SESSION VI

Diesel Engine Technologies for Emission Reduction I

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THE NORTHERN FRONT RANGE AIR QUALITY STUDY

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SUMMARY

Air pollution along Colorado's Front Range is manifested as visible haze that can range in color from grayish-white to brown. This "brown cloud," caused mainly by airborne particles, is observed most frequently during the winter, when low wind speeds and stagnant conditions accumulate pollutants from diverse sources. During the winter, the brown cloud accumulates in a shallow layer of stagnant air near the South Platte River. To understand the contribution of different pollution sources to the brown cloud, the Colorado General Assembly approved House Bill 1345 in 1995. This legislation established the Northern Front Range Air Quality Study (NFRAQS) to identify sources of air pollution along Colorado's Front Range. The study objectives were reaffirmed in the next session of the General Assembly with passage of HB 96-1179, which expanded the scope of the Study. Nearly 40 government, industry, and research organizations provided funding during the program.

The NFRAQS Technical Advisory Panel (TAP) established three policy-relevant objectives for the Study:

- Identify the sources of directly emitted $PM_{2.5}$ (airborne particles less than 2.5 micrometers in diameter)
- Determine the role of gas-phase nitrogen oxides, sulfur dioxide, and ammonia in forming ammonium nitrate and ammonium sulfate constituents of $PM_{2.5}$
- Identify the sources responsible for forming ammonium nitrate and ammonium sulfate $PM_{2.5}$.

As the legislation specified, Colorado State University managed the NFRAQS subject to concurrence on plans, selection of research groups and expenditures by the TAP. Fifteen research groups from throughout the United States participated in the three-year study. The NFRAQS program measured $PM_{2.5}$, which causes Denver's brown cloud. Scientists measured ambient meteorology, visibility, and air quality at several locations in the metro Denver area, north to Fort Collins, and along the South Platte River basin northeast to Fort Morgan during three separate periods – Winter 1996, Summer 1996, and Winter 1997.

KEY FINDINGS

The NFRAQS was designed to provide information to policy makers in Colorado who are responsible for managing air quality. The following key findings, based mainly on episodic observations made in Winter 1997, are organized by the Study's policy-relevant objectives.

Objective 1 – Identify the sources or contributors to $PM_{2.5}$ in the NFRAQS region

During the winter episodes of highest $PM_{2.5}$ concentrations in the metro Denver area, receptor modeling estimated that the most important sources or contributors to $PM_{2.5}$ were:

- Gasoline vehicle exhaust, 30%
- Diesel exhaust, 10%
- Dust and debris, 15%
- Wood smoke, 5%
- Meat cooking, 5%
- Particulate ammonium nitrate (formed in the atmosphere from a variety of sources), 25%

- Particulate ammonium sulfate (formed in the atmosphere from a variety of sources), 10%

During the episodes studied, the direct $PM_{2.5}$ contribution from gasoline-powered vehicles and engines was three times the direct $PM_{2.5}$ contribution from diesel-powered vehicles and engines. In contrast, in current emission inventories diesel vehicles are projected to produce more $PM_{2.5}$ emissions than gasoline-powered vehicles. High emitting or smoking gasoline-powered vehicles, which comprise a small fraction of the in-use vehicle fleet, produced nearly one-half of the gasoline exhaust particles. The diesel exhaust particles come from trucks, locomotives, construction equipment and other sources. $PM_{2.5}$ directly emitted from diesel vehicles and engines was one-third of that from gasoline vehicles and engines, even though diesel-powered vehicles comprise five percent of the regional vehicle miles traveled. Fine particles from road debris and dust, construction activities, and wind-blown sand contributed 16% of the total $PM_{2.5}$, an amount much lower than current emission estimates.

Particulate ammonium nitrate and ammonium sulfate are formed in the atmosphere from gas-phase emissions of ammonia, nitrogen oxides, and sulfur dioxide. These are called secondary particles because they are not emitted directly. Their sources are discussed in Objectives 2 and 3.

***Objective 2** – Determine the role of gas-phase nitrogen oxides, sulfur dioxide, and ammonia in the formation of ammonium nitrate and ammonium sulfate $PM_{2.5}$ particles*

The NFRAQS region is ammonia-rich. Agricultural operations produced the most of the ammonia in the Northern Front Range. Current ammonia emissions would have to be reduced 50% to achieve a 15% reduction in particulate ammonium nitrate levels. Further reductions in ammonia emissions would provide proportional decreases in ammonium nitrate concentrations.

***Objective 3** – Identify the sources responsible for the formation of ammonium nitrate and ammonium sulfate $PM_{2.5}$ particles*

Because of limitations in funding, NFRAQS scientists were unable to completely apportion the contributing sources to ammonium nitrate and ammonium sulfate $PM_{2.5}$ particles. Atmospheric models also have not been adequately developed to model the atmospheric formation of particles from their sources. However, the Study found that the majority of nitrogen oxides, and therefore, particulate ammonium nitrate, are produced by mobile sources. The formation of $PM_{2.5}$ nitrate particles is not a linear process. Reductions of nitrogen oxide emissions, the precursor to particulate nitrate, would result in less-than-proportional reductions in $PM_{2.5}$ ammonium nitrate particles. Three-fourths of the sulfur dioxide emissions, a precursor to particulate ammonium sulfate, are produced by coal-fired power stations.

RELATED FINDINGS

- The 24-hour or 1-hour federal air quality standards for particulate matter were not exceeded at any time during the Study.
- $PM_{2.5}$ episode concentrations have decreased substantially during the last twenty years. $PM_{2.5}$ concentrations during the NFRAQS were less than half those reported in 1978.

In the metropolitan Denver area:

- During the winter, emissions caused by mobile sources (exhaust from cars, trucks, construction equipment and locomotives, and dust from roads and construction activities) produced at least 75% of the $PM_{2.5}$.
- The Denver summer average $PM_{2.5}$ concentration during pollution episodes was 85% as high as during the winter, but its composition was different. Particulate carbon species were dominant (44% of the total). Dust was more important in the summer than in the winter.
- Fossil fuel combustion produced 75% of the particulate carbon species in the winter and 50% of the particulate carbon species in the summer.
- During the winter episodes studied, wood-burning emissions contributed 5% to $PM_{2.5}$. Meat cooking contributed 4% to the total $PM_{2.5}$. About 10 years ago, wintertime wood burning and meat cooking contributed about 35% of the observed $PM_{2.5}$ levels, demonstrating the benefits of the Colorado Department of Public Health and Environment's (CDPHE) program on wood burning restrictions.
- Less $PM_{2.5}$ ammonium nitrate occurred during the summer (8% of the total) than in the winter (25% of the total), because it evaporates at warm temperatures.

- Ammonium sulfate concentrations were nearly identical in Denver in both summer and winter (10-15% of the total).

In the northern, non-urban locations:

- Although air quality generally was worse in Denver than in other areas, the NFRAQS found that during pollution episodes, $PM_{2.5}$ concentrations sometimes were as high in rural locations northeast of Denver along the South Platte River as they were in downtown Denver. The Study did not determine whether the $PM_{2.5}$ was formed at or near those sites or whether it was transported from Denver, Boulder, Fort Collins, Greeley, or other locations.
- At the rural, northern NFRAQS sampling sites, the average composition of $PM_{2.5}$ during Winter 1997 pollution episodes was different from that in the urban locations, with a smaller fraction from gasoline (5-16%) and diesel emissions (3-7%), and larger portions of particulate ammonium nitrate (34-40%) and ammonium sulfate (11-14%), with 6-27% from dust.

The NFRAQS program began in the fall of 1995 and focused on policy-relevant topics. This summary describes how the scientists designed and conducted the study and it presents the most important NFRAQS findings from technical reports completed through September 1998. See the NFRAQS web site (http://nfraqs.cira.colostate.edu) for all data and technical reports.

SCOPE OF THE NFRAQS

During the three-year program, the NFRAQS scientists conducted comprehensive air quality and meteorological measurements, along with a series of concurrent measurements from the most important pollution sources expected to contribute to $PM_{2.5}$ concentrations during the winter and summer along Colorado's Northern Front Range. Fifteen research organizations from throughout the U.S. took part in the Study and they acquired millions of air quality and meteorological data points for subsequent analysis. The scientists constructed specialized equipment to measure direct emissions from meat cooking and wood burning. They also used state-of-the-art sampling equipment to measure emissions from nearly 225 gasoline and diesel-powered vehicles. They deployed sophisticated meteorological measurement equipment to characterize air motions and mixing, humidity, and temperature throughout the lower troposphere. The CDPHE provided daily forecasts during the air quality measurement periods, so that sampling could be conducted during episodes of high $PM_{2.5}$ concentrations. The CDPHE also audited air quality measurement sites to determine if measurements were being conducted in accordance with specifications for the Study.

The NFRAQS was carried out in three phases, designated as Winter 96, Summer 96 and Winter 97. Phase I, the Winter 96 study, a pilot project, ran from January 16 to February 29, 1996 when scientists collected samples at Welby in northeast metropolitan Denver (Figure 1). The Winter 96 study provided the opportunity to test sampling equipment for later use in Phases II and III and to gather baseline winter data for comparison with the major study in the winter of 1997. Scientists conducted Phase II, in the summer, from July 16 to August 31, 1996 at Welby, Golden, east of Longmont, and Fort Collins. Phase II provided summer $PM_{2.5}$ samples for comparing the $PM_{2.5}$ characteristics with Winter 96 and Winter 97 data. In Phase III, Winter 97 and the major phase of the NFRAQS, scientists collected samples from December 16, 1996 to February 9, 1997 at three "core" sites (Welby, Brighton, and Evans), and six "satellite" sites (Chatfield Reservoir, Highlands Ranch, downtown Denver, east of Longmont, Fort Collins, and Masters; Figure 1). At each location scientists obtained air quality and meteorological data, and, at some locations, 35 mm slides and time-lapse video recordings. The scientists and QCC members selected from many options all measurement methods and the location of the measurement sites that would provide data needed to achieve the Study's objectives.

The NFRAQS emphasized simultaneous collection of $PM_{2.5}$ from pollution sources and ambient air quality samples. The scientists analyzed samples for mass, chemical elements, ions, organic and elemental carbon, many organic compounds, and carbon-14 isotopic abundances. They organized the data, entered it into a documented database (available at the NFRAQS web site), and conducted tests to determine data validity, precision, and accuracy. Where possible, they evaluated sensitivity of conclusions to the range of conditions the data represent, and provided qualifications on the adequacy of the measurements to address each of the Study's objectives.

THE EMISSIONS INVENTORY

Emission inventories often provide a frame of reference for development of air quality management strategies, because they estimate emissions from different sources. Thus, the inventory must be accurate so policy makers can plan effective programs to reduce emissions. HB95-1345 called for a determination of the sources of air pollution in the NFRAQS region. Table 1, provided by the Regional Air Quality Council, lists pollutants and their sources for the six-county metro Denver area using methods developed prior to this study. The motor vehicle emission estimates were derived from emission models and factors developed from studies conducted as part of the NFRAQS by the CDPHE and the Colorado School of Mines, along with regional travel estimates.

$PM_{2.5}$ emissions listed in the table are directly emitted particles (called primary particles); they are different from $PM_{2.5}$ particles formed in the atmosphere from gas-phase precursor compounds (called secondary particles). Seventy-seven percent of the directly emitted PM_{10} (all particles having aerodynamic diameters up to 10 μm, including $PM_{2.5}$) is from road dust and sand. Nitrogen oxides (NO_x), sulfur dioxide (SO_2), and ammonia (NH_3) are precursors to the formation of secondary $PM_{2.5}$ ammonium nitrate and ammonium sulfate in the atmosphere. NO_x and gas-phase volatile organic compounds (VOCs) form ozone, and under summertime conditions in the Denver area, VOCs also form secondary organic carbon particles. Carbon monoxide (CO) does not contribute to $PM_{2.5}$ or impairment of visibility.

Table 1 shows what source types are thought to contribute to the each of the pollutants. Wood burning has been reduced substantially during the past ten years because of the CDPHE's wood burning restriction program, and it produces only 7% of the directly-emitted $PM_{2.5}$ (Table 1). Industrial sources comprise those sources having permits from the Colorado Air Pollution Control Division, such as refineries, print shops, auto body shops, and natural gas compressors. Area sources include vapors from gasoline transfer, paints, degreasers, solvents, and other sources.

According to this inventory, mobile sources produce 58% of the NO_x, 53% of the VOC and 94% of the CO, while power plants produce 73% of the SO_2 emissions. Estimates of ammonia (NH_3) emissions, provided separately by the CDPHE, are for areas outside of the six-county metro Denver area. For the entire NFRAQS region, the CDPHE estimates a total of 114 tons/day of ammonia emissions, of which agricultural operations produce 97 tons, or 85%. Humans produce the remaining 15%.

Emission inventories are relatively accurate for SO_2 and NO_x, the precursors of secondary $PM_{2.5}$ particles. In other parts of the country VOC emissions from mobile sources are currently underestimated by a factor of two or more. In the NFRAQS, scientists also observed substantial

Pollution Source Type	Pollutant and Daily Emissions, Winter 1995					
	$PM_{2.5}$, 27 tons	PM_{10}, 102 tons	Nitrogen Oxides, 346 tons	Sulfur Dioxide, 85 tons	Volatile Organic Compounds, 336 tons	Carbon Monoxide, 1578 tons
Gasoline Vehicle Exhaust	6 %	2 %	40 %	4 %	47 %	85 %
Smoking Vehicle Exhaust	<1 %	<1 %				
On-Road Diesel Exhaust	18 %	5 %	10 %	2 %	2 %	2 %
Off-Road Diesel Exhaust	7 %	2 %	8 %	2 %	4 %	7 %
Road Dust & Sand	27 %	50 %				
Unpaved Road Dust	15 %	28 %				
Construction Dust	1 %	2 %				
Wood Burning	7 %	2 %				
Coal-fired Power Stations	3 %	1 %	19 %	73 %		
Restaurant Cooking	5 %	1 %				
Natural Gas	2 %	<1 %	8 %	0 %		
Industrial Sources	10 %	8 %	14 %	20 %	10 %	1 %
Area Sources			<1 %	0 %	27 %	5 %
Biogenic Sources			1 %	0 %	9 %	0 %

Table 1. Direct emissions in percentages from pollution source types in the six-county metro Denver area, winter 1995, as reported by the Regional Air Quality Council ("Blueprint for Clean Air, Phase II Subcommittee Reports," April 24, 1998). Blanks indicate that no value was provided for a given source type and pollutant category. Values given with each pollutant are in tons per day. Total percentages for each pollutant may not equal 100 percent due to rounding.

differences between the inventory estimates for $PM_{2.5}$ and the receptor modeling estimates derived from the source and ambient $PM_{2.5}$ data collected during the Study. Additional research is needed to explain this difference.

RECOMMENDED FUTURE WORK

Budget and time constraints did not permit complete analysis of all the data collected in the NFRAQS. The NFRAQS scientists recommend the following future projects:

Emission inventory verification work is needed to understand:

- Discrepancies between observed and estimated contributions to $PM_{2.5}$ from gasoline and diesel engines.
- The relative importance of smoking vehicles, high emitters (not having a visible plume), and "puffing" vehicles (those that emit a puff of smoke when starting cold or when accelerating) to the NFRAQS gasoline vehicle $PM_{2.5}$ apportionment.
- In-use diesel fleet emissions and the influence of cold temperatures on their emission rates.
- Differences between NFRAQS results and inventory estimates of the contribution of dust to $PM_{2.5}$.
- Limited observations in different parts of Denver suggest that as little as 0.1% or as much as 2.5% of the in-use, light-duty vehicle fleet emits visible particles. Because smoking vehicles have $PM_{2.5}$ emission rates more than 100 times higher than those of new technology vehicles, these observations should be verified. The NFRAQS observation of the significance of high-emitting and smoking vehicles to the "brown cloud" should be investigated.
- Analysis of individual NFRAQS episodes should be performed, to provide additional insight regarding the dynamics of $PM_{2.5}$ formation and the importance of different pollutant source types, such as ground level vs. elevated sources, to observed $PM_{2.5}$ concentrations.
- The reasons for and sources of the relatively high $PM_{2.5}$ concentrations along the South Platte River to the north and east of Denver should be investigated. These concentrations may be confined to the high humidity, stagnant conditions near the River. The Study did not determine the sources of the secondary ammonium nitrate and sulfate particles at the rural sampling sites, so it is not clear whether the NO_x and SO_2 precursors leading to particle formation were produced nearby or whether they were transported from the urban areas.
- The relationships between $PM_{2.5}$ concentrations and visual air quality at NFRAQS sampling sites should be determined, using the high quality chemical and optical data collected during the Study periods.

ACKNOWLEDGMENTS

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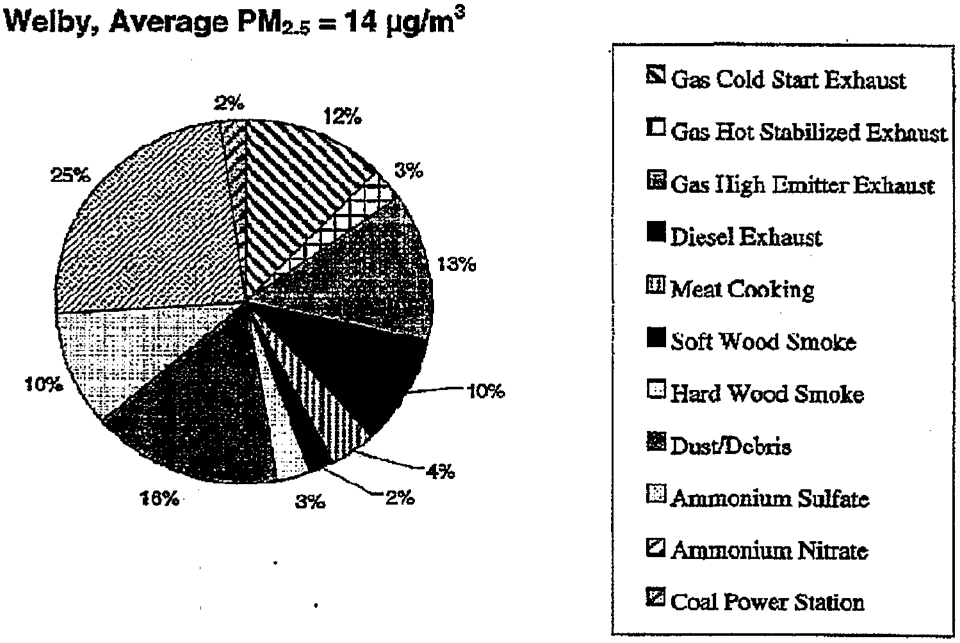

Figure 1. Average source and chemical contributions to the 24-hour average PM$_{2.5}$ concentration at Welby during the Winter 1997 NFRAQS episode periods, using receptor modeling with detailed speciation. Sources of ammonium nitrate and ammonium sulfate were not identified. Average concentrations during the entire winter season are lower than those shown. The day-to-day variability in apportionments is 15-30% with the exception of wood burning, which has greater variation due to burning restrictions. The uncertainty in the apportionments for any single sampling period is about 15-30%.

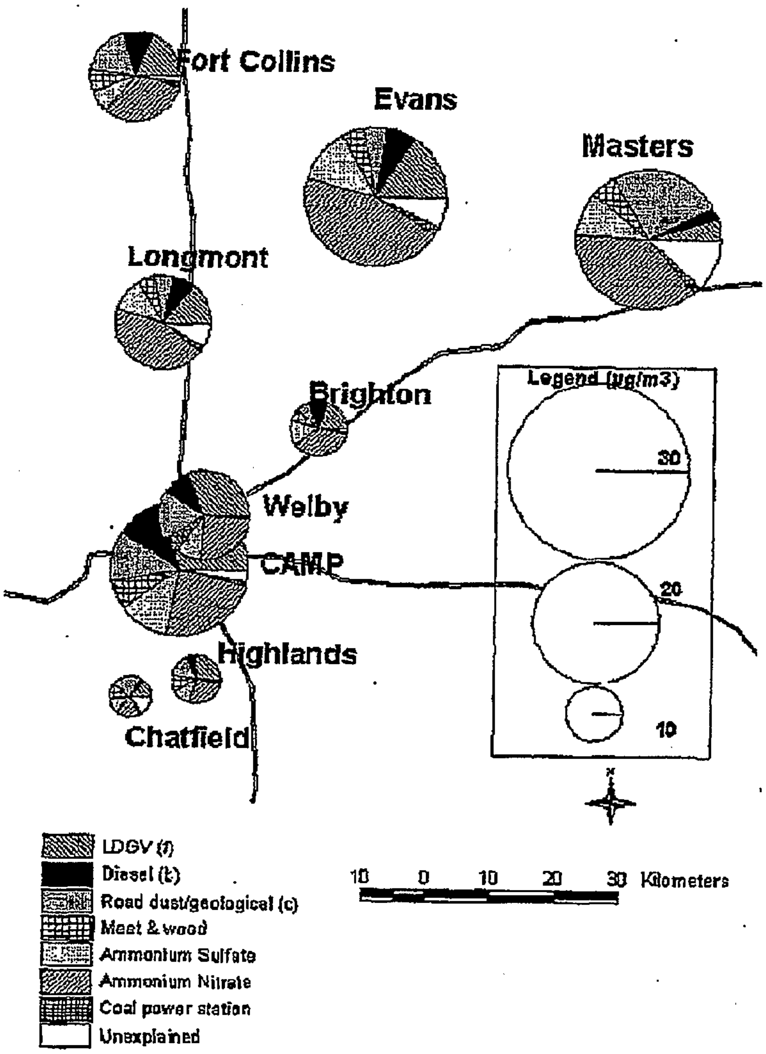

Figure 2. 24-hour average source and chemical contributions to PM$_{2.5}$ at all monitoring sites during the Winter 1997 NFRAQS episode periods, using detailed speciation with receptor modeling. Sources of ammonium nitrate and ammonium sulfate were not identified. Average concentrations during the entire winter season are lower than those shown. The day-to-day variability in apportionments is 15-30%, and the uncertainty in apportionments for any single sampling period is about 15-30%.

AN EXHAUST AFTERTREATMENT STRATEGY FOR OPTIMIZING DIESEL EMISSIONS REDUCTION, PERFORMANCE, FUEL AND COST

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ABSTRACT

Many technologies under development within the diesel engine industry seek to reduce or eliminate key pollutants, improve engine performance, save fuel or reduce costs. These technologies include *pre-combustion* elements such as air and fuel modifications, *in-cylinder combustion* elements such as combustion chamber and valve design and fuel injection, and *post-combustion* elements such as exhaust aftertreatment i.e. thermal oxidation, particulate and NOx traps, catalysts, and non-thermal plasmas. Most of these technologies are being developed as discrete systems and often face frustrating "trade-offs" such as emission reductions causing engine performance degradation and/or an fuel penalties or the common PM/NOx dilemma. This paper will discuss an approach aimed at eliminating these "trade-offs" through the combination of discreet technologies to form integrated and optimized systems for emission reduction.

The paper will present the business model of Ceryx Inc. a technology integrator and will present a unique relationship between Ceryx, Thermatrix, and Southwest Research Institute which has resulted in the integration of technologies for diesel emission reduction. Finally, the paper will focus on an integrated exhaust aftertreatment strategy, the four-way converter, which combines several key technologies to simultaneously reduce particulate matter (PM), unburned hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx), while maintaining engine performance, and minimizing fuel and capital costs.

INTRODUCTION

Beginning in the 1970's, diesel engine manufacturers have developed technological approaches in response to increasingly stringent air quality regulations. The characteristics and performance requirements of heavy-duty diesel engines, however, have prevented them from achieving emission levels commensurate with light-duty gasoline vehicles. Despite the fact that diesel engines provide significant advantages in fuel efficiency, reliability and durability, control of PM and NO_x emissions have presented a considerable challenge. This paper addresses the challenges faced by the diesel industry and offers an integrated, systems-level approach to technology development in answer to those challenges. The following slides were presented at the DEER 1998 conference and will be discussed in each subsequent section of this paper.

Poor air quality represents a serious threat to the health and quality of life of people across the globe, as well as increasing the burden on the U.S. and international economy. These threats exist despite progress being made at many local, state and federal levels to curb the growing pollution problem due to increased industrialization and the expansion of motor vehicle usage. Many approaches have been developed over the last decade to combat pollutants [primarily oxides of nitrogen (NO_x), hydrocarbons (HC), particulate matter (PM) and carbon monoxide (CO)] contributed by mobile sources. The paper will introduce the concept of an integrated four way converter device developed to simultaneously reduce the four key pollutants attributable to diesel engines: PM, HC, CO and NOx.

THE DIESEL CHALLENGE

- The diesel will continue to dominate globally due to its high efficiency, long service life and commercial viability
- While only 4% of all motor vehicles, diesels account for 40% of NOx and 75% of PM

Slide 1. The Importance of the Diesel Engine

The diesel engine has enjoyed worldwide dominance in stationary and mobile markets, given the fact that it is the most efficient prime mover available. Due to increased interest in the diesel as a means to reduce global warming, renewed focus has been placed on reductions in particulate matter and oxides of nitrogen. Many technologies currently under development within the diesel engine industry seek to reduce or eliminate these key pollutants, yet have difficulty in simultaneously improving engine performance, saving fuel or reducing costs, all four of which are critical elements to successful technology introduction.

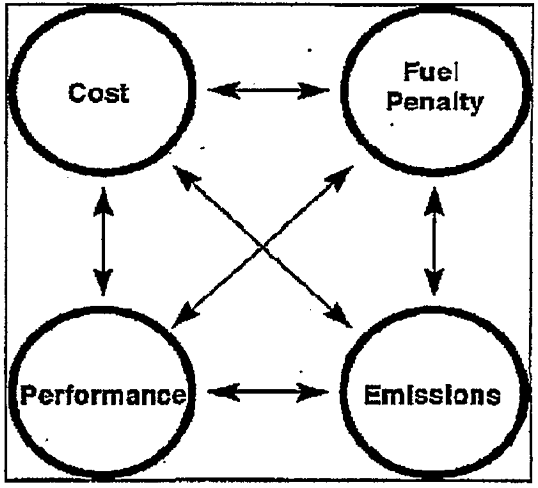
Key Criteria for New Diesel Engine Technology R&D Plan for the Office of Advanced Automotive Technologies

The National Research Council's Review of the Research and Development Plan for the Office of Advanced Automotive Technologies recommended the plan "should ensure that its program includes a major engineering effort to integrate particulate traps, reducing and oxidizing catalysts, plasmas, and fuel additives, as well as advanced materials, sensors, and controls, into a complete after-treatment system to control emissions."

Slide 2. Technology R&D Pla
for the OAAT

For too long it has been hoped that a 'silver bullet' solution to the emissions problems will emerge, be it advanced fuels, engine design, or after-treatment. A more realistic approach may be to look at the integration of technologies.

Since the invention of the compression ignition engine by Diesel in Germany and Stewart in England in the late 19th Century, progress towards improvement has been steady and on-going. The four primary factors motivating technical advancement of the CI engine are fuel economy, engine performance, emissions and cost. In the late 20th Century, these four factors continue to motivate and guide technological improvement. More recently, issues regarding emissions have become increasingly important with legislation forcing the emission factor to the forefront. Concerns over global warming and the drive to develop ultra-high mileage vehicles have led to renewed interest in the diesel.



Slide 3. Key Criteria for Diesel Engine Technology Selection

COST

The cost of new technology must always be addressed in a free market economy. In evaluating new technologies, the capital cost of the equipment, as well as operating costs including maintenance and fuel penalty must be calculated in the overall life-cycle costs of new equipment. All things being equal, the lower cost technology will always be preferred. However, different market sectors are affected differently by cost structure.

Each market sector has different price elasticities based upon such factors as air quality regulations, political environment, economic conditions, fuel and technology subsidies and competitors pricing strategies. The public transit sector, through the Environmental Protection Agency's Urban Bus Rebuild Program established to reduce particulate matter emissions from urban buses by 25%, and then later to 0.1 g/bhp-hr (0.13 g/kW-hr), has an artificial price ceiling that was established by the EPA, engine manufacturers and transit authorities at $7940 (1992 dollars).

This is a case of the cost criteria driving the technology development. Other market sectors, such as mining, are less sensitive to cost, and more sensitive to health and safety issues as they relate to emissions reduction. On-highway fleet owners and operators are highly sensitive to cost, as evidenced by their extreme reluctance to accept alternative fuel strategies and more complex and costly aftertreatment systems.

FUEL PENALTY

Fuel penalty is another cost factor which must be carefully examined when evaluating technologies. For most commercial operations using diesel engines as the prime mover, the fuel cost accounts for a majority of the life cycle costs associated with operating the engine. For many trucking fleets, fuel accounts for over 75% of total O&M costs. Many market sectors such as trucks, buses, and construction are highly dependent on low O&M costs, and are very sensitive to fuel pricing and engine maintenance costs. On the other hand, industries such as stand-by generators and mining applications, are less sensitive to fuel economy penalties associated with emission reduction strategies.

PERFORMANCE

Emissions reduction technologies must not significantly detract from engine performance defined as acceleration, peak torque, noise, vibration, and response. Exhaust aftertreatment technologies that create significant backpressure degrade engine performance significantly and can encounter barriers to introduction based on this criterion alone. Many diesel industry sectors rely heavily upon the performance of the diesel and cannot accept decreased performance as a trade-off for emission reductions.

Many state and local pollution reduction strategies have met with failure due to owners and operators disabling systems to increase their engine's performance. This is particularly true in areas where line-haul trucks encounter steep grades and higher altitudes. In the early 1990's, the CARB targeted several of the overpasses leading up to Lake Tahoe for its heavy-duty Vehicle Inspection Program, as many of the trucks were disconnecting aneroid valves to increase engine performance over the grade. While CARB viewed this as a violation of the smoking truck ordinance, the truckers were making economic decisions based on transport deadlines.

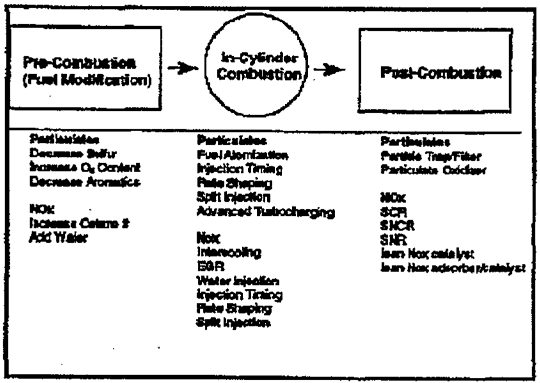
EMISSIONS

Given its relatively low initial cost, high efficiency (low fuel penalty), and excellent performance, the diesel engine has dominated most prime mover markets. However, the diesel's dominance is threatened by both the real and perceived impacts of its harmful pollutant emissions. In order to reduce emissions, at least one if not all three of the preceding criteria of cost, fuel penalty, and performance must be compromised. Clearly, the most attractive emission control technologies are those which offer the highest level of control while minimizing the deleterious effects on the other criteria.

Two opposing trends are also currently taking place with regard to the future growth of diesel vehicles worldwide. On one side, environmental agencies are focusing on smaller particles and ozone levels as contributing factors to decreased health and air quality. This translates to tighter control of fine diesel particles and oxides of nitrogen. Based on a series of studies in recent years, particulate standards have added two new $PM_{2.5}$ standards set at 15 $\mu g/m^3$ annual mean, and 65 $\mu g/m^3$, 24 hour average, while retaining the current annual primary PM_{10} standard of 50 $\mu g/m^3$.

As various countries focus increasing attention on particles less than 2.5 microns in size, the diesel becomes a larger target, as the majority of all diesel particles are in this range. On the other side, concerns over increased CO_2 and global warming have increased focus on lower carbon dioxide levels, where diesel engines are superior. The U.S. Partnership for a New Generation of Vehicles (PNGV) has identified the diesel engine as the powerplant with the highest potential to achieve these overall emission reductions.

Slide 4 shows an over-simplified diagram of the diesel engine, breaking emission control technologies into three primary components: pre-combustion, in-cylinder combustion, and post combustion. Pre-combustion is primarily relegated the flows entering the engine, namely the fuel and air. In-cylinder combustion is related to the geometry and process design of the engine the influences the liberation of energy and the formation and destruction of the pollutants. Post-combustion is defined as technologies to treat exhaust gases leaving the cylinder.



Pre-Combustion (Fuel Modification)

In-Cylinder Combustion

Post-Combustion

Particulates
Decrease Sulfur
Increase O_2 Content
Decrease Aromatics

NOx
Increase Cetane #
Add Water

Particulates
Fuel Atomization
Injection Timing
Rate Shaping
Split Injection
Advanced Turbocharging

Nox
Intercooling
EGR
Water Injection
Injection Timing
Rate Shaping
Split Injection

Particulates
Particle Trap/Filter
Particulate Oxidizer

NOx
SCR
SNCR
SNR
lean Nox catalyst
lean Nox adsorber/catalyst

Slide 4. Pre, In-Cylinder, and Post Combustion Technologies for Diesel Engine Emission Reduction

Internal combustion engine operation can be divided into three categories: pre-combustion, in-cylinder combustion and post-combustion. The pre-combustion phase involves such elements as fuel stock, combustion chamber design, compression ratio, injector system and others. The in-cylinder combustion phase involves parameters such as fuel metering, mixture and composition, the air/fuel ratio, uniform cylinder distribution, presence or absence of exhaust gas recirculation, valve timing, scavenging, fuel mass, volume and temperature. The post-combustion phase includes exhaust gas aftertreatment devices such as thermal afterburners, oxidation and reduction catalysts, particulate traps, and non-thermal plasmas.

Moderate control of NO_x (8 g/kWhr or 6 g/bhphr) and PM (0.7 g/kWhr or 0.5 g/bhphr) require further optimization of the overall combustion system. While traditional approaches such as variable fuel-injection timing, high pressure fuel injection and charge air cooling are suitable approaches, it is a combination of the pre, in-cylinder, and post-combustion elements of the engine that will ultimately correspond to U.S. federal emission standards for PM and NO_x. This is particularly true for PM, with tighter U.S. standards (0.13 g/kWhr or 0.10 g/bhphr) that became effective in 1994. Despite the requirement not to further limit PM in light of the NO_x requirements, in March of 1993 the EPA (Environmental Protection Agency) published a ruling reducing PM to 0.05 g/bhphr. In 1995 the EPA, California Air Resources Board (CARB) and automotive engine industry signed a Statement of Principles outlining their joint understanding of the actions required to meet a 2 g/bhphr NO_x limit by year 2004. This standard is expected to tighten once again upon further technological developments. In the U.S., urban buses are currently required to meet a 0.1 g/bhphr (0.13 g/kWhr) PM standard under certification standards set by the EPA. And the recent settlement between the EPA and seven major diesel engine manufacturers looks towards developing technologies aimed at meeting both PM and NOx standards.

CERYX

Ceryx Mission

- Integrate Pre-, In-Cylinder, and Post-Combustion Engine Technologies in a "Systems-Level" Cost-Effective Approach to achieve Emissions Reduction, Engine Performance and Fuel Economy.
- Example of the Integration Strategy: Proprietary 4-Way Converter.
- Example of Innovative Collaboration: Ceryx, Thermatrix and Southwest Research Institute teaming to win $1.65M 1998 NIST-ATP award.

Slide 5. The Ceryx Mission

Ceryx has established a mission of effectively integrating all of the elements of the diesel engine in a "systems-level" approach in which the positive elements of various technologies can be combined and integrated to enhance the effectiveness of each discrete system. The first example of this approach has been the proprietary four-way converter developed by the company, in conjunction with two key collaboration partners: Thermatrix Inc. of San Jose, California and Southwest Research Institute of San Antonio, Texas.

THERMATRIX

Thermatrix Background

- TMX formed in 1992
- Leading flameless industrial technology
- Over 70 commercial installations
- 60+ employees; Offices in CA, TN, UK
- IPO in 1996
- 12 US Patents; Many Pending
- TMX Diesel Systems formed in 1998

Slide 6. Thermatrix Background

Thermatrix is an industrial pollution control company that has successfully commercialized its proprietary flameless thermal oxidation (FTO) technology, with over 70 installations worldwide. The proprietary FTO technology is protected by more than 12 US Patents with many additional patents pending.

FLAMELESS THERMAL OXIDATION

Flameless Thermal Oxidation, the core of Thermatrix' proprietary technology, is described as a self-sustaining exothermic reaction stabilized within the void fraction of a porous inert medium (PIM). By definition, the PIM is non-catalytic, i.e. surface chemistry does not play a role in promoting or retarding the rates or activation energies of chemical reactions within the system. Unlike a catalyst, the non-catalytic media is not prone to poisoning and deactivation due to contaminants, or damage from over temperature operation.

Slide 7. Schematic of the Thermatrix Recuperated Flameless Thermal Oxidizer

A key feature of FTO is its operating temperature. The temperature for the FTO chemistry is between 800 and 1000 °C, which is significantly lower than the lower temperature limit of flammability, yet significantly higher than catalyst assisted combustion, which takes place in the temperature range of 200-600 °C. A key advantage of the relatively low FTO temperature is that little or no oxides of nitrogen are produced.

Recent development activity has demonstrated the applicability of the FTO technology towards the treatment of diesel engine emissions, specifically, the oxidation of particulate matter. Proof of concept and prototype testing has shown that the FTO technology is a feasible technology for post combustion treatment of diesel engine emissions, and that the technology shows significant advantages over competitive technologies.

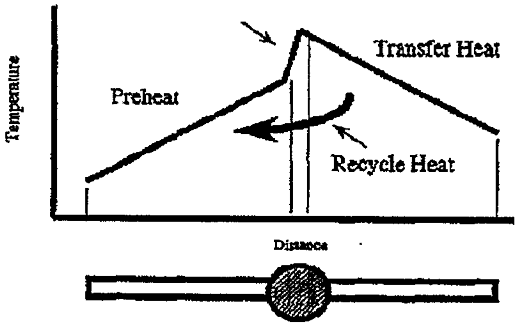
The primary competitive technology for diesel engine particulate matter emissions reductions is the diesel particulate filter (DPF). Unlike the DPF, the FTO technology does not trap particulate and therefore is not subject to plugging, which can cause high engine backpressure leading to engine performance degradation.

The enthalpy, or heating value of the exhaust stream from reciprocating engines is typically too low to fuel a self-sustaining reaction wave in an FTO; therefore additional energy, in the form of fuel or electric heating, must be added to the system. In order to minimize this addition of fuel to the system, heat recovery is employed in the form of a recuperator. The role of a recuperator is to transfer heat from a hotter exiting gas stream to the colder inlet gas stream. Slide 6 shows a schematic of a recuperative oxidizer, which forms the basis of the chemical reactor platform.

Slide 8 shows the profile of temperature versus distance, or location in the recuperative oxidizer. The profile consists of three primary regions: a preheat zone, a reaction zone, and a heat transfer/cool down zone.

FTO RESULTS

A prototype FTO system was tested on a 12 liter heavy duty truck engine certified to meet the 1996 EURO-II standards. The engine was coupled to an eddy current dynamometer and fully instrumented for steady-state mode testing. Propane was injected between the engine turbo charger exit and the inlet to the oxidizer in order to increase the exhaust gas temperature upon exothermic reaction within the oxidizer.

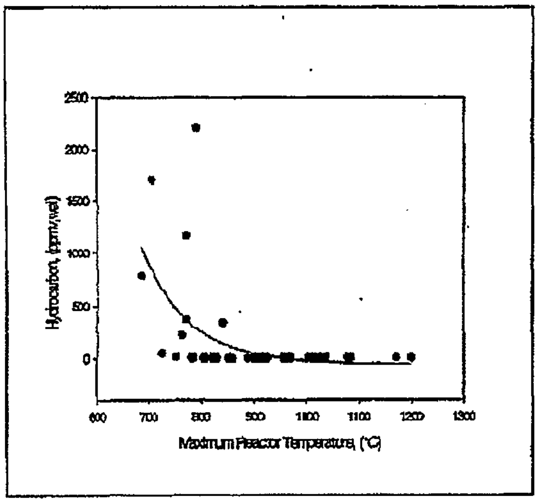


Slide 8. Reaction Zones

Unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx) and oxygen (O_2) were measured with standards instrumentation using a heated sampling valve and heat traced sample line. Particulate Matter (PM) was measured with an automated version of the AVL smoke meter which measures particulate filter loadings and reports them in Filter Smoke Number (FSN) units.

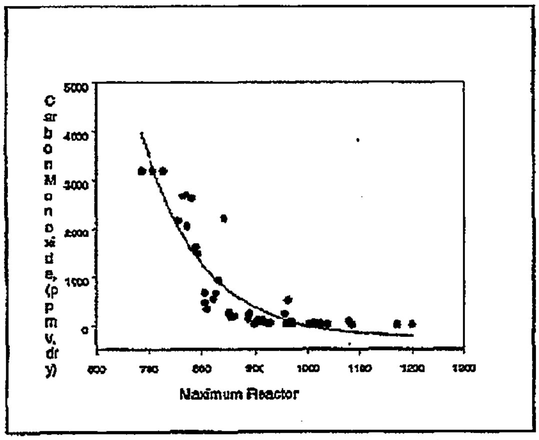
Throughout the testing, the engine speed and load were varied according to the 13-mode European test cycle. The data plotted in the following slides represents test results from a number of individual mode points. Due to proprietary nature of the work, the authors chose not to reveal mode specific data.

Slide 9 shows the HC emissions plotted against the maximum FTO reactor temperature. The results show near complete destruction of HC at temperatures above about 900 °C, and shows the emissions of unburned hydrocarbons decrease as a function of temperature. The lower temperature limit of FTO operations is somewhat defined as the point at which HC emissions increase to unacceptable levels.



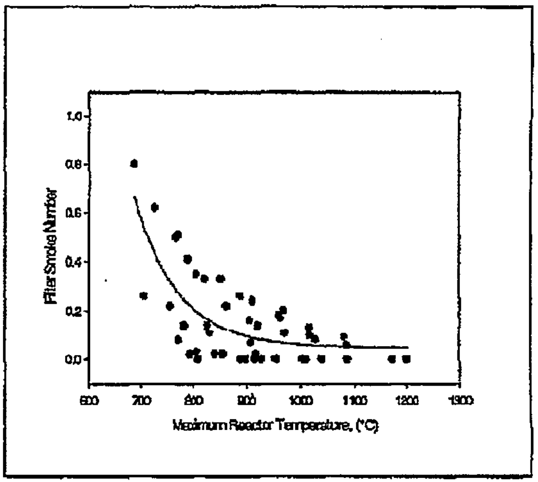
Slide 9. Hydrocarbon Emissions as a Function of Temperature

Slide 10 shows a plot of CO against maximum reactor temperature. Like HC emissions, the CO emissions decrease with increasing temperature reaching near non-detect levels at temperatures above 1000 °C. The higher temperatures required for CO oxidation compared to HC oxidation indicate the that CO oxidation is more difficult to oxidize in the FTO.



Slide 10. Carbon Monoxide Reduction as a Function of Temperature

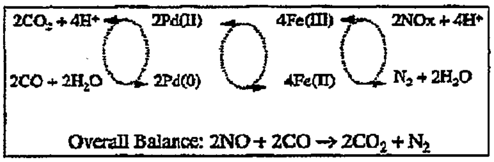
Slide 11 shows the measured PM as a function of reactor temperature. Like HC and CO, the PM destruction efficiency of the FTO is strongly dictated by the maximum reactor temperature. The discrepancy between different FSN results at constant temperature is a result of varying residence times in the reactor cause be different engine operating conditions. The results are encouraging because they show PM can be oxidized in a moderate temperature range (800-1200 °C), similar to HC and CO.



Slide 11. PM Emissions as a Function of Temperature

LEAN NOx CATALYST (LNC)

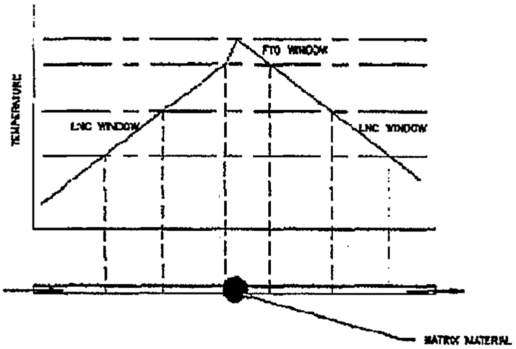
Southwest Research Institute has developed a novel lean NOx catalyst (LNC) based on inexpensive transition metals impregnated into molecular sieves on non-precious metal ligands. The catalyst operates under oxygen-rich conditions in a temperature range between 260-300°C. Unlike most lean NOx catalysts which use hydrocarbon as a reducing agent, the Southwest LNC uses CO as reductant and therefore shows promise for use in a diesel engine exhaust where HC levels tend to be quite low. Preliminary results with the catalyst tested on simulated exhaust containing at least 3%O_2 show NOx reductions of 50%. Additional work is planned for a series of tests on actual diesel exhaust. Slide 12 shows the schematic of the catalytic cycle.



Slide 12. Southwest LNC Cycle

THE FOUR WAY CONVERTER

Slide 13 shows the integration of the Southwest LNC and the Thermatrix FTO. Because the relatively cool diesel engine exhaust gases must be heated to temperature between 800-1000 C for complete oxidation of HC, CO, and PM to occur, the exhaust gases must pass through an lower temperature window that is ideally suited for NOx reduction with the LNC. It is the integration of the LNC within the FTO that provides the environment for both oxidation and reduction chemistry to occur in a compact configuration.



Slide 13. Reaction Zones for the Integrated FTO and LNC

The development of a four-way converter for diesel engines is the subject of intense research. The recent review by the Office of Advanced Automotive Technologies (OAAT) states, " The need to develop an after-treatment system to control emissions of NOx, particulate matter, hydrocarbons, and carbon monoxide (is identified) as the most important breakthrough technology required to make CIDI diesel engine competitive with spark-ignited engines." The report goes on to say "the after-treatment system will be technically sophisticated, involving sensors, controls, catalysts, and advanced materials to support complex physical and chemical processes."

The single unit should be capable of reducing NOx to N_2, and oxidizing PM, HC, and CO to CO_2 and H_2O , without oxidizing SO_2 to SO_3. The development of a cost effective four-way converter could lead to an overall improvement in fuel economy because the in-cylinder combustion process could be optimized for performance rather than emissions reduction.

The sulfate problem could be alleviated through the use of low sulfur fuels. Similar to the spark ignited engine, the four way converter will most likely be optimized by integrated pre-combustion and in-cylinder combustion strategies as well.

CONCLUSIONS

Solutions to the diesel engine emissions problems will require integrated technologies to achieve high emissions reductions without compromising fuel penalty or engine performance.

Ceryx Inc. is dedicated to integrating pre-, in-cylinder, and post- combustion technologies to develop optimized systems for diesel emission control. A prime example of a Ceryx technology integration is the unique collaborative relationship between Ceryx, Thermatrix and Southwest Research to combine proprietary FTO and LNC technologies to develop a four way converter for the simultaneous reduction of PM, HC, CO, and NOx.

Thermatrix has successfully applied its proprietary FTO technology toward to the treatment of diesel exhaust emissions. Tests on a 12 liter heavy duty truck engine have shown reductions of PM in excess of 90%, while destroying CO and HC to non-detect levels.

Southwest Research has developed a novel lean NOx catalyst which has achieved 50% NOx reductions in simulated exhaust. SwRI is continuing development of the lean NOx catalyst for application to diesel engine exhaust. The unique combination of the two in a single device for simultaneous PM and NOx destruction meets the four key criteria of new diesel technology development as well as the challenges set forth by upcoming emissions regulations.

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ENGINE COMBUSTION RESEARCH AT SANDIA'S COMBUSTION RESEARCH FACILITY

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ABSTRACT

Over the past several years the engine combustion work at Sandia National Laboratories' Combustion Research Facility has incorporated new, more realistic engine hardware and grown with respect to the number of different projects. The approach we are currently employing is to assemble experimental hardware that mimics a realistic engine geometry while maintaining optical access. For example, we are using multi-cylinder engine heads or one-cylinder versions of production heads mated to one-cylinder engine blocks. Optical access is then obtained through a periscope in an exhaust valve, quartz windows in the piston crown, windows in spacer plates just below the head, or quartz cylinder liners. The objective of this paper is to describe the ongoing projects.

Compression-Ignition Engines

(1) A one-cylinder version of a Cummins N-series production engine has been fitted with a window in the piston crown and a periscope system in an exhaust valve. Multiple imaging techniques have been used to study the in-cylinder processes. From these data, a new conceptual description of soot formation in an operating diesel is proposed. Also, planar laser-induced fluorescence imaging is being used to map the in-cylinder NO distribution in time and space. (2) A new small-bore optically accessible diesel engine has been designed and assembled. The 4-valve head has a centrally located common rail injector. Characterization of the in-cylinder flows in the engine is being conducted. (3) The diesel simulation facility consists of a constant-volume combustion vessel that has a disk-shaped combustion chamber. The vessel has been designed to evaluate fuel sprays and ignition at diesel conditions at the time of fuel injection. (4) The evaluation of the combustion process in a heavy-duty diesel engine utilizing alternative liquid fuels is a new project at Sandia. A one-cylinder Caterpillar engine is being used to conduct experiments evaluating alcohols and biodiesel.

Spark-ignition Engines

(1) In our port fuel-injection engine we are employing video imaging to investigate the evolution of liquid fuel films on combustion chamber walls during a simulated cold start. Flood-illuminated laser-induced fluorescence is used to observe the fuel films directly, and color video recording of visible emission from pool fires due to burning fuel films is used as an indirect measure of film location. (2) In our project on direct fuel injection we are utilizing a 3-valve prototype production head mounted to a single-cylinder engine. The in-cylinder flow field, the distribution of liquid and gaseous fuel, and the amount of wall wetting are being measure while varying engine tumble and swirl as well as injector type. (3) The diagnostic development engine, permits measurement of the in-cylinder gas composition and state in a 4-valve prototype production head. Broadband, multi-point Raman scattering is employed to make measurements of all major combustion species simultaneously. The temporally-resolved, multi-point measurement allows both the fluctuations in mixture composition and the length scales of the mixture homogeneities to be determined.

INTRODUCTION

The engine combustion department at Sandia National Laboratories' Combustion Research Facility has had a close interaction with the automotive industry for nearly 20 years. Our original research involved the application of advanced, primarily laser-based, diagnostics to optically accessible single-cylinder engines. Compromises in engine geometry were made to accommodate optical accessibility; for example, using valves and spark plugs mounted in the side wall of the combustion chamber allowed the use of a window providing nearly full-bore, optical access to the cylinder.

Over the past few years, advances in lasers, in computer speed and storage capacity, in electronics, and in detectors have enabled our researchers to consider more realistic geometries. Today, all of our single-cylinder engines employ production or prototypical engine heads. Optical access is accomplished via several means:

extended (Bowditch) pistons, periscopes in an exhaust valve, quartz cylinder liners, or windowed spacers between the piston liner and head.

This paper is intended to describe the current facilities and projects and present recent results. It is divided into two sections: compression-ignition and spark-ignition engines.

COMPRESSION–IGNITION ENGINES

Heavy–Duty Engine

Recognizing the need for a greater understanding of the diesel combustion process, a considerable effort has been made in recent years to obtain detailed in-cylinder measurements. These studies have significantly improved our understanding of diesel combustion. They have also contributed to the ability of manufacturers to meet strict emission standards without sacrificing engine performance. However, many aspects of diesel combustion remain unknown, and understanding them is critical to the development of future diesel engines that will have to meet even more stringent emission standards.

The optical-access engine used in this work is a single-cylinder, direct-injection, 4-stroke diesel engine based on a Cummins N-series production engine. The N-series is typical of heavy-duty size-class diesel engines, with a bore of 140 mm and a stroke of 152 mm. Figure 1 is a schematic illustration of the engine [1].

Our challenge in the heavy-duty diesel area is to develop a more complete understanding or a "conceptual model" of how diesel combustion proceeds. An accurate conceptual model would provide a framework for interpreting experimental measurements, guide the development of numerical modeling, and furnish engine designers with a mental image to focus their thinking. The development of advanced laser-based techniques has provided a means for making detailed in-situ measurements of the processes occurring inside of a reacting diesel fuel jet. Planar imaging allows specific species within the reacting jet to be measured with high spatial and temporal resolution, and many of these techniques can be designed to yield semi-quantitative and even fully quantitative data. We have applied diagnostics to investigate various aspects of the diesel combustion process in the general order that they occur, from the start of injection to the end of the apparent heat release [2].

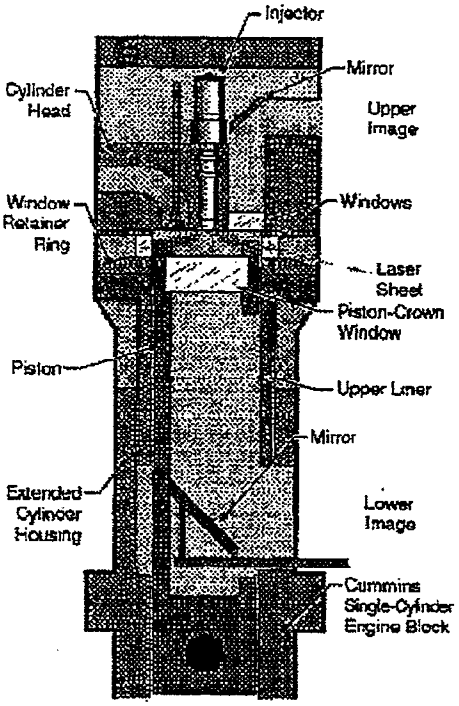

Figure 1. Schematic of optical-access diesel engine showing the laser sheet along the fuel jet axis.

To examine liquid-phase fuel we have employed elastic-scatter imaging through the piston crown. Liquid fuel was found to extend 23 mm into the combustion chamber [3]. Quantitative, planar laser Rayleigh scatter images of the vapor-fuel and air mixture illustrated that ahead of the liquid fuel jet, vapor-phase fuel extends across the chamber [4]. Chemiluminescence imaging has been used to examine the autoignition process while planar laser-induced fluorescence (PLIF) images of polycyclic aromatic hydrocarbon emissions were obtained to help determine whether the early combustion is volumetric or confined to the periphery of the jet [5]. Laser-induced incandescence and elastic-scatter images have been used to observe soot formation and distribution [6]. Finally, PLIF images of the OH radical have showed the development of the diffusion flame [7].

Figure 2 illustrates the theory of diesel combustion that was generally accepted prior to the application of laser-sheet diagnostics in diesel combustion research. Shown is a slice through the mid plane of the combusting fuel jet. The dark area depicts a region of dense fuel droplets (possibly with an intact liquid stream near the injector). This is surrounded by a region of more disperse, vaporizing droplets and vapor fuel. The diffusion flame forms around the jet periphery where the fuel and air meet.

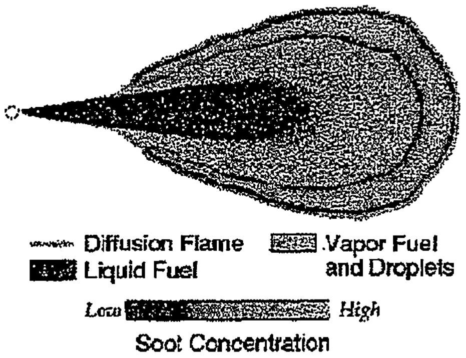

Figure 2. Schematic illustration of the "old" view of diesel combustion (prior to laser-sheet imaging studies), showing a slice through the mid plane of a rejecting jet.

The work at Sandia combined with results from other researchers has led us to a new description of diesel combustion during the mixing-controlled burn, prior to the end of fuel injection. This is shown in Figure 3.

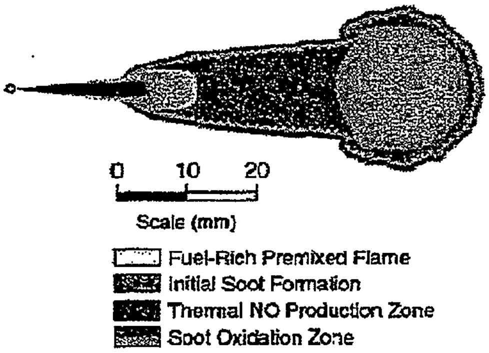

Figure 3. A schematic illustration of the conceptual model of DI diesel combustion derived from laser-sheet imaging for a typical time during the first part of the mixing controlled burn (i.e., prior to the end of injection).

The model shown in Figure 3 correlates virtually all of the data from a wide variety of imaging diagnostics, and it unifies these data in a description of how DI diesel combustion occurs for a typical, modern diesel-engine condition. Our work continues to explore in-cylinder diesel combustion. We seek to improve or expand the model in several areas: the region between the tip of the liquid fuel and the point at which soot appears; the burnout phase; how the model is affected beyond the operating conditions of this engine; and the effects of wall interactions and swirl.

Light-Duty Engine

The Partnership for a New Generation of Vehicles (PNGV) goal of producing an 80 mile-per-gallon automobile with a 400 mile cruising range requires significant technological advances in many areas. One of the most critical components is the engine itself. Of all possible engines, a high-speed, small-bore, direct-injection diesel engine is the strongest candidate. These engines offer high thermal efficiency, have demonstrated reliability, and are compatible with projected PNGV vehicle designs including both proposed hybrid-electric and high-efficiency mechanical drive trains. In addition, they have considerable potential for further improvements in performance, fuel economy and emissions, and the potential for meeting the PNGV cost and time frame goals.

Achieving the PNGV goals will require advances in many areas, including: the design of the fuel-injection/combustion systems and in-cylinder control of pollutant formation; exhaust aftertreatment; turbochargers; engine architecture, materials, and controls; and fuels. Among these, the design of the fuel-injection/combustion system and associated in-cylinder control of pollutant formation are two of the most critical. The current knowledge base in these two critical areas is inadequate, and a research program has been developed to provide better fundamental understanding.

A one-cylinder head has been specially designed for this project. It has 4-valves with central injection using a common rail configuration. Initial experiments have been conducted collecting chemiluminescence images and soot luminosity.

Diesel Simulation Facility

Meeting stringent new emissions regulations while maintaining or improving the efficiency of diesel engines is a difficult challenge for diesel engine manufacturers. Some of the design changes used to meet emissions regulations, such as retarded injection timing, result in less efficient engines. To compensate for these efficiency losses and to improve engine performance and power density, engine manufacturers have boosted in-cylinder gas densities through the use of turbocharging. This approach offers the potential for still greater improvements in diesel engine performance and emissions. However, little is known about the effects of gas densities higher than those in current technology diesel engines on injection, combustion and emissions processes.

The diesel-combustion simulation facility, shown in Figure 4, consists of a pressure vessel with complete optical access in which diesel engine conditions can be simulated over a much wider range of conditions than is possible in an engine. Conditions that can be simulated include high power density conditions with peak combustion pressures more than a factor of two higher than in present diesel engines.

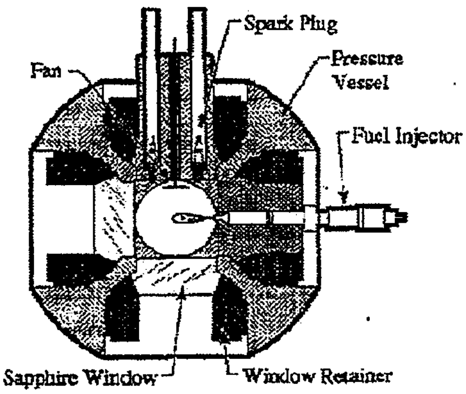

Figure 4. Schematic of diesel simulation facility.

A typical pressure history of a simulated diesel condition is shown in Figure 5. Prior to time zero, premixed gas is metered into the combustion vessel under well-stirred conditions. Just after time zero, a spark plug ignites the premixed charge which then burns (the first pressure rise). The hot product gases then cool due to heat transfer until the desired thermodynamic state for the diesel injection is reached. The fuel injector is then triggered and the diesel spray autoignites and burns (the second pressure rise).

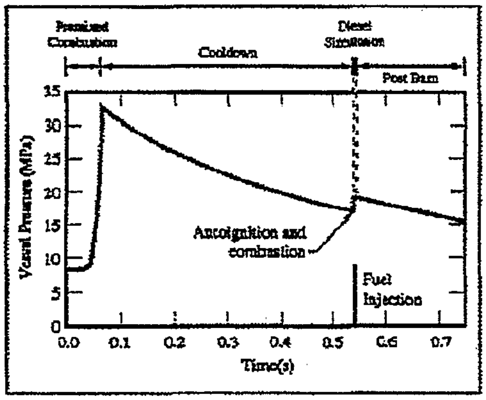

Figure 5. An example pressure history of the diesel simulation process for a combusting condition.

A recent key result has shown that in-cylinder gas density has a larger effect on the penetration of diesel jets than previously believed. This effect is caused by a dependence of penetration on the dispersion of a diesel jet, an effect that is not accounted for in common models for penetration. Penetration time and length scales have been developed that account for this effect and that correlate penetration data over an extremely wide range of conditions.

Work in this area will continue to explore the effects of various engine and injector parameters on the characteristics of the liquid phase. The goal is to determine the parameters controlling liquid penetration, the dependence of the liquid length on these parameters (the scaling), and to establish a comprehensive data base for model development.

Alternative Fuels

Presently, 27 percent of the transportation energy use and half of the transportation particulate and NOx emissions in the U.S. occur as a result of heavy-duty transportation. Moreover, the fuel for heavy-duty transportation is primarily petroleum-based (99 percent), and it is projected that by the year 2010, heavy-duty transportation alone will consume all the domestic petroleum production. The preferred engine for heavy-duty transportation is the diesel because of its high efficiency and reliability. This preference is not expected to change in the foreseeable future. As a result, development of advanced, high efficiency diesel engines that operate on alternative fuels or in a flexible-fuel mode, while meeting stringent new emissions regulations, will have significant payoff for efforts to reduce petroleum imports and improve the environment.

For industry to develop advanced and flexible-fuel engines, the knowledge base concerning the effects of alternative fuels on diesel ignition, combustion and emissions processes must be greatly expanded. Due to a significant research effort over the past several years with petroleum-based diesel fuels, our understanding of diesel combustion is improved considerably. This research has provided important new insight for the diesel engine designers, including a significantly changed picture of how diesel combustion occurs. However, additional research is required to determine how these diesel ignition, combustion and emissions processes change with alternative fuels.

The alternative fuels laboratory is in the process of final assembly. We will be using a Caterpillar one-cylinder engine with optical access similar to that of the Sandia/Cummins engine illustrated in Figure 1. The Caterpillar engine is a 4-valve, direct injection with a 1.7 liter combustion chamber. The fuels research will focus on using advanced laser-based diagnostics to understand the effects of various alternative fuels (e.g., biodiesel, alcohols, and blends of these with diesel fuel) on diesel combustion and emission formation processes.

SPARK–IGNITION ENGINES

Port–Injection

To meet future, ultra-low-emission vehicle regulations in California, significant reductions will need to be achieved in unburned hydrocarbon (UHC) emissions during cold start. Typically, more than 60 percent of the UHC emissions measured during the Federal Test Procedure occur in the first two minutes when the catalyst is not yet hot enough to efficiently convert the UHC in the exhaust. Also during this period, the temperatures of the port walls, intake valve(s), and combustion chamber surfaces are too low to fully vaporize the liquid fuel. As a result, even for closed-valve, port fuel injection (PFI), liquid fuel can enter the cylinder during intake, and exist in the combustion chamber both as droplets and films on the walls and in crevices. While it is believed that all liquid that remains suspended as an aerosol during compression does vaporize, it has recently become apparent that a significant portion of the liquid film on the walls survives compression heating, and exists there at the time of ignition. Perhaps even more surprising, the thicker of these liquid films appear to survive combustion. Thus, although it is well known that crevices are the main source of exhaust UHC under steady, operating conditions, it is likely that the diffusion-controlled burning of liquid-fuel films is a major contributor to UHC emissions during a cold start.

The work reported here involves a facility specifically designed for the study of cold-start phenomena in PFI engines [8]. A schematic of the engine facility is shown in Figure 6.

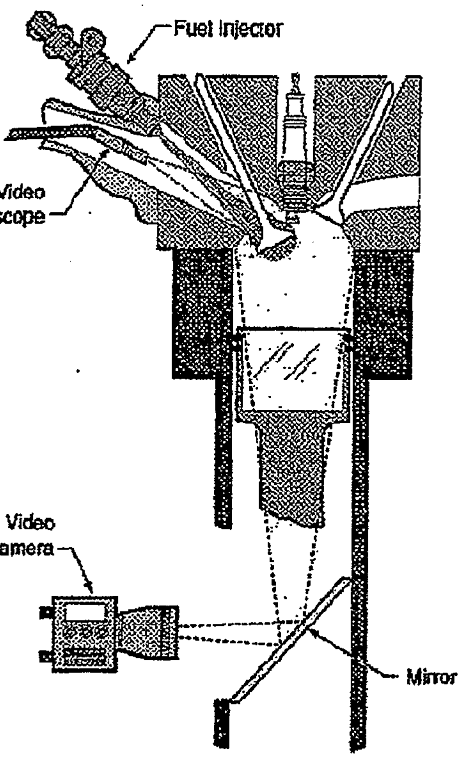

Figure 6. Single-cylinder research engine with extended "Bow ditch" piston for visualization of the combustion chamber.

As noted in the figure, the engine employs a Bowditch piston that provides optical access to 80 percent of the combustion chamber of a contemporary, 4-cylinder, DOHC head featuring four valves per cylinder with bifurcated intake ports. A single-cylinder crankcase is used, with the number three combustion chamber of the head mounted to the cylinder.

For the purpose of evaluating different injection timings, the repeatability of the test procedure is important. Rather than use an actual cranking start, for which there can be a high degree of variability, we maintain the engine at a constant coolant temperature and motor the engine at a constant speed. Fuel injection and ignition are then enabled for a specified number of engine cycles, typically ranging between 50 and 200. A master computer is dedicated to video image acquisition and capture. Software has been developed to annotate the video records in real time with an overlay, as illustrated in Figure 7. The number in the upper-left corner is the crank angle of the captured image. This can be fixed for a test sequence, or it can be incremented each cycle, producing a 'pseudo movie' that simulates the time evolution of an event by recording images at sequential crank angles that actually occur in different engine cycles. Shown on the right-hand side of the image in Figure 7 is a graphic display of the gross indicated mean effective pressure (IMEP).

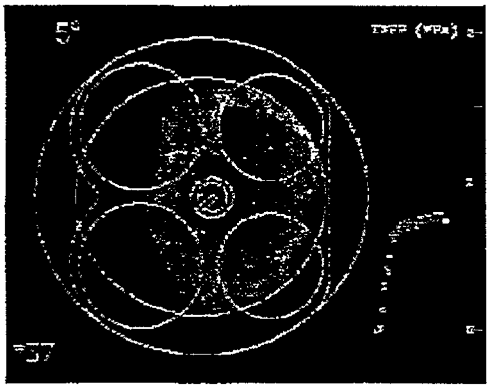

Figure 7. Single video frame, annotated with the crank angle of capture, cycle number, IMEP, and combustion chamber geometry. The concentric circles indicate the cylinder bore and clear aperture through the window in the piston. The larger valves on the left are the intake valves.

In recent experiments, we have used flood-illuminated laser-induced fluorescence to observe the fuel films directly, and color video recording of visible emission from pool fires. The engine was fueled with pump-grade 87 octane gasoline. The heavier ends of gasoline fluoresce when excited by a frequency-tripled Nd:YAG laser. Fluorescence from vapor phase fuel is much weaker than that from liquid fuel, so that vapor is not detected using this technique. A conventional color video camera was used to conduct the pool fire imaging. The pool fires are due to burning fuel films and are used as an indirect measure of fuel film location.

The techniques described above have been used to investigate the evolution of liquid fuel films on combustion chamber walls in a comparative study of open and closed valve injection, for coolant temperatures of 20, 40 and 60°C. In general, for all cases it was found that fuel films form in the vicinity of the intake valve seats. For closed valve injection, films also form below the intake valves and below the squish region between the intake valves and the cylinder wall, while for open valve injection additional fuel films form below the exhaust valves. It is expected that fuel films on the head near the exhaust valves are a direct source of unburned hydrocarbon emissions, that fuel films on the cylinder wall are a source of fuel blow by into the crankcase, and that pool fires are a source of soot.

Direct–Injection

The successful operation of direct injection engine is closely coupled to the fuel-air mixing process in the cylinder which, in turn, is coupled to the air motion and type of injection system. In this project we are investigating fuel-air mixing using an early injection (near-homogeneous charge) strategy. The in-cylinder flow field, the distribution of liquid and gaseous fuel, and the amount of wall wetting are to be evaluated while varying intake-charge tumble and swirl as well as injector type.

We are using a 3-valve, direct injection, spark ignition head mounted on a optically accessible engine. This head allows variation of the intake flow characteristics, and the engine incorporates a transparent cylinder and Bowditch piston. Diagnostic capabilities in the lab include laser-induced fluorescence, Mie and schlieren imaging, and laser Doppler velocimetry.

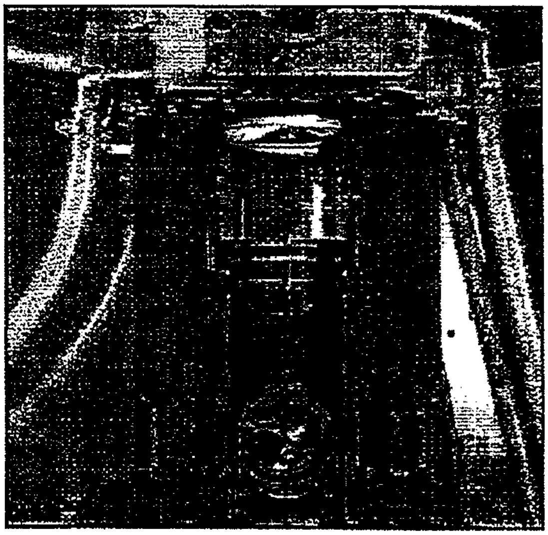

Figure 8. A spark-ignited, direct-injection research engine, with optical access.

Diagnostic Development

The challenge in this project is to develop and apply a diagnostic technique that is able to measure the composition and thermodynamic state of the in-cylinder gases in an operating engine. This information is important to understanding how well the fuel and air in the fresh charge are mixed, and how the fresh charge subsequently mixes with the burned combustion residuals. The composition homogeneity, and thermodynamic state of the resulting mixture strongly influences pollutant formation as well as such phenomena as misfire and cyclic variability.

The diagnostic technique is shown schematically in the Figure 9. Broadband, multi-point Raman scattering is employed to make measurements of all major combustion species, CO_2, O_2, N_2, CO, fuel, and H_2O, simultaneously. Mean species mole fractions measured from the beginning of the intake stroke, 0 CAD, to the top of the compression stroke, 360 CAD, are shown in Figure 10. The temporally-resolved, multi-point measurement allows both the fluctuations in mixture composition and the length scales of the mixture homogeneities to be determined. By measuring all major combustion species, the total gas density is determined, which specifies the thermodynamic state of the mixture.

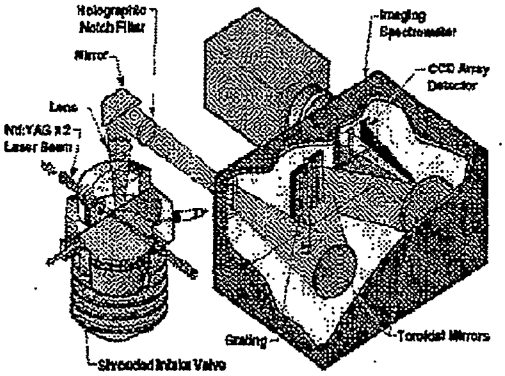

Figure 9. Schematic of the experimental apparatus employed for broadband, multi-point Raman scattering measurements. All major combustion species, the total gas density is determined, which specifies the thermodynamic state of the mixture.

The diagnostic technique described above and demonstrated in a side valve engine with a quartz window head is now being applied to an engine with a more realistic geometry. The engine head is a four-valve, pent-roof design with the side walls missing to enable a laser beam to interrogate the region near the spark gap. A quartz ring between the head and cylinder liner and an extended Bowditch piston are also being employed to provide additional optical access. In this new facility we are single-shot measurements of residual concentrations in a realistic operating engine.

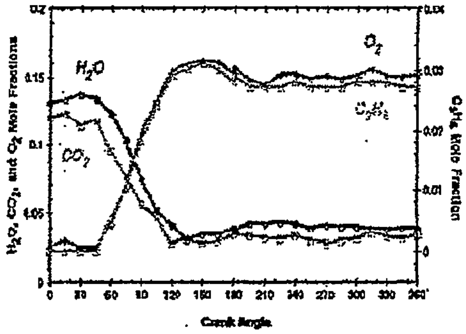

Figure 10. Mean mole fractions of the major species of combustion measured in a firing IC engine.

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LIQUID PHASE FUEL PENETRATION IN DIESEL SPRAYS

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ABSTRACT

Mie-scattered light imaging from the liquid-phase fuel in a diesel spray was used to investigate the maximum extent of liquid-phase fuel penetration (*i.e.*, the liquid length) and fuel vaporization processes in diesel sprays. The parameters varied in the investigation included: the injection pressure, the orifice diameter and aspect ratio, the ambient gas temperature and density, and the fuel volatility and temperature. The experiments were conducted in a constant-volume combustion vessel with extensive optical access. Fuels were injected with an electronically controlled, common-rail diesel fuel injector.

The dominant trends observed were that liquid length (a) decreases linearly with decreasing orifice diameter, (b) is independent of injection pressure, (c) decreases with increasing the ambient gas density or temperature, but in a non-linear manner, and (d) increases with decreasing fuel volatility. In addition, the results indicate that the liquid length of a multi-component fuel is controlled by its lower volatility fractions.

Two major conclusions were drawn from the observed trends. First, vaporization, like combustion in a diesel spray, is controlled by air entrainment into the spray (*i.e.*, by turbulent mixing). Atomization and local interphase transport processes, such as droplet evaporation, do not limit the rate of vaporization. Second, vaporization in a diesel spray occurs to a large extent through a batch distillation-type process with higher volatility components evaporating first and lower volatility components controlling the liquid length.

INTRODUCTION

Liquid-phase fuel penetration and vaporization are important factors in optimizing direct-injection diesel engine combustion processes, especially for the small-bore automotive diesels presently under development. Penetration of the fuel is needed to promote fuel-air mixing, but over penetration of the liquid-phase can lead to higher emissions if the liquid fuel impinges and collects on piston bowl walls. This research examines the effects of a wide range of parameters on the maximum extent of liquid phase fuel penetration in diesel sprays (defined as the "liquid length") with the goal of identifying the parameters and processes that control fuel vaporization and liquid-phase fuel penetration.

EXPERIMENT

The research was conducted in the optically accessible constant volume combustion vessel using an electronically controlled, common-rail diesel fuel injector. A detailed description of this diesel simulation technique is presented in Ref. 1. Parameters varied in the investigation included: the injection pressure, the orifice diameter and aspect ratio, the ambient gas temperature and density, and the fuel temperature and volatility. The ranges considered for the engine related parameters included those in current and proposed new diesel engine technologies. The fuels considered were cetane, heptamethylnonane (HMN), and a standard diesel fuel (DF2).

Time-averaged images of Mie-scattered light from the liquid-phase fuel in the diesel sprays were used to determine the liquid lengths. Figure 1 shows three of these images. Each image in the figure was acquired for a different ambient gas density with all other parameters held fixed. The light region in each image is Mie-scattered light from the liquid phase fuel in the diesel spray. The fuel was injected from left to right with an injector orifice located at the far left of each image. The liquid length is determined from images such as shown in Figure 1 by defining a threshold light intensity and then determining the maximum axial extent of the spray with a scattered light intensity above this threshold. The liquid lengths for the three images in Figure 1 are given in the lower right corner of each image.

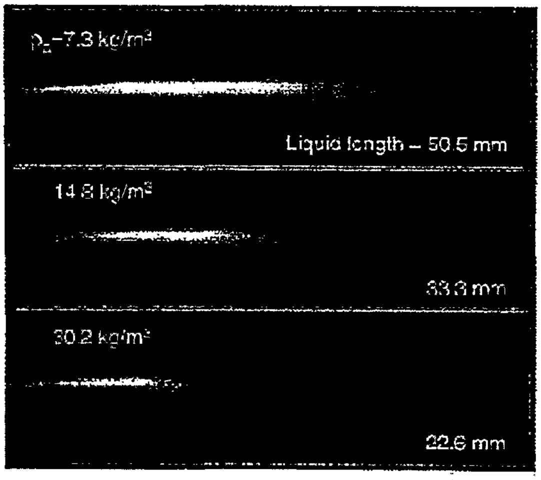

Figure 1. Time-averaged Mie-scattered light images for three sprays injected from left to right into the ambient gas density (ρa) given in each image. The orifice pressure drop and diameter, the ambient gas temperature, the fuel temperature, and the fuel were 135 MPa, 246 mm, 1000 K, 438K, and DF2, respectively.

RESULTS AND DISCUSSION

Two of the major trends observed in the liquid length data obtained from images such as those in Figure 1 are shown in Figures 2 and 3. Figure 2 shows that the liquid length has a linear dependence on orifice diameter, decreasing as the orifice diameter decreases for all conditions examined. Figure 3 shows that the liquid length is independent of the injection pressure for all conditions. The trends in Figures 2 and 3 are those that would be expected if the rate of fuel vaporization is controlled by the rate of air entrainment (*i.e.*, turbulent mixing), and therefore, strongly suggest that vaporization in a diesel spray is controlled turbulent mixing [1]. If vaporization were controlled by local interphase transport processes (*e.g.*, heat and mass transfer at droplet surfaces), liquid length dependencies on orifice diameter and injection pressure other than those observed in Figures 2 and 3 would be expected [1].

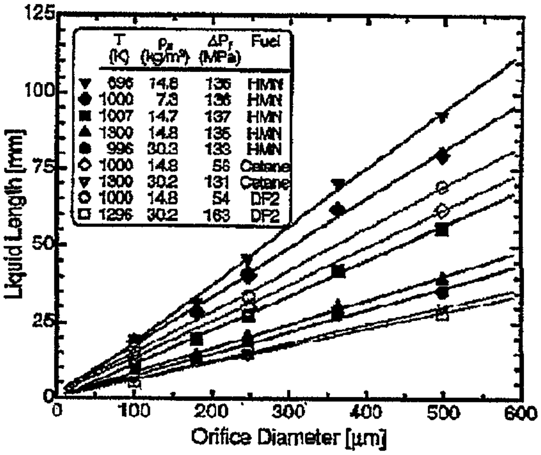

Figure 2. Liquid length versus orifice diameter for a wide range of conditions. The terms in the legend are the ambient gas temperature (T) and density (ρ_a), the orifice pressure drop (ΔP_f), and the fuel type. The lines in the figures are linear least squares fit to the data for each set of conditions given in the legend.

The results in Figure 2 are important for the small-bore engines currently being developed for automotive applications, since liquid fuel impingement on piston bowl walls is a concern in these engines. Figure 2 indicates that the smaller orifice sizes used in small-bore engines will help mitigate liquid impingement problems on piston bowl walls. Also, Figure 3 indicates that the current trend toward higher injection pressures in diesel engines for emissions control does not enhance liquid impingement on piston bowl walls.

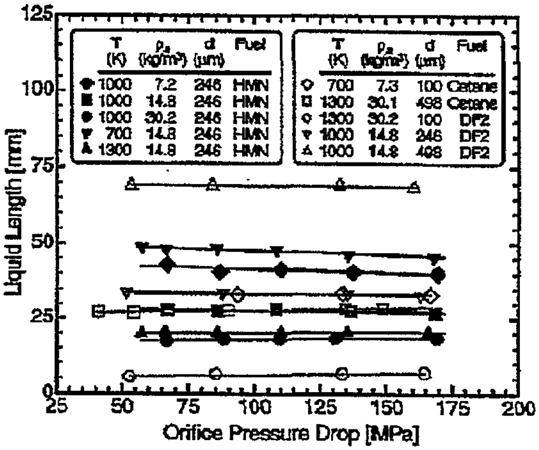

Figure 3. Liquid length versus the pressure drop across the injector orifice for a wide range of conditions. The term d in the legend is the orifice diameter. See Fig. 2 for definitions of the other terms. The lines in the figures are linear least squares fits to the data for each set of conditions given in the legend.

Figure 4 shows several other important trends observed in the data. Figure 4 is a comparison of the liquid lengths measured for the two single component fuels, HMN and cetane, at various ambient gas densities and temperatures. The results show that the liquid length decreases in a strong non-linear manner with increasing density or temperature for each fuel, similar to trends observed in an engine over a much narrower range of conditions [2]. Also, comparison of the liquid lengths for each fuel shows that the liquid length increases with decreasing fuel volatility (cetane has a 40 K higher boiling point than HMN). The fuel volatility effects are the most significant at lower temperature conditions (*i.e.*, cold start and light load engine conditions). Furthermore, comparison of all three fuels examined suggests that multi-component fuels, such as DF2, vaporize by a batch distillation-type vaporization process with the most volatile components vaporizing first [1].

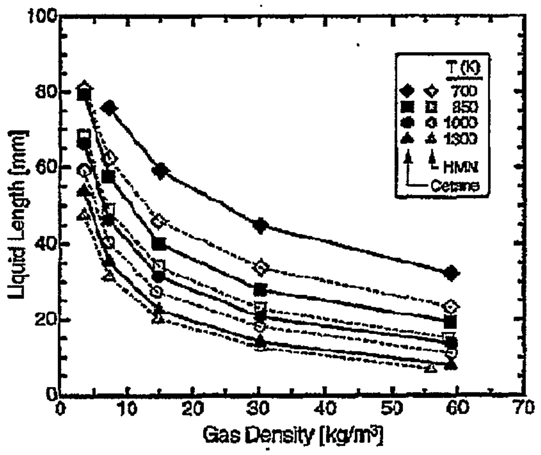

Figure 4. The effects of density, temperature and fuel volatility on liquid length. The lines identify the data for the different temperatures given in the legend. The solid lines pass through the cetane data and the dashed lines pass through the HMN data. The orifice pressure drop and diameter, the ambient gas temperature, and the fuel temperature were 136 MPa, 246 μm, 1000 K, and 438 K, respectively.

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