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EPA Staff Paper

on

Gasoline Sulfur Issues

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U.S. Environmental Protection Agency
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Executive Summary

In response to a Congressional mandate contained in the Clean Air Act, the U.S. Environmental Protection Agency (EPA) recently published a draft study of the air quality need for and the feasibility and cost-effectiveness of emissions reductions from light-duty vehicles (LDVs) and light-duty trucks (LDTs) beyond those required by the existing Tier 1 emission standards. EPA plans to follow this study by the end of 1998 with a notice of proposal for this next level of emission standards, Tier 2 standards. In evaluating the technical feasibility of additional emission controls, the draft Tier 2 study identified commercial gasoline sulfur levels as a potentially significant factor in determining the emission control potential of future vehicles. Hence, as part of establishing Tier 2 standards, the Agency will also establish a gasoline sulfur control program, to be proposed in the same time frame.

This paper presents EPA's current understanding of the impact of gasoline sulfur on emissions from current and future motor vehicles. The paper also explores what can be done by gasoline producers and automobile manufacturers to reduce sulfur's impact on vehicle emissions.

The Impacts of Gasoline Sulfur on Emission Control Systems

Modern gasoline-fueled vehicles use catalysts to reduce emissions of hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) by over 90 percent (%). Sulfur is a catalyst poison. Sulfur and sulfur oxides inhibit the reaction of HC, CO, and NOx on the catalytic surface. Sulfur also interferes with the management of oxygen on the catalyst surface, which must be precisely controlled to maximize NOx emission reductions. The degree of sulfur's interference appears to depend on many factors, such as the specific design of the catalyst, the range of exhaust temperatures experienced by the catalyst, the materials used to store oxygen in the catalyst, and the range of air-fuel mixtures fed to the engine. Of all of the noble metals used in modern catalysts, palladium appears to be the most susceptible to sulfur poisoning. Likewise, of oxygen storage media, ceria appears to be the most sensitive to sulfur. Palladium is currently the catalyst of choice of most vehicle manufacturers for their emission control systems designed to meet California's low emission vehicle (LEV) standards. Palladium is able to withstand higher temperatures, which allows the catalyst to be placed closer to the engine and start working sooner after a cold start. Ceria allows the catalyst to operate at its maximum efficiency over a wide range of vehicle operating conditions, which is critical to reducing emissions in-use and not just in the laboratory.

It is possible that future optimization of catalyst and engine designs could reduce the impact of sulfur on catalyst performance. For example, the increased use of the precious metal rhodium in catalysts and the maintenance of consistently high temperatures during typical

operation (e.g., above 650° C) may reduce the negative emissions impact of sulfur. Increasing the total precious metal content of the catalyst can also reduce the impact of sulfur, though at significant cost. However, due to sulfur's inherent chemical nature, it is highly unlikely that the impact of sulfur can be completely eliminated. As tighter emission standards require higher catalyst efficiencies, the impact of sulfur is bound to be more dramatic.

Automakers and oil companies have both recently completed extensive test programs to investigate the impact of sulfur on emissions from vehicles meeting California LEV standards. These vehicles are currently being sold in the Northeast and will be sold nationwide starting in 2001, as part of the voluntary National Low Emission Vehicle (NLEV) program. Some of the results of this testing are summarized in Table E1 below. Many of the vehicles tested failed their certified emission standards when using higher sulfur fuels.

Table E1. Average Increase in Emissions for LEVs and ULEVs Relative to 40 ppm Sulfur
[Source: CRC and AAMA/AIAM Test Programs]

Pollutant	NMHC		NOx	
Fuel Sulfur, ppm	150	330	150	330
All LDV/LDT1 [a]	26.7%	43.0%	65.7%	135.6%
All LDT2/LDT3 [b]	23.0%	26.4%	33.7%	65.5%
LDV/LDT1s Broken Down by NMHC+NOx Emissions with 40 ppm Sulfur Fuel				
9 Lowest Emitters	26.8%	44.0%	127%	264%
9 Highest Emitters	26.6%	42.1%	41.2%	84.2%
LDV/LDT1s Broken Down by the Sensitivity of NMHC+NOx Emissions to Sulfur				
9 Least Sensitive	32.2%	49.5%	31.0%	61.0%
9 Most Sensitive	25.1%	42.2%	122%	251%

[a] LDV = light duty vehicle (passenger car); LDT1 = light duty truck, class 1
[b] LDT2 = light duty truck, class 2; LDT 3 = light duty truck, class 3

These emission impacts are very significant, particularly for NOx emissions. For example, the data indicate that if a LEV LDV emits 0.30 grams per mile (g/mi) NOx with 40 parts per million by weight (ppm) sulfur fuel at 100,000 miles (which is the LEV emission standard for NOx), this vehicle would emit 0.71 g/mi NOx with typical non-California fuel. This level exceeds the NOx standard for Tier 1 LDVs, which these LEVs replaced. Even in RFG areas, after implementation of the Phase II RFG standards in 2000 (which are expected to result in average sulfur levels of 150 ppm), this LEV LDV would emit 0.50 g/mi.

Sulfur increased the emissions from every vehicle in these test programs (i.e., not one vehicle was completely insensitive to sulfur). However, some of the vehicles were less sensitive to sulfur than others. This variability is not surprising, given that these vehicles were primarily designed to be operated on California Phase 2 reformulated gasoline, which contains less than 40 ppm sulfur on average. As mentioned above, vehicle manufacturers may be able to directionally reduce the impact of sulfur in future vehicles.

To illustrate this variability, the impact of sulfur on four subsets of the 18 unique LDVs and LDTIs tested in the two industry programs are also summarized in Table E1. The impact of sulfur on NMHC emissions from the nine vehicles with the lowest NMHC+NOx emissions on California-like 40 ppm fuel is essentially the same as the impact of sulfur on the remaining nine vehicles. However, the impact of sulfur on NOx emissions from the nine vehicles with the lowest NMHC+NOx emissions on California-like 40 ppm fuel is much greater than the impact of sulfur on the remaining nine vehicles. This is consistent with the overall trend observed that sulfur's impact, particularly on NOx, increases as the overall stringency of emission control increases.

At the same time, NOx emissions from the nine vehicles showing the least sulfur sensitivity (in terms of NMHC+NOx emissions) are much less sensitive to sulfur than the remaining nine vehicles. The opposite is true for NMHC emissions, because the change in NOx emissions with higher sulfur is much greater than that for NMHC.

EPA expects that auto manufacturers should, in general, be able to reduce the sulfur sensitivity of LEVs and ULEVs to that of the nine least sensitive vehicles. However, one factor not reflected in these data is the need to meet stringent emission standards, applicable during periods of aggressive driving and use of the air conditioner, starting in 2001. These "off-cycle" standards will place additional limits on the fuel management strategy and catalyst designs used by manufacturers. In particular, more precise air-fuel mixture control will likely be required. This could eliminate one method which appears to reduce sulfur's emission impact, wide swings in the air-fuel ratio. Future Tier 2 vehicles may also have to meet more stringent emission standards than today's LEVs, which could further limit the manufacturers' choices for emission control system designs. EPA plans to further analyze the emission data produced in these test programs to determine the degree that off-cycle standards would affect manufacturers' abilities to design emission control systems with lower sulfur sensitivity.

While sulfur has a large impact on emissions from current low-emission vehicles, technological advances are also being made to improve the fuel efficiency of the nation's vehicles. Gasoline direct injection engines and fuel cells are two of the advanced powerplants being developed. Both of these technologies may be more sensitive to sulfur than current vehicles; current designs of these powerplants can tolerate very little gasoline sulfur. Therefore, gasoline sulfur removal is not only important to maintain the emission control potential of current vehicles, but is being highlighted by many as an important technology enabler in the future.

Finally, the automotive industry has expressed concern that sulfur will also interfere with the on-board diagnostics (OBD) systems designed to monitor catalyst performance. OBD catalyst monitors utilize oxygen sensors which incorporate catalytic materials which can be compromised by sulfur much like the exhaust catalyst. EPA has evaluated the impact of sulfur on OBD catalyst monitors in the past and determined that any significant impacts should be limited to a few specific model lines. EPA is willing to address any sulfur-related OBD compliance problems on a model-specific basis during certification.

Fuel and Vehicle Emission Controls as a System

Vehicles should be designed to meet emissions standards based, in part, upon the range of fuels that are used to certify the emissions performance as well as the range of fuels likely to be encountered in-use. Currently, the test fuels used by industry and EPA for federal vehicle certification reflect a narrow range of permitted fuel specifications and can differ substantially from the gasolines actually sold nationwide, particularly with respect to sulfur content. The sulfur level of the test fuel generally used in federal certification is typically less than 100 ppm, often approaching that of California certification fuel, which averages about 30 ppm sulfur. However, while California restricts the sulfur content of commercial gasoline to about 30 ppm on average, gasolines sold outside of California average over 300 ppm sulfur. Even federal Phase 2 reformulated gasoline, which will not be available until 2000, is expected to average 150 ppm, still well above that of typical federal certification test fuel.

For Tier 1 and earlier vehicles, this difference in sulfur levels between certification test fuel and commercial gasolines probably did not affect the emission control technology selected for use by automakers, since sulfur's effect on emissions from these vehicles was smaller. With advances in emission control technology, this is no longer the case. Therefore, the arguments in favor of changing the sulfur content of certification test fuel to match that of commercial gasoline are increasing. The only issue is whether the sulfur content of certification test fuel should be increased or that of commercial gasoline reduced, or both.

Increasing the sulfur content of the certification test fuel would either increase the stringency of the Tier 2 standards (by requiring the same level of emission reduction with a higher sulfur fuel), or result in numerically higher standards than would otherwise be established (to accommodate the sulfur impact). Reducing the sulfur content of commercial gasoline would do the opposite. It would also reduce emissions from the current fleet of vehicles, reduce sulfur dioxide and sulfate emissions from all vehicles, and potentially enable advanced low emission and fuel efficient technologies. These are the options available for addressing the current difference in sulfur levels between typical certification test fuels and commercial fuel.

Reducing the Sulfur Content of Commercial Gasoline

Sulfur occurs naturally in crude oil. As crude oil is refined, some of the sulfur ends up in gasoline. The amount of sulfur in the gasoline from any particular refinery can vary widely depending on the specific crude oil processed and the processing capability of the refinery.

While a number of refinery processing options are available to reduce the sulfur content of gasoline, the most likely technique would be to remove most of the sulfur from the products of the refinery's fluidized catalytic cracker (FCC) which typically end up in gasoline. These FCC products are the source of the great majority of sulfur in gasoline. Just as current sulfur levels vary between refineries, the cost of removing sulfur varies, as well.

Significant sulfur reductions would likely require investment in new refinery processing hardware, as well as increased operating costs. EPA, with help from the Department of Energy (DOE), has developed preliminary estimates of the cost to control sulfur from current average levels of all the gasoline produced in the Northeast and the Gulf Coast of the U.S. (see Table E2). MathPro, Inc. has also projected sulfur reduction costs for these refiners, plus those in the Midwest, under contract to the American Petroleum Institute (API). Both of these sets of projections are based on current sulfur removing technologies. As can be seen, the projected costs of sulfur removal increase substantially as sulfur is reduced from 100 ppm to 40 ppm. The MathPro/API projections are higher than those of EPA and DOE for control to 150 ppm and 100 ppm sulfur, but below the low end of EPA/DOE's projected cost range for 40 ppm sulfur. EPA and DOE are currently pursuing estimates of the cost of reducing sulfur levels for Midwest, Rocky Mountain, and Far West refineries.

Table E2. Preliminary Sulfur Reduction Costs (cents per gallon)

Sulfur Control Level (Average), ppm	EPA/DOE: Northeast and Gulf Coast Refiners With Current Technology	API/MathPro: Northeast, Midwest and Gulf Coast Refiners With Current Technology
150	1.1-1.8	2.7
100	1.9-3.0	3.4
40	5.1-8.0	5.1

While conventional technology is capable of reducing the sulfur content of gasoline, EPA has recently learned of emerging sulfur removal technologies which purport to be much less costly. Companies which license these technologies estimate that the cost of reducing sulfur to 40 ppm (on average) is about 1-2 cents per gallon. EPA and DOE are currently evaluating these technologies to assess whether these projected costs are reasonable. If so, then these new processes would dramatically reduce the projected cost of sulfur control.

Sulfur Control Program Considerations

Domestic and overseas automakers recently jointly petitioned EPA to implement an 80 ppm sulfur cap on all gasoline sold nationwide starting in 2004. (This cap is expected to result in an average sulfur level of about 40 ppm.) Several state organizations as well as automotive catalyst manufacturers have made similar recommendations. In contrast, the trade organizations representing the majority of gasoline refiners have proposed a regional sulfur reduction program. Under this proposal, gasoline sulfur would be limited to 150 ppm on average in a 22-state region during the summer, with a 300 ppm average sulfur restriction on gasoline sold elsewhere during the summer.

Clearly, a broad consensus now exists that the sulfur content of commercial gasoline must be reduced to protect the current investments being made in vehicle emission control technologies and to facilitate the achievement of even more stringent emission standards in the future. Questions remain regarding the appropriate level and form of the sulfur limit. The level of sulfur reduction, and whether the limit is based on a refinery average or a per-gallon maximum, will depend primarily on the factors already discussed. Once the technical concerns of the emission control systems are answered, the greatest difference between a sulfur standard based on average levels and one based on an absolute cap on sulfur content lies in the implications for compliance and enforcement of the requirement. An averaging standard would increase the recordkeeping and reporting requirements, and may necessitate the implementation of periodic surveys to ensure compliance not just at the refinery, but at the retail level. In addition, the identification of the appropriate level of sulfur control will help determine if gasoline sulfur levels must be fairly consistent over time and over different covered areas. Otherwise, compliance and enforcement will have to be designed to ensure that there are not great variations in sulfur levels between cities.

While the specific sulfur limit will be based largely on vehicle technology needs, the form of the sulfur program will be based, in part, on two additional factors: regionality and seasonality. If the ozone benefits of Tier 2 standards are of primary importance, as assumed by the refiners' associations proposal, a regional program could be defined to encompass most of the projected future ozone non-attainment areas, and could be designated only for the time of year when ozone is most problematic. Limiting sulfur control to specific regions of the country or to a specific season would likely reduce the cost of the program, as the cost of removing sulfur increases as more gasoline is affected. Under a regional program, refiners who find it less expensive to reduce sulfur will supply the majority of low sulfur gasoline, while others refiners would still have a market for higher sulfur fuel. Compliance costs under a program involving multiple sulfur levels would be somewhat more costly, however, since fuels would likely have to be segregated and compliance from the refinery to the retail level would have to be ensured.

A key requirement for a regional sulfur program is that the impact of sulfur be reversible. That is, emissions would return to their original low levels once use of high sulfur fuel ceased. While the available test data are limited, some vehicles' emissions appear to be reversible, while

others' are not easily reversible. The same factors described above which determine the sensitivity of a catalyst to sulfur (catalyst design, air-fuel ratio, and temperature) also appear to affect the ease of reversibility. Likewise, the reversibility of the sulfur effect could be impacted in the future by off-cycle emission controls. While the existence of sulfur reversibility would not in itself be sufficient reason to focus on a regional or seasonal sulfur program, its absence would be sufficient to only consider national and year-round sulfur limits. Also, any degree of irreversibility effectively increases the stringency of the emission standards for auto manufacturers and/or increases their in-use liability, since vehicles tested in an in-use recall program (even if tested with low sulfur fuel) could have been operated on higher sulfur fuel at some point in their lives.

Just as there are many benefits to a regional control program, there are numerous reasons for a single national sulfur standard. The Tier 2 vehicle standards are expected to apply nationally (e.g., all states except California); a single commercial gasoline sulfur standard applicable nationwide (all states except California) would allow vehicle manufacturers to design these vehicles for a single in-use federal fuel, instead of a range of in-use fuels. A single nationwide sulfur standard (particularly a per-gallon limit) would simplify the enforcement of the requirement and may decrease the possibility of sulfur-induced OBD problems. Local areas with inspection and maintenance (I/M) programs which lay outside of a sulfur control region would also avoid the need for special procedures and cut-points to compensate for their higher fuel sulfur levels. Furthermore, many of the emission reductions associated with the potential Tier 2 standards and gasoline sulfur reduction would be beneficial nationwide (e.g., reductions in particulate matter (PM) formed from VOC, NOx, and oxides of sulfur (SOx) emissions, reductions in air toxic emissions, etc.). A national sulfur limit would also be desirable if lower sulfur levels were needed to permit the future introduction of vehicle technologies which provide significant reductions in emissions or fuel consumption. California and Japan have imposed stringent sulfur limits and Europe will decide on a stringent sulfur limit shortly. Thus, without similar sulfur limits throughout the U.S., advanced technology designed for these markets may not be available in the U.S.

One additional argument for a national sulfur standard is that many areas outside of the region covered by the refining industry proposal are projected to only marginally attain the ozone standard in the future. If these areas experience economic and population growth, additional reductions in VOC and NOx emissions will likely be necessary to ensure maintenance of the ozone standard. Thus, it is not clear that a regional strategy similar to the region identified by the refiner associations is sufficiently large to ensure that ozone-related benefits occur in every area where they are needed.

The costs of a national program, however, are likely to be substantially greater than for a regional program. Controlling every gallon of gasoline will require that all refiners take action; there would be no market to accommodate the gasoline that is most expensive to control. Given that there are some regional variations in the sulfur content of gasoline, and that some refiners are better positioned than others to reduce gasoline sulfur, a national program could result in

significant variations in costs between regions, and individual refiners in some regions could experience greater economic hardship than the average refinery. The higher production costs of a national program could be offset in part by lower relative compliance and enforcement costs, but that depends on how the program is designed.

EPA's Next Steps

Based on the data and information obtained to date and the consensus among a wide variety of stakeholders, EPA staff recommend that the Agency develop proposed gasoline sulfur standards to be implemented coincidentally with the implementation of the planned Tier 2 emission standards for LDVs and LDTs. There are many issues, such as the health and welfare benefits of gasoline sulfur control, which will need to be addressed as EPA proceeds. This Staff Paper is intended to further dialog on these issues, and foster further research.

To identify the appropriate actions, EPA will work closely with all stakeholders. In May, 1998, a public workshop will be held to discuss the technical issues raised in this Staff Paper. Throughout the coming months, EPA will continue to interact with individual companies, trade organizations, the states, and environmental interests to determine the best approach to dealing with this issue.

EPA Staff Paper on Gasoline Sulfur Issues

I. Introduction

The U.S. Environmental Protection Agency (EPA) is considering setting limits on the sulfur content of gasoline at this time primarily because advanced automotive catalysts are more susceptible to poisoning by higher sulfur levels.[1] This susceptibility to poisoning has become a critical issue as motor vehicle emission standards have become more stringent. Setting a limit on sulfur content would also reduce emissions from current technology vehicles. The series of reports published by the joint efforts of the automotive and oil industries (Auto/Oil)[2] and other studies in the early 1990's demonstrated that higher fuel sulfur levels increased non-methane hydrocarbon (NMHC), carbon monoxide (CO), and oxides of nitrogen (NOx) emissions. With Tier 0 and Tier 1 vehicles, sulfur levels up to 500 parts per million (ppm) increased emissions by up to 15-20 percent (%) over emissions with sulfur levels around 40 ppm. While the effect of sulfur was significant, in-use levels of sulfur did not play a substantial role in defining the types of catalysts used on motor vehicles meeting Federal Tier 0 or Tier 1 standards.

Recent advances in both engine controls and catalyst designs have allowed a number of current production models to meet either California's low emission vehicle (LEV) or ultra-low emission vehicle (ULEV) standards without having to resort to novel emission control technology, such as electrically heated catalysts or hydrocarbon (HC) adsorbers, or to fuels other than gasoline. However, very recent test data show that emissions from vehicles designed to meet these LEV and ULEV standards can more than double with the use of higher sulfur gasoline. The sensitivity of these current LEVs and ULEVs to sulfur is a great cause of concern. Some LEVs have already begun to be sold in Northeast states under state-adopted California LEV programs and the recently established National LEV (NLEV) program. More LEVs will be sold nationwide beginning in 2001 under NLEV. Higher sulfur levels have the potential to significantly reduce the benefits of the NLEV program if left unchanged.

EPA is also in the process of evaluating whether potential federal Tier 2 standards should replace the NLEV program in 2004. EPA recently published a draft study mandated by Congress of the air quality need for and the feasibility and cost effectiveness of Tier 2 Standards.[3] EPA plans to follow this study by the end of 1998 with a notice of proposal for Tier 2 standards. As the emission control technology used to meet potential Tier 2 standards could be very similar in design to that used on LEVs and ULEVs, emissions from potential Tier 2 vehicles could also be very sensitive to sulfur and impede progress in developing emission controls capable of meeting

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[1] Sensitivity is used herein to refer to the percentage change in emissions for a specified change in fuel sulfur content (e.g., 50% emission increase for an increase in sulfur from 40 to 300 ppm).

[2] Auto/Oil Air Quality Improvement Research Program, various publications, 1992-1996.

[3] U.S. EPA, "Tier 2 Study," Draft Report to Congress, April 23, 1998.

more stringent emission levels. Thus, EPA has decided to evaluate the need for limits on the sulfur content of commercial fuel which would be developed in conjunction with the potential Tier 2 standards and proposed in the same time frame. This paper is the first step in the process of developing these commercial fuel sulfur limits.

The remaining sections of this paper discuss:

1) The interactions between sulfur and vehicle technology, including the effect of sulfur on emissions from LEVs and ULEVs, the ability of these vehicles to recover their emission performance after temporary operation on high sulfur fuel, and the effect of fuel sulfur on advanced vehicle technology designed for high fuel efficiency or extremely low emissions;

2) The impact of sulfur control on refinery operations, including the technology used to reduce sulfur levels, the cost of sulfur removal, and the ability of the industry to make the necessary investments;

3) Other fuel quality issues which could affect refiners' approaches to sulfur control, including limits on certain distillation properties of gasoline and limits on onroad or nonroad diesel fuel properties (particularly sulfur);

4) Actions which have been taken to reduce the sulfur content of gasoline in other countries;

5) Recommendations regarding levels of sulfur control which have been made by stakeholders to date; and

6) The paper's conclusions.

Before moving to these six remaining sections, it would be helpful to provide an overview of the key factors which affect the need for gasoline sulfur control and the direction these factors provide regarding the design of a sulfur control program for the U.S.

Tremendous progress has been made over the past several years in developing technology to reduce emissions from gasoline-fueled vehicles. This progress has focused on two inter-related areas: the exhaust catalyst and management of the air and fuel mixture inducted into the combustion chamber (e.g., the air-fuel ratio). Automotive catalysts are now far more efficient in removing NMHC, CO, and NOx emissions than they were just five years ago. These catalysts can also withstand much higher temperatures, which allow them to be placed closer to the engine. This in turns shortens the time it takes for the catalyst to begin operating ("light-off") after the engine is started, dramatically reducing emissions. Precise control of the air-fuel ratio is important, because the catalyst can only achieve its maximum efficiency when the air-fuel ratio is within a narrow range. Advanced computerized engine controls are able to maintain the proper air-fuel ratio over a wide range of operating conditions. At the same time, improved catalyst

promoters within the support material (washcoat) have improved the ability of the catalyst to withstand temporary swings in oxygen levels in the exhaust when the engine controls are not able to precisely control the air-fuel ratio.

Sulfur interacts chemically with both the catalyst and the washcoat which manages oxygen on the catalyst surface. Sulfur compounds adsorb onto the surface of these materials and prevent pollutants, oxygen, and other exhaust compounds from interacting with the catalyst surfaces. This inhibits the ability of the catalyst to convert pollutants into less harmful emissions. Emission control technology designed for California, which has the most stringent vehicle emission standards in the world, is often used eventually on vehicles sold in the rest of the U.S., Europe, and Japan, so those developing emission control systems have a tremendous incentive to develop technology for California. Since California restricts the sulfur content of gasoline statewide to no more than 80 ppm, catalyst developers have focused on developing catalysts for this low level of sulfur. They also evaluate their prototype catalysts with slightly higher 100 ppm sulfur fuel, as this is the typical upper limit of the sulfur level of the test fuel used by industry and EPA in the federal motor vehicle compliance programs (commonly referred to as Indolene).[4] This higher sulfur level can significantly reduce catalyst performance. However, this difference (100 ppm versus 30 ppm) is small relative to the sulfur levels of current U.S. gasoline outside of California, which averages over 300 ppm sulfur and can reach levels as high as 1000 ppm.

In the past, this difference in federal test fuel and commercial fuel sulfur levels appeared to cause only a small increase in emissions (e.g., 5-10% on average). This effect was considered in the development of the NLEV program, which involves the nationwide sale of vehicles certified on California low-sulfur fuel. Given the recent test programs which have demonstrated that LEV emissions increase to a much greater degree (in percentage terms), EPA staff believes that it is not appropriate to continue testing vehicles on gasoline with 50-100 ppm sulfur knowing that they will be operated on high sulfur fuels in-use. The issue is whether to perform certification and compliance testing with higher sulfur levels or whether to reduce the sulfur content of commercial gasoline to levels more consistent with those prevalent in California (or a combination of the two changes).

Key factors affecting this decision include: 1) the effect of sulfur on LEV and ULEV-like vehicles which will also meet other emission control requirements effective early in the next century; 2) the cost of reducing catalyst sensitivity; 3) the cost of removing sulfur from gasoline; 4) the effect of sulfur on emissions from the current fleet (Tier 0, Tier 1, and NLEV vehicles) prior to the turnover to Tier 2 vehicles, and the overall health and environmental benefits achieved by these emission reductions. These factors will be considered together, and can have significant impacts on the ultimate level of emission controls achievable through Tier 2 vehicles. For example, if they lead to a decision to select a commercial fuel sulfur limit above California's,

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[4] Indolene has typically averaged a sulfur level of 50-60 ppm, although recent batches at EPA's Ann Arbor, MI laboratory have been reported to contain in excess of 100 ppm.

the degree of emission control achievable by future vehicles may be limited, leading to higher numerical Tier 2 emission standards. Selecting a gasoline sulfur level very different from California's may also reduce or prevent further advanced technologies which are being developed for use in California from being extended to the rest of the U.S. These technologies include further catalyst developments focused on California's proposed Phase II LEV standards (LEV-II) and others which are focused on improved fuel efficiency.

In addition to options regarding the level of the commercial fuel sulfur standard, there may also be options regarding its geographical and temporal extent. In general, the costs of sulfur control decrease as the region of sulfur control shrinks, but so do the environmental benefits. For example, the potential Tier 2 vehicle standards are expected to apply nationally. A single sulfur standard applicable to all commercial fuel sold nationwide would allow vehicle manufacturers to design their vehicles for a single fuel, instead of two or more.

Many of the emission reductions associated with the potential Tier 2 standards and gasoline sulfur reduction would also produce benefits nationwide in addition to local benefits such as ozone reductions. For example, VOC, NOx, and sulfur oxide (SOx) emissions all form particulate matter (PM) in the atmosphere and are transported long distances. Thus, reductions in these emissions, regardless of their location, are likely to benefit areas currently not in attainment of the PM national ambient air quality standards (NAAQS). Emissions of air toxics (compounds which have been implicated in cancer and other health concerns) also affect human health, regardless of the vehicles' locations.

Automakers, state organizations, and others have recommended that EPA develop a national maximum sulfur limit to ensure the benefits of sulfur control. A single, nationwide per-gallon sulfur standard would tend to simplify enforcement of vehicle emission standards relative to an averaging standard or to multiple standards applying to different regions of the country. Both EPA and vehicle manufacturers could rely on the fact that vehicles tested in recall programs were operated on fuels similar to those on which compliance was originally determined. Furthermore, enforcement of the fuel standards would be much simplified if a single, per-gallon cap were defined.

On the other hand, representatives of the oil industry have proposed a regional, summer-only program, focusing on the ozone-related benefits of the potential Tier 2 standards. The majority of ozone nonattainment areas, and areas needing further emission reductions in order to maintain their compliance status, are in the East and Midwest. Also, high ozone is generally a summertime problem. However, a sulfur control program designed to provide low sulfur fuel to every area needing further emission reductions in order to attain or maintain their compliance status would impact every region of the country, could significantly complicate fuel distribution, and would not yield some of the other, non-ozone related benefits of gasoline sulfur reductions.

The primary benefit of a regional, seasonal sulfur program is economic. The economics of sulfur control in a refinery are such that the cost per gallon of control increases as the fraction

of the refinery's gasoline production affected by the standard increases. Therefore, a refiner can avoid the most costly controls if it can control less than 100% of its gasoline production. Also, individual refiners face different costs of sulfur control. With a regional program, some refiners facing higher control costs could choose to produce fuel for sale outside of the affected area or in areas with less stringent controls. While gasoline production costs would be less under a regional control program, the costs of transporting and storing gasoline would be somewhat higher, and the burdens to ensure compliance would be greater.

The most important factor affecting any regional or seasonal sulfur control program is the need for the sulfur effect to be temporary. Vehicles are operated during all seasons and often travel across state lines. Thus, under essentially any regional or seasonal program, many or all vehicles in ozone non-attainment and maintenance areas would be occasionally or regularly fueled with high sulfur gasoline. In order for sulfur control to reduce emissions over the life of the vehicle, the emission impacts of sulfur must only last as long as the vehicle is being operated on the higher sulfur fuel. This phenomenon whereby the emissions decrease quickly when low sulfur fuel is used after having increased as a result of high sulfur fuel use is termed reversibility. Reversibility is not a certainty, either for vehicles meeting California LEV or potential federal Tier 2 standards, or for those employing even more advanced designs. Some vehicles designed to meet the LEV standards have shown reversibility and other have not. Any significant degree of irreversibility would essentially eliminate consideration of regional and/or seasonal sulfur control strategies. Partial irreversibility would increase the stringency of the emission standards for manufacturers, since they need to design based in part on the fuels a car will see in-use, and vehicles tested in an in-use recall program could have been operated on higher sulfur fuel at some point in their lives. Manufacturers must compensate for this when they set their emission design targets under the standards. Thus, while reversibility does not in itself determine that a regional/seasonal program is to be preferred over a national program, it is a necessary component of any regional/seasonal program.

As the remainder of this paper discusses sulfur-related issues affecting vehicles and refineries, constant mention is made of how the various factors could affect the degree of commercial fuel sulfur control needed, as well as the nature of the sulfur control program. The reader is encouraged to keep these factors in mind as the details of vehicle and refinery operation are discussed.

II. Gasoline Sulfur's Impact on Vehicle Technologies

Tailpipe emissions from modern motor vehicles depend on both the emissions coming from the engine and the efficiency of the catalytic exhaust aftertreatment system in converting the HC, CO, and NOx to carbon dioxide, water, nitrogen and oxygen.[5] Fuel properties can impact both engine-out emissions and catalyst efficiency. For example, EPA has known that a wide range of fuel variables (Reid vapor pressure, oxygen, benzene, sulfur, olefins, aromatics, distillation properties) can affect emissions; the reformulated gasoline program is based on control of many of these fuel properties. Lately, limited evidence has indicated that the emissions impact of some of these fuel properties is diminishing as emission control technologies have advanced. However, recent research indicates that the emission impact of fuel sulfur may be increasing with advances in emission control technology. The purpose of this section is to summarize this research and estimate sulfur's emission impact on current and advanced vehicles.

The sulfur in gasoline increases exhaust emissions of HC, CO, and NOx by decreasing the efficiency of the three-way catalyst used in current and advanced emission control systems. This effect has been demonstrated through numerous laboratory and vehicle fleet studies.[6] The degree of sulfur inhibition has been shown to be variable and to depend upon both catalyst formulation and vehicle operating conditions, including:

- the type of precious metal, oxygen storage, support materials, and washcoat used,
- the catalyst surface area, cell structure, and layering of the washcoat,
- the oxygen content of the exhaust, and
- the operational temperature of the catalyst.

The precious metal type and content are selected based on their ability to oxidize CO and HC, reduce NO, achieve light-off temperature quickly, and be resistant to thermal aging. Only three catalytic materials are currently available which meet these criteria: platinum (Pt), rhodium (Rh), and palladium (Pd). These precious metals and their combinations vary in their sulfur sensitivity. Similarly, metal oxides such as ceria and others within the washcoat are selected for their ability to manage the oxygen concentration within the exhaust, their ability to support other beneficial reactions within the catalyst, and their ability to improve thermal stability of both the washcoat components and the precious metals. Improvements in the oxygen storage and release capabilities of catalysts have played a key role in the tremendous improvements in catalyst efficiency in recent years. Oxygen storage under lean conditions (excess oxygen) with subsequent release under rich conditions (lack of oxygen) reduces the sensitivity of three-way catalysts to perturbations in the air-to-fuel ratio encountered during operation of the vehicle. This has particularly improved the catalyst's ability to reduce NOx, as the catalyst's NOx

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[5] Unless otherwise noted, the term emissions will refer to tailpipe emissions and motor vehicle will refer to light-duty vehicles and trucks.

[6] See, for example, Auto/Oil Air Quality Improvement Research Program, Technical Bulletin No. 2, "Effects of Fuel Sulfur on Mass Exhaust Emissions," February, 1991.

efficiency inherently decreases quickly as soon as excess oxygen is present on the catalytic surface. The improved washcoats preferentially store excess oxygen until the exhaust returns to an oxygen-poor (i.e., rich) condition. Other improvements which have also enhanced the performance of recent catalysts include increased surface area per volume (small cells), thinner coatings of catalytic material, and layering of the washcoat and catalytic material.

Of the three precious metals currently used, palladium appears to be the most sensitive to sulfur poisoning, followed by platinum and rhodium. Laboratory studies have shown that palladium's ability to reduce automotive pollutants decreases more dramatically than platinum's. While sulfur's poisoning effect is primarily related to its presence on the surface of the catalyst, sulfur appears to penetrate into palladium, but not platinum or rhodium. This penetration slows the processes whereby sulfur can be removed from the surface of palladium relative to platinum or rhodium.

Of the various metal oxides used for oxygen storage and other purposes, ceria appears to be most sensitive and least reversible to sulfur poisoning. Sulfate penetrates the crystalline lattice of ceria and prevents ceria from taking up oxygen when the engine is operating lean and giving off oxygen when the engine is operating rich. The mechanisms of sulfur's interference in both catalytic activity and oxygen storage are discussed further in Appendix A.

While sulfur is a catalyst poison, it is not necessarily a permanent poison like lead. Stored sulfur compounds can be removed from the catalyst components under certain conditions. The ease of this removal depends on the chemical forms of the sulfur compounds, which are, in turn, dependent on the amount of oxygen present in the exhaust, the exhaust temperature, and the composition of the precious metals and other components of the catalyst. Sulfur from the fuel is oxidized during combustion to sulfur dioxide (SO_2). Under lean conditions, the SO_2 can react with metal oxides within the washcoat to form sulfates. This can be a particular problem with washcoats having a high ceria content. Sulfation of ceria reduces the ability to store oxygen within the catalyst, and inhibits other important chemical reactions that are helpful in promoting high catalyst efficiency. Similarly, under rich conditions, SO_2 is dissociated and the resultant sulfide strongly adsorbs onto precious metal surfaces. The adsorbed sulfide reduces the ability of HC, CO, and NOx to adsorb onto the surfaces and undergo the reactions necessary to oxidize or reduce them. Laboratory studies also suggest that sulfur increases the temperature required to "light-off" the catalyst after a cold engine start, as well as decreasing catalyst efficiency after warm-up.[7] Depending on these factors, high temperatures (650 to 700°C) and either rich operation, lean operation, or both, may be necessary to remove the sulfur compounds from the catalyst and reverse their adverse effects on catalyst performance after the vehicle has been refueled on lower sulfur gasoline.

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[7] Light-off temperature refers to the temperature (i.e., 350 to 400° C) at which the catalyst conversion efficiency reaches a specified, minimally acceptable level (e.g., 50%).

Laboratory studies provide excellent insight into the chemical mechanisms involved in the interaction between sulfur and the catalytic converter. However, these studies have limitations in predicting the impact of fuel sulfur on vehicle emissions. Their primary limitation involves the conditions of the experiments. Laboratory studies are usually conducted under conditions where the active surface of the catalyst is the limiting factor in determining catalyst efficiency. This is purposely done in order to observe the impact of sulfur most clearly. However, on a vehicle, operating conditions vary dramatically. Depending on the design of both the engine and the catalytic converter, other factors not affected by sulfur may limit overall catalyst performance. In these cases, the impact of sulfur on vehicle emissions will be less than observed in the laboratory.

Several vehicle fleet studies have been performed over recent years. These studies have demonstrated that significant reductions in HC, CO, and in particular, NOx emissions can be realized by reducing fuel sulfur levels. Although the results of these studies are in general agreement with laboratory results, there are some noticeable differences. Laboratory studies consistently show a significant degree of catalyst inhibition due to sulfur, whereas results from vehicle studies show a high degree of variability. This suggests that other factors can have a significant impact upon the degree of sulfur inhibition. Vehicle studies also indicate that sulfur has the greatest effect on emissions during warmed-up operating conditions. This suggests that the sulfur effect on catalyst light-off times reported in recent laboratory studies may not be as significant as shown in earlier laboratory studies.

This chapter examines the data which are available to estimate the impact sulfur has on today's cars and light trucks. Information is also presented about the reversibility of this sulfur impact (how quickly and completely the sulfur effect is reversed upon fueling with lower sulfur fuel). The chapter presents projections about how sensitive future technologies may be to sulfur, using test data and information gathered from recent test programs and from discussions with automotive and catalyst manufacturers. Finally, this chapter presents information on how sulfur impacts the operation of the catalyst monitoring systems known as on-board diagnostics (OBD).

A. Tier 0 Vehicle Emissions

A number of vehicle test programs were conducted in the early 1990's which evaluated the effect of fuel sulfur on emissions from Tier 0 vehicles (vehicles manufactured through 1993). These included test programs by the Auto/Oil Air Quality Research Program (Auto/Oil), EPA, and others. In 1993, EPA statistically evaluated all of the available data on vehicles which were technologically equivalent to 1990 model year vehicles and used the results in the Complex Model, which is used to evaluate compliance with federal reformulated gasoline requirements. The Complex Model predicts the impact of sulfur on tailpipe emissions for both normal- and high-emitting vehicles. Based on this model, the impact of reducing sulfur from the current national average of 330 ppm to 150 and 40 ppm is summarized in Table 1.

Table 1. Decrease in Emissions with Fuel Sulfur Decreasing from Average In-Use Level (330 ppm) for Tier 0 Vehicles [Source: EPA Complex Model]						
	NMHC		CO		NOx	
	150 ppm	40 ppm	150 ppm	40 ppm	150 ppm	40 ppm
Normal Emitters	4.6%	13.0%	4.4%	12.6%	5.0%	11.1%
High Emitters	-0.4%	-0.6%	3.5%	10.4%	1.7%	6.1%

The equations in the Complex Model are exponential in form.[8] Since developing the Complex Model, a number of investigations into the effect of sulfur on emissions from Tier 0 vehicles have concluded that other equation forms, such as logarithmic or square root, may better represent the sulfur-emission relationship. Such alternative equation forms would likely show only small deviations from the Complex Model in the range of 330 - 150 ppm, but may show large deviations from the Complex Model in the range 150 - 40 ppm. The Agency is currently evaluating the most appropriate form of the sulfur-emission relationship for Tier 0 vehicles in the context of revisions to the MOBILE[9] model.

In performing the analyses to support the Draft Tier 2 Study, EPA made a number of modifications to MOBILE5b to reflect more recent emission data which has become available since the model was developed in 1993. The result of these modifications is that the great majority of in-use Tier 0 vehicles are now projected to be normal emitters. Therefore, the sulfur impacts shown above for normal emitters now appear to be the most relevant to the Tier 0 vehicle fleet as a whole.

B. Tier 1 Vehicle Emissions

Only one test program has been performed evaluating the impact of sulfur on emissions from Tier 1 vehicles (vehicles manufactured to meet the emission standards which took effect in 1994). Auto/Oil tested six early Tier 1 light-duty vehicles (LDVs) on two sets of otherwise identical fuels containing nominally 40 ppm and 330 ppm sulfur. The results of this test program are shown below in Table 2. All of the vehicles tested met the Tier 1 emission standards, so they would all be considered normal emitters. As can be seen, the effect of sulfur on Tier 1 emissions

[8] The equations are in the form of an exponential of a polynomial, though the behavior of the model very closely follows polynomial curvature.

[9] MOBILE is a model developed by EPA for predicting in-use emissions for an entire fleet of motor vehicles (vehicles of different types and ages) in a specified calendar year. The most recent version of the model is MOBILE5b. EPA is currently working on the next version of the model, which will be called MOBILE6.

of NMHC and CO are somewhat greater than those observed for normal emitting Tier 0 vehicles, while that for NOx emissions is essentially the same.

Table 2. Decrease in Emissions with Fuel Sulfur Decreasing from Average In-Use Level (330 ppm) for Tier 1 LDVs [Source: Auto/Oil AQIRP]

	NMHC		CO		NOx	
	150 ppm	40 ppm	150 ppm	40 ppm	150 ppm	40 ppm
Normal Emitters	---	16.3%	---	16.4%	---	11.0%

C. LEV and ULEV Emissions

Two test programs evaluating the impact of sulfur on emissions from LEVs and ULEVs were recently completed by the Coordinating Research Council (CRC) and the auto industry. The CRC program consisted of twelve 1997 LEV passenger cars, representing six different models from five different vehicle manufacturers. The vehicles were tested with fuel sulfur levels of 40 (the baseline level to represent California certification and in-use fuel sulfur levels), 100, 150, 330, and 600 ppm. The remaining properties of the fuel represented national averages. The vehicles were first tested in an "as received" condition (average vehicle mileage of 10,000 miles) and with the catalysts bench-aged to simulate 100,000 miles of operation (although the oxygen sensors were original, low mileage sensors).

The auto industry testing was performed by members of the American Automobile Manufacturers Association (AAMA) and the Association of International Automobile Manufacturers (AIAM). The AAMA/AIAM program consisted of 13 production and production-intent LEV and ULEV LDVs and eight LEV and ULEV light-duty trucks (LDTs). A total of ten vehicle manufacturers participated in the program. The vehicles were tested at the same sulfur levels as the CRC program. The other fuel properties were those of California Phase II certification fuel. All vehicles were equipped with aged components to simulate 100,000 miles.

The results of the CRC and AAMA/AIAM programs have been combined.[10] Table 3 shows the percent increase in emissions associated with increasing the fuel sulfur level from 40 ppm to 150 ppm and 330 ppm, respectively, for both LDVs and LDTs designed to meet the LEV and ULEV standards. Only the 100,000-mile data are presented. Analogous impacts for the Tier 0 and Tier 1 vehicles discussed above are shown for comparison.

[10] The test results from each pair of LEVs in the CRC test program were averaged and assumed to represent a single vehicle. The results for vehicles from the same model line and certified set of emission standards which were tested in both the CRC and AAMA/AIAM test programs were also averaged and assumed to represent a single vehicle.

Table 3. Increase in Emissions with Fuel Sulfur Increases from Baseline (40 ppm) for LEVs and ULEVs (LDVs and LDTs) and Older Vehicles [Source: CRC and AAMA/AIAM Test Programs]						
Pollutant	NMHC		CO		NOx	
Sulfur, ppm	150 ppm	330 ppm	150 ppm	330 ppm	150 ppm	330 ppm
LEV and ULEV, LDVs and LDTs						
All LDV/LDT1 [a]	26.7%	43.0%	58.0%	75.8%	65.7%	136%
All LDT2/LDT3 [b]	23.0%	26.4%	12.5%	31.2%	33.7%	65.5%
LDV/LDT1s Broken Down by NMHC+NOx Emissions with 40 ppm Sulfur Fuel						
9 Lowest Emitters	26.8%	44.0%	---	---	127%	264%
9 Highest Emitters	26.6%	42.1%	---	---	41.2%	84.2%
LDV/LDT1s Broken Down by the Sensitivity of NMHC+NOx Emissions to Sulfur						
9 Least Sensitive	32.2%	49.5%	---	---	31.0%	61.0%
9 Most Sensitive	25.1%	42.2%	---	---	122%	251%
Tier 1 LDVs						
Normal Emitters	---	20.9%	---	21.1%	---	13.6%
Tier 0 LDVs and LDTs						
Normal Emitters	5.9%	16.3%	5.7%	15.8%	6.4%	13.8%
High Emitters	-0.6%	-1.6%	4.7%	12.9%	2.8%	7.6%

These results indicate that LEV and ULEV emission control technologies being utilized on LDVs are, on average, much more sensitive to sulfur than Tier 0 or Tier 1 technology. For example, the percentage increases in NOx emissions for LEV and ULEV LDVs are roughly 10 times greater than those for Tier 0 and 1 vehicles. Emissions from the LEV and ULEV LDTs are also more sensitive than the Tier 0 and Tier 1 vehicles tested earlier, but to a much lesser extent. The LDTs had a higher level of base emissions on 40 ppm sulfur fuel, which may indicate that their technology differs less dramatically from the Tier 1 LDVs tested earlier.

With respect to both LDVs and LDTs, the sensitivity of individual LEV and ULEV models to sulfur varies dramatically. The impact of sulfur on four subsets of the 18 LDVs and LDT1s tested in the two test programs are also summarized in Table 3.

The first breakdown of these vehicles was performed according to these vehicles' baseline NMHC+NOx emission levels on 40 ppm sulfur fuel. The impact of sulfur on NMHC emissions from the nine vehicles with the lowest NMHC+NOx emissions on California-like 40 ppm fuel is essentially the same as the impact of sulfur on the remaining nine vehicles. However, the impact of sulfur on NOx emissions from the nine vehicles with the lowest

NMHC+NOx emissions on California-like 40 ppm fuel is much greater than the impact of sulfur on the remaining nine vehicles. This is consistent with the overall trend observed that sulfur's impact increases as the overall stringency of emission control increases.

The second breakdown of these vehicles was performed according to their sensitivity to sulfur. This sensitivity was defined as the percentage change in NMHC+NOx emissions per change in sulfur concentration.[11] NOx emissions from the nine vehicles showing the least sulfur sensitivity (in terms of NMHC+NOx emissions) increase less than half as much due to high sulfur levels than the original 18 vehicles. However, the effect of higher sulfur levels on NMHC emissions from these nine least sensitive vehicles is roughly the same as the original 18. This is due to the fact that the change in NOx emissions with higher sulfur is much greater on average than that for NMHC emissions. Thus, the selection of the least sensitive vehicles in terms of NMHC+NOx emissions was roughly the selection of the least sensitive vehicles in terms of NOx emissions. As it turned out, those vehicles with the least sulfur sensitivity towards NOx emissions had slightly greater than average sensitivity towards NMHC emissions.

The sulfur sensitivity of the 9 least sensitive vehicles suggests that there are aspects of the emission control system that can be modified to reduce the average sulfur sensitivity of the LDV fleet in the future. It is likely that auto manufacturers should, in general, be able to reduce the sulfur sensitivity of future vehicles to that of the nine least sensitive LEVs and ULEVs. However, one factor not reflected in these data is the need to meet stringent emission standards applicable during periods of aggressive driving and use of the air conditioner starting in 2001. These "off-cycle" standards will place additional limits on the fuel management strategy and catalyst designs used by manufacturers. In particular, more precise air-fuel mixture control will likely be required. This could eliminate one method which appears to reduce sulfur's emission impact, wide air-fuel ratio swings. Future Tier 2 vehicles may also have to meet more stringent emission standards than today's LEVs, which could further limit the manufacturers' choices for emission control system designs. EPA plans to further analyze the emission data produced in these test programs to determine the degree that off-cycle standards would affect manufacturers ability to design emission control systems with lower sulfur sensitivity.

D. Sulfur Reversibility

Sulfur has an almost immediate effect on catalyst performance, with the sulfur level of the fuel primarily impacting the speed with which the catalyst is affected. One tankful of fuel containing high levels of sulfur will inhibit catalyst performance to essentially the same degree as several tankfuls of fuel with somewhat lower sulfur content. However, the return of catalyst performance upon refueling on low sulfur fuel is not as prompt with the higher sulfur fuel.

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[11] Mathematically, this sensitivity is the sum of the percentage change in NMHC emissions multiplied by the base NMHC emissions plus the percentage change in NOx emissions multiplied by the base NOx emissions, all divided by the sum of base NMHC emissions plus base NOx emissions.

The potential reversibility of the sulfur effect could have substantial consequences for the design of a commercial sulfur control program. If sulfur's effect on catalyst performance is not substantially reversible, sulfur controls must be uniform nationwide and year-round, as the benefits of a regional sulfur control program would be permanently compromised whenever vehicles traveled between low and high sulfur areas. Similarly, under these circumstances a seasonal sulfur control program would compromise essentially all vehicles' emission performance since higher sulfur fuel would be used part of the year. On the other hand, if the sulfur effect is quickly and completely reversible, this may enable control of commercial fuel sulfur regionally and/or seasonally. However, the other benefits of nationwide sulfur standards, enablement of future engine and emission control technology, and reductions in ambient PM, etc., would still need to be considered before a regional control program could be determined to be appropriate.

In an effort to better understand and quantify sulfur reversibility, EPA reviewed the available literature, including a literature review submitted to EPA by the American Petroleum Institute (API).[12] EPA found that a number of laboratory studies have been performed to understand the nature of sulfur's impact on catalyst performance and the reversibility of this impact. In contrast, relatively few vehicle test programs have been performed to investigate sulfur reversibility. The vehicle test programs discussed above utilized special procedures when vehicles switched from one fuel to another to ensure that no sulfur-related effect was carried over from the previous test fuel. These procedures generally involved vehicle operation which is not typical of in-use driving. Thus, these programs provide little insight into the reversibility of the sulfur impact under typical in-use driving conditions.

In addition to this information from the technical literature, EPA has obtained data from individual companies that suggest sulfur is easily reversible for some vehicles and not easily reversible for others during normal driving. For example, Chrysler provided sulfur reversibility data for a 1997 LEV-certified Dodge Neon. Emissions were measured with 40 ppm fuel, with 800 ppm fuel after 300 miles of in-use operation with 800 ppm fuel, and then again on 40 ppm sulfur fuel after about 100 miles of light urban in-use driving with 40 ppm fuel. Figures 1a, 1b, and 1c show that CO and NOx emissions returned to the baseline 40 ppm sulfur levels upon the return to 40 ppm fuel, while NMHC did not. This suggests that CO and NOx performance was reversible after this type of driving, while NMHC performance was irreversible. It should be noted that even though NMHC did not recover, the increase in NMHC emissions at 800 ppm was only 13% over the emissions on 40 ppm sulfur fuel, which is much smaller than the average sulfur impact on LEV emissions summarized in Table 3 above. To return the NMHC emissions to their baseline, 40 ppm sulfur levels, Chrysler operated the vehicle through a number of severe accelerations to increase catalyst temperature and obtain a rich exhaust mixture.[13] This procedure returned the NMHC emissions to the original level.

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[12] Truex, Timothy J., "Potential for Improved Sulfur Tolerance in Three-Way Automotive Catalysts," Center for Environmental Research and Technology, University of California at Riverside, November 26, 1997.

[13] Five to 10 wide-open throttle accelerations from 30 to 70 miles per hour.

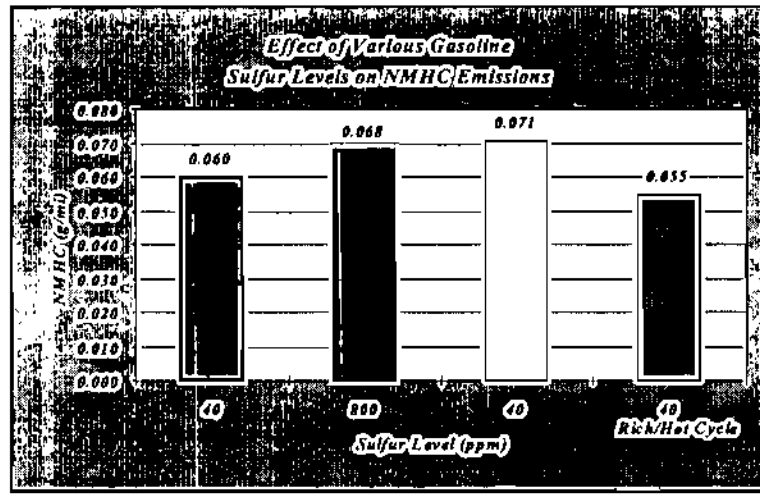

Figure 1a: Sulfur Reversibility Study on a 1997 LEV Dodge Neon Effect of Sulfur on NMHC Emissions

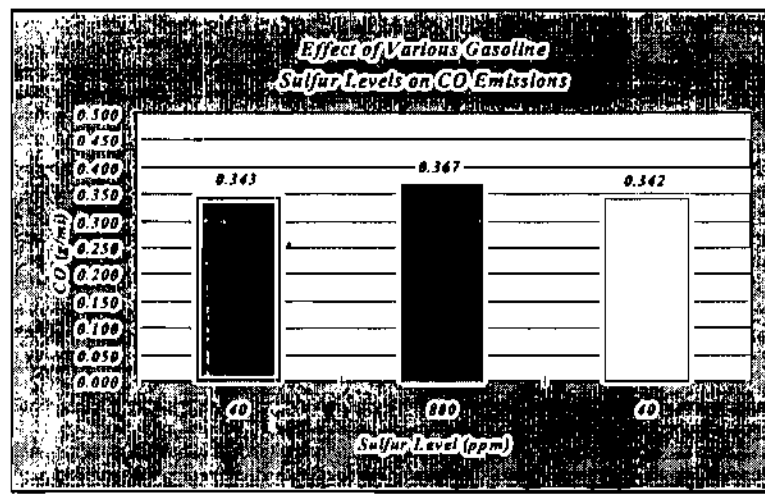

Figure 1b: Sulfur Reversibility Study on a 1997 LEV Dodge Neon Effect of Sulfur on CO Emissions

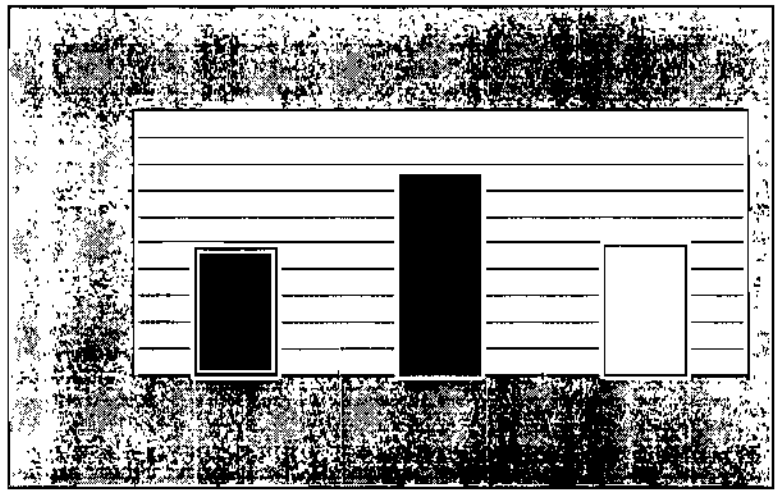

Figure 1c: Sulfur Reversibility Study on a 1997 LEV Dodge Neon Effect of Sulfur on NOx Emissions

Ford also provided EPA with emission data to demonstrate the ability to reverse sulfur's effect on the catalyst used in a ULEV Escort. Ford tested the Escort sequentially on 40 ppm, 600 ppm, and 40 ppm sulfur fuel, operating the vehicle through the same series of severe accelerations performed by Chrysler on the Dodge Neon. This severe operation did not return catalyst performance to its baseline, 40 ppm level. Ford then repeated these accelerations with the vehicle's fuel controls modified to provide a very rich exhaust mixture. Figures 2a, 2b, and 2c show the emissions from the Escort during this test program. As can be seen, NMHC, CO, and NOx emissions did not fully recover after refueling with 40 ppm sulfur fuel and the series of severe accelerations. However, with the excessively rich engine calibration, the emissions performance for all three pollutants recovered fully.

While this excessively rich operation would not typically occur in-use with this vehicle, it is even more unlikely to occur in the future because EPA's new off-cycle emission standards, governing emissions occurring during acceleration and while driving with the air conditioning system operating, will dramatically reduce the amount of time vehicles operate rich.[14] As described at the beginning of this chapter, this can have consequences for sulfur reversibility. Therefore, it is important to understand how the amount and degree of rich operation occurring with today's vehicles impacts the degree of sulfur reversibility seen with these vehicles.

[14] Phase-in of these requirements begins with model year 2001.

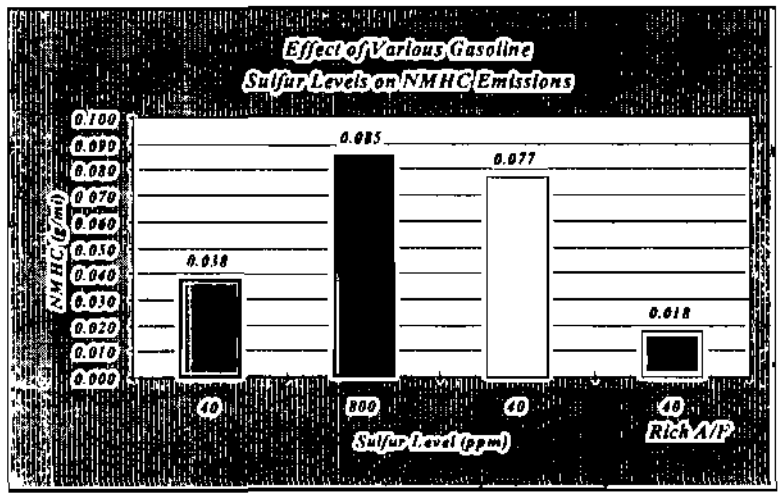

Figure 2a: Sulfur Reversibility Study on a ULEV Ford Escort Effect of Sulfur on NMHC Emissions

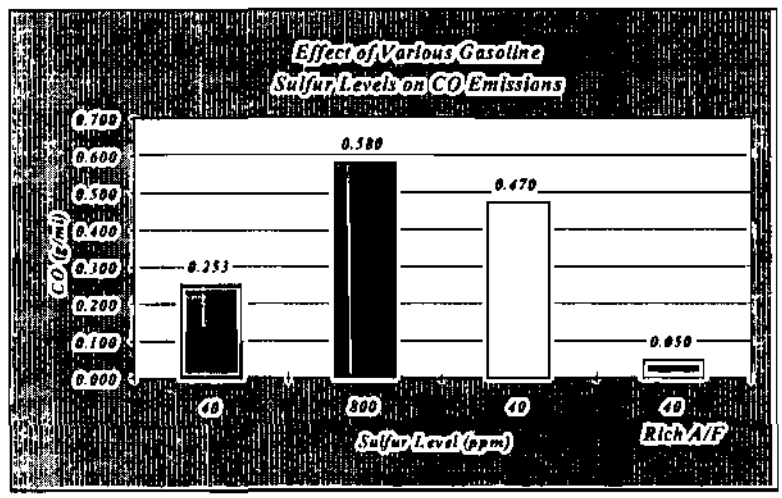

Figure 2b: Sulfur Reversibility Study on a ULEV Ford Escort Effect of Sulfur on CO Emissions

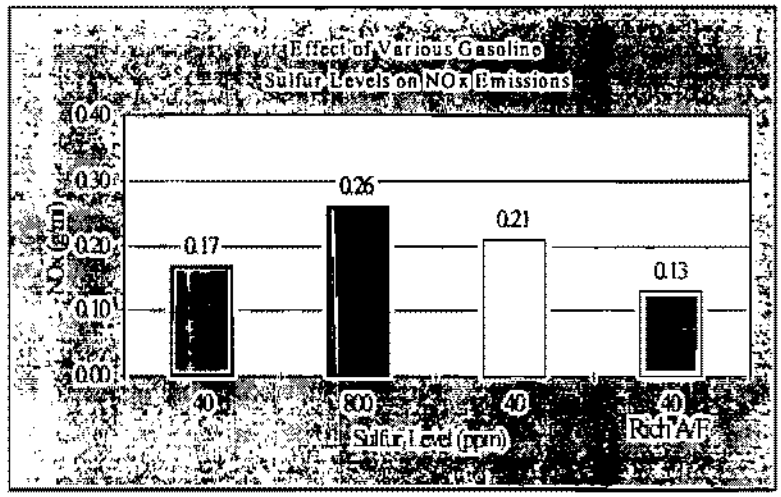

Figure 2c: Sulfur Reversibility Study on a ULEV Ford Escort Effect of Sulfur on NOx Emissions

Finally, API provided EPA with data for a 1995 Mazda Protegé transitional low emission vehicle (TLEV) equipped with an enhanced catalyst that allowed the vehicle to meet LEV standards with 40 ppm sulfur fuel. The vehicle was tested twice at 40 ppm, followed by a single test at 100 ppm, a single test at 600 ppm, a single test at 300 ppm, and then two more tests at 40 ppm. There was no special vehicle operation in between refuelings. Figures 3a and 3b show that, although the Protegé did not achieve complete reversibility, it came very close, experiencing about 85% recovery for NMHC and CO. The data in Figure 3c does indicate full reversibility for NOx, but this result is tempered by the fact that the NOx emissions were erratic over the different sulfur levels.

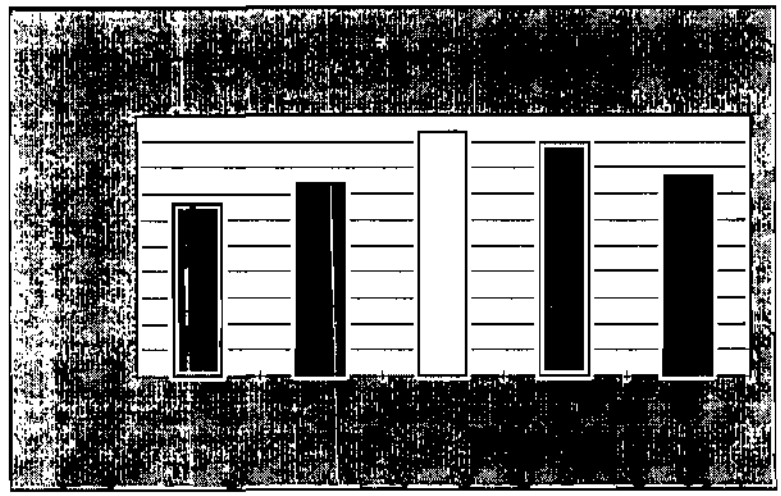

Figure 3a: Sulfur Reversibility Study on a 1995 Mazda Protegé TLEV Effect of Sulfur on NMHC Emissions

Figure 3b: Sulfur Reversibility Study on a 1995 Mazda Protegé TLEV Effect of Sulfur on CO Emissions

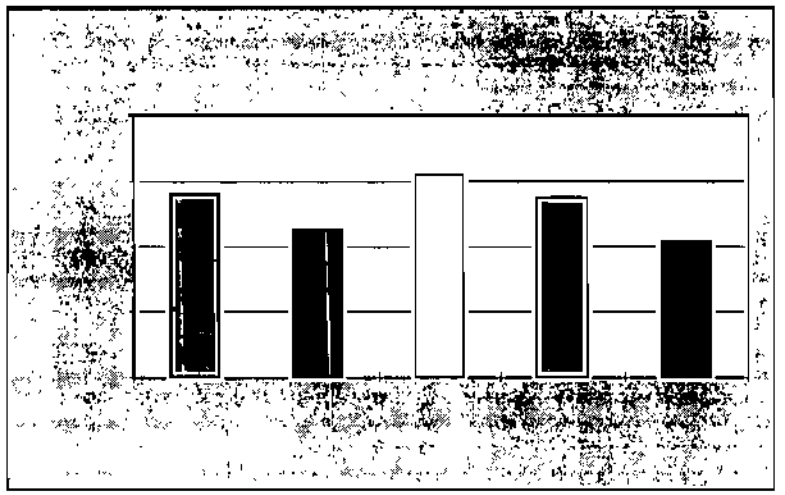

Figure 3c: Sulfur Reversibility Study on a 1995 Mazda Protegé TLEV Effect of Sulfur on NOx Emissions

In addition to these individual vehicle test results, CRC is currently performing a test program to explicitly evaluate sulfur reversibility with LEVs. The program involves the six LEV models tested in the CRC LEV-sulfur emissions test program described earlier and is scheduled to be completed by the end of May 1998. This program will assess reversibility after light urban operation and after more severe high speed, high load operation (i.e., the EPA US06 cycle). This program will further our knowledge of the degree of reversibility of current LEVs and facilitate a more accurate projection of the degree of reversibility achievable with potential Tier 2 vehicles.

E. Sulfur Tolerant Automotive Technologies

One of the clearest observations from the CRC and auto industry sulfur test programs is that there is a great deal of variability in vehicle sulfur sensitivity. While none of the vehicles were immune to sulfur's inhibition of catalyst performance, some of the vehicles showed that they were far less sensitive than others. In order to determine if it is possible to develop automotive technology that is substantially less sulfur-sensitive, EPA is in the process of evaluating the detailed emission and operating data obtained in the two LEV test programs. The goal of this research is to identify those technologies which are more and less sensitive to sulfur and whether the less sensitive technology can be applied to all manufacturers' vehicles (large and small, car or truck) in a cost-effective manner. In addition to analyzing the data from both industry test programs, EPA is also reviewing the latest technical literature, and meeting with vehicle and catalyst manufacturers and other researchers in this field to ensure that all available data are incorporated into this assessment.

At this time, it is clear that there are no catalyst designs currently available that are fully sulfur tolerant. The results of virtually every laboratory, engine dynamometer, and vehicle fleet study has shown that all automotive catalyst designs, whether they use Pd, Pt, Rh or any

combination of the three, have some inhibition in performance resulting from sulfur. However, some catalyst designs are more tolerant of sulfur than others.

There is a broad range of opinions regarding the feasibility of developing sulfur resistant catalyst technology. C.H. Bartholomew of the Department of Chemical Engineering at Brigham Young University stated at a recent CRC Symposium[15] that sulfur tolerant catalysts could be developed with a significant investment in research money and time, but that it is unlikely that a catalyst could be developed that could tolerate more than 100 ppm to 200 ppm sulfur with no emissions degradation. A representative of Degussa/ICT, a catalyst manufacturer, stated that it was possible to develop a Pd/Rh catalyst system that was more resistant to sulfur, but that there would still be some deterioration in HC and CO performance due to sulfur. Christopher Bennett of Johnson-Matthey, another catalyst manufacturer, stated that results from some of their studies indicate that Pd-only catalyst performance may be improved through washcoat formulation, and that these performance improvements were observed both in the presence and the absence of sulfur. Studies by Johnson-Matthey also showed that similar washcoat formulations, when applied to Pd/Rh catalysts, could also result in more active catalyst. However, laboratory and engine dynamometer testing indicated that these advanced washcoat formulations still exhibit a substantial decrease in catalytic performance when exposed to an increase in sulfur levels.

Heinz Robota of Allied Signal Emission Components (ASEC) Manufacturing, a manufacturer of catalysts and other emission control components, stated at the symposium that there are trade-offs in sulfur tolerant catalyst designs. He claimed that good hydrocarbon sulfur resistance may result in poor NOx conversion resistance to sulfur and vice versa, while the Automobile Emissions Control by Catalyst (AECC), an association of European emission control manufacturers, claimed that sulfur resistant catalysts are not an option because achieving this capability would necessitate trading off catalyst performance for the removal of some pollutants.

Recent discussions between EPA and several catalyst manufacturers have suggested that there may be some techniques available to make catalysts more tolerant of sulfur. However, in addition to an economic cost of doing so, there will also likely be an overall loss in catalytic activity. This means that the catalyst may perform better with high sulfur levels than today's highly active catalysts, but that the sulfur-tolerant catalyst will not perform as well (at either low or high sulfur levels) as today's catalysts perform with low sulfur fuel. Thus, higher sulfur levels still imply higher emission levels, though possibly not as high as is indicated by some of the today's LEVs which are very sensitive to sulfur. According to these catalyst suppliers, sulfur will still be technology constraining. Although these companies believe they can make catalysts that achieve low emissions even with moderate levels of sulfur, they can make considerable improvements in catalyst performance and emission reductions with even lower sulfur levels. Therefore, catalyst designs that might appear in Japan, Europe, and California, where sulfur levels are very low, may not be available in the rest of the United States.

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[15] CRC Auto/Oil Symposium, "The Search for Sulfur-Tolerant Emission Control Systems," Dearborn, MI, September 11-12, 1997.

In addition to catalyst design, the calibration of the fuel control system can have a significant effect on a catalyst's ability to tolerate sulfur. Systems and components such as air-fuel ratio controls and exhaust gas recirculation can have an effect on how sulfur reacts on the catalyst surface. This fact was supported at the CRC symposium by Johnson Matthey and also by Ray Paggi of Texaco Fuels and Lubricants. Paggi stated that evidence for this was the fact that some Tier 0 and Tier 1 production vehicles appear to be somewhat tolerant to sulfur and that fuel system calibrations appeared to be one of the contributing factors.

A discussion of several potential catalyst design features which may reduce sulfur sensitivity is contained in Appendix A. API is currently performing a research program to investigate the potential for developing sulfur tolerant catalyst designs. They hope to have a final report discussing their findings in the near future.

F. Projected Impacts on Advanced Engine Technologies

Based on information in the technical literature and information received from automotive manufacturers, it appears that gasoline sulfur may also have a detrimental impact on advanced engine technologies. An example is the gasoline direct-injection (GDI) engine. There are a growing number of vehicles currently sold in Japan which utilize direct fuel injection for gasoline engines. The advantages of GDI include up to a 30% improvement in fuel economy, improved engine response under variable operating conditions, and more rapid starting with less cold enrichment. As a result, GDI engines should produce lower levels of NMHC and CO_2 emissions. The very lean (>19:1 air-fuel ratio) operation typical of GDI engines results in low engine-out NOx emissions in comparison to more conventional, stoichiometric spark ignition engines. However, this lean operation poses a considerable barrier to NOx control using current three-way catalyst technologies, and very low tailpipe NOx emission standards would require reductions beyond the low engine-out levels.

Conventional spark ignition engines maintain an air-fuel ratio near stoichiometry (i.e., neither lean nor rich) to allow operation within the narrow window of operating conditions necessary for efficient removal of CO, hydrocarbons, and NOx. Under lean conditions, the ability of the catalyst to reduce NOx decreases substantially. Some GDI engine designs compensate by using a NOx trap to store NOx emissions while the engine is running lean. This stored NOx is then released when the engine is operating near stoichiometry, permitting the three-way catalyst to effectively reduce the NOx. Selective catalytic reduction (SCR) of the NOx is another approach being investigated. With SCR, a reducing agent is introduced into the exhaust which facilitates the reduction of NOx, even under lean conditions. Both the NOx trap/three-way catalyst and SCR are often collectively referred to as "lean-NOx" catalysts.

Some lean NOx catalyst strategies appear to be more sensitive to fuel sulfur than LEV catalysts or the catalysts expected to be used on post-LEV vehicles. Information supplied by Toyota at the CRC Symposium indicates that NOx emissions increase dramatically with

increased fuel sulfur for one lean-NOx catalyst system. NOx emissions doubled when fuel sulfur increased from 30 to 70 ppm, and quadrupled with sulfur levels of 500 ppm. Systems using SCR without a NOx trap may or may not be as sensitive to sulfur.

An important question regarding the use of GDI engines is their capability to achieve low NOx levels even with low sulfur gasoline. While low sulfur levels may enable the lean NOx catalyst systems mentioned above, it is not clear what level of NOx emissions vehicles with GDI engines would be able to meet, even with these catalysts. LEV-like NOx emission levels appear to be feasible, at least with some GDI designs. However, the ability of this technology to reduce NOx emissions below these levels is more uncertain. Thus, it is important to characterize the emission control potential of these engines with both low and high sulfur levels. This technology is described in further detail in Appendix A.

The fuel cell is another promising propulsion system that is being developed for possible introduction to consumers early in the next century. A fuel cell is an electrochemical device, similar to a battery, that generates electricity from a chemical reaction between hydrogen and oxygen. The necessary hydrogen can either be provided by a compressed gas (e.g., hydrogen, methane) or extracted from a fuel, such as gasoline or methanol, carried on the vehicle. The electricity produced from a fuel cell drives a traction motor that in turn drives the wheels. In comparison to conventional electric vehicles, fuel cell use gives a vehicle long range, good performance, rapid refueling, and similar (low or even zero) emission levels.

If gasoline is used to provide the hydrogen for fuel cells, the sulfur content of the gasoline can be very important. Although fuel cell technology is still in its infancy, it has become clear that the extraction of hydrogen from gasoline will simultaneously produce hydrogen sulfide and/or sulfur dioxide from the sulfur contained in the gasoline. These sulfurous compounds can reduce the efficiency of the fuel cell either through clogging of membranes or adsorption and subsequent inhibition of hydrogen dissociation. Current fuel cell research makes use of gasoline containing less than 40 ppm sulfur; it is not clear that all fuel cells can tolerate even this level of sulfur and nor whether future developments will result in fuel cells that can tolerate even higher levels of sulfur.

G. Sulfur's Effect on OBD Catalyst Monitors and Implications for I/M Programs

EPA's OBD regulations require that the OBD catalyst monitor identify those catalysts with efficiencies reduced to the extent that tailpipe emissions would have emissions increases exceeding 1.5 times the applicable HC standard. Current catalyst monitor designs do not actually measure catalyst efficiency, but measure the oxygen storage capacity of the catalyst and infer HC conversion efficiency from these readings. Sulfur can interfere with the catalyst's oxygen storage. In some cases, sulfur can decrease oxygen storage and cause the OBD system to determine that the catalyst has insufficient efficiency. In other cases, the chemical form of the

sulfur adsorbed on the catalyst can mimic stored oxygen and cause the OBD system to determine that the catalyst has sufficient efficiency, when in fact it does not.

EPA evaluated the potential of sulfur's interference with the proper operation of OBD catalyst monitors in 1997.[16] EPA concluded that there were not sufficient data to indicate a broad-based sulfur-related problem with OBD catalyst monitors. However, EPA also found that there might be a need, in a limited number of cases, for manufacturers to adjust their California-certified OBD systems for operation on higher sulfur levels outside of California. These adjustments would reduce the possibility that sulfur would cause the OBD system to prematurely illuminate the malfunction indicator light (MIL). EPA indicated that it would consider allowing such adjustments on a case-by-case basis.

EPA also acknowledged that it was not aware of any adjustments which could be made in the short term to eliminate the potential for high sulfur levels to cause "false-passes," where emissions exceed the monitor threshold but do not illuminate the MIL. This issue does not represent a customer inconvenience, as would a "false-failure." However, it could reduce the effectiveness of the OBD catalyst monitor, particularly in an inspection and maintenance (I/M) program, since the monitor may not detect a poorly performing catalyst.

The LEV and ULEV emission data presented above in Table 3 indicate that higher sulfur levels have the potential to increase emissions in the range that the OBD system is designed to detect (i.e., 1.5 times the applicable emission standards). However, the performance of the OBD systems on these test vehicles was not reported in the test programs. EPA is not aware of any other new data which has become available since the OBD-sulfur study was completed last year. Thus, the possibility of an interference of the OBD catalyst monitor by higher sulfur levels still exists. EPA has previously indicated to automobile manufacturers that it would consider any impacts of sulfur on OBD catalyst monitors during vehicle certification on a model-by-model basis. This approach still appears to be appropriate.

A regional sulfur control program could also affect I/M programs located outside of the sulfur control region. The emissions measured in these I/M programs would likely be higher than those measured elsewhere, possibly necessitating the use of unique emission cutpoints for LEVs and Tier 2 vehicles. As mentioned above, since sulfur may affect the operation of the OBD system on selected vehicle models, these I/M programs located outside of the sulfur control area would need to incorporate this information into their checking for the presence of OBD failure codes.

Also, one study of a TLEV showed that sulfur can have an inordinate affect on emissions over a loaded I/M test after a prolonged idle, which can occur while a vehicle is waiting in line

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[16] EPA, "OBD & Sulfur Status Report: Sulfur's Effect on the OBD Catalyst Monitor on Low Emission Vehicles," March 1997 and updated September 1997.

for an I/M test.[17] Thus, higher sulfur levels in-use may necessitate the use of special pre-conditioning procedures for the I/M testing of LEVs and Tier 2 vehicles.

[17] Beck, D.D., W.A. Short, T.E. Angelos and R.R. Dils, "IM240 Emission Tests with a 2.2 L Corsica TLEV," SAE Paper No. 942001, 1994.

III. Cost of Reducing Gasoline Sulfur

The data presented in the previous chapter indicate that control of sulfur in gasoline may be necessary to achieve an appropriate level of emissions reduction from potential Tier 2 vehicles and to enable the use of advanced technology vehicles in the U.S. Control of gasoline sulfur would also provide significant emissions reductions from NLEVs and older technology vehicles and resolve concerns about the compatibility of current gasolines with existing emission control hardware. The cost of reducing gasoline sulfur levels will be an important factor in evaluating the level and geographical extent of any required sulfur reductions. This chapter summarizes data regarding current sulfur levels in different grades and types of gasoline, and presents an overview of how sulfur is removed from gasoline. Following that is a discussion of refinery cost modeling that EPA is currently performing jointly with the U.S. Department of Energy (DOE). Preliminary cost estimates for gasoline sulfur reduction are presented, and additional aspects of a sulfur control program which may affect the costs to the refining industry are discussed.

A. Current Sulfur Levels in U.S. Gasoline

Sulfur occurs naturally in crude oil. As crude oil is refined, some of the sulfur ends up in gasoline. The amount of sulfur in the gasoline from any refinery depends on a number of factors: the amount of sulfur in the crude oil, the fraction of gasoline produced from heavier petroleum compounds,[18] and the amount of desulfurization being applied to gasoline blendstocks and gasoline precursor streams in the refinery.

There are a number of standards or limits which affect the amount of sulfur in gasoline. There is a 1000 ppm maximum sulfur specification for gasoline, developed by the American Society for Testing and Materials (ASTM), which most refiners meet voluntarily and some states have adopted by law. Federal reformulated gasoline (RFG) subject to the Complex Model is currently limited to 500 ppm sulfur due to the valid range limits of the Complex Model. Nearly one-third of U.S. gasoline is covered by the RFG requirements. Gasoline sold in California is subject to the California Phase 2 RFG Program (also known as the California Cleaner Burning Gasoline Program) requirements, which includes an annual average sulfur limit of 30 ppm sulfur, with no individual gallon exceeding 80 ppm.[19] Because refiners want to ensure that they will not exceed the annual average limit and some refiners have elected to certify their gasoline to

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[18] The conversion of high boiling hydrocarbons to gasoline-like material tends to put more sulfur into gasoline, since the sulfur contained in crude oil is generally concentrated in the high boiling material.

[19] California provides an alternate approach permitting refiners to comply with a per-gallon "flat limit" of 40 ppm. Under either the 30 ppm average standard or 40 ppm flat limit standard, refiners can use California's Predictive Model to identify and certify alternative fuel formulations which provide equivalent emission performance. These alternative formulations can involve either more stringent or more lenient sulfur limits, but in no case can these exceed the 80 ppm per gallon cap applicable to all gasoline sold in California.

alternative requirements which may involve even more stringent sulfur control, California gasoline sulfur levels currently average about 20 ppm.

API and NPRA recently surveyed their member companies to determine the qualities of gasoline and other petroleum products sold during the summer of 1996.[20] This survey, summarized in Table 4, showed that gasoline had the following average sulfur levels during that period.

Table 4. Average Sulfur Levels in Gasoline Sold Outside California (ppm): Summer, 1996 Production By Octane Grade and Gasoline Type

Gasoline Type	Regular Grade	Intermediate Grade	Premium Grade	All Grades
Conventional	400	350	142	346
Federal Reformulated	366	353	200	316
All Gasoline	394	351	159	340

Starting in the year 2000, refiners producing summertime gasoline for sale in RFG areas must meet a NOx reduction standard which is expected to result in lower gasoline sulfur levels in those areas, since sulfur control is believed to be the most cost-effective means to achieve the NOx reduction. Refiners have projected that their summertime Phase II RFG sulfur levels will average about 150 ppm. Sulfur levels could be higher in the winter, since winter RFG is subject to less stringent NOx reduction requirements.

Because of the wide range of gasoline sulfur levels seen in the U.S., it is likely that any sulfur control program will require sulfur reductions in at least some of the gasoline currently produced. An evaluation of the costs of sulfur control requires an understanding of how sulfur ends up in gasoline and what technologies are available to refiners to remove the sulfur. The following section addresses these issues.

B. Refinery Operations Affecting Sulfur

Most sulfur in gasoline (up to 97%) comes from gasoline feedstocks produced in the fluidized catalytic cracker (FCC), one of the key refinery processes for gasoline production.[21] Without any treatment of the sulfur levels of the feed entering the FCC unit, or of the gasoline

[20] American Petroleum Institute and National Petroleum Refiners Association, "Survey of Refining Operations and Product Quality," Final Report, July 1997.

[21] MathPro, Inc., "Costs of Producing Gasolines With Low Sulfur Content," Final Report, April 28, 1997

streams exiting the unit, sulfur levels can be 1000-2000 ppm in the FCC gasoline blendstocks. In general, the heaviest portion of FCC gasoline contains the most sulfur, with the heaviest 10% contributing about one-third of the total sulfur. A more complete explanation of these refinery processes is presented in Appendix D.

One means to reduce the sulfur content of gasoline, and other refined products, is to switch to a lower sulfur crude oil. However, it is not possible for all refiners to rely on this strategy because the supply of low sulfur crude oil is limited and with increased demand its price would likely rise. In addition, it may be difficult for refiners to maintain the same product mix if they switch to low sulfur crude oils, since low sulfur crude oils tend to be lighter. The volume and range of products that can be produced from lighter crude oils may or may not match the refiner's market plans. (Even with a change to lower sulfur crude oils, many refiners may still need to add new equipment to further reduce their gasoline sulfur levels.)

While the specific configuration and capabilities vary by refinery, there are generally two main options for removing sulfur from gasoline. Both of these options involve "hydrotreating," a process which uses hydrogen gas at high pressures and temperature to force out the sulfur compounds.[22] When adding the capacity to hydrotreat a particular stream, refiners may have to add facilities to produce more hydrogen as well as facilities to recover the sulfur removed from gasoline. Refiners may also have to augment utility facilities to ensure sufficient support for these new processing units.

Of the two main options for reducing gasoline sulfur, the less costly and less capital intensive approach is to hydrotreat the gasoline blendstocks produced by the FCC. Depending on the level of sulfur desired in the finished gasoline, part or all of the FCC gasoline blendstock can be hydrotreated. It is least expensive to hydrotreat the heaviest portion of the FCC gasoline because that portion contains the greatest amount of sulfur, and this stream usually undergoes less octane loss when hydrotreated.[23] This strategy requires a distillation tower to separate the heavier FCC output streams from the lighter products. A downside to hydrotreating the FCC gasoline is that it reduces the volume of gasoline produced, thereby adding slightly to the cost of producing lower sulfur gasoline. To achieve very low sulfur levels in gasoline, the lighter portion of the FCC gasoline blendstock may have to be hydrotreated as well, which can result in a significant octane loss, depending on the specific hydrotreating process used. The octane value lost with hydrotreating must be recouped by octane producing units in the refinery, or by the addition of high octane oxygenates. A relatively new sulfur removal technology licensed by Mobil, called OCTGAIN, does not cause as much octane loss for the same reduction in gasoline

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[22] Another option for very limited sulfur reduction is achieved by extraction. This is not a commonly used approach, because in most cases a substantial volume of sulfur reduction is required, or a substantial reduction in sulfur levels is needed; extraction cannot meet these needs.

[23] Hydrotreating impacts not only sulfur-containing compounds but also compounds which contribute octane, such as olefins. If olefins are hydrotreated, their octane value is reduced and the refiner must make up for the octane by blending other, higher octane, components.

sulfur as older processes. An OCTGAIN unit has been built in one refinery in the U.S. and another unit is under development in Europe.

EPA has become aware of a new FCC gasoline hydrotreating technology which may permit refiners to remove sulfur from the FCC gasoline while minimizing the drawbacks of traditional hydrotreating (octane loss, lost volume) at a significant cost savings. This process is licensed by CDTECH and is termed catalytic distillation, indicating a process which performs hydrotreating with a catalyst while distilling the gasoline into different temperature ranges. In terms of gasoline sulfur reduction, the most important potential for this technology, hydrotreating the heavy FCC gasoline, has not yet been tested in a commercial application. Thus, uncertainties in the cost of this emerging technology will remain until a commercial application can verify the efficacy and cost estimates. EPA has learned that at least one refiner plans to install this technology in their refinery during 1998.

An alternative to hydrotreating the gasoline from the FCC unit is to hydrotreat the FCC feed stream. This approach avoids a decrease in gasoline octane and generally improves the quality of other products produced in the FCC unit, such as distillates. It can also achieve very low sulfur levels. However, this tends to be a more expensive and capital intensive approach, because a larger stream of material is processed. For some refiners this may be an attractive option since this approach allows the processing of heavier, higher sulfur crude oils, reduces sulfur levels in diesel fuel,[24] and increases overall gasoline yield. Few refineries in the U.S. currently have FCC feed hydrotreating capacity.

The other major way to remove sulfur in gasoline blendstocks is with a hydrocracker. Hydrocrackers are essentially FCC units with hydrotreating capacity combined in the same unit; this process both upgrades and hydrotreats the stream being treated.[25] Hydrocrackers are generally used when the feedstock is too poor for upgrading with an FCC. For example, some crude oils are high in heavy metals, nitrogen, or sulfur, which would poison an FCC catalyst. For this reason, some refineries have hydrocrackers for upgrading the heavy gas-oil streams normally fed to the FCC. This is particularly common in California refineries which process Alaskan crude which is high in sulfur and heavy metals. Hydrocrackers are capital-intensive processes, similar to that of FCC feed hydrotreaters. Because of the high capital expense and because most refineries already have FCC units, many refiners outside of California would have to incur substantial costs and process changes to adopt hydrocracking capabilities. Like feed hydrotreaters, hydrocrackers would allow treatment of heavier, higher sulfur crude oils and may be more suitable for environmental programs which involve changes to both diesel fuel and gasoline.

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[24] If diesel fuel sulfur levels were required to be reduced as well, FCC feed hydrotreating becomes a more attractive option as the sulfur levels of both streams are reduced simultaneously. See Chapter IV: Other Fuel Issues for more discussion of this issue.

[25] Berger, Bill D., Anderson, Kenneth E., Modern Petroleum, "A Basic Primer of the Industry," Pennwell Books, 1981.

The modeling of gasoline sulfur reduction in refineries has shown that the most economic approach to removing sulfur from gasoline is to hydrotreat the gasoline-like material leaving the FCC unit. When the OCTGAIN process has been included in a refinery model, including the model used by EPA, it has been selected (based on the economic and performance data provided to the model) over other sulfur reduction processes. The models also typically purchase oxygenates to help make up the octane shortfall caused by hydrotreating, and this oxygenate addition also helps to reduce sulfur in gasoline through dilution. The refinery models tend to show that hydrotreating the FCC feed and the installation of hydrocracking capacity are less economically attractive to refiners. The following section provides a brief overview of the modelling EPA has performed to estimate gasoline sulfur control costs.

C. Cost Estimation Methodology

EPA has been working with DOE to develop cost estimates for gasoline sulfur control, using Oak Ridge National Laboratory's refinery yield model (ORNL-RYM). (Appendix B presents additional information about how the modeling work to be done was defined.) In planning the refinery modeling runs to be performed, EPA considered a range of geographic areas that could be covered by a low sulfur gasoline program, based on the range of vehicle technology issues being addressed and the emissions reductions which could be achieved. In consideration of these issues, the geographic areas identified for consideration included: 1) the entire U.S., excluding California; 2) the 37-state Ozone Transport Assessment Group (OTAG) region; and 3) the 22-state OTAG region covered by the proposed NOx State Implementation Plan (SIP) call. Table 5 shows the percentage of national gasoline affected for each of these potential areas of control.

Table 5. Gasoline Production Impacted by Potential Control Areas

Sulfur Control Area	Gasoline Volume (percent of U.S. total, outside California)
22-state OTAG Region	59%
37-state OTAG Region	89%
Entire U.S., excluding California	100%

A national control strategy is one of the options being evaluated because of its consistency with the expected national applicability of potential Tier 2 standards, the possibility that the sulfur impact may not be fully reversible, and the other emissions benefits, such as reductions in air toxics and primary and secondary PM, that could be achieved from current vehicles. In addition, as discussed in Chapter II, a national program may enable the use of certain advanced technology vehicles and would remove any remaining concerns that onboard diagnostic systems may malfunction due to interference by sulfur. A national program would also create

nationally uniform enforcement standards and compliance procedures for industry to abide by, possibly reducing compliance costs and making it easier to ensure that gasoline is meeting the new standards relative to a smaller program.

Figure 4 shows the area covered by the 37-state OTAG region. This region was identified as a potential sulfur control area because this was the region that was considered during the OTAG process to identify strategies to control the transport of ozone. However, it excludes 11 projected future ozone nonattainment and maintenance areas in seven other states, affecting a 1990 population of 13.4 million people. As Figure 4 shows, the 37-state OTAG region almost exactly corresponds to the fuel distribution area from the refineries in PADDs 1, 2, and 3.[26] Covering the entire volume of gasoline sold in these three PADDs may tend to simplify enforcement of a sulfur control program compared to a smaller program affecting only a fraction of the gasoline sold in these regions.

The 22-state OTAG region (also shown in Figure 4), although smaller than the 37-state region, encompasses many of the expected future ozone nonattainment and maintenance areas as well as many of the areas which contribute to the transport of ozone. However, it would exclude even more such areas than the 37-state OTAG region discussed above. The 22-state OTAG region is sufficiently limited in gasoline demand to exclude production by some refineries located in PADDs 1-3 for which sulfur reduction would be very expensive, which would result in lower costs for a given sulfur level compared to a program affecting a larger volume of gasoline. However, the complexities in enforcing a smaller program, particularly one that covers only a fraction of the gasoline produced in a given PADD, would probably increase. Because of the gasoline distribution system for the refineries that would produce gasoline for this region, a program may have to be implemented to prevent "dumping" of high sulfur gasolines into uncontrolled areas.

[26] U.S. refineries are grouped regionally into five Petroleum Administration Districts for Defense (PADDs) to represent the production and distribution systems. See Figure 8 for the division of the U.S. into the five PADDs.

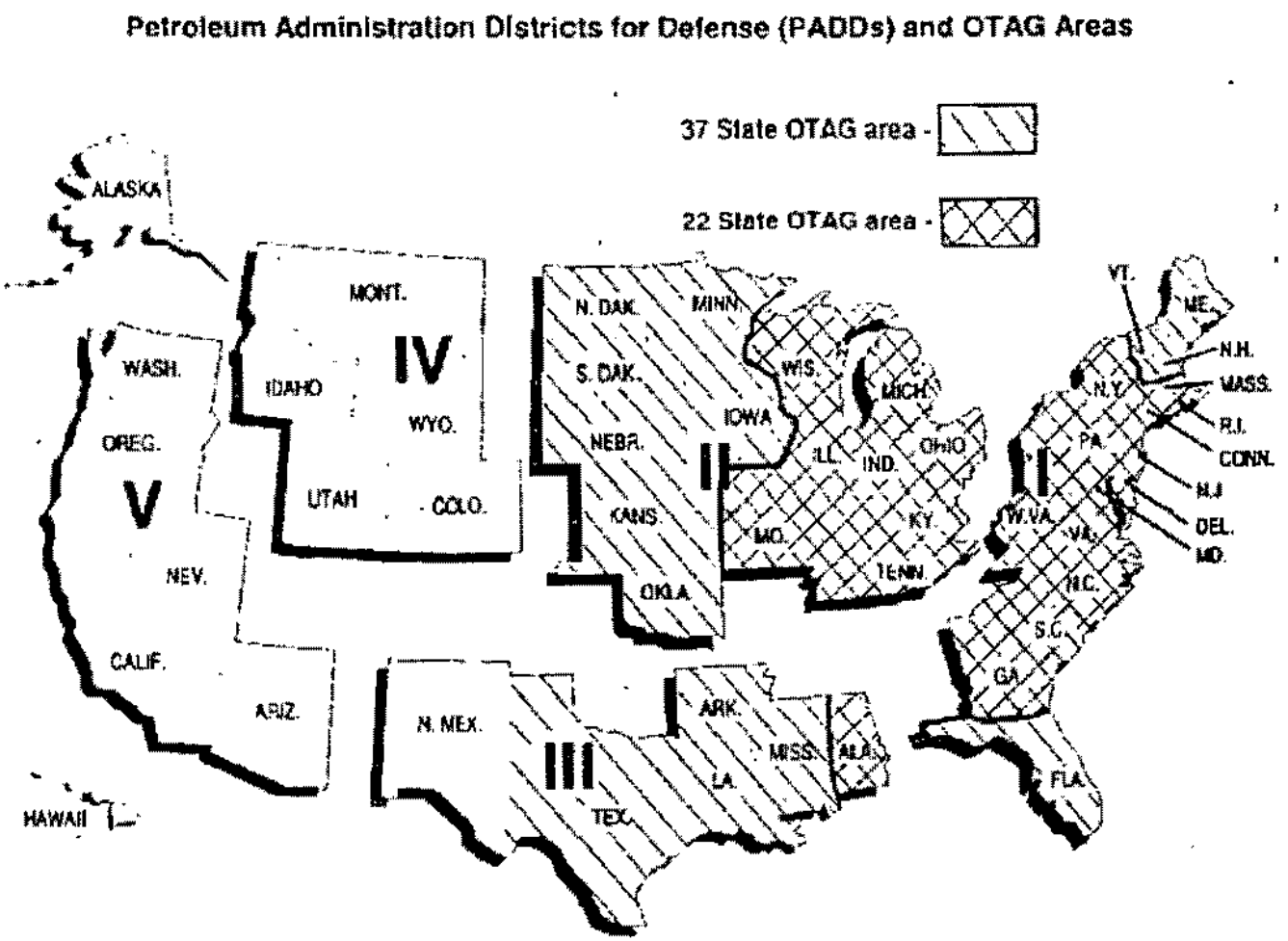
Petroleum Administration Districts for Defense (PADDs) and OTAG Areas
37 State OTAG area -
22 State OTAG area -
ALASKA
HAWAII
WASH.
OREG.
V
CALIF.
NEV.
ARIZ.
MONT.
IDAHO
IV
WYO.
UTAH
COLO.
N. DAK.
S. DAK.
NEBR.
KANS.
OKLA.
MINN.
IOWA
MO.
WIS.
ILL.
MICH.
IND.
OHIO
KY.
TENN.
N. MEX.
III
TEX.
ARK.
LA.
MISS.
ALA.
GA.
FLA.
S.C.
N.C.
VA.
W.VA.
II
PA.
N.Y.
VT.
ME.
N.H.
MASS.
R.I.
CONN.
N.J.
DEL.
MD.

Figure 4

D. Gasoline Sulfur Reduction Cost Estimates

EPA has developed preliminary cost estimates for sulfur control in PADDs 1 and 3, assuming that all of the gasoline produced in each PADD is controlled. The costs of reducing gasoline sulfur levels from the current average sulfur level of 340 ppm down to average levels of 150 ppm, 100 ppm, and 40 ppm have been estimated. These sulfur control levels were chosen because they matched the sulfur levels of the AAMA/AIAM and CRC test programs described in Chapter II. EPA used the results from the ORNL-RYM model to estimate the net costs to the industry using a pre-established cost estimation methodology, with a few modifications, as described in Appendix B.[27] The estimated costs, listed in Table 6, include the cost of any projected decreases in fuel economy associated with the use of oxygenates to reduce sulfur levels. As explained in Appendix B, the costs were derived based upon estimates of summer production costs, as this season represents the most severe sulfur control season for a refiner. However, as sulfur controls were assumed to be in effect year-round, the resultant capital costs were amortized over the entire year.

Table 6. Preliminary Estimates of Sulfur Reduction Costs
(Volume-Weighted Average for PADDs 1 and 3, 8% Return on Investment)

Sulfur Control Level		
150 ppm	100 ppm	40 ppm
1.1 - 1.8 c/gal	1.9 - 3.0 c/gal	5.1 - 8.0 c/gal

The cost estimates in Table 6 should be considered to be only roughly indicative of the potential cost of commercial gasoline sulfur control. These cost estimates only represent those for East Coast and Gulf Coast refiners (PADDs 1 and 3), and thus do not cover all of the major gasoline producing regions in the country which would be affected by a national sulfur control program. Also, these costs were developed without inclusion of some of the latest technologies for sulfur removal, including the process for catalytic distillation developed by CDTECH mentioned previously. At a recent conference on sulfur removal technologies,[28] CDTECH representatives claimed that sulfur control from current average levels down to about 40 ppm (on average) could be achieved with the CDTECH catalytic distillation process at a cost of 1-2 cents/gallon. Other designers of new sulfur removal technologies made similar claims. As indicated earlier, EPA plans to gather additional information about new technologies, and if appropriate, will include these technologies in future evaluations of sulfur removal costs. EPA will also be estimating the costs of gasoline sulfur control to refiners in the rest of the country.

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[27] Lester Wyborny, MEMORANDUM to Susan Willis, "Review of the Cost-Effectiveness of Phase II RFG NOx Control," February 27, 1997.

[28] International Fuel Quality Information Center, "Fuel Quality and Technology Briefing," Detroit, MI, March 9, 1998.

This will facilitate more precise estimates of the costs of both regional and national control programs, as well as the impact of using the most advanced sulfur removal technology.

E. Other Sulfur Control Cost Studies

In addition to performing the analysis discussed above, EPA has reviewed several other recent estimates of the costs of gasoline sulfur control. During the period when the Ozone Transport Assessment Group (OTAG) was developing costs for NOx control strategies, the American Automobile Manufacturers Association contracted with MathPro to estimate the cost of gasoline sulfur reduction.[29] MathPro estimated the cost of gasoline sulfur reduction in all the gasoline produced by PADDs 1, 2, and 3 from the current average sulfur level down to 40 ppm. A range of prices for the oxygenate methyl *tertiary*-butyl ether (MTBE) was assumed in the modeling. If an MTBE price of 84 cents/gallon is assumed (to be consistent with the EPA/DOE work described in the previous section), the cost of sulfur control estimated by the MathPro analysis is 5.5 cents per gallon of summertime gasoline.

The MathPro/AAMA cost estimate falls near the lower end of the range of preliminary costs estimated by EPA/DOE. However, caution must be exercised in comparing different refinery modeling studies without understanding the differences in the premises of the studies, which may result in differences in cost. For example, the MathPro study included the cost of sulfur control in PADD 2 refineries. It is expected that PADD 2 costs would be higher than the average of PADD 1 and 3 costs. Thus, adding PADD 2 costs to EPA's estimates would be expected to increase the average costs, since PADD 2 refineries currently produce higher sulfur gasoline (on average) than PADD 1 and 3 refiners. By contrast, resolution of some of the other modeling differences between the EPA/DOE work and the MathPro/AAMA work could tend to push the MathPro estimates higher.

Recently, API also contracted with MathPro to estimate the cost of gasoline sulfur reductions.[30] That study estimated the cost of sulfur reduction from current average sulfur levels down to average levels of 150 ppm, 100 ppm, and 40 ppm.[31] To estimate these costs, MathPro used a refinery modeling methodology similar to that used for AAMA, modeling the combination of PADDs 1, 2, and 3. However, the refinery model used for API was re-calibrated to represent the actual 1996 summertime gasoline qualities determined through the API survey of gasoline qualities referenced above in section A. The MathPro/API-estimated costs are summarized in

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[29] MathPro, Inc., "Costs of Producing Gasolines with Low Sulfur Content," work performed for AAMA, April 28, 1997.

[30] MathPro Inc., "Costs of Alternative Sulfur Content Standards for Gasoline in PADDS 1-3," Study for the American Petroleum Institute, February 5, 1998.

[31] The MathPro analysis also considered a low sulfur gasoline scenario in which reformulated gasoline had an average sulfur level of 100 ppm and conventional gasoline had an average sulfur level of 246 ppm. The cost for this scenario, assuming an MTBE price of 90 c/gal, was estimated to be 1.90 c/gal.

Table 7 below. Like the AAMA analysis, these costs are similar to those estimated by ORNL for EPA/DOE, even though there were significant differences in the premises on which these modeling exercises were based. However, the MathPro/API estimates for control to 150 ppm or 100 ppm are at or above the upper end of the EPA/DOE ranges, while the MathPro/API estimate for 40 ppm sulfur is closer to the lower end of the EPA/DOE range. EPA will continue to analyze the MathPro/API analysis to better understand the causes of these differences.

Table 7. Estimated Cost of Reducing Gasoline Sulfur, cents/gallon [a]
[Source: MathPro for API]

Average Sulfur Control Level (ppm):	150	100	40
Cost (c/gal):	2.7	3.4	5.1

[a] average of summer and winter costs based on an MTBE price of 90 c/gal

F. Cost-Effectiveness of Sulfur Control

EPA typically considers cost-effectiveness (the cost of reducing a ton of emissions) when evaluating emission control programs. Calculating cost-effectiveness allows comparisons between various emission control strategies that are aimed at achieving reductions in the same pollutant (e.g., the cost of a motor vehicle or fuel control strategy compared to the cost of various stationary source control strategies for reducing emissions of NOx). Cost-effectiveness is a useful tool for comparison, although other criteria are also used to determine which regulatory programs to pursue.

In determining the cost-effectiveness of a regulatory option, both the costs and the resulting emissions reductions must be quantified. The estimation of the cost is the most straightforward of the two factors. The costs of vehicle standards can be derived from estimated per-vehicle costs, multiplied by total affected sales. Similarly, the costs of a sulfur control program can be derived from an estimated cost per gallon, multiplied by affected sales.

It is the estimate of the emissions benefits to be achieved that can be more difficult, particularly when the control program being evaluated involves more than one significant benefit. Cost-effectiveness is most easily determined when a single pollutant is being controlled, or at least reductions in the emissions of one pollutant are the predominant benefit. Cost-effectiveness becomes more difficult to calculate when multiple benefits (e.g., reductions in NMHC, CO, NOx, toxics, and SOx, enablement of future technology, etc.) are significant, as is expected under potential Tier 2 and gasoline sulfur standards. Not only is it difficult to determine how to weight, on a relative basis, the various emissions reduced (e.g., is a ton of NOx reductions as beneficial as a ton of SOx), but it can also be difficult to compare the resulting cost-effectiveness estimates with estimates of the cost-effectiveness of other control strategies that may not have valued these emissions reductions in the same way.

Recently, representatives of the API Economics Committee (including a representative of NPRA) presented a proposed cost-effectiveness methodology to EPA.[32] This methodology combined the evaluation of Tier 2 standards and gasoline sulfur standards and focused on the ozone-related benefits from both the current and future vehicle fleets. API and NPRA recommended that this methodology be used to determine the optimum mix of lower sulfur fuel requirements and improved vehicle technology. They identified the specific types of data needed for this approach, as well as gaps in the available data.

G. Other Issues Affecting Sulfur Control Costs

In addition to the production cost for the average refinery, there may be other issues which could affect the costs to the refining industry of a sulfur control program. For example, one consideration is whether the program should be defined based on an average sulfur level, or based on a per-gallon limit on sulfur. The preliminary cost estimates by EPA, as well as the other cost estimates cited previously, were for the costs for the average refinery controlling sulfur to an average level. If such a sulfur reduction standard were promulgated, a refiner would have to control the volume-weighted average sulfur level of its gasoline batches at or below the averaging standard. While an averaging standard leads to reduced sulfur levels overall, over the year some batches of gasoline would be higher and others lower than the standard. These batch-to-batch variations are due to the variances in the day-to-day operations of the refineries, including variations in the sulfur content of the crude oils processed and both inadvertent and required maintenance shutdowns of certain units.

As explained in Chapter II, batches of gasoline with sulfur levels above a certain (as yet unidentified) level may cause serious complications for some emission control hardware. Furthermore, the compliance costs associated with an averaging program are likely to be higher than the costs for a program which provides an absolute cap on sulfur content, because of the complexities of enforcing an averaging standard (as discussed in the next section). For these reasons, it may be more desirable to establish a maximum per-gallon limit on gasoline sulfur levels. With such a cap, refiners could not exceed the specified level in any batch.

A per-gallon limit affects the refining industry much differently than an averaging standard. This is because a cap forces an individual refiner to install capital equipment or take other actions to reduce high sulfur batches to a greater degree than would be necessary under an averaging program. Even if some of the historic variations in gasoline sulfur level were reduced, under a per-gallon limit a refiner would have to produce gasoline which, on average, would be substantially lower than the cap to ensure that they comply.

Since the cost estimates derived from refinery models are all based on compliance on average, it is difficult to evaluate the costs of a per-gallon limit. EPA has performed an analysis,

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[32] "API/NPRA/EPA Meeting - 3/10/98 - Tier 2 Sulfur Control Cost-Effectiveness"

presented in Appendix C, to estimate a range of average sulfur levels that could arise if a per-gallon cap were implemented. Using this approach, EPA may be able to estimate the costs of a sulfur cap using costs derived from refinery modeling which yields costs for control on average.

A second issue to consider in defining a sulfur control program is whether all refiners will be able to make the investment needed to control sulfur. As with any regulatory program, a gasoline sulfur control program - particularly one that affects the majority of gasoline produced in the country - may result in particular hardship for some individual refineries. If a refinery supplies a limited geographic area and if few other refiners can easily supply the same area, the costs of the sulfur control program in that area may be substantially higher than the average costs experienced elsewhere. In defining a sulfur control program, EPA plans to evaluate whether the opportunity exists to include program design strategies which may result in reduced costs and increased flexibility for the regulated industry, particularly those refiners most adversely affected by the program. Examples of these strategies include trading and banking of credits for early or excess compliance with standards, delayed implementation for small refiners, and phase-in of the requirements (by fraction of production or by increasing stringency) over several years, to spread out costs and investment. No estimates of the cost savings, other benefits, or emissions implications that would result from pursuing such strategies have yet been made, and the introduction of additional compliance options will further complicate the enforcement of the program requirements.

H. Enforcement of a Gasoline Sulfur Standard

There are a variety of forms that a gasoline sulfur control program can take, and the ultimate decision regarding which form is most appropriate will depend heavily on the costs incurred by the regulated industries. However, there are also enforcement implications for each of the various choices, and the costs to industry of these different enforcement and compliance burdens cannot be easily quantified, although they must be taken into consideration. The enforcement implications are described here briefly; a more detailed discussion and evaluation of these issues will appear in any regulatory documents EPA develops in the future.

A nationwide, per-gallon gasoline sulfur standard would be the most straightforward program from an enforcement perspective. In this case, the Agency may be able to focus primarily on the sulfur level of individual batches at the refinery gate and/or collect and analyze gasoline samples for sulfur content at all levels of distribution. It is possible that the current reporting requirements for all gasoline under the anti-dumping regulations could help serve this purpose, avoiding the need to implement new reporting procedures for gasoline sulfur.

If, however, any alternative form of a gasoline sulfur control program were implemented, the compliance burden would increase. For instance, allowing averaging to meet a sulfur standard might require: 1) a more complex set of compliance procedures for refiners to prove that their volume-weighted, annual average sulfur levels meet the standard, 2) sampling surveys to

establish appropriate compliance within a given area, and/or 3) imposition of downstream sulfur standards which require distributors to establish compliance with the standard to ensure that the gasoline sold at the retail level meets the standard, just as the gasoline that left the refinery did. Furthermore, an averaging standard could require an enforcement program involving retail-level fuel quality surveys and the threat of tightening standards (ratchets) to ensure that the average sulfur standard applicable to a given area is actually being met in-use. A regional program could lead to the use of segregated storage and distribution systems, to ensure that low-sulfur gasoline is being delivered to the correct area(s). Finally, the inclusion of phased-in requirements, credits for early compliance, and delayed implementation might require additional enforcement protocols having precedent in such fuels control programs as the phase-out of lead in gasoline. The Agency will consider these and other enforcement implications in designing the most appropriate sulfur control program.

IV. Other Fuel Issues

Few refinery operations are totally independent, and variations in the volume or quality of one refinery product can impact the volume and quality of another product. Sulfur removal technologies vary, and depending on which technology is selected, gasoline alone can be impacted, or other refinery products, such as the distillates used for diesel fuel and other products, can also be affected. Similarly, controlling fuel properties other than gasoline sulfur can impact the cost of gasoline sulfur control.

The impact of gasoline sulfur control on other refinery products is addressed directly in the refinery model, as non-gasoline sulfur specifications must be met both before and after gasoline sulfur control. The primary issue in this section is the potential impact of changes to non-sulfur properties of gasoline or other fuels on the cost of gasoline sulfur control. Also, these other fuel controls could increase the overall economic impact on a given refinery. Details on the refinery interactions between gasoline sulfur control and the control of diesel fuel properties can be found in Appendix D.

This chapter summarizes several other fuel properties which may have significant impacts on emissions and that vehicle and engine manufacturers may request improvements in these properties to facilitate compliance with emission standards in the future. The first section discusses the distillation properties of gasoline, which collectively represent the ease with which liquid gasoline vaporizes and thus has implications for combustion and other phenomenon. A number of automobile manufacturers have indicated that current levels of gasoline distillation properties are limiting their ability to meet stringent emission standards. The second section highlights several diesel fuel properties that may be implicated in elevated emissions. Additional controls in either of these areas could impact a given refiner's decisions regarding the technological means through which sulfur is removed from gasoline, and therefore the cost of gasoline sulfur control.

A. Distillation Properties of Gasoline

It is widely understood that there is a relationship between the distillation properties of gasoline and the emissions which result upon combustion of the fuel. Gasoline distillation characteristics are typically described in terms of the temperature at which a given percent of the fuel (e.g., 10%) evaporates during a standardized distillation test. Thus, T10 is defined as the temperature at which 10% of the fuel has evaporated, T50 is the temperature at which 50% of the fuel has evaporated, and so on.

The auto industry has defined the "driveability index" of a fuel, calculated from the equation [DI = 1.5(T10) + 3.0 (T50) + T90],[33] as a measure of the potential for a vehicle to experience "driveability" problems - hesitations, stalls, etc. - as a result of the fuel. According to the auto industry, a driveability index in excess of 1200 indicates that the fuel may result in driveability problems.[34] Auto industry representatives have also shared with EPA data which suggests an historical trend of increasing values of the driveability index in gasolines sold nationwide.

Previous studies of the effect of fuel properties on emissions have demonstrated that hydrocarbon emissions, in particular, are correlated with high values of individual distillation temperatures, such as T50 and T90. High hydrocarbon emissions can also be assumed to occur during instances of poor driveability,[35] such as hesitation during acceleration or engine stalls, since such situations indicate that a significant amount of engine misfire is occurring. Engine misfire typically indicates that most or all of the fuel inducted into the cylinder leaves the engine unburned. The fuel does not ignite because an insufficient amount of the fuel injected into the intake manifold vaporizes to produce a flammable mixture in the engine cylinder. (Combustion of gasoline requires a specific amount of gasoline vapor, combined with oxygen; if too much of the gasoline remains liquid, combustion will not occur.)

When misfire occurs, it also causes a large amount of fuel and oxygen to be sent to the catalyst. If misfire occurs over a sufficient length of time, this excess fuel and oxygen can increase catalyst temperatures to the point where the catalyst is permanently damaged. Small amounts of misfire are unlikely to be noticed by the driver, but can still significantly increase tailpipe emissions of hydrocarbons. Whenever noticeable driveability problems are encountered, emissions are likely to have increased substantially.

If the distillation properties of all gasoline were similar, automotive engineers could account for the situations where insufficient vaporization may occur when calibrating the amount of fuel to be injected during accelerations. Fuels with high distillation temperatures vaporize less, leading to lean air-fuel mixtures at the beginning of accelerations. Fuels with low distillation temperatures vaporize more, leading to rich air-fuel mixtures at the beginning of accelerations. However, when fuels with different distillation characteristics are encountered, there is currently no practical way to measure or sense the distillation properties of a fuel on the vehicle and adjust the calibrations based on this information.

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[33] Where the T10, T50, and T90 represent the temperatures at which 10%, 50% and 90% of the gasoline evaporates, measured in degrees Fahrenheit.

[34] Although oxygenates decrease the T50 of the gasoline (and thus reduces the driveability index), it has been suggested that oxygenated gasolines may result in driveability problems with a driveability index over 1150.

[35] Increased emissions resulting from driveability problems may not be reported on tests conducted under the federal test procedure (FTP), since tests in which hesitations or stalls occur may have been invalidated.

The primary solution to misfire is to enrich the air-fuel mixture during accelerations (i.e., increase the amount of fuel injected), so that the air-fuel mixture in the cylinder is flammable even when fuels with high distillation temperatures are encountered. While this avoids misfire with these heavier fuels, it increases hydrocarbon emissions whenever fuels with lower distillation temperatures are used. Some manufacturers have indicated to EPA that they have had to compromise their engine calibration strategies in order for their engines to perform satisfactorily on those commercial fuels with the highest distillation temperatures. This leads to sub-optimum catalyst performance.

EPA is just beginning an evaluation of the available information on the impacts of distillation properties on emissions. Although data exists which demonstrates the impact of some distillation properties on emissions for Tier 0 vehicles, there is much less data for Tier 1 or later model vehicles. A few manufacturers have submitted limited data on individual LEVs which suggest an increased sensitivity, relative to older technologies, to changes in fuel distillation properties. These data suggest the potential for increased emissions as distillation properties deviate in either direction from some (as yet undefined) optimal level. Furthermore, as discussed in Chapter II, under the new "offcycle" emission standards soon to take effect, manufacturers may be unable to program their vehicles to enrich the air-fuel mixture to compensate for high distillation temperatures. EPA has not yet estimated the cost of reducing gasoline distillation temperatures, or reducing the range of gasoline distillation temperatures.

EPA has not recently conducted any refinery modeling of the control of gasoline distillation properties, the interaction of the control of both sulfur and distillation properties. Even without specifically modeling the control of both parameters, there is likely to be some interaction. Sulfur is contained in the highest boiling portion of the gasoline-like material produced by the FCC unit (FCC gasoline). Refiners will likely evaluate shifting some of this material to the distillate pool versus desulfurizing it. Desulfurization will likely affect both the amount and octane of the FCC gasoline. This evaluation of the operation of the FCC unit and processing of the highest boiling portion of the FCC gasoline would also provide refiners an opportunity to include process modifications to reduce the mid-range or upper-range distillation temperatures of their gasoline. However, the FCC unit is not the only refinery process which produces high boiling material. Both the alkylation unit and the catalytic reformer also produce significant quantities of higher boiling material which can increase the distillation temperatures of finished gasoline. Both of these materials contain very low levels of sulfur, as the sulfur contained in the materials sent to these units is removed in order to protect the alkylation and reforming catalysts. Therefore, while there will likely be some interaction between sulfur and distillation temperature control, it does not appear to be a strong one.

B. Diesel Fuel Properties

EPA currently restricts the sulfur content of onroad diesel fuel to 500 ppm. A cetane index minimum of 40 also applies to this fuel. EPA does not have any regulations applying to

the quality of diesel fuel used in nonroad diesel engines. However, during 1998 and 1999, EPA will review the appropriateness of the 2.4 gram per brake horsepower-hour (g/BHP-hr) HC plus NOx standard applicable to new onroad heavy-duty diesel engines sold in 2004 and beyond. This technology review will include consideration of fuel quality improvements. Sulfur in diesel fuel is known to be a problem with lean-NOx catalyst technology, which was addressed in Chapter II above. While control of nonroad diesel fuel quality appears less likely, it is possible that a sulfur limit similar to that applicable to onroad diesel fuel could be implemented to facilitate the use of oxidation catalysts or to reduce sulfate particulate. In 2001, EPA will be conducting a similar review of the feasibility of the future standards applicable to new nonroad heavy-duty diesel engines. EPA (and California) are also conducting evaluations of the health effects of exposure to diesel exhaust, including particulate emissions from diesel engines. The results of these evaluations could have implications for future decisions about diesel fuel composition.

Although any new controls applied to diesel fuel can potentially impact a given refiner's decisions regarding the means through which sulfur is removed from gasoline, it appears that diesel sulfur control has the potential for the greatest refinery interactions with gasoline sulfur control. As indicated above, a gasoline sulfur standard would most likely lead refiners to remove sulfur from gasoline blendstocks. More stringent diesel sulfur standards would likely lead refiners to remove sulfur from diesel fuel blendstocks, as opposed to other strategies, such as switching to lower sulfur crude oils. However, if both changes were made at the same time, refiners might remove sulfur from feedstocks going to both gasoline and diesel fuel (e.g., the feedstream to the FCC unit) and reduce the total cost of sulfur control. Also, a single large hydrogen plant could be built, instead of two smaller units, again at a cost savings.

The Agency's modeling of gasoline sulfur reductions costs completed to date has not modeled the cost of the simultaneous imposition of any diesel fuel program with gasoline sulfur control. However, the Agency is planning to perform such a study to understand the costs and other implications of implementing programs affecting both gasoline and diesel fuels at the same time.

Although diesel sulfur control may have the most significant refinery interactions with gasoline sulfur control, controls applicable to other diesel fuel properties also have the potential to impact the way a refinery operates, and thus may also impact gasoline sulfur control. The need for changes to diesel fuel properties other than sulfur will also be evaluated in the context of the technology review for the model year 2004 standard of 2.4 g/BHP-hr for onroad diesel engines and the technology review for standards applicable to nonroad diesel engines proposed for 2001.

V. Gasoline Sulfur Reduction Programs in Other Countries

This paper focuses primarily on the concerns with gasoline sulfur levels in the United States. However, other countries are also taking steps to limit the sulfur content of gasoline as well as diesel fuel. The characteristics and operating circumstances of national and regional gasoline refining industries differ to some degree from country to country. While most refiners have access to the same crude oils, some utilize local crude oils with unique compositions. Also, the mix of refined products differs from country to country. For example, the market in some countries is more oriented to distillates (e.g., diesel fuel) and others to gasoline. However, the primary benefits of sulfur control in other countries are the same as those here - to enable advanced emission control technologies and to reduce emissions from current or future vehicles. Harmonizing emission standards and test procedures across national boundaries which meet the levels of control EPA determines to be appropriate is also a long-term goal of EPA. While considerable effort is still required to achieve this goal, it cannot be achieved without harmonizing those aspects of fuel quality which affect vehicle technology and emissions. Thus, international regulatory activity on vehicle standards and fuel quality should be considered as EPA proceeds to develop regulatory programs affecting both vehicles and gasoline sulfur levels. This chapter presents an overview of the current and proposed gasoline sulfur standards in other countries as well as international requirements and activities for reducing gasoline sulfur levels.

A. Canada

In Canada, the Canadian General Standards Board (CGSB) has adopted voluntary standards for gasoline sulfur following a consensus process involving the producers (refineries and importers), users (e.g., automobile manufacturers), and other parties (e.g., governments). This process is very similar to the process followed by ASTM in the U.S. The CGSB's standard for gasoline sulfur is 1000 ppm, which is the same as the level established by ASTM in the U.S. Although CGSB's standard for unleaded gasoline specifies a maximum sulfur content of 1000 ppm, there are no federal requirements that limit gasoline sulfur levels. However, the Canadian government is currently considering reductions in gasoline sulfur levels nationwide.[36] Recommendations to reduce sulfur to levels as low as 30 ppm on average/80 ppm maximum have been made, although no final decisions have been reached. The Canadian government is collecting comments on the range of recommendations, and will hold a public meeting in May 1998 to gather additional comments.

Individual Canadian provinces have adopted the CGSB standard, or some other standard, for gasoline produced in that province. For example, Ontario has adopted the CGSB limit, while Quebec's "Règlement sur les Produits Pétroliers" limits the maximum level of sulphur in gasoline

[36] See Reports referenced in: Glenn Allard, Environment Canada, Memorandum to Steering Committee members, Sulphur in Gasoline and Diesel Studies, *Reports Concerning Sulphur in Gasoline and Diesel Fuels*, 29 August 1997.

to 1500 ppm. British Columbia has cleaner burning gasoline regulations which specify average sulfur reductions, but also permit compliance by demonstrating that reductions in NOx emissions have been achieved, as determined using the U.S. EPA's Complex Model. Hence, while the sulfur levels specified in the regulations are expected to be seen on average, the potential exists for some gasoline to have higher sulfur levels (while still meeting the NOx emissions performance standards). British Columbia's regulations specify that beginning in 1999, the annual average sulfur level of any primary distributor must not exceed 150 ppm in Southwest B.C. and Vancouver Island. Beginning in 2000, the annual average must not be greater than 200 ppm for the rest of the province.

B. European Union and Countries within Europe

Recently, the European Parliament adopted fuel quality specifications for gasoline and diesel fuel. These fuel specifications include a 150 ppm cap on gasoline sulfur beginning in the year 2000. Beginning in the year 2005, this sulfur cap is lowered to 30 ppm. The Parliament must now reach a "common position" with the European Council of Ministers. A common position is anticipated and a final rule for the European Union is expected between May 15 and June 1 of 1998.[37] In addition, Sweden and Finland have had tax incentive programs since 1994 that encourage gasolines with sulfur levels below 100 ppm.[38]

C. Other Countries

In addition to the United States, Canada, and Europe, other countries around the world are also implementing programs to limit gasoline sulfur levels. A summary of the current and expected future gasoline sulfur standards for various countries around the world is presented below in Table 8.[39] In Mexico, cleaner-burning fuels are required in Mexico City during the winter. In October 1996, the state-owned oil company PEMEX began offering and promoting a gasoline called *magna reformulada*. This gasoline has been described as "comparable to CARB Phase 2 RFG." However, the sulfur level of this gasoline can be as high as 500 ppm. The *magna reformulada* fuel may be expanded to Monterrey and Guadalajara in the future. In addition, the government plans to subsidize the retail price of the fuel.[40]

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[37] Memorandum from Fred L. Potter, Information Resources, Inc., to Margo Oge, U.S. EPA, *European Parliament Passes Tight Fuel Specifications*, 18 February 1998.

[38] Tushingham, Dr. Mark, "International Activities Directed at Reducing Sulphur in Gasoline and Diesel," Environment Canada, 25 August 1997.

[39] Alfred, Kenneth R., "Why Fuel Sulfur Varies Worldwide," Hart's Fuel Technology & Management, January/February 1998. [Refer to this document for sulfur levels in the following countries: Germany, Austria, Switzerland, France, United Kingdom, Central/So. Europe, Latin America, Asia (except Japan), and Australia.

[40] Tushingham, 25 August 1997.

Japan has established a maximum per-gallon limit for sulfur in gasoline of 100 ppm. However, in 1996, Japanese regular gasoline had an average sulfur level of 27 ppm whereas the average sulfur level of premium gasoline was 7 ppm. Although in the future there is a possibility that Japan may set similar gasoline standards to those of the U.S. or the European Union (through the new Japan Clean Air Program), there will most likely be no additional improvements in gasoline sulfur levels in the near term due to the very low sulfur levels already seen in the country.[41] Elsewhere in Asia, Thailand regulations require a cap of 1000 ppm sulfur in unleaded gasoline.

In Australia, the government of the state of New South Wales (NSW) proposed to reduce sulfur in gasoline to 100 ppm initially with a further reduction to 40 ppm. The current sulfur standard of NSW gasoline is approximately 200 ppm. Australian gasoline overall has an average sulfur level of 175 ppm in regular unleaded gasoline and 151 ppm in premium unleaded.

[41] Idemitsu Kosan Co., Ltd., "Clean Air Program in Japan," Presentation to the U.S. EPA, December 1997.

Table 8. Summary of Gasoline Sulfur Levels in Other Countries					
Country	*Current Avg.Sulfur(ppm)*		*Current Sulfur Standard*	*Future/Proposed Sulfur Standard*	*Effective Date*
	Regular	Premium			
European Union (Parliament)	300		500 ppm	150 ppm 30 ppm	2000 2005
Sweden			Recommended 100 ppm (tax incentive)		
Finland			Recommended 100 ppm (tax incentive)		
Germany, Austria, Switzerland	176	115			
France	466	249			
United Kingdom	348	287			
Central/So. Europe	257	124			
Canada	343		1000 ppm	50-360 ppm	varies
Atlantic	276				
Quebec	364				
Ontario	470				
Prairies	228				
British Columbia[a]	273			250 avg or 1993 baseline 150 ppm avg in SW BC 200 ppm avg. rest of BC	1996 1999 2000
Mexico			500 ppm max (Mexico City)	500 ppm max (Monterey & Guadalajara)	
Latin America	623	503			
Japan	<100	<100	100 ppm max		
Thailand			1000 ppm		
Asia (except Japan)	245	159			
Australia	175	151			
New South Wales			200 ppm	100 ppm; 40 ppm later	

[a]British Columbia's regulations also permit compliance with NOx emissions reductions, determined using EPA's complex model, which may result in higher sulfur levels than specified here.

VI. Stakeholder Positions on Sulfur

A number of parties have taken positions regarding the need for and appropriateness of gasoline sulfur control for the benefit of potential Tier 2 vehicles and the fleet as a whole. The following sections summarize the positions taken by various interested parties on this issue.

A. Automotive Industry

AAMA and AIAM have jointly petitioned EPA to limit gasoline sulfur level for all gasoline (outside of California) "as soon as possible" to the level that is "as low as practicable but in no case greater than 40 ppm per gallon by weight...or, ... no greater than 30 ppm annual average by weight with a per gallon cap of 80 ppm."[42] The petition claims that sulfur control is necessary for the following reasons:

- Higher sulfur levels will reduce the benefits of current and advanced technology vehicles by impairing the emission control systems.
- Fuel sulfur contributes to air quality problems such as particulate, sulfur oxides, and air toxics emissions.
- The sulfur impact on emission control systems is irreversible under normal operating conditions.
- If sulfur is not controlled, more fuel-efficient technologies will not be introduced in the U.S. because of their great sensitivity to sulfur.

The petition also states that sulfur reduction technology is available to refiners, is a cost-effective means to reduce emissions, and is already used in California and in other countries. EPA is currently in the process of reviewing the petition.

Several individual automakers have also released positions on the need for gasoline sulfur control. Chrysler Corporation has concluded that high fuel sulfur levels reduce catalyst efficiency, increase tailpipe emissions, and are a barrier to lean burn technology.[43] To address these issues, they have recommended California sulfur levels (30 ppm on average, 80 ppm max.)

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[42] American Automobile Manufacturers Association and Association of International Automobile Manufacturers, "Petition to Regulate Sulfur in Gasoline Under Section 211(c) of the Clean Air Act." Before the United States Environmental Protection Agency, March 19, 1998.

[43] Boltz, Ronald R., "What's Coming - Emission Control Standards and Technology," presentation to the CRC Auto/Oil Symposium: *The Search for Sulfur-Tolerant Emission Control Systems*, Dearborn, MI, September 11, 1997.

Similarly, Ford Motor Company has concluded that the catalyst technologies presently being developed for 2002 model year and later vehicles will not be capable of meeting LEV/ULEV standards with fuel sulfur levels greater than 300-500 ppm.[44]

B. Oil Industry

API and NPRA recently recommended a sulfur control program which they believe will meet environmental needs and will be less costly than the approach advocated by the auto industry.[45] Acknowledging that Tier 2 vehicles will benefit from sulfur control, API and NPRA advocate a regional fuels program, under which all gasoline sold in ozone nonattainment areas and the 22 OTAG states would be limited to 150 ppm sulfur, on average, during the summer ozone season. The gasoline sold in the rest of the country would be limited to 300 ppm, on average, during the same period. The industry recommends that this program begin January 1, 2004, or when the Tier 2 standards take effect, whichever is sooner. These recommendations are based on claims of significant NOx emissions reductions and a cost to the industry of about $3 billion, equivalent to a production cost increase of about two cents per gallon of gasoline sold in the recommended covered areas.

Tosco, an independent refiner, has recommended that all gasoline produced in the U.S. outside of California meet a per gallon cap of 80 ppm sulfur.

C. Catalyst Manufacturers

Catalyst manufacturers have expressed views which support many of the conclusions reached by the automotive manufacturers. For example, the Manufacturers of Emission Controls Association (MECA) has recommended setting a near-term cap on sulfur in the 180-220 ppm range and a longer term cap of 80 ppm.[46] MECA cited several factors which influence the impact sulfur has on catalyst performance and the degree to which the impact is reversible, and suggested that catalysts designed for LEVs may see a greater impact and less reversibility than earlier models. An international association of European catalyst manufacturers and designers has also concluded that sulfur's impact on catalyst conversion efficiency increases at very low emission levels.[47] This organization claims that the development of a sulfur resistant catalyst

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[44] Gandhi, Haren S., "Effect of Fuel Sulfur on Automotive Three Way Catalysts," presentation to the CRC Auto/Oil Symposium: *The Search for Sulfur-Tolerant Emission Control Systems*, Dearborn, MI, September 11, 1997.

[45] "API/NPRA Sulfur Recommendations," March 20, 1998.

[46] Manufacturers of Emission Controls Association, "The Impact of Gasoline Fuel Sulfur on Catalytic Emission Control Systems," October 1997.

[47] Searles, R.A., Automobile Emissions Control by Catalyst (AECC), "The Effect of Sulfur on Durability and Performance of Catalyst Based Emission Controls," 18 June 1997.

would require a trade-off between catalyst performance and removal of other pollutants. Furthermore, they state that sulfur has an immediate effect with just one tankful, although most of the catalyst performance will be restored when low sulfur fuel is used. They also raise questions about the long term durability of emission control systems operated on high sulfur fuel.

D. State and Local Air Quality Managers

Recently, the State and Territorial Air Pollution program Administrators (STAPPA) and the Association of Local Air Pollution Control Officials (ALAPCO) jointly resolved that EPA should adopt a two-phase national cap on sulfur in gasoline, specifying levels of approximately 200 ppm by 2001 and no higher than 80 ppm by 2005.[48] This resolution was based on a number of findings of the organizations, including the belief that reducing sulfur in gasoline can decrease emissions from vehicles, the fact that EPA recently promulgated new ambient air quality standards for ozone which will require additional emissions reductions, and their desire that states and localities get maximum emission reductions from EPA's motor vehicle control programs.

E. OTAG recommendation

OTAG, which is comprised of representatives from each of the 37 states in the Eastern half of the U.S., was formed to identify options for controlling the transport of ozone and ozone precursors. In addition to supporting the use of Federal reformulated gasoline, OTAG recommended that EPA adopt an "appropriate" sulfur standard to "further reduce emissions and assist the vehicle technology/fuel system to achieve maximum long term performance."[49]

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[48] STAPPA/ALAPCO RESOLUTION ON A NATIONAL GASOLINE SULFUR CAP, Adopted October 28, 1997.

[49] Ozone Transport Assessment Group, "Recommendation: Gasoline," Approved by the Policy Group, May 13, 1997.

VII. Conclusions

Based on the data and information obtained to date, EPA staff believe that some level of gasoline sulfur control is appropriate. While it is probable that vehicle emission control technology will continue to develop and that catalysts may be able to be designed to be less sensitive to sulfur, complete sulfur tolerance appears highly unlikely. The ability to design emission control systems to achieve complete reversibility of the sulfur effect appears possible. However, the need for manufacturers to meet stringent off-cycle emission standards beginning in 2001 will increase the difficulty of both of these tasks, particularly that of achieving easy reversibility under normal driving. Therefore, it appears appropriate to evaluate various levels of sulfur reduction, applicable in both regional areas and across the entire nation, while the Agency is developing Tier 2 standards for 2004 and later LDVs and LDTs.

The appropriate sulfur level for commercial gasoline remains to be determined. EPA is continuing to conduct refinery modeling in order to better estimate the cost of sulfur control, including the use of advanced sulfur removal techniques. EPA will also be analyzing the detailed emission data contained in the two industry LEV-sulfur test program in order to develop improved estimates of the sulfur sensitivity and reversibility of Tier 2 vehicles. When determining the appropriate sulfur level for commercial gasoline, EPA will also address the current mismatch of sulfur between commercial gasoline and EPA test fuel.

To identify the appropriate sulfur control strategy and Tier 2 standards, EPA will continue to work closely with interested parties, gathering their input along the way. A public workshop will be held in May, 1998, to discuss the technical issues raised in this Staff Paper. Throughout the coming months, EPA will continue to interact with individual companies, trade organizations, the states, and environmental organizations to determine the best approach to dealing with this issue. Staff are recommending that the Agency develop proposed gasoline sulfur standards to be implemented coincidentally with the implementation of the planned proposed Tier 2 emission standards for LDVs and LDTs.

EPA Staff Paper on Gasoline Sulfur

Appendices

(Transmitted as a Separate File, app-fin.wpd)

STATEMENT OF THE U.S. ENVIRONMENTAL PROTECTION AGENCY ON COURT'S DECISION ON CLEAN AIR RULES
May 14, 1999

"EPA stands by the need for the health protections embodied by the clean air standards and the science behind them. The soot and smog standards put in place almost two years ago will protect the health of 125 million Americans, including 35 million children. In fact, today's ruling from a panel of judges from the U.S. Circuit Court of Appeals for the District of Columbia does not question the science and process conducted by EPA justifying the setting of new, more protective standards. However, the panel called into question the constitutionality of the primary public health provisions of the Clean Air Act that on numerous occasions have been ratified by Congress and, until now, the courts. These provisions have afforded the American people with strong public health protections for over 25 years. EPA is currently reviewing all options to preserve these standards, but intends to recommend an appeal to the Department of Justice. If the courts fail to uphold these protective standards, Congress must ensure that these protections are preserved for the American people and EPA stands ready to work with them."

R-51 ###

THE US COURT OF APPEALS FOR THE D.C. CIRCUIT DECISION ON EPA'S PUBLIC HEALTH AIR STANDARDS FOR SMOG AND SOOT

Ignoring Supreme Court Law:

- On May 14, 1999, in a split decision (2 to 1), a panel of the U.S. Court of Appeals for the D.C. Circuit ignored over a half century of Supreme Court law. It held that the Clean Air Act -- as applied in setting the new public health air quality standards for ozone (smog) and particulate matter (soot) -- is unconstitutional as an improper delegation of legislative authority to the Environmental Protection Agency (EPA).

  - In constructing the programs that provide many of this nation's most important public health and safety standards, Congress, EPA and other federal agencies have relied on a 64-year history of Supreme Court and Court of Appeals jurisprudence sustaining similar Congressional delegations of authority.

  - The panel's split decision -- a radical departure from that well-established case law -- carries with it dangerous implications for not only the new public health air quality standards, but also for many other federal laws or rules enacted to protect the health of the American people.

  - In a vigorous dissent, Judge Tatel declared that "the court ignores the last half-century of Supreme Court nondelegation jurisprudence, apparently viewing these permissive precedents as mere exceptions to the rule laid down 64 years ago [in a 1935 case]."

Upholding EPA's Science and Process:

- Despite the constitutional ruling, the Court rejected the central arguments of industry's claims. The Court did not question the science on which EPA relied to develop the health standards or criticize EPA's decision making process. The Court stated that:

  - "the growing empirical evidence demonstrating a relationship between fine particle pollution and adverse health effects amply justifies establishment of new fine particle standards."

  - there was "ample support" for EPA's decision to regulate coarse particulate pollution.

  - EPA complied with the Regulatory Flexibility Act as amended by the Small Business Regulatory Enforcement Fairness Act (SBREFA) and Unfunded Mandates Reform Act (UMRA).

Delaying Public Health Protections:

- If not overturned, the Court decision will jeopardize or put on hold the new public health air standards for soot and smog which would protect the health of 125 million Americans, including 35 million children. Taken together, these harmful pollutants contribute to acute health effects ranging from premature death to exacerbated asthma and other respiratory problems.

The Decision: Specifically, the Court's decision:

- did not question the need to provide the American public with strong health protections through tightened smog and soot standards.

- rejected the claim that EPA consider costs when setting national air quality standards.

- left the 8-hour ozone standard in place, but stated that it "cannot be enforced."

- vacated the revised coarse particle (PM10) standards, but the old PM10 standards still apply.

- The Court asked for further briefing on several issues. On June 18, 1999, the Court ruled that the PM2.5 standard should remain in place. However, the Court will allow parties to apply for the standard to be vacated if "the presence of this standard threatens a more imminent harm". Presumably, the "harm" refers to the burden on sources complying with the regulations.

- EPA strongly disagrees with the decision. On June 28, 1999 EPA and the Department of Justice filed a petition for rehearing *en banc* asking the entire DC Circuit to reverse the decision of the panel.

Providing Americans with Cleaner Air:

- As a result of an initial interpretation of the Court's ruling, EPA believes it can continue to move forward with other vital clean air programs that will provide the American people with important health protections, including:

  - proceeding with its proposal for cleaner vehicles and cleaner gasoline.

  - ensuring the air quality monitoring program continues and the PM 2.5 monitors are put in place.

  - continuing support for voluntary "right-to-know" programs managed by states and coordinated through EPA, such as the Ozone Action Days and the air quality data submitted to EPA's Internet Ozone Mapping Site.

  - designating areas as attainment or nonattainment for the new 8-hour ozone standards.

- EPA is continuing to evaluate the impacts of this decision on, and next steps for, other clean air efforts, including the effect of the decision on areas where the 1-hour ozone standards and the old PM10 standards have been revoked.

- On May 25, 1999, in a separate case, a 3-judge panel of the same court (including the two judges who wrote the majority in the air standards case) issued an order partially staying the implementation of the EPA plan to reduce the state-to-state transport of smog (NOx SIP call), which will protect the health of millions of Americans in the eastern U.S. This is not a ruling on the merits of the plan, but a delay to allow all parties to argue their case before the court. EPA is evaluating the order, and, in the fall, will join a number of states in arguing before the court the need to move forward with these important health protections. Revised 6/28/99

THE WHITE HOUSE

Office of the Press Secretary

(Seattle, Washington)

For Immediate Release May 14, 1999

STATEMENT BY THE PRESS SECRETARY

We are deeply disappointed by the Court of Appeals' ruling today on clean air standards, particularly given the court's explicit recognition that there is a strong scientific and public health rationale for tougher air quality protections. We will continue to do everything within our power to ensure that the American people are adequately protected against smog, soot, and other harmful air pollutants. The Administration is studying the ruling closely and will decide in the near future on a specific course of action.

30-30-30

American Trucking Associations, Inc. v. USEPA,

Nos. 97-1440 and 97-1441 (D.C.Cir. October 29, 1999)

Summary of Opinions Re EPA's Request for Rehearing of May 14, 1999 Decision

General Summary

- In July 1997, EPA issued health-based air quality standards for ozone and particulate matter. In response to challenges filed by industry and others, a three-judge panel of the United States Court of Appeals for the District of Columbia issued a split opinion on May 14. The relevant portions of this opinion are summarized below.
- On June 28, 1999, EPA filed a petition for rehearing on three aspects of the May 14 decision.
  - The petition gave the original three-judge panel the opportunity to reconsider and modify portions of its May 14 decision.
  - The petition also asked the entire D.C. Circuit to rehear three issues and reverse the decision of the original panel.
  - The three aspects at issue were whether the panel erred:
    - in determining that the Act, as applied and without further clarification, represents an unconstitutional delegation of legislative authority;
    - in concluding that EPA lacks authority to implement the revised, more stringent ozone NAAQS;
    - in determining that EPA must consider alleged benefits of ozone pollution to address health risks posed by the sun's natural rays when setting an ozone NAAQS.
- On October 29, 1999, the Court responded to EPA's petition.
  - The original three-judge panel kept most of its original decision as issued on May 14, but it partially modified one aspect of its decision (see the "Ability to Enforce Ozone Standard" section below).
  - Rehearing before the entire court was denied, although the majority of voting judges voted in favor of rehearing.
  - On the key constitutional issue, of the nine judges who voted, five voted **in favor** of granting the petition for rehearing in front of the entire Court. (Two judges did not participate in the decision for unspecified reasons.)
    - -The petition for rehearing was denied, however, because the court rules require a majority of the 11 active judges to vote for rehearing (rather than a majority of the voting judges).
    - -A vigorous opinion in favor of rehearing, stated that the panel's decision on the constitutional issue was "fundamentally unsound" and went on to conclude that "the panel implicitly asserts a greater role for a reviewing court than is justified."
- The industry challengers to the July 1997 health-based air quality standards did not seek rehearing on any of the issues they lost in the May 14 decision -- including those portions of the panel's decision that upheld key aspects of the science EPA relied on and the process EPA followed in setting the standards.

Summary of Specific Issues

- **NONDELEGATION DOCTRINE:**
  - May 14 Panel Decision: In the May 14 decision, the Court held (2 to 1) that the Clean Air Act, as applied and absent further clarification, is unconstitutional because it "effects an unconstitutional delegation of legislative power."
    - The Court stated that "the factors EPA uses in determining the degree of public health concern associated with different levels of ozone and PM are reasonable."
    - However, the Court said that when EPA considers these factors for non-threshhold pollutants, "what EPA lacks is any determinate criterion for drawing lines" to determine where the standard should be set.
    - The vigorous dissent on this issue stated that the relevant Clean Air Act provision's "delegation of authority is narrower and more principled than delegations the Supreme Court and this court have upheld since [a 1935 case relied on by the majority]."
  - October 29 Panel Decision on Rehearing Request: In a split opinion reiterating its earlier views, the panel denied rehearing on this issue.
  - Request for Rehearing Before the Entire Court: Of the nine judges voting, five voted to have the entire Court rehear the case -- six votes were needed to grant rehearing. Four of these five clearly said that the panel's decision on the nondelegation doctrine should be reversed.
    - In a strongly worded opinion, three judges concluded that, "Not only did the panel depart from a half century of Supreme Court separation-of-powers jurisprudence, but in doing so, it stripped the Environmental Protection Agency of much of its ability to implement the Clean Air Act, this nation's primary means of protecting the safety of the air breathed by hundreds of millions of people."
- **ABILITY TO ENFORCE THE REVISED OZONE STANDARD**
  - May 14 Panel Decision: In the May 14 decision, the Court held pardoxically that the Clean Air Act allows EPA to revise the primary ozone standard, but stated that the revised ozone standard "cannot be enforced."
  - October 29 Panel Decision on Rehearing Request: In response to EPA's petition for rehearing, the panel modified this portion of the opinion.
    - The panel replaced language in the May 14 decision stating that the revised ozone standard "cannot be enforced" with language saying that it could be enforced "only in conformity with Subpart 2."
      - -The majority did not explain what it meant to enforce a revised ozone standard "in conformity with Subpart 2," which sets out specific requirements for enforcing the pre-existing 1-hour ozone standard.
      - -The concurring opinion states that this "leaves open the possibility that the new ozone standard can be implemented in areas that have attained the old standard."
  - The panel also changed the May 14 decision to say that Subpart 2 does not bar EPA from enforcing a revised secondary air quality standard. This replaced language that would have

precluded EPA from enforcing a revised secondary standard before an area had attained the pre-existing 1-hour standard.

- The panel also modified its rationale for not vacating the 8-hour ozone standard. It continues to allow the 8-hour standard to remain in effect because "the parties have not shown that the standard is likely to engender costly compliance activities in light of our determination that it can be enforced only in conformity with Subpart 2."

- Request for Rehearing Before the Entire Court: The petition for rehearing this issue before the entire court was denied.

- **CONSIDERATION OF UVb RADIATION**

  - May 14 Panel Decision: In addressing whether EPA should have considered alleged benefits of ground-level ozone as a shield in blocking ultraviolet (UVb) radiation, the May 14 decision held that EPA must consider whether ground-level ozone has a beneficial effect, and if so, consider such effects in assessing ozone's net effects on health.

  - October 29 Panel Decision on Rehearing Request: The petition for rehearing on this issue was denied.

  - Request for Rehearing Before the Entire Court: The petition for rehearing on this issue was denied.

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EPA430-R-99-011
November 1999
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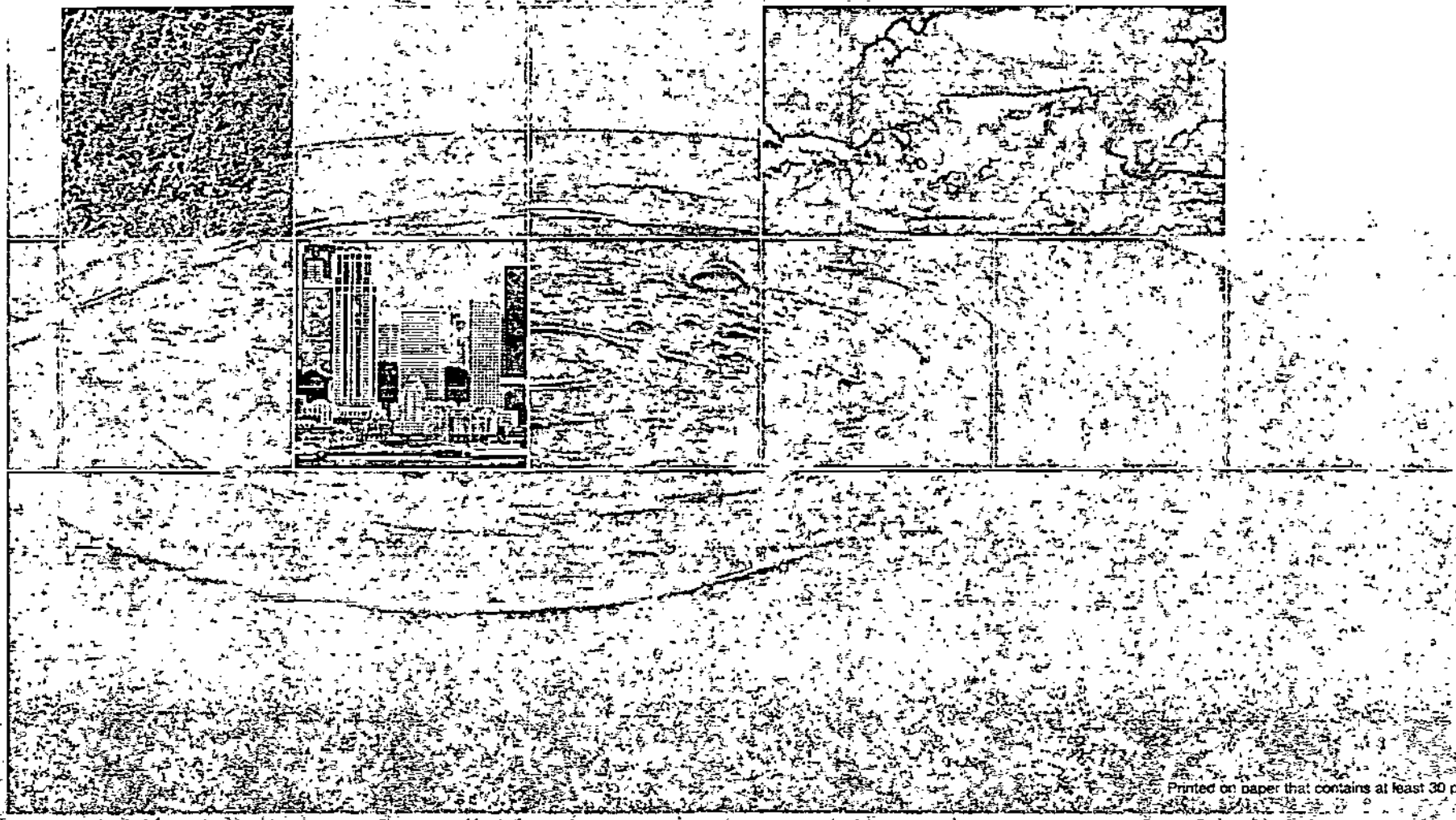
Progress Report on the EPA Acid Rain Program



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Environmental Protection
Agency

Office of Air Quality
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Research Triangle Park NC 27711

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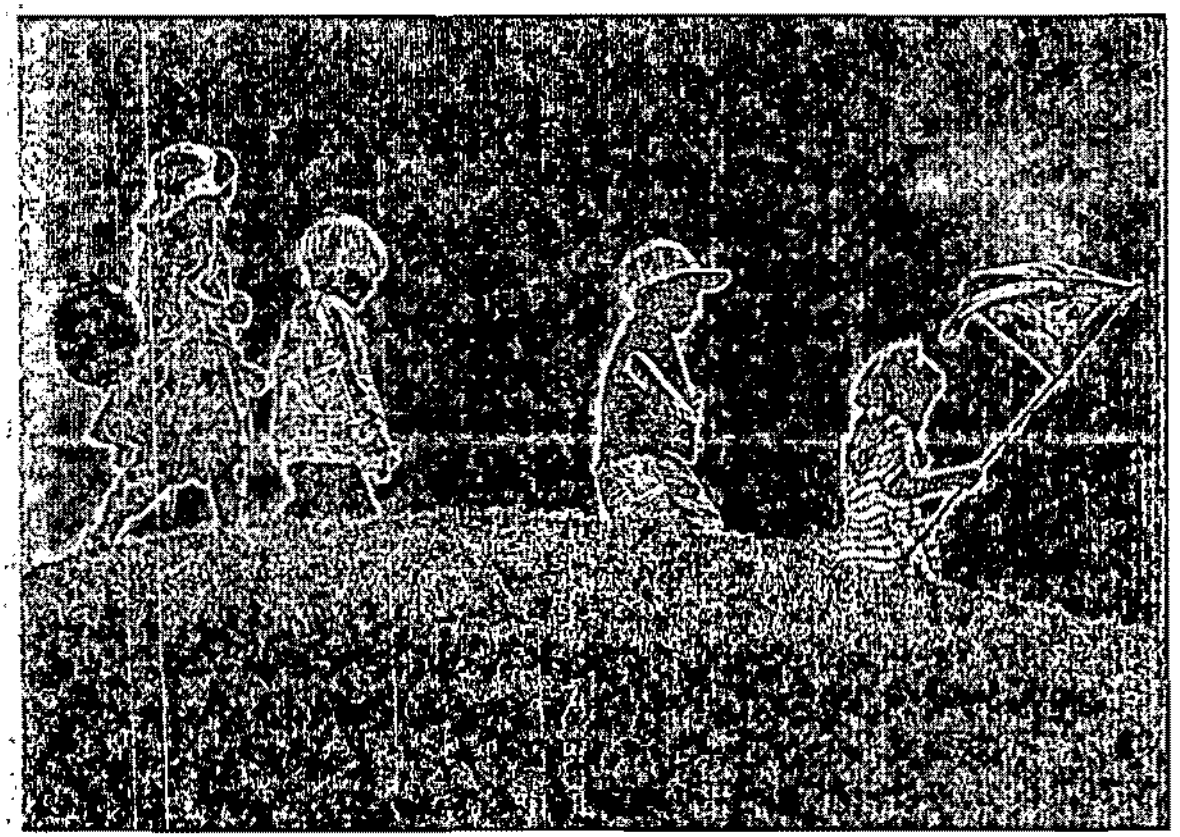
Latest Findings on National Air Quality: 1999 Status and Trends



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