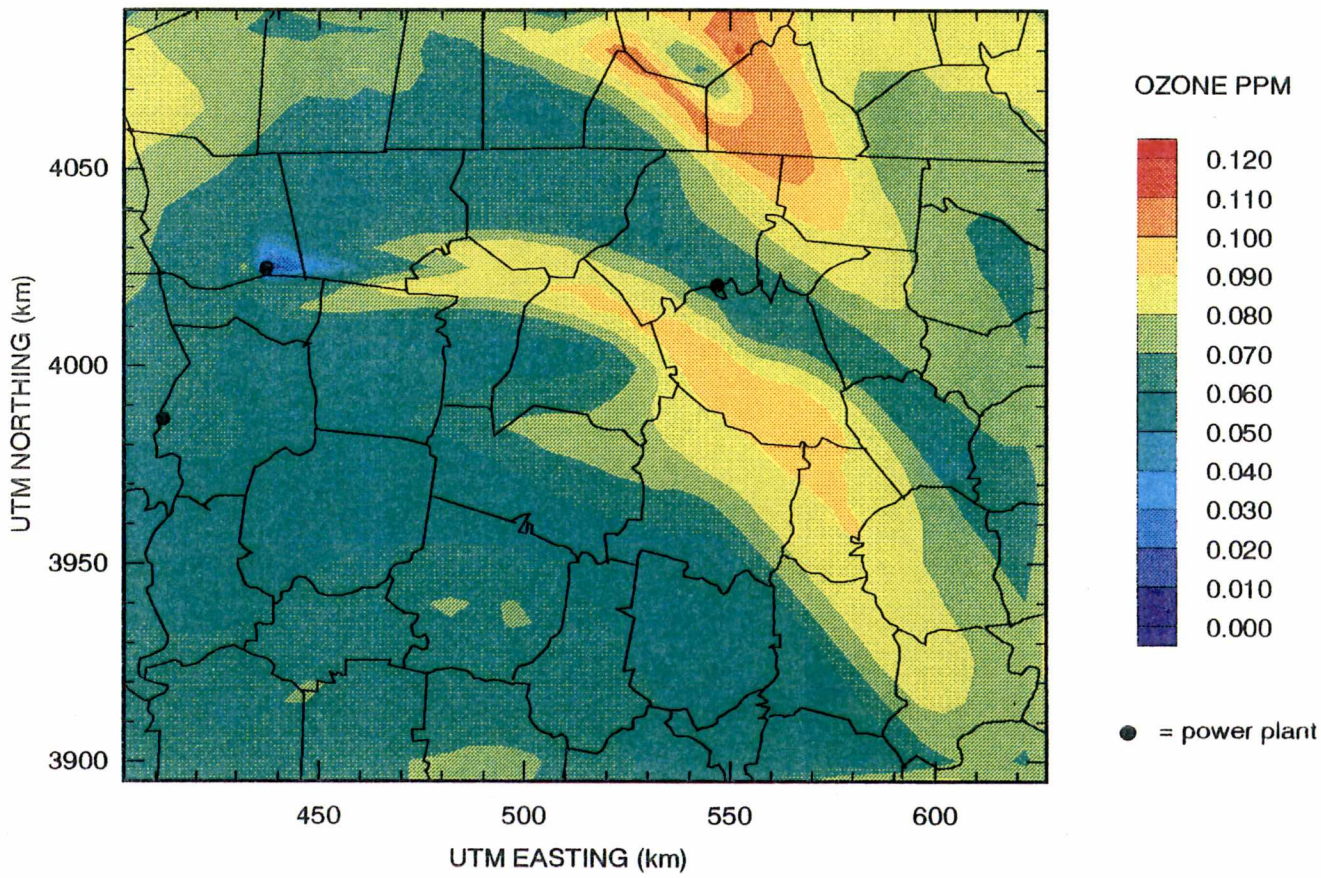


Figure 4-24. UAM simulation without New Johnsonville's NO_x emissions for June 24, 1988 Maximum daily ozone concentration in a cell is 0.113 ppm at 5 p.m.

in these emissions. The maximum ozone concentration observed from the NO_x reduction runs remained the same, again showing that on June 24, 1988 the maximum domain ozone concentration was associated with transport into the domain from sources in Kentucky, north of the modeling domain.

Figure 4-25 is the difference plot showing the relative contribution of New Johnsonville's NO_x emissions to ozone concentrations. Adjacent to the plant is an area of scavenging, but otherwise, there is no other scavenging seen in this plot. The maximum ozone concentration is found within the orange portion of the plume. This area represents the maximum ozone concentration reduction which was predicted to result from a hypothetical reduction in NO_x emissions at New Johnsonville.

The maximum ozone concentration reductions on June 24 did not occur at the time of the base case maximum ozone concentration (5 p.m.). The 25% and 50% NO_x reductions predicted maximum ozone concentrations at 4 p.m., while the 75% and 100% NO_x reduction runs predicted maximum ozone concentration reductions at 6 p.m. The 5 p.m. ozone concentration reductions differed by only 1 ppb from the maximum ozone concentration reductions.

The locations of the maximum ozone concentration reductions were not the same as the location as the maximum base case ozone concentrations. The locations of the maximum ozone concentration reductions from the difference matrices

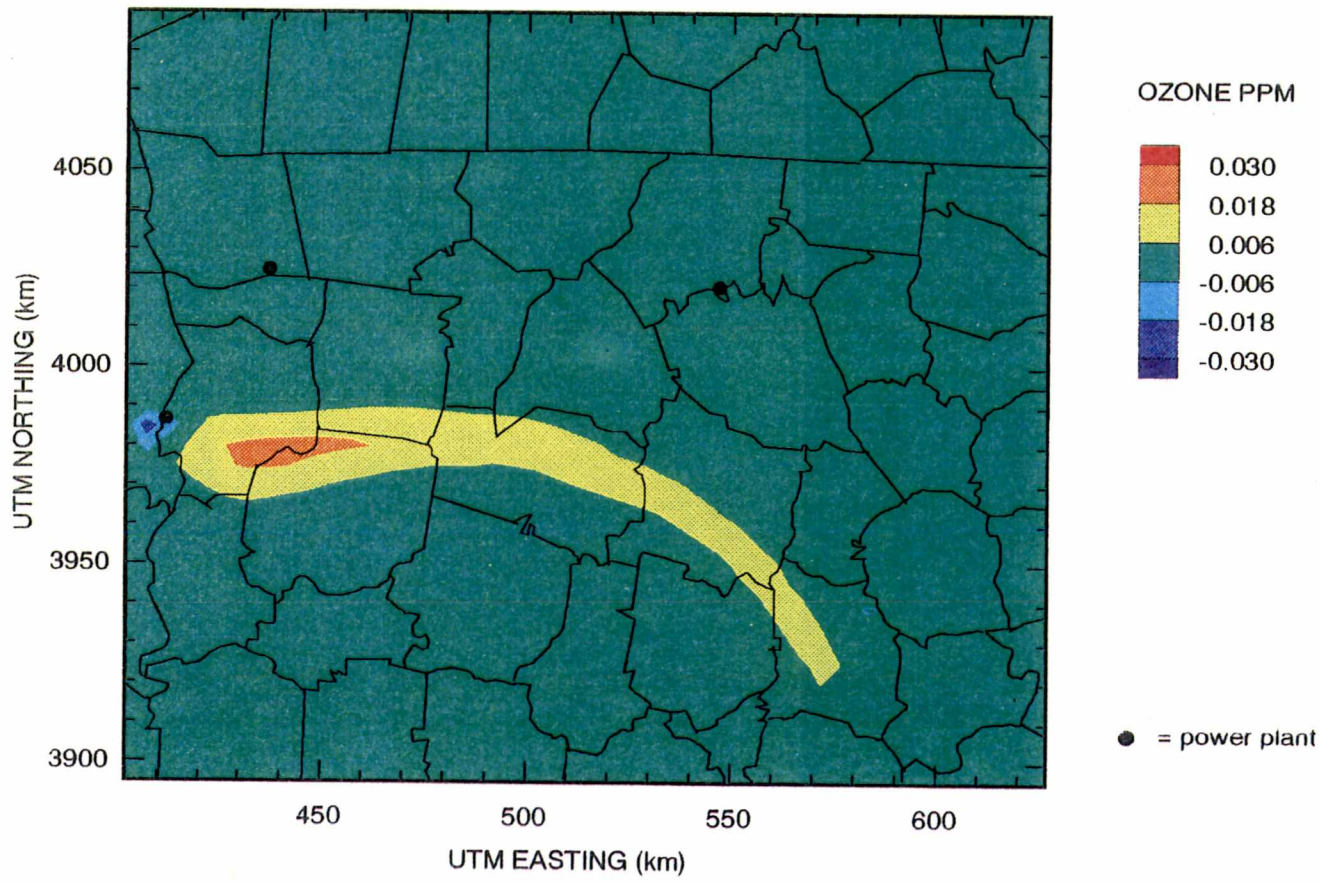


Figure 4-25. UAM Difference Plot of New Johnsonville's NO_x emissions for June 24, 1988 Maximum ozone concentration is 0.021 ppm at 6 p.m.

varied as the NO_x reductions varied, but all four were located along the center line of the plume, shown in orange in Figure 4-25.

Figures 4-26 and 4-27 plot of the maximum ozone concentration reduction in ppb versus the reduction of NO_x. The first figure has the NO_x reduction in percent, while the second graph has NO_x in lbs per hour. The hourly NO_x emissions reduction in tons per hour represents the average NO_x reduced per hour for the immediate 8 hour period that preceded the hour associated with the maximum ozone concentration reduction.

4.3.2. New Johnsonville Steam Plant: August 1, 1988

Figure 4-28 shows the predicted ozone concentration isopleth plot with no NO_x emissions from New Johnsonville Steam Plant for August 1, 1988. Similar to the results from Cumberland and Gallatin for this day, the maximum ozone concentration for the NO_x reduction runs remained the same. On this day, the maximum domain ozone concentration was not due to New Johnsonville's NO_x emissions, but most likely due to the emissions from the urban plume.

Figure 4-29 is the difference plot showing the relative contribution of New Johnsonville Steam Plant's NO_x emissions. The maximum ozone concentration reduction was located in the orange area within the plume, with some scavenging in the general vicinity of the plant. The shape of the plume is

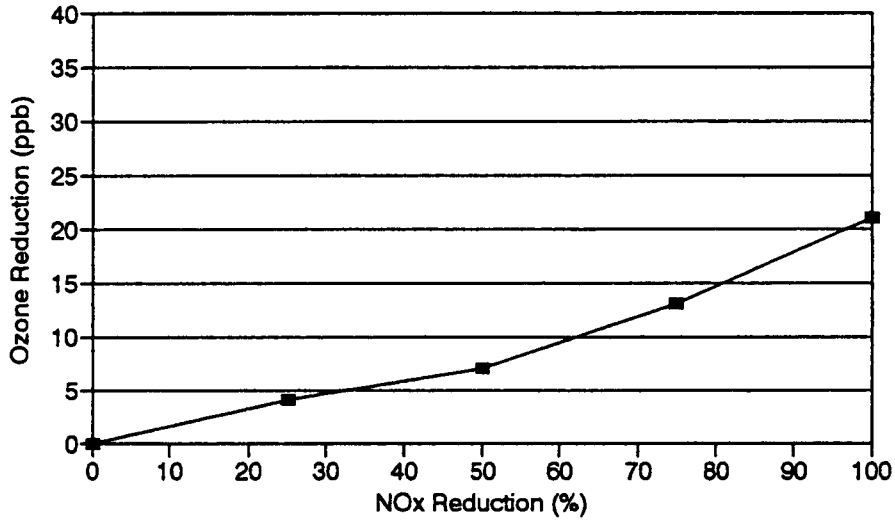


Figure 4-26. Reduction in Ozone Concentration vs. NO_x Reduction for New Johnsonville June 24, 1988 (% NO_x)

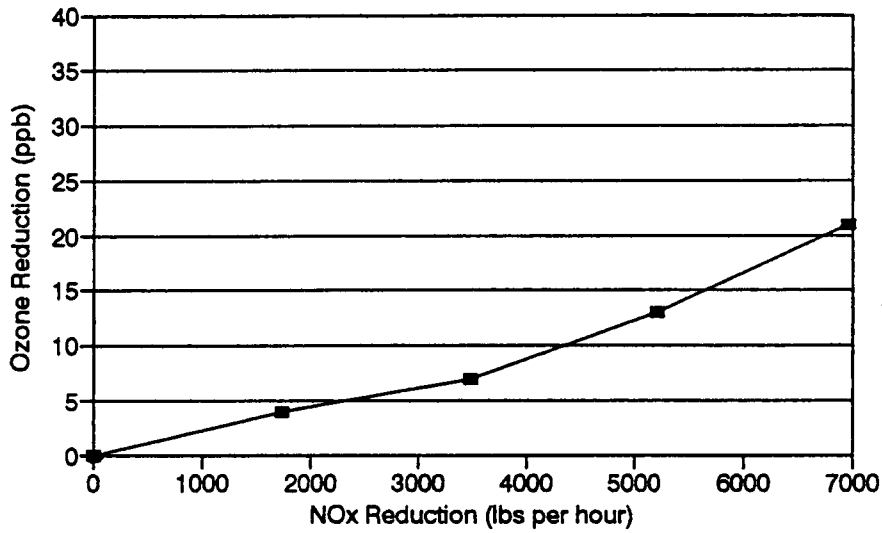


Figure 4-27. Reduction in Ozone Concentration vs. NO_x Reduction for New Johnsonville June 24, 1988 (pounds per hour NO_x)

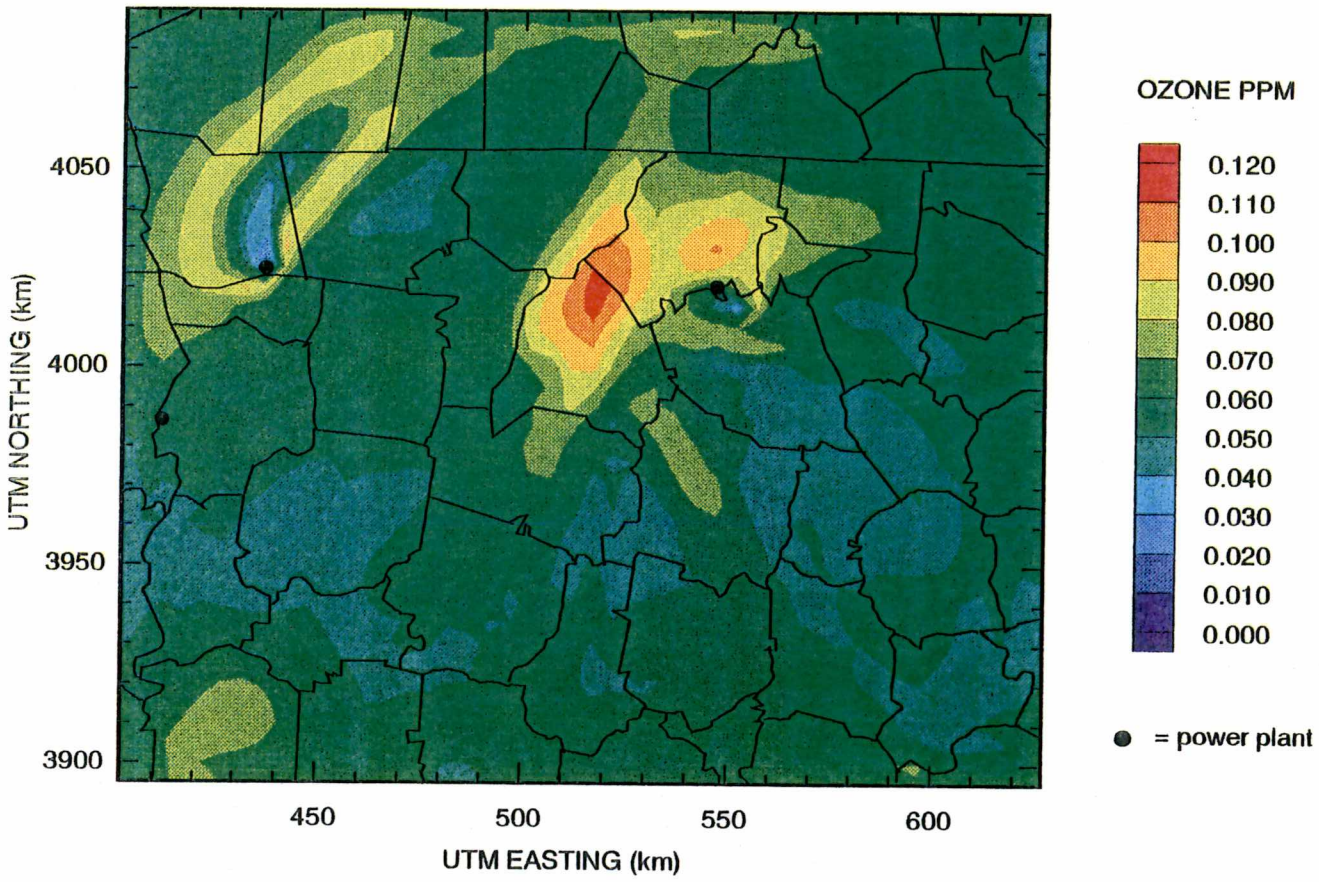


Figure 4-28. UAM simulation without New Johnsonville's NO_x emissions for August 1, 1988 Maximum daily ozone concentration in a cell is 0.115 ppm at 5 p.m.

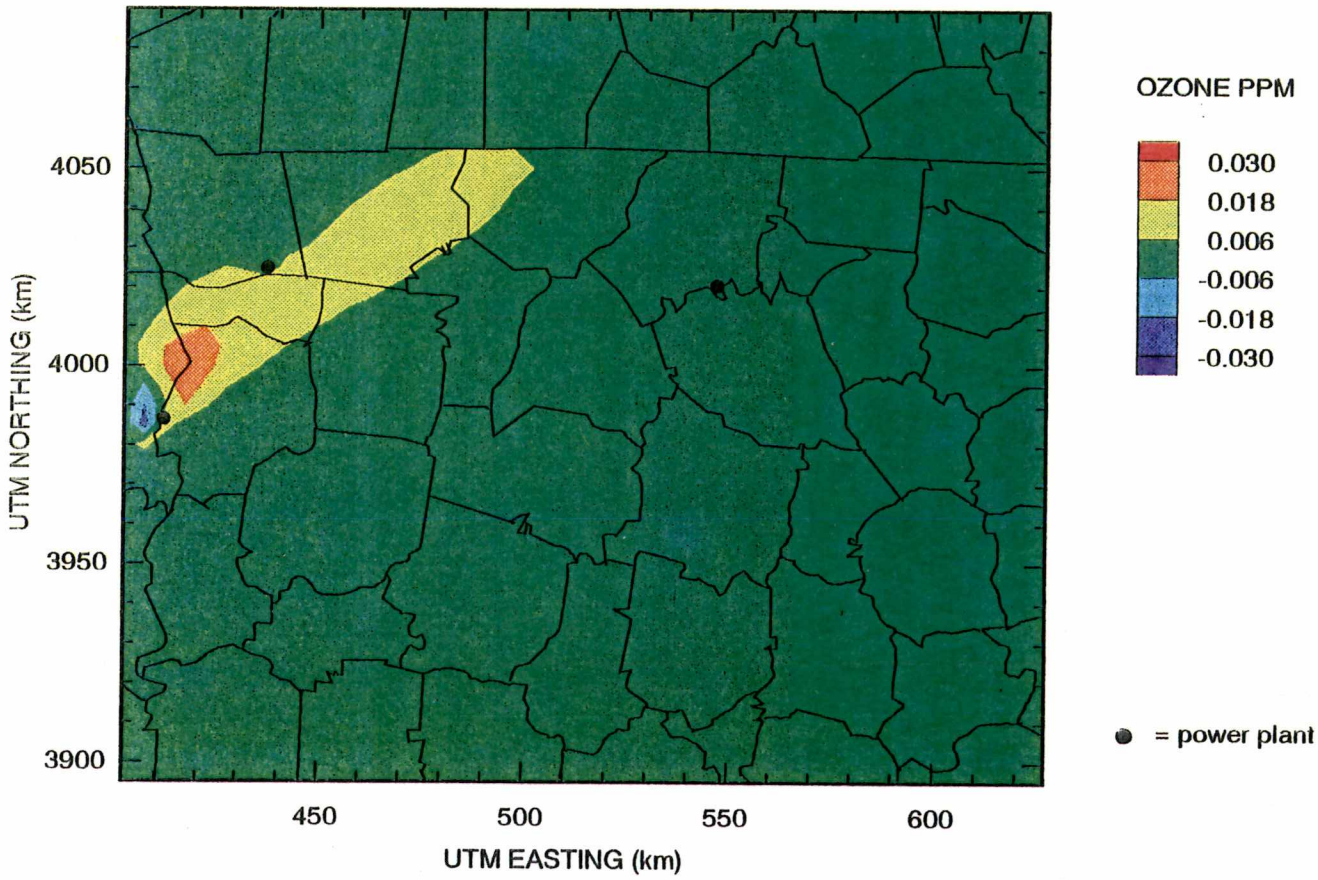


Figure 4-29. UAM Difference Plot of New Johnsonville's NO_x emissions for August 1, 1988 Maximum ozone concentration is 0.025 ppm at 4 p.m.

distorted around the area where Cumberland's plume was located in the base case scenario, showing that the plumes combined and reacted with one another.

Based on the results in the chart at the beginning of Section 4.3, on August 1, 1988 it was predicted that a 25% reduction in New Johnsonville Steam Plant's NO_x emissions would reduce ozone concentrations by 5 ppb, whereas a 100% reduction (or absence of the plant) would have created a 25 ppb reduction. New Johnsonville Steam Plant's contribution to ozone on August 1, 1988 was predicted to be 25 ppb.

The location of the maximum ozone concentration reduction differed from the location of the maximum base case ozone concentrations. The 25%, 50%, and 75% NO_x reductions predicted maximum ozone concentrations reductions in the same cell, but the maximum ozone reduction from the 100% difference matrix moved 6 km south. The first three reduction runs had maximum ozone concentration reduction at 5 p.m., the hour in which the base case maximum ozone concentration occurred, while the 100% difference matrix predicted the maximum ozone concentration reduction at 4 p.m. The 5 p.m. ozone concentration for this last run differed only 1 ppb from the maximum ozone concentration reduction.

Figures 4-30 and 4-31 plots of the maximum ozone concentration reductions in ppb versus the reduction of NO_x. The first figure has the NO_x reduction in percent, while the second figure has NO_x in equivalent pounds per hour. The

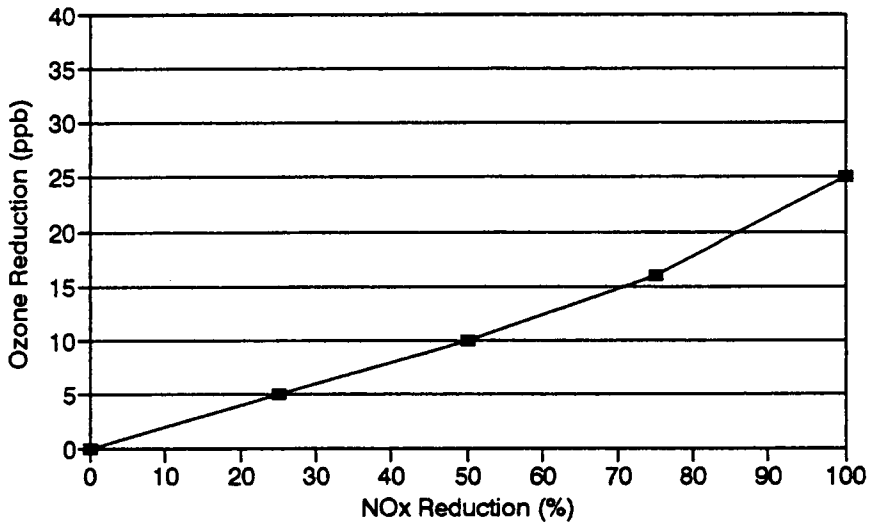


Figure 4-30. Reduction in Ozone Concentration vs. NO_x Reduction for New Johnsonville August 1, 1988 (% NO_x)

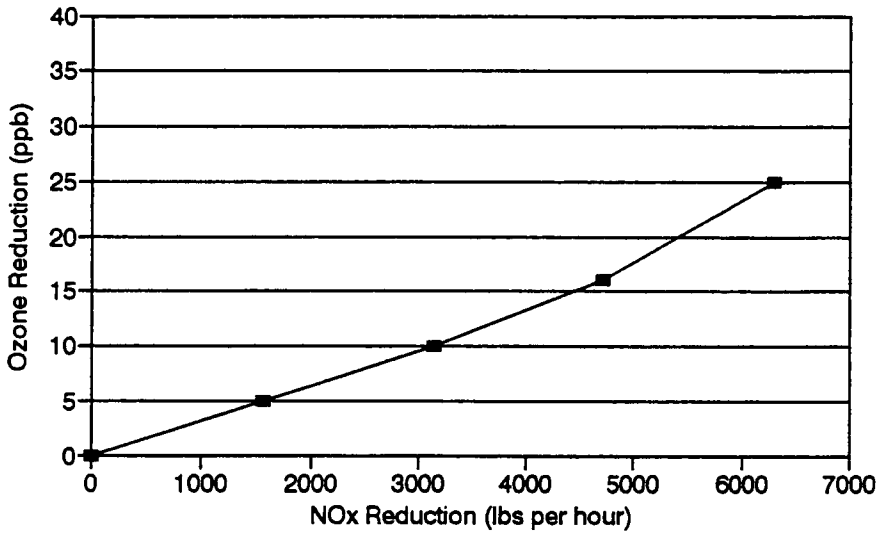


Figure 4-31. Reduction in Ozone Concentration vs. NO_x Reduction for New Johnsonville August 1, 1988 (pounds per hour NO_x)

hourly NO_x emissions reduction in tons per hour represents the average NO_x reduced per hour for the immediate 8 hour period that preceded the hour associated with the maximum ozone concentration reduction.

4.4. DISCUSSION

The following chart summarizes all of the maximum ozone concentration reductions that were produced from each NO_x reduction run. These values, in parts per billion, were obtained from the difference matrices for the NO_x reductions, created by subtracting the values obtained in the NO_x reduction runs from the base case run.

Maximum Ozone Concentrations Reductions (ppb)

	Cumberland				Gallatin				New Johnsonville			
	25	50	75	100	25	50	75	100	25	50	75	100
June 24	8	18	29	39	3	6	11	19	4	7	13	21
August 1	6	12	19	26	7	18	28	36	5	10	16	25
August 3	na	na	na	na	5	12	21	34	na	na	na	na

These values represent the maximum ozone concentration reductions that each plant could achieve based on the specified levels of NO_x reduction within the modeling domain.

All of the graphs in the sections above show that

reductions in NO_x emissions from power plants would result in subsequent reductions in the ozone concentrations. The actual location and time of the occurrence of the "maximum ozone concentration reductions" was not necessarily the same as the location and time of occurrence of the peak ozone concentration for that date.

Another point that should be noted is that the modeling domain on the whole is generally more sensitive to NO_x emissions than to VOC emissions as demonstrated by previous analyses. However, the plumes created by the power plants also contain an area of VOC sensitivity. These areas, located immediately downwind of the plumes near the centerline of the plumes, are those which show up as negative values on the ozone isopleth plots of the difference matrices. These areas exhibit the depletion of ozone due to the NO_x plumes, while at the same time, the edges of the plume exhibit a production of ozone as discussed earlier. In other words, the presence of high NO_x concentrations caused a depletion in the immediate downwind vicinity of the plume. As a result, potential reductions in NO_x emissions near the plants actually had the effect of increasing ozone concentrations just downwind of the plant. While these areas of influence are relatively small compared to the areas where the presence of NO_x causes increases in ozone, they are predicted to exist. To illustrate this effect in quantitative terms, the following chart shows the incremental ozone increases which were

predicted to occur just downwind of the plumes for 25 to 100% reductions in NO_x. In general, the ozone increases ranged from 3 to 13 ppb depending on the plant and percent NO_x reduction. It should be emphasized that the areas of influence were small compared to the areas where the ozone concentrations were reduced as NO_x reductions were made.

Incremental Positive Ozone Concentrations (ppb) With a 25% Incremental Decrease in NO_x Emissions

	Cumberland				Gallatin				New Johnsonville			
	25	50	75	100	25	50	75	100	25	50	75	100
June 24	8	10	11	10	3	3	5	8	4	3	6	8
August 1	6	6	7	7	7	11	10	8	5	5	6	9
August 3	na	na	na	na	5	7	9	13	na	na	na	na

In order to assess the overall effect that NO_x emissions from power plants in the Middle Tennessee Area have on tropospheric ozone concentrations, a graph was made in which the maximum ozone reduction was plotted against the reduction in the amount of NO_x emissions to see if a consistent relationship existed throughout the urban area for all plants on each episode date. Figure 4-32 shows this plot for June 24, 1988 for all power plants. There exists a definite correlation for each plant; an increase in the reduction of NO_x emissions resulted in an increase in possible ozone

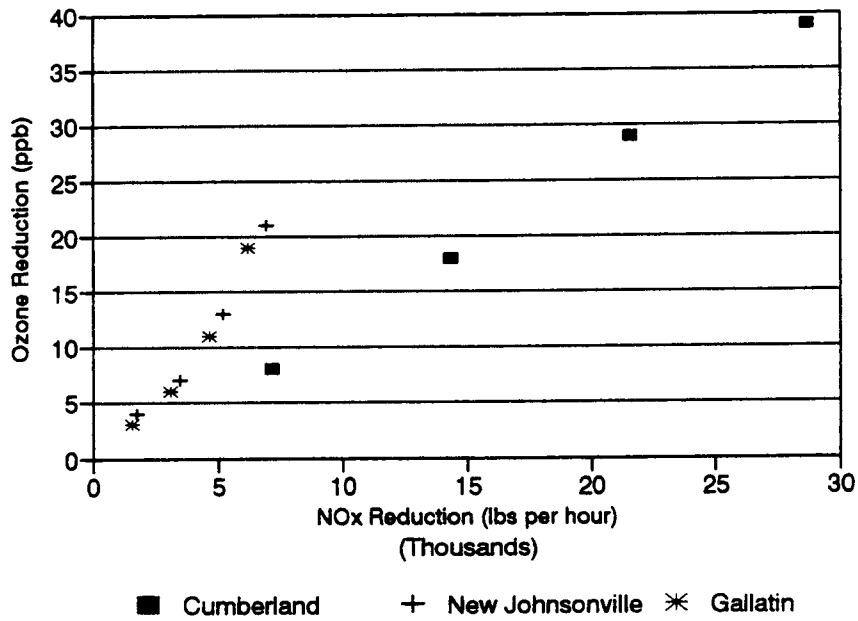


Figure 4-32. Reduction in Ozone Concentration vs. NO_x Reduction for All Power Plants June 24, 1988

reductions. However, it is obvious that there is no consistent relationship among the plants. While the effects of New Johnsonville and Gallatin appear to be similar, Cumberland has an entirely different relationship. Similar observations were made for the plants on August 1, 1988, as shown in Figure 4-33.

The final plot, Figure 4-34, shows the overall plot of ozone reductions versus the reduction of NO_x in pounds per hour for all plants and dates combined. These NO_x emissions include Cumberland for June 24 and August 1, Gallatin for June 24, August 1, and August 3, and New Johnsonville for June 24 and August 1. The amount of ozone reduction that the two smaller plants, Gallatin and New Johnsonville, had with an increase in NO_x reduction are similar, whereas the relationship for Cumberland is quite different. For all three plants, the plot does show some generic qualities as to the effects of NO_x emissions on ozone formation in that reductions in the amount of NO_x emitted from the power plants do result in ozone reductions in all cases.

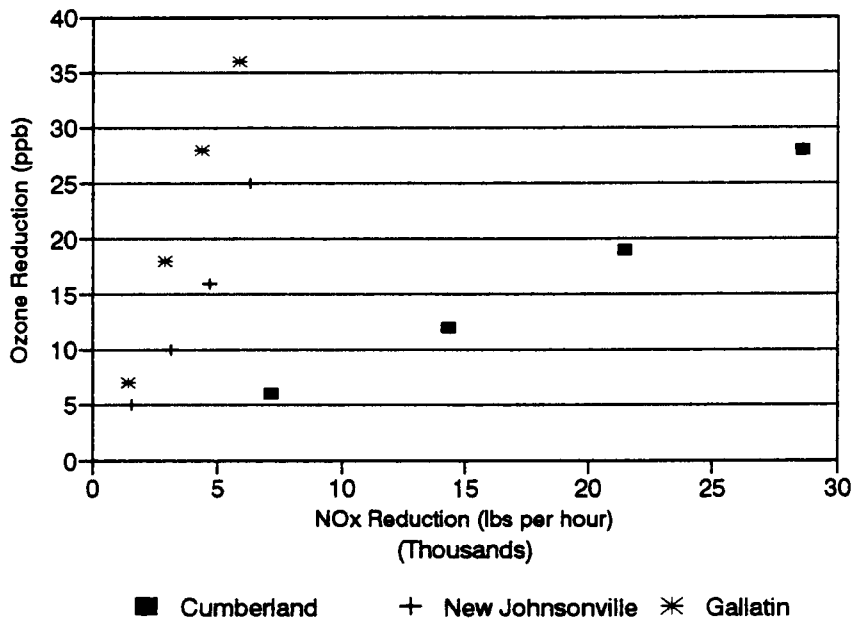


Figure 4-33. Reduction in Ozone Concentration vs. NO_x Reduction for All Power Plants August 1, 1988

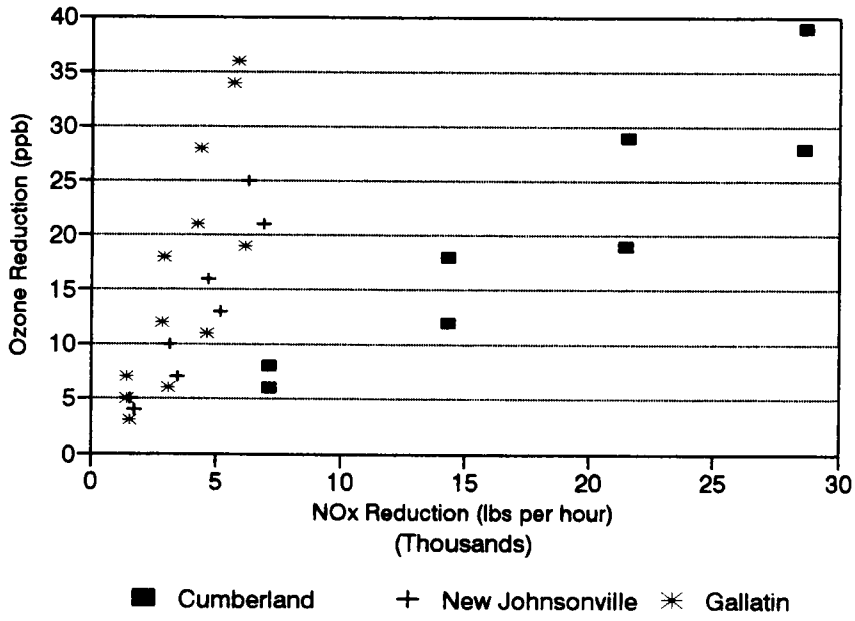


Figure 4-34. Reduction in Ozone Concentration vs. NO_x Reduction for All Power Plants for All Days

5. CONCLUSIONS

This thesis studied the effect that the NO_x emissions from power plants in the Middle Tennessee area had on tropospheric ozone. The study was performed by using the Urban Airshed Model to model reductions in NO_x emissions from each of the three power plants located in this area.

The "maximum ozone concentration reductions" obtained from the difference matrices are the maximum possible ozone reductions that occurred from reductions in NO_x emissions within the modeling domain. The 25% to 100% reduction NO_x emissions from Cumberland Steam Plant produced reductions in ozone concentrations of 6 to 39 ppb along the immediate edges of the plume. Ozone concentrations were reduced from 5 to 36 ppb when the NO_x emissions were reduced from 25 to 100% from Gallatin Steam Plant. Finally, reducing NO_x emissions by 25 to 100% from New Johnsonville Steam Plant decreased ozone concentrations from 4 to 25 ppb. Although these maximum concentrations in the difference matrices shifted in time and space among the NO_x reduction runs, the changes were shown to be minimal when the ozone concentrations were compared for the same hours. The changes in the location of these maximums only shifted 5 to 10 km.

The response that was seen from reductions in NO_x emissions distinguishes that the Middle Tennessee area is very sensitive to NO_x emissions. Previous analyses have

demonstrated that the area was relatively insensitive to VOC changes; however, the areas within the power plant plumes (immediately downwind of the plume) with the highest NO_x emissions are in fact more sensitive to VOCs. These areas were shown as the negative values on the ozone isopleth plots which came from the difference matrices, suggesting that potential reductions in NO_x emissions near the plants actually had the effect of increasing ozone concentrations just downwind of the plant. These areas of influence are small as compared to the areas where the presence of NO_x causes an increase in ozone.

The results from this study also show that the relative change in maximum contribution to ozone due to NO_x differs depending on the size of the power plant. Reductions in NO_x by 7000 lbs from a 2600 MW plant and also from a 1200 MW plant do not produce the same reductions in ozone in this area. This is due to the fact that even with the reductions from the 2600 MW plant, the percentage of NO_x emissions still being emitted from the plant is high as compared to the smaller plant.

The determination of the total effects from NO_x emissions from power plants lies in the examination of the acute effects of the short term maximum ozone concentrations versus the chronic effects from the increase in ozone due to reductions in NO_x emissions. Further study would be required to truly solve this conflict. From this study, the significance of the

NO_x emissions from the power plants in the Middle Tennessee Area is that a reduction in these emissions would produce reductions in ozone concentrations in those parts of the plumes which are most sensitive to NO_x emissions. These reductions in ozone could help to decrease the ozone concentrations in an area of nonattainment for ozone or to reduce the risk of short term effects of high ozone concentrations.

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VITA

Andrea Elizabeth Early was born in Petersburg, Virginia on January 18, 1971. After living in Chester, Virginia for 9 years, her family moved to Johnson City, Tennessee. It was in Johnson City where she graduated from University High School in 1988. She received a Bachelor of Science in Mathematics from the University of Tennessee in December of 1992. In January of 1993 she entered the graduate program in Environmental Engineering at the University of Tennessee and received a Master of Science in May of 1995. She became Mrs. Robert Wilkins Slaney on September 24, 1994. She began working for Ogden Environmental and Energy Services in Nashville, Tennessee in January of 1995.