significant market drivers, such as global emissions regulations, can provide a glimpse of what will lead additive development in the next ten plus years.

This presentation provides a historical perspective on petroleum additive industry. The traditional approaches to methodology for developing new additives and lubricating oils are contrasted to novel, alternative ways of lubricating engines of the future. We speculate that during the next decade, through the utilization of combinatorial chemistry and virtual testing, the development of intelligent, structure specific additives becomes a reality. These novel approaches can maximize the desired attributes of any chemical compound(s) while minimizing undesirable side effects and promote invention of new classes of additives with superior performance characteristics. Examples of extended oil drain interval concepts and a necessity for building an intimate interface between equipment manufactures and lubricant companies are also discussed.

This presentation is Attachment 19

G. LUBRICANTS.

Knowing the base stock and additive technology leads to a finished lubricant, a diesel engine oil in this case. However, the research and development that goes into the final step is time, resource and manpower consuming. The presentations on lubricants range from discussions on the impact of lubricants on the catalyst systems to methodology to identify the impact of lubricants on the system. The current DEO programs and costs of development of implementing a new DEO product are described.

"Lube Oil Contribution to Emissions: Emerging Issues", W. S. Key, Oak Ridge National Laboratory, Knoxville, TN 37932

Much attention has been focused on diesel fuel formulation and its impact on exhaust emissions and on emission control (EC) devices. To date a comparable effort has not been placed on evaluating the effects of lube oil formulation. Some prior work when coupled with future trends suggests that lube oil formulation may also be of concern. This concern is elevated by the increasing demands from future exhaust emission regulations as well as the sensitivity of EC devices needed to meet these regulations to some exhaust constituents such as sulfur. This talk provides the authors perspective on the current status on which issues need to be addressed in light of the concerns and the level of effort currently underway.

This presentation is Attachment 20.

"Impact of Engine Oil Consumption on Diesel Engine Emissions", Kent Froelund, Engine Research Department, Southwest Research Institute, San Antonio, TX 78228

The engine oil contributes to the engine exhaust emissions through oil consumption. Measurement methods for oil consumption mapping for steady-state conditions as well as transient conditions will be discussed. SwRI typically normalizes steady-state oil consumption data by dividing it by the engine fuel consumption. These normalized data, hereby deemed "relative oil consumption", enables a direct comparison between data obtained for different engine types, makes, displacement, etc. Examples are provided of mapping of the relative oil consumption versus engine speed and load, which leaves a characteristic "fingerprint" of an engine. Transient oil consumption is treated as well. Finally, the sensitivity of oil consumption to oil parameters such as viscosity and volatility is discussed.

This presentation is Attachment 21.

"New Emissions Regulations - Impact on Engine Design and Oil Formulation", G.P. Fetterman, Jr., Infineum USA L.P., Linden, N.J. 07036

This presentation starts with a look at the changes in the EPA emissions limits for diesel engines from 1988 through 2002, and makes the observation that the problem areas are not HC and CO, but rather the trade-off between NOx and PM. It then looks at the historical balance between these two, and how engine design has been modified to meet limits to date. Next it looks at the need for EGR to meet the 2002 goals and discusses the new PC-9 oil category targeted to lubricate EGR equipped engines. There is a brief discussion as to why EGR is a concern and a look at the anticipated costs of PC-9 followed by the required timing of the new tests and a discussion of what could happen if the category is delayed. Finally, the paper addresses some of the expected formulation impacts of PC-9, and most of these are directly counter to the anticipated needs of future engines with exhaust gas aftertreatment.

This presentation is Attachment 22A.

Similar issues on the subject are described in an NPRA paper presented by G. P. Fetterman at the Lubricants and Waxes Meeting, November 11-12, 1999 in Houston TX.

This paper is Attachment 22B.

"Future API PC-9 Engine Oil Category", August (Augie) Birke, Equilon Enterprises LLC, Houston, TX 77082-3101

API Service Categories for HD Engine Oils are developed by those branches of the Technical Societies and Trade Associations focused on Engine Lubricants. API Service Categories for HD Oils, e.g., CH-4, CG-4, etc., designate minimum performance requirements that a lubricant must meet to insure successful performance in diesel engines. The most recent HD API Service Category is CH-4.

Currently the industry is engaged in the development of the next Service Category for HD engines equipped with EGR These engines are designed to meet the October 2002 emissions standards for On-Road trucks.

Details on how the performance tests are selected, the procedure used to set performance limits and the costs involved will be highlighted for the next API Service Category for HD lubricants...currently designated as PC (Proposed Category) 9.

This presentation is Attachment 23.

"*Catalyst Compatible Diesel Engine Oils - DECSE Phase II*", Shawn D. Whiteacre, Cummins Engine Company, Columbus, IN 47201

The continued development of high performance, low emission diesel engines will require careful integration of engines, emission control systems, fuels, and lubricants. A research program is underway to study lubricant effects on the performance and durability of advanced diesel emission control systems. The Diesel Emissions Control - Sulfur Effects (DECSE) program explored in Phase I the detriments of diesel fuel sulfur on various NOx and PM control technologies. With drastic reductions in fuel sulfur presently under consideration, the contribution of the sulfur in the lubricant is potentially significant. Other non-sulfur containing lubricant additives may also impact exhaust catalyst durability. DOE, EMA, MECA, API, NPRA, and CMA will explore lubricant effects in a joint research endeavor within DECSE Phase II. The work group plans to identify lubricant derived emission components that are detrimental to the emission control system. This information is critical to provide formulation guidelines for future base oils and lubricant additive packages, and to identify design constraints for engine manufacturers and emission control system suppliers.

(The DECSE Program was recently renamed the Advnced Petroleum-Based Fuels, Diesel Emission Control (APBF-DEC) Program; it is referred to as the DECSE Program throughout this document.)

This presentation is Attachment 24.

H. PARTICULATE.

There has been about a 90 percent reduction in particulate emissions from diesel engines since 1974. Part of this came about because of excellent cooperative research on diesel emissions. The health effects issues of the late 70's and early 80's also stimulated in-house and cooperative research. The sulfur issue came to light at about the same time. Several SAE Technical papers in the early 1980's addressed issues such as sampling (SAE No. 852081) and composition of particulate and unregulated emissions including sulfate formation (SAE No. 840413). In March 1985, there was a Coordinating Research Council Workshop on Particulates in Dearborne, MI where some of the same issues we are debating were raised by an international group of scientists. The reductions in emissions we have seen since then are primarily due to engine design changes. Higher compression ratios, more efficient burning of the fuel have significantly reduced the particulate emissions, but at the same time, making it a drier particulate and changing the particle morphology. Dr. Kittleson in the next presentation addresses some of these changes. He has been a leader in the particulate area since the 1970's and his knowledge of the diesel particulate composition and structure is without question a key to solving some of the needs discussed at this workshop.

"Diesel Exhaust Particle Morphology: Nanoparticle Formation", David B. Kittelson, Center for Diesel Research, University of Minnesota, Minneapolis, MN 55455

The presentation gives an experimental (physical) and theoretical description of nanoparticle formation by engines. It suggests that nanoparticles may be formed from engine exhaust during atmospheric dilution by nucleation and growth of sulfate / SOF particles, or during the expansion stroke by nucleation and growth of metallic ash particles. Evidence suggests that current on-road engines emit mainly sulfate / SOF nanoparticles while engines running with high ash fuels or metallic fuel additives emit ash nanoparticles. Sulfate / SOF nanoparticle formation is extremely sensitive to sampling and dilution conditions. As elemental carbon is removed from engine exhaust, nanoparticle formation becomes more likely because volatile nanoparticle precursors that would have otherwise been adsorbed by the carbon nucleate to form new particles. Ash and sulfur from lube oil are likely to play an increasingly important role in nanoparticle formation as the sulfur content of the fuel is reduced and combustion improvements reduce elemental carbon formation.

This presentation is Attachment 25.

I. TRIBOLOGY.

The current EPA method of measuring particulate by trapping PM on a filter at moderate temperatures has long been an issue of controversy but until a better method to measure particulate by number or mass comes along, the methodology is the best current technology available. Therefore, removal of sulfur from the fuel is necessary if the diesel engine is to meet future EPA standards, not only from the catalysts needs, but also the necessity to reduce PM. In reducing sulfur in the fuel, and possibly diesel engine oils, we must consider other system requirements. Reducing sulfur in the fuels and lubricant leads to a fluid that has poorer friction and wear characteristics and possible compatibility problems with components, such as filters and seals, in the engine. Two presentations address this issue, the one by F.A. Kelley, an eminent tribologist, will directly address the issues and needs of this workshop. The second presentation by G.R. Fenske reviews the findings of a recent DOE friction and wear workshop at ANL. Although the workshop covers many tribology issues related to other industries, some of the issues and research topics have a direct relationship to the "Low Emissions Diesel Engine Oil" issues and needs.

"Tribology Needs for Low Emission Diesel Engine Oils", Frank A. Kelley, Program Manger, Advanced Materials Technology, Caterpillar Inc., Peoria, IL 61656

As manufacturers strive to develop engine and vehicle technologies that appropriately addresses environmental concerns while providing advances in productivity and value, a number of challenges arise which must be dealt with in key tribological systems and interfaces. Customers and users place high demands on equipment and expect to produce good results for their efforts. Changes in lubrication system technology to accommodate new system approaches to reduce emissions are particularly challenging. Implications on lubricant technology development are quite pronounced because lubricants are very tightly integrated into the relative success or failure of these systems. It is easy to show that changes in one area can have a negative impact on another. It will be important to find lubricant formulation and system design approaches that can favorably improve compatibility with the environment without sacrificing needed performance or cost. This presentation discusses the needs and expectations surrounding heavy-duty engines and vehicles and identifies a number of tribological challenges that must be addressed in achieving an appropriate balance. It will be necessary to develop a higher degree of sophistication in the development process to account for the increasing number of interacting effects that must be taken into account. This includes a need to develop faster, less costly ways to define acceptable fluid performance requirements.

This presentation is Attachment 26.

"Friction and Wear Workshop", George R. Fenske, Argonne National Laboratory, Argonne, IL 60439

Over the past few years, the US Department of Energy Office of Transportation Technologies has sponsored a series of workshops soliciting input form industry on critical needs in the areas of aerodynamic drag, friction and wear, thermal management, and brakes and rolling resistance. Reducing friction and wear in engines and drive trains represents one of these approaches that will enable the development of fuel-flexible, energy-efficient, heavy-duty transportation systems. This presentation reviews the findings of the Workshop on Reducing Friction and Wear in Heavy Vehicles that was held at Argonne National Laboratory in March of 1999.

This presentation is Attachment 27.

J. OTHER.

Two other presentations are included in this report that review research programs related to the interests of the low emissions diesel engine oils workshop. The first one is the

Coordinating Research Council program overview and the second covers research programs in progress on soybeans, a renewable resource.

The CRC was established in 1942 with the support of API and SAE and has had continuous cooperative industry and government research efforts on fuels, lubricants and environmental areas.

The soybean program was the result of congressional action and is managed by Omni Tech International, Ltd for the United Soybean Board. Although the Soy programs are diverse in nature, new lubricants and additives research are being funded in the program.

"CRC Program Overview", Brent K. Bailey, Coordinating Research Council (CRC), Atlanta, GA 30346

The Coordinating Research Council, Inc. (CRC) was established in 1942 with two supporting members, the American Petroleum Institute and the Society of Automotive Engineers. CRC serves as a focal point for collaborative efforts between the fuels, lubricants, and domestic equipment industries. Efforts are directed towards generating statistically valid data on interactions of fuels, lubricants, and vehicle systems on vehicle and automotive equipment performance, emissions, and resultant air quality. Information developed by CRC is made publicly available and is used 1) by industry to ensure optimum compatibility and customer satisfaction and 2) by industry, Government, and the public to enhance joint achievement of clean air and other applicable goals.

This presentation is Attachment 28.

" New, Non-Food Uses of Soybean Products", Blaine Rhodes, OmniTech International, Ltd, Midland, MI

The national program of the United Soybean Board for development of new commercial markets and uses of products made from soybeans are outlined, with concentration on the New Uses Section as managed by Omni Tech International, Ltd., of Midland, MI. Examples of products developed in the subsections of the New Uses Program – Coatings and Inks, Adhesives, Lubricants, Plastics, and Specialty Products – are reviewed with special attention to automotive and diesel crankcase motor oils.

A brief report on the progress of field trials of soybean oil-containing motor oils concludes the presentation

This presentation is Attachment 29.

K. Questions & Answers

Some of the comments to questions following the technical session presentations are recorded below. The comments are not comprehensive and are included as additional input to the discussions.

API PC-9 engine builders will use EGR to meet the next level of reductions in emissions. As a result the PC-9 oil will be required to meet the engine lubrication requirements. Will be ready by 2002.

Cost of development of PC-9 will be over $40M. Once the test matrix is developed it will cost the lubricant manufacturers over $350,000 to certify an oil under this new category.

HDD alone is a 400 million gallon per year market. This means under the API rules the base stocks have to be available to all manufacturers to keep a level playing field.

PC-9 is an evolution from the previous CH-4. After API finalizes the tests and procedures it requires one year before an oil can be licensed and put on the market. This is to allow all manufacturers and formulators the opportunity to get an oil on the market.

PC-10 will be the 2007 oil category. Discussions have already started on this category. This is where involvement should be. PC-9 is too far along.

ZDDP was first used in 1941 by Lubrizol. Serious questions remain whether complete removal is practical. Reducing concentration may be a fix.

ZDDP is the most widely used and effective additive and is the highest total contributor of sulfur in the oil (0.25 to 0.6 % sulfur)

Base oils in GP II contain only 0.001 to 0.003 % Sulfur. Group I can be from 0.1 to 0.4 % sulfur. The question is whether a sufficient quantity of GP II will be available at refineries. Currently the base stock mix is 2/3 GP 1 and 1/3 GP 2. Regarding availability of GP 2 and 2 1/2+, seven years is not a long time to get ready.

Oil consumption is now 2000 mi. / qt, shooting for 4000 mi. / qt. Therefore, additives must do a better job.

Considering reducing ZDDP in half. May have to change dispersant/detergent package.

Easiest fix is to come up with a sulfur tolerant catalyst.

Lubricants must be new and old engine compatible.

DOE-MECA-EMA started DECSE in 1998. Oil used in phase I. had 0.35 % sulfur. See information on internet.

Evolutionary approach means there is no radical change in the field. Revolutionary changes in additives can result in significant field failures even though lab and dynamometer tests are satisfactory. The metallurgy may also have to be changed if new additives are used.

DECSE agreed on set of study questions:

- What are the effects of emissions out - oil composition effects.
- How to study aged oil.
- Oil consumption effects.
- Additive contribution effects.
- Sulfated ash, zinc, phos, volatility, olefins, etc. need to be looked at.

Task 1. Select an engine with EGR and measure engine out emissions.
Task 2. Conduct bench tests using knowledge from Task 1.

EGR will mean an increase in soot and additional additives will be needed. Indications are soot adsorbs additives and renders them ineffective. Need to understand the fundamentals.

Closed crankcase needed? Maybe.

Oil consumption rate - need good way to measure rate? Look at specific lubricant component as a tracer. Also need new and better sensors.

PM filters do have size exclusion limits.

The smaller the particulates the higher the surface area.

Method to trap sulfur? Absorber.

Sulfur products the same from fuel and lubricant? Some are, some are not.

Ceramic engine? May be a way. Need to design whole system.

L. BREAKOUT GROUP INPUT

Five work or breakout groups were charged to take into account all of the workshop presentations, the knowledge and experience of the group members and to come up with their views on program(s) that DOE should consider participating in. Each group was to come up with priorities, program recommendations, key participants and estimates of time and cost of the proposed programs.

The five areas covered by the groups were: 1) Additives, 2) Basestocks, 3) Alternative Lubricants, 4) Alternative Fuels and 5) Catalysts.

A. Additives.

Additive issues: Main issue is the extent of catalyst deactivation that can result from current lubricant additive packages.

If revolutionary additive package changes result in low or no sulfur and phosphorus, low or no ash & metals, the results on the catalysts are unknown. Need to determine what a revolutionary additive change would do to solve the aftertreatment problems. Also, what would the compatibility be with other components in the system. May require development of components such as seals, gaskets, etc.

Projects:
- Need a good catalyst deactivation test,
- Need engine durability tests (3 engines),
- Fundamental test and model development needed to study additive mechanisms for catalysts deactivation and wear,
- Revised engine parts development may be necessary,
- Particulate effects on additives unknown.

Prioritized Work Scope:
1. Develop a test to study catalyst effectiveness and to evaluate oils. Cost may be $3M. Need data by 2002. (Some aspects of this project parallels the DECSE lubricant program and could be integrated with the DECSE lubricant study). Program already has a group of industry and government people cooperatively involved.
2. EGR will result in increased particulate loading . The effect of up to 8% particulate in the lubricant on properties, morphology/ultrafines (increased surface area) and especially the additive effectiveness needs to be established. Determine effect of particulate loading on additives. Two-year program, cooperative university - industry program, estimated cost $500K.
3. Development of new additives: Estimate an evolutionary approach would require about $1M DOE research/ $9M in research by additive mftrs. Target - 2004.
4. Determination of what hardware changes will be requires for new oils. Overlaps with additive development; an additional $500K is required.

B. Basestock Breakout Group:

Basestocks: The basestock comprises 80 % or more of the DEO. Need to determine basestock options and what properties influence the suitability of the basestock:
- Volatility, low sulfur, low nitrogen, low aromatics;
- Balance of aromatics and saturates;
- Dependence on additives selected.

Need to develop newer and faster methods of characterizing properties of basestocks and the additive effectiveness in new and used basestocks.

Projects: Piggyback on lubricants work being pursued on other programs.

1. Need evaluations of basestocks using low/zero sulfur fuels, common DI/VI package, GP 1 oil (Group 1, GF-3) oil, GP 2 oil, GP 2+ oil , GP 4 oils and engine emissions with new and used oils. Target 2004, Cost $1M.
2. Engine oil/market capacity evaluation (NPRA should do).
3. Engine population and growth survey to evaluate demand for new oils (EMA should do).
4. Methods development for product characterization.

C. Alternative Fuels Breakout Group:

Two leading alternative fuels for diesel engines are the Fischer-Tropsch and Biodiesel. Initial use will most likely involve use of alternate fuels as blends (20%) in low sulfur diesel fuel. Both NOX and Particulates are reduced when using FT. Some needs include:

- Alternate fuels effect on lubricants,
  - Fischer - Tropsch
  - Biodiesel
- Need monitoring of fate of fuels and some monitoring of effect on lubricants.
- Screening studies - MeOH type (MeOH blowby products in crankcase were detrimental to the lubricant. Extraction of additives occurred).
- Need to start studies using 2007 fuels.
- Quality control of vegetable oils and products such as methyl soyate need better product control if they are be used as a fuel or as an additive in diesel fuel.
- Maintenance studies limited. Need data.
- Compatibility of alternative fuels and lubricants with system components
- Ability to meet performance, durability and emissions requirements.

Projects:

1. Screening studies of alternate fuels and lubricant incompatibilities.
2. Industry standards organizations assessment of role of alternate fuel in low sulfur fuel.
3. Market development of alternate fuel, performance, PC-9 type testing.
4. Follow-up development & testing of engine, lubricant, basestock, & additive package.

Cost: $2M, 5 years

D. Alternative Lubricants Breakout Group:

Alternate lubricants include vegetable oils, synthetic esters and polyolesters, polyolefins. Two other options discussed in the meeting were using a segregated system and vapor phase lubrication. The vegetable oils and synthetics fluids have the added interest in that they are biodegradable.

Alternative Lubricant Issues:

- What happens to lubricants in conversion from sump to exhaust?
- What additives are needed to overcome drawbacks and what is their compatibility with system and their effects on emissions?
- Lubricant blends screening and evaluation (Government / Academia)
- Engine design - split engine system. (Industry / Academia)
- Recycling/disposal issues (Industry / Government / University)
- Contaminant removal (University)
- Vapor phase lube studies (University / Industry)
- Effect of lubricant on morphology - ultrafines.

Projects:

1. Current programs exist that have developed basic data on vegetable oils and have overcome low temperature and oxidation problems through blending and use of selective additives. Indications are significant PM reductions in emissions are obtained with these lubricants. Need is to extend laboratory testing to engine testing to evaluate long-term performance using low sulfur, FT and BD20 fuels. Conduct program to develop these lubricants as an alternative. 5 years, $1M.
2. Evaluate alternative lubricant effect on particulate morphology and particle distribution. 2 years, $1M.
3. Vapor phase lubricant of a single cylinder engine was demonstrated in the late 1980's. Develop a segregated system using vapor phase lubrication. 5 years, $1M.

E. Catalysts/Traps/Aftertreatment:

Issue: Impact of lubricant changes on emission control devices.

Projects:

1. Evaluation of fundamental deactivation & effects fields
2. Feasibility & demonstration of integrated systems (evaluation)
3. Evaluation of fundamental mechanisms in conjunction with different materials.

Conduct all three. Time: 5 years, Cost: $3 - 5 M. Integrate with DECSE Project.

4. Basic research to develop; 1) a post-combustion system compatible with current lubricating oils when using ultra low sulfur fuel and 2) an effective EGR particulate removal trap. Time: 4 years, $40million.

This is an accelerated comprehensive 4-year program was discussed that would include an extensive literature search of developments the past two years, followed by an extensive fundamental research project dealing with understanding the interaction of selected known catalyst deactivators and various catalyst formulations. This would include extensive research on trap materials and their structural characteristics, their resistance to heat and temperature, developing the regeneration process and evaluating the economics of these processes. A third phase would cover the system development from the mechanical and electronic stand-point with emphasis on advanced development engines for heavy duty and light duty diesel applications. The final phase would involve durability evaluation of the entire package both in controlled environments and field tests. The cost of the overall program would be $8 - 10 million per year.

IV. DISCUSSION.

1. CATALYSTS/TRAPS/AFTERTREATMENT.

It was essentially a consensus of the group that the efficiency and durability of the current Post-Combustion Systems (Catalysts/Traps) are reduced due to the presence of sulfur, phosphorus and metals in the exhaust stream being treated. The problem is the lack of specific information on the mechanism and to what extent each species causes problems. Several analytical tools are available to study systems but care must be taken to interpret results since reactions are not homogeneous in the systems. Analysis location (front, middle, and back) can lead to different conclusions. There is a need to obtain data on the mechanism and extent of poisoning and coating of active sites of aftertreatment traps and catalysts by the fuel and lubricant.

The ultimate fix would be to develop a sulfur tolerable catalyst. This would require revolutionary change. Time and investment costs make this an unlikely solution by the 2007 timeframe. The next best solution is to have a nation-wide ultra low sulfur fuel to enable optimizing current post combustion aftertreatment technologies. To do this will require development of an engine test to quantify the rate of deactivation due to each of the species of concern, sulfur, phosphorus and metals. This would allow establishing long term catalyst efficiency and durability.

Testing to establish engine out and catalyst out information will vary with engine design. Multiple (3 or more) engine designs will most likely be required to establish baseline data.

Several systems should be evaluated since there is no obvious winner of any of the systems described at the conference.

2. FUEL ALTERNATIVES.

Fuel alternatives include Ultra-low sulfur fuel, Fischer-Tropsch, B20 biodiesel, alcohols, Natural Gas, Hydrogen, Oxygenates. These fuels and fuel additives cover a wide range of properties and considerable data exists on these fuels, neat and in blends.

A critical review of the available data is needed to select the better candidates for the near future.

To compete in a non-crisis environment, a fuel must be available in sizable supply with a distribution infrastructure in place. The fuel should run in both available and next generation engines, have acceptable performance and public acceptance.

Both biodiesel and Fischer-Tropsch reduce emissions but the quantity available in the near future may be an issue. Best approach may be to use blends. Blending can occur upstream or downstream and use current distribution infrastructure. Using blends needs in future generation vehicles needs to be considered in R&D programs. This means that fuel property tests, emissions and other screening tools need to be standardized for evaluating these fuels. Astm standards will be required for new fuels and blends.

New fuels will also require screening tests to determine compatibility with the lubricants. Field data over time will be essential to establishing system durability.

3. LUBRICANTS.

The same problem exists here as was discussed for fuel sulfur. There is not any good quantitative data on the extent to which lubricant additives interfere with after-treatment systems. Zinc, phosphorus and some metal additives are suspect but it is not clear whether elimination, modification or simple reduction of the common additives in the oil is required to solve the problem. There is a question as to the role of the additives and whether the problem gets worse with aging (use) of the oil.

EGR will be required by most diesel engines to meet 2004 regulations. Cooled EGR results in condensation and recirculation of nitric acid and sulfuric acid into the engine combustion chamber and increases the particulate level in the lubricant. This leaves a number of issues to be resolved. There is the issue of how to resolve the TBN requirements. To deal with the additional acid may require modification of the TBN. Lower levels of a more active TBN or higher levels of a less active TBN are two options to be considered. In addition, increased soot levels may require a more potent or higher levels of a soot dispersant. The soot problem is complicated by the fact that the extremely large surface area of the soot may absorb additives and lead to increased wear problems. The soot may also affect the required concentration levels to insure adequate lubricant performance.

The lubricant problem is further complicated by the increased stress occurring as a result of customer demands for better oil control and increased drain periods. Current 2000 mile per quart oil consumption rates will approach 4000 mile per quart levels, or higher in the next decade. Higher risks in engine reliability and durability will occur if the low emissions diesel engine oil requires a revolutionary change in additives.

It is difficult to isolate problems in engines due to the complexity of chemical and mechanical processes occurring simultaneously. This leads to a need for innovative bench tests to explore the problems prior to engine testing.

The industry is struggling to meet difficult deadlines with PC-9 and PC-10 requirements for diesel engine oils for 2002 and 2007, respectively. Cooperative efforts between the engine, additive and basestock manufacturers to develop the PC-9 specifications and test requirements is high. Cost of development of the test matrix for PC-9 is estimated to be over $40 million. Once the test matrix is developed, cost to the lubricant manufacturers to certify an oil and obtain an API license under the new category will be over $340,000, assuming the oil passes the test matrix on its first try.

Alternative lubricants containing a mix of synthetic fluids and vegetable oils may be a possible route to low emissions diesel engine oils. Current programs have show the potential for such lubricants but there is a need to accelerate current programs (USDA/PSU/SwRI) and include an increase in engine and field testing.

4. BASESTOCKS.

The role of the basestocks is usually underestimated. They make up 80 to 86 % of current finished DEO and can range from essentially pure synthetics to very complex hydrocarbon mixtures. As a result, there are many questions on what properties are key to the suitability of basestocks - volatility, low sulfur, low nitrogen, low aromatics. The properties of the basestock can be a factor in engine out emissions and they can also be a factor in fuel economy.

Impact of basestock composition on particulate emissions is not known at this point. Factors that appear to impact particulates are viscosity, volatility, oxidation and thermal stability of compounds, and the deposit forming tendencies (can result in loss of oil control). API Group 2, 3 and 4 type base oils have reduced or no sulfur. Additional data on additive compatibility and effectiveness as sulfur and aromatics is reduced needs to be obtained. A big question with these base oils is whiter they will be available in sufficient quantity to satisfy the volume requirements. Heavy duty diesel engine oil volume alone is over 400 million gallons per year.

Vegetable oils are possible alternative basestocks. Currently, they are used in niche markets and may only become a viable engine oil basestock if the government, for environmentally reasons, imposes requirements for increased biodegradability on the use of petroleum basestocks. Even then, blending vegetable oils with biodegradable synthetics would be required to meet the lubricant volumes required.

5. ADDITIVES.

Current additive technology is the result of decades of evolution and the technology is built on a solid base of laboratory, engine and field tests. This gives current DOE's a large safety factor. Developing the next generation of low sulfur, metals, and phosphorus DEO, without relying on current additive technology, is no longer an evolutionary process. Even to cut the sulfur content in half may require a revolutionary approach. To accomplish this will require an understanding of both the additive and additive-materials reactions.

Conceptual strategies for consideration for development of low emissions DEO ranged from super-stable to decomposable base fluids that had fuel value. Others include:

- An environmentally friendly lubricant with low volatility and new additives that have limited or no effect on aftertreatment system.
- A low or non-ash consumable lubricant containing reduced sulfur and phosphorous;
- A segregated system using vapor-phase lubrication.
- A reduced or non-additive lubricant with component modifications such as coatings, modified materials, or self lubricated components.

Again, as in the case of alternative fuels, the first step is to quantify the extent to which additives result in reduced catalyst efficiency. This includes evaluation of aging (use) of on additive effectiveness and engine out emissions.

6. PARTICULATES

In addition to after-treatment studies, research on particulate morphology and the related health effects issues need to be resolved. Kittleson's work at the U of Minn. is the most advanced in the U.S. on particle characterization. The presence of nanoparticles and whether they are soot or non-soot organic and inorganic materials needs to be resolved. Once characterized, the health effects issues of the particulate can be addressed. Particulate matter reduction through reduction of the soluble organic fraction by tailoring the basestock is possible. Alternative and synthetic basestocks have shown the feasibility of this. Tailoring of Group 2 and 3 petroleum base stocks may also reduce PM.

The second major particulate issue is the fact that EGR will increase the soot loading in the lubricant. Some work is already in progress to develop baseline information using samples containing up to 3-4 % soot loading. With EGR the soot loading may go as high as 8% and there is a need to determine how this affects the reformulating of the next generation of lubricants. Characterization of the soot in the oil also needs to be done. Surface area and activity of the soot with additives will help define the additive mix required for the next generation of lubricants.

PC-9 and PC-10 are the next two DEO classifications. The test matrix for these oils is still unresolved and the particulate is a significant issue in the final test matrix to be established for these oils.

7. TRIBOLOGY.

The removal of sulfur from the fuel and reduction of current sulfur and phosphorus containing additives in the lubricants will impact the friction and wear of the engine