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Final Report

to

Department of Energy
Office of Transportation Technologies
Office of Transportation Materials

On

Advanced Lubrication Systems & Materials

(DE-AI01-92CE50354)

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Final

DISCLAIMER

Summary

This report described the work conducted at the National Institute of Standards and Technology under an interagency agreement (DE-AI01-92CE50354) signed in September 1992 between DOE and NIST for 5 years. The interagency agreement expires on September 30, 1997.

The interagency agreement envisions continual funding from DOE to support the development of fuel efficient, low emission engine technologies in terms of lubrication, friction, and wear control encountered in the development of advanced transportation technologies. However, in 1994, the DOE office of transportation technologies was reorganized and the tribology program was dissolved. The work at NIST therefore continued at a low level without further funding from DOE. The work continued to support transportation technologies in the development of fuel efficient, low emission engine development.

Under this program, significant progress has been made in advancing the state of the art of lubrication technology for advanced engine research and development. Some of the highlights are:

1. Developed an advanced high temperature liquid lubricant capable of sustaining high temperatures in a prototype heat engine
2. Developed an novel liquid lubricant which potentially could lower the emission of heavy duty diesel engines
3. Developed lubricant chemistries for ceramics used in the heat engines
4. Developed application maps for ceramic lubricant chemistry combinations for design purpose
5. Developed novel test methods to screen lubricant chemistries for automotive air-conditioning compressors lubricated by R-134a (Freon substitute).

Most of these finding have been reported to the DOE program office through Argonne National Laboratory who manages the overall program. A list of those reports and a copy of the report submitted to the Argonne National Laboratory is attached in appendix A. Additional reports have also been submitted separately to DOE program managers. These are attached in Appendix B.

This concludes any legal requirements under the interagency agreement, if you have any questions, please call Stephen Hsu at 301-975-6120 or address any inquiry to:

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APPENDIX A

Argonne National Laboratory Report list
&
A copy of the report submitted by NIST

A list of Argonne National Lab. Reports

1. Semiannual Progress Report, DOE-OTM Tribology Program, Oct. 1992-March 1993, ANL/OTM-93/1, May, 1993. - Removed for separate processing (M98020303)
2. Final Semiannual Progress Report, DOE-OTM Tribology Program, April-September 1993, ANL/OTM-93/2 - Removed for separate processing (TI940200722; 9800120628)
3. DOE-OTM Tribology Program, Bimonthly Progress Report, Oct.-Nov. 1992, ANL/OTM/BM-92/4
4. DOE-OTM Tribology Program, Bimonthly Progress Report, Dec., 1992 - Jan. 1993, ANL/OTM/BM-92/5
5. DOE-OTM Tribology Program, Bimonthly Progress Report, Feb. - March 1993, ANL/OTM/BM-93/1
6. DOE-OTM Tribology Program, Bimonthly Progress Report, April-June, 1993, ANL/OTM/BM-93/2
7. DOE-OTM Tribology Program, Quarterly Progress Report, July - Sept. 1993, ANL/OTM/BM-93/3

LUBRICATION TECHNOLOGY

FOR ADVANCED ENGINES

An Assessment of Industrial Needs

and a Proposed Program

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Submitted to
The US Department of Energy
Office of Transportation Technologies
Office of Transportation Materials

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EXECUTIVE SUMMARY

The transportation industry is facing stiff overseas competition, environmental regulations, and rapid technological changes. Energy conservation will become increasingly crucial in the face of traffic congestion, global warming, and population explosion. With the advent of new materials, many technologies heretofore not feasible have come within grasp. In the last decade, many such technologies such as low heat rejection engines and advanced gas turbine engines have been under active development. More recently, propelled by the environmental concerns and the clean air act, alternative fueled engines are under active consideration. Effective lubrication, in many instances, has become the technological barrier. This is because of the introduction of new materials, harsh operating environments, and the lack of thermally stable additives in the lubricant. The lack of lubrication technology is particularly obvious when it involves new materials such as ceramics, coatings, plastics, and novel alloys.

Emission regulations have also propelled extensive engine re-design to meet the increasingly stringent emission standards. This is particularly true in the heavy duty truck industry. Many of the new design concepts used to combat emissions while striving to retain the current fuel economy and durability criteria have to introduce new materials into the engine. Engine operating conditions in terms of temperature and load generally tend to increase to accommodate higher power densities and fuel economy. New materials are under increasing stresses and the need to protect them by effective lubrication has never been higher. Unfortunately, current lubrication technology for these new materials may not be applicable and the potential lubricant market is not large enough to warrant priority investment by the lubricant and additive industries. The lack of effective lubrication for new materials often scales back the advanced engine design and forces the engine developers to accept a lower goal than originally targeted.

The lubricant itself is a subject of discussion. Current mineral oil based lubricants are extraordinarily versatile. The major additive chemistries developed decades ago have been effective in meeting the technological changes by adjustments in formulations and the addition of inhibitors. With the advent of new materials, major innovations in anti-wear chemistries are needed to lubricate these new surfaces. The demand for biodegradable lubricants calls into question the basic molecular structures of the mineral oil-derived base oils. The need to reduce emissions, especially diesel particulates and hydrocarbons, reinforces the demand for new and novel synthetic molecular structures as well as ashless additive chemistries. Advanced engines such as low heat rejection engines and gas turbines demand much higher temperature stability from the lubricant, well beyond the stability range of mineral oils. The introduction of alternative fuels such as alcohols, natural gas, and others causes many unforeseen problems such as the formation of a large quantities of water/alcohol emulsion in the lubricant under certain operating conditions whereby many of the additives are extracted by the water/alcohol phase leading to increased wear in diesel injectors and cams, valves, lifters. Lubricants used with the new refrigerants designed to replace Chlorofluorohydrocarbons (CFC) to protect the atmospheric ozone layer can be improved to provide longer durability, and better wear characteristics of the automotive compressors.

Under these circumstances, a technical assessment was conducted by the National Institute of Standards and Technology under the sponsorship of the Office of Transportation Materials, Office of Transportation Technologies in the Department of Energy to define the future lubrication needs for current and advanced engines. The assessment consisted of literature reviews, one-on-one discussions with engine designers, component developers, materials suppliers, and engine manufacturers. In addition, a three-day intensive workshop was held on September 21-23, 1992 at Northwestern University, Evanston, Illinois. A selected group of industrial experts was invited to attend the workshop. During the workshop, the attendees highlighted the current and future concerns of their respective industries and arrived at a general consensus on priority technological areas and defined the opportunity for a cooperative research and development program among industries, academia, and government laboratories.

In the automotive area, the short term needs identified are in component technology development such as high power density gears and the continuously variable transmission (CVT). Computational design models and integrated system analysis deserve attention. Alternative fuels introduce many unexpected lubrication problems; none of them are disabling, but the impact on durability and maintenance practice raises concerns. The most significant lubricant issue looming over the industry is the air conditioner compressor wear and durability introduced by the replacement of the chlorofluorocarbons (CFC) with environmentally compatible hydrofluorocarbons (HFCs). New lubricants have been identified for introduction into future production models, but the search for improved lubricants continues. In addition, the retrofit issue of potentially 40-50 million cars already on the road makes this issue of national importance. A concerted effort by academia, government, and industry on this issue is urged to develop a timely solution to maintain competitiveness and to address a very important environmental issue.

In the longer time frame, fuel economy and safety are the key issues for the automotive industry. Control of friction and wear of new materials, especially for light weight materials both in service as well as in the manufacturing of this class of materials by novel lubrication technology is important. The industry also feels that better bench tests are needed to screen materials and lubricants to avoid costly mistakes and premature failures and remain a priority topic.

In the diesel industry, there is a consensus building that for lubrication of new materials, new and novel lubricant structures are needed to solve many technological issues in new engine designs, emission controls, and environmental compatibility (biodegradability and recyclability). Better bench test methodology and modeling of the component and engine performance are needed to reduce the technology development cycles. High temperatures introduced in the combustion chamber may improve energy efficiency significantly and may hold promise for future fuel efficient, environmentally compatible engines. However, achievement of this goal depends on the availability of cost-effective ceramics and ceramic coatings. Lack of effective lubrication for ceramics has limited the temperatures in such systems. There is a consensus that this is an important issue, that an industry/government/academia cooperative venture may be needed which will benefit the industry as a whole.

Alternative fuels in diesel industry are also an important concern. Currently, fuel injector wear and engine wear are evident from the alcohol-containing fuel tests. This is due to extraction of additives from conventional lubricants. Some alcohol compatible chemistries have been developed but the technology is not wide spread and the mechanism not clearly understood. This is a continuing concern. For natural gas engines, some of which may be used in the 10 metropolitan areas mandated by the Clean Air Act Amendments of 1990, valve recession wear is a concern. Ceramic inserts may be an answer, but the durability and design criteria are not currently understood. Part of the issue is the lack of effective lubrication for ceramics.

In the lubricant/additive industry, there is an increasing recognition that new chemistries are needed for new materials and that there is an urgent need for high temperature stable additives for the next generation of engines and components. However, the current market pressure is such that heavy investment in long term research is not likely. The industry itself needs better research infrastructural support which has been eroding in the last decade. Foreign competitions are beginning to surface. The time may be ripe for a concerted effort to bring the additive industry, engine manufacturers, components designers, and government (national labs and government programs) together to address this critical issue in lubrication technology.

Most of the industrial participants in the workshop indicated that they are willing to participate in such an effort in principle. The specific level of participation would depend on the specific subjects proposed.

A research program based on the findings from the literature review, workshop, one-on-one discussions, and visits has been proposed. Timely adoption of the program will assist the transportation industry in this country to remain competitive. The proposed research program addresses industry needs identified in four areas:

I. High Temperature Liquid Lubricants for Advanced Engines

- 1.1 Development of Cost-Effective 300°C Synthetic Base Fluids
- 1.2 Development of High Temperature Stable Additives
- 1.3 Ultra-High Temperature Lubrication Systems

II. Lubrication Technology for New Materials

- 2.1 Lubrication Base Technology for New Materials (Same Materials)
- 2.2 Lubrication Technology for New Materials (Dissimilar Materials)
- 2.3 Lubrication Technology for Cost-Effective Forming/Fabrication of New Materials
- 2.4 Design Guidelines for Materials-Lubricant Combination
- 2.5 Application Insertion and Field Testing

III. Environmental Friendly Lubricants

3.1 Emission Control Technologies for Engines
3.2 Environmentally Compatible Lubricants

IV. Lubrication Technologies for Engine Durability and Component Developments

4.1 Fuel Efficiency Technologies
4.2 Million-Mile Engines
4.3 Engine Components and New Engines
4.4 Bench Simulation Development for Engine Performance

1.0 INTRODUCTION

In 1992 a comprehensive technical assessment was conducted to define the future lubrication needs for current and advanced engine designs. The assessment consisted of literature reviews, one-on-one discussions with engine designers, component developers, materials suppliers, and engine manufacturers. In addition, a three-day intensive workshop was held on September 21-23, 1992 at Northwestern University, Evanston, Illinois. The attendees of the workshop were industrial experts specifically invited to attend the workshop. During the workshop, the attendees highlighted the current and future concerns of their respective industries and arrived at a general consensus on priority technological areas and defined the opportunities for a government program that will serve their needs. The results of the assessment and the proceedings of the invited workshop are presented in this report.

2.0 BACKGROUND

To better understand the lubrication technology needed for advanced engines and its significance to future engine development it is important to have a good perspective on the incentives and motivations driving engine development and the technical trends in that development (Table 1). From the early days, the driving force in engine development has been to achieve high power density with durable components and engines. High power density means greater performance in a smaller, lighter engine. This inherently means higher service temperatures and more severe environment for the lubricant. Improved durability means longer service lives for the engine components, reduced failures, and less frequent maintenance intervals for the engine in spite of the increased temperatures, pressures, and speeds. In short, the components have to be better protected as servicing conditions become more severe. In the past several decades, these challenges have been met with improved materials, surface coatings, higher oil additive levels, and improved formulations. However, for some advanced engine concepts, the lubrication technology is inadequate. The engine technology, enabled by the availability of the new and better materials, has undergone a renaissance of ideas and innovations and the current lubrication technology has become the technology barrier for some of the advanced engine concepts.

Table 1

Trends in Engine Development

High Power Density	Alternative Fuels
Durability	Manufacturability
Fuel Economy	Recycling
Emissions	Low Cost Materials and Designs
Use of new materials	Use of Light Weight Materials

Additionally, recent issues such as emissions, fuel economy, recycling, and manufacturability have been superimposed on power density and durability. These have led to major modifications in current engines and the development of a whole series of new engine concepts. These developments require an acceleration of engine lubrication and materials technology. The primary factors have been the Clean Air Act Amendment of 1990 (global warming), the Energy Security Act of 1992 (fuel economy), and the Energy Policy Act of 1992 (energy conservation and alternative fuels). Global warming and emission control efforts have led to the replacement of CFCs in air conditioning units in automobiles, innovative redesign in diesel engines, and the use of alternative fuels. Fuel economy concerns have resulted in component friction reduction, use of light weight materials, and better engine tuning. Both emission control and fuel efficiency have a profound effect on engine design and a renewed demand for improved lubrication technology.

Increasing emphasis on competitiveness by engine manufacturers has led to demands for quality enhancements, low maintenance, on-board engine diagnostics, longer warranty periods, lean production techniques, and the demands for and the use of cost-effective materials and designs. The same forces also drive the need for new and innovative lubrication technologies in improved materials processing (forming, rolling, machining) as well as better materials protection in engine components. These issues are discussed in the following sections.

2.1 EMISSION CONTROL

Environmental concerns have surged to the forefront of the world's agenda after the end of the cold war. In the US, the passage of the Clean Air Act Amendments of 1990 and the outlook for widespread adoption of the more stringent California standards by local jurisdictions are driving development efforts toward low emissions in all segments of the engine-vehicle industry. From an emissions standpoint, vehicles can be considered in two broad categories: light duty (cars, light duty trucks and vans) and heavy duty (trucks, buses, and off-road equipment).

For automotive and light duty vehicles, the California clean air requirements are usually taken as a goal. These are listed in Table 2. These standards require an increasing percentage of an auto maker's fleet sold in California to meet progressively tighter emission control levels for hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) during the next ten years. Vehicles are certified on a chassis dynamometer using the US EPA testing cycles. Tail pipe emissions of HC, CO and NO_x are measured and recorded in grams/mile. These are compared to the established standards for each pollutant.

The challenges presented by the California requirements will not be met easily. Some of the approaches being explored and/or being developed are: improved cold-start control; improved air/fuel ratio control; low crevice volumes in piston and gasket areas, fast-burn combustion, variable valve timing; low thermal inertia exhaust manifolds, exhaust-port liners; catalyst improvements, and fuel system improvements. These changes will affect lubrication requirements; moreover, in the battle against emission, the lubricant itself contributes to the HC emission.

Table 2

California Clean Air Emission Requirements

Model Year	0.39 HC 7.0 CO 0.4 NOx	To 50,000 miles 0.25HC, 3.4CO, 0.4NOx To 100,000 miles .31HC, 4.2CO, 0.4NOx	Transitional low-emission vehicles 0.125HC, 3.4CO, 0.4NOx	Low-emission vehicles 0.075HC, 3.4CO, 0.2NOx	Ultra-low emission vehicles 0.040HC, 1.7CO, 0.2NOx	Zero-emission vehicles 0.0HC, 0.0CO, 0.0NOx
2003				75	15	10
2002				85	10	5
2001				90	5	5
2000				96	2	2
1999		23		73	2	2
1998		48		48	2	2
1997		73		25	2	
1996		80	20			
1995		85	15			
1994	10	80	10			
1993	60	40				
1992	100					
1991	100					

Figures for exhaust standards are in grams per mile; HC=hydrocarbons; CO=carbon moNOxide; NOx=nitrogen oxide
California's new rules require an increasing percentage of an automaker's fleet to meet progressively tighter emissions standards.
For example, by 2003, 75 percent of sales must have low emissions, 15 percent ultra-low emissions and 10 percent zero emissions.

Emission standards for heavy duty diesels (class 7 and 8 trucks) are becoming increasingly stringent nation-wide. These standards are shown in Table 3 and are measured in grams per brake-horsepower-hour.

Table 3

US Heavy Duty Truck Engine Emission Standards
As Required by the Clean Air Act Amendments of 1990

	Limits, gm/BHp-Hr			
	1990	1991	1994	1998
HC	1.3	1.3	1.3	1.3
CO	15.5	15.5	15.5	15.5
NOx	6.0	5.0	5.0	4.0
Particulates	0.6	0.25	0.10	0.10

Starting in October 1993, the sulfur in diesel fuel will be limited to 0.05 percent by weight from the current specification of 0.4 percent, and the minimum cetane index will be at least 40 (1). These changes are aimed at alleviating some diesel particulate and HC emissions and will lessen the lubricant overbasing requirement to neutralize the acids from the oxidation of sulfur components in the fuel. At the same time, the elimination of the majority of the fuel sulfur compounds may affect component wear, the extent of which is uncertain. Additionally, the 1998 reduction in the NO_x level must be considered. The heavy duty diesel industry appears to have met the 1994 standards with cleaner fuels and many engine re-designs. The outlook for 1998 at which time, the NO_x level will be reduced to 4.0 with the particulate level at .01, is uncertain. No one knows with any certainty how or if they can be met with the current technology.

The use of alternative fuels offers some hope to meet these requirements at least in major metropolitan areas where air pollution is increasingly a concern. The use of alternative fuels, while solving some emission problems, also introduces a host of new problems associated with engine durability, corrosion, lubrication, fuel distribution and supply, fuel storage and safety. Some of these issues will be discussed in more detail below.

One major driving force for emissions control is contained in the Energy Policy Act of 1992 (3). This acts mandates the use of alternative fuels in federal and local government automobile fleets. For example, by FY 1999, seventy-five percent of government vehicles must be equipped to use alternative fuels and fuel them at commercial facilities. In addition, this act requires the government to "carry out a program on techniques relating to improving natural gas and other alternative fueled vehicle technology". Many specific technology areas are included in the program (Table 4). The availability of new lubrication technologies for new materials could limit the rate and extent of technological development in this important area. New designs enabled by new materials will form the basis of many solutions in alternative-fueled vehicles and these will have a significant impact on engine lubrication systems.

Table 4

Alternative Fuel Program Areas
Energy Policy Act of 1992

Fuel Injectors	Engine Durability
Carburetion	Ignition
Manifolds	Multi-Fueled Engines
Combustion	Emissions Control
Power Optimization	Novel Compression Concepts
Energy Efficiency	Fueling Technologies
Lubricants & Detergents	Advanced Materials
Valve and valve train wear	

Also included in Title XX Reduction of Oil Vulnerability is an advanced diesel emissions program which requires the government to conduct a five year program on "diesel engine combustion and engine systems, and fuels and lubricants to reduce emissions of oxides of nitrogen and particulates". The goal is to assist diesel manufacturers to meet current and future NO_x and particulate emissions.

2.2 FUEL EFFICIENCY

The drive for a major fuel economy improvement in automobiles has been brewing for some time. While vehicle manufacturers have met or exceeded the original fuel efficiency standards established in the 1970's after the oil crisis (Figure 1), the increase in car population, the lack of road construction and the resulting traffic congestion, and much longer time of ownership of vehicles have put additional pressure on continual improvement in fuel economy. It has been estimated that in order to maintain the current emission level of pollutants, the average fuel economy of automobiles will have to double or triple by the year 2010. The previous improvement has been accomplished by many of the advances in engine designs such as four valves per cylinder, fuel injection, variable valve-timing, better air-fuel ratio control, friction reduction, and weight reduction. This approach has more or less run its course. New technology and radical design changes utilizing light weight materials, alternative fuels, and advanced propulsion systems are needed to meet the future national goals of environmentally responsible vehicles.

On the diesel side, the Energy Policy Act also mandates in Title XXI that the government carry out a five year program "to improve the efficiency of heat engines" which will include field demonstrations, incorporation of materials that increase engine efficiency, and advanced engine design for electric and industrial power generation. Currently, the average fuel economy for heavy duty trucks is about 11.8 L/Km (5 gpm). With the 1994 and 1998 emission standards looming in the future and increasing traffic congestion around major metropolitan cities, fuel economy is expected to drop significantly. High efficiency engines enabled by the availability of new materials (e.g. low heat rejection engine with ceramic parts and coatings in conjunction with light weight vehicles) may provide options for future technology to meet these challenges.

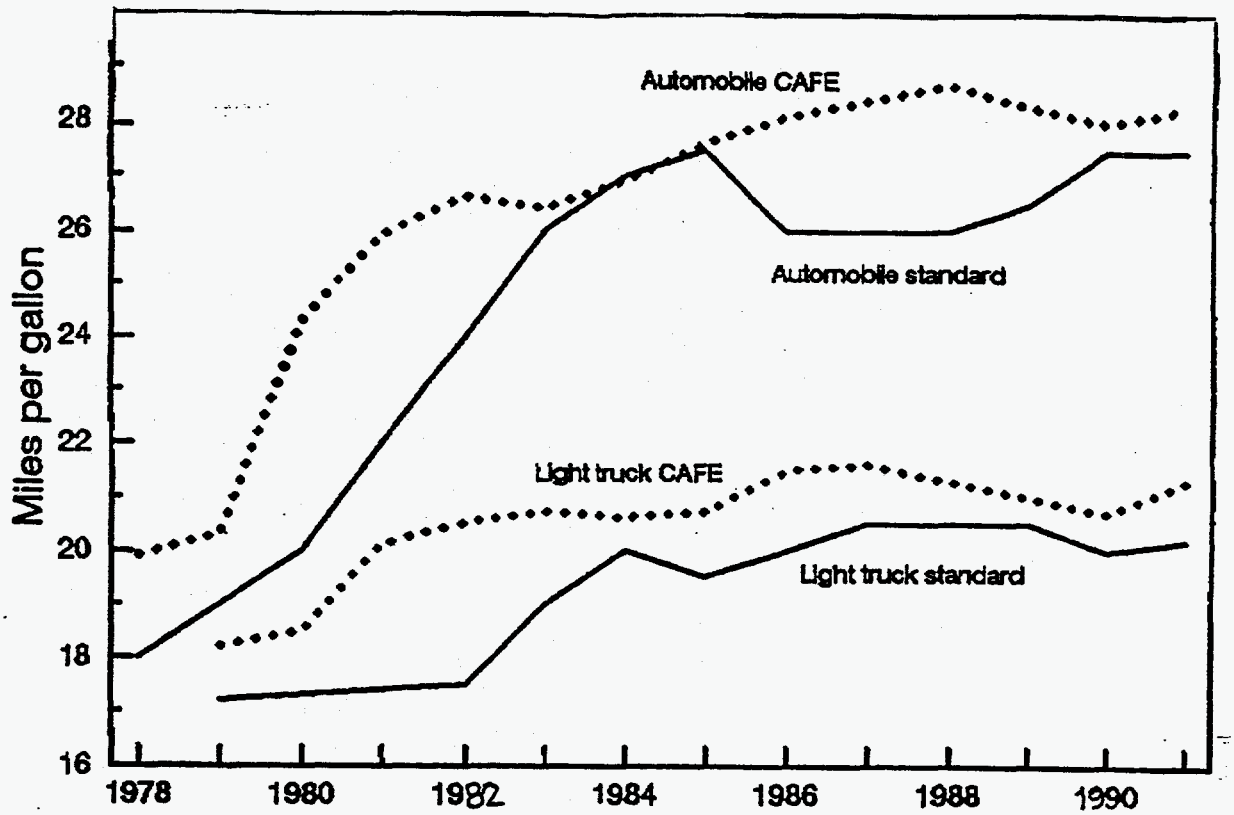


Figure 1. Corporate average fuel economy (CAFE) standards and sales-weighted fuel economies for automobiles and light trucks, 1978-91

2.3 ALTERNATIVE FUELS

The Energy Policy Act defines alternative fuels as those shown in Table 5. Other fuels might be cleaner or reformulated gasoline, vegetable oils, shale oil, fuel oil, coal slurries, and cleaner diesel fuels.

Table 5

Alternative Fuels

Methanol	Hydrogen
Denatured Ethanol	Coal Derived Liquid Fuels
Alcohol Mixtures with Fuel	Electricity
Natural Gas	Other
Liquified Petroleum Gas	

Current reciprocating piston engines require a narrow range of fuel properties for high performance. Substitution of a wide variety of alternative fuels requires substantial engine modifications and re-optimization to maintain performance and fuel efficiency. Among the many potential problems facing alternative fuelled vehicles, durability, safety, and performance seem to be the top concerns. Without proper engine modifications and adjustments, just substituting a potentially clean-burning alternative fuel does not assure low emissions, effective operation or equal durability. Some of the areas most sensitive are the fuel system components (injectors, pumps, bearings); seals, whose construction materials may not be compatible with the fuel, and the engine components (rings and valves) which may be subject to increased corrosive, abrasive or adhesive wear. Current valves and valve train components are lubricated by the heavy fractions of the diesel fuel, such as sulfur containing C_8 olefins. Once clean fuels such as natural gas or methanol are used, such lubricating elements are absent, and significant wear of the valves and valve seat inserts occurs. In fact, such observations have been recently confirmed by prototype engine testing (4). Combination of lubrication technology and materials may be necessary to provide suitable solutions to this challenge. Each alternative fuel has a different chemical compositions and introduces a unique set of requirements to an engine; thus unique lubrication and wear problems will be found for each alternative fuel. These should be defined early in a program so that focused action can be taken to overcome the barriers.

2.4 LIGHTWEIGHT AND NEW MATERIALS

One of the most significant technological advances in the last five years has been the unprecedented progress made in materials sciences. A new generation of materials which are stronger, harder, lighter, and wear and corrosion resistant has come into being. With these materials made available, engine designers have begun exploring different materials in engine components. Emphasis has been placed on ceramics, ceramic coatings, composites (both metal- and ceramic-matrix composites), light weight metals like aluminum, titanium and magnesium, and polymer blends (5).

Advanced and reinforced polymers possess many of the required properties and are being designed into a growing number of engine applications (6) such as valve covers, oil pans, manifolds, and a variety of smaller engine parts (7). This trend is expected to continue as higher temperature, higher strength polymer blends become available. The predominant use of these polymers is expected in structural parts to reduce weight; the question is one of durability and cost. Hot lubricating oils coming into contact with these materials may extract plasticizers from the polymer blends and cause the engineered plastics to degrade and fracture. On the other hand, plasticizers extracted from the plastics may react with the additives in the lubricant causing accelerated lubricant degradation and subsequent engine damage.

Ceramics have been in existence since early civilization. The advent of modern advanced ceramics, however, occurred only in the last decade. Tremendous strides have been made recently in making ceramics stronger, tougher, and more reliable. The unique high temperature strength of ceramics makes possible higher combustion temperatures such that the potential amount of energy that can be recovered is larger, hence increasing energy efficiency. This gives

rise to the concept of "heat engines or low heat rejection engines". As a result, the use of ceramics in engine components has been proposed for many years (8-9). Although progress has been slow it is now clear that they will eventually be used in certain critical applications like valves (10), cam followers (11), turbo charger rotors (12), tappets (13), and rolling contact bearings (14) to assure longer wear lives at higher temperatures. The most suitable ceramic to date for use in engine parts where concentrated contacts occur appears to be silicon nitrides and efforts are under way in industry and government agencies to develop practical engine components. It is also clear that ceramic coatings will be used not only for wear resistance but also as thermal barriers (15-16). Generally the coatings are extensions of technology developed for the aircraft gas turbine. Coatings for thermal-barrier applications are typically Cr_2O_3, ZrO_2, and $ZrO_2.Y_2O_3$ (17-19). Wear resistance of ceramics and ceramic coatings have been studied extensively. Results suggest high friction and high wear for unlubricated contacts; a suitable lubrication technique will be needed to control the friction and wear of ceramics.

Unfortunately, lubrication of advanced materials proves to be a challenge. For decades, because of the extraordinary versatility of modern petroleum-based lubricants, and the predominant use of iron and steel alloys in engines, lubrication technology has largely been taken for granted. Current antiwear chemistries have been developed empirically based primarily on the reactions between steel and phosphorus, steel and sulfur, and occasionally other metallic elements with nitrogen and oxygen. When new materials based on entirely different elements in the periodic table are used, new anti-wear chemistries have to be developed. Progress is slow and requires extensive study because of the lack of understanding of the basic lubrication mechanisms between material surfaces and various chemistries. Yet this type of knowledge is critical for the introduction of ceramics into engines. It took almost fifty years and many engine tests to optimize the metal lubrication chemistries. Hopefully, with a concerted effort among universities, government, and industries, new chemistries can be developed in time to meet the new energy and environmental challenges. Specific research topics such as chemistries for different ceramics, their load capacity, wear rates, friction levels, wear transitions, and additive-additive compatibility require systematic study and compilation into a guide-map for designers' use. These can be called lubrication application maps. Such maps for various new materials and lubricant chemistry combinations, once developed, will ensure that industries can take advantage of the new materials available and develop suitable technologies.

The use of light weight metals in engine parts is increasing. A favorite component area is the piston (21-25) to reduce inertia effects; however, other components such as valves, connecting rods, and oil pans have been suggested (26-28). These light weight metals are difficult to lubricate, are erosion prone, and may have much higher wear rates and lower load capacity. Although alloys such as Al-Si and Al-Pb have been developed to improve the wear resistance, the trend seems to be toward the use of ceramic or nickel coatings on steels and metal-matrix composites.

Metal-matrix composites (MMC's) have been under intensive development for many years because of their high strength to weight ratios. Both fiber composites (29-32) and particle composites (33-35) are now being considered for pistons and wear parts as well as engine blocks

(36). The lubrication and wear behavior of MMC's has received very little attention to date. From a chemical point of view, many of the elements used to make the composites are not transition metal-based, anti-wear chemistries probably will need to be changed. A recent conference (37) covers dry sliding behavior of MMC's but provides very little information concerning lubrication. The same conclusion can be applied to coatings, many of which are made of titanium, tungsten, and cobalt. Lubrication may be an issue.

In light weight materials, the cost of the materials is often controlled by the fabrication cost; for example, the speed of rolling and the ease of fabrication of the aluminum alloys determine the final component cost. For automotive structural applications, cost is a critical factor. Compared with pure aluminum, the addition of alloying elements to make wear resistant aluminum alloys increases the brittleness of the material, and the rolling speed has to be significantly reduced thereby increases the cost. Significant advances can and should be made in the area of light weight materials fabrication to reduce the cost.

2.5 ADVANCED ENGINE DEVELOPMENT

In response to the previously discussed driving forces (Table 1), engine developments have been accelerating in recent years. Engines under active consideration are shown in Table 6.

Table 6

Advanced Engine Development

Light Duty Vehicles	Heavy Duty Vehicles
Advanced Spark Ignition Engines	Advanced Diesels
Two Cycle Engine	Turbocharge
Automotive Gas Turbine	Turbocharge-Intercooler
Rotary Engine	Turbocompounded
Electric and Hybrid Electric	Million Mile Diesel
Fuel Cells	Low Heat Rejection Engine
	Heavy Duty Gas Turbine

For the spark ignition engine the trend to four and six cylinder designs is expected to continue (38). Displacements are expected to increase slightly. Down-sizing of the engine is expected in order to fit into smaller compartments, thus enhancing vehicle styling. Rapid changes are expected in detailed engine technology to obtain "higher specific power and greater component precision to reduce friction and dynamic forces." Better control of combustion processes (39) are foreseen with breathing enhancements, e.g., turbocharging, variable engine geometries (intake valve closing, variable stroke, variable displacements, intake tuning and variable valve

actuation devices). Variable valve actuation appears to be a promising approach which can optimize the tradeoffs between engine performance, economy, emissions and idle stability (40). However, the major unresolved problems with these devices appear to be high friction and limited durability. Lubrication requirements based on these developments would be higher lubricant temperature, smaller bearings operating at higher temperatures, and the need for low friction surfaces or designs. Improved emission controls are expected to continue with emphasis being placed on detailed changes in piston, piston ring and liner to minimize oil consumption.

It is further expected that new materials will gradually find use in all advanced engines where their use will reduce weight, increase durability or lower manufacturing costs. Effective lubrication of such materials is, as previously stated, an unresolved question.

The two-stroke engine has drawn new interest because of reduced size and weight, improved fuel injection technology, and low cost (41). Both wet and dry pump engines have been used in the past. Exhaust emissions and combustion control are major areas of concern. A major problem (42) is lubrication. Conventional 4-stroke wet pump lubrication systems cannot be used because oil is drawn past the rings into the combustion process. "Lubricant and lubrication systems for these engines will need to be as carefully engineered as any other critical component."

Developmental work continues on the automotive advanced gas turbine (AGT) engine concept. The major changes affecting lubrication in this technology are the higher temperatures and the anticipated use of ceramics. Cooling is limited so high temperature materials and lubricants must be isolated. Of major concerns in the AGT are the main shaft bearings and the regenerator seals. Bearing temperatures are expected to reach 315°C which is beyond the range of conventional lubricant capacity but within bearing material capability. Aircraft gas turbine bearing systems reach temperatures about 100°C lower; however, higher temperatures (400°C) are anticipated. Thus developments in the aircraft field would benefit auto applications. However, in both applications; engineers are hoping for a breakthrough in solid lubrication which would eliminate the fluid lubricating system and remove the thermal barriers. The regenerator seal is much more difficult. A continuously rubbing surface seal is required to operate at 1000°C. Current plasma spray coatings utilizing CaF_2 are limited to about 875°C. The main problem is to find solid lubricants operable from room temperature to 1000°C and to then develop processing technology for coating application. Coating wear lives of 3000 hours or more are needed; this is a formidable problem.

The rotary engine has been introduced in Europe, Japan and the U.S. with only marginal success. Even after significant investment by GM, Deere and Mazda chronic problems have been encountered with high emission levels, low fuel economy and short wear life of apex tip-seals on the rotor.

There is currently considerable interest in electric, hybrid-electric, and fuel-cell propulsion. However, lubrication requirements appear to be within current technology, with the exception of certain hybrid engines.

The primary focus in advanced diesel development is three fold: meet emission standards, meet alternative fuel requirements, and make significant improvements in durability so that engine overhaul is extended routinely to a million miles instead of the current 300,000 miles. The first two objectives were discussed previously. The million mile engine developmental goal has to be discussed in the context of emission as well as alternative fuels. The desire to continuously improve durability has always been there. In the past, wear and materials limitations have put a cap on some engine component life. Yet the time to first overhaul increased from 100,000 miles to 300,000 miles in the last two decades. With the availability now of so many new materials with significantly improved properties, the prospect of extending the overhaul time to a million mile appears within reach. Yet without resolution of the lubrication issue, many of the new materials cannot survive long term usage. The addition of components of significant shorter lives due to the need to meet the emission standards and/or to be compatible with alternative fuels may shorten the current 300,000 miles time frame. In addition to lubrication requirement of new materials, considerable challenges remain even for conventional materials to endure a million miles of operation. Far better protection of metal surfaces and design methodologies would have to be developed for such engines.

Most of the major manufacturers of heavy duty engines have designed, built and tested turbo-compounded engines. The increased power density from such engines (as turbocharged engines) leads to somewhat lower fuel consumption. It also means higher engine temperatures and lower durability. This is directly opposite to longer component life requirements. All of the wear parts in the engine need lubrication attention including valves, valve stems, valve guide cams, cam followers, injectors, nozzles, and fuel pumps. Most critical are the combustion chamber related components because of the hostile environment for lubricants. There is also a need for low cost manufacturing technology.

There is also a trend toward less cooling and only one fluid. Cooling requirements may be handled by the lubricant. Such a trend would put new demands on the lubricant.

The low heat rejection engine has been under development for many years and some success has been achieved. Because cylinder temperatures have been reduced for increased efficiency the distinction between the advanced diesel and the low heat rejection engine have become blurred. The present thrust of the low heat rejection engine is toward low fuel consumption. The general approach is to reduce the thermal losses from the engine by reducing or eliminating the cooling system and recovering more of the increased energy from the exhaust gases. This is accomplished by using advanced high temperature materials, such as monolithic ceramics or more recently by using thermal barrier coatings on pistons, liners, fire deck, valves and ports. This, of course results in much higher engine operating temperature. Top ring reversal temperatures up to 500°C (932°F) are expected. This is beyond the capability of current lubricants in conventional systems and represents the limiting problem in this engines development. A variety of approaches are being investigated which show promise but a much more concentrated effort is needed to define materials and operating requirements and to evaluate feasible alternative lubrication systems.

Application of gas turbines to passenger cars is really a more demanding requirement than for trucks. This technology also benefits from aircraft gas turbine developments and the problems (high temperature lubricant, bearing materials, and seals) are essentially the same. A key factor for commercial gas turbine applications will be to minimize costs.

From this brief review of engine developments it is clear that lubrication problems abound. Fluid lubricant temperature limits are being reached and alternative systems must by explored. A key feature will be oil control in the ring-liner area aided by dynamic cylinder models. Alternative fuels will require a revisiting of engine component materials. New materials are being introduced for weight and thermal control. Such materials will require new lubrication approaches. Solid lubrication systems will be necessary for certain high temperature applications.

These problems are of sufficient magnitude that they can not be solved in general but rather within the confines of very specific engine requirements, that is for specific geometries, operating conditions, materials, lubricant additive packages, oil residency times, etc. To define these problems in greater detail, a workshop was held, along with an extensive survey of industrial needs. The results are contained herein.

3.0 INDUSTRIAL WORKSHOP

Based on the information gathered from literature and one-on-one visits and discussions, there appeared a wide-spread interest in lubrication research. A decision was reached to hold an invited workshop where industrial experts could come together and discuss topics of mutual interest. Technical experts primarily from industries were invited to attend a three day workshop where various topics were discussed in detail and research needs were defined. A technical survey form was sent to participants before the workshop. This was followed with a second survey distributed at the workshop after the initial presentations. Additional visits and one-on-one discussions were also held after the workshop with several industrial and government personnel for further definition and clarification. The results are described in the following sections.

3.1 WORKSHOP FORMAT AND ORGANIZATION

The workshop was held at Northwestern University, Evanston, Illinois on September 21-23, 1992. The purpose of the workshop was "to solicit industrial inputs on future research needs in advanced lubrication technologies for transportation". Forty-four invited experts participated. Table 7 shows the breakdown in terms of academia, government, and industry. Names and addresses of participants are listed in Appendix I while the organizations represented are listed in Table 8.

The workshop format utilized technical presentations and in depth discussions by small groups. The list of technical presentations is given in Table 9 highlighting various topics. After one and one half days of presentations, the attendees were divided into five groups each led by a chairman. The groups and their chairmen are shown in Table 10. Each group was given a questionnaire detailing the various technological areas and a list of technical projects. The groups then discussed the various areas and projects together. Each group could add new projects or delete the ones suggested. A consensus in the group was then reported to the main workshop. In addition, each participant was asked to fill out the questionnaire individually after the group discussion to provide more details on alternative views. This was designed to receive the full input of each companies views in addition to the consensus reached in the group.

Important tools used in this workshop were the survey forms and questionnaire. A technical survey form was sent to the invitees before the workshop to get the sense of issues and topics to be discussed in the workshop. Based on the results of this survey, a detailed questionnaire was designed listing technological areas and possible technical projects within each of these areas. The participants then prioritize the technology areas and technical projects. Each group and each participant was then asked to divide the work among industry, academia, and government laboratories. The survey and the questionnaire are shown in Tables 11 and 12.

In the parts that follow, the results of the workshop will be presented in three groups: automotive, heavy duty diesel, and lubricant/additives. Each group will contain a short

summary of the technical presentations, followed by the survey results and the panel summary.

Table 7

Workshop Attendees

Lubricant/additive	8
Auto Industry	6
Diesel Industry	7
Engine Components	2
National Laboratories	4
Universities	8
Government	3
Small businesses	6
TOTAL	44

Table 8

Organizations Represented

Amoco Oil	Allied Signal	Adiabatics
Amoco Chemical	SwRI	Caterpillar
Ethyl	GRI	Cummins
Lubrizol	Argonne National Lab	Detroit Diesel
Ciba Geigy	US Army, Ft Belvoir*	Ricardo NA
Mobil*	US Army, TACOM	General Motors
Pennzoil*	DOE, OTM	Ford
Shell*	NIST	Chrysler*
Northwestern Univ.	Penn State Univ.	Univ. of IL, Chicago
Harrison Division GMC	GM Allision	Borg Warner
Eaton	Wear Sciences	BIRL, NWU
TRW	Surface Res. & App.	Deere*

* Returned survey, but could not attend the workshop.

Table 9

Technical Presentations

Automotive Engines and their Components	
Future Automotive Engine Lubrication Concerns	Dr. Shirley Schwartz, GM
Automotive Engine Lubrication	Dr. Larry Ting, Ford
Automotive Component Technology	Dr. Frank Savel, TRW
A Technical Assessment of Continuously Variable Speed Transmission	Dr. Herbert Cheng, NWU
Continuously Variable Transmission	Dr. Phil Mott, Borg-Warner
Lubricants for Compressors in Mobile Air Conditioning Systems using R-134A Refrigerant	Dr. Vaughn Hackworth, Harrison
Heavy Duty Truck Engines	
Diesel Engine Lubrication Tech.: Future Research Needs	Dr. Frank Kelley, Caterpillar
1994 and Beyond: Diesel Engine Technology	Dr. Tom Gallant, Cummins
Lubrication Needs for Coatings in Advanced Engines	Dr. Malcolm Naylor, Cummins
Lubrication Needs for TACOM and other Heat Engines	Dr. Roy Kamo, Adiabatics
IC Engine Lubrication Technology: The Role of Analysis/modeling	Dr. Rifat Keribar, Ricardo NA
Lubrication Needs for Alternative Fuelled Engines	Dr. Nabil Hakim, Detroit Diesel
Adv. Materials Demonstration in a Natural Gas Engine	Mr. Bob Burrahm, SwRI
Advanced Materials	
Materials for Diesel Engines	Dr. Mike Haselkorn, Caterpillar
Perspective on Lubrication Technology Needs for Energy Conversion Systems	Dr. Bill Nieman, Allied Signal
Surface Modification of Tribological Components in Transportation	Dr. George Fenske, Argonne National Lab
Lubricant/Additives	
Molecular Engineered Lubricants	Dr. Dick Coy*, Shell Thornton
Lubrication Trends	Dr. Stephen Roby, Lubrizol

* Could not attend due to bad weather

Table 10

Workshop Panels and Their Chairmen

Automotive

Panel 1. Chairman: Dr. Phil Mott, Borg-Warner

Transmission, Gears, Components

Panel 2. Chairman: Dr. Vaughn Hackworth, GM Harrison

Future Lubrication Needs

Heavy Duty Diesel

Panel 3. Chairman: Dr. Malcolm Naylor, Cummins Engine

Lubrication of Materials, Ceramic and Coatings

Panel 4. Chairman: Dr. Frank Kelley, Caterpillar

Million Mile Engine

Lubricant/Additives

Panel 5. Chairman: Dr. Stephen Roby, Lubrizol

Future Additive Research Needs

Table 11

Technical Survey

Company name:_____ Industry_____
Major products_____ Co.Size_____
Location_____ Government contract? _____

*I want my answers to be kept confidential*_____

1. What are the roles of new materials in your company's technology?

2. What are the most critical issues dealing with the new materials?

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation_____Fuel economy_____Cost_____
Durability_____Repair cost_____Performance_____
Maintenance cost_____Innovation_____Materials_____

5. What are the key research agenda of your company in the next 3-5 years?

6. What are the key research agenda of your company in the next 5-10+ years?

7. Which topics you think should be handled by the industry, government, universities?

industry	govt programs	govt labs	universities

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock_____ New Additives_____
Molecular Engineered Lub._____ Additive mechanism_____
Thermally stable dispersant_____ Additive-add. interaction_____
Bench test development_____ New measurement meth._____
Low friction materials_____ new additives for ceramic_____
New lub. for new materials_____ high temp. liq. Lub._____
High temp. solid lub._____ Lub. application guide_____
Stability mapping of lub._____ Methanol compatible lub._____

9. The most important materials that you would like to see research be conducted on?

Superalloys_____ Ceramics_____
Metal matrix composite_____ Aluminum alloys_____
Engr. Plastics_____ Coatings_____

10. The major factors for change in lubrication technologies are:

Emission control_____ Materials change_____
Higher temp._____ Extended drain intervals_____
Alternative fuels_____ Fuel economy_____
Higher stress_____ Durability (less maint.)_____
Higher quality_____ Smaller engines_____
Change in design_____ Higher power density_____

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission_____ Transmission_____
Gears_____ Valve train_____
Ring-liner_____ Bearing_____
Brakes_____ Fuel injectors_____
Piston_____ Catalytic convertors_____
Particulate trap_____ Chemical filter(remove acid,soot)____
Electrical contacts_____ Seals_____

12. Of all the topics mentioned in the survey (but not limited to), IF you would support a research effort outside your company, what topics would you choose? IF the topics are different from what you would support in the government lab., list differently.

Table 12

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Name_____
Company_____

1. Based on the needs you heard from industry and based on your views, what are the most critical areas to address in the next 3-5 years?

2. Same question as 1, the time frame is 5-10 years.

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issue?

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? which one you would be willing to collaborate with? which one you would be willing to support financially?

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you join such consortium?

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,D,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2....I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking
Automotive					
Gears					
Transmission					
CVT					
Long drain					
Friction reduction					
Light Wt. materials					
New mat'ls lub. chem.					
Alternative fuel lub.					
R-134a lubrication					
Heavy duty diesel					
Ceramics lub. chem.					
lub. applica-tion maps					
Coatings lub.					
Liq lub. for particulate control					

Research topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking
Liq. lub. for Hi Temp Eng					
Alter. fuelled engines					
valves for natural gas engines					
Million miles engine					
Advanced materials lub.					
Biodegradabl e lubricants					
Lubricant/ additives					
Molecular Engineered basestocks (MEB)					
MEBs for traction					
MEB for low friction					
Hi T dispersants					
Hi T Oxid. inhibitors					
Additives for ceramics					
Ashless Anti-wear					

Research topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking
Additives for coatings					
Multi-func-tional add.					
Time-release additives					
Additive-add. Interactions					
Anti-oxidant mechanisms					
Anti-wear mechanisms					
Other projects					

Comments and suggestions:

4.0 AUTOMOTIVE ENGINES AND THEIR COMPONENTS

There were seven speakers from the automotive industry, component supplier, and academia. They aired their concerns on lubrication, friction control, new materials, component technology development, and compressor wear as a result of Freon replacement. Both short term and long term issues were discussed. After the presentations, the speakers and others interested in the automotive engines were organized into two small groups: transmission, gears, and components; future engine lubrication needs. Various projects ideas were presented, the original list in the questionnaire was modified and prioritized. The consensus was presented as the panel report from each group. In the following sections, a short summary of each presentation will be highlighted, followed by the list of projects, and the panel reports.

The titles and speakers are shown below:

Future Automotive Engine Lubrication Concerns	Dr. Shirley Schwartz, GM
Automotive Engine Lubrication	Dr. Larry Ting, Ford
Automotive Component Technology	Dr. Frank Savel, TRW
A Technical Assessment of Continuous Variable Speed Transmission	Dr. Herbert Cheng, NWU
Continuous Variable Transmission	Dr. Phil Mott, Borg-Warner
Lubricants for Compressors in Mobile Air Conditioning Systems using R-134A Refrigerant	Dr. Vaughn Hackworth, Harrison

4.1 TECHNICAL PRESENTATIONS

4.1.1 Dr. Shirley Schwartz, GM

Dr. Shirley E. Schwartz of General Motors described some of their concerns with engine lubrication. The main thrusts are : extended life of the engines and the lubricants, emission control, reduction of energy consumption, and alternative fuel lubricants. Some of the topics are shown in Table 13 below.

Table 13

Technical Areas of Active Interest

- Increase the useable life of lubricants and filters
- Develop bench tests that correlate to dynamometer and field
- Speed the process of putting new materials into appropriate applications
- Develop test methods to confirm that new lubricants, materials, components provide a benefit

Each of these areas was described in some detail with specific application examples. Various tactics can be used to extend the oil change interval: develop a better oil, develop engine systems that cause less oil degradation and determine conditions which shorten oil life. Extending the life of the oil is not simple because of the many different conditions which affect oil quality. Examples were given of oil degradation from oil-water emulsion created under short-trip driving conditions. Many chemical additives added to provide wear and corrosion protection were extracted by the water phase and caused premature wear and other problems. The use of alternative fuels such as M-85 and pure alcohol fuels exacerbated this type of oil degradation. A study was described where the formation of this kind of emulsion was directly observed in cars fitted with transparent oil sumps and other instruments. She concluded by stating that the process was modeled and an oil-change indicator was developed to protect the vehicles. However, while a quick technological solution was found, the detailed mechanism of this kind of degradation was not understood and new additives and lubricants resistant to this kind degradation are needed.

Another issue she raised was that now a wide variety of new materials are now available for use in engines and components. Many of the vendors and suppliers came to the engine manufacturers with either biased data or inadequate data. The engine manufacturer could not possibly evaluate all of the materials. She suggested that material suppliers should develop adequate materials property data bases and design guidelines, perhaps in conjunction with government laboratories, to provide an objective view, not only to the advantages but also the limitations of the materials. This would assist the engine manufacturers to take advantage of the new materials technology promptly.

Improved bench test methods are also needed to determine the range of conditions over which the lubricant, lubricant/material combinations are effective. Better correlations are needed between the laboratory bench tests and various engine services. To do this, the failure mechanisms of engine components in actual service conditions need to be identified. Laboratory bench tests should be developed to simulate the same failure mechanisms and correlated with the conditions causing failure.

This has not been done because the difficulties and the resources required to analyze a single component failure are enormous and only the most critical problems can receive the attention. She felt that the universities and the government laboratories could perform a very useful service if they could focus on some of these issues in conjunction with the engine manufacturers.

4.1.2 Dr. Larry Ting, Ford Motor Co.

Dr. Larry Ting from the engine research department discussed the engine and component research and design needs. He cited rings, valves, and bearings as potential problem areas. The problems would be due to increased temperatures and higher loads at higher power densities. His current area of interest was the ring/liner interface contact problem which accounts for a significant fraction of the frictional losses in the engine as well as hydrocarbon emissions from the thin oil film left on the cylinder liner in the upper cylinder. Models had been constructed

to describe the ring/liner contact phenomena including friction, oil film thickness, oil consumption, and oil flow paths which has provided much useful information. However, there is a need to construct a comprehensive integrated model which included all of the above factors since they are obviously interrelated. He described his experience in this area and showed some experimental results on piston ring friction and scuffing. A test rig had been designed and built to simulate the ring-liner behavior. A sketch is shown in Figure 2 and a typical data trace is shown in Figure 3. Basically this rig allowed friction to be continuously monitored using a ring liner segment. When plotted against the Sommerfeld number, a continuous plot of friction co efficient (Figure 4) results. Studies included ring profiles, geometries, oil viscosities, additives and operating conditions. The ultimate result would be the optimum design for maximum fuel economy and durability.

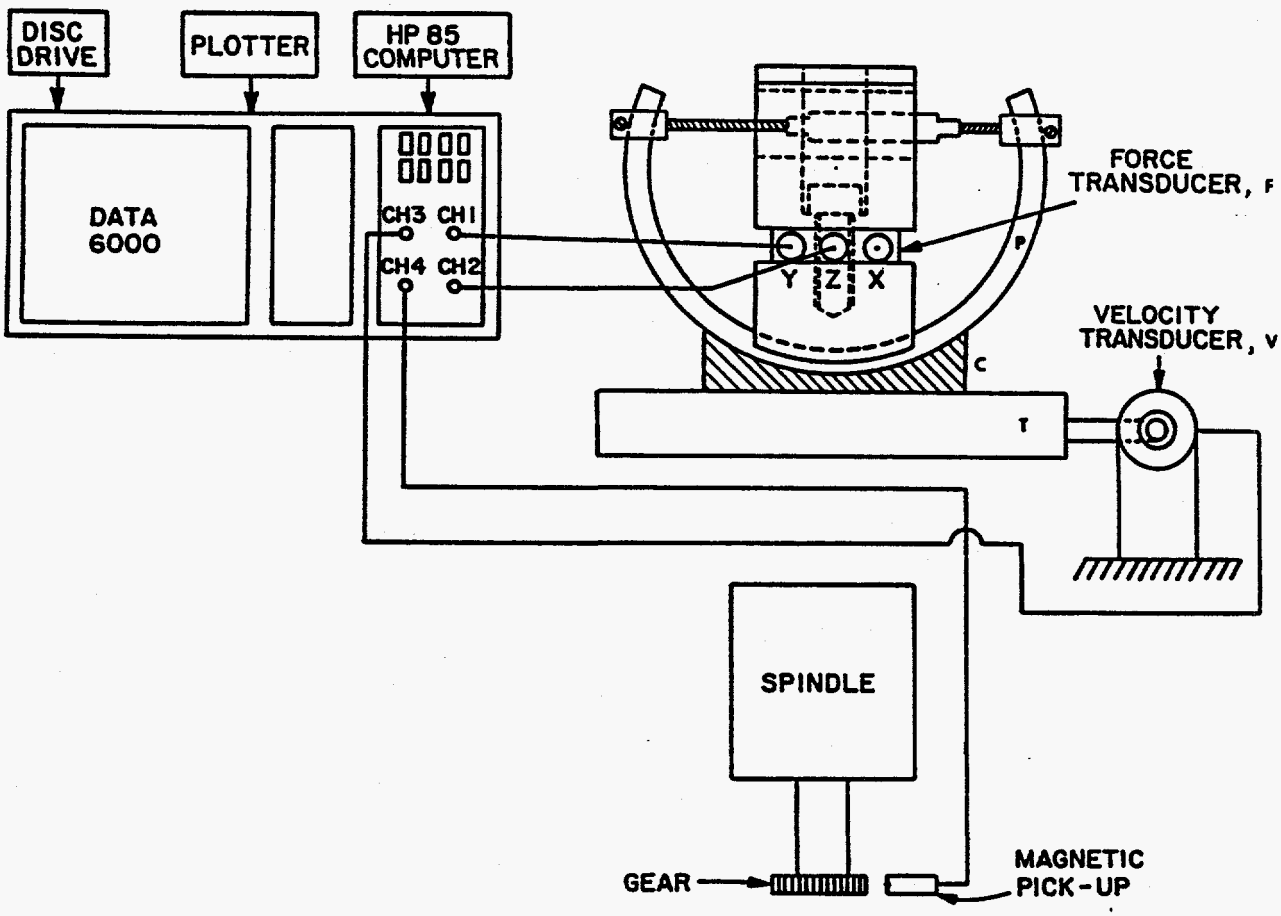


Figure 2. Arrangement of acquiring, processing, analyzing, and storing the velocity, force, and crank-angle degree information.

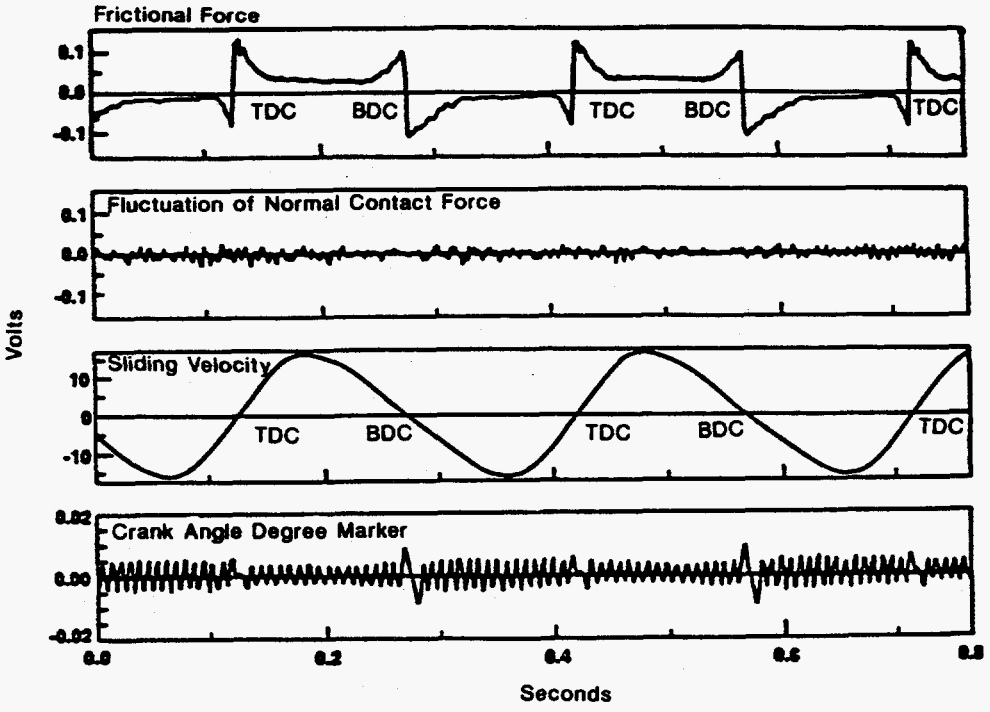


Figure 3. Captured Traces of Frictional Force, Fluctuation of Normal Contact Force, Bore Specimen Sliding Velocity, and Crank Angle Degree Marker - 200 rpm, 40 N Contact Load, 5W30 Oil.

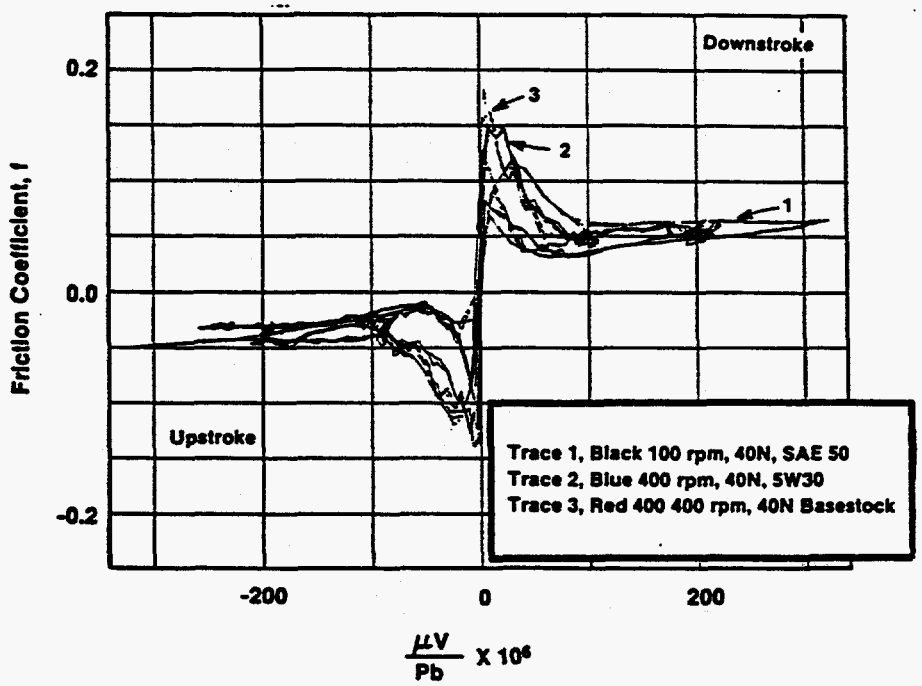


Figure 4. Comparison of Stribeck Relations Obtained by Using Various Types of Lubricants Run Under the Same Load but Different Speed Conditions.

4.1.3 Dr. Frank Savel, TRW

Dr. Savel discussed the current efforts in automotive component technology development. He stated that the component technology was driven by customers needs. Every year, usually a survey was sent to customers requesting information on the component technology the customers were contemplating. The most recent survey listed topics shown in Table 14 in order of importance. These were cost reduction, weight reduction, emission reduction, improved reliability and durability, optimum engine performance, power, and valve train system engineering. The expectation in the future was that the component technology customers would demand greater contributions from the component suppliers in terms of technology and cost-effectiveness as competition with foreign engine manufacturers heated up. The future customer expectations are shown in Table 15. He suggested that this was the result of several factors. Engine development cycle was being reduced while the engine performance tests required to prove design concepts had been increasing. Furthermore, the component suppliers were being required to take increasing responsibility for field performance even though the design cycle was being reduced and the design rules were becoming more complex.

Table 14

Current Customer Priority of Component Technology

1 Cost Reduction
2 Weight Reduction
3 Emission Reduction
4 Improve Reliability/Durability
5 Optimum Engine Performance and Power
6 Valve Train Systems Engineering

Table 15

Future Component Technology Customer Expectations

More analytically derived design proposals
More up-front rig and engine tests
Reduce component design cycle time
Responsibility for field performance
Performance (cost-effective solution)

Using the valve as an example he showed typical valve operating conditions and established failure modes. Currently, most problem areas were with wear of the face seat and valve stem guide. Wear was the current predominating issue. He also reviewed analytical techniques which were primarily based on materials properties and concluded that wear was becoming the dominant failure mode in engine components and analytical procedures for predicting wear and the influence of lubrication were needed. Especially, the design guidelines and modeling of wear were extremely inadequate at this time. A concerted effort in this critical topical area by government, academia, and industry was needed to tackle this very complicated, materials dependent, system dependent problem. In his view, component technology lies at the heart of automotive technology and competitiveness.

4.1.4 Dr. Herbert Cheng, Northwestern University

Dr. Cheng of Northwestern University reviewed the current status of the continuously variable transmission (CVT) technology. Such transmissions are of interest because of their inherently higher efficiency (15-20% higher under transient operating conditions than the automatic transmission) and their faster response time. The faster response time enhances performance and the driveability of the car. Three versions of CVT design had emerged: the full toroidal (UK), the semi-toroidal (Japan), and the metal belt (Borg Warner, US). These are shown in Figure 5.

Many of the lubrication issues have been resolved for smaller engines and successful CVTs have been put into commercial production. However, there is a continuing problem with the scrubbing losses (microslip), Figure 6, which causes wear and pitting. For the semi-toroidal this occurs within the drive system; for the metal belt system it occurred at the belt-sheave interface at the exit point.

For larger engines, this problem is more severe, and developmental efforts are currently being pursued. He concluded that the surface pitting is due to the low oil-film to roughness ratios (Figure 7). Because of the high contact pressures this led to spalling in the semitoroidal cut. Reliability of the contacts could be improved by the generation of an effective micro-EHL film through improved surface roughness and texture, lubricant rheology and micro-EHL analysis. Improved materials could also make a major contribution.

4.1.5 Dr. Phil Mott, Borg Warner

Dr. Phil Mott gave the industrial perspective of the status of the continuously variable transmission (CVT). He reviewed the history of the CVT development, the designs, their advantages and disadvantages, and the current developmental effort related to capacity improvements. The current limitation to torque capacity is wear at the strut-sheave interface.

A typical CVT now in use is shown in Figure 8. The sheave diameter of the shaft is electronically controlled to change the speed ratios of the input and output shafts. Torque was transmitted through a metal belt connecting the sheaves. This transmission has given satisfactory

performance as have transmissions designed by others. The fuel economy improvement for this transmission is compared with a 4-speed automatic in Figure 9. Improvements of 10 to 15 per cent could be achieved.

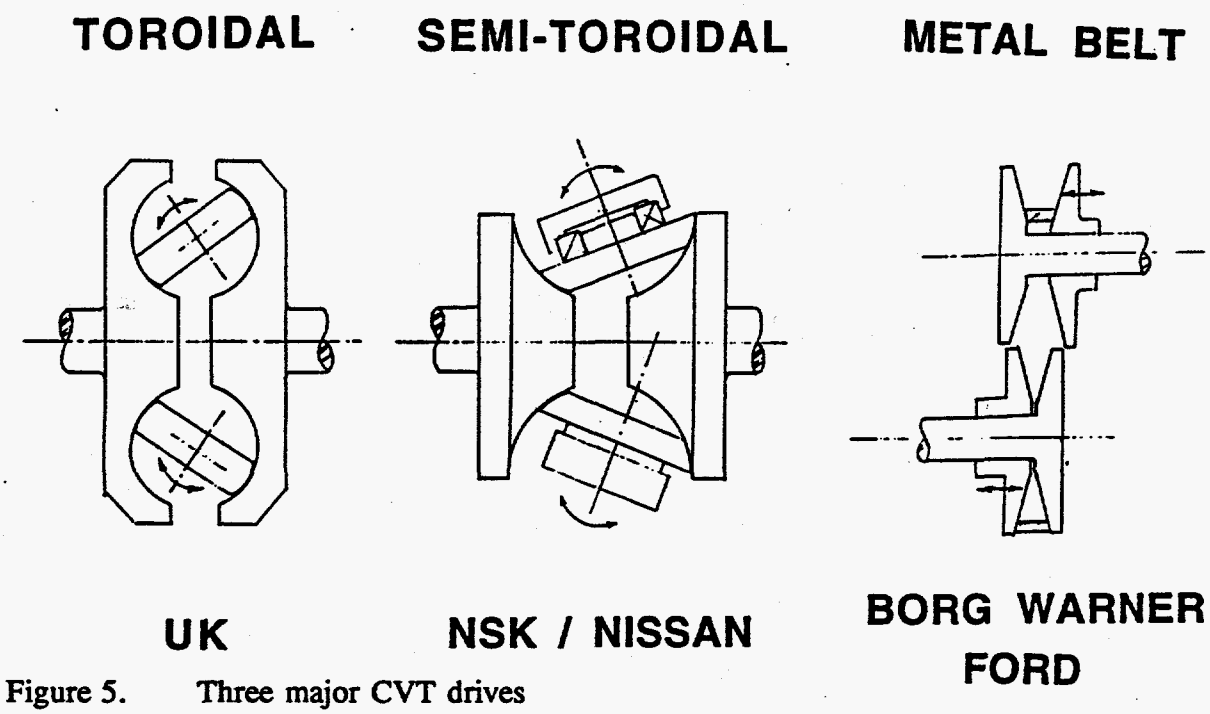


Figure 5. Three major CVT drives

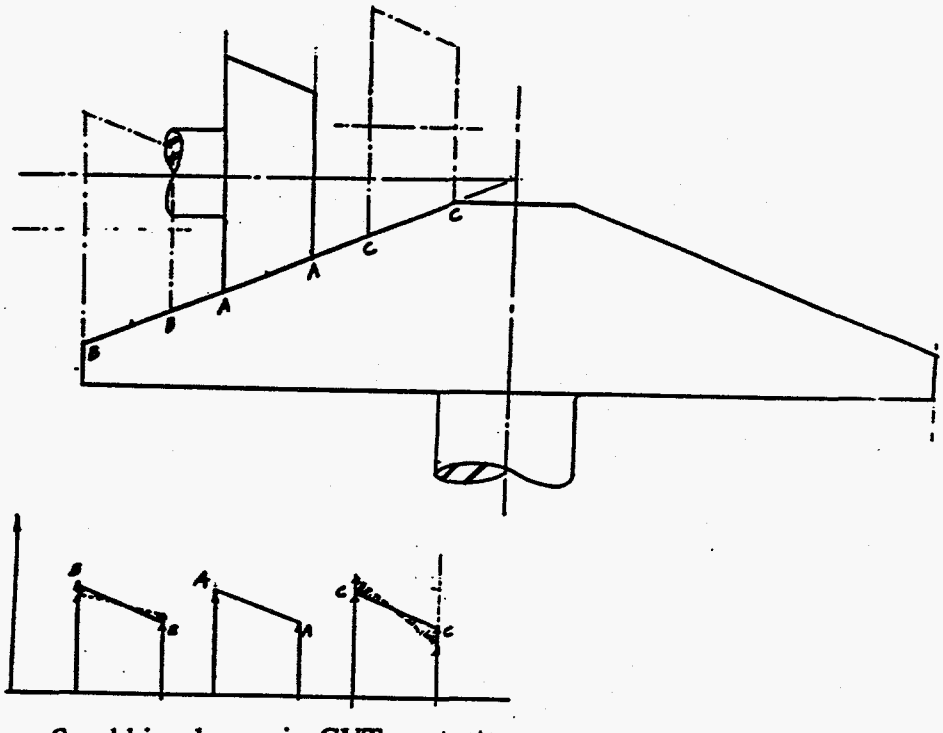
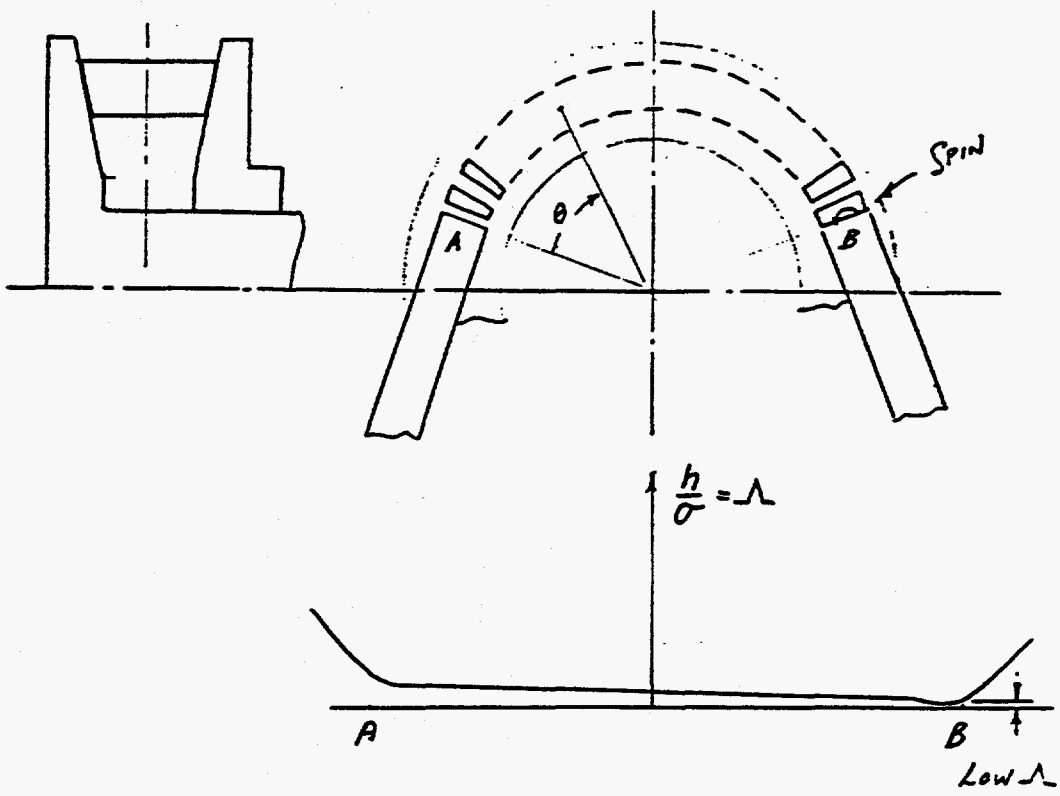


Figure 6. Scrubbing losses in CVT contacts



- **AT THE EXIT, THE FILM IS VERY THIN. A SMALL RELATIVE SPIN BETWEEN THE BLOCKS AND SHEAVES CAN CAUSE CRACKS AND GENERATE PITTING WEAR ON THE SHEAVES.**

Figure 7. Mode of lubrication

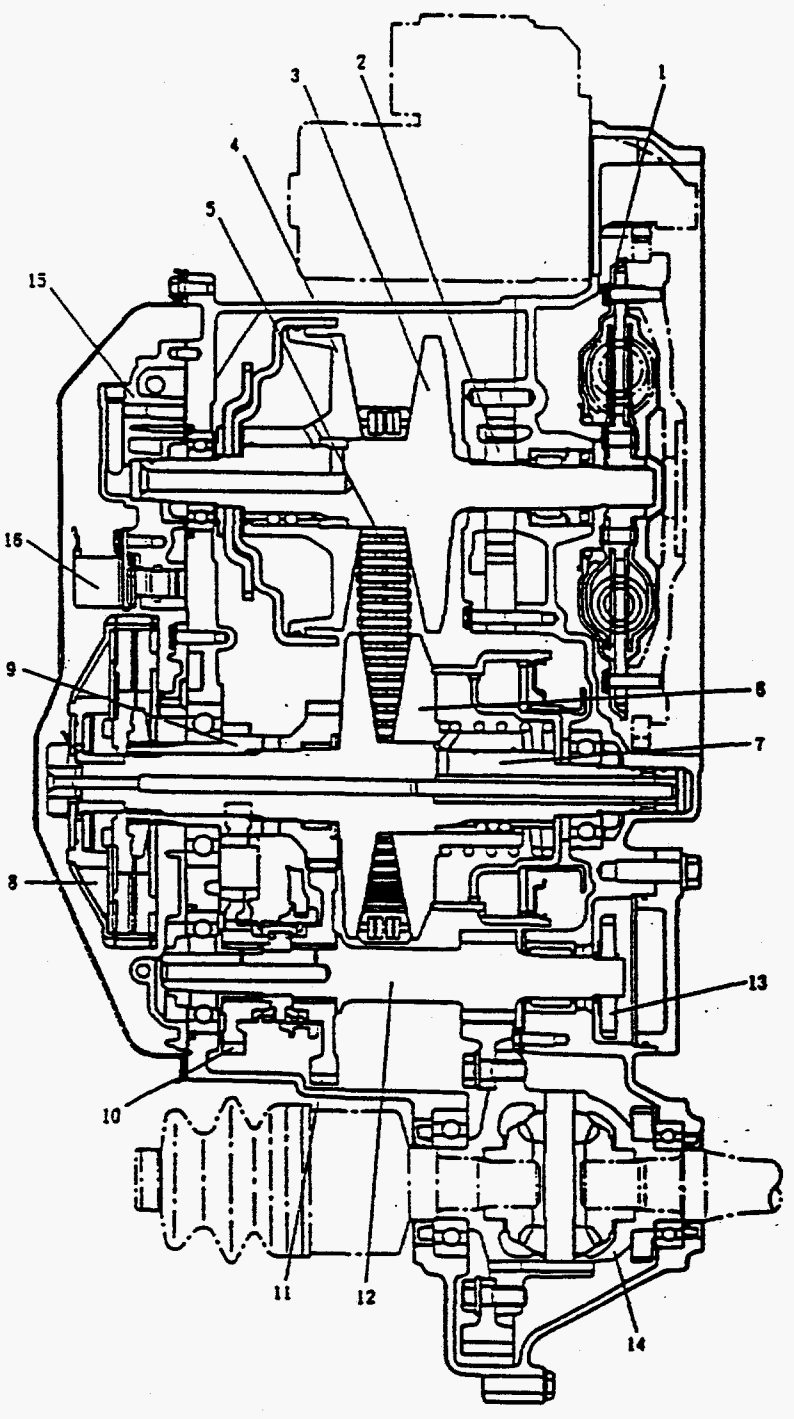


Figure 8. A schematic of the current CVT. SCVT 2F-3

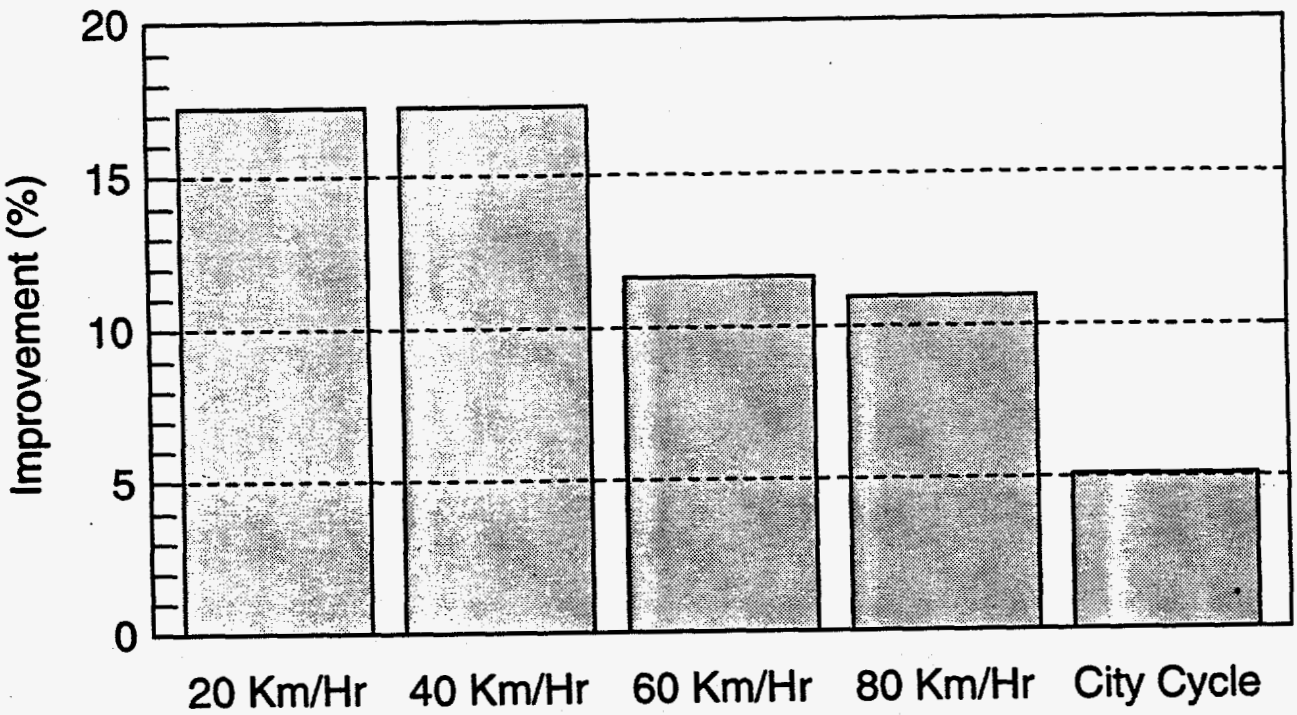


Figure 9. Comparison of CVT with a 4-speed automatic transmission

Problems have arisen with higher capacity engines (5 liter). Specifically, wear and galling at the sheave-belt interface. The tribology of this interface must be better understood including better lubricants, improved materials, higher traction coefficients to prevent slip and improved wear resistance.

4.1.6 Dr. Vaughn Hackworth, GM Harrison Radiator Division

Dr. Vaughn Hackworth described the effort that his division is making to substitute the current chlorofluorocarbons (CFCs) used in mobile air-conditioning systems. CFCs are being phased out of the industrial applications by international accord to safeguard the ozone layer and reduce the greenhouse effect. Ozone depletion allows more ultraviolet radiation to reach the surface of the earth causing increased skin cancer and crop damage. In the greenhouse effect, the CFC's and other gases (e.g. CO_2) absorb infrared radiation, which leads to global warming. CFC's currently contribute to about 15-20% of this effect. A generation of new refrigerant, the hydroflurocarbons (HFC) (one of the leading candidates is R134a) has been developed to replace the CFCs. Such replacement could eliminate the CFCs' contribution to ozone depletion, and could substantially reduce their global warming contribution.

A typical air conditioning compressor (V5) is shown in Figure 10 along with the materials of construction. In operation the lubricant is circulated with the refrigerant to lubricate the various sliding components: the wobble plate, the ball pivots, the guide bar and the pistons. Technically, this is an extremely complex system with different materials pair under a variety of sliding conditions. Studies have shown that the CFCs decompose to release chlorine atoms which absorb onto the various material surfaces providing lubrication. Since the chlorine is gone, there is no lubricant available in the system. Addition of chlorine-containing chemicals plugged the capillary tubes in the compressor.

Figure 11 compares the lubricating effectiveness of the old CFC (CFC-12) and the new R-134a. In laboratory tests with steel/steel combinations, CFC-12 gave low friction coefficients for a period of 10 minutes while HFC-R134a gave high friction after approximately one minute. Compressors run with 134a also suffered shorter life as compared with the CFC-12. Although a new lubricant has been developed by chemical industry and has been selected for the 1993 model year, the search continues for better lubricants. In addition, the industry is facing a massive retrofit problem. After 1994, old CFC-containing compressors will be replaced with the new HFCs when repair or refill occurs, the system would have to perform adequately. In designing the new compressors, material substitution with HFCs was possible to counterbalance some of the wear issues in conjunction with the new lubricant. In retrofitting, one has to live with the old materials which were designed for the original CFC units. He pointed out that there were about 40 to 50 million cars on the road for retrofitting.

He suggested that this is an extremely important national problem with significant economic impact on several industries. Current research efforts are viewed as inadequate and many mechanisms are not understood and this severely hampers efforts to develop effective solutions. He called for more attention by the scientific community and the government funding agencies

to provide some of the critically needed information. Specifically, more science and a better understanding of the nature of the lubrication process are needed. Better bench tests which were capable of predicting performance are also needed. The role of lubricant chemistries and the effects of various materials need to be understood so that systems can be designed intelligently rather than trial and error.

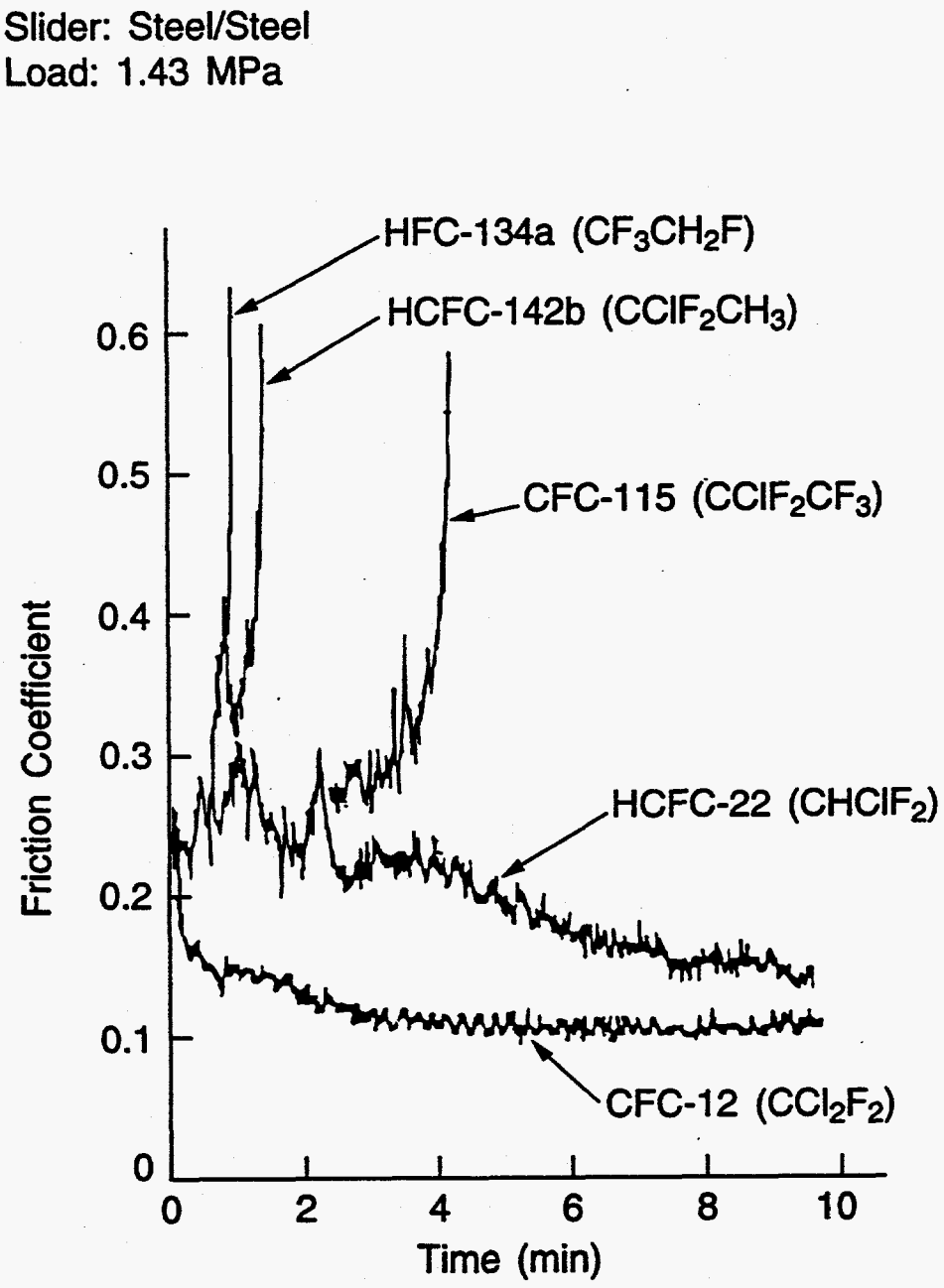


Figure 10. V5 compressor cross section at full stroke

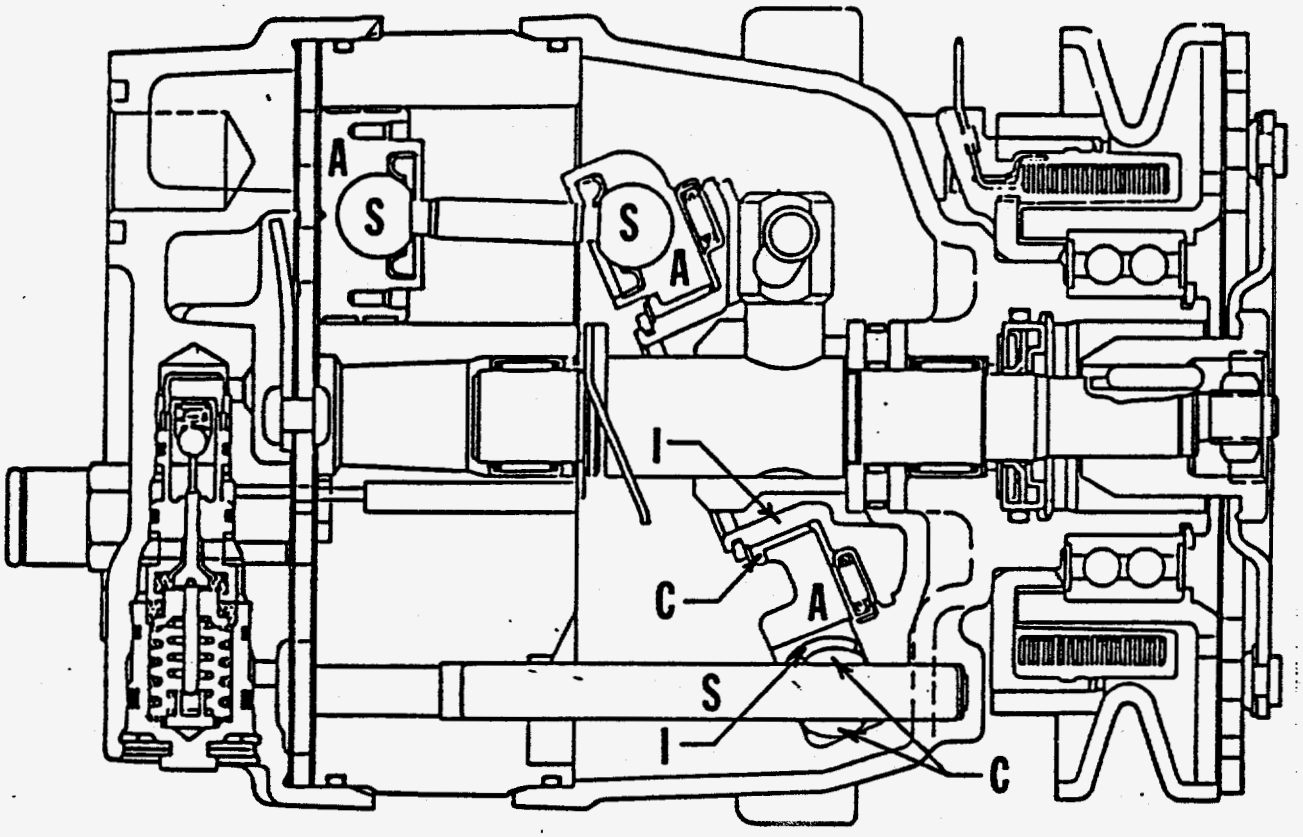


Figure 11. Friction coefficient under various refrigerant-gas environments

4.2 PANEL DISCUSSIONS AND REPORTS

Two groups met to consider automotive engines and component technology. One group was led by Phil Mott who concentrated on component technology. The other group was led by Dr. Vaughn Hackworth and looked into the issue of future lubrication technology for automotive application.

4.2.1 GROUP 1 Transmissions and Gears, Dr. Phil Mott, Borg Warner, Chairman.

High Power Density Gearing

For next generation automatic transmissions, the power density of gears will have to be increased considerably, to meet the fuel economy without sacrificing the durability. The development of high power density gearing is a critical concern. These high power density gears must operate at higher contact stresses and temperature with a lubricant film thickness smaller than the average roughness. The problem is to develop these gears with improved materials, surface roughness and texture, along with lubrication to meet the power and life requirements. A program is needed to develop methods to determine and evaluate the effects of surface roughness texture, near surface microstructure, and lubricant film to roughness ratio on contact fatigue life. This work should be coordinated with automotive companies to determine and evaluate the optimum surface roughness, material, lubricant and lubrication system for maximum life.

Valve Stem Guide Wear

To meet 1996 emission requirement, a tighter valve stem seal will be required. The starved lubrication caused by this new seal introduces a critical problem on valve stem wear. The lack of adequate lubrication between the valve stem and the guide increases the stem wear dramatically. Wear reduction through improved lubrication mechanism is the major problem. A program is needed to determine lubrication and wear mechanisms of a reciprocating sliding pair for current as well as for a list of selected improved stem materials. This work should be coordinated with automotive companies to determine and evaluate the optimum stem/guide interface for minimum wear.

CVT Contact Tribology

Until recently larger engines/vehicles have not been able to take advantage of the fuel economy and emission enhancements offered by the continuously variable speed transmission. Although advancements in belt technology have dramatically increased the torque ratings, applications of CVT technology in the U.S. will be limited until wear improvements can be achieved at the sliding CVT contacts. The primary problem is that for larger power metal belt CVT drives, surface degradation and wear at the traction contacts have been shown to be the remaining major problems of these drives. Program objective should be as follows:

- Determine the lubrication and wear mechanisms at the critical CVT sliding interface.
- Develop improved surface roughness and texture, materials and lubricants to reduce wear.
- Collaborate with lubricant industries to seek high traction fluids compatible with other transmission components.
- Collaborate with CVT companies to develop and evaluate improved CVT contacts for maximum wear life.

4.2.2 Group 2 Future Automotive Lubrication Needs, Dr. Vaughn Hackworth, GM, Chairman.

The consensus of this panel as to critical areas which should be addressed in the next 3-5 years and those for 5-10 years are given in Table 16. High priorities are given to reduced emissions and providing a data base on new materials and lubricants.

A list of specific projects for consideration is given in Table 17 along with a priority ranking. This table also lists priority rankings for industry, government and universities. Those areas given a high priority for government involvement were:

- Lubrication of light weight materials
- Lubrication chemistry of new materials
- Alternative fuels lubrication
- Friction reduction

The group found the workshop interesting and informative. If the workshop would result in some consensus and action, then the workshop would have served its purpose. With respect to continual involvement and meeting, most thought it would be useful to meet once a year to review the progress and exchange ideas. The majority of the group found a consortium that focused on better bench tests to predict engine and field experience would be attractive; concerns about proprietary and competitive issues would prevent their joining a more general consortium in this area.

Table 16

Critical Areas for Automotive Engines and Their Components

Next 3-5 Years

Highest Priority	Reduced emissions
Priority A	Better test methods Improved fuel economy Increased durability
Priority B	Lubricants for new materials Lubricant compatibility with alternative fuels High temperature lubricants (liquid & solid) Improved additives Lubrication of new materials (e.g. ceramics) Lower manufacturing costs

Next 5-10 Years (No consensus on priority rank)

Data base on new materials and lubricants
Appropriate materials for future applications
Improved modeling techniques
Lubricants for alternative fuels
Combustion physics
Optimized combustion chamber and piston

Important Areas Individual Companies will address

Emissions/Ecology, including lubricant for R-134a
Improved bench tests
Three-dimensional engine lubrication/combustion models
1700°F solid lubricant for regenerator seals
Solid lubricant for automotive gas turbine bearings

Table 17

Ranking of Projects/Ideas for Automotive Engines and Components R&D

Projects/Topics	Overall Ranking	Who Should be Involved Ind	Gov't	Univ
Friction Reduction	A	1**	4	2
R134a Lubrication	B	2	5	4
Light Wt. Materials	C	3	1	1
Long Drain Oils	D	4		
CVT	E	5		
New Materials Lub. Chem	F	6	2	3
Transmission	G	7		
Gears	H	8		
Alternative Fuel Lub.	V. Low to V. High Ranking - No Consensus Reached		3	5
Bench Tests*	Should fit in, but no good ideas on how to do it.			

* Added to the original list
** Ranking

5.0 HEAVY DUTY DIESEL ENGINES

A total of eight speakers gave presentations on this subject. There was a sense of urgency as well as a genuine sense of community as the diesel industry faces stiff competition abroad, and stringent pollution regulation internally in the US. The technology is complex and in meeting the 1994 emission standards, all of the obvious steps have been taken. How to meet the 1998 NO_x standard while maintaining durability and fuel economy without incurring a major cost increase remains the top priority for the industry. The list of presentation topics and speakers is shown below:

Diesel Engine Lubrication Tech.: Future Research Needs	Dr. Frank Kelley, Caterpillar
1994 and Beyond: Diesel Engine Technology	Dr. Tom Gallant, Cummins
Materials for Diesel Engines	Dr. Mike Haselkorn, Caterpillar
Lubrication Needs for Coatings in Advanced Engines	Dr. Malcolm Naylor, Cummins
Lubrication Needs for TACOM and Other Heat Engines	Dr. Roy Kamo, Adiabatics
Internal Combustion Engine Lubrication Technology: The Role of Analysis/modeling	Dr. Rifat Keribar, Ricardo NA
Lubrication Needs for Alternative Fuelled Engines	Dr. Nabil Hakim, Detroit Diesel
Adv. Materials Demonstration in a Natural Gas Engine	Mr. Bob Burrahm, SwRI

5.1 TECHNICAL PRESENTATIONS

5.1.1 Dr. Frank Kelley, Caterpillar

Dr. Frank Kelley reviewed the critical issues and future research needs of the diesel engine industry. The critical issues that impact lubrication technology are listed in Table 18.

Improved performance could be achieved by reduced fuel consumption and increased power density. The ramifications of these changes are higher operating temperatures and increased component stresses. These changes strongly impact the performance of the lubricant. Increased durability means reduced infant mortality and longer engine miles between overhauls. A current goal would be one million miles. This could now be achieved with close adherence to maintenance requirements and the use of high quality lubricants. The goal is to do this more consistently even with higher temperatures and more severe lubricant operating conditions.

Many current efforts are aimed at meeting government environmental regulations. Among these, one is to develop environmentally compatible lubricants. This means less particulates, less oil consumption, more biodegradability, longer oil change intervals, and more recycled oils.

Although the tendency is to move toward the dedicated fluids for optimum performance, the current trend is to find a single fluid that could be used for lubrication, cooling, and compatible with as many components in the engine as possible. Multi-fuel-compatible lubricants is also a target.

Table 18

Diesel Engine Lubrication Technology: Critical Issues

Performance

- Reduced Fuel Consumption (Higher Temperature Operation)
- Increased Power Density (Increased component stresses)
- Fluid Performance Characteristics
  - Low Tendency for Deposit Formation
  - Adequate Materials Compatibility
  - Good Fuel/Contamination Handling Capability
  - Adequate Viscosity
  - Low Volatility
  - Good Thermal Stability

Durability

- Reduced Infant Mortality
- 1,000,000 miles to Overhaul
- Critical Tribological Interfaces
  - Piston Rings/Cylinder Liners
  - Valve Stems/Valve Guides
  - Valve Seats/Valve Faces
  - Crankshafts and Rods/Bearings
  - Valve Train
  - Fuel Injection Components
  - Turbochargers/Seals

Emissions/Environmental

- Meet Regulations: Oils must contribute less to particulates
  Need to understand particulate formation mechanisms
  Need to understand role of volatility/viscosity in oil consumption
- Environmental Friendliness: Biodegradability/Toxicity; Extended oil change periods; Recycling

Application Flexibility

- Single Fluid (Lubrication and Cooling): Heat transfer characteristics; Low temperature characteristics; Impact of degradation on characteristics
- Universal Fluid vs. Dedicated Fluid
- Alternate Fueled Engines

Cost Reduction/Productivity

- Shorten Product Development Cycles: Bench tests that correlate with field experience; Analytical tools to aid designers
- Provide Diagnostics/Prognostics: On-board monitoring of oil/equipment condition; Proactive vs. preventive maintenance

Cost reduction to the engine manufacturer implies shorter product developmental cycles. Lubrication technology could assist in this endeavor by providing bench tests that correlated with field performance and experience. Analytical models dealing with lubrication, combustion, materials are needed to aid designers. Engine users could reduce maintenance costs using engine diagnostics such as on-board oil monitors and wear particle diagnostics to detect and prevent costly repairs.

Based on the above discussions, the diesel engine research needs are summarized in Table 19.

Table 19

Diesel Engine Lubrication Technology:
Future Research Needs
Lubrication Research Needs

- Advanced liquid lubricants
- Heat transfer characteristics of lubricants
- Tribological materials for critical components
- Lubricant additives for ceramic wear reduction
- Alternate fuel compatible lubricants
- Bench test/field correlations
- Analytical methods to predict oil consumption

5.1.2 Dr. Tom Gallant, Cummins Engine Co.

Dr. Tom Gallant discussed the lubrication technology needs for advanced diesel engines including the low heat rejection engine. The goals of the advanced diesel concepts such as the LHRE include: improved fuel efficiency requiring top ring reversal temperatures of 500°C; improved durability by controlling piston and ring deposits; and reduced particulate emissions by appropriate lubricant selection. For the diesel particulates, the lubricant contribution has been about 25 percent (Figure 12), while it has been estimated that in the 94 engines, it will rise to about 35-45 percent dependent on engine designs. Public research programs could assist the industry in solving these problems by providing the basic understanding that is currently lacking. More specifically these needs are:

- Better understanding of oil consumption mechanisms
- Fundamental understanding of deposit control
- Introduction of high temperature and wear resistant materials
- Real time analytical tools to understand oil consumption
- Improved fuel-injection systems for wear and corrosion
- Reduced cam wear with improved materials and lubricant additives
- NO_x reduction technologies and improved material for wear and corrosion control

A summary of the lubrication technology developments needed for 1994 and beyond are given in Table 20.

Table 20

1994 Technology Needs

- Reduced particulate emissions through oil chemistry, accurate modelling and real-time measurement system for oil consumption
- Development of low friction and wear materials, coatings, or surface treatments and manufacturing capabilities.
- Research into fuel additives for improved durability of fuel-injection system.
- Understanding of boundary layer lubrication requirements for specific materials, coatings, and surface treatments.

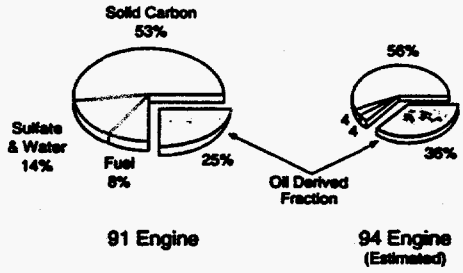


Figure 12. Diesel particulate composition

5.1.3 Dr. Mike Haselkorn, Caterpillar

Dr. Haselkorn discussed materials needs for advanced diesel engines. He began by pointing out that most diesel manufacturers such as Caterpillar have certain engine development objectives (Table 21) such as low emissions, fuel efficiency, flexible fuels, higher power densities, low noise, and product differentiation from competitors. Of these the first three were currently the most important since improvements were needed to meet 1994 and 1998 emission standards. One approach to meeting these requirements was to increase the engine combustion temperatures; for example exhaust temperatures from 400°C to 600°C. When this was done, current materials and lubricants would be inadequate. Ceramics could and were being used to solve the material problems but their lubricating requirements were still not defined. In addition, materials property information under engine operating environment was needed. Extrapolation of bench performance test results on materials and lubricants into engine performance was not satisfactory at this time. When these problems were resolved, ceramics might eventually find usage in many engine applications.

Caterpillar was currently engaged in several programs on inserting new materials into diesel engines. Two programs, wear resistant coatings and continuous fiber ceramic composites were described.

Table 21

Caterpillar Engine Objectives

Low Emissions	particulates, NOx
Fuel Efficiency	0.25 g/HP-Hr
Flex Fuel	gas, alcohols, residual fuels, others
Power/Response	weight: H.P.
Low Noise	combustion; mechanical
Product Differentiation	

5.1.4 Dr. Malcolm Naylor, Cummins

Dr. Malcolm Naylor reviewed the results of a recently completed program on piston ring coatings for lubricated operation at 350°C. A wide variety of ceramic, advanced metals and ceramic coatings were selected and evaluated in bench tests sliding against cast iron with drip lubrication under a variety of operating conditions including the addition of used oil and soot. The best performance was obtained with plasma sprayed Cr_3C_2 with a nickel chromium binder, WC with cobalt binder and Cr_2O_3. Wear ratios were generally higher with used oil possibly due to corrosive wear, but the effect was much smaller with ceramic coatings. The choice of the liner material also had a major effect. Engine tests were run with the better coatings and a reasonable correlation was obtained between the engine tests and the bench tests.

5.1.5 Dr. Roy Kamo, Adiabatics

Dr. Ray Kamo, president of Adiabatics, discussed the status of TACOM (Army Tank and Automobile Command) engines. He first showed a plot of top ring reversal temperatures as a function of BMEP (Figure 13) for current water cooled engines and for the uncooled "adiabatic" engines. Other engine concepts would fall somewhat in between these two extremes. However, he noted that because of lubricant inadequacies there is a limit of 310°C (590°F) Top Ring Reversal Temperature (TRRT). This significantly limits the engine output.

The advanced insulated engine concept was the first approach to extend this limit. This concept along with the component materials is shown in Figure 14. The lubricant used was MRI-1 which is a synthetic polyester. This engine build was successfully run with a low heat rejection rate of 12.3 BTU/BHP-Min. This compares to 21.5 for the normal engine.

The proposed engine concepts under consideration had the TRR temperatures reaching above 310°C (590°F). These are shown in Figure 15. Concept I has been successfully achieved with the polyester lubricant as previously described. Concept II is a standard design concept but requires a higher temperature oil [425°C (797°F) TRR]. To date such an oil is not available although a number have been proposed and are being evaluated. Concept III is a hybrid piston with the top rings lubricated by solid lubricants, while the lower rings could be oil lubricated since they operate in a much cooler regime. This approach should be investigated further. This hybrid piston concept is shown in more detail in Figure 16.

Based on available information Roy Kamo proposes the lubricant-temperature matrix of Figure 17. As the heat rejection rate is decreased from 21 BTU/HP/Min to 12 the top ring reversal temperatures will increase to 649°C (1200°F). In this region self lubricating materials will be necessary. In the 14 to 17 BTU region polyphenyl ether may suffice if some of its inherent lubricity problems can be resolved.

Some approaches to lubricants, piston assemblies, solid lubricants and high temperature valves were reviewed.

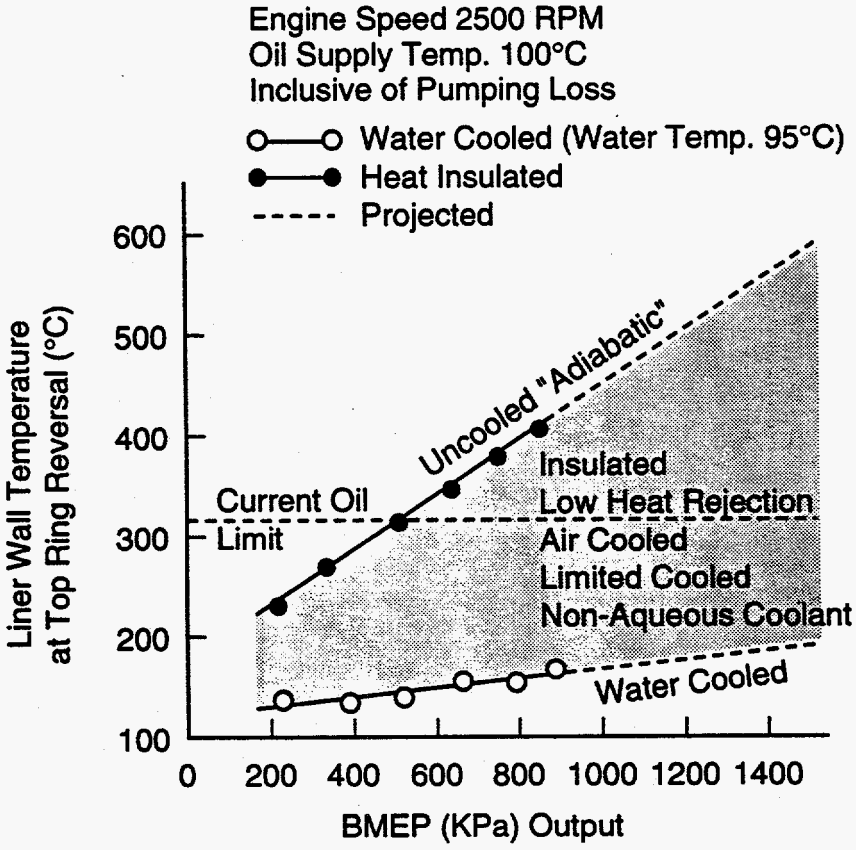


Figure 13. Top ring reversal (TRR) temperature versus diesel engine output

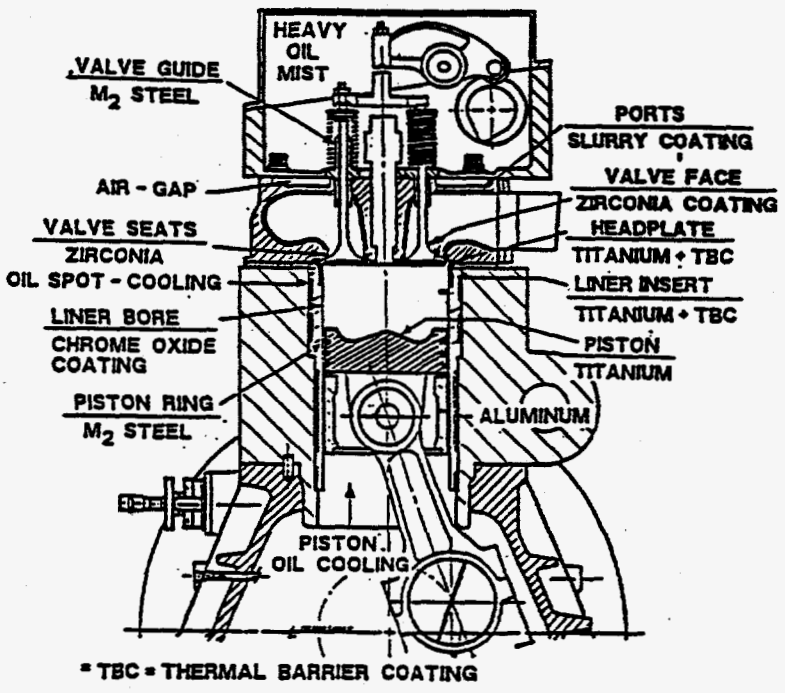


Figure 14. Advanced insulated engine concept

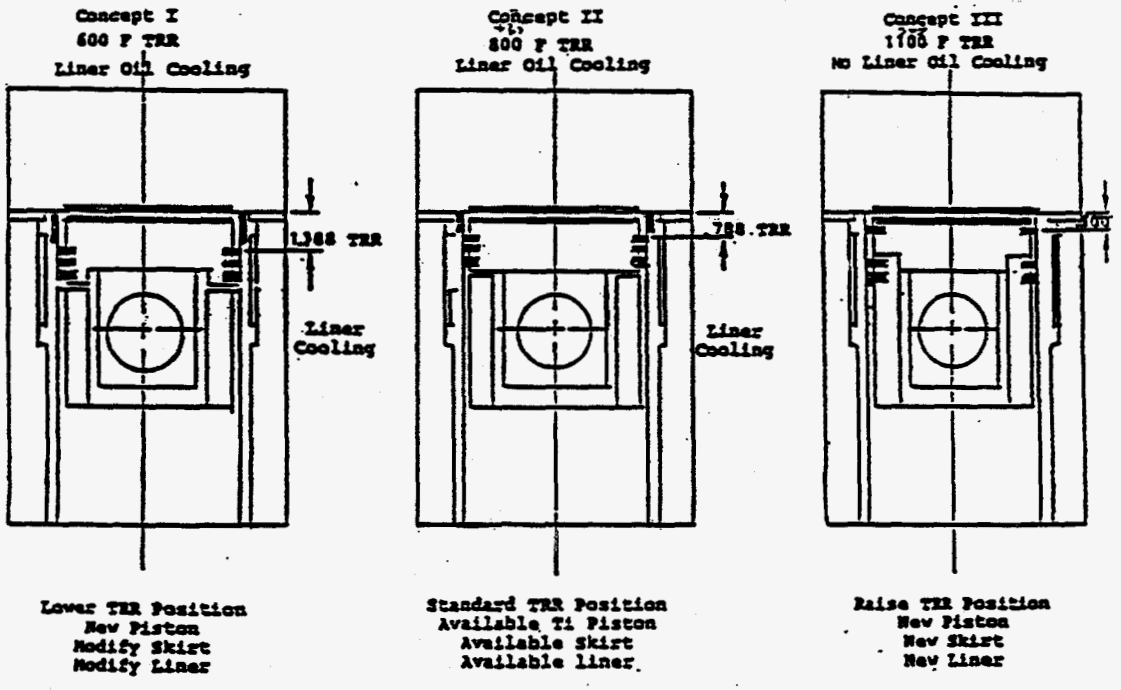


Figure 15. Proposed Tribology engine concepts

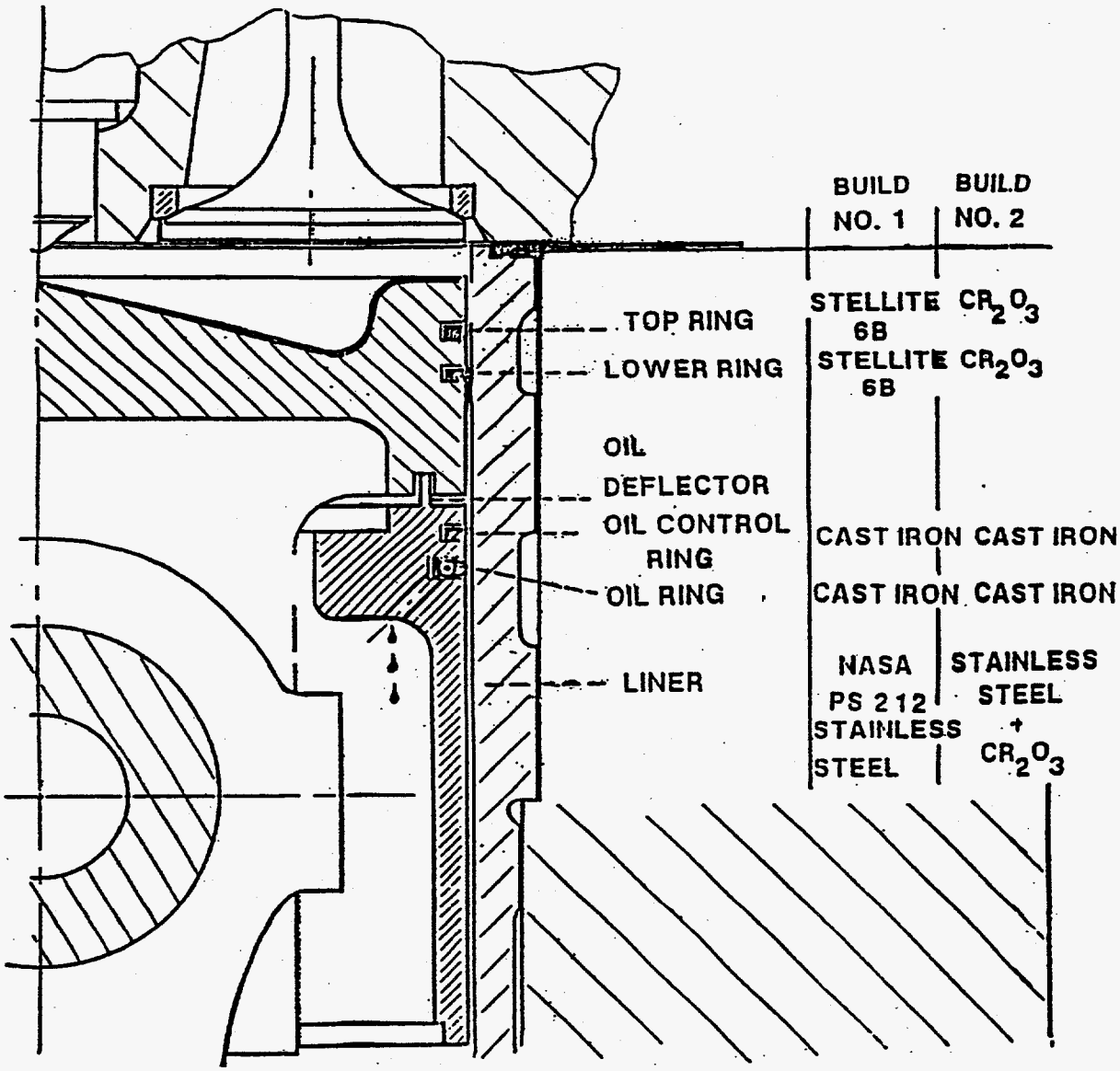


Figure 16. Proposed "Hybrid Piston" Concept

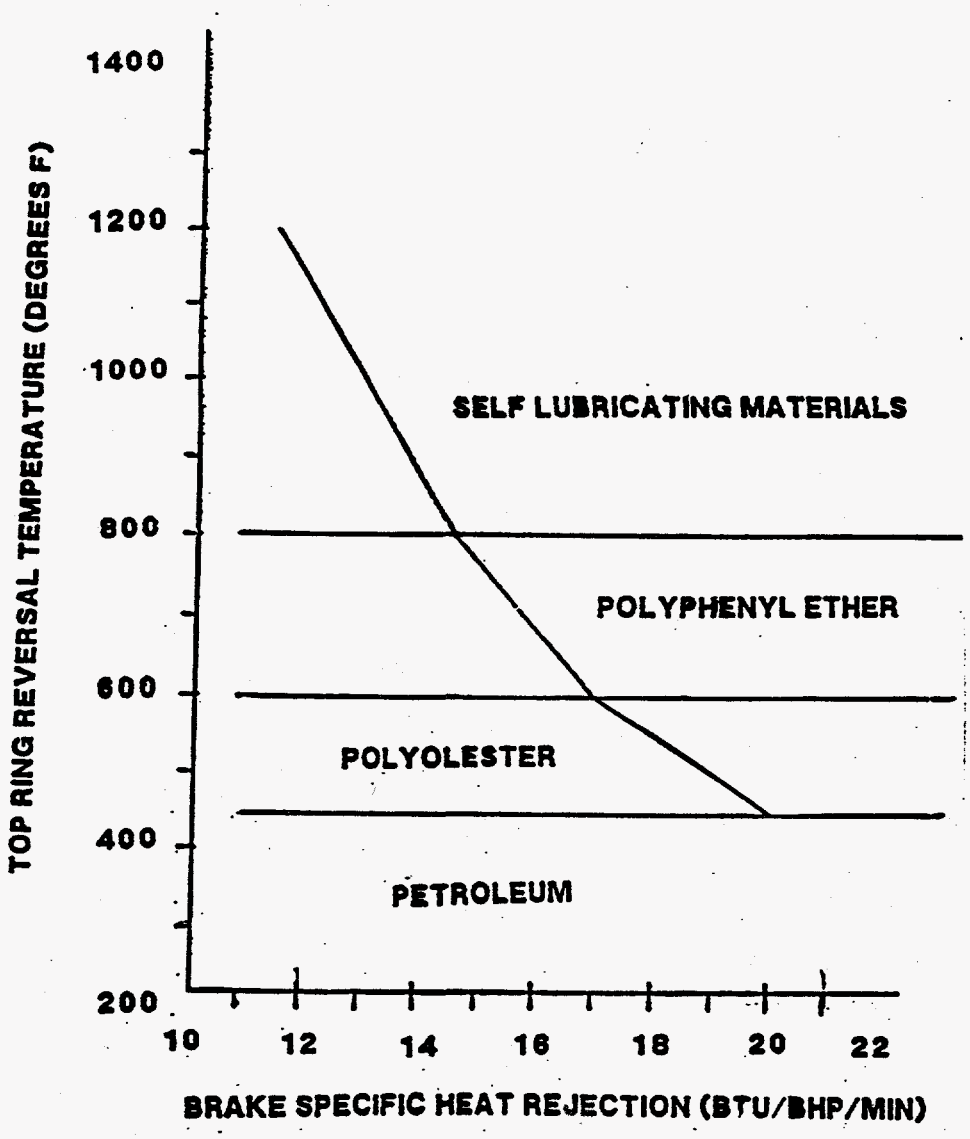


Figure 17. Piston ring and cylinder liner lubrication of an Adiabatic diesel engine

5.1.6 Dr. Rifat Keribar, Ricardo NA

Dr. Keribar of Ricardo North America discussed how lubrication issues related to the broader engine issues such as emissions, fuel economy, noise etc. (Table 22) thus defining some of the current areas of concern. He then discussed the present status of mathematical analysis and modeling of engine components with an emphasis on lubrication. He used three examples currently in use to illustrate how modeling can be used to better define engine conditions but which also indicate approaches for improved lubrication, better materials and designs, and strategy in meeting the environmental concerns. These examples were hydrodynamic and elastohydrodynamic lubrication of piston-cylinder components, wear-load analysis of engine rings and valves, and oil consumption analysis of a ring pack. The author concluded that powerful hardwares are increasingly making integrated models possible and such models could be a valuable and indispensable tool in the development of advanced engines.

Table 22

Engine R&D Perspective

Lubrication Issues:

- Engine friction
- Component wear
- System design/size
- Oil consumption
- Sealing, blowby
- Component dynamics
- High temperature stability of lubricants
- High temperature materials behavior

Broader Engine Issues:

- Efficiency, fuel economy
- Durability, maintenance cost
- Power density, fuel economy, cost
- Emissions, maintenance cost
- Power density, fuel economy
- Noise, driveability
- Durability, maintenance cost
- Durability, Cost

A very important area for analysis was oil consumption (Table 23) since it impacts strongly on emissions. Integrated models of ring motions, inter-ring gas dynamics and ring lubrication in conjunction with oil transport had been developed through R&D in the industry and universities. While very useful insights and understanding had emerged, prediction of oil consumption had been elusive, due to complexity of oil transport mechanisms (Table 23, Figure 18). Some theoretical estimates of oil and evaporative losses had been made, however, more experimental work was needed to complete the understanding and to help developing representative models.

Table 23

Oil Consumption Mechanisms

Transport Mechanism	
	Transport of oil as a film
	Transport of oil by inter-ring gas
Consumption Mechanism	
	1. "throw-off"
	2. evaporation
	3. "blow-back"

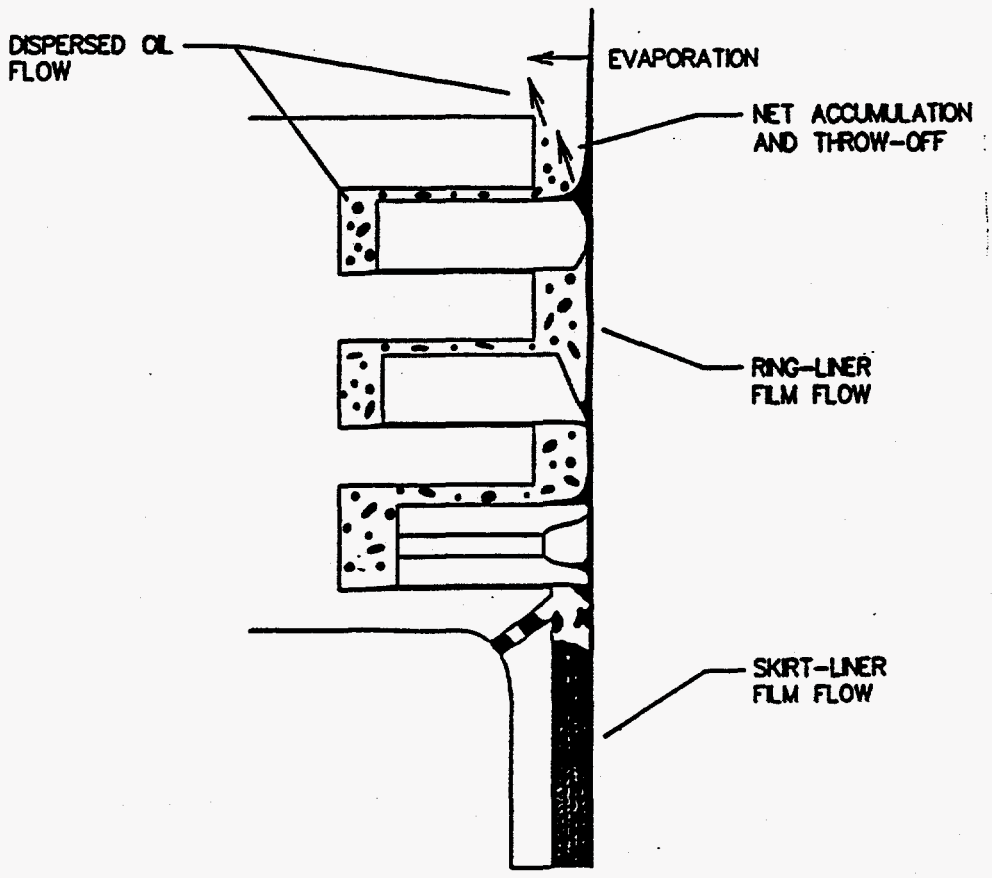


Fig 18. Oil Transport/Consumption Mechanisms

5.1.7 Dr. Nabil Hakim, Detroit Diesel

Dr. Nabil Hakim of Detroit Diesel reviewed some of the issues and concerns with alternative fuelled engines. Injector wear and deposit formation are the two major concerns. Some of the additives in conventional lubricants are sometimes extracted by the water-alcohol emulsions formed under certain engine operating conditions. This caused premature wear of the engine components and the fuel injectors. Some additive suppliers have developed compatible lubricants for alternative fuels, but this technology is not widely available. Therefore, the use of inappropriate lubricant could cause damage. The deposit issue was partly caused by extraction, partly by accelerated degradation by reactive species from alternative fuel combustion. He concluded that more research is needed to understand the interplay among materials, alternative fuels, and lubricants.

5.1.8 Mr. Bob Burrahm, SwRI

Mr. Bob Burrahm of Southwest Research Institute gave a presentation of the current status of the demonstration projects sponsored by the Gas Research Institute (GRI). In natural gas fuelled engines, valve recession and wear has been the key concern. Various advanced materials are used to fabricate the valve and valve seat inserts and will be tested in actual engines.

As shown in Figure 19, valve wear remains a problem in natural gas engines in spite of major design efforts to reduce wear (Table 24). However, in a recent SwRI project it was shown that certain ceramic materials such as silicon nitride and powdered metals reduced wear 60-100 percent. To capture these benefits a new industry team has been set up consisting of Caterpillar, Norton, TRW, EATON, COORS and NIST to evaluate improved materials in a Caterpillar 3516 lean burn natural gas engine. This is a 16 cylinder engine running at 1800 RPM. A total of 8000 hours will be accumulated with periodic valve recession measurements. Multiple ceramic insert and valve materials will be evaluated. This technology will be disseminated to industry.

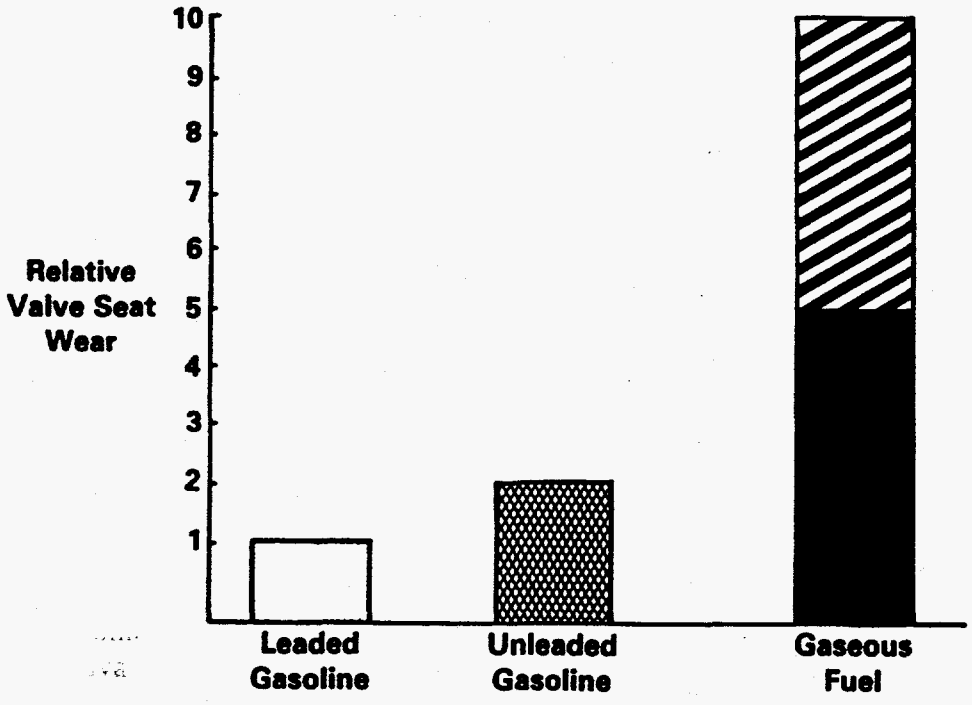


Figure 19. Valve Seat Wear Comparison

Table 24

Valve/Seat Design Practices

- 30 degree face angle
- Stiffer valve heads
- Stiffer cylinder heads
- Valve rotators
- Materials
- Valve/seat cooling
- Lubricants
- WEAR PROBLEM STILL EXISTS!

5.2 PANEL REPORTS

Participants interested in diesel engine technology were divided into two groups: one on materials for diesel engines, one on million mile engines. After extensive discussions, the groups gave the following reports.

5.2.1 Group 3 Materials for Diesel Engines, Dr. Malcolm Naylor, Cummins Engine Co., Chairman.

This group discussed lubrication issues related to ceramics and ceramic coatings, and other materials potentially applicable in diesel engines. They gave high priority, A, rankings to the areas listed in Table 25. The highest priority was given to lubrication problems that would arise with the use of alternative fuels. They further noted that injection pressures are increasing which would further impact lubrication problems with alternative fuels. New test methodology for scuffing, wear, friction, film formation and lubricant oxidation would be needed to properly evaluate the expected lubricant improvement. Increased generation and use of wear maps was suggested but they should represent realistic conditions perhaps with component geometries such as ring-liner, valve-seat, or injector plunger-barrel. Most important they should correlate with engine test results.

A lower priority (B) was given to the projects listed in Table 26. Those projects recommended for government action are listed in Table 27. Most of these are concerned with additive mechanisms in either fuel or lubricants.

Special consideration was given questions concerning the lubrication of ceramics such as the need and the role of lubricant additives with both ceramic/ceramic contacts and ceramic metal contacts; boundary lubrication mechanisms, and additives to improve performance.

This group felt that future workshops should be held on a once per year basis with small working groups for specific projects meeting twice per year. The potential exists for consortia in specific areas.

Table 25

High Priority Projects in Heavy Duty Diesel

Alternate fuel lubrication (A^+)
Test methodology/correlation (A^+)
Particulate control
High temperature lubricant
Universal oil
Soot generation mechanisms & interactions
Fuel lubricity additives

Table 26

Lower Priority Projects in Heavy Duty Diesels

Million mile engine
Biodegradable lubricants
High temperature additives
Ashless antiwear additives
Multifunctional additives
Antiwear mechanisms
Vapor phase lubrication
Oil condition monitor
Solid lubricants

Table 27

High Priority Areas/Projects for Government Research in Heavy Duty Diesel

Antiwear mechanisms
Test methodology & correlation
Fuel lubricity additives
Antioxidant mechanisms
Solid lubricants
Oil condition monitor

5.2.2 Group 4 Heavy Duty Diesel Million Mile Engine, Dr. Frank Kelley, Caterpillar, Chairman.

This panel considered the technology involved in the development of a high durability, long life engine. This concept was entitled the "Million Mile Engine", meaning one million operational miles could be accumulated before overhaul was necessary. After determining the critical issues, they were classified into near term (3-5 years) and longer term (5-10) years. These are listed separately in Table 28 in order of priority. The numbers in the table give the priority for the government participation and the letters show which organization should take the lead.

This panel felt that workshops were very useful and could be held once per year with smaller groups meeting twice per year. Consortia would be useful to address areas of broad applicability.

Table 28

Projects and Priority in Heavy Duty Diesels

Critical Areas in 3-5 Years Area	Govt Priority	Leadership
Long drain oils	1	I
Anti-oxidant mechanisms	2	U
Antiwear mechanisms	3	U
Million mile engine	4	I
Alternative fuel engine	5	G
Fuel injector durability	6	I
Low consumption/low particulate oil	7	G
Additive-additive interactions	8	U
Natural gas engine valves	9	G
Critical Areas in 5-10 Years		
On board oil rejuvenation	1	I
Universal oils	2	I
Bench-field correlations	3	G
Biodegradable fluids	4	G
Oil consumption mechanisms	5	U
High temperature lubricants	6	I
High temperature dispersants	7	I
High temperature oxidation inhibitors	8	I
Molecular engineered base stocks	9	U
Tribological system modeling	10	U
Advanced materials lubricants	11	I
Light weight materials lubrication	12	I

I-Industry; U-University; G-Government

6.0 LUBRICANT/ADDITIVE INDUSTRIES

Since the early 1970s, most of the lubrication research has shifted from the major oil companies to the additive companies. To date, almost all the major additive chemical companies are US companies. In the last ten years, however, the additive industry has seen increasing market pressures and recently some consolidation has occurred. At the same time, research in additive technology surges in Europe and Japan. The additive industry traditionally guards its technology and information jealously and has not been very receptive to collaboration or cooperation. However, the market pressure has also kept the industry's research efforts focused on near term commercial products. When it comes to experimental engines, new materials lubrication, or a limited niche market in defense application, R & D efforts by the major additive companies have been limited. At the same time, many of the long term technology programs sponsored by the government encounter barriers in lubrication technology.

After the recent consolidation, there is considerable interest among some oil and additive companies to reexamine the long term technology issue facing the industry. Inputs from many people in the lubricant/additive industry were received. Unfortunately, some were prevented from attending the workshop by bad weather, or emergencies at the last minute.

There were two technical presentations scheduled. Dr. Dick Coy from Shell Thorton Research Center encountered bad weather at London's Heathrow airport and his flight was canceled. He was supposed to speak on the recent advances in molecular engineered lubricants. Dr. Stephen Hsu, being somewhat familiar with the subject, gave a brief description of the subject. In short, due to the advances in molecular dynamics and the availability of supercomputers, it is possible now to calculate different molecular structures and predict their physical properties. Chemical synthesis of the optimized molecule then gave rise to the otherwise unavailable desired property. Some lubricant molecules, thus designed have been commercialized here and abroad. In one case it has been reported that this new class of lubricants possessed superior traction and could improve the energy conversion of gears significantly. The calculations were largely on physical properties, chemical properties were too complex.

The other speaker was Dr. Stephen Roby of Lubrizol Corp. He described the lubrication trends in passenger car motor oils, heavy duty diesel oils, two-cycle engine oils, and the changes mandated by environmental regulations. He pointed out that the two major factors that drive the lubrication industry are government regulations and lubricant performance regulations.

In passenger car motor oils two major recent changes are the use of the chemical manufacturers' product approval codes which will require new test procedures and requalification. A second change is the implementation of the API "SH" qualification in July 93. Technology can meet current needs but specifications are changing rapidly and the changes are accelerating.

Specifications are also changing rapidly for heavy duty diesel oils. One of the primary problems is soot in the oil, its effect, and how it can be removed. There is major interest in after

Specifications are also changing rapidly for heavy duty diesel oils. One of the primary problems is soot in the oil, its effect, and how it can be removed. There is major interest in after treatments for soot, for example soot traps in the exhaust.

Two-cycle engines present a major problem since the lubricant is burnt with the fuel. This is a major source of pollution in some areas. The net result is that emission proposals are motivating new technology, smaller engines may be eliminated and new and higher quality oils are being demanded including biodegradability.

The major concern however is for development of environmentally friendly lubricants for a wide variety of industries. The problem is that a wide variety of requirements are specified; unfortunately, some of these are mutually incompatible. Amendments to the 1990 clean air act mandate many changes in passenger car and diesel fuels and in the use of alternative fuels. Each change in fuel will require a corresponding change in engine lubricants, additive packages and materials to combat wear, preignition, lubricant oxidation, deposits, and emissions. New bench tests will be needed to make these changes, particularly those that correlate with field performance.

6.1 Panel Report

Group 5 - Lubricant and Lubricant Additives, Dr. S. Roby, Lubrizol, Chairman.

Dr. Roby first pointed out some of the constraints that the lubricant industry faces when contemplating a lubricant development program. The sales volume must justify the development costs. Many people do not realize the magnitude of such costs which include not only the synthesis costs but also performance testing, patent protection, compliance with regulations both local and national and product marketing. Some needs, like special ceramic lubricants, may be urgently needed but lack sufficient volume to justify industry attention.

The projects requiring attention are listed in order of priority in Table 29. The area of high temperature lubrication was recommended for a working consortium which includes government, industry and academia.

This group found the workshop interesting and informative and suggested a frequency of once per year. Opinion was divided on formation of a lubrication consortium; however, they indicated that they would be willing to listen to specific proposals and then decide at what level and in what form they would participate.

Table 29

Lubricant and Lubricant Additive Areas

Area	Leadership
High temperature lubricants	C
Additive mechanisms	I or U
Additive-additive interactions	I
Additives for coatings	I
Additives for ceramics	I
High Temperature dispersant	I
Molecular engineered base stocks	?

I-Industry; U-University; C-Consortium

7.0 OTHER RELATED PROGRAMS AND INDUSTRIES

Besides the three major industrial groups dealing with the land transportation systems, additional inputs were provided by representatives from the aerospace industry, materials community, and other related government programs. In this section, these inputs are summarized.

7.1 TECHNICAL PRESENTATIONS AND SUBMITTED INFORMATION

There were four presentations and two submitted contributions. These are listed below.

Tribological Research Needs in the Aerospace Industry	Dr. Bill Nieman, Allied-Signal Corp.
Trends in Rotocraft and Ground Vehicle Propulsion Lubrication Requirements and Future Considerations Driving those Trends	Dr. Robert Bill, US Army Vehicle Propulsion Directorate
Heavy Duty Transport Program	Mr. John Fairbanks, DOE (talk given by Dr. Perez).
OTM Tribology Program	Dr. Joseph Perez, DOE
Engineered Surfaces and Interfaces	Dr. George Fenske, Argonne National Lab.
The Role of Government in Fostering Industrial Cooperative Research	Dr. J. J. Eberhardt (presented by Dr. Perez)

7.1.1 Dr. Bill Nieman, Allied-Signal Corp.

Dr. Bill Nieman recently made a survey of the tribology research needs among the various operating divisions within the Allied Signal Corp. Allied Signal manufactures a variety of aircraft engines, auxiliary power units, and components for business aviation and regional airlines. They are also deeply involved in materials development for aircraft industry components and structures: silicon nitride, filament reinforced ceramic matrix composites, ceramic coatings, high temperature aluminum alloys and low density aluminum alloys.

Some of the short and long term research interests in tribology are listed in Table 30.

Table 30
Tribological Research Interests

Component lubrication in the temperature range 200-650°C (392-1202°F)
Longer term component lubrication 500-1000°C (932-1832°F)(solid lubricants)
Lubricant lifetime extension
Lubrication for space system actuators (10-20 years)
Lubricants for machining of high performance materials
Lubrication of advanced materials

7.1.2 Dr. Robert Bill, U.S. Army Vehicle Propulsion Directorate

Dr. Bob Bill submitted a contribution to the workshop entitled "Trends in Rotocraft and Ground Vehicle Propulsion Lubrication requirements and Future Considerations Driving those Trends." This contribution covered a wide range of disciplines but the emphasis in this summary is on lubrication.

The trends in reciprocating engine lubrication are shown in Table 31. The major changes foreseen are an increase in temperature from 204-260°C (400-500°F) to 371-427°C (700-800°F) and pressures from 250 PSI to 400 PSI. It is anticipated that advanced synthetic lubricants and self-lubricating materials will be available to meet the requirements; however, solid lubrication and vapor phase lubrication are also under consideration.

Table 31
Trends in Reciprocating Engine Lubrication

- Present top ring reversal temperature in 200-260°C (392-500°F) range and IMEP in 250 psi range
  - Represent limits mineral oil based lubricants used
- Trend over next 10 years, along various engine development paths, is toward top ring reversal temperature 371-427°C (700-800°F), IMEP in 400 psi range, and increased speeds
  - Advanced synthetic lubricants required
  - Self lubricating ring/liner materials
- Alternate technologies considered
  - Solid lubricated ring/liner
  - Vapor phase lubrication

The trends in gas turbine bearing lubrication are shown in Table 32. In the next 10 years bearing temperatures are seen increasing to 371-427°C (700-800°F) which will require substantial progress in corrosion and oxidation inhibition. This probably represents the limit of fluid lubrication. Other technologies like high hot hardness steels, ceramic bearings, adaptive lubrication systems, powder lubricated ceramic bearings and magnetic bearings should also be considered.

The conclusion is that in all propulsion applications, trends are toward more aggressive operating conditions: higher temperatures, increased loading and higher speeds. Liquid lubrication technology will have to be significantly advanced, augmented or in some cases supplanted by alternative technologies; however, alternative technologies must generally be viewed as high risk. Tribology is viewed as an enabling technology to major propulsion programs at high levels in DoD.

Table 32

Trends in Gas Turbine Main Shaft Bearing Lubrication

- Present max temperatures in 204-232°C (400-432°F) range
  - Represents limit of CI synthetic diester/polyol ester base oils
- Progressive steps over next 10 years to 371-427°C (800-700°F) bearing compartment temperatures
  - Requires substantial progress in corrosion and oxidation inhibition
  - Represents limit of PFPE base lubricants
- Complementing technologies being addressed
  - Further advances in H^3 bearing materials
  - Ceramic bearing systems
  - Adaptive lubrication systems
- Alternate technologies considered
  - Solid (powder) lubricated systems in conjunction with ceramic bearings
  - Magnetic bearings

7.1.3 Heavy Duty Transport Program, Mr. John Fairbanks, DOE (Talk given by Dr. Joe Perez)

An overview of the Heavy Duty Transport Technology Program was presented by Dr. Perez for John Fairbanks who expressed considerable interest in the workshop but was unable to attend. This program is on a reasonable schedule to accelerate heavy duty diesel engine development in order to achieve a fuel economy of 0.25 lb/bhp-hr brake specific fuel consumption for

commercial engines introduced in the year 2000. This will be a 20 percent improvement in fuel consumption as well as a 20 percent reduction in CO_2. These diesel improvements can be obtained with thermally optimized designs, nearly doubling the top ring reversal temperatures, doubling the charge-air boost pressure and improving turbocharger efficiency from about 60 to 72 percent, and insulating the combustion chamber. In some engines, the block water cooling system will be eliminated and a high temperature synthetic liquid lubricant will be used as a coolant (where necessary) and for lubrication. Engine manufacturers are working on both liquid and vapor lubrication schemes. These programs have accelerated the introduction of advanced materials including ceramics, ceramic fiber reinforced metals and parts formed by powder metallurgy. Several programs have been initiated recently addressing NO_x reduction as well as particulate reduction. The major changes in the program are the increased emphasis on emission reduction technology. One new innovative program is considering incorporation of a NO_x reduction additive into the diesel fuel. This approach has shown promise in single cylinder engine tests.

7.1.4 DOE OTM Tribology Program, Dr. Joseph Perez, DOE

Mr. Joe Perez, Program Manager of the Tribology Program, described the DOE Office of Transportation Materials current program on tribology. He pointed out that a new era began in 1991 when there was a shift from long-term high risk projects to near-term industrial relevant programs. The new program direction will include advanced lubrication topics, alternative fuels compatible materials, environmentally friendly lubricant technology and support for the Office of Transportation Technologies' engine programs. The goals of the program are listed in Table 33 and its approach in Table 34. Dr. Perez emphasized that he is particularly interested in industrial inputs and industry participation in defining the future lubrication program.

Table 33

Office of Transportation Materials' Tribology Program

Goals

- Improve competitiveness
- Reduce energy dependence
- Environmentally compatible

Table 34

Office of Transportation Materials' Tribology Program

Approach

- Input on possible areas for interaction
  - One on one
  - Surveys
  - Workshops
- Multi-Year Program Plan
- Industry Input/Comments
- Review
- Implement

7.1.5 Engineered Surfaces and Interfaces, Dr. George Fenske, Argonne

Dr. George Fenske presented the Argonne program on surface modification of tribological components. The goal of the program is to improve the friction and wear properties of component surfaces used in advanced diesel, gas turbine and electric vehicles.

The areas of study are listed in Table 35. Friction and wear tests have been run on most of the examples listed. Examples of the benefits of each process are given in Figures 19-23. Adherent silver coatings were deposited to reduce the friction of ceramics by assisted PVD silver films (Figure 19). High reactive rate sputter deposition of TiN increased contact fatigue resistance of steels (Figure 20) while the ion beam deposition of diamond like carbon had the same effect (Figure 21). Of particular interest was the almost 10 fold increase in life of MoS_2 films formed by ion beam mixing over sputter deposition (Figure 22). Low friction was obtained with plasma-assisted CVD diamond coatings (Figure 23).

It was shown that significant advances have been achieved in developing surface modification processes to improve the friction and wear performance of engine components during boundary and mixed lubrication. Extensive laboratory friction and wear testing of surface-modified steels, superalloys, and ceramics show significant improvements in the friction and wear properties at elevated temperatures. Programs are now underway to transfer surface modification technology to industrial applications.

Table 35

Areas of Industrial Interest in Surface Modification Technologies

Beam-Assisted Physical Vapor Deposition

TiN	Ag, Sn
Cr_2O_3	CaF_2, BaF_2
Mo	Ni, Ti
DLC	B, B_2O_3

High-Rate Reactive Sputtering

TiN, ZrN, HfN
TiC, ZrC, HfC
.....

Ion Beam Deposition

Diamond-Like Carbon (DLC)

High Current-Density

Ion Implantation

N, C
B, Si, Ti

High-Energy Ion Implantation and Mixing

MoS_2
Ag/CaF_2

Plasma-Assisted CVD

Polycrystalline Diamond

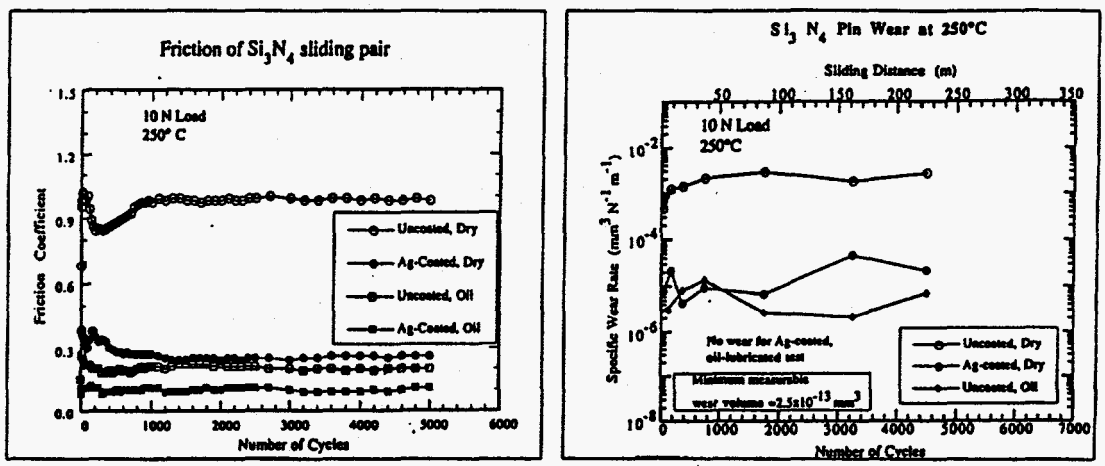
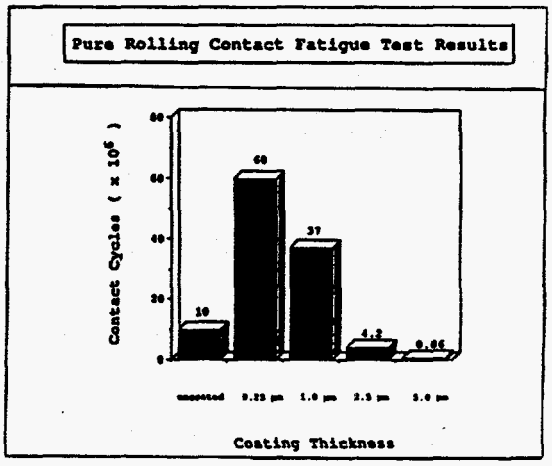


Figure 19. Beam-Assisted PVD of Lubricous Coatings on Ceramics

Developed HRRS process utilizing unbalanced dc-magnetron mode to increase bombardment of film with energetic plasma ions

Characterize RCF and scuffing performance of HRRS-coated steels

- Resistance to RCF and scuffing significantly enhanced by thin TiN coatings
- Hard coatings show greater improvements when applied to smooth, hard substrates

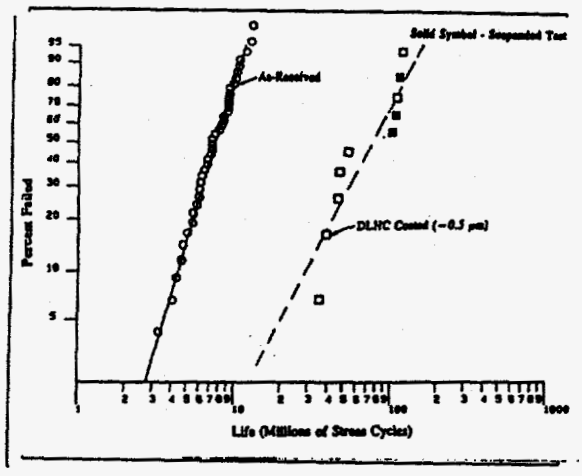


- Unlubricated friction coefficients of 0.1 observed for TiN/TiN couples

Figure 20. High-Rate-Reactive-Sputter Deposition of Nitrides and Carbides

Deposition of smooth, hard DLHC coatings on steels and ceramics

- Reduced Wear
- Reduced Friction
- Longer Lifetimes



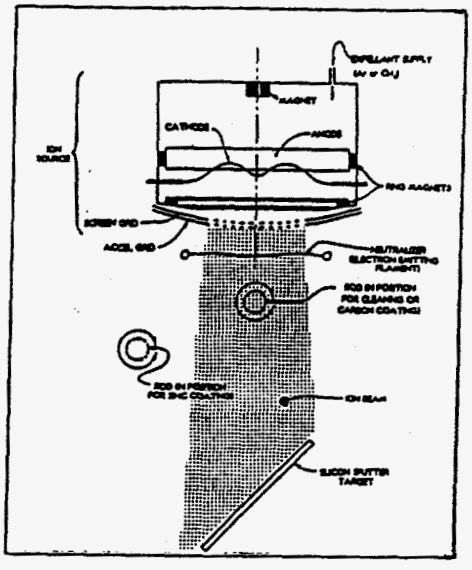


Figure 21. Ion-Beam Deposition

Developed process to form MoS_2 in near-surface regions of ceramics via high-energy implantation of Mo and S

Developed process to "stitch" PVD MoS_2 coatings to ceramics, thereby extending lifetimes

Developed process to mix layered PVD coatings of CaF_2/Ag deposited on ceramics. Films exhibited low friction at elevated temperatures

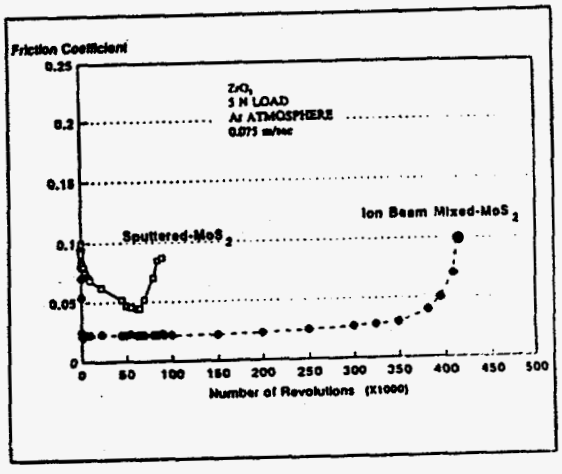


Figure 22. High-Energy Ion Implantation and Mixing

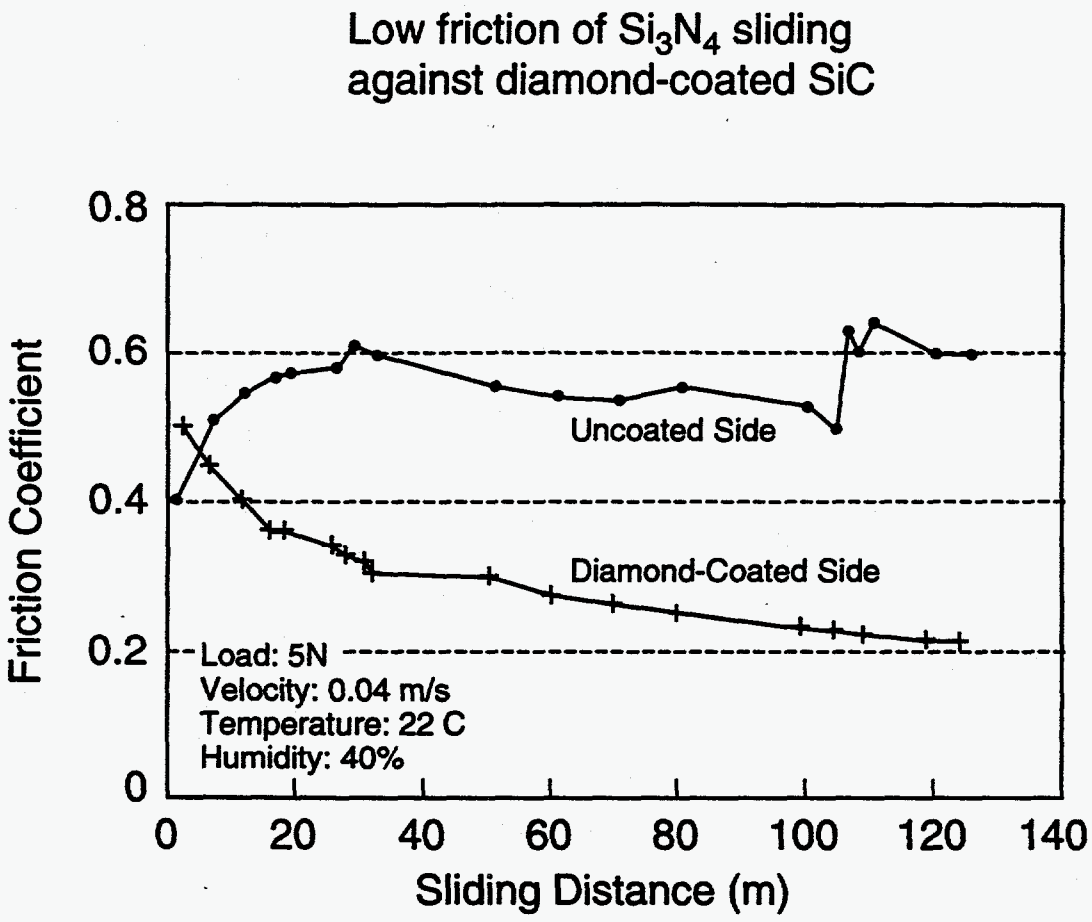


Figure 23. Plasma-Assisted CVD of Diamond

7.1.6 The Role of Government In Fostering Industrial Cooperative Research, Dr. J. J. Eberhardt (Presented by J. Perez)

Dr. Eberhardt, Director of the Office of Transportation Materials was unable to attend the sessions due to conflicting prior commitment. However, Dr. Perez from the OTM office presented an informational talk based on Dr. Eberhardt's 1992 SAE presentation. He summarized appropriate legislation and policy acts that have led to increased industry - government cooperation, Table 36. The various mechanisms found on Table 37 were discussed in some detail. The information was useful to the participants individually and in setting a positive tone for cooperative industry - government - academia programs such as this workshop.

Table 36

Legislation and Policy on DOE Technology Transfer

- Bayh-Dole Act of 1980
- Stevenson-Wydler Technology Innovation Act of 1980
- National Cooperative Research Act of 1984
- Federal Technology Transfer Act of 1986
- National Competitiveness Technology Transfer Act of 1989
- National Defense Authorization Act of 1990
- Executive Order 12591 of April 10, 1987

Table 37

Technology Interchange Mechanisms
for Leveraging Federal R&D

- Advanced Manufacturing Initiative (DOE/DP)
- Advanced Technology Projects Program (DOC/NIST)
- Consortia
- Contract R&D
- CRADA's
- Cost Sharing Agreements
- Licensing
- Regional Manufacturing Technology Centers (DOC/NIST)
- Scientist and Engineer Exchanges
- Technology Maturation Process
- Government R&D User Facilities
- Pilot Centers (HTSC)
- Information Dissemination

8.0 TECHNICAL SURVEY AND QUESTIONNAIRE RESULTS

8.1 TECHNICAL SURVEY

Prior to the workshop a technical survey was sent to approximately 100 people (30 responded) working in the lubrication field. This survey asked questions relative to the workshop and was used in planning the workshop. Since these forms were filled out prior to the meeting, they represent completely independent inputs. The survey form has been shown in Table 12. A summary of the response to each question is given in the following paragraphs.

Question 1. What are the roles of new materials in your companies technology? Do you see it as a prime motive force for new technology?

Many of the respondents stated that materials played a supportive role in their organizations to meet new requirements. They noted that materials are a limiting factor in many technologies and new materials were under continuous review. Several respondents noted that advanced materials were one of several technologies in which major economies must compete.

Question 2. What are the most critical issues dealing with the new materials? What new materials are useful?

The responses provided no consensus but a variety of individual responses. If there was a theme it was that many new materials (ceramics, composites, etc.) were being introduced and data on properties, relative cost, manufacturability, performance in specific applications, quality control, supply reliability and test methods were needed.

Question 3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

Almost all respondents stated that lubrication of new materials was a concern to them. All chose to phrase impacts in negative terms such as: unable to meet government mandates, limited performance and durability, limit engine development and usage, increased warranty costs and higher wear. The sense of the answers was that new materials are seen as they key technology in reaching the established goals and their effective lubrication is essential in both processing and use.

Question 4. What are the major driving forces influencing the technologies essential to your business?

The responses given are shown below in Table 38. The major driving forces in order of importance are: cost, emission, performance, durability and fuel economy.

Table 38

Major Driving Forces

	No. of responses
Cost	18
Emissions	17
Performance	16
Durability	14
Fuel Economy	12
Maintenance Cost	5
Repair Costs	3
Innovation	3
Materials	3
Innovation	3

Question 5. What is the key research agenda for your company in the next 3-5 years?

For the automobile companies the research agenda was primarily the continued refinement of the spark ignition engine with the application of new materials, greater efficiency, process and component modeling, better test methods, and cost reduction. For the diesel engine the answer was much more concise; fuel economy and lower emissions to meet government regulations. Those not associated with the auto or diesel business directly were more concerned with test methodology and lubrication fundamentals.

Question 6. What is the key research agenda of your company in the next 5-10 years?

For the auto companies the agenda shifted to newer types of engines and components. Electric propulsion, variable valve timing, higher temperature and lower weight components. One concludes that lubrication research in a 10 year time frame would be very different from a 3-5 year period. For the diesel engine, emissions and fuel economy remained dominate but at higher temperatures.

Question 7. Which topics do you think should be handled by Industry? Government? and Universities?

This question provoked a wide range of responses with little consensus. For the government high-risk futuristic technologies, standards, and basic research supplying data and mechanistic understanding seem to prevail with emphasis also placed on technology transfer and technology feasibility demonstration. Several specific items mentioned were high temperature liquid lubricants and lubrication for severe and harsh environments.

The responses for government laboratories was much more definite. The establishment of data bases was frequently mentioned along with new test methodology. Global technology monitoring was suggested as a very useful pursuit. Long range research was also frequently mentioned. The majority of the respondents felt that the industry should take the lead in developing the technologies and the universities should train students and explore new ideas.

Question 8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

The responses are given in Table 39 in order of importance. It should be noted that this list gives a somewhat different perspective to the important issues. New lubricants, additives and materials are high on the list while data bases recommended previously received little support. Test methodology remained an important consideration as well as low friction materials. The questions as to who should do the work proved to be inconclusive.

Table 39

Issues in Lubrication That Need to be Addressed

Bench Test Development	11
New High Temp. Additives	11
High Temp. Liquid Lubricants	10
High Temp. Solid Lubricants	9
Additive Mechanisms/interactions	8
New Measurement Methods	8
Low Friction Materials	7
Advanced Materials Lubrication	6
New Lubricant Base Stocks	6
Thermally Stable Dispersants	5
Molecularly Engineered Lubricants	5
Additive Interactions	4
Stability Mapping	4
Additives for Ceramics	3
Methanol Compatible Lubricants	3
Lubricant Application Guide	2

Question 9. What are the most important materials that you would like to see research be conducted on?

The responses, given in Table 40 list ceramics, coatings and metal matrix composites as the most important topics.

Table 40

Most Important Materials From the Technical Survey

Ceramics	17
Coatings	14
Metal Matrix Composites	9
Plastics	7
Aluminum Alloys	6
Super Alloys	4

Question 10. What are the major driving forces for change in lubrication technology?

The overall response is given in Table 41. The responses were not uniform across auto, diesel, lubricant, government and independents. Emissions, extended drains and higher temperatures were ranked highest for diesel engine representatives. Higher temperatures, better quality, material changes, and power density were most cited by auto companies. The independents favored emission control and higher temperature lubricants.

Table 41

Major Driving Forces for Change in Lubricating Technology

Emission Control	17
Higher Temperatures	15
Alternative Fuels	10
Higher Power Density	9
Extended Drain Oils	9
Fuel Economy	6
Material Changes	6
Durability	6
Design Changes	5
Better Quality	4
Smaller Engines	2
Higher Stress	2

Question 11. Which of the following component technologies do you think is the most important to you?

Of the 14 engine components the following received the most responses with only minor differences in priorities: ring-Liner, valves, bearings, fuel injectors, pistons.

Question 12. What are the maximum temperatures you think the engines of the future will have? In 3-5 years? In 10-15 years?

There were many responses, but because of the many engines, the answers were all over the map. In general, there was a perception that engine temperatures would rise in the future; just how much, was not clear. The majority seemed to put the temperature rise at about 10-38°C (50-100°F) barring revolutionary technology advancement.

Question 13. Of all the topics mentioned (but not limited to) which do you think is the most important? Which would your company be interested in participating in? Which do you think the government should concentrate on?

The response to these questions are essentially the same as question 8.

Question 14 - Would you like to see a consortium set up? Would you participate?

Of the 30 responses, 21 said yes, 4 no, and 5 did not answer to both questions.

8.2 QUESTIONNAIRE RESULTS

After the technical presentations, a detailed questionnaire was distributed to each participant in the workshop. This on one hand, served as a beginning discussion point for the small group discussions; at the same time, this served as a barometer to gauge the attitudes of the participants after they had a chance to listen to the others, discuss the issues, and had some time to consider some of the issues raised during the workshop. In addition, the workshop organizers were concerned that forcing some level of consensus in a panel environment might eliminate some important individual inputs. Therefore, each workshop attendee was given a questionnaire to fill out. The questions are listed in Table 12 in section 3 of this report. In addition, a list of possible project ideas was also included. The individual attendee was asked to prioritize them according to his/her perspective. Nineteen responses were received, some from people who could not attend the workshop for one reason or the other. The results are summarized in the following paragraphs where each question is given, along with a summary of results. In many cases the answers to the questions were the same as that reported by the panel. Such responses are generally not included; the emphasis is on new inputs.

In general the questions were analyzed on the basis of the respondents' association either auto industry, diesel industry, components and independents and lubricant or additive suppliers.

Question 1. Based on the needs you heard from industry and based on your views what are the most critical areas to address in the next 3-5 years?

Almost all respondents noted the general requirements of emission controls, durability, manufacturing costs, fuel economy, environmental friendliness, longer life and weight reduction. The areas most recommended, regardless of the association, were the following:

- High temperature lubricants
- Better test methodology with engine and field correlations
- Modeling of component or lubrication performance
- Lubricants for new materials, databases, and mechanistic understanding

Representatives of the automotive industry emphasized the coming use of new materials, the importance of acquiring a working knowledge of their tribological properties and the development of effective lubricants. They noted the gradually increasing temperatures and the need for improved high temperature lubricants. Solid lubricants were generally associated with advanced propulsion systems like the low heat rejection engine or the automotive gas turbine.

The diesel engine representative responses were very similar to that of panels with emphasis being placed on alternative fuels, low particulates, improved component life and extended drain oils.

Component suppliers and other industries (research laboratories, material suppliers, and academia, etc.) made recommendations similar to those of the panels but with more emphasis on modeling, such as oil consumption modeling. A suggestion was also made for a new look at solid lubricants that were compatible with the liquid lubricant, as well as a self-lubricating materials. The approach being suggested was that higher temperature lubrication could be achieved if part of the lubricating capacity could reside in the materials rather than in the fluid.

Lubricant suppliers were interested in theoretical approaches which would tie additive chemistry to performance.

Thus based upon responses to this question the following projects could be added to the workshop recommendations:

- High temperature self lubricating materials
- Modeling and predicting performance of components and lubricants

Question 2. The same question as number 1 expect for a longer time frame, 5-10 years.

Some respondents had difficulty in differentiating needs between the two time frames given. In fact many answered "same as question 1" for question 2. Presumably a "need" is a "need" and solutions are desired in as short a period of time as possible. Generally the answers emphasized the more fundamental issues such as modeling, understanding and development of new materials.

Question 3. Is there any particular area that you think is so important that you or your company will address it regardless of other considerations? If so, would you be willing to work with others on the issue?

Response to this question was limited, suggesting that either the in-house research is limited or that there is unwillingness to even disclose generic topics for fear of competitors. All of the groups (auto, diesel, etc.) mentioned emissions. Most of the projects were the same as listed in question 1.

Question 4. Which of the supplied list of projects do you like most and which should the government work on?

A careful analysis was made of the responses to this question because it represented a very important input to the planning process. The projects suggested by individual respondents listed in order of importance are listed in Table 42. These are the ones suggested for government involvement.

The highly rated projects, regardless of who does the work, were essentially the same as those given by the panels with reduced emissions, million mile engine, test methodology and high temperature solid lubricants receiving the most response.

Table 42

Projects Suggested for Government Involvement

Advanced materials lubrication
Alternative fuel lubrication
Particulate Control
High temperature lubricants
Bench test methodology
Lubricant application maps

Question 5. Same question as number 4 but in any area.

Most respondents chose not to answer this question (Question 4 was fairly comprehensive). However, one respondent mentioned cost-effective manufacturing processes like ceramic machining, superfinishing of bearings, etc. Another suggested metal working friction and lubrication in manufacturing.

Question 6 - What is your reaction to this type of workshop? How often should it be held?

All of the respondents thought the workshop was very beneficial and most felt that it should be held once per year (with a longer lead time).

Question 7 - Should a consortium be formed and would you participate?

All of the respondents except 4 voted in favor of a consortium and would participate depending, of course, on management approval and the specific nature of the technical areas proposed.

9.0 CONCLUSIONS

The results of the literature search, workshops and survey indicate that without considerable lubrication developments the goals of current prototype or advanced engine systems will not be met. Some of the most critical issues are summarized in the following paragraphs.

Temperatures will continue to increase for both the spark ignition engine (TRR 300°C) advanced diesels (TRR 500°C), the auto gas turbine (bearing temperatures 315°C regenerator seals 1000°C) and the aircraft gas turbine (bearing compartment, 400°C). Current lubricants both liquid and solid are inadequate for such temperatures. The most critical problems are with the additives and their interactions at such temperatures and with current lubricant delivery systems. New additives are needed for lubricant oxidation and deposit control on high temperature components. Advanced lubricant delivery systems should be developed which control the flow of fluid in precise amounts necessary to fulfill the lubricant function. Excess amounts only increase emissions and form deposits. Effective solid lubricant delivery systems are needed for rolling contact bearings and other engine components.

New solid lubricants must be isolated for use at 650°C in the regenerator seals of the automotive gas turbine. These are isolated applications; however, their identification would encourage utilization in lower temperature applications.

Current materials are generally adequate to meet anticipated tribological requirements; however, a variety of new materials are being introduced for reasons of weight reduction, cost considerations, thermal behavior, mechanical properties, and increased durability. Those receiving primary attention are ceramics, metal matrix composites and light weight metals: aluminum, magnesium and titanium. Lubrication science has been built around steel surfaces and problems are anticipated in both component manufacturing and use.

A review of DOE research indicates over 50 programs whose direct objectives are the development of ceramics, ceramic composites, and ceramic coatings for engine components. They are finding their way into engine service. Unfortunately very little is known about ceramic lubricants or lubrication except that friction coefficients are comparable to those metals. Some essential properties like load capacity, interface temperatures, fluid film behavior, surface fatigue, and wear rates have not been defined. More definitive research will be necessary.

Metal matrix composites, mostly aluminum based, have been under intensive development for many years because of their high strength to weight ratios. Both fiber and particle composites are under consideration for pistons, engine blocks, gears and other engine parts. The lubrication and wear properties of these materials are virtually unknown and must be investigated. An interesting approach being explored is to make such materials self lubricating so that lesser demands are placed on the fluid lubricant.

Self-lubricating materials, if they can be fluid lubricated at lower temperatures, are seen as a possible alternative to continued development of fluid lubricants. The lubricating capacity of the

system is thus built into the materials and allows dry lubrication at maximum temperature or the use of more stable fluids with poorer lubricating capacity.

The use of light weight metals in engine and structural parts is increasing. Most of these *light* weight metals are difficult to lubricate, are erosion prone, have much higher wear rates, lower load capacity and present metal working lubrication problems in high speed production. Petroleum base stocks appear to be adequate but new antiwear and EP additives will be necessary for general usage.

Lubricants account for 25 to 35 percent of diesel engine particulates. Particulate control in exhaust emissions is an absolute necessity mandated by law. This is not a simple task since basic mechanisms are not known. Better lubricant control in the ring liner area will be needed as well as better detergents and exhaust traps. Fuel additives are also receiving attention in DOE programs.

The introduction of alternative fuels will have a major impact on wear of engine components, in particular the fuel system components, (injectors, fuel pumps) and the corrosive wear of fuel wetted parts (rings, valves, pistons). Other fuel economy issues such as lower weight and lower friction will put emphasis on new materials previously discussed. These new materials will not benefit greatly by the vast technology built up for steel components and current additive packages. Two major changes in components driven by fuel efficiency are the introduction of the continuously variable transmission, and higher pressure gears.

For heavy duty diesel engines, there are demands for reduced oil changes in engines. Five thousand miles is considered excessive with 30,000 miles being more realistic to conform to other maintenance requirements. Approaches include not only improved oils and additives but also on board oil monitoring and rejuvenation, better filtration and a better understanding of oil consumption mechanisms.

Engine developments are seen to be more evolutionary than revolutionary; however, the technology cycle has been shortened due to foreign competition, government regulations, and changes in customer preferences. Lubricant, material and lubrication system changes will be driven in the near term by environmental concerns and fuel efficiency. However, in the longer term increased durability, longer life, and down sizing will be of increasing concern. Component wear rates and higher temperatures will be a concern. Components of major concern are rings, valves, bearings, and pistons.

As engine temperatures gradually increase due to higher power density and engine insulation to capture heat energy, lubricant viscosities will decrease and fluid films will give way to increased instances of boundary lubrication, with a possible increase in both friction and wear. The most critical areas will be in the rings and bearings which are designed for complete fluid film lubrication. Such increases in friction and wear are undesirable, and improved component designs will be necessary. Some approaches under consideration are rolling contact bearings, attenuated pistons, ring removal with controlled piston clearances, solid lubricated top rings and

hydrostatic lubrication.

Although lubrication theories, techniques, and systems are well advanced there are several areas which will require attention. First of all, as new technology is being introduced, lengthy prototype evaluations should be avoided if possible. There is almost universal agreement that improved life and performance prediction techniques must be developed as well as better test methods which correlate with engine service. This would be a major undertaking with a very high payoff in productivity. The two areas where modeling would be particularly beneficial are in oil consumption and lubricated wear behavior. Those most knowledgeable feel that the techniques are now available to do an integrated analysis of the engine system, e.g., combustion, thermal, and fluid film analysis of the piston, ring, and liner behavior.

Almost all of the industries representatives attending the workshop stressed the need for improved test methodologies particularly those that would better simulate field service. In subsequent discussion it was suggested that a user facility be established where test methods could be developed and used by industry.

Based upon the findings of this workshop a program has been outlined in Table 43.

Table 43

Proposed Program

I. High Temperature Liquid Lubricants for Advanced Engines

- 1.1 Development of Cost-Effective 300°C Synthetic Base Fluids
- 1.2 Development of High Temperature Stable Additives
- 1.3 Ultra-High Temperature Lubrication Systems

II. Lubrication Technology for New Materials

- 2.1 Lubrication Base Technology for New Materials (Same Materials)
- 2.2 Lubrication Technology for New Materials (Dissimilar Materials)
- 2.3 Lubrication Technology for Cost-Effective Forming/Fabrication of New Materials
- 2.4 Design Guidelines for Materials-Lubricant Combination
- 2.5 Application Insertion and Field Testing

III. Environmental Friendly Lubricants

- 3.1 Emission Control Technologies for Engines
- 3.2 Environmentally Compatible Lubricants

IV. Lubrication Technologies for Engine Durability and Component Developments

- 4.1 Fuel Efficiency Technologies
- 4.2 Million-Mile Engines
- 4.3 Engine Components and New Engines
- 4.4 Bench Simulation Development for Engine Performance

10.0 A PROPOSED PROGRAM

LUBRICATION TECHNOLOGIES
FOR
ADVANCED ENGINES
A Joint Industry-Government-University Program

BACKGROUND

The transportation industry has, since the 1800's, been the technology leader in the field of lubrication and tribomaterials. Most advances have been made in meeting the requirements of advanced power systems for ground, rail and air transportation. The automobile spark ignition engine has provided this leadership in lubricants. The first engines were lubricated with fatty oils or unrefined paraffinic mineral oils with broad boiling point ranges and undesirable contaminates. Oil changes were required every 300 miles. Even with these frequent oil changes, hard carbon deposits rapidly built up which had to be scrapped from pistons, rings, valves and cylinders approximately every 1000 miles. Since 1915 lubricants have rapidly evolved to meet new engine requirements. A list of some of the major developments are listed in Table 1. The modern oil is a highly sophisticated product with accurately controlled properties and a variety of additives (friction modifiers, antiwear, antioxidants, corrosion inhibitors, detergents, dispersants, antifoam, viscosity index improvers and viscosity improvers. Because of this almost any change in engine design requires a re-examination of the motor oil and engine lubrication practices.

Table 1
ENGINE LUBRICANT CHRONOLOGY

1915	Mineral Oils
1919	Friction Modifiers Added
1920's	Fractional Distillation
1921	Oil Viscosity Specifications
1930's	Solvent Dewaxing
1931	Pour Point Depressant Additives
1933	Clay Absorption Purification
1935	Detergent/Dispersant Additives
1936	Antioxidants
1941	Standardized Performance Tests
1940's	Multigrade Oils
1946	Dithiophosphate Antioxidants
1947	Zinc Dithiophosphate Antiwear
1960	Hydrocracking
1969	Super-Refining
1970	Oil Drains to 7000 miles
1975 - Present	Energy Conservation Modifications

It is known that in the next 10 years there will be many engine design changes. These changes will result from the insertion of new materials technology and engine design changes to meet performance, environmental cost, and competitive requirements.

Insertion of New Materials Technology

During the last 20 years a great deal of effort has been devoted to advanced materials technology. The Government has been a leader in materials research and development as well as maintaining a large number of material laboratories. This emphasis will continue if the recommendations of a recent study (2) are followed.

Because of this effort a wide variety of new materials and coatings are now available along with cost effective fabrication methods. Furthermore, a much better understanding of failure modes such as wear, surface fatigue, and corrosion has been developed so that new materials can be applied in an application with some confidence. These two factors assure an accelerated effort to insert new materials and coatings into automotive applications. This trend is already apparent as indicated in Table 2 which lists materials and the components for which new materials are being considered.

Unfortunately materials are lubricant specific in both fabrication and use. Current motor oils are based upon their use with hardened steel components. There is no assurance that the same oil will be completely effective with a new material and there are many reasons to believe that they will not. Effective lubrication is based on material lubricant reactions which will vary from material to material (e.g. titanium is not effectively lubricated with motor oils). Effective lubrication is also based on the formation and maintenance of a fluid film in certain applications. Its ability to do this depends on the properties of the contacting materials. With some materials (e.g. ceramics) it will be difficult to assure fluid film lubrication.

These new materials enable the development of technologies that are otherwise impractical and can address many of the issues facing the nation in energy conservation. Effective lubrication is also an enabling technology which must be addressed if the new materials are to be fabricated and used in vehicle manufacture.

Engine Design Changes

Some of the major challenges facing engine designers, past and present are listed in Table 3 along with their lubrication consequences. Increased power density and higher durability have been major concerns from the earliest days of engine design and remain so. New emphasis on durability is prompted by foreign competition, the need for lower maintenance costs, reduced warranty costs, and customer satisfaction. Since 1978, fuel efficiency has been a major factor in engine design. Although vehicle manufacturers have met or exceeded the original CAFE standards, new standards are soon expected. To meet these standards emphasis is being directed to use of light materials, use of alternative fuels and precise

engine tuning which in themselves introduce sever lubrication problems as shown in Table 3. More recently the passage of the Clean Air Act Amendments of 1990 and the Energy Policy

Table 2

ADVANCED MATERIALS

Material	Potential Vehicle Applications Under Consideration
Ceramics	Valves, cam followers, turbocharger rotor, tappets, rolling contact bearings, regenerators, seals, turbine rotors, injector needle valves catalytic converters, filters
Advanced Coatings	Cylinders, piston rings, valve face, valve seats, exhaust ports, piston skirt, turbine blades
Lightweight Alloys	Piston, valves, connecting rods, oil pans, journal bearing materials, body panels, engine blocks, radiators, transmission cases
Metal Matrix Composites	Pistons, engine blocks, crankshafts
Engineering Plastics	Valve covers, oil pans, manifolds, bushings, tubing, self lubricating fuel system components, fan blades, body panels, fenders, doors, bumper systems, piston rings, gears, thrust washers

act of 1992 will place further demands on lubrication. The Clean Air Act requires an increasing percentage of an auto makers fleet to meet progressively tighter emissions standards for hydrocarbons, carbon monoxide, and nitrogen oxide during the next ten years. Emissions from heavy duty vehicles include particulates. Since 25 to 35 percent of particulates are derived from lubricants considerable work must be carried out both on the lubricant and on oil control in the piston ring area.

The energy policy act mandates the use of alternative fuels. The proposed fuels are generally poor lubricants and require revisiting wear in the fuel system, rings, liners, valves, and injectors. A change in fluid may also require a change in seal materials to make them oil compatible. Pollution control and reduced manufacturing costs are still major factors controlling engine designs and materials usage. Of major concern is the need for new refrigerants. Satisfactory compounds have been found but they have poor lubricating characteristics.

In order to meet the challenges presented in Table 3 new engines are being designed and current engines modified. Those currently under development are listed in Table 4. Some of the major trends affecting lubrication are discussed in the following paragraphs based on a recent workshop and assessment (3).

Table 3

Challenges	Lubrication Consequences
1. Increased Power Density	Higher cylinder temperatures. High power density gears and journal bearings lower friction surfaces. Improved additive & basestocks. High temperature component materials & coatings.
2. Increased Durability	Better engine deposit control, wear resistant components. Control of oil quality. Improved antiwear additives. Long drain oils.
3. Fuel Efficiency	Reduced component friction.
4. Use of Alternative Fuels	Lubrication of fuel system components. Compatible seal materials. Increased ring and valve wear. Problems unique to each fuel.
5. Use of Lightweight and Advanced Materials	Information lacking on lubricating effectiveness. New tailored lubricants will be needed. New lubricant technology.
6. Reduced Emissions	Reduce particulates derived from lubricant. Improved oil control in ring liner area. Improved valve sealing. Clean burn lubricants.
7. Pollution Control	New lubricant for air conditioning systems. Biodegradable lubricants. Use of recyclable materials. Improved sealing.
8. Manufacturing Cost Reduction	Lower cost, easier fabricated materials. Improved metal working lubricants.

For the spark ignition engine the trend to four and six cylinder designs is expected to continue (4). Down-sizing of the engine is expected (to enhance styling). Rapid changes are expected in detailed engine technology to obtain higher specific power. Better control of combustion processes are foreseen with breathing enhancements (e.g. turbocharging) with variable engine geometries and variable valve actuation (5). These design changes will place increased demands on the lubricant. New high temperature motor oils and additives will needed capable of lubrication to 300°C with sump temperature to 175°C. There will be

Table 4

ENGINES UNDER DEVELOPMENT

Advanced Spark Ignition
Advanced Diesel
10^6 Mile Diesel
Low Heat Rejection Diesel
Two Cycle
Gas Turbine
Rotary
Hybrid Electric
Fuel Cells

expanded use of advanced materials to reduce engine weight and size and to reduce dynamic forces. The use of these materials will require new lubricants and application maps indicating where they can be used. Friction reducing efforts will continue particularly with variable geometry designs which require additional control devices. This means a new emphasis on friction reducing additives and coatings. Downsizing will also require higher power density gears and journal bearings. Emphasis on environmental concerns will continue with the development of improved seals and new lubricants to accommodate new refrigerants in air conditioning systems. To reduce maintenance, longer oil drain periods are necessary; this will require improved detergent additives and minimum oil consumption. The continuous variable transmission (CVT) to increase fuel economy is still a desirable feature but requires improved lubrication or materials technology if it is to be applied to large engines. Of particular significant to the fact that these accelerated engine developments will require more rapid test methodology with improved field correlation, improved modeling to predict performance and improved data bases for materials application.

Advanced diesel designs are being driven primarily by reduce emissions, use of alternative fuels, improved durability and a significant increase in cylinder temperatures. The latter two representing the 10^6 mile engine (between overhauls) and the low heat rejection engine. Low emission requirements will greatly accelerate efforts to control lubricant particulates. This will require a better understanding of oil consumption and mechanisms. Oil film control in the ring-lines area may be necessary and probably new fuel or lubricant additives. Alternative fuels will also be a major emphasis requiring improved lubrication and wear of fuel wetted components: injectors, pumps, valves, rings and seals. Fuel lubricity additives will probably be needed as well as compatible seals. Such problems have already been identified. Increased durability is a design goal for the 10^6 mile engine. Long drain oils will be a requirement. This will mean better oils particularly in regard to ring-piston deposits. Oil condition monitoring will be necessary and on board oil rejuvenation desirable. Improved durability also means reduced wear of engine components with improved materials and anti wear additives.

Temperatures will continue to increase. For advanced diesels from 230°C to 300°C. Top ring reversal temperatures in the low heat rejection engine will be 310° to 410° region with an ultimate goal of 500°C. To reach such temperatures new lubricants will be needed with emphasis on antioxidants, high temperature dispersants and ashless anti wear additives. For the highest temperatures, approaching 500°C, new lubrication concepts should be explored. Some which should receive consideration are self lubricating upper ring materials, separate upper cylinder lubrication systems supplying minimum amounts of clean burning lubricants, or vapor lubrication systems. The lack of effective high temperature lubricants is the limiting factor in most advanced engine designs. This is the conclusion reached by a recent NSF panel on engines which states "The major technical challenge (in engines) is the development of lubricants or novel lubrication schemes capable of operating at these high temperatures". With higher temperatures new materials (probably ceramic coatings) will be necessary to control heat flow and reduce wear (because of ultra thin fluid films).

There is renewed interest in the two stroke engine because of new fuel injection technology, higher power density, reduced weight, smaller size and lower manufacturing costs. Exhaust emissions area a major concern with either the dry or wet sump designs. With the dry sump lubricant is added or burnt with the fuel; with the wet sump oil can be drawn past the rings into the combustion process. One approach to solving this problem would be a clean burn lubricant which is technically feasible but has received little attention.

Work continues on the automobile gas turbine (AGT) in both U.S. and Japan. This engine is characterized by higher temperatures (1300°C Turbine Inlet) and the wide use of ceramic components. Initial designs will require bearing temperatures of 315°C. This is about 100°C higher than that in the aircraft gas turbine. Concerns here are lubricant stability and effective lubrication rather than with the bearing materials. The main area of concern however is with the regenerator seals which operate at temperatures of 1000°C. This is far beyond current technology and new lubricating materials and coatings must be isolated.

The rotary engine has been introduced in Europe, Japan and the U.S. with only marginal success. Even after significant investments by several organizations, chronic problems have been encountered with high emission levels, low fuel economy and short wear life of the apex tip seals on the rotor. Interest may not return even if the wear problem is solved.

Although there is considerable interest in the electric, hybrid electric, and fuel cells for propulsion systems, no lubrication problems have been identified.

Summary

It is clear that current engine designs have reached the limit of available lubrication technology. Primary limitations are in the area of temperature capabilities, emissions control, and long term engine durability. The use of advanced materials will also be delayed if this lubricating capacity is unknown. Considerable development work is needed to extend current lubrication limits to meet design requirements for fuel economy, emissions, and

alternative fuel usage imposed by recent legislation. To resolve these questions in the shortest period of time a joint industry/government/university program is proposed which is prescribed herein.

PROGRAM

General

In developing engine concepts the designer has many options available to him to meet the different challenges listed in Table 3. His designs will usually be based on the well established limits of current technology. If the lubrication limits are too low then other requirements must be compromised. A technology program must be devised which sets higher limits in critical areas. Using the technical literature, the results of workshops, surveys, and technical discussions with engine developers it is clear that there are several critical areas for advanced lubrication technology: high temperatures, environmentally friendly lubricants, improved durability, and the insertion of higher performance materials. A program to address these critical areas is described herein. This program (unlike the formidable task of the engine designers) addresses each issue independently with the goal of establishing new limits for each of critical areas. Each program area consists of four or five project areas which are necessary to reach the overall program goals. The end results of all programs will be engine testing by industry of the developed concepts. This program plan is described in more detail in the following pages.

Method of Operation

Project work will on an overall program basis be divided so that 50% of the work will be conducted by industry and 20% by universities.

Steering Group

An overall steering group will be appointed consisting of 10 persons with expertise in advanced engine design, environmental specialties, component design, engine materials, and engine lubricants and additives. The steering group will be primarily from industry and meet once per year to review the work and make recommendations.

Dissemination of Information

Reporting will consist of bi-monthly progress reports, annual reports and topical reports at the conclusion of each project segment.

Program Structure

This is an industry driven program. We propose to form a consortium linking industries, government labs, and universities together. Industries will contribute engine component

testing as well as direct funding to universities for specific projects within the framework of the overall program. A steering committee will be formed. Under the steering committee, five area working groups will be established to identify, coordinate various projects. This is necessary because the diverse nature of the customers and technical areas. Most of these groups will consist of industrial participants who identify the need and set the priority, the researchers who conduct the research, and independent experts who offer advice. The working groups will meet once every three months to ensure adequate coordination. The steering group will consist of the chairpersons of the working group, the program managers, and independent experts. The group will meet at least once a year.

To date, NSF has agreed to participate in the steering committee and where appropriate, provides direct funding to universities based on the industrial input. The project will be coordinated by the working groups.

It is also proposed to set up a user facility at NIST combining the state-of-the-art instrumentation of lubricating film analysis with equipment capable of understanding the mechanisms of lubrication and failure. No such facility currently exists, and this has hampered the development of technology at universities and small and medium companies. Counterparts in Europe and Japan have such facilities and we are at a considerable handicap in this country. The site at NIST is proposed because of several factors: geographically easily accessible; considerable equipment already exist; substantial technical expertise is already there to assist industry.

Detailed Program Description

The proposed program is divided into 5 projects which address independent areas of advanced engine lubrication technology. Each project is described separately in the following paragraphs.

1.0 LUBRICANTS FOR ADVANCED DIESEL ENGINES

Obj.: To develop a liquid lubricant capable of lubricating engine components at 450°C for 5 minutes.

Why: To enable engine industry to take full advantage of the synthetic lubricants to improve fuel efficiency, engine durability, emission compliance. Current mineral oil based lubricants operates at 320°C for the same duration. This limits engine design flexibility and fails to take full advantage of the availability of new materials.

How: Lack of thermally stable additives limits the advantage of the synthetic lubricants currently available. Propose to sponsor programs in the additive industry to develop the necessary components. Insufficient market incentive exists for industry to develop the projects which are vital to the government's programs.

Phase I: Three years

1.1 Development of cost-effective 300°C synthetic base fluids (500K/yr)

- 1.1.1 Easily decomposable fluids (250K) (I)
- 1.1.2 Superstable molecular engineered lubricant (250K) (I)

1.2 Development of high temperature stable additives (1,250K/yr)

- 1.2.1 300°C dispersants (250K) (I)
- 1.2.2 Organic acid neutralizers (250K) (I)
- 1.2.3 400°C detergents (250K) (I)
- 1.2.4 350°C metal deactivators (250K) (I)
- 1.2.5 300°C anti-wear agents (250K) (I)

1.3 Advanced engine component development

Phase II: Three years subsequent to Phase I; can be accelerated to run parallel

1.3 Ultra-high temperature lubrication systems (1,800K/yr)

- 1.3.1 Development of novel high temperature fluids
  - 1.3.1.1 Designed life structures (250K) (I)
  - 1.3.1.2 400°C cost-effective fluids (250K) (I)
- 1.3.2 Development of novel lubrication systems
  - 1.3.2.1 400°C additives (500K) (I,U)
  - 1.3.2.2 Liquid lubricant compatible solid lubricants (250K) (I,G,U)
  - 1.3.2.3 Self-lubricating composites (250K) (G,U)
  - 1.3.2.4 Novel surface treatments (300K) (I,G,U)

2.0 LUBRICATION TECHNOLOGY FOR NEW MATERIALS

Obj.: To develop lubrication technologies for new materials; provide design guidelines for the components made from new materials.

Why: Cost-effectiveness and durability are key barriers to the introduction of new materials into transportation industries. Lack of effective lubrication makes new materials susceptible to premature failures and poses high risk to designers.

How: Explore chemistries that will react with new materials, establish application guidance for wear life prediction as a function of stress, temperature, and chemistries.

Phase I

2.1 Lubrication base technology for new materials (same materials)

- 2.1.1 Lubrication chemistries for ceramics (150K) (G,U)
- 2.1.2 Lubrication chemistries for metal matrix composites (150K) (G,U)
- 2.1.3 Lubrication chemistries for light weight materials (150K) (G,U)
- 2.1.4 Lubrication chemistries for coatings (150K) (G,U)

2.2 Lubrication technology for new materials (dissimilar materials)

- 2.2.1 Lubrication chemistries for ceramic-metals (150K) (G,U)
- 2.2.2 Lubrication chemistries for MMC-metals (150K) (G,U)
- 2.2.3 Lubrication chemistries for ceramic composites-metals (150K) (G,U)
- 2.2.4 Lubrication chemistries for coatings-metals (150K) (G,U)

2.3 Lubrication technology for cost-effective forming/fabrication of new materials

- 2.3.1 Lubrication technology for light weight materials forming/rolling (250K) (I)
- 2.3.2 Lubrication technology for ceramic machining/composite machining (150K) (G,U)
- 2.3.3 Lubrication technology for metal casting/steel rolling (150K) (G,U)

Phase II

2.4 Design guidelines for materials-lubricant combination

- 2.4.1 Application maps for ceramic-lubricants (250K) (G,U)
- 2.4.2 Application maps for ceramic-metal-lubricants (250K) (G,U)
- 2.4.3 Application maps for ceramic-MMC-lubricants (250K) (G,U)
- 2.4.4 Application maps for coatings-metals-lubricants (250K) (G,U)

Phase III

2.5 Application insertion and field testing

2.5.1 Field trials for ceramics-metal-lubricants/ceramic-ceramic (500K) (I)
2.5.2 Field trials for MMC-metal-lubricants (500K) (I)
2.5.3 Field trials for coatings-metal-lubricant (500K) (I)

3.0 ENVIRONMENTALLY FRIENDLY LUBRICANTS

Obj.: To develop lubricants that are biodegradable; capable of controlling emissions; freon replacements, alternative fuels lubrication

Why: Environmental concerns in waste disposal, global warming, ozone depletion, zero emission engines, and freon replacements

How: Explore new concepts, new synthesis, as well as focusing on specific components and systems to achieve environmental goals.

3.1 Emission control technologies for engines

3.1.1 Lubricants for particulate control (150K) (G,U)
3.1.2 Oil consumption control and modelling (250K) (I)
3.1.3 Alternative fuel lubrication (250K) (I,U)
3.1.4 Novel technologies for emission control (250K) (I)

3.2 Environmentally compatible lubricants

3.2.1 R-134 lubrication (250K) (I,G,U)
3.2.2 Biodegradable lubricant development (250K) (I,G,U)
3.2.3 Standards for biodegradable lubricants (250K) (G)
3.2.4 Novel structures for industrial applications (250K) (I,U)

4.0 LUBRICATION TECHNOLOGIES FOR COMPONENT AND ENGINE DURABILITY

Obj.: To provide the critical lubrication technology which enables new engine designs and new component developments necessary for international competitiveness.

Why: Durability and component reliability are two key competitiveness factors for future engines. As cost of ownership goes up, operating economy and maintenance costs will be a key criterion for purchase. This is especially crucial for U.S. heavy duty diesel engines and off-highway industries.

How: Durability and engine component life technologies are intimately linked to the materials and lubrication technology. A systematic research and development effort will provide competitive edge.

4.1 Million-mile engines

4.1.1 On board oil monitoring and rejuvenation (250K) (I)
4.1.2 Lubrication of life system development (500K) (I,G,U)
4.1.3 Wear resistant materials development (500K) (I,G,U)
4.1.4 Wear and fatigue life prediction models (500K) (I,G,U)

4.2 Engine components and new engines

4.2.1 Valve/valve seat materials life prediction (250K) (I,G)
4.2.2 Ring/liner interface design (250K) (I)
4.2.3 Lubrication for two-cycle engines (500K) (I)
4.2.4 Novel engine technology (500K) (I,U)

5.0 LUBRICATION TECHNOLOGIES FOR ADVANCED SI ENGINES

Goals: Improve the fuel efficiency and lubrication performance of advanced development engines for automotive application.

Why: Advance spark ignition engines are being designed with higher fuel efficient components and higher power densities. These developments place a greater demand on lubricant durability and component performance.

How: Selected studies will be made of components, materials and lubricants to reduce friction and prevent the build up of engine deposits which degrade performance.

5.1 Fuel efficiency technologies

5.1.1 CVT system development (500K) (I,U)
5.1.2 High temperature friction modifier (250K) (I)
5.1.3 High efficiency gears development (250K) (I)
5.1.4 500°C self lubricating materials (250K) (I,G)

5.2 Bench simulation development for engine performance

5.2.1 Engine deposit simulations (150K) (G,U)
5.2.2 Oxidation life predictor (150K) (G,U)
5.2.3 Piston varnish simulations (150K) (G,U)
5.2.4 Engine wear simulations (150K) (G,U)

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12.0 APPENDIX

APPENDIX A

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APPENDIX B

QUESTIONNAIRE I

TECHNICAL SURVEY

QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Allied-Signal* Industry: *Aerospace & Automotive*
Major products: *Aerospace* Co.Size: *128/yr 93,000 employees*
Location: *Des Plaines, IL* Government contract?_____

*I want my answers to be kept confidential*_____

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

2. What are the most critical issues dealing with the new materials? What new materials are useful?

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes, (Impacts are obvious). A-S doesn't do lubricant design but needs lubricants for future materials wear pairs.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *7*	Fuel economy *8*	Cost *2*
Durability *5*	Repair cost	Performance *1*
Maintenance cost *6*	Innovation *4*	Materials *3*

5. What are the key research agenda of your company in the next 3-5 years?

   New materials & coatings: can costs/product constraints justify their application. Processability and serviceability are critical. Reduce product defects.

6. What are the key research agenda of your company in the next 5-10+ years?

   Improve efficiency, reduce costs in adapting new materials and technologies to products. Higher operating temps and lower weights, leveraged by processability, reliability, costs, competition's performance.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock	Additives *oil costs*
Molecular Engineered Lub.	Additive mechanism *oil costs*
Thermally stable dispersant	Additive-add. interaction
Bench test development	New measurement meth. *Industry & Gov't.*
Low friction materials *Industry & Gov't.*	New additives for ceramic
New lub. for new materials	High temp. liq. Lub. *Industry & Gov't.*
Temp. solid lub.	Lub. application guide
Stability mapping of lub.	Methanol compatible lub.

9. The most important materials that you would like to see research be conducted on?

Superalloys *3*	Ceramics *1*
Metal matrix composite *5*	Aluminum alloys *4*
Engr. Plastics *6*	Coatings *2*

10. The major factors for change in lubrication technologies are:

Emission control	Materials change *3*
Higher temp. *1*	Extended drain intervals
Alternative fuels	Fuel economy
Higher stress	Durability (less maint.)
Higher quality *2*	Smaller engines
Change in design	Higher power density *4*

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission	Transmission
Gears *1*	Valve train
Ring-liner	Bearing *1*
Brakes *2*	Fuel injectors
Piston	Catalytic convertors *1*
Particulate trap	Chemical filter(remove acid,soot)
Electrical contacts	Seals *1*

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

3-5 yrs = 300 - 450 °C
10-15 yrs = 450 - 1000 °C

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Lubrication for new materials.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Consortium could be useful for pre-competitive stages of research. Would consider joining. Depends on focus, participation (needs to be miltidisciplinary). Consortia likely to be formed with industry with government interaction today. Tomorrow?

COMMENTS:_____

RETURN THE SURVEY TO:

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Allison Gas Turbine* Industry: *Gas Turbine*
Major products: *Gas Turbine* Co.Size: *about 7,000 employees*
Location: *Indianapolis,MN* Government contract? *50% Milt 50% Commerce*

I want my answers to be kept confidential *Yes please*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   To achieve higher temperature for improved fuel economy and reduce size. Yes.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Strength under mechanical and thermal stress, friction wear processing. Ceramics, Metal Oxides.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes. Positive impact - None
   Negative impact - Limited performance (engine) to present level.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation_____	Fuel economy__x__	Cost_____
Durability_____	Repair cost_____	Performance_x_____
Maintenance cost_____	Innovation_____	Materials_____

5. What are the key research agenda of your company in the next 3-5 years?

   Develop high temperature (1800 °F +) solid lubrication of regenerator seals.
   Develop lubrication of ceramic bearings by surface generated reactions using ethylene and other gases.

6. What are the key research agenda of your company in the next 5-10+ years?

   To develop (or obtain) high temperature lubrication technology for regenerators, bearings and gears.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Product Development	*High Risk*	*Research/Process*	*Research*

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock		Additives	
Molecular Engineered Lub.		Additive mechanism	
Thermally stable dispersant		Additive-add. interaction	
Bench test development		New measurement meth.	
Low friction materials		New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	
Temp. solid lub.		Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	x
Metal matrix composite		Aluminum alloys	
Engr. Plastics		Coatings	

10. The major factors for change in lubrication technologies are:

Emission control		Materials change	
Higher temp.	x	Extended drain intervals	
Alternative fuels		Fuel economy	
Higher stress		Durability (less maint.)	
Higher quality		Smaller engines	
Change in design		Higher power density	

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	
Gears	3	Valve train	
Ring-liner		Bearing	2
Brakes		Fuel injectors	
Piston		Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	1

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

3-5 yrs Automotive Gas Turbine Inlet Temp 2250 °C Max Lube Temp 1800-1900 °C.
10-15 yrs Automotive Gas Turbine Inlet Temp 2500°C Max Lube Temp 2000-2100°C.

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

1. For the automotive Gas Turbine-Solid Lubrication.
2. Ceramics and Solid Lubrication.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes. Yes.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Amoco Oil Co.* Industry: *Petroleum*
Major products: *Fuel & Lubricants* Co.Size: _____
Location: *Naperville, IL* Government contract? *Not in product areas*

I want my answers to be kept confidential *Yes please*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Technology is currently being developed to meeting larger volume lubricant requirements with a few specialty products for targeted markets.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Lubricant base oils that have high stability or that break down clearly at high temperature.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Lubricant of ceramics at high temperatures presents a challenge and may limit the use of engines with limited cooling.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation x	Fuel economy x	Cost x
Durability	Repair cost	Performance x
Maintenance cost	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   Provide good quality products at lowest cost. Provide a few specialty products in todays market.

6. What are the key research agenda of your company in the next 5-10+ years?

   Same as #5.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Develop lubricant to provide improved services in current applications.	*Support work on the development of lubricants for more severe operating environments, such as space applications.*	*Carry out demonstrations programs on new lubricants and applications. Develop new techniques for evaluating performance.*	*Basic Research lubricants for larger range applications. Develop new techniques for understanding and evaluating lubricant performance.*

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock	*Industry*	Additives	*Industry*
Molecular Engineered Lub.		Additive mechanism	*Universities*
Thermally stable dispersant	*Gov't & Univ*	Additive-add. interaction	
Bench test development		New measurement meth.	*Gov't & Univer.*
Low friction materials		New additives for ceramic	
New lub. for new materials	*Industry*	High temp. liq. Lub.	*Industry & Gov't*
Temp. solid lub.		Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	*Industry*

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	x
Metal matrix composite		Aluminum alloys	
Engr. Plastics	x	Coatings	x

10. The major factors for change in lubrication technologies are:

Emission control	x	Materials change	x
Higher temp.	x	Extended drain intervals	
Alternative fuels	x	Fuel economy	x
Higher stress	x	Durability (less maint.)	x
Higher quality		Smaller engines	x
Change in design		Higher power density	x

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	x
Gears		Valve train	x
Ring-liner	x	Bearing	x
Brakes		Fuel injectors	x
Piston	x	Catalytic convertors	x
Particulate trap		Chemical filter(remove acid,soot)	x
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

Piston temperatures will be about the same as now in 3-5 years, but the oil should be exposed to higher temperatures because of the higher placement of the top ring to reduce emissions and because of retarded injection to reduce emissions.

We don't know that maximum temperatures will be in 10-15 years. It depends on approaches used to control NOx emissions, which could involve lower engine temperatures or higher temperatures of NOx control catalysts are developed.

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Effects of emissions regulations on lubricant requirements such as:

Minimizing lube effects on catalysts
Reducing deposits in low emissions engines
Minimizing oil consumption on emissions from oil consumption

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Rather than form a consortium. I feel that periodic meetings to share information would be worthwhile.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Borg Warner Automotive* Industry: *Automotive*
Major products: *Automotive Chain System* Co.Size: *1500*
Location: *Ithaca, NY* Government contract? *None*

I want my answers to be kept confidential *No*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   We are continually pushing our steel and plastic technology to improve the performance of our products. Of course prime motive force.

2. What are the most critical issues dealing with the new materials? What new materials are useful.

   High speed wear, low velocity, slip.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes. Widescale application of CVT in U.S.A. will require improvements in tribology.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation x	Fuel economy x	Cost x
Durability x	Repair cost	Performance x
Maintenance cost	Innovation x	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   Supply of engineering systems which improve overall vehicle efficiency and cost effectiveness.

6. What are the key research agenda of your company in the next 5-10+ years?

   Improvement of systems engineered projects. For example CVT systems, variable value timing systems, improved efficiency power transmission and engine timing systems.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt programs	Govt labs	Universities
Short term product development	*Activities which will improve the competition position of industry In addition activities which will improve the efficiency of current vehicle fleet.*		*Long term research*

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock	Additives
Molecular Engineered Lub.	Additive mechanism
Thermally stable dispersant	Additive-add. interaction
Bench test development	New measurement meth.
Low friction materials	New additives for ceramic
New lub. for new materials	High temp. liq. Lub.
Temp. solid lub.	Lub. application guide
Stability mapping of lub.	Methanol compatible lub.

9. The most important materials that you would like to see research be conducted on?

Superalloys	Ceramics
Metal matrix composite	Aluminum alloys
Engr. Plastics x	Coatings

10. The major factors for change in lubrication technologies are:

Emission control	Materials change
Higher temp.	Extended drain intervals
Alternative fuels	Fuel economy x
Higher stress	Durability (less maint.)
Higher quality	Smaller engines
Change in design	Higher power density x

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission x	Transmission x
Gears	Valve train x
Ring-line	Bearing
Brakes	Fuel injectors
Piston	Catalytic convertors
Particulate trap	Chemical filter(remove acid,soot)
Electrical contacts	Seals

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

3 - 5 = 300 °C
10 - 15 = 450 °C

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Activity	Company Participation	Gov't
CVT	*Yes*	*Yes*
Engine timing system parasitic losses	*Yes*	*Yes*
Extended draw intervals	*Yes*	*Yes*

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes

COMMENTS: *I believe that CVT is a technology which clearly is worthy of government assistance. It offers the single most reliable method of improving fuel economy. BWA has invested over 100 million to develop a system of up to 4-5 liters. To further this tribological research should be done to help the automotive companies as a whole.*

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Caterpillar Inc.* Industry: *Heavy Equip/Construction*
Major products: *Earthmovers, Engines* Co.Size: *55,000*
Location: *Peoria, IL* Government contract? *DOC/ICC & DOE/WRCC*

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   New materials are extremely important in advancing our technology. New materials will allow components to be put in place that would otherwise not be possible.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Availability of property data. Oxide ceramics, nitrides.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Lubrication of new materials is a big concern, particularly availability of effective additives for ceramics.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation x	Fuel economy x	Cost x
Durability x	Repair cost x	Performance x
Maintenance cost x	Innovation x	Materials x

5. What are the key research agenda of your company in the next 3-5 years?

   Fuel economy, lower emissions.

6. What are the key research agenda of your company in the next 5-10+ years?

   Same as above. Higher temperature engines will come into the picture more.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Bench/field correlations	*High temp. liq. lube*	*Bench test methods*	*Stability*
New lube for new	*solid lube*	*New measurement*	*mapping.*
New lube additives		*methods*	*Additives*
			mechanisms

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock		Additives	
Molecular Engineered Lub.		Additive mechanism	
Thermally stable dispersant		Additive-add. interaction	
Bench test development	x	New measurement meth.	
Low friction materials		New additives for ceramic	x
New lub. for new materials	x	High temp. liq. Lub.	x
Temp. solid lub.		Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	x
Metal matrix composite	x	Aluminum alloys	
Engr. Plastics		Coatings	

10. The major factors for change in lubrication technologies are:

Emission control	x	Materials change	
Higher temp.	x	Extended drain intervals	x
Alternative fuels		Fuel economy	
Higher stress		Durability (less maint.)	
Higher quality		Smaller engines	
Change in design		Higher power density	

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	x
Gears		Valve train	
Ring-line	x	Bearing	
Brakes		Fuel injectors	
Piston		Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

Will depend on availability of stable, liquid lubricants hottest temperatures are likely to be tapering groove of pistons.

Current ~ 300 °C
3 - 5 ~ 330 °C
10 - 15 ~ 400 °C

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Liquid lubricants and additives for new materials, higher temperature operation.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes. Consortiums would be useful. Would consider joining.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Chrysler* Industry: *Automotive*
Major products: *Automobiles/Trucks* Co.Size: *5000 Plus*
Location: *Auburn Hill, MI* Government contract? *None*

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   New materials provide opportunities to meet the requirements of our customers & government. My current experience is that they have a more supportive role for new technology. (Instead of being a prime motive force).

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Material, mechanical properties, useful life, consistency from production process,, and relative cost. Materials offering fatigue strength at temperature and good tribological properties (Application = i.c. engines).

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes-If lubrication is not effective, performance and durability become limited.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation x	Fuel economy x	Cost x
Durability x	Repair cost	Performance x
Maintenance cost x	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   I.C. (S.I.) engine refinement.

6. What are the key research agenda of your company in the next 5-10+ years?

   New types of I.C. engines. Electric propulsion systems.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Design & develop for production with test data feedback to supplies & universities.	*Certain regulations/ performance requirements coordination of consortiums.*	*Basic R&D test data feedback to universities.*	*Basic R&D Strategy Development test data analysis*

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock	Additives
Molecular Engineered Lub. x	Additive mechanism
Thermally stable dispersant	Additive-add. interaction
Bench test development	New measurement meth.
Low friction materials x	New additives for ceramic
New lub. for new materials	High temp. liq. Lub. x
Temp. solid lub.	Lub. application guide
Stability mapping of lub.	Methanol compatible lub. x *(Industry)*

9. The most important materials that you would like to see research be conducted on?

Superalloys	Ceramics x
Metal matrix composite x	Aluminum alloys
Engr. Plastics	Coatings

10. The major factors for change in lubrication technologies are:

Emission control x	Materials change x
Higher temp. x	Extended drain intervals
Alternative fuels x	Fuel economy x
Higher stress	Durability (less maint.)
Higher quality x	Smaller engines
Change in design x	Higher power density

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission	Transmission
Gears	Valve train
Ring-liner x	Bearing
Brakes	Fuel injectors
Piston x	Catalytic convertors
Particulate trap	Chemical filter(remove acid,soot)
Electrical contacts	Seals x

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15- years?

For piston components
3 - 5 ~ 550 °F
10 - 15 ~ ?

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Most important: Materials for electric propulsion systems (focus-battery tech.) Government should focus on this, and an industry consortium has already been set-up.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes. See above.

COMMENTS: *Thank you for the survey input opportunity due to workload I will not be able to attend the workshop on September 21-23, 1993.*

Alex G. Masko

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *John Crane* Industry: *Fluid Sealing*
Major products: *Mechanical Seal* Co.Size: *~ $250 Million/annual sales*
Location: *Morton Grove* Government contract? *Yes*

I want my answers to be kept confidential *Yes*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

They are critical in niche applications. They could be prime motive forces, but not necessarily all the time.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

Appropriate test methods to make sure new materials are going to perform new materials of high hardness, thermal conductivity, stiffness, but low thermal expansion density and chemically inert will be most desired.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

Yes-If lubrication is not available, our products wear fast.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *1*	Fuel economy	Cost *3*
Durability	Repair cost	Performance *2*
Maintenance cost	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

Develop materials test methodology to quickly evaluate materials in the test lab without full scale simulation.

6. What are the key research agenda of your company in the next 5-10+ years?

Develop robust design and material combinations to be applied to most applications.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Applications	*Consortium to*	*Basic data*	*Fundamentals*
Market identification	*sponsor applied research*	*collection/ measurement*	*Analysis Tools*
	of consortiums.		

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock		Additives	
Molecular Engineered Lub.		Additive mechanism	
Thermally stable dispersant		Additive-add. interaction	
Bench test development	*1*	New measurement meth.	
Low friction materials	*2*	New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	
Temp. solid lub.		Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys	*3*	Ceramics	*1*
Metal matrix composite		Aluminum alloys	
Engr. Plastics	*4*	Coatings	*2*

10. The major factors for change in lubrication technologies are:

Emission control	*1*	Materials change	
Higher temp.		Extended drain intervals	
Alternative fuels		Fuel economy	
Higher stress		Durability (less maint.)	
Higher quality		Smaller engines	
Change in design		Higher power density	

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	
Gears		Valve train	
Ring-liner		Bearing	
Brakes		Fuel injectors	
Piston		Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	*1*

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Sliding wear mechanisms and test methodologies

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes, very likely we would consider participation.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Cummins* Industry: *Diesel Engines*
Major products: Co.Size: *3-4 B. Sales*
Location: Government contract?

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Materials is the limiting factor in many technologies that would improve fuel economy.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Evaluating performance is a critical issue- bench tests have not been correlated to engine tests.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes, durability.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *x*	Fuel economy *x*	Cost
Durability	Repair cost	Performance
Maintenance cost	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   Emission/fuel economy.

6. What are the key research agenda of your company in the next 5-10+ years?

   Emission/fuel economy.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock		Additives	
Molecular Engineered Lub.		Additive mechanism	
Thermally stable dispersant		Additive-add. interaction	
Bench test development		New measurement meth.	
Low friction materials		New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	
Temp. solid lub.		Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	x
Metal matrix composite		Aluminum alloys	
Engr. Plastics		Coatings	x

10. The major factors for change in lubrication technologies are:

Emission control	xx	Materials change	
Higher temp.		Extended drain intervals	x
Alternative fuels		Fuel economy	x
Higher stress		Durability (less maint.)	x
Higher quality		Smaller engines	
Change in design		Higher power density	x

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	
Gears		Valve train	
Ring-liner	x	Bearing	x
Brakes		Fuel injectors	
Piston		Catalytic convertors	x
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Oil consumption modelling (Gov't).
Manufacturing of ceramics and surface coatings.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes, yes.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Cummins Engine Co.* Industry: *Transportation*
Major products: *Diesel Engines* Co.Size: *3-5 B/Yr Sales*
Location: *Columbus, IN* Government contract? *Yes, please*

I want my answers to be kept confidential *Yes*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Higher strength, higher fatigue strength-higher pressure-improved emission, perform greater wear resistance, lower friction-durability, fuel consumption, thermal insulation-improved fuel economy, performance, emission, greater corrosion resistance-improved fuel systems-improved emissions. economy.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Materials R&D-testing and evaluation-integrity with manufacturing-establishing new supply-scuffing and wear resistant coatings for in-cylinder components and fuel system, thermal barrier coatings for in-cylinder components.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   To be determined new materials may not need special lubrication, in fact maybe less sensitive to lube formulation.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *x*	Fuel economy *x*	Cost *xxx*
Durability *x*	Repair cost *x*	Performance *x*
Maintenance cost *x*	Innovation *x*	Materials *x*

5. What are the key research agenda of your company in the next 3-5 years?

   Meeting 1994-1997 emissions requirements.

6. What are the key research agenda of your company in the next 5-10+ years?

   Continued emphasis on emissions, fuel economy, durability/reliability and lower cost.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
R&D testing and evaluation with mfg. implementation.	*Advanced technology.*	*Applied research develop coorelations between bench tests and engine test.*	*New concepts, basis tribology research.*

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock *Chem., Oil/Industry*	Additives *Oil/additives/Industry*
Molecular Engineered Lub. *Chem, Oil, Ind.*	Additive mechanism *Nat. Labs/Universities*
Thermally stable dispersant *Add.In.,Nt.Lb*	Additive-add. interaction *Labs/Univers.*
Bench test development *Nat. Labs/Industry*	New measurement meth. *Nat Labs/Univers.*
Low friction materials *Industry*	New additives for ceramic *Oil/Add/Indus.*
New lub. for new materials *Oil/Add/Indust*	High temp. liq. Lub. *Oil/Add/Industry*
Temp. solid lub.	Lub. application guide *Industry*
Stability mapping of lub. *Nat. Labs*	Methanol compatible lub. *Oil/Add/Industry*

9. The most important materials that you would like to see research be conducted on?

Superalloys	Ceramics x
Metal matrix composite x	Aluminum alloys
Engr. Plastics	Coatings x

10. The major factors for change in lubrication technologies are:

Emission control x	Materials change ?
Higher temp. x	Extended drain intervals x
Alternative fuels x	Fuel economy x
Higher stress x	Durability (less maint.) x
Higher quality x	Smaller engines x
Change in design x	Higher power density x

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission	Transmission
Gears	Valve train x
Ring-liner x	Bearing x
Brakes	Fuel injectors x
Piston x	Catalytic convertors x
Particulate trap	Chemical filter(remove acid,soot) x
Electrical contacts	Seals x

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

Top eng. universal temp:			*Sump temp:*		
3-5 yrs	=	*200 °C*	*3-5 yrs*	=	*120 °C*
10-15 yrs	=	*250 °C*	*10-15 yrs*	=	*150 °C*

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Would be interested-participating in all topics checked-questions 8 & 11. Also need program on anti-scuff additives for high pressure diesel fuel injectors. Most important program: effect of lub or emissions. Also need programs on lubrication of cams and bearings.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes, would consider joining based on projects selected and internal resource constraints. Funding sources/level of funding needs to be addressed.

COMMENTS: *Need greater understanding of oil degradation and consumption mechanisms in engines. Also need programs on filtration.*

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Department of Energy* Industry: *N/A*
Major products: *R & D* Co.Size: *20,000 +*
Location: *Washington,D.C.* Government contract? *N/A*

I want my answers to be kept confidential *No*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Reliability, durability, strength, erosion and corrosion resistance.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Handled by another office.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *x*	Fuel economy *x*	Cost *x*
Durability *x*	Repair cost	Performance *x*
Maintenance cost *x*	Innovation	Materials *x*

5. What are the key research agenda of your company in the next 3-5 years?

   R & D in automotive engines covering fuel economy and emissions.

6. What are the key research agenda of your company in the next 5-10+ years?

   Same as above.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities

All of the Above Captions.

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

None of these are handled by my office.

New Lub. base stock	Additives
Molecular Engineered Lub.	Additive mechanism
Thermally stable dispersant	Additive-add. interaction
Bench test development	New measurement meth.
Low friction materials	New additives for ceramic
New lub. for new materials	High temp. liq. Lub.
Temp. solid lub.	Lub. application guide
Stability mapping of lub.	Methanol compatible lub.

9. The most important materials that you would like to see research be conducted on?

Superalloys	Ceramics x
Metal matrix composite	Aluminum alloys x
Engr. Plastics	Coatings x

10. The major factors for change in lubrication technologies are:

Emission control x	Materials change x
Higher temp. x	Extended drain intervals
Alternative fuels x	Fuel economy
Higher stress	Durability (less maint.)
Higher quality	Smaller engines
Change in design	Higher power density

11. Which of the following component technology do you think is the most important to you?

Where every Ceramics fits.

Continuous variable transmission	Transmission
Gears	Valve train
Ring-liner	Bearing
Brakes	Fuel injectors
Piston	Catalytic convertors
Particulate trap	Chemical filter(remove acid,soot)
Electrical contacts	Seals

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

2500 °F , 3000 °F +

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

(the government should)- R&D , high risk.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes, choice made at a higher level.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Detroit Diesel* Industry: *Heavy Duty Transport*
Major products: *Diesel Engines* Co.Size: *$1.2B/Year*
Location: *Detroit, MI* Government contract? *Many*

I want my answers to be kept confidential *Yes*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Materials are very significant technology facet. However, it is not a "prime motive" force for new technology.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Expanding the capabilities of current materials to meet new customer, regulatory and market challenges is foremost. Second is the application of new (but economically available) material to resolve same issues.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   It is a concern. However, I feel that it is over-played. Lubrication is a system problem. New materials -components is generally one part only of the triobological pair. Lubricants compatible with the other components work well.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *1*	Fuel economy *1*	Cost *1*
Durability *1*	Repair cost *2*	Performance *2*
Maintenance cost *2*	Innovation *3*	Materials *3*

5. What are the key research agenda of your company in the next 3-5 years?

   Will discuss on contact.

6. What are the key research agenda of your company in the next 5-10+ years?

   Will discuss on contact.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Current product Eng. Product Improvements. Technology Application to current & new products.	*High risk Product Programs that may not be attractive in terms of return-on-investment.(ROI) Programs that will enhance U. S.*	**Support/Service function for Industry & Univer. *Keep on top of global relevant tech. Developments*	**Basic and applied research. *Support Industry as a partner.*

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock	x	Additives	x
Molecular Engineered Lub.	x	Additive mechanism	x
Thermally stable dispersant	x	Additive-add. interaction	x
Bench test development	x	New measurement meth.	x
Low friction materials		New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	
Temp. solid lub.		Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	x

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	
Metal matrix composite	x	Aluminum alloys	
Engr. Plastics		Coatings	x

10. The major factors for change in lubrication technologies are:

Emission control	x	Materials change	
Higher temp.	x	Extended drain intervals	x
Alternative fuels	x	Fuel economy	
Higher stress		Durability (less maint.)	x
Higher quality		Smaller engines	
Change in design		Higher power density	

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	
Gears		Valve train	x
Ring-liner	x	Bearing	x
Brakes		Fuel injectors	xxx
Piston	x	Catalytic convertors	
Particulate trap	x	Chemical filter(remove acid,soot)	x
Electrical contacts		Seals	x

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

That is a (very) general question. Lubricated interfaces may be up to 600-700 °F in 3-5 years. Higher by 50 to 100 °F in 10-15 years!

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

**Longer oil drain interval * Universal oil for all heavy duty engines, *On board oil condition monitor.*

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes. Yes.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Eaton Corp.* Industry: *Auto- OEM*
Major products: *OEM for Automotive* Co.Size: *$4 B/Sales*
Location: *Southfield, MI* Government contract? *None*

I want my answers to be kept confidential *No*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   If new materials make products more cost effective we use them otherwise not.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Performance characteristics and cost effectiveness.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes, materials must demonstrate suitability for use in a particular environment before they are considered.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation x	Fuel economy x	Cost x
Durability x	Repair cost x	Performance x
Maintenance cost x	Innovation x	Materials x

5. What are the key research agenda of your company in the next 3-5 years?

   More products, and more cost effective products.

6. What are the key research agenda of your company in the next 5-10+ years?

   More products, and more cost effective products.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Patentable subject material.	*Help American Industry Compete.*	*Research that industry can't afford.*	*Teach practical application of Science & Techn.*

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock	x	Additives	x
Molecular Engineered Lub.	x	Additive mechanism	x
Thermally stable dispersant	x	Additive-add. interaction	x
Bench test development	x	New measurement meth.	x
Low friction materials	x	New additives for ceramic	x
New lub. for new materials	x	High temp. liq. Lub.	x
Temp. solid lub.	x	Lub. application guide	x
Stability mapping of lub.	x	Methanol compatible lub.	x

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	x
Metal matrix composite		Aluminum alloys	x
Engr. Plastics	x	Coatings	

10. The major factors for change in lubrication technologies are:

Emission control	x	Materials change	x
Higher temp.	x	Extended drain intervals	x
Alternative fuels	x	Fuel economy	x
Higher stress	x	Durability (less maint.)	x
Higher quality	x	Smaller engines	x
Change in design	x	Higher power density	x

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	
Gears		Valve train	x
Ring-liner		Bearing	x
Brakes		Fuel injectors	
Piston		Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Develop methods and standards for friction and wear testing. *Help America Industry use American Products!!*

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes.

COMMENTS: *J. Edler, Eaton Corp., P.O. Box 766, Southfield, MI 48037*

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Ethyl* Industry: *Petroleum Additives*
Major products: Co.Size:
Location: Government contract?

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

2. What are the most critical issues dealing with the new materials? What new materials are useful?

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation x	Fuel economy	Cost
Durability	Repair cost	Performance x
Maintenance cost	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

6. What are the key research agenda of your company in the next 5-10+ years?

Predict performance in depth.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock		Additives	x
Molecular Engineered Lub.		Additive mechanism	x
Thermally stable dispersant		Additive-add. interaction	
Bench test development	x	New measurement meth.	
Low friction materials		New additives for ceramic	
New lub. for new materials	x	High temp. liq. Lub.	
Temp. solid lub.		Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	
Metal matrix composite		Aluminum alloys	
Engr. Plastics	x	Coatings	

10. The major factors for change in lubrication technologies are:

Emission control	x	Materials change	
Higher temp.		Extended drain intervals	
Alternative fuels		Fuel economy	
Higher stress		Durability (less maint.)	
Higher quality		Smaller engines	
Change in design		Higher power density	x

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	x
Gears	x	Valve train	
Ring-liner		Bearing	
Brakes		Fuel injectors	
Piston		Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Bench test development.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

COMMENTS:

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Ethyl Corp.* Industry: *Chemical*
Major products: *Additives, Chemicals* Co.Size: *6,000*
Location: *Richmond, VA* Government contract? *None*

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Some plastics. No.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Prevent wear & deposits.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Not currently.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *x*	Fuel economy	Cost *x*
Durability *x*	Repair cost	Performance *x*
Maintenance cost	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   Develop cost-effective lubricants for crankcase, ATF, gear and industrial oils.

6. What are the key research agenda of your company in the next 5-10+ years?

   Same as #5-with moves to higher temperature and new materials/regulations as needed.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
New additives formulation testing.	*(*See below comment)*	*(*See below comment)*	*(*See below comments)*

(mechanism and long range as ideas occur to researchers)*

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock		Additives	*x*
Molecular Engineered Lub.	*?*	Additive mechanism	*Govern.*
Thermally stable dispersant	*x*	Additive-add. interaction	
Bench test development	*x & Govern.*	New measurement meth.	
Low friction materials		New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	*Govern.*
Temp. solid lub.		Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	
Metal matrix composite		Aluminum alloys	*x*
Engr. Plastics		Coatings	

10. The major factors for change in lubrication technologies are:

Emission control		Materials change	
Higher temp.	*x*	Extended drain intervals	*x*
Alternative fuels		Fuel economy	
Higher stress	*x*	Durability (less maint.)	
Higher quality	*x*	Smaller engines	
Change in design		Higher power density	*x*

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	
Gears		Valve train	
Ring-liner		Bearing	
Brakes		Fuel injectors	
Piston	x	Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

3-5 yrs. = 300 °C (small areas)
10-15 yrs. = 400 °C

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

High temp. dispersants and antioxidants

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Sounds good-makes sense too.

COMMENTS: *Being new to Ethyl, I'm not sure about support for questions 13. Generally, I see a problem with sharing real chemical information.*

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Gas Research Inst.* Industry: *Natural Gas*
Major products: *R&D* Co.Size: *275*
Location: *Chicago, IL* Government contract? *Gov't Co Funding*

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   (a) Improve durability of natural gas fired reciprocating engines; compressed natural gas storage.

   (b) No.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   (a) Cost, reliable supply.

   (b) Silicon nitride.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Do not know at this time.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation x	Fuel economy	Cost x
Durability x	Repair cost x	Performance
Maintenance cost x	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   Introduce engine technologies to improve natural gas position as fuel for stationary and vehicular engines.

6. What are the key research agenda of your company in the next 5-10+ years?

   Low emissions technologies.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Product development, technology application.	*Technology transfer*	*Applied Research*	*Basic Research*

8. What are the most important issues in lubrication technology that you would like to see done? By whom? What should the government do?

New Lub. base stock	*Industry*	Additives	*Industry*
Molecular Engineered Lub.	*Government*	Additive mechanism	
Thermally stable dispersant	x	Additive-add. interaction	
Bench test development		New measurement meth.	
Low friction materials	*Government*	New additives for ceramic	
New lub. for new materials	*Government*	High temp. liq. Lub.	*Govern.*
Temp. solid lub.		Lub. application guide	*Government*
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	
Metal matrix composite	x	Aluminum alloys	
Engr. Plastics	x	Coatings	x

10. The major factors for change in lubrication technologies are:

Emission control	x	Materials change	
Higher temp.		Extended drain intervals	
Alternative fuels	x	Fuel economy	
Higher stress		Durability (less maint.)	x
Higher quality		Smaller engines	
Change in design		Higher power density	

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	
Gears		Valve train	
Ring-liner		Bearing	
Brakes		Fuel injectors	
Piston		Catalytic convertors	x
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

    (a) Science and Technology impacting pollution emissions and engine durability.
    (b) Natural gas related R&D.
    (c) Technology transfer.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

    (a) Yes
    (b) Yes

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *General Motors* Industry: *Automotive*
Major products: *Cars & Trucks* Co.Size: *Large*
Location: *U.S.A.* Government contract?

I want my answers to be kept confidential *Yes*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Role of new materials is to do a better job than current materials.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Improved performance, wear, resistance, strength, etc. Powder metals are finding more use.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes, If new materials and their lubricants are not created, we have difficulties meeting some government mandates.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *x*	Fuel economy *x*	Cost *x*
Durability *x*	Repair cost *x*	Performance *x*
Maintenance cost *x*	Innovation *x*	Materials *x*

5. What are the key research agenda of your company in the next 3-5 years?

   New test methods, new products.

6. What are the key research agenda of your company in the next 5-10+ years?

   Understanding processes, new products.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
New products.	*Don't know.*	*New materials.*	*Fundamental studies.*

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock	Additives
Molecular Engineered Lub.	Additive mechanism
Thermally stable dispersant	Additive-add. interaction
Bench test development	New measurement meth. *Industry*
Low friction materials	New additives for ceramic
New lub. for new materials	High temp. liq. Lub.
Temp. solid lub.	Lub. application guide
Stability mapping of lub.	Methanol compatible lub. *already-oil co.*

9. The most important materials that you would like to see research be conducted on?

Superalloys	Ceramics
Metal matrix composite	Aluminum alloys
Engr. Plastics	Coatings
(other	*x)*

10. The major factors for change in lubrication technologies are:

Emission control	Materials change
Higher temp.	Extended drain intervals *x*
Alternative fuels	Fuel economy
Higher stress	Durability (less maint.)
Higher quality	Smaller engines
Change in design	Higher power density

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission	Transmission *x*
Gears	Valve train *x*
Ring-liner *x*	Bearing *x*
Brakes	Fuel injectors *x*
Piston *x*	Catalytic convertors *x*
Particulate trap	Chemical filter(remove acid,soot) *x*
Electrical contacts	Seals

(none of the above)

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

I assume you mean engine oil temperature. Peak oil temperatures will almost certainly by 5 or 10 °C on the (current oil temps are typically 100 °C on the freeway and can reach 175 °C under worst case conditions).

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Hard to say.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

(1) Probably not - groups such as the Coordinating Research Council already do some of these things.

(2) Maybe. Maybe Not.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Harrison Div/GMC* Industry: *Automotive Components*
Major products: *Air Cond. Compressors* Co.Size: *12,000 employees*
Location: *Lockpart, NY* Government contract? *None*

I want my answers to be kept confidential *Yes*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Materials technology has not been really recognized as a barrier and has not been considered a driving force for the development of better compressors. Attitudes are changing, however, as a result of the need to switch to a replacement refrigerant for R12.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Improved materials/coatings for bearing surfaces. Improved lubricants to allow for higher performance or use of lower cost, more easily machined materials. Improved bench test that can be correlated with component performance.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes. Unavailability of technology can lead to increased warranty costs.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation_____	Fuel economy_____	Cost_____x_____
Durability_____x_____	Repair cost_____	Performance_____
Maintenance cost_____	Innovation_____	Materials_____

5. What are the key research agenda of your company in the next 3-5 years?

   Company is more development oriented than research oriented. Main thrust for compressor products will be on reduced noise and vibration and higher operating rpm.

6. What are the key research agenda of your company in the next 5-10+ years?

   Possibly, replacement for the R134 air conditioning system.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock	x	Additives	x
Molecular Engineered Lub.		Additive mechanism	x
Thermally stable dispersant		Additive-add. interaction	
Bench test development	x	New measurement meth.	
Low friction materials	x	New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	
Temp. solid lub.		Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	
Metal matrix composite		Aluminum alloys	x
Engr. Plastics		Coatings	x

10. The major factors for change in lubrication technologies are:

Emission control		Materials change	
Higher temp.		Extended drain intervals	
Alternative fuels		Fuel economy	
Higher stress	x	Durability (less maint.)	x
Higher quality	x	Smaller engines	
Change in design		Higher power density	

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	
Gears		Valve train	
Ring-liner		Bearing	x
Brakes		Fuel injectors	
Piston		Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

Not applicable for Harrison.

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Development of bench tests that are truly predictive of behavior of materials in the component in service.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

The requirements for technology may be too specific, and to varied to be developed effectively by a large consortium. The more people (interests) involved, the more general becomes the output.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Mobil R&D* Industry: _____
Major products: *Petroleum Products* Co.Size: _____
Location: *Princeton, NJ* Government contract? _____

I want my answers to be kept confidential *Yes*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   (1) Limited to specialty products (experimental).
   (2) Not at this time.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   ?

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   (1) Yes
   (2) Depends on lubricant volumes effected.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation x	Fuel economy x	Cost x
Durability	Repair cost	Performance x
Maintenance cost	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   Emission regulations.
   Fuel Legislation.

6. What are the key research agenda of your company in the next 5-10+ years?

   Engine and machinery requirements.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock *Industry*	Additives *Industry*
Molecular Engineered Lub. *Industry*	Additive mechanism *Industry*
Thermally stable dispersant *Industry*	Additive-add. interaction *Industry*
Bench test development *Industry*	New measurement meth. *?*
Low friction materials *Industry*	New additives for ceramic *Government*
New lub. for new materials *Industry*	High temp. liq. Lub. *Industry*
Temp. solid lub. *Government*	Lub. application guide *Industry*
Stability mapping of lub. *Government*	Methanol compatible lub. *Industry*

9. The most important materials that you would like to see research be conducted on?

Superalloys	Ceramics *x*
Metal matrix composite	Aluminum alloys
Engr. Plastics *x*	Coatings *x*

10. The major factors for change in lubrication technologies are:

Emission control *x*	Materials change
Higher temp. *(Surface Temp)* *x*	Extended drain intervals *x*
Alternative fuels	Fuel economy *x*
Higher stress *(Surface Temp)* *x*	Durability (less maint.)
Higher quality	Smaller engines
Change in design *x*	Higher power density *x*

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission	Transmission *x*
Gears *x*	Valve train *x*
Ring-liner *x*	Bearing *x*
Brakes	Fuel injectors *x*
Piston *x*	Catalytic convertors
Particulate trap *x*	Chemical filter(remove acid,soot)
Electrical contacts	Seals

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

?

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

(Most important to mobil)- New lubricants (high volumes)
(Government)- Coatings solid lubes-databases.
Government should continue development of new databases of high quality (ACTIS program).

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

COMMENTS: *Above comments are personal. They may or may not reflect those of my Company. I feel industry should have greater input as to the areas funded by government, and specific research projects.*

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Penn State* Industry: *Education*
Major products: *Student-Tribo Research* Co.Size: *Large*
Location: *State Coll.,PA* Government contract? *Top 10 Un. in Coun*

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   We have a center for advanced materials and a materials research lab. We are currently trying to pull our Tribology efforts together.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Ability to get realistic and repeatable samples of these new materials in order to assess their problems with respect to tribology.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   (1) Yes

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation x	Fuel economy	Cost
Durability	Repair cost	Performance x
Maintenance cost	Innovation x	Materials x

5. What are the key research agenda of your company in the next 3-5 years?

   To provide fundamental tribology data is improve existing mechanic of system. To study tribological needs with new materials and new machine concepts.

6. What are the key research agenda of your company in the next 5-10+ years?

   Same as question #5.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities

All topics require industry-research lab. cooperation. High risk problems need govt-program cooperation. University research is greatly enhanced by industry cooperation.

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock		Additives	
Molecular Engineered Lub.		Additive mechanism	
Thermally stable dispersant		Additive-add. interaction	
Bench test development	1	New measurement meth.	
Low friction materials		New additives for ceramic	2
New lub. for new materials	3	High temp. liq. Lub.	4
Temp. solid lub.		Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys	1	Ceramics	2
Metal matrix composite	3	Aluminum alloys	
Engr. Plastics		Coatings	

10. The major factors for change in lubrication technologies are:

Emission control	3	Materials change	2
Higher temp.	1	Extended drain intervals	
Alternative fuels	4	Fuel economy	5
Higher stress		Durability (less maint.)	
Higher quality		Smaller engines	
Change in design		Higher power density	

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	
Gears		Valve train	3
Ring-liner	1	Bearing	
Brakes		Fuel injectors	2
Piston		Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	4
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

Ring reversal temp: *700-800 °F 3-5 years*
> 900 °F 10-15 years

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Ring tests-operating unit correlation for new materials higher temperatures, etc.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes - Yes

COMMENTS:_____

RETURN THE SURVEY TO:

Stephen Hsu
Chairman, Lubrication Workshop
3051 Materials and Life Science Building
Department of Materials Science and Engineering
Northwestern University
2145 Sheridan Road
Evanston, IL 60208

QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Pennzoil Co/Prod.Subs.* Industry: *Oil*
Major products: *Motor oil* Co.Size: *$2 Billion*
Location: *Woodlands, TX* Government contract? *None*

I want my answers to be kept confidential *Yes*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   As a supplier to the automotive and other industries, our products must be compatible with new materials.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes, somewhat we look to the OEM's to tell us which materials are of concerns.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *x*	Fuel economy *x*	Cost *x*
Durability	Repair cost	Performance
Maintenance cost	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

6. What are the key research agenda of your company in the next 5-10+ years?

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Product development and all related tasks, e.g., short & med term R&D.	*Very futuristic technologies -something we don't know how to do at all! And support Gov't Labs.*	*Building data data bases that have long term value throughout industry-e.g. API data books. Possibly support far out -only if industry won't.*	*Physical & chemical understanding -why new inventions.*

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock	Additives
Molecular Engineered Lub.	Additive mechanism
Thermally stable dispersant	Additive-add. interaction *O.K. Gov't.*
Bench test development	New measurement meth. *O.K. Gov't.*
Low friction materials	New additives for ceramic
New lub. for new materials	High temp. liq. Lub. *for far-out tech.*
Temp. solid lub.	Lub. application guide
Stability mapping of lub.	Methanol compatible lub.

9. The most important materials that you would like to see research be conducted on?

Superalloys	Ceramics
Metal matrix composite	Aluminum alloys
Engr. Plastics	Coatings

10. The major factors for change in lubrication technologies are:

Emission control x	Materials change x
Higher temp.	Extended drain intervals
Alternative fuels x	Fuel economy x
Higher stress	Durability (less maint.)
Higher quality	Smaller engines
Change in design	Higher power density

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission	Transmission
Gears	Valve train x
Ring-liner	Bearing
Brakes	Fuel injectors x
Piston	Catalytic convertors x
Particulate trap	Chemical filter(remove acid,soot)
Electrical contacts	Seals x

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Documenting properties of new materials, developing predictive tools.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Depends on the terms- would join if it will provide us with a competitive advantage.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Reese & Company* Industry: *Yes*
Major products: *Ag Equipment* Co.Size: *40,000 employees*
Location: *Moline, IL* Government contract? *None*

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Roles - add value
   Force - no

2. What are the most critical issues dealing with the new materials? What new materials are useful?
   Issue - value
   Useful - none ?? - What is new?

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Minimal.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *x*	Fuel economy *x*	Cost *xxx*
Durability *xxx*	Repair cost *x*	Performance *xx*
Maintenance cost *xx*	Innovation	Materials

(value xxx)

5. What are the key research agenda of your company in the next 3-5 years?

   Improved planting and harvesting methods.

6. What are the key research agenda of your company in the next 5-10+ years?

   Same as question #5.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
x	*x*	*x*	*x*

(All of the above)

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock		Additives	
Molecular Engineered Lub.		Additive mechanism	
Thermally stable dispersant	x	Additive-add. interaction	
Bench test development		New measurement meth.	
Low friction materials		New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	
Temp. solid lub.		Lub. application guide	x
Stability mapping of lub.		Methanol compatible lub.	x

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	
Metal matrix composite	x	Aluminum alloys	x
Engr. Plastics		Coatings	x

10. The major factors for change in lubrication technologies are:

Emission control	x	Materials change	
Higher temp.	x	Extended drain intervals	x
Alternative fuels	x	Fuel economy	x
Higher stress		Durability (less maint.)	
Higher quality		Smaller engines	
Change in design		Higher power density	

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission	?	Transmission	
Gears	x	Valve train	x
Ring-liner		Bearing	
Brakes		Fuel injectors	
Piston		Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

3 - 5 yrs 350 °C
10 - 15 yrs ?????

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Value. None. None.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

No. No.

COMMENTS: *You are assuming that improved materials will result in a desired improvement in a product's value to a "customer". There are other solutions which do not involve materials. I do not care about the improvements in materials; only the improvement in customer value.*

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Ricardo North Amer.* Industry: *Engines (consulting)*
Major products: *Eng. Consulting, R&D* Co.Size: *25 (US) 400 (UK)*
Location: *Burrridge, IL* Government contract? *Yes*
(Tribo., alt. Fuel, durability)

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Roles - Not any direct roles
   Force - Yes

2. What are the most critical issues dealing with the new materials? What new materials are useful?
   What new materials are useful?

   Low friction and wear at elevated temperatures. Ceramics.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   We are interested in mechanical and lubrication (friction/wear) properties of new materials, and the trade-off between these properties.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *x*	Fuel economy *x*	Cost *x*
Durability *x*	Repair cost	Performance *x*
Maintenance cost	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   Continued work toward developing techniques for design analysis of engines vis-a-versa optimization from the standpoint of friction and wear loads.

6. What are the key research agenda of your company in the next 5-10+ years?

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
System (engine)	*System (engine)*	*Materials*	*Materials*
● *R&D needs*	*Materials, standards*	*standards*	*measurements*
● *Friction & wears loads*	*Materials measurement techniques.*	● *R&D needs*	*techniques.*
Lubricants (Oil Industry)	*Analysis techniques.*	● *Friction & wears leads*	*Analysis techniques.*

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock_____	Additives_*Oil Industry*_____
Molecular Engineered Lub._____	Additive mechanism_____
Thermally stable dispersant_____	Additive-add. interaction_____
Bench test development_*Government*_____	New measurement meth._*Universities*_____
Low friction materials_*Government Labs.*_____	New additives for ceramic_____
New lub. for new materials_____	High temp. liq. Lub._*Oil Industry*_____
Temp. solid lub._*Government Labs.*_____	Lub. application guide_____*x*_____
Stability mapping of lub._*Oil Industry*_____	Methanol compatible lub._____*x*_____
System Analysis & ? _*Industry*_____	System Friction and Wear Loads_*Industry*_____

9. The most important materials that you would like to see research be conducted on?

Superalloys_____	Ceramics_____*x*_____
Metal matrix composite_____	Aluminum alloys_____*x*_____
Engr. Plastics_____	Coatings_____

10. The major factors for change in lubrication technologies are:

Emission control_____	Materials change_____
Higher temp._____*x*_____	Extended drain intervals_____
Alternative fuels_____	Fuel economy_____
Higher stress_____	Durability (less maint.)_____*x*_____
Higher quality_____	Smaller engines_____
Change in design_____*x*_____	Higher power density_____

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission_____	Transmission_____
Gears_____	Valve train_____*x*_____
Ring-liner_____*x*_____	Bearing_____*x*_____
Brakes_____	Fuel injectors_____*x*_____
Piston_____*x*_____	Catalytic convertors_____
Particulate trap_____	Chemical filter(remove acid,soot)_____
Electrical contacts_____	Seals_____

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

Peak temp.: 3-5 years 1200 °C, 10-15 years 1250 °C

Lubricated Zones (e.g.) ?: 3-5 years 475 °C, 10-15 years 500-525 °C

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

High temperature materials and lubricants; system (e.g. engine) tribological optimization.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes

COMMENTS: *I think a link should be forged between industries that manufacture and engineer systems (engines, compressors, machine tools, etc.) and those who develop materials and carry out materials R&D. The former can characterize their systems (i.e. temperature premieres) and incidently carry out detailed lubrication analysis (of bearings, pistons, vibration, etc) or measurements to predict friction and wear loads on lubricated contacts. The latter can characterize and sometimes model material behavior, but generally do it in a manner removed from specific systems. Through such a coupling there may be an opportunity for a more accelerated development of material for future tribological needs various systems. Such a link can be fostered by government agency sponsored R&D.*

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *SURI* Industry: _____
Major products: *R&D* Co.Size: *25,000 employees*
Location: *San Antonio, TX* Government contract? _____

I want my answers to be kept confidential _____

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   New materials must be incorporated into existing engines with as little "pain" as possible.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Manufacturability in the final product; i e., ceramic valve seat inserts are difficult to finish machine after installation in the cylinder head casting.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   No.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *3*	Fuel economy _____	Cost _____
Durability *1*	Repair cost _____	Performance _____
Maintenance cost *2*	Innovation _____	Materials _____

5. What are the key research agenda of your company in the next 3-5 years?

   Emissions reduction from engines.

6. What are the key research agenda of your company in the next 5-10+ years?

   Emissions elimination from vehicles.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Application of technology	*Feasibility demonstrations*	*Extended basic research*	*Basic research*

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock		Additives	
Molecular Engineered Lub.		Additive mechanism	
Thermally stable dispersant		Additive-add. interaction	
Bench test development		New measurement meth.	
Low friction materials		New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	
High Temp. solid lub.	x	Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	x
Metal matrix composite	x	Aluminum alloys	
Engr. Plastics		Coatings	

10. The major factors for change in lubrication technologies are:

Emission control	x	Materials change	
Higher temp.		Extended drain intervals	
Alternative fuels	x	Fuel economy	
Higher stress		Durability (less maint.)	x
Higher quality		Smaller engines	
Change in design		Higher power density	

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	
Gears		Valve train	x
Ring-liner	x	Bearing	
Brakes		Fuel injectors	
Piston	x	Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Southwest Research* Industry: *Independent R&D Lab.*
Major products: *Testing & Development* Co.Size: *2600 employees*
Location: *San Antonio, TX* Government contract? *Some*

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   I see new materials driving evolutionary changes, but not the motivating force. The materials must fill a need rather than finding a use for new materials.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Evaluation of durability over the useful life. Determination of tolerance to abuse is also critical.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes. If lubrication technology is not available, then current technology will have to continue to be used.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *x*	Fuel economy	Cost
Durability *x*	Repair cost	Performance *x*
Maintenance cost *2*	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   We are responsive to client needs, therefore, they determine the agenda.

6. What are the key research agenda of your company in the next 5-10+ years?

   See above.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities

No Response.

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock	Additives
Molecular Engineered Lub.	Additive mechanism
Thermally stable dispersant	Additive-add. interaction
Bench test development	New measurement meth.
Low friction materials	New additives for ceramic
New lub. for new materials	High temp. liq. Lub. *Industry*
High Temp. solid lub.	Lub. application guide
Stability mapping of lub.	Methanol compatible lub.

9. The most important materials that you would like to see research be conducted on?

Superalloys	Ceramics
Metal matrix composite	Aluminum alloys
Engr. Plastics	Coatings

10. The major factors for change in lubrication technologies are:

Emission control x	Materials change
Higher temp. x	Extended drain intervals
Alternative fuels	Fuel economy
Higher stress	Durability (less maint.)
Higher quality	Smaller engines
Change in design	Higher power density

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission	Transmission
Gears	Valve train
Ring-liner x	Bearing
Brakes	Fuel injectors x
Piston	Catalytic convertors
Particulate trap x	Chemical filter(remove acid,soot)
Electrical contacts	Seals

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

3-5 years: T.R.R. of 700 °F and T.R.R. of 800 °F

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Higher Temperature Lubricants.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

We would consider participation considering the fact that we are a not-for-profit Institution.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *Surface Research* Industry: *R&D(50% Trib)most in Transp*
Major products: *R&D;5% Lubricants(sale)* Co.Size: *small*
Location: *Lenexa, KS* Government contract? *50%*

I want my answers to be kept confidential *In Kansas City metro area*

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   The majority of our work is in development, evaluation and some sales of new materials. Advanced materials are one of the seven or so technologies which the major economies- U.S., Japan, Europe- all realize they must excel in to compete in the world economy.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Broad question - difficult to answer. Conventional wisdom is transition of new materials into application, driven by performance requirements and enabled by economical processing methods and favorable life cycle costs. In transportation, new lubricants and lightweight structural materials are continually needed.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Very much so, but in particular is development of new lubricants. Neither environmental nor performance requirements of new engines can be met without new lubricants.

4. What are the major driving force influencing the technologies essential to your business?
   (Customers of our R&D services are motivated by all. Most important are marked.

Emission regulation *x*	Fuel economy *xx*	Cost
Durability *x*	Repair cost *x*	Performance *xx*
Maintenance cost	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   In transportation tribology, development of new high performance liquid and solid lubricants and additives. Also bench/engine test correlation. Now also using computer-assisted molecular design.

6. What are the key research agenda of your company in the next 5-10+ years?

   Same as question #5.

7. Which topics you think should be handled by the industry, government, universities?

(Each should do what their people are best at, in general).

Industry	Govt. Programs	Govt. Labs.	Universities
Product development.	*Support key technology development by means of contracts to industry.*	*Analytical method development, data base.*	-

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock	*Industry*	Additives	*Industry*
Molecular Engineered Lub.	*Ind/Gov't*	Additive mechanism	
Thermally stable dispersant		Additive-add. interaction	
Bench test development	*Gov't/Univer*	New measurement meth.	*Gov't/Univer*
Low friction materials		New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	*Industry*
High Temp. solid lub.	*Industry*	Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	
Metal matrix composite		Aluminum alloys	
Engr. Plastics		Coatings	

(Lubricates)

10. The major factors for change in lubrication technologies are:

Emission control	*1x*	Materials change	
Higher temp.	*1x**	Extended drain intervals	*2x*
Alternative fuels	*2x*	Fuel economy	*1x**
Higher stress		Durability (less maint.)	
Higher quality		Smaller engines	*1x**
Change in design		Higher power density	*1x**

**All related*

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	*x (May include CVT)*
Gears		Valve train	
Ring-liner	x	Bearing	
Brakes		Fuel injectors	x
Piston	x	Catalytic convertors	x
Particulate trap		Chemical filter(remove acid,soot)	x
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

Depends on location and engine. In heavy duty diesel engines, projection 8 years: Sump Temp 80 °F higher, top ring Temp 100 °F higher, piston undercrown Temp 200 °F higher than current.

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

Emission control, high performance lubricant development and insertion of new materials.

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

"Possibly" to both.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *TRW* Industry: *Automotive*
Major products: *Valves* Co.Size: *8 Billion*
Location: *Cleveland, OH* Government contract?_____

*I want my answers to be kept confidential*_____

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Yes

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Material property extrapolation

   M.P. = f(time,temp)

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes. How can lubrication be modeled? The Mat'l that is chosen for an application.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation *3*	Fuel economy *5*	Cost *1*
Durability *4*	Repair cost *7*	Performance *2*
Maintenance cost *6*	Innovation *8*	Materials *x*

5. What are the key research agenda of your company in the next 3-5 years?

   New material development product & process modeling.

6. What are the key research agenda of your company in the next 5-10+ years?

   Analytical eng. product modeling process modeling identify new mat'l?

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities
Applications.	*Programs common to all engine groups.*	*Mat'l property equations.*	*SPL studies.*

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock_____	Additives_____
Molecular Engineered Lub._____	Additive mechanism_____
Thermally stable dispersant_____	Additive-add. interaction_____
Bench test development_____	New measurement meth._____
Low friction materials_____	New additives for ceramic_____
New lub. for new materials_____	High temp. liq. Lub._____
High Temp. solid lub._____	Lub. application guide_____
Stability mapping of lub._____x_____	Methanol compatible lub._____

Equations that describe deposit formation. Equations that describe levels of lub on a surface.

9. The most important materials that you would like to see research be conducted on?

Superalloys_____	Ceramics_____x_____
Metal matrix composite_____	Aluminum alloys_____x_____
Engr. Plastics_____x_____	Coatings_____x_____

10. The major factors for change in lubrication technologies are:

Emission control_____x_____	Materials change_____x_____
Higher temp._____	Extended drain intervals_____
Alternative fuels_____x_____	Fuel economy_____x_____
Higher stress_____	Durability (less maint.)_____
Higher quality_____	Smaller engines_____x_____
Change in design_____	Higher power density_____x_____

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission_____	Transmission_____
Gears_____	Valve train_____x_____
Ring-liner_____	Bearing_____
Brakes_____	Fuel injectors_____
Piston_____	Catalytic convertors_____
Particulate trap_____	Chemical filter(remove acid,soot)_____
Electrical contacts_____	Seals_____x_____

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

Maybe lower > 1400 °F

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

Yes. Yes.

COMMENTS:_____

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QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *U. S. Army* Industry: *N/A*
Major products: *RDTE* Co.Size: *ca 1000*
Location: *Ft. Belvoir, Va* Government contract? *N/A*

I want my answers to be kept confidential

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Allowing the development of product specifications that meet/satisfy new engine/powertrain/system requirements. Yes.

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   High-temperature operability
   Environmentally compatible
   Cost and availability

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Yes. If the technology is not available, new system will not be able to be fully developed because of these existing barriers.

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation	Fuel economy	Cost x
Durability x	Repair cost x	Performance x
Maintenance cost x	Innovation	Materials

5. What are the key research agenda of your company in the next 3-5 years?

   Development of "environmentally compliant" heavy duty engine oils suitable for use in low emissions and pre-1994 engines and capable operating on varying qualities of diesel/distillate fuels.

6. What are the key research agenda of your company in the next 5-10+ years?

   Development of heavy duty engine oils for low heat rejection and advanced diesel engines and incorporate powertrain requirements into a common oil.

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock		Additives	
Molecular Engineered Lub.		Additive mechanism	
Thermally stable dispersant		Additive-add. interaction	
Bench test development	x	New measurement meth.	x
Low friction materials		New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	
High Temp. solid lub.	x	Lub. application guide	x
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys		Ceramics	x
Metal matrix composite		Aluminum alloys	
Engr. Plastics		Coatings	

10. The major factors for change in lubrication technologies are:

Emission control	x	Materials change	
Higher temp.	x	Extended drain intervals	
Alternative fuels		Fuel economy	
Higher stress		Durability (less maint.)	
Higher quality		Smaller engines	
Change in design	x	Higher power density	x

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	x
Gears		Valve train	x
Ring-liner	x	Bearing	
Brakes		Fuel injectors	
Piston	x	Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	x

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

COMMENTS:

RETURN THE SURVEY TO:

Stephen Hsu
Chairman, Lubrication Workshop
3051 Materials and Life Science Building
Department of Materials Science and Engineering
Northwestern University
2145 Sheridan Road
Evanston, IL 60208

QUESTIONNAIRE I
TECHNICAL SURVEY

Company name: *U. S. Army-TACOM* Industry: *Government*
Major products: *Mobility Systems* Co.Size: _____
Location: *Warren, MI* Government contract? _____

I want my answers to be kept confidential _____

1. What are the roles of new materials in your company's technology? Do you see it as a prime motive force for new technology?

   Role of new materials- Ceramic coatings-In-cylinder thermal insulation and substrate material protection. Thin ring and liner wear coatings. Monolithic ceramics - Valves, valve seats, bushings, injector plunger cam rollers. Other wear applications-High Temp Alloys- Titanium aluminides (high strength and high temp).

2. What are the most critical issues dealing with the new materials? What new materials are useful?

   Monolithic ceramic and ceramic coating durability remains the most critical issue. Titanium alumunides look like they may work for LHR head/head face plate, but current costs are extremely high. Low thermal expansion ceramics NZP also offer potential for solving LHR component development challenges.

3. Is lubrication of new materials a concern to you? If yes, what are the positive and negative impacts if such technology is not available?

   Lubrication effectiveness for high specific output low heat rejection diesel engines is critical in meeting compactness and durability goals at the higher operating temperatures. (TRR 550F and sump temperatures 350F).

4. What are the major driving force influencing the technologies essential to your business?

Emission regulation _____	Fuel economy *3*	Cost *4*
Durability *2*	Repair cost *4*	Performance *1*
Maintenance cost *4*	Innovation _____	Materials _____

5. What are the key research agenda of your company in the next 3-5 years?

   Advanced Propulsion
   Electric Drive Systems

6. What are the key research agenda of your company in the next 5-10+ years?

   Advanced Propulsion
   Advanced Suspension

7. Which topics you think should be handled by the industry, government, universities?

Industry	Govt. Programs	Govt. Labs.	Universities

We would have to look at overall areas and where expertise lies in each to best solve the problems.

8. What are the most important issues in lubrication that you would like to see done? By whom? What should the government do?

New Lub. base stock	2	Additives	7
Molecular Engineered Lub.	3	Additive mechanism	
Thermally stable dispersant	4	Additive-add. interaction	9
Bench test development	6	New measurement meth.	
Low friction materials	5	New additives for ceramic	
New lub. for new materials		High temp. liq. Lub.	1
High Temp. solid lub.	8	Lub. application guide	
Stability mapping of lub.		Methanol compatible lub.	

9. The most important materials that you would like to see research be conducted on?

Superalloys	4	Ceramics	1
Metal matrix composite	3	Aluminum alloys	
Engr. Plastics		Coatings	2

10. The major factors for change in lubrication technologies are:

Emission control		Materials change	
Higher temp.	2	Extended drain intervals	
Alternative fuels		Fuel economy	
Higher stress		Durability (less maint.)	
Higher quality		Smaller engines	1
Change in design	3	Higher power density	1

11. Which of the following component technology do you think is the most important to you?

Continuous variable transmission		Transmission	*(Military Specific)* 6
Gears		Valve train	4
Ring-liner	1	Bearing	5
Brakes		Fuel injectors	3
Piston	2	Catalytic convertors	
Particulate trap		Chemical filter(remove acid,soot)	
Electrical contacts		Seals	

12. What are the maximum temperatures you think the engines of the future would be? In 3-5 years? In 10-15 years?

3-5 yrs (TRR 550F Sump 350F)
10-15 yrs (TRR 550F Sump 350F)

13. Of all the topics mentioned (but not limited to), which do you think is the most important? Which would your company be interested in participating? Which do you think the Government should concentrate on?

14. Would you like to see a consortium of government labs, industries and universities setup to jointly solve these challenges? If such a consortium were set up, would you consider joining?

COMMENTS: *Given the right circumstances and focus on technical challenges to be solved with applicability to military propulsion systems, yes we would be interested.*

RETURN THE SURVEY TO:

Stephen Hsu
Chairman, Lubrication Workshop
3051 Materials and Life Science Building
Department of Materials Science and Engineering
Northwestern University
2145 Sheridan Road
Evanston, IL 60208

APPENDIX C

QUESTIONNAIRE II

LUBRICATION WORKSHOP

Please note that not all participants answered all of the questions. Only the projects which the participants had ranked are shown in the attached tables.

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Allied Signal

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
   1) environmentally friendly fuels/lubricants
   2) bench scale tests that simulate dyno and field data
   3) baseline data for real systems with materials/additives to be used in '95-97 autos and trucks and tractors

2. Same question as 1, the time frame is 5-10 years.
   1) cooperative technology development mechanisms
   2) bench scale tests that simulate dyno and field data
   3) compatible lubricant for new materials and coatings

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
   solid lubricants compatible with ceramics and coatings at high temps...
   project to generate good baseline data for multiple component combinations
   Workshop idea is good. Follow-up 1 year, 1/2 year.
   project to generate good baseline data for multiple component combinations

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
   Workshop idea is good. Follow-up 1 year, 1/2 year.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive					E			
Gears	2	5	5	3	C			
Transmission								
CVT								
Long drain								
Friction reduction	1	1	1	1	A			
Light Wt. materials	1	1	1	1	A			
New mat'ls lub. chem.	2	2	2	3	B			
Alternative fuel lub.								
R-134a lubrication								
Heavy duty diesel					E			
Ceramics lub. chem.	2	2	2	2	B			
lub. applica-tion maps	4	4	4	4	D			
Coatings lub.	2	2	2	2	B			

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control								
Liq. lub. for Hi Temp Eng	1	1	1	2	A			
Alter. fuelled engines								
valves for natural gas engines								
Million miles engine								
Advanced materials lub.	1	1	1	1	A			
Biodegradabl e lubricants								
Lubricant/ additives					E			
Molecular Engineered Basestocks (MEB)								
MEBs for traction								
MEB for low friction								
Hi T Dispersants	2			2	B			
Hi T Oxid. inhibitors	2			2	B			

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Allison Gas Turbine

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
High temperature liquid lubes and additives
Development of ceramics and other high temperature materials and coatings
High temperature solid lubricants

2. Same question as 1, the time frame is 5-10 years.
Same as #1 above

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
Development of high temperature solid lubricant for the automotive gas turbine regenerators sealing system and bearing. Yes (with company approval) this work is required to advance the development of the innovative gas turbine.

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
High temperature solid lubrication. Cannot commit on financing.

5. Same question as #4, but any project or area.
Ceramic automotive gas turbine regenerator seals and bearings.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
Good provided there is a positive outcome resulting from participant input. Once per year.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Yes (with company approval)

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears	2	2	1	2	H	3	1	3
Transmission	2	2	2	4	G	2	1	3
CVT	5	4	3	5	F	3	2	5
Long drain	-	-	-	-				
Friction reduction	6	8	2	8	B	5	3	2
Light Wt. materials	8	5	1	8	D	3	1	4
New mat'ls lub. chem.	8	7	7	7	A	3	1	5
Alternative fuel lub.	7	3	7	6	C	4	2	2
R-134a lubrication	6	4	8	7	E	2	1	4
Heavy duty diesel								
Ceramics lub. chem.	6	6	2	7	C	2	2	2
lub. applica-tion maps								
Coatings lub.	6	5	2	7	B	2	3	3

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control								
Liq. lub. for Hi Temp Eng								
Alter. fuelled engines								
valves for natural gas engines								
Million miles engine								
Advanced materials lub.	6	6	2	6	A	2	4	3
Biodegradabl e lubricants								
Rubicon Additives								
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)								
MEBs for traction								
MEB for low friction								
Hi T Dispersants								
Hi T Oxid. inhibitors								

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Amoco Oil Company

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
   1) reduced emissions
   2) improved fuel economy
   3) energy independence
   4) larger life engines and lubricants

2. Same question as 1, the time frame is 5-10 years.
   Same and alternative fuels lubricants needs

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
   Main emphasis will be on fuel and lubricant improvements to reduce emissions - No.

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
   Long life engines and lubricants - spirit and will.
   Lower emissions - Improved fuels and lubes for this will be supplied.
   Improved fuel economy.

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
   Emphasis seems to be in higher engine temperatures whereas other approaches such as higher efficiency may be more desirable.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
   Amoco will probably not joint because of limited funds available for lubricants research.

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears	2	2	2	2	I		8	
Transmission	3	4	4	4	H		6	
CVT	4	7	3	3	F		5	
Long drain	6	6	9	9	G		7	
Friction reduction	7	8	7	10	B		2	2
Light Wt. materials	9	9	6	6	C	1		1
New mat'ls lub. chem.	5	5	5	5	E	3	4	3
Alternative fuel lub.	10	10	10	8	A	2	1	
R-134a lubrication	8	3	8	7	D	4	3	4
Heavy duty diesel								
Ceramics lub. chem.								
lub. applica-tion maps	4			8	F		6	
Coatings lub.								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	5		6		E	3	5	
Liq. lub. for Hi Temp Eng								
Alter. fuelled engines	8	10	10	9	A	1	1	1
valves for natural gas engines	10	9			C	2	3	
Million miles engine	9			10	B		2	
Advanced materials lub.	6							
Biodegradable lubricants	7		9		D		4	2
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)								
MEBs for traction								
MEB for low friction								
Hi T Dispersants								
Hi T Oxid. inhibitors								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics								
Ashless Anti-wear								
Additives for coatings								
Multi-func-tional add.	8		9	9	B		2	
Time-release additives	6	9	7		C		3	
Additive-add. Interactions	7		8	10	D		4	
Anti-oxidant mechanisms	10				F		5	
Anti-wear mechanisms	9	8			G		6	
Low friction Lubricants		10	10	8	A		1	
Lub. for low emission					E			
Other projects								

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Borg Warner

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Improvements in tribological and materials which will result in improved fuel economy, lower emission and are not harmful to the environment.

2. Same question as 1, the time frame is 5-10 years.
Establish tests which accurately portray full environments.

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
We will address improvements in sheave/belt wear, however our likelyhood of success is poor without outside experience.

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
1. CVT (OBVIOUSLY) - financial as well
Spirit and Goodwill
High speed valve actuation and tribilogical influence
Compatibility of ATT with chains/clutches/gears/BEARINGS

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
Good. If projects are specifically related to us 4 times/year. If not related 1 time/year.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Absolutely.

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears	3	5	5	5	E			X
Transmission	5	7	5	5	D			X
CVT	6	8	8	8	A			1
Long drain	3	8	8	7	B	X		
Friction reduction	5	7	7	6	C	X		2
Light Wt. materials	6	7	1	4		X		4
New mat'ls lub. chem.								
Alternative fuel lub.	7	7	6	5				
R-134a lubrication	-	-	8	6		3		
Heavy duty diesel								
Ceramics lub. chem.								
lub. applica-tion maps								
Coatings lub.								

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Caterpillar

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Emmissions/durability/fuel economy
Initial oil drum/monitor/emissions
Development of test method/data base/
Development of lubricant for LHR - 900°F (415°C)

2. Same question as 1, the time frame is 5-10 years.
Fuel economy/durability/powder density
Altrnative fuels
Development of lubricant for LHR 800°F (415°C)
Universal engine oil diesel/alternative fuels
On board oil regenation
In cylinder oil catalysis

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
All - quite possibly not at same level
Will work under "right" times (generic technology)
University - move research into commerical application
Kamo solid lubrication approach more important

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?

5. Same question as #4, but any project or area.
See next page

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
Yes, no more than 2 x per year.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Yes, depends if the technology generated is generatic.
Yes, if it become engine, component specific - No!

5. (Continued)

Ceramic Programs

- Development of test methology for correlating bench tests to engine testing tube properties

- Effect of ceramic surface on oxidation wear additivs fo lubricant

- Ceramic contamination
  acid/N_2O/root

- Effect of lubricant on ceramic wear

- Do ceramics require additives for anti-wear (eliminate component from lub oil)

- Lubricants when enable Al_2O_2 to provide good friction and wear

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears								
Transmission								
CVT								
Long drain								
Friction reduction								
Light Wt. materials								
New mat'ls lub. chem.								
Alternative fuel lub.								
R-134a lubrication								
Heavy duty diesel								
Ceramics lub. chem.	8	9	5	5	C			
lub. applica-tion maps	3	3	2	2	D			
Coatings lub.								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	5	5	9	10	B			
Liq. lub. for Hi Temp Eng	8	9	5	6	A			
Alter. fuelled engines	8	8	8	8	A+			
valves for natural gas engines	2	2	2	2	D			
Million miles engine	8	8	9	9	B			
Advanced materials lub.	(Ceramic)							
Biodegradable lubricants	6	6	9	8	B			
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	3				E			
MEBs for traction								
MEB for low friction								
Hi T Additives	8	8	8	8	B			
Hi T Oxid. inhibitors								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics								
Ashless Anti-wear	8	5	8	8	B			
Additives for coatings								
Multi-func-tional add.	9	8	5	8	B			
Time-release additives	4	4	4	4	E			
Additive-add. Interactions	5	5	5	5	D			
Anti-oxidant mechanisms	8	7	7	6	C			
Anti-wear mechanisms	8	7	7	5	B			
Other projects								
Vapor Phase Lab	4	4	4	5	B			
All "engine" oil	8	8	8	8	A			
On board motor oil cond	5	5	5	5	B			
root generation/ interaction	8	8	8	8	A			

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Eng corelatable test meth	9	9	9	9	A+			
Fuel lubricants additives	8	8	8	8	A			
Cam rolling contact	5	6	6	6	C			
Solid lub	8	7.5	7.5	7.5	B			

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Caterpillar Inc.

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Million mile (durable) engine, long drain oils, fuel injection durability

2. Same question as 1, the time frame is 5-10 years.
Bench/field correlations, high temp lubes

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
Oil consumption mechanisms, bench/field correlations, fuel injection durability

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
Very useful. Should have one year.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Yes, must be well-defined, generic program that addresses industry needs.

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears	5	4	1	3	D			
Transmission	6	6	5	7	C			
CVT	7	6	6	7	C			
Long drain	9	9	9	9	A			
Friction reduction	4	5	5	4	C			
Light Wt. materials	7	7	6	7	B			
New mat'ls lub. chem.	4	4	5	5	C			
Alternative fuel lub.	4	4	4	4	B			
R-134a lubrication	4	4	5	5	B			
Heavy duty diesel								
Ceramics lub. chem.	8	6	6	7	C			
lub. applica-tion maps	7	4	4	4	C			
Coatings lub.	6	6	6	6	C			

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	7	6	8	6	A			
Liq. lub. for Hi Temp Eng	9	8	8	9	B			
Alter. fuelled engines	8	8	8	9	A			
valves for natural gas engines	8	5	6	7	B			
Million miles engine	10	6	8	9	A			
Advanced materials lub.	7	6	7	6	B			
Biodegradabl e lubricants	8	4	9	8	B			
Oil Coas. mechanism	8	7	6	7	B			
Bench test engine correl	9	7	6	9	B			
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	8	7	7	7	B			
MEBs for traction	7	8	6	4	D			
MEB for low friction	9	8	7	8	C			
Hi T Dispersants	8	8	7	5	B			
Hi T Oxid. inhibitors	8	8	7	5	B			

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics	8	8	6	7	C			
Ashless Anti-wear	8	4	8	6	C			
Additives for coatings	7	5	4	4	D			
Multi-func-tional add.	6	4	3	4	C			
Time-release additives	7	5	5	6	C			
Additive-add. Interactions	7	7	7	7	A			
Anti-oxidant mechanisms	8	8	8	8	A			
Anti-wear mechanisms	8	8	8	8	A			
Other projects								
Extended oil change								
Vapor phase lub	6	7	7	6	B			
Univ eng oil	8	8	8	8	A			
Onboard cond monitor	9	7	7	6	C			
Fuel eng durability	9	8	7	7	A			
Onboard oil rejuv.	9	9	9	9	A			
Trib modeling	8	6	7	6	B			

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company CIBA-GEIGY

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
High temperature liquid lubricant
Lubricant bench test development

2. Same question as 1, the time frame is 5-10 years.

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
"Environmentally friendly" lubricants

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
Twice a year pending project progress of working group.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Yes (assuming my corporation has no objections)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control								
Liq. lub. for Hi Temp Eng								
Alter. fuelled engines								
valves for natural gas engines								
Million miles engine								
Advanced materials lub.								
Biodegradabl e lubricants								
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	Very long term							
MEBs for traction	Very long term							
MEB for low friction	Very long term							
Hi T Dispersants	8	5	0-2	10	H		X	
Hi T Oxid. inhibitors	10	5	7	8	F		X	

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics	5	5	5	5	L	X	X	
Ashless Anti-wear	10	8	9	5	G		X	
Additives for coatings	5	5	0	5	I		X	
Multi-func-tional add.	7	5	5	5	J		X	
Time-release additives	8	5	5	5	K		X	
Additive-add. Interactions	10	7	5	10	B	X	X	X
Anti-oxidant mechanisms	10	7	5	8	D	X		X
Anti-wear mechanisms	10	8	5	8	E	X		X
Hi temp lubricant	10	8	10	10	A			X
Bench test development	10			10	C	X		
Other projects								

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company John Crane

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
   - *Property Data Base - fluid, matrial characteristics and tribological properties such as wear, friction coefficients*
   - *Test methodology*

2. Same question as 1, the time frame is 5-10 years.
   - *Better understanding of lubrication, friction and wear fundamentals*

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
   Test methodology. We will be willing to collaborate and possibly support financially.

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
   Beneficial. Once a year.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
   Yes. We will participate in consortiums on subjects of interest.

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears								
Transmission								
CVT								
Long drain								
Friction reduction								
Light Wt. materials								
New mat'ls lub. chem.								
Alternative fuel lub.								
R-134a lubrication								
Heavy duty diesel								
Ceramics lub. chem.	7	6	6	6	6-I			
lub. applica-tion maps	4	4	4	4	3-O			
Coatings lub.								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	8	8	9	8	8-B			
Liq. lub. for Hi Temp Eng	9	9	8	9	9-A			
Alter. fuelled engines	9	9	10	9	9-A			
valves for natural gas engines	6	7	6	5	6-J			
Million miles engine	9	7	6	7	7-C			
Advanced materials lub.								
Biodegradabl e lubricants	6	6	9	6	7-D			
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	6	4	4	4	5-K			
MEBs for traction								
MEB for low friction								
Hi T Dispersants	7	7	7	7	7-E			
Hi T Oxid. inhibitors								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics								
Ashless Anti-wear	7	7	7	7	7-F			
Additives for coatings								
Multi-func-tional add.	8	7	7	8	7-G			
Time-release additives	4	4	4	4	4-N			
Additive-add. Interactions	6	5	5	5	5-M			
Anti-oxidant mechanisms	5	5	5	5	5-L			
Anti-wear mechanisms	6	7	7	7	7-H			
Other projects								
Test methodology	9	9	9	9	9-A	1		

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Cummins

-

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
   1. *Low oil-derived particulates (HD diesel), low oil consumption*
   2. *Compatibility with alternate fuels*
   3. *Compatibility with exhaust gas recirculation, NO_x reducing fuel additives*
   4. *Improved cam-roller LCF life (would also combine with CVT lubrication)*
   5. *Fuel lubricity improvement*

2. Same question as 1, the time frame is 5-10 years.
   1. *Low oil-derived particulates, low oil consumption*
   2. *Fuel economy (low friction)*
   3. *Extended drain interval*
   4. *Wear reduction (1,000,000 mile engine)*
   5. *Chemically active filtration*

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
   All emissions - related topics especially.
   Collaboration may be possible on generic projects which would benefit the heavy duty diesel industry as a whole.

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
   Liquid lube for particulate control, alternate fuelled engine, million mile diesel engine.
   Would support. Collaboration might take the form of testing candidate lubes. We would cost share if awarded DOE contracts, but probably not provide direct funding.

5. Same question as #4, but any project or area.
   Lube for EGR, NO_x reducing fuel additives, catalysts
   Cam-roller RCF - collaboration with CVT efforts possible, some funding may be possible
   Fuel lubricity improvement - collaboration possible

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
   Very important - we need more DOE support for lubricant development programs.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
   In favor, but decision to join would be based on projects to be funded (must be of relevance to Cummins) and on resource constraints, especially financial. Needs to have strong support from oil/additive companies.

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears								
Transmission								
CVT								
Long drain								
Friction reduction								
Light Wt. materials								
New mat'ls lub. chem.								
Alternative fuel lub.								
R-134a lubrication								
Heavy duty diesel								
Ceramics lub. chem.	6	6	5	5	D	8	16	
lub. applica-tion maps	3	2	2	2	E	12		8
Coatings lub.	6	6	5	5	D	7	15	9

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	10	10	10	10	A	1	1	
Liq. lub. for Hi Temp Eng	9	7	8	9	B	5	8	7
Alter. fuelled engines	10	10	10	10	A	2	2	4
valves for natural gas engines	6	5	7	6	C		13	
Million miles engine	10	7	7	9	B		7	
Advanced materials lub.								
Biodegradabl e lubricants	6	4	10	8	C	6	12	
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	6	6	6	6	C	11	14	6
MEBs for traction								
MEB for low friction								
Hi T Dispersants	7	5	8	5	C		10	
Hi T Oxid. inhibitors	7	5	8	5	C		9	

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics								
Ashless Anti-wear	7	5	8	5	C		11	
Additives for coatings								
Multi-func-tional add.								
Time-release additives								
Additive-add. Interactions								
Anti-oxidant mechanisms	7	3	7	4	D	9		1
Anti-wear mechanisms	6	6	2	3	D	10		2
Other projects								
Lube for EGR & No_x red additives & fuel	10	10	10	10	A		5	
HDD cam RCF life	10	8	8	8	B		4	3
Fuel lubricity additives	10	8	10	10	A	3	3	5
Extended drain (diesel)	9	8	10	8	B	4	6	

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Cummins

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Bench tests and predictive models that correlated with existing near future engines.

2. Same question as 1, the time frame is 5-10 years.
Mechanisms and design logic for bench tests.

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
High temp. lubricants and long term lube performance (long drain oil)

5. Same question as #4, but any project or area.
Cost effective manufacturing processes like ceramics machining, CBN superfinish of bearings, etc.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Yes. But true cooperation has to be achieved.

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears								
Transmission								
CVT								
Long drain	10	10	10	10			1	
Friction reduction								
Light Wt. materials								
New mat'ls lub. chem.	8	7	7	8		2	3	
Alternative fuel lub.	8	8	8	8		1	1	
R-134a lubrication								
Heavy duty diesel								
Ceramics lub. chem.								
lub. applica-tion maps	5			5		3		
Coatings lub.	10	6	6	8			1	

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	8	5	10	8		2	1	2
Liq. lub. for Hi Temp Eng	10	5	5	5		1	2	
Alter. fuelled engines								
valves for natural gas engines								
Million miles engine	10	6		8			1	
Advanced materials lub.	10	5	5	5		2		
Biodegradabl e lubricants								
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	10			2		1		
MEBs for traction								
MEB for low friction								
Hi T Dispersants	8	5	5	8		6		
Hi T Oxid. inhibitors	8	5	5	8		7		

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics	5	5	5	5		8		
Ashless Anti-wear	7	7	5	7		9		
Additives for coatings	10	5	5	10			3	
Multi-func-tional add.								
Time-release additives	2			2				5
Additive-add. Interactions	10	6	6	10		4		2
Anti-oxidant mechanisms	10	5	5	8		3		
Anti-wear mechanisms	8	5	5	8		3		
HTLL	10	6	6	10		1	1	
Other projects								
Bench tests	5	5	5	8		2	2	2

Comments and suggestions:
We need good bench tests, good models and constant push from Government for tech. consolidation and foresee needs.

QUESTIONNAIRE II
LUBRICATION WORKSHOP Company Ethyl Corp.

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Relationship of additive chemistry to performance and CMA protocol testing.

2. Same question as 1, the time frame is 5-10 years.
Raising the thermal/oxidative stress ceiling of lubricants through novel chemistry and formulation technology.

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
Question 1

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
Antioxidant and antiwear mechanisms.

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
High temperature lubricants consortium.

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears					E			
Transmission					B			
CVT					F			
Long drain					G			
Friction reduction					A			
Light Wt. materials					C			
New mat'ls lub. chem.					H			
Alternative fuel lub.					D			
R-134a lubrication								
Heavy duty diesel								
Ceramics lub. chem.					F			
lub. applica-tion maps								
Coatings lub.					G			

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control					B			
Liq. lub. for Hi Temp Eng					C			
Alter. fuelled engines					A			
valves for natural gas engines					D			
Million miles engine					E			
Advanced materials lub.					I			
Biodegradabl e lubricants					H			
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	5	5	5	1	I			
MEBs for traction								
MEB for low friction								
Hi T Dispersants	9	8	5	5	D		X	
Hi T Oxid. inhibitors	8	6	5	5	E			

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics	2	3	3	1	K			
Ashless Anti-wear/no metals but <u>with P</u>	7	9	10	7	C			
Additives for coatings	5	5	5	4	H		X	
Multi-func-tional add.	6	4	4	6	G			
Time-release additives								
Additive-add. Interactions	8	7	5	5	F		X	
Anti-oxidant mechanisms								
Anti-wear mechanisms								
Additive Mechanisms	10	8	8	10	B	X	X	X
Hi temp. lube.	10	7	10	10	A			
Other projects								

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP Company Ethyl Corp.

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Increase high temperature performance of lubricants

2. Same question as 1, the time frame is 5-10 years.
Same, but new materials may

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
High temp lubs - little chance of chemical cooperation on proprietary additives
Spirit and good will - ceramic lubrication and working with OEM's
Financial support - very unsure of this

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
If my management will agree to participate in a meaningful manner with cost sharing. Once or twice.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Yes

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears	7	5	5	7	D		X	
Transmission	8	5	5	8	C		X	
CVT	4	4	4	4	P		3	
Long drain	7	7	7	7	E		6	
Friction reduction	7	8	8	7	F		7	
Light Wt. materials	4	5	5	4	I		5	
New mat'ls lub. chem.	4	5	5	4	H	5		
Alternative fuel lub.	4	4	4	4	O		4	
R-134a lubrication	5	2	10	5			5	
Heavy duty diesel								
Ceramics lub. chem.	3	5	5	3	K	3		
lub. applica-tion maps	3	3	3	3	L		3	
Coatings lub.	5	5	4	4	J		4	

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	5	8	7	8	C		7	
Liq. lub. for Hi Temp Eng	9	9	9	8	C		9	
Alter. fuelled engines	6	6	6	6	L		6	
valves for natural gas engines	7	7	7	7	H		7	
Million miles engine	7	7	7	7	E		7	
Advanced materials lub.	5	5	5	5	N		5	
Biodegradabl e lubricants	4	4	4	4	U			4
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	2	2	2	2	Z			2
MEBs for traction	2	2	2	3	Y			2
MEB for low friction	3	3	3	3	X			3
Hi T Dispersants	10	9	9	10	A		10	
Hi T Oxid. inhibitors	9	8	8	9	B		9	

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics	5	5	5	5	M		5	
Ashless Anti-wear	2	2	2	2	2	2		
Additives for coatings	3	3	3	3	T			3
Multi-func-tional add.	7	7	7	7	P		7	
Time-release additives	4	4	4	4	R			4
Additive-add. Interactions	10	4	4	4	Q			4
Anti-oxidant mechanisms add	4	4	4	4	R	4		
Anti-wear mechanisms	3	2	2	3	S			3
Hi temp lube	10				A			
Other projects								

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Ford Motor Company

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
For automotive engines, fuel economy (friction reduction), emission control and reduction, engine durability, weight reduction, and manufacturing cost. Optimum engine component design information consider; the above requirements.

2. Same question as 1, the time frame is 5-10 years.
3-D CFD (computational fluid dynamics) piston (piston ring lubrication and oil consumption analyses. Interaction of burned gas with oil in combustion chamber/ring crevice volumes, and the related power generation, emission, oil consumption problems. Optimum 3-D combustion chamber, piston assembly... design information maximizing fuel economy, life of the engine ...etc.

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
- *3-D engine lubrication/combustion/part flow analyses and validation.*
- *Improved friction/wear bench test techniques performing simulated tests satisfactorily and effectively*

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
Need a copy of project list.

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
Yes, once a year

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Yes, would like to join the consortium

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears	8	5	5	5		6	7	3
Transmission	8	8	5	7	E	4	5	5
CVT	8	9	5	8	D	3	4	4
Long drain	5	5	8	8	C	0	3	0
Friction reduction	10	10	8	8	A	1	1	1
Light Wt. materials	10	8	8	8	B	2	2	2
New mat'ls lub. chem.	9	8	9	7	F	5	6	6
Alternative fuel lub.	8	10	9	9	?			
R-134a lubrication	8	5	10	7	?			
Bench test								
Heavy duty diesel								
Ceramics lub. chem.					F	6		4
lub. applica-tion maps	8							
Coatings lub.					D	4	6	5

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	8		10	5	E	5	7	
Liq. lub. for Hi Temp Eng	8		8		B	2	4	3
Alter. fuelled engines	7	8	8	5				
valves for natural gas engines					?			
Million miles engine	8	10	10	7	A	1	3	
Advanced materials lub.	7	7	5	5	C	3	1	1
Biodegradabl e lubricants	8	7	10	5	G	7	2	2
Lubricant/ additives	9	9	9	8				
Molecular Engineered Basestocks (MEB)								
MEBs for traction								
MEB for low friction	5							
Hi T Dispersants								
Hi T Oxid. inhibitors								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics								
Ashless Anti-wear	7	8	8	7				
Additives for coatings								
Multi-func-tional add.	8	7		8				
Time-release additives								
Additive-add. Interactions								
Anti-oxidant mechanisms								
Anti-wear mechanisms	8	8	8	5				
Other projects								
3-D engine	10	8	?	?	A	?	?	?
Lubrication modelling								

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company General Motors

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Coatings for wear resistance
High temperature lubes
Better basic understanding of tribology/additives

2. Same question as 1, the time frame is 5-10 years.
Same as 1

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
Tribology in high power density gearing
Understanding the role of surface finish in concentrated contacts

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
There is no problem in gear technology today. GM could potentially collaborate/support such a problem. Other topics are not of interest.

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
They are necessary to start new projects. Most of those discussed have been in place for a long time. If an appropriate "general" project can be identified GM would participate.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Yes - gears

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears	8	5	5	8	A			
Transmission								
CVT	4	4	4	4	C			
Long drain								
Friction reduction								
Light Wt. materials								
New mat'ls lub. chem.	8	5	5	8	B			
Alternative fuel lub.								
R-134a lubrication								
Heavy duty diesel								
Ceramics lub. chem.								
lub. applica-tion maps								
Coatings lub.								

QUESTIONNAIRE II
LUBRICATION WORKSHOP Company General Motors

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Finding lubricants for new materials.
Finding suitable test methods for lubricants & materials.

2. Same question as 1, the time frame is 5-10 years.
Finding appropriate materials for future applications.

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
1. Emissions/ecology
2. Maybe/maybe not.

4. The workshop has supplied a list of projects with brief description, of the projects listed, *(1)* which one(ones) you like the most? *(2)* Which one you would support in spirit and good will? *(3)* Which one you would support politically? *(4)* Which one you would be willing to collaborate with? *(5)* Which one you would be willing to support financially?
(1)(2) Oil degradation models
(3) Hard to say
(4) Hard to say
(5) Realistically, funding is not available at the present time.

5. Same question as #4, but any project or area.
Same as 4.

6. *(1)* What are your reaction to workshop of this type? *(2)* Will you be willing to participate in the follow- up activities such as working group on a specific topic? *(3)* Once a year? *(4)* Twice a year? *(5)* Four times a year?
(1) Some interesting information
(2) Maybe/maybe not
(3) Maybe (every other year is probably better
(4) No
(5) No

7. *(1)* After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? *(2)* If yes, will you joint such consortium?
(1) Hard to say, probably not
(2) Hard to say, probably not

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Ran	G	I	U
Automotive	?	?	?	?				
Gears	0	1	1	0	J	10	9	9
Transmission	2	2	1	1	I	10	5	
CVT	maybe 2	3	2	2	E	10	3	
Long drain	probably 5	2	8	5	F	10	3	
Friction reduction	5	8	5	5	E	10	2	5
Light Wt. materials	4	8	8	5	E	9	2	5
New mat'ls lub. chem.	4	2	2	4	G	8	5	5
Alternative fuel lub.	0	?	4	2	J	10	5	
R-134a lubrication	8	2	10	10	B	9	1	
Heavy duty diesel								
Ceramics lub. chem.								
lub. applica-tion maps								
Coatings lub.								

Research Topics	Competitiveness	Energy Conservation	Environmental Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control								
Liq. lub. for Hi Temp Eng								
Alter. fuelled engines								
valves for natural gas engines								
Million miles engine								
Advanced materials lub.								
Biodegradable lubricants								
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	1							
MEBs for traction	1							
MEB for low friction	5							
Hi T Dispersants	1							
Hi T Oxid. inhibitors	2							

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Harrison Div/GMC

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Emissions reduction
Better bench tests

2. Same question as 1, the time frame is 5-10 years.
Better fuel economy - lowered CO_2 to reduce greenhouse effect

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
Better lubricants for compressor for A/C systems.

4. The workshop has supplied a list of projects with brief description, of the projects listed, *(a)* which one(ones) you like the most? *(b)* Which one you would support in spirit and good will? *(c)* Which one you would support politically? *(4)* Which one you would be willing to collaborate with? *(e)* Which one you would be willing to support financially?
Automotive
- *R134-a Lube - (a), (b), (c), (d)*
- *1*

5. Same question as #4, but any project or area.
Bench test development - (a), (b), (c), (d)

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
These workshops are a good idea, if some sort of consensus can be developed as to what action is required and how to go about it. I think twice a year is good, if the group is really "empowered" and can influence direction and events.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
I still have doubts that a lubricants consortium would be effective because there are so many diverse interests and needs. A consortium would have to be so generic that I don't believe real progress could be made. I believe significant effort should be placed on focused goals with a defined and relatively short period for their accomplishment. I think the objective is implementation of results of R&D work.

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears	1	2	1	1	J		10	
Transmission	5	7	5	5	C		4	
CVT	3	5	5	3	I		8	
Long drain	7	1	3	3	G		9	
Friction reduction	4	6	5	5	D	3	3	2
Light Wt. materials	7	7	5	5	F	6	5	
New mat'ls lub. chem.	5	5	5	4	G	5	7	4
Alternative fuel lub.	7	7	7	4	A	1	1	1
R-134a lubrication	7	5	7	4	B	2	2	
Antiwear mechanisms	6	4	4	8	E	4	6	3
Bench tests								
Heavy duty diesel								
Ceramics lub. chem.								
lub. applica-tion maps								
Coatings lub.								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control								
Liq. lub. for Hi Temp Eng								
Alter. fuelled engines								
valves for natural gas engines								
Million miles engine								
Advanced materials lub.								
Biodegradabl e lubricants								
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	7							
MEBs for traction								
MEB for low friction								
Hi T Dispersants								
Hi T Oxid. inhibitors								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics								
Ashless Anti-wear								
Additives for coatings								
Multi-func-tional add.								
Time-release additives								
Additive-add. Interactions								
Anti-oxidant mechanisms								
Anti-wear mechanisms	6	4	4	8				
Other projects								

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Penn State

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
The development of meaningful laboratory tests that correlate with end use applications and demonstrate the physicla and chemical principles involved.

2. Same question as 1, the time frame is 5-10 years.
Same as 1.

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
Yes - reducing the time to move research findings into commercial applications. A group or consortium effort is essential and we continue to be interest in working with end use applications.

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
This is one of the better workshops I have participated in. I would participate in follow up activities if financially feasible.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Yes and yes.

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears								
Transmission								
CVT	5	5	5	5	5			
Long drain								
Friction reduction		x			H			
Light Wt. materials								
New mat'ls lub. chem.								
Alternative fuel lub.			x		B			
R-134a lubrication			x		D			
Solid lubes	5	5	5	5	5			
Heavy duty diesel								
Ceramics lub. chem.	4-5	4-5	4-5	4-5	I			
lub. applica-tion maps	3	3	3	3				
Coatings lub.	4-5	4-5	4-5	4-5				

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	8	8	8	8	C			
Liq. lub. for Hi Temp Eng	10	10	10	10	A			
Alter. fuelled engines	9	9	9	9	B			
valves for natural gas engines	6	6	6	6	G			
Million miles engine	5	5	5	5	5			
Advanced materials lub.	like ceramic lube				E			
Biodegradabl e lubricants	5	5	5	5	5			
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	4	4	4	4	4			
MEBs for traction	4	4	4	4	4			
MEB for low friction	4	4	4	4	4			
Hi T Dispersants	5	5	5	5	5			
Hi T Oxid. inhibitors	5	5	5	5	5			

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics		5		5	F			
Ashless Anti-wear	8	8	8	8	J			
Additives for coatings								
Multi-func-tional add.	8	8	8	8	8			
Time-release additives	4	4	4	4	4			
Additive-add. Interactions	4	4	4	4	4			
Anti-oxidant mechanisms	5	5	5	5	5			
Anti-wear mechanisms	8	8	8	8	8			
Other projects								
Engine correctable bench wear test	9	9	9	9	A			
Vapor phase lube	9	9	9	9	9			
Univ engine lube	8	8	8	8	8			
Soot generation interactions	8	8	8	8	8			
Air cond. monitoring	5	5	5	5	5			
Fuel lub add	8	8	8	8	8			

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Ricardo North America

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
   - *oil consumption mechanism - understanding modeling, component design*
   - *lub between bench tests - engine tests*
   - *extended oil interval*
   - *onboard man hours*
   - *lubricant bench test*
   - *fuel ignition durabiliy - NG, diesel*

2. Same question as 1, the time frame is 5-10 years.
   - *high temp lub - additives*
   - *universal engine oils/diesel/methanol/NG*
   - *vapor phase lubrication*
   - *lubricant tests for 1M mile equipment - piston engines*

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
   - *oil consumption mechanisms*

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
   More frequently for smaller groups.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
   Yes

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears	4	4	3	3	E		X	
Transmission	5	4	4	3	E		X	
CVT	6	4	4	4	E		X	X
Long drain	8	2	9	7	B	X	X	
Friction reduction	6	7	6	6	B		X	X
Light Wt. materials	7	6	6	5	B	X	X	
New mat'ls lub. chem.								
Alternative fuel lub.	6	7	7	5	C	X	X	X
R-134a lubrication	6	2	9	1	B	X	X	
Fuel ignition durability	8	7	9	6	A	X	X	
Heavy duty diesel								
Ceramics lub. chem.	7	7	5	5	C	X		X
lub. applica-tion maps	6	6	6	5	C	X		X
Coatings lub.	7	7	5	5	C	X	X	

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	7	5	8	5	B	X	X	X
Liq. lub. for Hi Temp Eng	7	6	6	5	B	X	X	
Alter. fuelled engines	7	7	8	7	A	X	X	
valves for natural gas engines	7	6	6	6	B	X	X	
Million miles engine	8	5	5	6	C	X	X	
Advanced materials lub.	8	6	6	5	B	X	X	X
Biodegradabl e lubricants	8	4	9	5	B	X	X	X
Univ eng oil	8	6	7	8	A	X	X	X
Extended oil change	8	5	8	8	A	X	X	X
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	7	5	5	6	C	X	X	X
MEBs for traction								
MEB for low friction								
Hi T Dispersants								
Hi T Oxid. inhibitors								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics								
Ashless Anti-wear	8	4	6	7	B			
Additives for coatings								
Multi-func-tional add.								
Time-release additives								
Additive-add. Interactions								
Anti-oxidant mechanisms								
Anti-wear mechanisms								
Other projects								
Oil consumption mechanisms	8	6	8	5	B	X	X	X
Bench test/engine test corr.	7	5	5	8	C	X	X	X
Modeling: 1-component/ engine 2-lubricant 3-wear mech	8	7	6	6	B	X	X	X

Comments and suggestions:

QUESTIONNAIRE II
LUBRICATION WORKSHOP

Company Southwest Research Inst.

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Lubricants compatible with alternate fuels
Database on new materials and lubricants
Emissions reduction

2. Same question as 1, the time frame is 5-10 years.
High temp lubricants

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
Lubricants for alternative fuelled engines. Yes.

4. The workshop has supplied a list of projects with brief description, of the projects listed, *(a)* which one(ones) you like the most? *(b)* Which one you would support in spirit and good will? *(c)* Which one you would support politically? *(d)* Which one you would be willing to collaborate with? *(e)* Which one you would be willing to support financially?
(a) Reduced emissions
(b) 1 million mile engine
(c) 1 million mile engine
(d) a. and b.
(e) None - not for profit organization

5. Same question as #4, but any project or area.
Same answer as # 4

6. What are your reaction to workshop of this type? *(a)* Will you be willing to participate in the follow- up activities such as working group on a specific topic? *(b)* Once a year? *(c)* Twice a year? *(d)* Four times a year?
(a) Yes
(b) Yes
(c) No
(d) No

7. After the workshop and the discussions, *(a)* do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? *(b)* If yes, will you joint such consortium?
(a) No
(b) No

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears	2	2	-	2	D	5	4	5
Transmission	2	2	-	2	D	5	3	5
CVT	4	8	6	1	A	5	2	5
Long drain	2	6	4	3	B	5	4	5
Friction reduction	6	10	4	3	A	3	1	2
Light Wt. materials	6	8	4	4	B	2	1	1
New mat'ls lub. chem.	2	4	4	0	C	2	2	3
Alternative fuel lub.	2	4	8	2	B	3	4	5
R-134a lubrication	2	0	6	2	C	3	4	3
Heavy duty diesel								
Ceramics lub. chem.	2	1	2	2	E			
lub. applica-tion maps	2	1	2	2	E			
Coatings lub.	2	2	2	2	E			

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control	2	-	10	2	A			
Liq. lub. for Hi Temp Eng	6	3	2	2	C			
Alter. fuelled engines	2	5	8	2	A			
valves for natural gas engines	5	5	6	2	B			
Million miles engine	2	3	2	3	D			
Advanced materials lub.	2	3	2	2	D			
Biodegradable lubricants	2	3	8	2	B			
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)	6	6	8	5	A			
MEBs for traction	-	-	-	-	-			
MEB for low friction	8	9	6	7	A			
Hi T Dispersants	8	6	3	3	B			
Hi T Oxid. inhibitors	8	6	3	3	B			

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics	3	2	3	2	E			
Ashless Anti-wear	8	2	3	3	C			
Additives for coatings	4	2	3	2	E			
Multi-func-tional add.	6	2	3	2	D			
Time-release additives	6	2	3	2	D			
Additive-add. Interactions	?	2	3	2	?			
Anti-oxidant mechanisms	8	2	3	4	C			
Anti-wear mechanisms	8	2	3	4	C			
Other projects								

Comments and suggestions:

Limit to two days for this sort of activity.

QUESTIONNAIRE II
LUBRICATION WORKSHOP Company Wear Sciences

1. Based on the needs you heard fro m industry and based on your views, what are the most critical areas to address in the next 3-5 years?
Lube additive for high temp
Solid lubrication T≥ 500°C
Long drain olils
Self lubricating piston rings & other components

2. Same question as 1, the time frame is 5-10 years.
Modeling of tribological processes
Hi temp lubricants T≥ 400°C
Low friction materials

3. Is there any particular area that you think it is so important that you or your company will address it regardless of other? If so, would you be willing to work with others on the issued?
100°C solid lubricants for regenerator seals

4. The workshop has supplied a list of projects with brief description, of the projects listed, which one(ones) you like the most? Which one you would support in spirit and good will? Which one you would support politically? Which one you would be willing to collaborate with? Which one you would be willing to support financially?
Collaborate with tribomaterials development for high temperatures and solid lubricant

5. Same question as #4, but any project or area.

6. What are your reaction to workshop of this type? Will you be willing to participate in the follow-up activities such as working group on a specific topic? Once a year? Twice a year? Four times a year?
Once a year.

7. After the workshop and the discussions, do you favor the formation of a consortium linking the government, industry, and universities together to address the area of lubrication technologies? If yes, will you joint such consortium?
Yes

Please take a moment to examine the following projects/ideas. They are compiled for the purpose of starting the discussion. Please rank them on the scale of 0-10 (10 being the highest), and on the overall ranking column, assign a rating of A,B,C,E,E etc. (A being the highest priority). After you have done that, please supplement your ranking by G1, G2...I1, I2...U1, U2...(G stands for government, I for Industry, U for university, 1 being the highest priority)

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Automotive								
Gears								
Transmission								
CVT								
Long drain								
Friction reduction								
Light Wt. materials								
New mat'ls lub. chem.								
Alternative fuel lub.								
R-134a lubrication								
Heavy duty diesel								
Ceramics lub. chem.	7	3	5	5	A	X		
lub. applica-tion maps	9	3	3	8	A	X		
Coatings lub.	7	3	5	5	B		X	

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Liq. lub. for particulate control								
Liq. lub. for Hi Temp Eng	10	8	3	8	A	X		
Alter. fuelled engines								
valves for natural gas engines	5	5	9	5	B		X	
Million miles engine								
Advanced materials lub.	10	5	3	9	A	X		
Biodegradabl e lubricants								
Lubricant/ additives								
Molecular Engineered Basestocks (MEB)								
MEBs for traction								
MEB for low friction								
Hi T Dispersants								
Hi T Oxid. inhibitors								

Research Topics	Competitive-ness	Energy Conservation	Environmen-tal Impact	Economic Impact	Overall Ranking			
					Rank	G	I	U
Additives for ceramics								
Ashless Anti-wear								
Additives for coatings								
Multi-func-tional add.								
Time-release additives								
Additive-add. Interactions								
Anti-oxidant mechanisms								
Anti-wear mechanisms								
Other projects								
Modeling	8	7	7	8	A		X	X
Hi temp solid lubricants	3	7	8	9	A	X		

Comments and suggestions: