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ENGWEAR

DIESEL ENGINE LUBRICANT CONTAMINATION AND WEAR

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ABSTRACT

Diesel engine lubricant contamination is a major cause of engine component wear, leading to loss of engine performance and life. In addition, contamination accelerates breakdown of the engine lube oil, reducing its useful service life. Contaminant particles the size of or larger than the dynamic lubricant oil films separating moving component surfaces cause a major portion of diesel engine wear. The size of these harmful particles is 20 microns and smaller. This paper reviews the nature of diesel engine lubricant contamination, the primary modes of lubrication, and the mechanisms of engine wear. The relationship between contamination and wear of several major engine components is then discussed. In addition, the highlights of important diesel engine contamination studies are reported.

1.0 INTRODUCTION

The diesel engine is receiving increasing attention as a power plant because of its fuel efficiency and life advantages. Over seventy percent of the trucks manufactured today use diesel engines.

Major functions of lube oil include cooling, friction reduction, and wear control. The lube oil develops a lubricating film between moving surfaces, which reduces friction and wear. However, the engine oil is a depository of impurities. These are in the form of solid, liquid, and gaseous contaminants. If uncontrolled, these contaminants can build up to excessive levels. High levels of lubricant contamination cause wear of mechanical components as well as breakdown of the lube oil. The result is performance degradation, reduced engine life, and short oil service life.

This paper reviews the predominant forms of diesel engine oil contamination, the modes of lubrication, and the mechanisms of wear of engine components. The link between contaminant particle size and lubricating film thickness is established. Wear of diesel engine components is then reviewed, followed by a discussion of important diesel engine contamination wear studies.

2.0 DIESEL ENGINE LUBRICANT CONTAMINATION

2.1 TYPES OF CONTAMINANT

Lubricant contaminants degrade the life and performance of diesel engines. These contaminants fall into three categories:

1. Solid particles, including wear debris, which damage mechanical components and catalyze lubricant breakdown.
2. Liquid contaminants, including fuel and water, which hinder the proper operation of the lubricant and its additives.
3. Gaseous contaminants, including combustion products, which corrode component surfaces and break down the oil.

The predominant types of diesel engine oil contaminants, along with primary sources and major problems these impurities cause, are listed in Table 1.

Table 1

Contamination of Diesel Lube Oil

Type	Primary Sources	Major Problems
Metallic Particles	Engine Wear	Abrasion, Fatigue and Lubricant Breakdown
Metal Oxides	Engine Wear and Corrosion	Abrasion and Fatigue Corrosion
Sand and Dust	Combustion Blowby	Abrasion and Fatigue
Soot	Combustion Blowby	Lubricant Breakdown
Exhaust Gases	Combustion Blowby	Lubricant Breakdown
Fuel	Combustion Blowby	Lubricant Breakdown
Water	Combustion Blowby	Corrosion and Lubricant Breakdown
Acids	Combustion Blowby and Lubricant Breakdown	Corrosion

2.2 INGRESSION OF LUBRICANT CONTAMINATION

Contamination enters the engine lube system by four routes: 1) built-in from manufacture and assembly, 2) external ingression, 3) internal generation, and 4) maintenance actions.

2.2.1 BUILT-IN CONTAMINATION

Diesel engine manufacturers take great care during the manufacture and assembly processes to ensure high quality control. However, casting materials, machining swarf, abrasives, polishing compounds, and even lint remain after manufacture and overhaul. These built-in contaminants can rapidly damage moving engine parts.

2.2.2 EXTERNAL INGRESSION

External ingression is a major source of hard particle contamination. Airborne particles, in the form of sand, salt, and other minerals, enter through the engine intake system and mix with the atomized fuel, which is compressed and then burned. Since most of these particles have melting points considerably above the temperatures reached in the diesel combustion process, they remain hard abrasive solids. Airborne contamination has been shown to be the greatest cause of ring-to-cylinder wear (1).

The strong pressure shock wave created during combustion forces gases through the piston ring clearances. This process, known as blowby, carries particles into the engine oil. Particles may also be retained in the oil film. They are then wiped by the rings into the oil sump on the next down stroke of the piston.

Exhaust gases are similarly driven into the lube oil as blowby gases. These exhaust gases include unburned fuel, water, nitrous oxide, soot, and other partially burned hydrocarbons. Higher levels of exhaust gas recirculation have been shown to increase lube oil particulate contamination (2). New rules issued by the Environmental Protection Agency requiring stricter nitrous oxide and exhaust particulate controls take effect in 1988. Although new ceramic combustion technologies are under development to reduce exhaust gas particles, it is likely that these regulations will lead to higher percentages of exhaust gas recirculation, resulting in further deterioration of oil properties.

Other paths for external ingression of contaminants into the engine oil include crankcase breathers, which can admit large quantities of dust and water directly into the oil sump, and diesel fuels contaminated with particles. In addition, water combined with anti-freeze compounds such as glycol can be forced into the oil cavity under pressure through defective head gaskets, or, occasionally, through a crack in the block.

2.2.3 INTERNAL GENERATION

Internal generation of contaminants is by wear of mechanical component parts and by lubricant breakdown. Mechanical component wear from abrasion, fatigue, adhesion, and corrosion releases harmful particles into the oil. The wear debris is in the form of hard metal particles and of abrasive metal oxides. Wear debris particles of sizes not controlled by standard filtration can build up to grossly contaminate the lube oil. As shown in Figure 1, more than 99 percent of these particles are less than 20 microns in size.

Lubricant breakdown is the loss of important properties of the oil plus accumulation of harmful materials derived from the oil. These materials include acids, sludges, gels, and additive precipitates. These contaminants can wear moving component parts as well as clog flow passages and heat exchange surfaces.

If wear debris and materials from lubricant breakdown accumulate in the oil, the result is more wear, generating more contaminants. The process of particles wearing surfaces and generating new particles that in turn cause more wear is known as the chain-reaction-of-wear.

2.2.4 MAINTENANCE ACTIONS

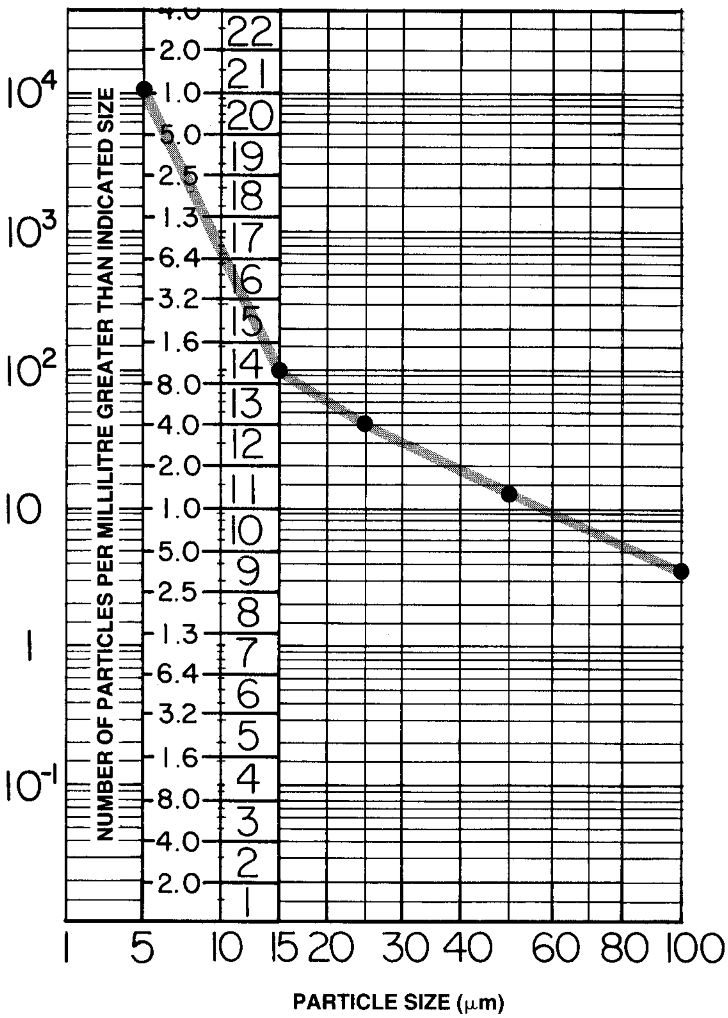
During maintenance activities contaminants are introduced into the lubrication system. Opening rocker covers, the engine head, even the oil filler cap allows entrance of dust and water. Simply making and breaking a fitting generates tens of thousands of damaging particles. In addition, new oil contains contaminant particles.

3.0 LUBRICATION IN DIESEL ENGINES

The lubricant performs a variety of important functions in diesel engines, including reducing friction, cooling, and minimizing wear of component surfaces. Lubrication of each component depends on the relative motion and on the lubrication mode developed between opposing surfaces.

Figure 1

TYPICAL CONTAMINATION LEVELS MAINTAINED BY STANDARD DIESEL ENGINE PAPER OIL FILTERS (ISO CODE: 21/14)



PARTICLE COUNT SUMMARY:

PARTICLES GREATER THAN SIZE SHOWN	NUMBER PER MILILITER
5 μm	10,671
15 μm	104.2
25 μm	41.7
50 μm	14.2
100 μm	3.7

3.1 RELATIVE SURFACE MOTION

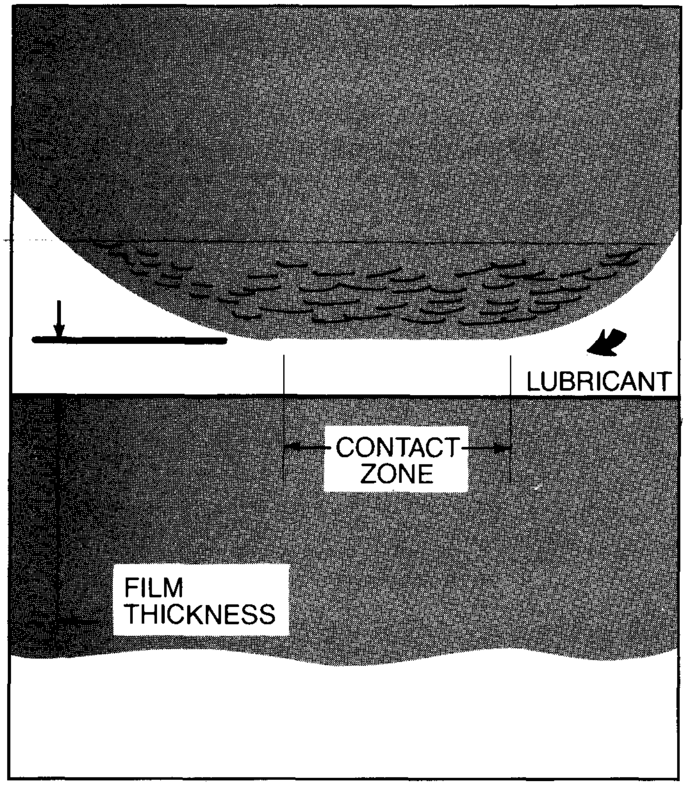
There are three types of relative motion which can take place between diesel engine component surfaces (3): rolling, sliding, and squeezing.

3.1.1 ROLLING CONTACT

Rolling contact takes place in ball and roller bearings and in gear drives. As shown in Figure 2, large compressive forces act between the component surfaces. The lubricant is swept into the contact zone by the rolling motion. Particles larger than the thickness of the lubricant film separating the opposing surfaces indent and pit the surfaces.

Figure 2

ROLLING CONTACT

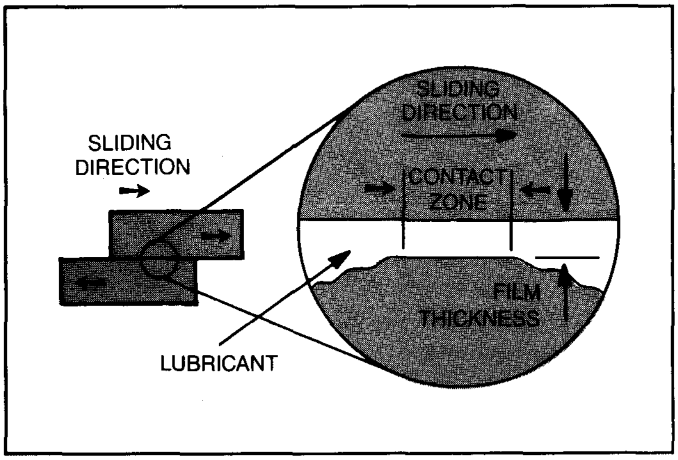


3.1.2 SLIDING CONTACT

Sliding contact takes place in journal bearings and ring-cylinder contacts. During sliding contact the lubricant is swept into the contact zone by the relative motion of the two surfaces, Figure 3. The presence of particles larger than the dynamic film thickness leads to severe abrasive wear. Hard particles cut away material from the component surfaces, with the simultaneous generation and release of new contaminant particles into the fluid.

Figure 3

SLIDING CONTACT

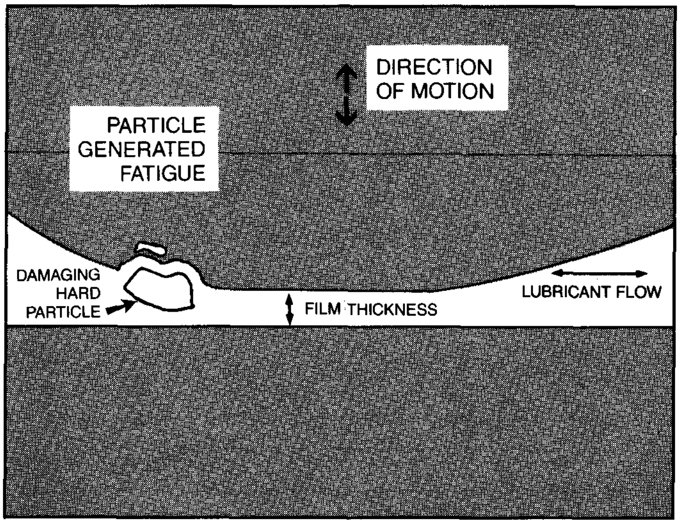


3.1.3 SQUEEZE CONTACT

Squeeze contact takes place because of linear forces and vibration. The valve-to-cam follower contact is a good example. In squeeze contact, Figure 4, motion perpendicular to the opposing surfaces forces lubricant in and out of the contact zone. Particles caught between the surfaces will roughen and dent the components. This leads to abrasive removal of material, fretting, and fatigue.

Figure 4

MECHANISM OF SQUEEZE CONTACT

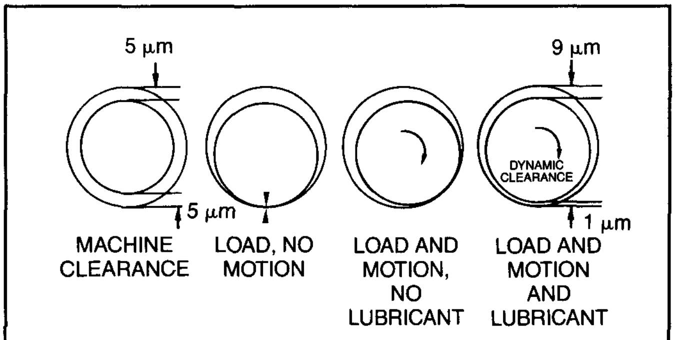


3.2 MODES OF LUBRICATION

In lubricated contacts, dynamic clearances are maintained by oil films between moving surfaces. The lubricant film thickness, as shown in Figure 5, is the distance between the two moving surfaces. Compressive forces (the load) act to push the moving surfaces together. Tangential forces (shear) tend to displace the surfaces horizontally. A film of oil supports the load between the opposing surfaces and keeps them separated. The thickness of the oil film is related to the mode of lubrication. There are three fundamental modes of lubrication: Hydrodynamic, Elastohydrodynamic, and Boundary. For all modes of lubrication, the oil film thickness is proportional to the viscosity of the fluid and to the relative speed of the two surfaces.

Figure 5

DYNAMIC CLEARANCES



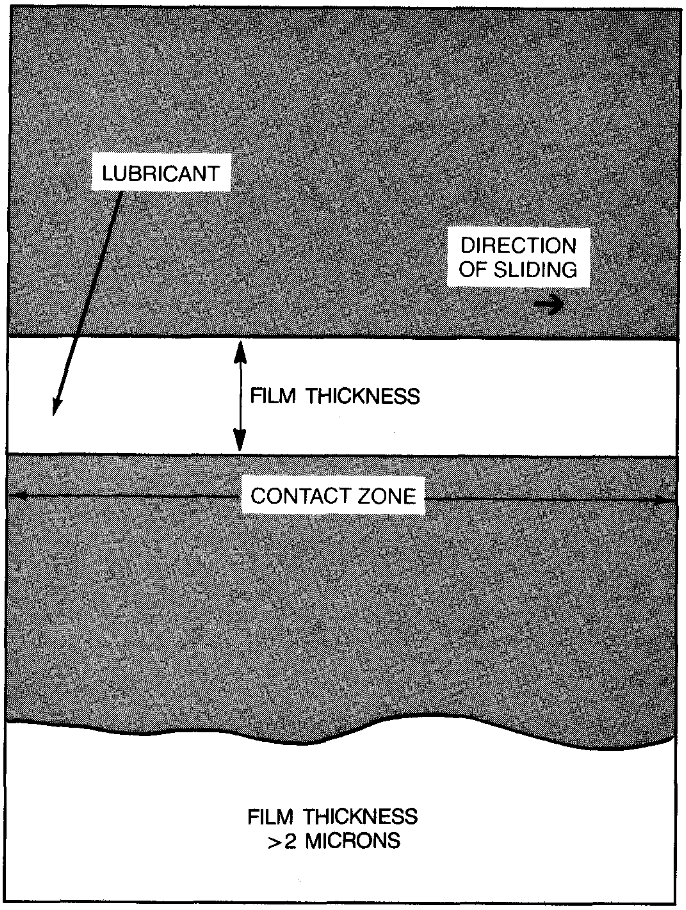
When two surfaces in relative motion are separated by a lubricant film, dynamic clearances are not equal to the machine clearances, but depend on load, rotational or linear speed, and oil viscosity.

3.2.1 HYDRODYNAMIC LUBRICATION

Under conditions of hydrodynamic lubrication the oil is swept into the contact zone by the relative motion of opposing surfaces. This is illustrated in Figure 6a. The lubricant film, usually larger than 2 microns, develops up to 50,000 psi pressure in the contact zone. This pressurized film supports the load between component surfaces. There is little or no deformation of the component surfaces in the contact zone. Studies show that wear rates and particle generation are less when the ratio of film thickness to surface roughness (average height of asperities) is greater than three to one. Under these circumstances, mechanical surface wear is negligible unless solid particles the size of or larger than the oil film thickness are present.

Figure 6a

HYDRODYNAMIC LUBRICATION



3.2.2 ELASTOHYDRODYNAMIC LUBRICATION

Under conditions of elastohydrodynamic lubrication the oil is swept into a highly loaded concentrated contact, Figure 6b. Film thickness varies between 0.05 and 2 microns. In the contact zone there is considerable elastic deformation of the surfaces. The fluid film at the contact zone develops as much as 350,000 psi pressure. This extreme pressure greatly increases the viscosity of the oil within the contact zone. The high pressure in the contact zone causes solid particles the size of or larger than the lubricant film to indent or furrow deeply into the component surface.

3.2.3 BOUNDARY LUBRICATION

Figure 6c illustrates the conditions that exist during boundary lubrication. Low speeds, high loads, and squeeze contact between component surfaces can starve the contact zone of lubricant. In addition, start up, shutdown, and high temperature thinning of the oil are duty cycle conditions that can lead to oil starvation. The remaining lubricant film between the surfaces is 0.001 to 0.05 microns thick. High stress or heat at the asperity contact sites may displace this boundary layer of lubricant, leading to adhesive wear. Because of the extremely thin film, very fine particles can cause surface damage.

It is important to note that a component can shift between the three modes of lubrication several times during a single duty cycle.

Figure 6b

ELASTOHYDRODYNAMIC LUBRICATION

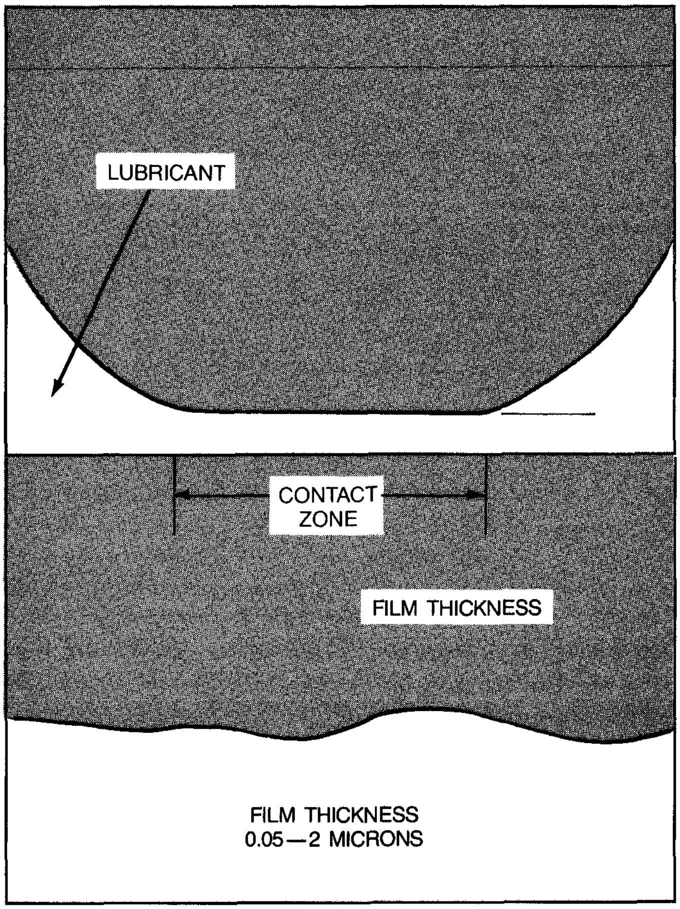
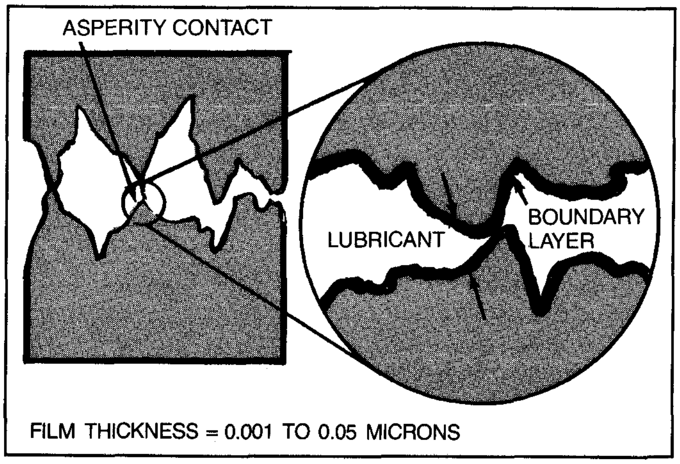


Figure 6c

BOUNDARY LUBRICATION



4.1 WEAR AND CONTAMINANT PARTICLE SIZE

There is an important relationship between the size of contaminant particles and the thickness of dynamic lubricant films separating opposing surfaces. Particles the size of and larger than the lubricant film thickness cause wear of component surfaces. These particles bridge the gap maintained by the oil film, making simultaneous contact with both surfaces. This focuses the force between the surfaces, causing damage and resulting in component wear.

An extensive survey of the technical literature for oil film thicknesses in diesel engine components is summarized in Table 2. Most of these dynamic clearances are between 0 and 20 microns. Contaminant particles the size of or larger than these dynamic clearances produce a major portion of the wear experienced by diesel engine oil wetted components.

TABLE 2
DIESEL ENGINE COMPONENT OIL FILM THICKNESSES

Component	Oil Film Thickness (microns)
Ring/Cylinder	0.3 -7
Rod Bearings	0.5 - 20
Main Shaft Bearings	0.8 - 50
Turbocharger Bearings	0.5 - 20
Piston Pin Bushing	0.5 - 15
Valve Train	0 - 1.0
Gearing	0 - 1.5

As a demonstration of the link between contaminant particle size and oil film thickness, the results of a diesel engine wear test by Cummins Engine Company (4) are summarized in Table 3. In this test contaminant particles in different size ranges were evaluated for effect on engine wear. It was demonstrated that particles the size of the dynamic oil clearances produced the most diesel engine wear. Even contaminants containing large particles up to 80 microns did not cause as much damage as did contaminants with particles concentrated in the 0 to 10 micron size range.

TABLE 3
EFFECT OF CONTAMINANT SIZE ON WEAR

Dust Size (µm)	Wear Rate (mg/hr)			Wear	
	Mains	Rod	Rings	Total	Relative
0-5	11.9	14.4	28.4	54.7	3.34
5-10	16.1	20.0	23.6	59.7	3.64
0-80	6.2	5.1	14.5	28.8	1.76
10-20	7.4	4.6	4.4	16.4	1.00

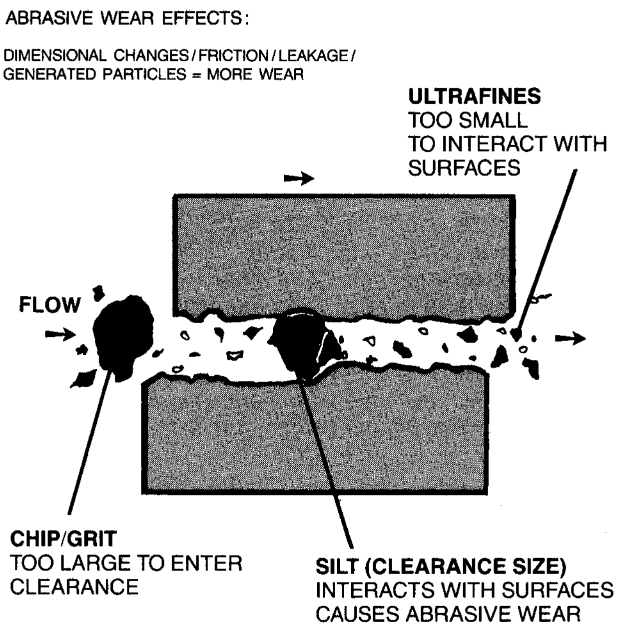
4.2 MECHANISMS OF WEAR

There are five forms of wear that occur in diesel engine components: abrasion, fatigue, adhesion, corrosion, and lubricant breakdown. Abrasion, fatigue, and adhesion involve mechanical damaging of surfaces; corrosion and lubricant breakdown involve chemical reactions.

4.2.1 ABRASION

Abrasive wear by contaminant particles involves the rapid cutting away of component material. As shown in Figure 7, an abrasive particle abutting one surface slides along and ploughs through the opposing surface. Material is cut away in a single pass. The rate of abrasive wear is proportional to the number of contaminant particles the size of or larger than the dynamic lubricant film. The results of abrasive wear are: roughened surfaces, loss of clearance, misalignment, and generation of fresh wear debris. Particles generated from this process are similar to microscopic machine chips. These particles add to the oil contamination and accelerate the chain-reaction-of-wear.

Figure 7
ABRASIVE WEAR



Abrasive wear is the primary wear mechanism. Particles enter the clearance between two moving surfaces, bury themselves in one of the surfaces, and act like cutting tools to remove material from the opposing surface. The size of particles causing the most damage are those equal to and slightly larger than the clearance. Most diesel engine components have dynamic clearances less than 20 micrometres. To protect opposing surfaces from abrasive wear and fatigue, particles of approximately this clearance size range must be removed.

4.2.2 FATIGUE

Fatigue of a component surface is due to an accumulation of microscopic cracks at or just below the component surface. These cracks accumulate over an operating period, eventually combining to form voids which undermine the surface. Large quantities of material then break away, leaving a cratered surface and releasing work hardened particles into the oil which continue the chain-reaction-of-wear. As shown in Figure 8, by focusing the force between loaded surfaces, particles larger than the lubricant film dent and crack the surfaces. For component surfaces in rolling or squeeze contact, surface fatigue caused by particles may be the primary wear mechanism.

4.2.3 ADHESION

Adhesive wear occurs when the boundary layer lubricant film between the asperities of two opposing surfaces is displaced. This is shown in Figure 9. Metal-to-metal contact between surfaces can lead to spot welding of these asperities. As the asperities of the moving surfaces part, the microscopic spot welds often break asymmetrically, removing material from the surface with the lower yield strength.

The result is high friction, wear, and heat generation. If a large number of spot welds are produced simultaneously, the surfaces can no longer move apart and seizure occurs. Degradation of surfaces by particles, such as roughening and misalignment, can lead to surface-to-surface contact and adhesive wear.

Figure 8

FATIGUE

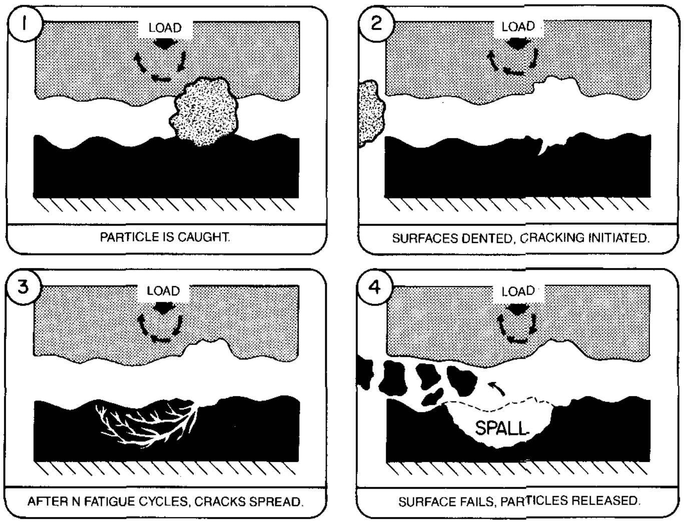
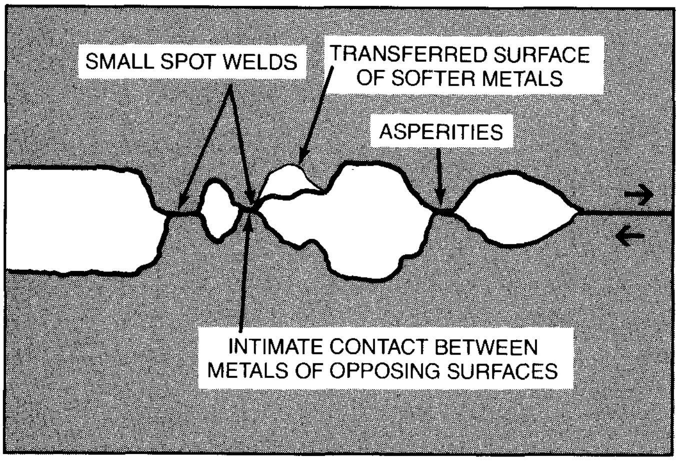


Figure 9

MECHANISM OF ADHESION



4.2.4 CORROSION

Corrosion is a reaction between aggressive chemicals and component surfaces. Aggressive chemicals include water, dissolved oxygen, and NO_X from the combustion gases. Two mechanisms by which corrosion degrades surfaces are: 1) the reaction products dissolve in, and are removed by the lubricant, and 2) the reaction products form a brittle crust, often of abrasive metal oxides, which breaks away from the surface. Particles from these corrosion crusts add to the lubricant contamination, accelerating the chain-reaction-of-wear.

Corrosion is often accelerated on surfaces damaged by contaminant particles. These worn surfaces have cracks that allow corrosive chemicals to penetrate through protective surface films and react with the underlying material.

4.2.5 LUBRICANT BREAKDOWN

Lubricant breakdown is the loss of important oil properties, such as viscosity, and the build-up of harmful materials derived from the lubricant. Lubricant breakdown can be caused by several mechanisms. Fuel and water can mix with the lubricating oil to form precipitates and gels. Soot particles, carried into the lubricant with blowby gases along with wiping of the piston-rings, can combine with anti-wear and viscosity additives in the oil to reduce wear tolerances(5) and increase viscosity(6). It has been shown that particles of fresh wear debris have catalytic surfaces that accelerate oil oxidation. Oxidation of the oil leads to varnishes, sludges, and increased oil acidity.

5.0 DIESEL ENGINE COMPONENT WEAR

5.1 LUBE OIL

The lube oil is one of the most important engine components. Breakdown of the lubricant, as discussed in Section 4.2, can be caused by contamination. Metallic wear particles accelerate oil oxidation, resulting in sludges and oil acidity. Soot, a product of incomplete fuel combustion, is similar to lamp black (7). By virtue of its tremendous total surface area, soot can leach out additives from the engine oil. At high concentration levels, soot can aggregate and precipitate, fouling flow passages and working clearances. This process is aggravated by water and fuel contamination.

In the engine filtration field test discussed in Section 6.1, oil cleanliness was maintained by various levels of filtration. For those engines in which particle contamination was maintained at low levels, oil service life was more than doubled.

5.2 PISTON-RINGS/CYLINDER

The piston-rings have a reciprocal sliding motion. The outside of most piston-rings is rounded and chrome-plated to produce the best oil film thickness and wear resistance.

As the pistons start to move in the cylinders, a hydrodynamic oil film is formed between the ring and cylinder surfaces which helps to prevent wear.

When there is little or no relative motion between the rings and the cylinder (e.g. prior to start and at top and bottom dead center), the fluid film is thin (See Figure 10) (8). This is when wear will most likely occur, since the oil is being squeezed from the contact area.

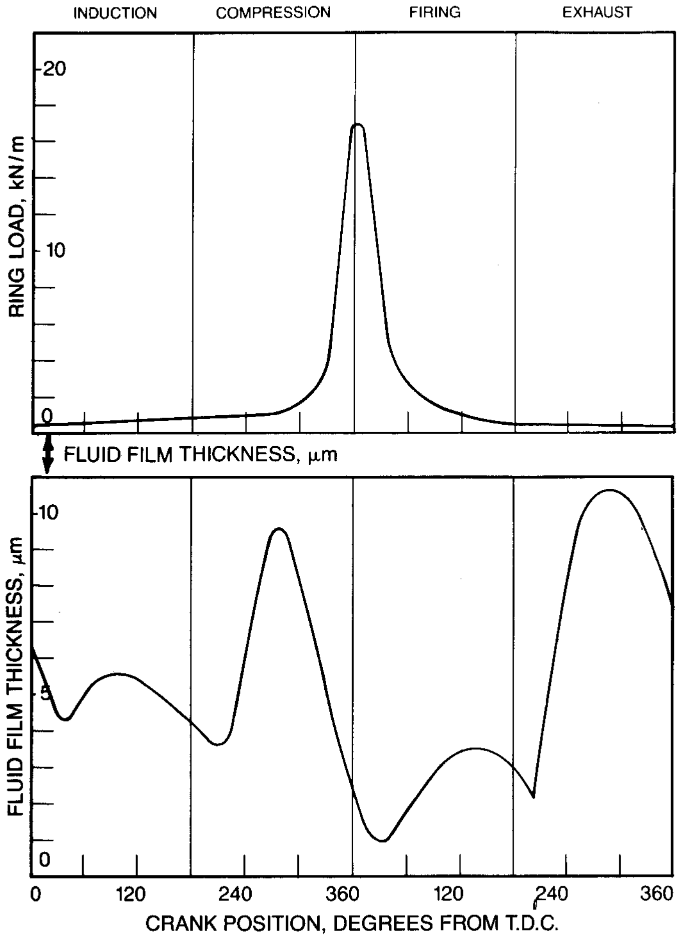
When the piston reaches the bottom of its travel, the walls of the cylinder are completely exposed to the high temperatures and products of combustion, as well as to contaminant particles ingressed with the air and fuel. The thin layer of lube oil left by the previous pass of the piston may also become partially oxidized. Deposits formed are either expelled in the exhaust on the upstroke or are swept into the oil sump by the piston rings on the downstroke. When the piston reaches the top of its stroke, new oil is splashed or sprayed onto the walls of the cylinders washing a portion of the previously contaminated oil film into the sump.

If the combustion by-products and particulate contamination drawn in with the air and fuel bridge the oil film between the ring and cylinder, wear occurs. Wear particles can also be supplied to the contact areas by contaminants already present in the oil. The major sources of these contaminants are prior blowby, lubricant breakdown, and component wear. Particles generated by wear between piston-ring and cylinder range up to 30 microns in size and are work-

Figure 10

PREDICTED RING LOADS AND FILM THICKNESSES BETWEEN PISTON RING AND CYLINDER OF AN AV1L DIESEL ENGINE

NOTE: LOAD IS GREATEST WHERE FILM THICKNESS IS LEAST



hardened. These particles are abrasive to other engine components as well as to the rings and cylinders.

5.3 PISTON SKIRT/CYLINDER

Contact between the piston skirt and the cylinder or liner is often overlooked as a form of wear. Scuffing can occur between these two parts during cold starts and other severe operating conditions, Figure 11 (9). Particles generated by this type of contact are quite abrasive as a result of work hardening and can range in size from silt to 60 microns and larger. These metal particles contribute to the chain-reaction-of-wear, causing extensive damage if not controlled.

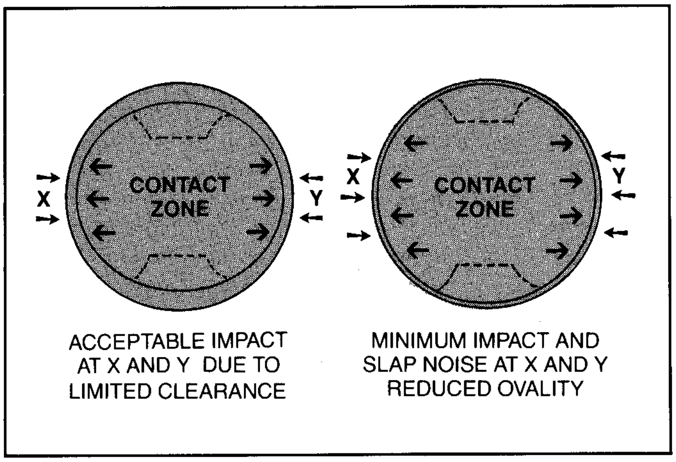
5.4 VALVE TRAIN

The valve train functions to open and close the intake and exhaust ports to the combustion area at a specified time. The rotational sliding speed and high lifting loads between the cam lobes and follower cause lubrication problems. In many diesel engines, this cam-to-follower interface receives the heaviest wear because of low oil film thicknesses. Extremely small particles circulating in the lube oil can bridge the space between the surfaces and cause wear.

Location of the valve train at the top of the engine also generates extensive carbon deposits due to heat. These carbon deposits have been shown to adversely affect the anti-wear additives in the oil.

Figure 11a

PISTON CYLINDER CONTACT

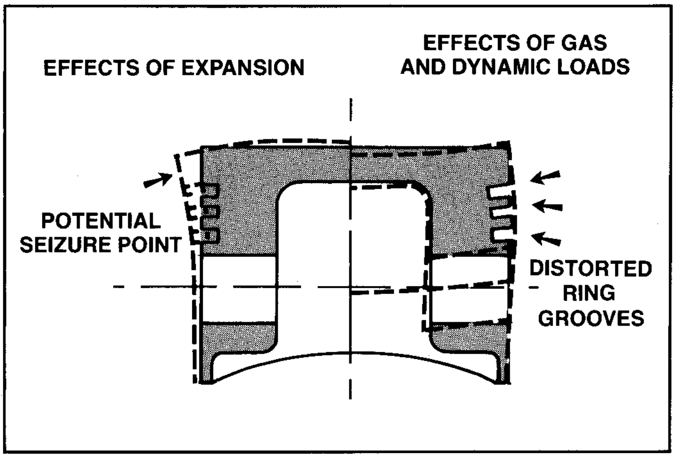


Stiction of the valve in the valve guide can lead to extensive power loss. Stiction is produced by carbon deposits and hard particles lodged between the valve and guide. This causes the timing of the port openings and closings to vary, causing incomplete combustion in the cylinder as well as combustion in the exhaust manifold (backfiring). Even if stiction is temporary, permanent power loss can result from a burnt valve seat.

Rocker arms and followers are often supported by plain bearings. These bearings are lightly loaded and have restricted movement. However, high temperatures and poor lubrication produce small lubricant film thickness and lead to severe abrasive wear problems (scoring). Under cold start conditions, the lube oil can take several minutes to reach these rocker arm bearings, further reducing film thickness.

Figure 11b

PISTON DEFORMATION



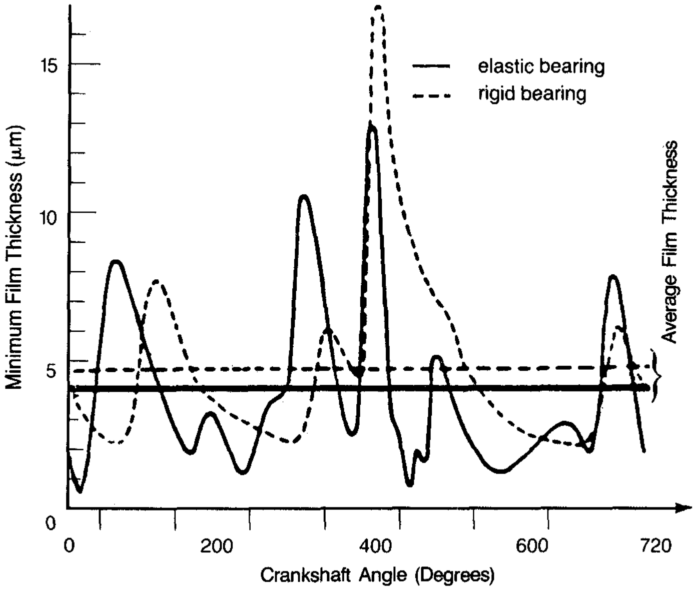
5.5 PLAIN BEARINGS

Plain bearings are used to support the cam and main drive shafts and to transmit the power delivered to the drive shaft by the piston and rods. Average oil film thicknesses are approximately 4-5 microns as shown in Figure 12 (10). Plain bearings are also used on many accessories, such as turbo-chargers and oil pumps. Another form of plain bearing is the thrust bearing used in turbo-chargers. This sliding contact bearing absorbs the high axial loads generated by the turbo-charger compressors.

Most plain bearings have a soft running surface applied by the manufacturer to absorb particulate contamination while supplying a good cold start self-lubricating surface. Because of their softness, these surfaces depend on the lube oil film thickness to prevent wear. Hard contaminant particles can embed in the soft liner of the bearing. If securely embedded in the bearing and large enough to bridge the oil film thickness between surfaces, this hard particle contamination causes wear of the journal. If the particles are larger than the oil film thickness but are not securely embedded in the soft bearing surface, they can score both the bearing and journal by a tumbling abrasive action. As shown in Table 3, test data indicate that a majority of wear on diesel engine plain bearings is caused by particles 10 microns and smaller.

Figure 12

FILM THICKNESS FOR ELASTIC AND RIGID PLAIN BEARINGS



5.6 ACCESSORY DRIVES

Many diesel engine accessories are gear driven. These gears shift from sliding to rolling contact and back to sliding contact as the teeth mesh and then separate. While driving relatively light loads, the contact area of these gears is quite small so contact pressure is high. With lubricant contamination larger than one micron, scoring abrasive wear occurs in the sliding contact areas and fatigue and abrasive wear occur under rolling contact. Oil pumps are also subject to wear between the housing and sides of the gears, which have a circular sliding friction contact with a typical clearance of approximately twenty-five microns.

6.0 HIGHLIGHTS OF DIESEL ENGINE STUDIES

6.1 DIESEL ENGINE FIELD TESTING

In 1985, an extensive field test of full flow lube oil filtration on diesel engines was conducted by Pall Industrial Hydraulics Corporation. The ability of three levels of full flow filtration to protect engines in a harsh environment was evaluated:

1) High efficiency, prototype medium
2) High efficiency composite-synthetic medium ($\beta_{10}>75$)
3) Standard paper medium ($\beta_{60}\sim75$)

Each level of filtration was applied sequentially to each of four heavily-used haul trucks. This arrangement ensured that the effect of filtration efficiency could be evaluated across a range of engine histories and operating characteristics.

The engines used in this study were DDA 16V149 diesels powering Wabco 150 ton diesel electric trucks used for hauling an abrasive mineral, molybdenum ore. The field test site was the Duval-Sahurita open pit mine near Tucson, Arizona.

The trucks were operated around-the-clock, with a three part work cycle:

CYCLE	DURATION
Descend into Mine	5 minutes
Dwell for Loading	4 minutes
Ascend and Dump	10 minutes
Total Cycle Time	19 minutes

The three media grades were operated for 500 hours each on four different trucks for a total of 6000 hours of testing. The finest rated filters were allowed to operate for longer intervals until the differential pressure across the test filter had reached the change-out value.

During the test, extensive analyses were performed on more than 250 upstream and downstream oil samples and filter specimens, including:

1. Optical particle counts over a range of 5 to 100 microns, upstream and downstream of filter.
2. Spectrographic analysis for major diesel wear metals and lubricant additives.
3. Filter differential pressure, with engine speed at 1650 RPM.

Additional laboratory tests were conducted to determine engine lube oil soot levels, API class CD diesel lube oil flow characteristics, post-test residual filter life, and filtration efficiency.

Highlights of these tests demonstrate:

1. If engine oil contamination is properly controlled lube oil service life can be more than doubled without adverse engine wear or lubricant degradation.
2. Over the 500 hour test interval, contaminants greater than 5 microns were controlled up to 20 times better by the 10 micron absolute composite-synthetic filter than by the standard filter (See Figure 13).
3. Spectographic oil analysis revealed significant reductions in four diesel engine wear metals on those engines using composite-synthetic medium filters (See Figure 14). Since the accuracy of spectrographic oil analysis is severely limited for particles 5 microns and larger (11), these results do not completely reflect the dramatic reduction in wear debris achieved with the composite-synthetic filter medium.
4. The 10 micron absolute composite-synthetic fil-

ters had clean pressure drops equivalent to those found in the standard paper filters.

5. The composite-synthetic filters were found to maintain high filtration efficiency levels under severe operating conditions for more than twice the recommended service life of the standard paper filters.

Figure 13

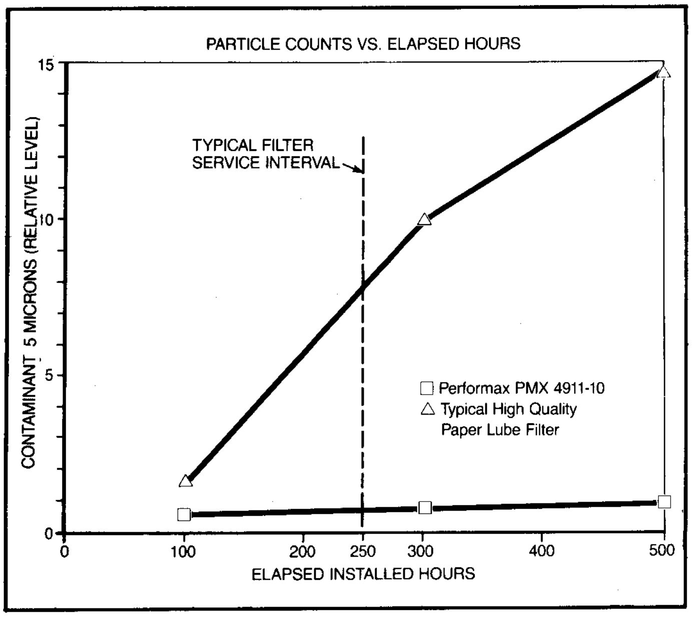
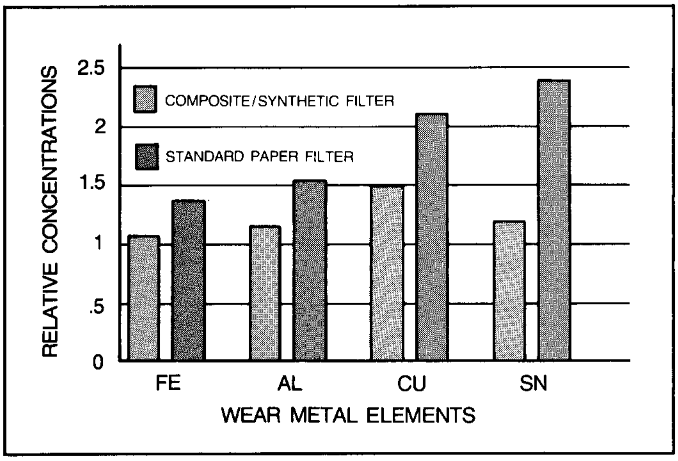


Figure 14

WEAR METAL ELEMENTS CONCENTRATIONS AT 500 HOURS



In summary, this field test demonstrated that composite-synthetic medium filter elements with $\beta_{10}>75$ achieved control of contamination in the critical 0-20 micron size range, as well as larger particles. This control exceeded the ability of conventional pleated paper filters, and was maintained for more than 500 service hours. By controlling particle contamination the chain-reaction-of-wear is broken, leading to significantly reduced wear and extended life of critical engine components oil service life.

6.2 FRICTION REDUCTION

J. Fodor and F. Ling have reported recently (12) that the internal friction of a 6 cylinder diesel engine was reduced 2.1 percent by replacing the standard filter (rating unreported) with a 6 micron (rating method unreported) full flow filter. Installation of an ultrafine bypass filter (rating unreported) further reduced this friction slightly. Contamination levels were reduced from 0.016 (percent by weight) with standard filtration to 0.005 with fine full flow filtration. Iron wear levels measured by ferrography were reduced from 1.7493 grams per (2 hour) cycle with standard filtration to 0.5307 grams per cycle with the full flow fine filtration. The friction pressure changes were equated to a 3.6 percent increase in fuel economy using full flow, 6 micron filtration. This can be compared to the 0.6-0.9 percent fuel economy gain experienced when converting from SAE 40 to multigrade lube oils.

7.0 CONCLUSIONS

1. Diesel engine lube oil contamination causes wear of engine components. Wear of these components leads to loss of performance, increased maintenance and overhaul costs, lower fuel efficiency, and shorter lube oil service life.
2. Oil contamination causes wear which generates more contamination. This process is the chain-reaction-of-wear. This proceeds by internal wear generating fresh wear debris; by internal wear opening dynamic sealing surfaces, allowing contaminant ingression from the environment, and by lubricant breakdown generating varnishes and sludges.
3. There is an essential link between the thickness of the dynamic oil film developed between moving surfaces and the size of wear causing contaminant particles. Particles the size of or larger than the oil film thickness cause wear off the moving surfaces.
4. The oil film thicknesses of critical diesel engine components are between 0-20 microns. This is the size of contaminant particles that must be controlled to minimize wear of diesel engine parts.
5. If contaminant particles in the 0-20 micron range are maintained at low levels, the chain-reaction-of-wear is broken. Not only is the wear minimized, but less contamination is generated during engine operation.
6. Standard paper filters cannot control particles in the 0-20 micron size range.
7. It has been demonstrated that by controlling particles 0-20 micron in diameter, composite-synthetic medium filters with $\beta_{10}>75$ maintain excellent diesel engine lube oil cleanliness.

8.0 RECOMMENDATIONS

The benefits of maintaining excellent lube oil cleanliness include improved engine performance, higher fuel efficiency, longer engine life, reduced maintenance costs and longer lube oil service life. In order to achieve these benefits, it is recommended that full flow composite-synthetic medium filters capable of controlling contaminant particles in the 0-20 micron size range be incorporated into diesel engine lubrication systems.

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