State of California
AIR RESOURCES BOARD

Staff Report: Utility Engine
Regulation Status Report

PUBLIC MEETING TO CONSIDER PROGRESS TOWARD COMPLYING
WITH THE 1999 UTILITY ENGINE REGULATIONS

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I. INTRODUCTION

The Air Resources Board (the Board or ARB) was required to consider regulating emissions from off-road mobile sources by the California Clean Air Act (CCAA) of 1988 as codified in the Health and Safety Code (HSC) Sections 43013 and 43018. Included in the off-road category are construction and farm equipment, marine vessels, locomotives, utility engines, off-road motorcycles, and off-highway vehicles.

Engines used in utility and lawn and garden equipment were the first off-road category subject to emission control regulations because of their significant emissions impact and because of a court order requiring Board action by January 1991. Consequently, the utility and lawn and garden engine (utility engine) regulations were originally approved by the Board on December 14, 1990, and became effective on May 31, 1992. The utility engine regulations, as initially adopted, applied to engines produced on or after January 1, 1994 (the 1994 implementation date was also a requirement of the court order). However, upon consideration of a petition filed by industry, the Board in April 1993 delayed implementation for one year, making the regulations applicable to engines produced on or after January 1, 1995. On July 5, 1995, the Administrator of the United States Environmental Protection Agency (U.S. EPA) signed the authorization for the utility engine regulations resulting in the first enforceable California off-road emission control regulations.[1]

The utility engine regulations include exhaust emission standards and provisions for emission test procedures, labels, warranty, and production compliance programs. With regard to the emission standards, the regulations contain a two-tiered approach; the first tier, Tier I, was implemented on January 1, 1995, while the second tier, Tier II, is set to be implemented beginning January 1, 1999. With an implementation date of January 1, 1999, manufacturers were given roughly eight years of lead time to comply with the Tier II emission standards. Thus just over three years remain before the Tier II standards are to be implemented.

Recently the U.S. EPA promulgated its 1997 gasoline utility engine program similar to the California Tier I program and is conducting regulatory-negotiations to set the federal Phase II utility engine standards.[2] The U.S. EPA appears to be making progress in developing useful life exhaust emission standards, evaporative and fuel spillage emissions standards, and in-use emissions compliance programs. Although the U.S EPA's efforts are positive improvements to the utility engine control program, it appears that the proposed Phase II regulation will fall short of California's emission control goals as prescribed by California's State Implementation Plan (SIP). The difference in the Federal and California standards may prove to be an issue of controversy because manufacturers have expressed their desire to comply with one set of standards and procedures for the U.S. market to reduce costs and complexity. While staff recognizes the importance of a harmonized emission control program for the U.S., as stated before, the federal program is not expected to meet California's air quality goals (see Section III, "Summary of Recommended Action" for further detail).

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1. The authorization to enforce the California utility engine regulations was signed by the EPA administrator on July 5, 1995, and printed in the Federal Register on July 20, 1995 (59 Fed. Reg. 37440 (July 20, 1995)).

2. For the past few years, the U.S. EPA has been conducting a Reg-Neg process prior to adopting their own small utility engine rule. The Technology Task group was established at the September 1993 Reg-Neg Committee meeting to help the Committee explore appropriate technology to reduce the emissions from spark-ignited utility engines.

In addition to the emission standards and other requirements, the California utility engine regulations include a directive for ARB staff to present industry progress reports to the Board prior to the implementation of the 1999 emission standards. The relatively lengthy lead time was provided by the ARB because the standards were considered "technology forcing," requiring time for research and development efforts. Concurrently such lead time also provides the ARB the opportunity to review industry progress and take appropriate action should any significant technological feasibility concerns arise. This, the first utility engine status report, begins with a brief background on the utility engine category and is then followed by the current status of meeting the Tier I emission standards (i.e., 1995 compliance). The emphasis of this report, the status of meeting the Tier II emission standards, is then discussed, accompanied by staff's recommendations. Finally, Section IV ("Discussion") of the report provides a more in-depth look at the technological feasibility of meeting the Tier II emission standards.

II. BACKGROUND

A. UTILITY ENGINE CATEGORIES

Utility engines are divided into two categories: the lawn and garden category and the general utility category. The lawn and garden category includes equipment such as walk-behind mowers, riding mowers, lawn tractors, snow blowers, leaf blowers, edge trimmers, string trimmers, tillers, chain saws, and other miscellaneous lawn and garden implements. The general utility category includes equipment such as pumps, generators, compressors, grinders, welding machines, stump beaters, vibrators, finishers, concrete cutters, portable saw mills, portable refrigeration units, and other miscellaneous utility equipment.

In general, small utility equipment (including lawn and garden and general utility) is powered by gasoline (and some diesel) internal combustion engines rated less than 25 horsepower (Hp). While there are some two cylinder designs, this category primarily consists of two-stroke and four-stroke single cylinder engines. Both the two-stroke and four-stroke engines are carbureted and have either horizontal or vertical crankshafts depending upon their end-use application.

The utility engine category is further broken down into two subcategories: handheld equipment and non-handheld equipment. The handheld standards were created because staff recognized that two-stroke engines were necessary for certain small utility equipment. However, recent developments have shown that this may no longer be the case as four-strokes engines are now available in certain handheld applications. The emission standards for hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx) and particulate matter (PM) are shown in Tables 1 and 2 below. The equipment in each of these subcategories must meet a different set of emission standards for 1995-1998 and 1999. Most importantly, the 1999 standards represent approximately a 70 percent HC emission reduction from the 1995 standards.

Table 1.

1995-1998 Utility Engine Emission Standards

HANDHELD EQUIPMENT		EMISSION LEVELS IN g/bHp-hr*			
YEAR	DISPLACEMENT	HC	CO	NOx	PM
1995-98	Less than 20 cc**	220	600	4.0	-----
	20 cc to <50 cc	180	600	4.0	-----
	50 cc and greater	120	300	4.0	-----

NON-HANDHELD EQUIPMENT		EMISSION LEVELS IN g/bHp-hr		
YEAR	DISPLACEMENT	HC + NOx	CO	PM
1995-98	less than 225 cc	12.0	300	0.9
	225 cc and greater	10.0	300	0.9

*grams per brake horsepower-hour (g/bHp-hr)
*cubic centimeter (cc)

Table 2.

1999 Utility Engine Emission Standards

HANDHELD EQUIPMENT		EMISSION LEVELS IN g/bHp-hr			
YEAR	DISPLACEMENT	HC	CO	NOx	PM
1999 and later	all	50	130	4.0	0.25

NON-HANDHELD EQUIPMENT		EMISSION LEVELS IN g/bHp-hr		
YEAR	DISPLACEMENT	HC + NOx	CO	PM
1999 and later	all	3.2	100	0.25

It is estimated that in 1989, two-stroke utility engines emitted 53 tons per day (tpd) of total exhaust HC, 164 tpd of CO, and 0.2 tpd of NOx in California. Four-stroke utility engines were estimated to emit 17 tpd of HC, 331 tpd of CO, and 1.8 tpd of NOx. Additionally, staff has estimated that evaporative emissions, including spillage, accounted for an additional 15 tpd of HC emissions. To put the significance of these emissions in perspective, the HC emissions from utility engines were estimated to be equivalent to the HC emissions from 3.5

million new 1991 model passenger cars driven an average of 16,000 miles in their first year of operation.

B. CURRENT STATUS

Handheld equipment is typically powered by (gasoline fueled) two-stroke engines primarily because unlike a four-stroke design, two-stroke engines have multi-positional operation capability. Compared to a four-stroke design of equal power, two-stroke engines are also lighter in weight. However, as shown in Table 3, two-stroke engines typically emit HC and CO emissions much higher than their four-stroke counterparts.[3] Also note that two-stroke engines emit significant levels of PM. For comparison, heavy-duty diesel truck engines must comply with a 1994 0.10 g/bHp-hr PM standard.

With regard to non-handheld equipment, they are typically powered by either gasoline or diesel fueled four-stroke engines. While their emissions are inherently lower than two-stroke engines, the potential for significant emission reductions still exists.

Industry has made commendable progress toward lowering exhaust emission levels of two- and four-stroke utility engines. This is evident upon a comparison of the uncontrolled emission levels, shown in Table 3, with the 1995 certification emission levels, shown in Table 4 (see also Attachment 1 for a further breakdown by engine class of the 1995 average certification levels). Presently 201 utility engines have been certified to Tier I levels. It should be noted that while industry's progress toward lowering the exhaust emission levels is significant, it has not been accomplished through the use of advanced technology. Rather, the accomplishments have been made mostly through the use of relatively simple engine modifications and carburetor enleanment.

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3. Air Resources Board Mailout #90-64, "Staff Report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Regulations Regarding the California Exhaust Emission Standards and Test Procedures for 1994 and Subsequent Model Year Utility and Lawn and Garden Equipment Engines," (October 22, 1990).

Table 3.

Comparison of Exhaust Emission Rates
From Two- and Four-Stroke Gasoline Utility Engines

	Emission Levels in g/bHp-hr		
APPLICATION	HC + NOx	CO	PM
Uncontrolled two-stroke Utility Engines	150-301	500-900	>3.0
Uncontrolled four-stroke Utility Engines	5-55	200-700	N/A

Table 4.

1995 Certification Emission Averages from Non-Handheld
and Handheld Gasoline and Diesel Utility Engines

	Average Emission Levels in g/bHp-hr		
APPLICATION	HC + NOx	CO	PM
Gas Handheld Two-Stroke Utility Engines	149	325	N/A
Gas Non-Handheld Four-Stroke Utility Engines	7.7	237	N/A
Diesel Non-Handheld Utility Engines	7.4	5.5	0.6

III. SUMMARY OF RECOMMENDED ACTION

Over the past few months, ARB staff met with engine and catalyst manufacturers who shared their progress toward attaining the Tier II emission standards, the types of technology they are evaluating, and the advantages and disadvantages of each technology. Based on these data, staff believes significant progress toward complying with the 1999 standards has been made to date. Accordingly, staff believes industry is on schedule with their research and development efforts for compliance with Tier II emission standards and recommends that the Board maintain the standards as originally approved.

A brief summary of industry's progress and California's unique situation follows along with staff's detailed recommendation.
A more in-depth technological feasibility discussion appears in Section IV, "Discussion."

A. PROGRESS OF COMPLIANCE WITH THE 1999 STANDARDS

1. Gasoline Powered Engines - Technology and Feasibility

In 1990, when the Board adopted the utility engine regulations, the ARB believed that advanced emission control technologies would be necessary to achieve the Tier II emission standards, with the most likely technology being the catalytic converter. The ARB based the emission standards for Tier II compliance on test data supplied by industry and gathered by ARB contractors. The ARB also relied on data gathered from experience with automotive emission controls which show that catalysts are capable of attaining conversion efficiencies well beyond the levels required to meet the Tier II emission standards.

Although automotive catalysts routinely attain conversion efficiencies well above 95 percent, the ARB assumed that catalysts for utility engine use need only reach efficiencies of 60-70 percent. The ARB established the emission standards at this level to account for possible difficulties in adapting the technology to the specific needs of utility engines.

Since the ARB regulations were initially proposed in 1990, industry has indicated that the use of catalysts on utility engines may involve problems with packaging, economically supplying air to the catalyst for oxidation of excess emissions, high exhaust and surface temperatures, and durability of the catalyst because of excessive heat, vibration, and possible contamination. However, over the past years many of these problems have been minimized for most applications with tremendous effort being made to resolve other problems. To date, the majority of successes obtained from adding a catalyst to an engine have been with four-stroke engines demonstrating
50-60 percent emission reductions in HC + NOx. Catalyst companies report that they can produce catalysts that fit into existing mufflers at a cost to the manufacturer of $5-10 per packaged catalyst.

Although catalysts may be the least expensive and most promising technology to use to comply with the Tier II emission standards, other technologies have been examined as well. Many engine modifications currently used in higher-cost commercial utility engines to optimize durability and performance have not yet been applied to these low-cost utility engines. Therefore, the potential exists to employ a variety of engine modifications to these engines to assist in compliance with the Tier II emission standards. These modifications may require substantial attention to changes in the fuel delivery system and design of existing engine components. None of these modifications are considered technologically challenging or infeasible; all have been used in the automotive industry. For two-stroke engines, manufacturers contend that it is essential to reduce scavenging losses.[4] Additionally, the

Portable Power Equipment Manufacturer's Association (PPEMA) has identified fuel injection, enleaned carburetion, catalysts, and shifting from two-stroke to four- stroke engines as the most feasible technologies for Tier II compliance. The staff agrees with this position.

To date, the majority of small utility engines are based on the side-valve (L-head) engine design. Recently, however, due to impending emission control regulations as well as customer preference, there has been a market shift from L-heads to overhead valve engines (OHV). Most manufacturers favor this trend because OHV engines generally provide greater emission reduction potential than L-head engines. As of October 1995,
75 out of 156 of the Tier I California certified gasoline powered engine families were OHV engine families. With regard to meeting Tier II standards, L-head engines will likely fall short.

With regard to shifting from two-stroke to four-stroke designs, at least one manufacturer, Ryobi, has developed a lightweight, four-stroke engine (without a catalyst) for handheld applications. Ryobi certified this engine to Tier I emission standards by using an OHV four-stroke engine, exhaust gas recirculation (EGR) technology, and carburetor modifications. As noted in their 1992 press release (Attachment 2), Ryobi believes that with minor adjustments the engine can meet the 1999 Tier II emission standards for handheld equipment. Based on Ryobi's success as well as additional data, staff believes four-stroke engines are a feasible alternative to two-stroke engines for compliance with the 1999 handheld standards. Four-stroke technology can likely be used in most handheld applications, with the exception of commercial chainsaws (see Section IV, "Discussion" for further explanation).

Based on recent catalyst developments, staff believes that the other most likely option for handheld equipment manufacturers to meet the 1999 emission standards is to use advanced control technologies such as catalytic converters. Non-handheld equipment manufacturers

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4. In two-stroke gasoline engines, one of the major sources of unburned HC emissions is the loss of unburned fuel exiting the exhaust port during combustion. Scavening occurs when the exhaust and the intake events overlap, as the piston finishes its downward stroke and begins its movement from the bottom of the cylinder to the top. The exhaust port is left open while fresh fuel and air flow into the combustion chamber. This results in fuel losses out the exhaust ports as well as very high HC emissions. Studies have reported the fresh fuel losses associated with scavenging to be as high as 30 percent for conventional two-stroke engiens. (Research Proposal, "Engine, Fuel and Emissions Engineering, Inc., September 1993).

will most likely comply with Tier II standards by use of catalysts and other advanced control technologies (see Section IV "Discussion" for additional details).

2. Diesel Powered Engines -
Technology and Feasibility

Diesel engines inherently emit low HC and CO emissions and relatively moderate NOx and PM emissions. With regard to meeting the 1999 HC + NOx emission standards, manufacturers of small diesel utility engines have investigated the use of three-way and oxidation catalysts. For HC and PM control, however, oxidation catalysts will likely be the type of catalyst used if manufacturers chose to employ this technology. Although oxidation catalysts for small utility diesel engines have not yet achieved commercial viability, they are expected to be available in the future. Recent test programs conducted by both the U.S. EPA and industry have demonstrated that oxidation catalysts are capable of reducing HC emissions by 30-40 percent and PM emissions by 25-40 percent.

In addition to catalysts, small diesel utility engine manufacturers are investigating a number of engine modifications to improve the air/fuel mixing which will in turn decrease HC and PM emissions. Most notably is the method with which the fuel is injected into the engine. Fuel is injected directly into the combustion chamber (direct fuel injection or DI) or into a pre-chamber where it first mixes with air before entering the combustion chamber (indirect fuel injection or IDI). Some diesel engine manufacturers have indicated that DI is essential for complying with Tier II emission standards, while others have indicated they will modify the IDI system to achieve the necessary emission reductions. Other modifications to improve the air/fuel mixing include: increasing the number of holes per fuel injector nozzle, redesigning the fuel spray pattern, using high pressure technology (which could likely reduce NOx and PM emissions by 20-40 percent), and non-modulated EGR system (demonstrated to reduce NOx emissions by 10-30 percent in medium sized diesel engines; 25-100 Hp).[5]

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5. Jeff J. White, Southwest Research Institute, "Development of Baseline and Controlled Exhaust Emission Rates For Off- highway Vehicle Engines," ARB Contract No. A198-076, (July 1993).

3. Alternate Fuel Powered Engines - Technology and Feasibility

As discussed further in Section IV, "Discussion," a few engine manufacturers are also investigating alternate fuel use such as liquefied petroleum gas (LPG), compressed natural gas (CNG), and electric motors to achieve Tier II emission standards. Some manufacturers have shown greater progress than others in assessing alternate fuel use, as demonstrated by the two manufacturers that have already certified engines using LPG.

B. CALIFORNIA'S UNIQUE SITUATION

The federal CAA requires a comprehensive SIP to demonstrate ozone attainment for ozone nonattainment areas classified as serious, severe or extreme; there are six such areas in California. The SIP, submitted to the U.S. EPA on November 15, 1994, is ARB's commitment to develop and implement regulations which will result in specified emission reductions in California. Reductions in mobile source emissions are essential if attainment of the federal ozone standard is to be realized. Off-road mobile sources account for 17 percent of ozone precursor emissions in the state, of which utility engines contribute 3 percent. The utility engine 1999 Tier II standards are essential to reaching the SIP's HC emission reduction goals. By 2010 the Tier II standards are expected to result in a statewide reduction of approximately 58 tpd of HC emissions (HC emissions from utility engines in 1990 were 70 tpd), an 85 percent reduction as required by the SIP.[6] As stated earlier, there are concerns regarding the impact of the federal program on California's air quality goals. Therefore, the staff will continue to monitor the U.S. EPA's progress and work to harmonize the future programs as much as possible while maintaining the emission reduction goals necessary for ozone attainment in California.

C. STAFF RECOMMENDATION

As demonstrated in the past, despite concern over meeting Tier I emission standards, industry has successfully certified 201 gasoline, diesel, and LPG-powered engines to the 1995 emission standards (7 of which have catalysts). Given the advances in developing technology that industry has made to date, the staff expects a similar outcome with the Tier II emission standards. Based on information gathered throughout individual workshops with

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6. The estimated emission reduction does not reflect the impact of the federal preemption of farm and construction equipment.

manufacturers as well as information obtained from the U.S. EPA and Society of Automotive Engineers' (SAE) publications, the staff believes that manufacturers are on schedule with their
Tier II research and development efforts. It is anticipated that the three years remaining should be sufficient time to resolve any remaining obstacles.

Catalyst technology is in place for use on non-handheld engines and is expected to be used successfully to bring those engines into compliance with Tier II emission standards by 1999. Remaining obstacles are similar to those other industries have encountered and overcome; a similar outcome is expected from the utility engine industry.

For handheld engines, one engine manufacturer, Ryobi, has already successfully met the Tier II emission standards. As previously indicated, Ryobi currently has in production a handheld four- stroke engine that can, with minor adjustments, meet the Tier II emission standards. The Ryobi engine can be used in many handheld applications including weed-trimmers and blowers. This engine technology is available to interested manufacturers as an alternative to producing a complying engine of their own.

At present staff recommends maintaining the Tier II emission standards as originally approved by the Board. In addition, staff recommends that an evaluation of a more comprehensive control program be considered. For example, it is likely that the U.S. EPA will adopt in-use compliance standards and test procedures for their Phase II utility engine rule. It may be in California's best interest to adopt similar provisions. Moreover, staff will continue to work with industry and follow the U.S. EPA's Regulatory Negotiations (Reg-Neg) over the next year to determine if changes to the emission standards and compliance requirements are needed for 1999. One manufacturer plans to conduct a California specific cost analysis which will be shared with staff sometime next year. As directed by the Board, staff will return in 1996 with another update on industry's progress. Thus the staff proposes that no change in the utility engine regulations is appropriate at this time.

IV. DISCUSSION

Over the past few months, ARB staff met with numerous engine and catalyst manufacturers who have shared their progress toward attaining the Tier II emission standards, the types of technology they are evaluating, and the advantages and disadvantages of each technology. The following discussion is a detailed technical feasibility survey to enhance that which appears in Section III, "Summary of Recommended Action." The discussion is based on information submitted by manufacturers as well as the EPA Reg-Neg and SAE publications. (see also Attachment 3 for a summarized table of available technologies).

GASOLINE POWERED ENGINES - TECHNOLOGY AND FEASIBILITY

1. Catalyst Technology

As stated previously, catalysts appear to be the most promising technology available for complying with the Tier II utility engine emission standards.

a. Catalyst Characteristics

Catalysts are constructed using one of two primary substrates, either metal or ceramic. Ceramic seems to be the popular choice by the majority of the catalyst companies primarily because of its low cost, flexibility in designing its cell shape and cell density, and its superior high temperature strength characteristics. As with automotive catalysts, the substrate can be coated with one or more of three noble metals, palladium (Pd), platinum (Pt), and/or rhodium (Rd). Palladium is the coating of choice for small engines, as palladium catalysts are relatively inexpensive, thermally resistant and very successful at reducing HC emissions. The substrate can have different configurations depending on the manufacturer's design. Reportedly, whether a ceramic or metal substrate is used, each is capable of achieving equivalent emission reduction efficiencies.

b. Catalyst Efficiency and Durability

Catalyst companies have reported 50-60 percent reductions in HC + NOx emissions from new catalyst-equipped four-stroke engines, without any other engine modifications. One catalyst company has demonstrated that a 75 percent HC emissions reduction is feasible (testing done on four-stroke engines), while another has demonstrated a 50-60 percent HC emission reduction and a 95 percent NOx emission reduction (testing done on a 50 cc moped engine). These reductions were achieved using just the catalyst (i.e., no other engine modification). To achieve further emission reductions, a system wide solution is likely, including modifications to the engine and air/fuel delivery system in combination with a catalyst. As an example of this system wide approach, an SAE paper reports an over 90 percent reduction of combined HC and NOx emissions from a 5 Hp four-stroke engine upon installation of a catalyst and air injection system.[7] The baseline HC + NOx emissions of 19.5 g/bHp-hr

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7. Jeff J. White, James N. Carroll, and Charles T. Hare, Southwest Research Institute, and Jacline G. Lourenco, California Air Resources Board, "Emissions Control Strategies for Small Utility Engines," SAE #911807, (Septmeber 1991).

dropped to
1.1 g/bHp-hr, well below the Tier II emission standards.[8] The reduction in CO was equally impressive, a 96 percent reduction from 507 g/bHp-hr to 40 g/bHp-hr occurred, which is also well below the Tier II emission standards.

An inexpensive way to increase the efficiency of a ceramic based catalyst is to increase the density of the substrate cells. Because the catalyst in a utility engine is small in size, the substrate is only in contact with the oxidizing compounds for a relatively short period of time. Therefore, increasing the density of the substrate cells allows more time for oxidation to occur and, in turn, increases the efficiency of the catalyst.

Durability is another issue concerning catalyst success. The durability of catalysts can be greatly affected by exposure to high exhaust temperatures and vibration. Existing technology can significantly diminish sensitivity to high temperature with the use of high temperature washcoats and/or substrates and management of the air supply to the converter. To address vibration concerns (as well as temperature control) a ceramic substrate is typically wrapped in a vermiculite matting. Utility engine manufacturers have indicated that vermiculite has been successfully used to overcome the vibration problem.

Corning, Incorporated, and Englehard Corporation recently conducted durability tests on two-stroke motorcycle engines with catalysts.[9] These tests demonstrated that a ceramic catalyst substrate can be adequately mounted to a two-stroke engine to compensate for the differences in thermal expansion of the catalyst substrate and the steel can. Additionally, the catalysts were able to endure the severe vibration and high temperature conditions encountered in a two-stroke engine (typically 1.53-3.06 G's and 900 F at partial load to 1450 F at full load). These results can be extrapolated to the less severe environment of a four-stroke engine because the vibrational forces present in a two-stroke engine's exhaust are three to four times higher.

As shown in Table 5, the Corning/Englehard study reports mounting designs that can resist

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8. Tier II emission standards for non-handheld equipment: 3.2 g/bhp-hr HC + NOx, 100 g/bhp-hr CO, and 0.25 g/bhp-hr PM.

9. K.P. Reddy and P.L. Scott, Corning, Inc., and H.S. Hwang and J.J. Mooney, Englehard Corp., "Durability of Ceramic Catalytic Converters for Motorcycles," SAE #951768, (September 1995).

inlet gas temperatures of 1832 and 1922 F at vibration accelerations of 60-70 G's. All three converters passed the 100 hour vibration test without showing visible damage to the can, mat, or catalyst substrate. No functional failures of the catalyst substrate were reported either.

Table 5

Details of Hot Vibration Tests - SAE #951768

SUBSTRATE SIZE	INLET GAS TEMP F	ACCELERATION G's	FREQUENCY Hz	RESULT
55 x 40 mm	1832	60	185	passed 100 hrs
40 x 60 mm	1832	60	160	passed 100 hrs
40 x 60 mm	1922	70	180	passed 100 hrs

Catalyst durability and efficiency has been demonstrated by Tomi Industries as well. Tomi Industries is best known as a major manufacturer/supplier of air and oil filters for utility engine applications. Although, over the past few years, they have expanded their operation by manufacturing ceramic foam substrates. Tomi Industries performed a successful 300-hour durability test on a four-stroke engine equipped with a ceramic foam substrate. The durability test consisted of dynamometer testing as well as field testing. A 40 percent conversion efficiency was maintained throughout the durability testing with no change in catalyst out emissions. Other catalyst and engine manufacturers have not met with as much success as Tomi (i.e., most report typical deterioration factors ranging from 1.25-2).

c. Packaging

The ARB staff does not believe that packaging should be a significant problem in adapting catalysts for utility engine use. The modest efficiencies required should be met with the use of fairly small catalysts that can be easily incorporated into existing engine/muffler designs. This has already been demonstrated on seven catalyst-equipped engine families certified to the 1995 Tier I emission standards.[10] Several other companies have indicated that combined muffler/catalyst packaging will be their goal. These manufacturers estimate a

10. The emissions results from the certified systems are low compared to the Tier I standard of 10 g/bhp-hr HC + NOx and approach the Tier II standard of 3.2 g/bhp-hr HC + NOx; Kohler has certified a liquefied petroleum gas engine with a catalyst that emits less than 4 g/bhp-hr HC + NOx. See also Attachment 1.

muffler/catalyst package will cost the engine manufacturer as little as $5-10; the cost may be double or triple that value to the consumer. Although ceramic catalyst substrates are less expensive to produce than metal catalyst substrates, packaging the ceramic is more costly than packaging the metal, resulting in almost the same overall cost.

d. Heat Management

High catalyst surface temperatures are primarily a concern for safety reasons. However, these surface temperatures can reportedly be reduced by use of compact, high-efficiency insulation and shielding that will not aggravate packaging constraints. The vermiculite wrapping mentioned earlier is an example of this type of shielding. Another strategy to reduce surface temperature is to reduce the temperature of the exhaust itself. Exhaust temperatures can be maintained at low levels through carburetor enleanment to reduce the amount of unburned fuel that must be catalyzed or by adding dilution air to the exhaust stream. Air management devices, such as air injectors and reed valves, can provide this dilution air. These techniques are commonplace in the automotive industry and are also used in motorcycles, which use engines similar to utility engines. However, utility engine manufacturers have reported that air injection could cost as much or more than the engine itself and therefore may be too costly for the benefit received. More research is required in this area. Air injection technology is discussed further in Section (IV)(A)(2)(c)(i).

Briggs and Stratton (B&S) indicated during the U.S. EPA's Reg-Neg process that "exothermic heat and operating temperature increases can be significantly reduced by limiting catalyst conversion efficiencies to reasonable levels." The B&S data indicate that the mid efficiency (B&S's term) catalyst system applied to a current non-handheld, four-stroke engine can achieve a 46 percent reduction in HC + NOx and a 56 percent reduction in CO in the laboratory. These reductions are promising, as the Tier II emission standards represent a 60-70 percent HC + NOx reduction from the Tier I emission standards.

In the past, engine and catalyst manufacturers have commented that flames emitted from the catalyst/muffler have also been a problem. However, flames may be avoided through improved air/fuel management and through use of solid-state ignition systems to minimize misfire. The use of screens or grates as flame arresters could also reduce concern for flames. Some engine and catalyst manufacturers reported they believe flames from the exhaust are now manageable and they do not consider it a problem for some applications any longer.

Currently there are catalyst companies that are producing and marketing applicable catalysts ready for use. For example, Elof Hansson, AB, currently sells a small aftermarket catalyst, GreenCat, for use with the B&S Quantum, Sprint, Max, and Classic engine lines. Their testing shows about a 50 percent HC + NOx and CO emission reduction in the B&S Quantum engine. It should be noted while Elof Hansson, AB, stands by their findings, B&S performed testing on the GreenCat over two years ago. They were dissatisfied with the performance and durability demonstrated by the GreenCat.

The potential solutions identified above concerning catalyst durability, packaging, air availability, and heat management can be a applied to two-stroke engines, as well as four-stroke engines. However, less success has been demonstrated on two-stroke engines because the exhaust and skin temperature produced by the catalyst has been well beyond the allowable forestry temperature limits.[11] The high temperature concern on two-stroke engines is particularly problematic while maintaining compliance with the Tier II levels. However, most catalyst and engine manufacturers have recently shown great interest in solving the exhaust and skin temperature problem, indicating that this barrier may soon be overcome. Industry contends that the solutions are known but are not suitable for all applications at this time. Given the advances in developing technology that the industry has made to date, it is likely that manufacturers will be able to overcome any remaining catalyst-related obstacles prior to the Tier II implementation date.

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U.S. EPA Test Results On
Catalyst-Equipped Engines

As part of the U.S. EPA's efforts to develop a small off-road engine rule, the Reg-Neg committee has tested four-stroke engines equipped with catalysts. The test results have been positive, showing that the California Tier II emission standards are achievable and that temperature concerns can be addressed. In fact, the U.S. EPA test results include at least three non-handheld engines that meet the California Tier II emission standards (see Table 6). Although these engines are not as yet ready for production, they demonstrate that manufacturers have made significant strides in developing the necessary technology to comply with the regulations. Other test results from the U.S. EPA are also encouraging, as they indicate development of improved technology capable of achieving new engine reductions more than 50 percent below the ARB's Tier I

11. Title 36 CFR 261.52 directs the Forest Service to prohibit the operation or use of "any internal or external combustion engine without a spark arresting device properly installed, maintained and in effective working order meeting either: (1) Department of Agriculture, Forest Service Standard 5100-a; or (2) appropriate SAE recommended practice J335 and J350 (a)". The SAE J335 requirements pertaining to skin and exhaust temperature are as follows: (a) Exposed Surface Temperature: exhaust system should be designed so that the exposed surface temperature does not exceed 550 F; (b) Exhaust Gas Temperature: The exhaust system should be designed so that the exhaust gas temperature does not exceed 475 F.

emission standards (Tier II emission standards are about 70 percent below the Tier I emission standards).

Table 6

U.S. EPA Testing Results

CONFIGURATION/NON-HANDHELD	Emission Levels in g/bHp-hr HC + NOx	CO
Oversized Cat + Constant Shop Air in Cat at All Modes	1.12	41.79
Proof of Concept 4.5 Hp OHV With Oversized Catalyst	4.03	6.72
FUJI with Catalyst	4.91	228.36
B&S High Efficiency Catalyst	4.94	96.27
11 Hp OHV w/air Injection From Shop Air	2.74	67.91
Propane Fuel with 3-way Catalyst and A/F Control	1.72	0.22

(1999 Tier II non-handheld standards-
3.2 g/bHp-hr HC + NOx and 100 g/bHp-hr CO)

Precision Combustion Engineering also examined the use of catalyst technology on utility engines for the U.S. EPA. This program included the testing of two small generator engines, one two-stroke and one four-stroke, with prototype catalysts. The July 1993 EPA report states that:

> " Laboratory testing on the four-stroke and two-stroke engines showed that the prototypes reduced the emissions of HC and CO significantly (95-99%) while leaving NOx essentially unchanged. The HC and CO reductions are far more than sufficient to meet CARB's 1999 emission standards. NOx is not necessarily below the standard since it cannot be controlled with an oxidation catalyst such as small engines will use, but it is known that it can be reduced in other ways. Both the converter casing skin temperature, and the exhaust temperature were at or below that of a conventional muffler. This clearly demonstrates the technical feasibility of using this technology for the control of emissions, and the compliance with emission standards for all utility engines."

It should be noted that although the ARB considered the catalytic converter to be the most promising technology to comply with its Tier II emission standards, and expects most utility engine manufacturers to use catalysts to comply, other emission control technologies also hold promise, as discussed below.

2. Other Modifications

a. Engine Modification

Engine manufacturers contend that regardless of whether a catalyst is used, modifications to the engine itself are necessary to achieve the 1999 Tier II emission standards. These modifications include: structural improvement, piston ring changes to provide increased sealability, improved oil sealing, and re-design of air passages for additional cooling. None of these modifications are technologically challenging; all have been used in the automotive industry. As previously discussed, manufacturers also contend that it is essential to reduce scavenging losses in two-stroke engines.

b. Fuel System Modifications

Achievable fuel system modifications include further enleanment of the air/fuel mixture and other changes to the carburetor (e.g., carburetor limiter caps and accelerator pumps to improve transient response) or the possible use of a vaporizing carburetor. In terms of cost, these technologies may be moderate as compared to the cost of a catalyst. Direct fuel injection is a higher cost technology option.

i. Enleaning the Carburetor

A major concern of controlling HC and CO with a catalyst is linked to the air/fuel ratio. Currently controlled engines are calibrated at air/fuel ratios around 11.5 to 1 (the stoichiometric ratio is 14.6 to 1). This means that, on current engines, insufficient oxygen is in the air/fuel mixture to burn all of the fuel entering the engine. Hence a catalyst system must supply extra air, complete the combustion, dissipate the resulting heat, and cool the higher temperature exhaust.

If the air/fuel ratio can be made leaner, the demands placed on the catalyst can be reduced. However, barriers to enleanment include decreased cold starting performance and lagging response to load changes and increased engine temperatures. Automotive manufacturers solved these problems by warming inlet air, providing extra fuel during acceleration, and modifying the cooling system. Simple versions of the devices used in automobiles should be readily applicable to utility engines. Automobile manufacturers have also used high energy ignition systems and induced combustion chamber turbulence, which allow leaner engine calibration. All of these low-cost techniques should be applicable to utility engines.

ii. Vaporizing Carburetor

Another fuel system modification currently being examined is the use of a vaporizing carburetor. The technology, developed by the Woodside Group, allows stable engine operation at lean air/fuel ratios at partial power and richer air/fuel ratios at full power. The carburetor results in faster and more complete combustion, decreasing fuel consumption while reducing HC and CO emissions. NOx emissions increase slightly, but combined HC + NOx emissions drop substantially; the U.S. EPA tests of the vaporizing carburetor on a B&S Quantum engine indicated a 42 percent HC + NOx reduction, and a 75 percent CO reduction.[12] Brake specific fuel consumption dropped nine percent.

The U.S. EPA report notes that the technology "is currently in a prototype stage which is contained in a bolt-on box to the existing engine. It may be used with spark retard due to faster burning, EGR and catalysts to further lower emissions." The report goes on to note that the vaporizing carburetor may extend the engine's useful life due to clean operation and reduced carbon buildup on combustion chamber surfaces.

iii. Direct Fuel Injection

Direct fuel injection provides the greatest opportunity to reduce scavenging losses from two-stroke engines and, for some engine designs, may provide improved engine performance at leaner operating conditions than comparable carbureted systems.

Many of the fuel injection components used on utility engines would be based on existing automotive technology. Some of the actual components used on automobiles may be directly transferable to the larger displacement utility engines. However, this is not the case for smaller utility engines because the fuel system's components must be smaller in size and be specifically designed to accurately deliver extremely small amounts of fuel. The design of the fuel injection system must also consider the unique conditions under which these engines operate (high vibration, high temperatures, small enclosures and contaminated environments). In addition to the injector(s), some fuel injection systems will require development of other related equipment such as sensors, pumps, and a regulated electric power source. Because the cost of a fuel injection system for utility engines is typically high when compared to the cost of the engine itself, most manufacturers have reported that they

12. Cheryl Caffrey, United States Environmental Protection Agency, "Emission Testing Report - Vaporizing Carburetor on Briggs and Stratton Quantum Engine," (August 1995).

do not plan on using it. However, the cost of fuel injectors, electronic engine controls, and associated sensors has fallen dramatically in recent years as production volumes have increased to meet the requirements of on-highway vehicles, making this technology increasingly more practical for off-highway engines.[13]

c. Exhaust System Modifications

Air injection and EGR are two exhaust system modifications that engine manufacturers have investigated. These modifications are comparatively higher cost technologies.

i. Air Injection

The two most common air injection technologies include one-way passive valves and air pumps. A well designed air injection system can provide optimum exhaust oxygen content for maximum reduction of HC and CO emissions with a catalyst or thermal reactor. The application of air injection technology must be optimized for all engine designs in order to account for differences in engine/muffler tuning and specific exhaust emissions. Note that while motorcycle manufacturers use air injection technology universally to comply with current emission standards, the use of air injection on small utility engines does have limitations, including the affects of supply air on catalyst temperatures and an engine power loss, required if a pumping type air injection system is used to provide the air. The majority of engine manufacturers stated that this technology was cost inhibiting. Presently electronic air injection technology may cost as much or more than the engine itself. However, a simple mechanical control system would be significantly less expensive: reed valves cost $1.50-3 each and air pumps $5-15 each.

ii. Exhaust Gas Recirculation

EGR technology may be used to reduce NOx emissions. EGR works by mixing a small amount of exhaust gas with fresh air/fuel entering the cylinder. This lowers the peak combustion temperature, and thus reduces NOx formation.

Although EGR is used extensively in the automotive industry, it does have limitations with regard to small utility engine applications. When EGR is used on small utility engines, the durability of the design must be considered because small passages exposed to recirculated exhaust gases tend to plug easily.

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13. ibid. 5.

The majority of EGR work has been done on four-stroke engines with very little attention paid to two-stroke engines. Two-stroke engines have more natural EGR and may be less responsive to additional EGR rates. Therefore EGR has greater potential for use on four-stroke engines.

3. Overhead Valve Engines Replacing Side Valve Engines

To date, the majority of small utility engines are based on the L-head design. The L-head engine is a relatively "old" design which the automotive industry abandoned in the early 1950's in favor of more efficient OHV engines. Small utility engine manufacturers continue to use L-head engines because they provide adequate power for utility equipment applications and are less expensive than OHV engines. In addition to being less efficient, L-head engines tend to have problems managing high engine temperatures because of their design. These high temperatures are a problem because they tend to distort the exhaust valve seat area, causing unburned fuel mixture to leak when the valve is in its closed position resulting in higher emissions.

The technical support document, part of the 1990 utility engine Staff Report, includes a cost benefit analysis of using OHV engines rather than L-head engines.[14] The analysis concluded that OHV engines are likely to be between $5 and $15 more expensive than comparable powered L-head engines. Manufacturers have recently provided similar cost estimates. This cost differential is important because when compared to the average cost of high sales volume engines (e.g., approximately $100), the $5-15 difference is not very significant. Most manufacturers favor the shift to OHV's primarily because OHV engines generally provide greater emission reduction potential than L-head engines. With regard to meeting Tier II standards, L-head engines will likely fall short. For this reason, as well as consumer demand, a number of utility engine manufacturers have already made the change from L-head engines to OHV engines. As of October 1995, 116 of the Tier I California certified engine families were OHV engine families.

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Technology and Feasibility Specific to
Handheld Equipment

In the handheld equipment category, there is a distinction between two-stroke and four-stroke engines. Because handheld equipment must be held during operation and able to function properly in multiple positions, manufacturers frequently use two- stroke engines that offer the

[14] ibid. 3.

advantages of high power to weight ratios and multi-position use. Emission control of two-stroke engines is complicated because they have higher engine-out HC emissions than four-stroke engines primarily due to scavenging (see Table 2). Additionally, they run fuel-rich to provide engine cooling, and oil is mixed with the fuel to provide lubrication. Furthermore, potential emission control concerns in general are exacerbated for handheld equipment engines because less space is available for modifications and/or add-on control equipment. Weight can also be an issue, as additional controls may negate some of the advantages of the two-stroke engine's greater power to weight ratio. Recognizing these issues, the ARB regulations provide for more lenient Tier I and Tier II emission standards for engines used in handheld equipment.

Although small four-stroke engines for handheld applications currently do not have total multi-positional capability, they would offer a number of advantages to the consumer when used instead of two-stroke engines. The engines not only require no premixing of the fuel with the lubricant, they are also quieter, less susceptible to spark-plug fouling, easier to start, and more accommodating with respect to altitude or carburetor adjustment. While the cost of these engines is currently higher than comparable two-stroke engines, because of lower production volumes and a greater number of mechanical parts, the cost of redesigning two-stroke engines to meet Tier II levels may offset this cost difference. Further, as four-stroke engines' production volumes rise, economies of scale should reduce the costs associated with production.

Four-stroke technology can likely be used in most handheld applications with the possible exception of commercial chainsaws, due to their total multi-positional capability requirements. The current stage of development of four-stroke technology has not yet reached a point where it can meet the challenge of commercial chainsaws. However, it should be noted that in California these chainsaws are not the major focus of concern compared to the rest of the utility engine category (especially compared to engines used in trimmers and blowers). This is primarily because chainsaws used in residential applications are seldom used, and therefore their emissions contribution is relatively minor. For the larger chainsaws used in commercial applications, the emissions contribution is much greater. However, while this is a concern, California is preempt from controlling the emissions from most of these equipment due to the federal Clean Air Act (CAA).[15]

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15. The federal CAA ammendments of 1990 prohibited any state regulation of new construction and farm equipment below 175 Hp. In discussions to determine the proper applications of the preemption, ARB staff and industry agreed that chainsaws with engines greater than 45 cubic centimeter (cc) displacement should be considered preempt.

As noted before, Ryobi has developed a lightweight, four-stroke engine (without a catalyst) for handheld applications. Ryobi believes with minor adjustments the engine can meet the following emission levels: 24 g/bHp-hr HC, 120 g/bHp-hr CO, and 3.8 g/bHp-hr NOx. These levels are all below the 1999 Tier II emission standards for handheld equipment. This engine type should be suitable for most consumer applications; it has been certified (see Attachment 4) and is currently available for purchase. On April 10, 1995, Ryobi announced they would be willing to license their product to any interested engine manufacturer, enabling the industry to comply with the Tier II emission standards (See Attachment 5).

Success in controlling two-stroke emissions was also seen at the September 1990 SAE Off-Highway Congress, where data were presented to show the emissions benefit of a catalyst on small two-stroke engines.[16] The HC and CO emissions were reduced up to 55 percent with no impact on NOx. Another SAE paper reports that HC + NOx emissions from an 82 cc two-stroke engine were reduced 90 percent by use of fuel injection, a catalyst and air injection, while CO was reduced 98 percent.[17]

Kawasaki Heavy Industries, Limited, evaluated the effects of exhaust timing retard and enleanment of the carburetor mixture on mass emissions using a 25 cc two-stroke engine.[18] A significant reduction of HC and CO was demonstrated, 48 and 85 percent respectively. As a trade-off, NOx increased but only to 1.7 g/bHp-hr; still lower than half of the Tier II 4.0 g/bHp-hr.

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16. F. Laimbock and C. Landerl, Graz University of Technology, Austria, "50 cc Two-Stroke Engines with Catalysts for Mopeds, Chainsaws, and Motorcycles," SAE #901598, (September 1990).

17. Huei-Huay Huang, Ming-Horng Jeng, Nien-Tzu Chang, Yue-Yin Peng, James H. Wang, and Wei-Li Chiang, Industrial Technology Research Institute, "Improvement of Exhaust Emissions from a Two-Stroke Engine by Direct Injection System," SAE #930497, (March 1993).

18. Shinichi Tamba, Masaru Yamamoto, Tsuneyoshi Yuasa, and Isao Yoshimizu, Kawasaki Heavy Industries, Ltd., "Emission Reduction for Small Utility Two-stroke Engine," SAE #951767, (September 1995).

Fuel injection has also been pursued for use in two-stroke engines; testing by the U.S. EPA of a fuel injection system designed by a small California engineering firm (BKM, Inc.) have produced emission values of 22-29 g/Hp-hr HC, 43-71 g/bHp-hr CO, and 0.95-1.26 g/bHp-hr NOx for a 66 cc chainsaw. These levels are well below the 1999 emission standards.

As shown in Table 7, the results from more recent U.S. EPA tests on larger handheld equipment are equally promising. The HC + NOx levels achieved for handheld engines were less than half the Tier II standard. Achieving complying CO levels is more problematic, but two of the four engines tested are below the Tier II standard.

Table 7

U.S. EPA Testing Results

	Emission Levels in g/bHp-hr	
CONFIGURATION/HANDHELD	HC + NOx	CO
Four-stroke Engine w/Catalyst	8.65	39.55
BKM - DFI two-stroke Engine	25.99	70.15
Stihl With Enleanment and Catalyst	10.67	189.55
Stihl Fuel Injection	20.15	200.00

(1999 standards- 50 g/bHp-hr HC; 4 g/bHp-hr NOx; 130 g/bHp-hr CO)

An additional example of the emission reductions achievable comes from tests of a catalyst-equipped chainsaw tested by Fuel Management Systems for the Swiss Forestry Agency (as shown in Table 8). Although the tests were not performed using the ARB certification test cycle, the results showed an 87 percent reduction of HC emissions from baseline. Such results indicate that substantial reductions could be achieved in certification.

Table 8

Catalyst-Equipped Chainsaw Results

	Emission Levels in g/bHp-hr		
CONFIGURATION	HC	CO	NOx
	[%]*	[%]*	[%]*
Carburetor (baseline) Without Catalyst	21.89 [100]	50.97 [100]	0.12 [100]
LS-12	2.84	5.67	0.61

With Catalyst	[13]	[11]	[508]

*Percentage as compared to baseline model, without catalyst.
(Results listed are the average of two runs each).

B. DIESEL POWERED ENGINES - TECHNOLOGY TYPE AND FEASIBILITY

1. Catalyst Technology

As previously stated, diesel manufacturers have investigated the use of three-way and oxidation catalysts on small utility diesel engines. To specifically control/reduce NOx, the use of a three- way catalyst is impractical because diesel cycle engines inherently run very lean. Thus the excess air present in the exhaust inhibits the catalytic reduction of NOx. However, for HC and PM control an oxidation catalyst will likely be used.

A test conducted by an engine manufacturer on a 1995 certified diesel utility engine using an oxidation catalyst yielded a
30-40 percent HC emission reduction with a slight PM increase. Additionally, testing conducted by Southwest Research Institute (SWRI), on engines slightly larger than utility engines
(25-100 Hp), demonstrated oxidation catalysts capable of
25-40 percent PM emission reduction.[19] The PM increase in the engine manufacturer's testing was attributable to the use of a diesel fuel with a sulfur content greater than California diesel fuel. Based on the PM reduction shown in the SWRI study, it follows that if a low-sulfur fuel (California diesel) is used, an oxidation catalyst may provide both HC and PM emissions reduction. However, the full emissions reduction potential of oxidation catalysts can only be achieved on diesel engines running at high loads when the exhaust temperature is hot enough to activate the catalyst. This is because a diesel engine is usually operated at partial load for long periods of time with an exhaust temperature lower than the catalyst's required light-off temperature. Issues regarding catalysts for diesel engines are otherwise similar to those aforementioned pertaining to gasoline powered engines.

2. Engine Modifications

Engine modifications explored by small diesel utility engine manufacturers are redesigned fuel injectors, high pressure injection, direct fuel injection, and combustion chamber design. Some of these modifications appear to be more feasible than others, as discussed below.

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19. ibid. 5.

a. Redesigned Fuel Injectors

Diesel engine manufacturers have experimented with decreasing the size of the fuel injector holes in order to control the penetration of the fuel spray into the combustion chamber and, in turn, improve combustion efficiency. Fuel penetration is important because as cylinder size becomes smaller, the geometry of the combustion chamber limits the space available for the injector spray, resulting in fuel impingement on the wall of the combustion chamber. This fuel impingement leads to higher levels of HC and PM. While this strategy holds significant promise, the hole size itself becomes a limitation. Engines currently in production use nozzle hole sizes down to 0.20 millimeter (mm) diameter. Even though it is now feasible to manufacture nozzles with hole sizes reduced another 20 percent (at increased cost), manufacturers state that the risk of hole blockage while in customer service becomes greater.

In addition to decreasing the size of the injector holes, diesel engine manufacturers are also attempting to increase the number of holes per nozzle and redesign the fuel spray pattern to substantially improve the air/fuel mixing.

b. High Pressure Injection Technology

Significant reductions in NOx and PM could likely be achieved with high pressure injection technology; probably in the range of 20-40 percent for both pollutants.[20] High injection pressure creates the desired pressure drop across the nozzle holes which improves fuel atomization. The required pressure can be achieved by reducing the nozzle hole size; however, these engines are already limited by the size of the nozzle holes, as discussed previously. High pressure can also be achieved by reducing the number of holes, but this typically results in an unacceptable distribution of fuel in the combustion chamber, leading to reduced power output and increased exhaust emissions. A third way to increase the injection pressure is to increase the fuel pump plunger diameter. Unfortunately, limitations are imposed by the geometry of the fuel pump body and its ability to withstand the high pressure generated.

c. Direct Fuel Injection Combustion
System Modifications

Diesel engines are divided into two categories according to their combustion chamber design: DI engines, which have a single open combustion chamber which fuel is injected directly,

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[20]. ibid. 5.

and IDI engines, where the chamber is divided into two regions and the fuel is injected into the pre-chamber which is connected to the main chamber or other type of orifice.

While fuel economy and performance are advantages of the DI design, IDI engines offer considerably lower emissions of both NOx and PM, at least for naturally aspirated diesel engines. Based on testing Southwest Research Institute conducted on Lister-Petter engines, the IDI engine design reduced NOx by
40-45 percent, and smoke by an average of about 35 percent, compared to the DI engine.[21] It should be noted that these results are for a specific engine and may not be necessarily true for other engine designs. Utility engine manufacturers hold opposite views on whether DI or IDI technology should be used to comply with Tier II emission standards.

At least one diesel utility engine manufacturer, currently producing IDI engines, believes that the DI method for diesel combustion is critical for complying with Tier II emission standards. DI engines are thermally efficient, have good startability, higher durability, and better reliability than IDI engines. Additionally, DI engines tend to consume less oil and operate at lower temperatures so cooling requirements are less demanding than for IDI engines. Consequently, DI systems require substantially smaller cooling systems than do IDI systems which is beneficial to small utility engines based on their weight and size concerns. As mentioned before, Southwest Research Institute conducted a comparison test between Lister-Petter's LPW series engines which are offered in both DI and IDI versions for identically sized 2, 3, and 4 cylinder models. Overall, the DI versions were found to be 10-15 percent more efficient than the IDI versions.

On the other hand, some diesel utility engine manufacturers wish to continue using IDI technology. These manufacturers have made several improvements which have provided for substantial PM emission reductions. The changes include modifications to the cylinder head and the adoption of a more compact nozzle design to minimize disturbance to the gas flow in the pre-chamber. Additionally, manufacturers have upgraded the fuel pump; this provides close control of the injection characteristics and the timing which in turn reduces HC emissions. Furthermore, the injection timing has been retarded at high loads to counteract the tendency for the NOx emissions to increase as a consequence of the more efficient (hotter) combustion process. The manufacturer's cost increase incurred by these modifications is $15/cylinder. A reduction in PM emissions to 0.36 g/bHp-hr has been demonstrated from these improvements so far, which falls a short of the Tier II PM emission standard (0.25 g/bHp-hr). It is unclear at this point whether further work in this direction will achieve the Tier II emission standards.

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21. ibid. 5.

d. Combustion Chamber Design

Although the development of technology to reduce the exhaust emissions within the combustion chamber design is not a new concept for the engine industry as a whole, development has just recently begun in the utility engine component of the industry. History has demonstrated that piston design can have a significant effect on the combustion process, improving the air/fuel mixing process which results in more complete combustion and lower emissions. Innovative piston bowl shapes provide the possibility of further reductions of both NOx and PM emissions. The degree of improvement will be highly dependent on specific engine design and technological sophistication of the engine.

Utility engine manufacturers utilized combustion chamber redesign methods to meet the Tier I emission standards and investigation is ongoing to further refine the design for the Tier II emissions standards. Although the development of this technology is time consuming, manufacturers believe it will result in one of the most efficient and cost-effective ways to obtain emission reductions.

3. Exhaust Gas Recirculation

EGR technology has been used in large diesel engines in the past and should be successfully transferred to small utility engines. It appears feasible to implement a simple, non-modulated EGR system on a small to medium size diesel engine (25-100 Hp) and reduce NOx emissions by 10-30 percent.[22] The major drawbacks of EGR, however, is increased smoke and PM emissions and an increase in engine wear due to contamination of the lube oil. Several studies have suggested that increased engine wear associated with EGR is directly linked to the sulfur content in the fuel and the formation of sulfuric acid. On the positive side, the low-sulfur diesel fuel available in California should help to considerably reduce durability problems associated with EGR. For optimum effectiveness, EGR

[22.] ibid. 5.