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Review of Lubricant Contamination and Diesel Engine Wear

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Review of Lubricant Contamination and Diesel Engine Wear

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ABSTRACT

Lube oil contamination is a primary reason for engine wear. The wear processes promoted by oil contamination lead to diminished fuel efficiency, shorter useful oil service life, reduced component life, and loss of engine performance. Contaminant particles responsible for this damage are in the size range of the dynamic lubricant films separating moving engine component surfaces: 10 microns and smaller. By making simultaneous contact with opposing surfaces these harmful particles focus the load onto a small area, degrading the surface. This paper reviews the nature of lubricant contamination, the modes of lubrication, and the primary mechanisms of engine wear. The correlation between contamination and wear of engine components, as well as several important studies quantifying the effect of contamination on engine wear and performance, are discussed. It is concluded that operating with clean lube oil, maintained by 10 micron filtration ($\beta_{10} \geq 75$), results in a diesel engine having better fuel economy, longer oil change intervals, superior performance, and greater durability.

The Diesel Engine is receiving increasing attention as a power plant because of fuel efficiency and life durability advantages. Over seventy percent of the trucks manufactured today use diesel power. A key component to the successful operation of the diesel engine is the lubricating oil. Major functions of the diesel engine lube oil include: cooling, friction reduction, and prevention of adhesion between component surfaces. It is, however, to

the the misfortune of diesel engines and their operators that the engine oil is also a depository of solid, liquid and gaseous impurities. High levels of lubricant contamination cause wear of mechanical components as well as breakdown of the lube oil. The result is performance degradation, short oil service intervals, and reduced engine life.

This paper is an endeavor to establish a framework for understanding the tribological associations between diesel engine components and lube oil contamination. Because of the high levels of solid impurities found in engine oil, and new technologies for controlling these materials, emphasis is placed on particulate contamination. The fundamental relationship between contaminant particle size and lubricating film thickness evolves from discussions on the nature of oil contamination, modes of engine lubrication, and mechanisms of component wear. With this essential concept in mind, wear of diesel engine components is then examined. This is followed by a review of several documented diesel engine wear studies, in which the effect of contamination is quantified by varying particle concentrations using different levels of filtration. In addition, a recent survey of engine oil contamination is presented which indicates the current contamination levels present in most engines, as well as improvements that can be attained.

2. DIESEL ENGINE LUBRICANT CONTAMINATION

TYPES OF CONTAMINATION - There are three categories of oil contaminants active in engine wear processes:

1. Solid particles, including wear

debris and soot, which damage mechanical components and catalyze lubricant breakdown.

2. Liquid contaminants, including fuel and water, which corrode metals and hinder the functioning of lubricants.

3. Gaseous contaminants, including acidic combustion products, which corrode component surfaces and degrade the oil.

The magnitude of contamination problems is illustrated by the contaminant size distribution of an in-line oil sample taken from a typical engine operating with standard paper filtration. As shown in Figure 1, there

are well over 10,000 particles >5 microns per milliliter of lube oil. Furthermore, ~90 percent of these particles are less than 10 microns in size. (This and related engine samples are discussed in detail in Section 7).

The predominant types of contaminants found in diesel lube oils, along with the primary sources and major problems associated with these contaminants, are listed in Table A.

TABLE A
PREDOMINANT IMPURITIES IN DIESEL ENGINE OIL

Type	Primary Sources	Major Problems
Metallic Particles	Component Wear	Abrasion Surface roughening leading to Adhesion Catalysis of Lubricant Breakdown
Metal Oxides	Component Wear Oxidation of metallic particles	Abrasion Surface roughening leading to Adhesion
Minerals (i.e. silica sand)	Induction Air	Abrasion Surface roughening leading to Adhesion
Exhaust Gases	Combustion Blowby	Acids promoting Lubricant Breakdown
Soot	Combustion Blowby	Interfere with additives Abrasive Wear Heavy deposits Oil thickening/ gellation
Water	Combustion Blowby Coolant Leaks	Metal Corrosion Promotes Lubricant Breakdown
Glycol	Coolant Leaks	Lubricant Breakdown
Fuel	Blowby-Rich Mixture	Lubricant Breakdown
Acids	Combustion Blowby Lubricant Breakdown	Metal Corrosion Autocatalysis of Lubricant Breakdown

INGRESSION OF LUBRICANT CONTAMINATION - Contaminants enter the engine lube system by four routes: 1) built-in from manufacture and assembly, 2) external ingression, 3) internal generation, and 4) maintenance actions.

Built In Contamination - During production and assembly diesel engine manufacturers clean engine parts and flush subsystems. Nevertheless, casting materials, machining swarf, abrasives, polishing compounds, and even lint occasionally, remain after manufacture and overhaul. These built-in contaminants can rapidly harm moving engine parts.

External Ingression - In this process, materials in the environment enter the lube system. External ingression is a

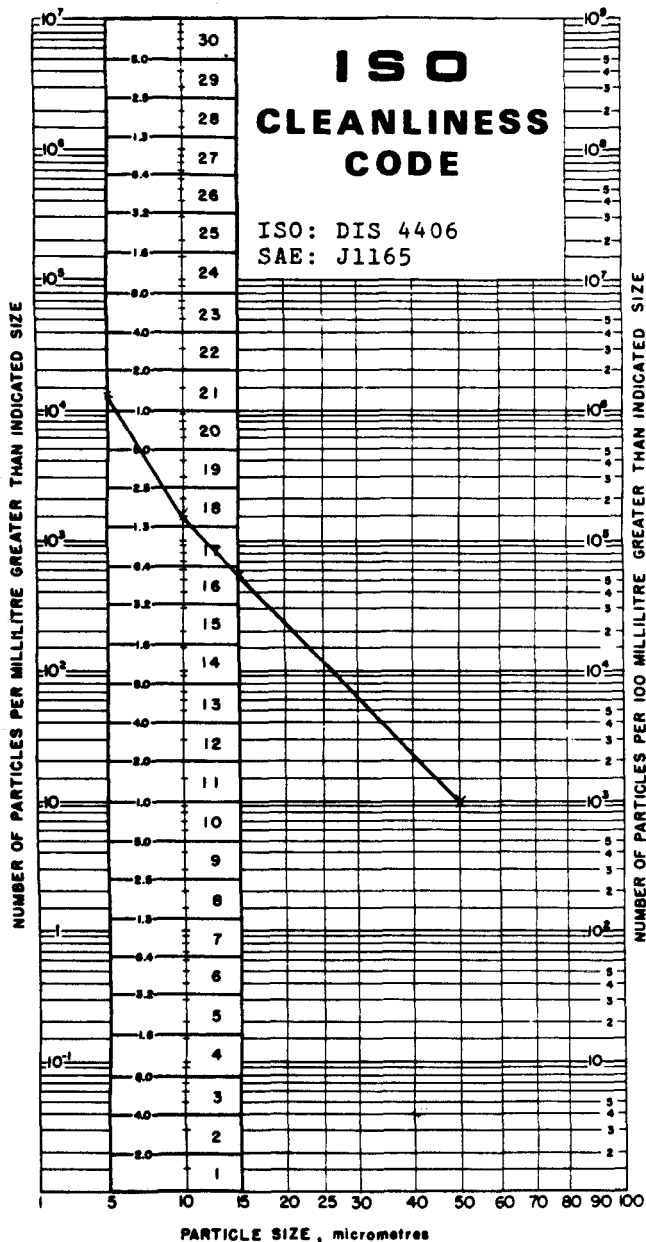


Figure 1. Representative oil suspended particle distribution maintained by standard paper filter.

major source of hard particulate contamination. Ingression routes include the oil fill cap, crankcase breathers, dirty dipsticks, and contaminated fuels. 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 cracks in the block.

The primary path for airborne particulate matter is through the air induction system. Particles, in the form of sand, salt, and other minerals, are carried through the engine air inlet and mixed with fuel vapor, which is then compressed and burned. Strong shock waves during combustion force gases through the piston ring/cylinder clearances. In this process, known as blowby, particles are carried by the gases into the engine oil. Particles may also be retained in the oil film coating the cylinder wall, which is then wiped by the rings into the oil sump on the next down stroke of the piston. Since most airborne mineral particles are refractory materials with melting points considerably above combustion temperatures, they are delivered into the lube oil as hard, abrasive solids with sharp cutting edges.

The blowby exhaust gases driven into the lube oil include unburned fuel, water, oxides of sulfur and nitrogen, and partially burned hydrocarbons, especially soot. Many of these materials can degrade lube oil and may corrode metals. Increasing the amount of exhaust gas recirculation has been shown to elevate lube oil particulate contamination(1)*. New rules issued by the E.P.A. require reduced nitrous oxide and soot emissions. Although ceramic exhaust components are being developed to reduce these emissions, it is likely that these regulations will lead to higher percentages of exhaust gas recirculation, resulting in additional contaminant loading of the lube oil.

Internal Generation - Contaminants are generated within the engine block by mechanical component wear and lubricant breakdown. Lubricant breakdown products include acids, sludges, gels, and additive precipitates. These contaminants can corrode engine parts as well as clog flow passages and heat exchange surfaces. The wear debris is usually in the form of hard metal particles and abrasive metal oxides.

Wear debris accumulating in the oil promotes more wear, which then generates more debris. The process of particles

wearing surfaces and generating new particles that in turn cause more wear can snowball into excessive levels of contamination and high rates of wear. This vicious cycle is known as the chain-reaction-of wear.

Maintenance Actions - During maintenance activities contaminants are introduced into the lubrication system. Opening rocker covers, the engine head, and 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 often contains significant quantities of contaminant particles.

3. MECHANISMS OF WEAR

There are five major wear mechanisms in diesel engines: abrasion, fatigue, adhesion, corrosion, and lubricant breakdown. Abrasion, fatigue, and adhesion involve mechanical damaging of surfaces; corrosion and lubricant breakdown involve chemical reactions. For all forms of wear, the influence of lubricant contamination is considerable. In many engines contamination is the predominant driver of wear; in other engines contamination accelerates otherwise benign wear modes.

ABRASION - Abrasive wear by contaminant particles involves cutting away material from component surfaces. As shown in Figure 2, an abrasive

ABRASIVE WEAR EFFECTS:

DIMENSIONAL CHANGES/FRICTION/LEAKAGE/
GENERATED PARTICLES = MORE WEAR

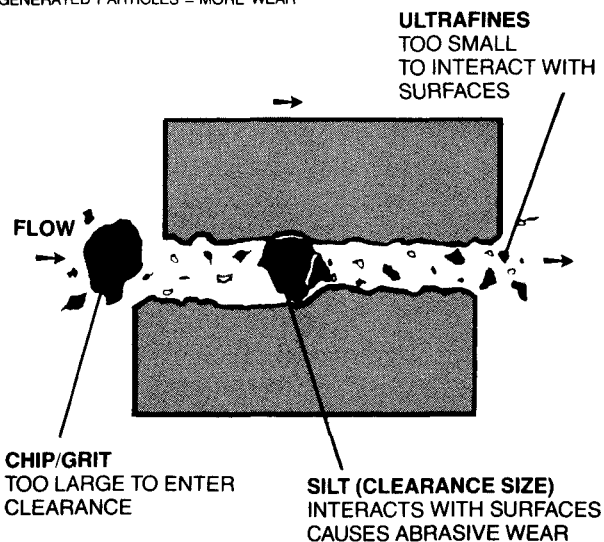


Figure 2. Abrasive wear.

*Numbers in parentheses designate references at end of paper.

particle abutting one surface slides against and plows through the opposing surface. Material is cut away in a single pass. The rate of abrasive wear of a component is proportional to the number of contaminant particles making simultaneous contact with the component's opposing surface. Consequences of this wear mechanism are: roughened surfaces, loss of clearance, misalignment, and generation of fresh wear debris. Particles generated in this process have the form of microscopic machine chips. These particles add to the oil contamination and contribute to the chain-reaction-of-wear. In addition, the process of dragging particles through the solid surface material adds to the overall frictional losses of the engine.

FATIGUE - Fatigue of a component surface is due to an accumulation of microscopic cracks at, or just below, the working surface. These cracks accumulate with operating time, eventually combining to form voids undermining the surface. Large quantities of material then break away. This wear mechanism leaves a cratered surface and releases work hardened particles into the oil which continue the chain-reaction-of-wear. As shown in Figure 3, by focusing the force between

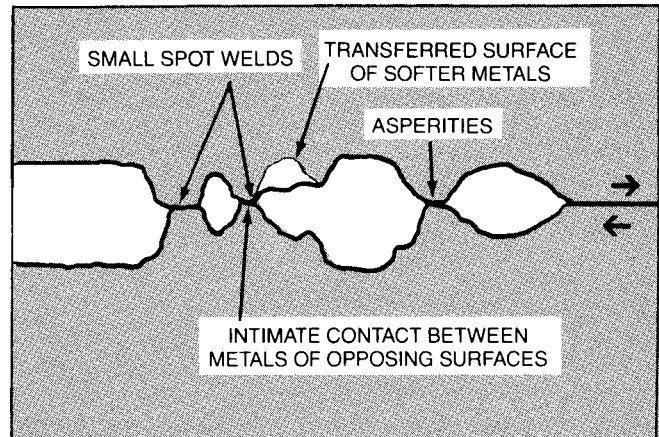


Figure 4. Mechanism of adhesion.

asymmetrically, removing material from the surface with the lower yield strength. The result of this process is high friction, wear, and heat generation. If a large number of spot welds are produced simultaneously, the opposing surfaces do not release and the component seizes. Degradation of surfaces by particles, such as roughening and misalignment, can lead to surface-to-surface contact and adhesive wear.

CORROSION - Corrosion is a reaction between aggressive chemicals and component surfaces. These chemicals include components of the combustion gas (water, oxygen, and NO_x and SO_x) as well as air pollutants from the environment. Particulate contamination accelerates corrosion rates, since worn surfaces have cracks allowing chemicals to channel through protective surface films and react with the underlying material.

Corrosion may degrade surfaces by two mechanisms:

- a) The reaction products dissolve in, and are removed by, the lubricant. This opens clearances and leads to misalignment and improper sealing.
- b) The reaction products form a brittle crust, often of abrasive metal oxides. These oxide crusts occlude clearances and flow passages. Upon release from surfaces, these crusts break up into hard particles, adding to the contamination level of the lubricant and continuing the chain-reaction-of wear.

LUBRICANT BREAKDOWN - Lubricant breakdown is the loss of important oil properties, such as viscosity, and the accumulation of harmful products of oil degradation. Lubricant breakdown can be

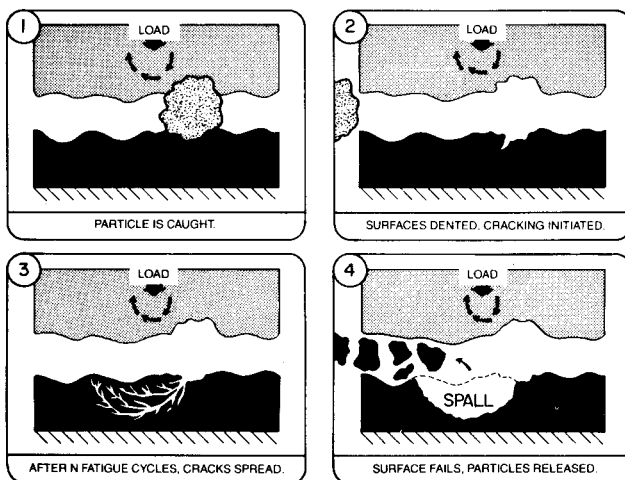


Figure 3. Fatigue.

loaded surfaces, particles larger than the lubricant film dent the surface and generate cracks. For component surfaces in rolling or squeeze contact, surface fatigue caused by particles may be the primary wear mechanism.

ADHESION - When the asperities of two opposing surfaces come into direct contact there may be regions of local welding between the surfaces, as shown in Figure 4. As the asperities of the opposing surfaces separate, these microscopic spot welds often break

caused by several mechanisms. Fuel and water may mix with the oil to form precipitates and gels. Soot particles, carried into the lubricant with blowby gases, combine with anti-wear and viscosity additives in the oil to reduce wear tolerances(2) and increase viscosity(3). In addition, particles of fresh wear debris have catalytic surfaces that promote oil oxidation(4). Along with loss of additives, oxidation of the oil leads to varnishes, sludges, and increased oil acidity.

4. LUBRICATION IN DIESEL ENGINES

Metal-to-metal contact between opposing surfaces in motion greatly increases friction and wear. This process is exacerbated by the high temperatures of an operating diesel engine. Lubricants are used in order to minimize the friction and wear of engines. The primary lubrication process is the formation of an oil film between moving surfaces. This film of oil supports the load between the opposing surfaces and keeps them separated. Compressive forces (the load) act to push the moving surfaces together. Tangential forces (shear) tend to displace the surfaces horizontally.

The thickness of a full lubrication film of is the distance between opposing surfaces, as illustrated in Figure 5. For all modes of lubrication

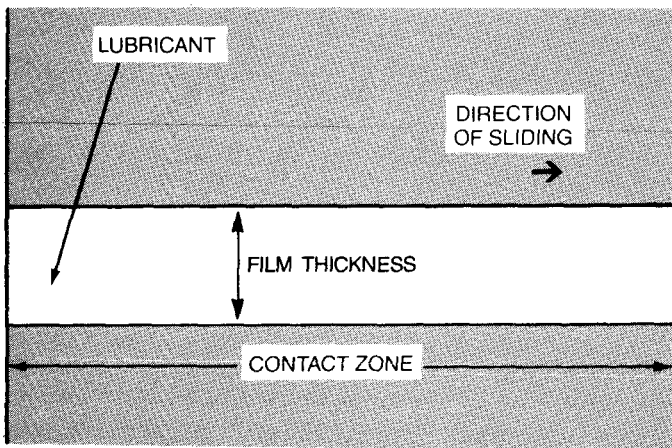


Figure 5. Full film lubrication.

the oil film thickness increases with fluid viscosity and the relative speed of the opposing surfaces. In addition, the thickness of this dynamic oil film is related to the mode of lubrication. There are three fundamental lubrication modes: Hydrodynamic, Elastohydrodynamic, and Boundary. It is important to note that a component can shift between the three modes of lubrication several times

during a single duty cycle.

HYDRODYNAMIC LUBRICATION - Just as water on a wet road can form a low friction film under a fast rolling tire (hydroplaning), lubricating oil is swept into the contact zone of a component by the relative motion of opposing surfaces. In hydrodynamic lubrication, typical of diesel engine sliding contacts, the oil film thickness is usually larger than 1 micron and there is little or no deformation of the component surfaces. In the contact zone, the lubricant film can develop up to 50,000 psi pressure, which supports the load between component surfaces. Wear rates and particle generation are lower 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.

ELASTOHYDRODYNAMIC LUBRICATION - This lubrication regime is typical of rolling contact bearings. There is considerable elastic deformation of the surfaces in the contact zone. The full oil film develops as much as 350,000 psi pressure, which greatly increases the viscosity of the oil within the contact zone. Film thickness varies between 0.05 and 2 microns. Because of high pressures in the contact zone, solid particles the size of, or larger than, the lubricant film can indent and furrow deeply into component surfaces.

BOUNDARY LUBRICATION - Low speeds and high loads, such as occurs during start-up, shutdown, and high torque conditions (i.e. long hills) can starve the contact zone of lubricant. This is exacerbated by high temperature thinning of the oil. The resulting breakdown of the full oil film permits contact between asperities on opposing surfaces. Under these circumstances, certain substances in the oil may form a last layer of resistance against the adhesive wear associated with direct metal-to-metal contact, as illustrated in Figure 6. These materials may be naturally occurring in the petroleum basestock, or formulated into the oil as part of the additive package (in which case these anti-adhesive wear compounds are commonly referred to by the misnomers of anti-wear and extreme pressure (E.P.) additives). This boundary layer between opposing asperities is 0.001 to 0.05 microns thick. High stress or heat at the asperity contact sites may displace the boundary layer, leading to adhesive wear. Because these layers are

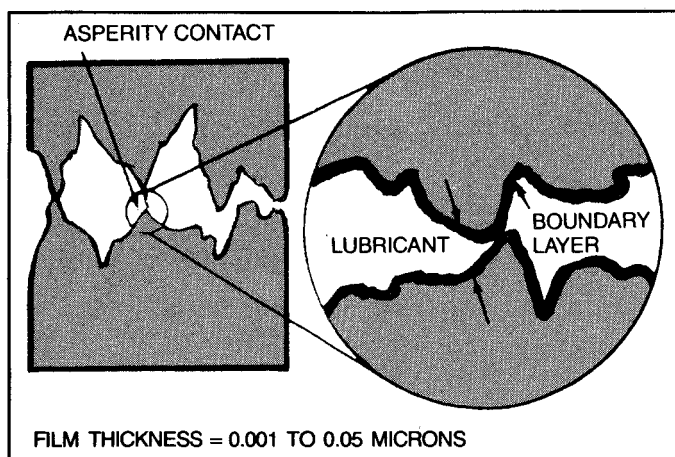


Figure 6. Boundary lubrication.

extremely thin, very fine particles can cause surface damage.

5. WEAR AND CONTAMINANT PARTICLE SIZE(5)

There is a fundamental relationship between component wear, the size of contaminant particles, and the thickness of dynamic oil films separating opposing surfaces. Particles the size of, and larger than, the oil film thickness generate component wear. By bridging the dynamic clearance maintained by the oil film, these particles make simultaneous contact with both surfaces, thus focusing the load onto the small areas of particle contact. The resulting surface stresses can be greater than 500,000 psi, well beyond the elastic limit of component materials. If one surface is rolling on the second, the high local stress produced by particle contact will pit the surface, leading to fatigue. The more common situation in diesel engines is sliding contact. During sliding, the high local stress at the region of particle contact results in abrasive removal of material. Abrasive wear increases friction, opens clearances, and leaves the surface furrowed and roughened. The ultimate result is greater friction and wear leading to lower fuel efficiency, loss of engine performance, and reduced component life.

Because of the tribological connection between contaminant particle size and the dynamic clearances of engine components, it is useful to consider the size ranges of both parameters. The results of an extensive search of the technical literature for diesel engine component oil film thicknesses are summarized in Table B. Although there is some variation with duty cycle, the majority of dynamic clearances are between 0 and 20 micrometers. This size range

TABLE B
DIESEL ENGINE COMPONENT OIL FILM THICKNESSES

Component	Oil Film Thickness (microns)
Ring-to-Cylinder	3.0 - 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

corresponds to the distribution of oil suspended particles typical of diesel engines operating with standard paper filtration as shown in Figure 1. The large majority of particles are smaller than 20 micrometers with a build-up of contaminant in the <10 micrometer size range.

The connection between contaminant particle size and oil film thickness has been demonstrated in a diesel engine wear test by Cummins Engine Company(6) and is summarized in Table C. In this

TABLE C
RELATION OF ENGINE WEAR RATES AND CONTAMINANT PARTICLE SIZE

Particle Size* (microns)	Component Wear Rates (mg/hr)			Total Wear mg/hr Relative	
	Main Bearings	Rods	Rings		
0-5	11.9	14.4	28.4	54.7	3.34
5-10	16.1	20.0	23.6	59.7	3.36
10-20	7.4	4.6	4.4	16.4	1
0-80	8.2	5.1	14.5	28.8	1.76

* Fractions of AC Fine Test Dust

[From reference 6]

test, the engine was challenged with hard particles in different size ranges. It was found that particles the size of the dynamic oil clearances produced the greatest diesel engine wear rates. Even abrasive powders containing large particles up to 80 microns did not cause as much damage as test contaminants with particles concentrated in the 0-10 micron range. Within the 0-20 micron dynamic clearance size range, particles less than 10 microns generated about 3.5 times more wear than particles greater than 10 microns. This is likely due to the thinner films at higher loads experienced by most components during the engine cycle. Particles 20 microns and greater should not be ignored. However, this study indicates that to minimize engine wear emphasis must be placed on controlling particles in the 10 micron size domain.

6. DIESEL ENGINE COMPONENT WEAR(7)

LUBE OIL - The lube oil is one of

the most important components of an engine. Breakdown of the lubricant, as discussed in Section 3, is accelerated by contaminant particles. The surfaces of fresh metallic wear particles provide convenient reaction sites for oil oxidation. The reaction products lead to varnishes, sludges and increased oil acidity. Field studies have shown (Section 7) that when particle contamination is maintained at low levels, oil change intervals can be extended by a factor of 2 or more.

PISTON RINGS/CYLINDERS - Piston rings have a reciprocal sliding motion. As the pistons start to move in the cylinders, a hydrodynamic oil film develops between the ring and cylinder surfaces. This dynamic oil film provides some protection against mechanical wear processes. As illustrated in Figure 7, at those nodes

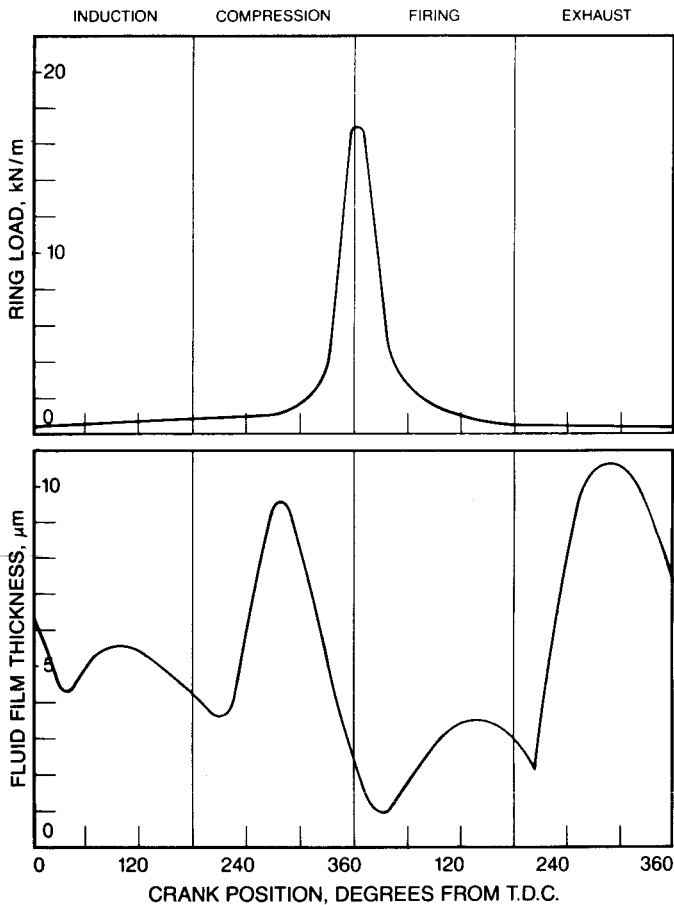


Figure 7. Predicted ring loads and film thicknesses between piston ring and cylinder of an AVIL diesel engine. (from Reference 8)

in the duty cycle with little or no relative motion between ring and cylinder (e.g. prior to start and at top and bottom dead center), the fluid film is thinnest(8). At these points the

full lubricant film collapses and the mode of lubrication is boundary lubrication. As anticipated by the higher friction of boundary lubrication, 40-50% of the friction losses of an engine are attributed to the ring/cylinder assembly, with two-thirds of the loss assigned to the top compression ring(9).

Because of these severe conditions, the ring/cylinder contact is extremely sensitive to contamination. Airborne particulate contamination has been found to be the greatest cause of ring-to-cylinder wear(10). Particles may also be drawn into the engine block with the lube oil and fuel. Particulate contamination bridging the oil film between ring and cylinder results in abrasive wear. Abrasive wear of the ring/cylinder contact leads directly to increased friction, more blowby, compression losses, and diminished fuel efficiency. In addition, rough surfaces protected only by boundary films (i.e. at the top dead center position) have harsher asperity contact. The higher contact stresses tend to break through the boundary layer, inducing metal-to-metal contact. Thus hard particle abrasion also provokes the high friction and wear rate of the adhesive wear mode.

Particles generated by piston ring/cylinder wear range up to 30 microns in size and are work-hardened. These particles are abrasive to other engine components as well as to the rings and cylinders. When the piston reaches the top of its stroke new oil is sprayed onto the walls of the cylinders, washing these fresh wear particles into the sump. From the common oil sump these abrasive particles circulate throughout the engine, continuing the chain-reaction-of-wear.

A thin layer of oxidized oil forms when the piston reaches the bottom of its travel, exposing the walls of the cylinder to the high temperatures of combustion. If not thoroughly removed by the oil spray, particles and oxidized oil agglomerate into surface deposits which interrupt spreading of protective oil films.

PISTON SKIRT/CYLINDER - Direct contact between the piston skirt and cylinder or liner, as illustrated in Figure 8, is often overlooked as a form of engine wear. This process can lead to scuffing of the liner surface during cold starts and severe operating conditions(11). The work hardened particles released in this process are quite abrasive, and can be 60 microns or larger in size. These particles contribute to the chain-reaction-of-

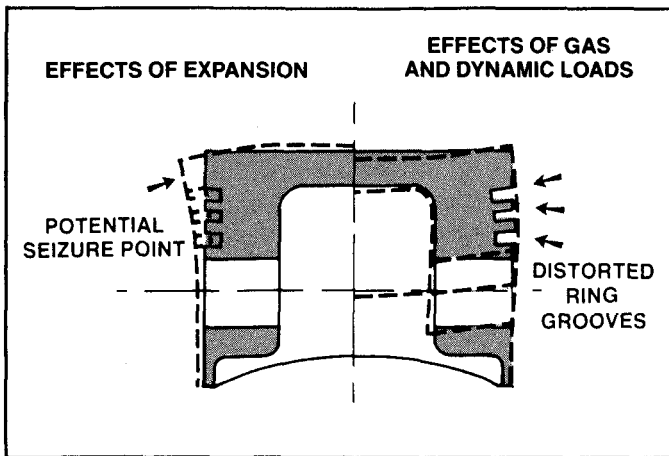


Figure 8a. Piston deformation.

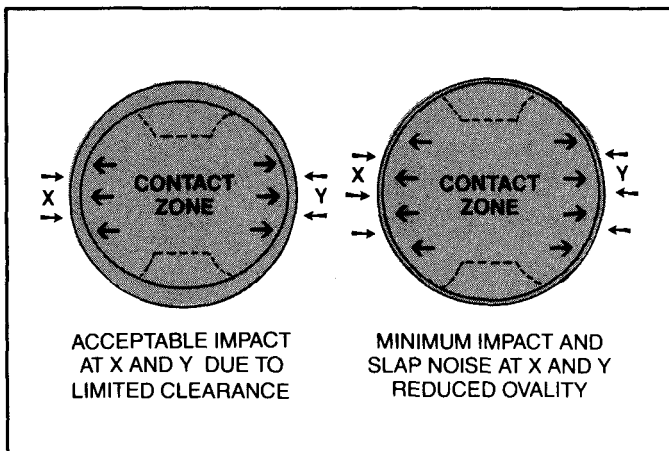


Figure 8b. Piston cylinder contact.

wear.

VALVE TRAIN - The valve train functions to open and close the intake and exhaust ports of the combustion chambers at specific moments in the cycle. Relatively low sliding speeds and high loads between the cam lobes and follower encourage lubrication problems. In many diesel engines the 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 produce abrasive wear.

High temperatures at the valve train location on top of the engine block lead to accumulation of carbon deposits. These carbon deposits, reinforced by particulate contamination, can lodge between the valve and guide, resulting in stiction. Striction results in power loss. It causes the timing of the port openings and closings to vary, leading to incomplete combustion and the possibility of combustion in the exhaust manifold (backfiring). In addition, permanent power loss can result from a burnt valve seat.

Rocker arms and followers are often supported by plain bearings. Although lightly loaded with restricted motion, high temperatures and poor oil supply may produce thin lubricant films easily bridged by contaminant particles. In addition, there is often a transient period of lubricant starvation during cold starting as pressurized oil flow takes up to several minutes to reach the bearings. During these periods of insufficient lubrication, a severe form of abrasive wear, scoring, can occur.

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. Plain bearings are also used on many accessories, such as turbochargers and oil pumps. Another form of plain bearing is the thrust bearing which absorbs the high axial loads generated by turbocharger compressors. The average film thickness at these bearings is 4-5 microns (12), as shown in Figure 9.

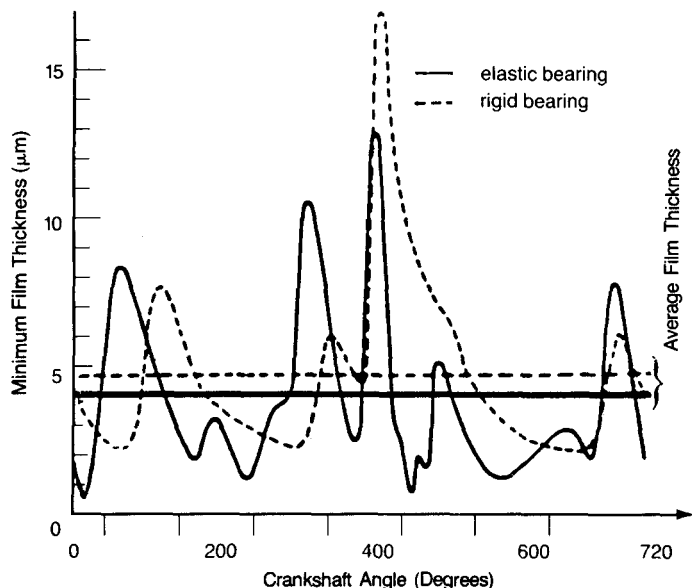


Figure 9. Film thickness for elastic and rigid plain bearings. (From Reference 12)

Most plain bearings have a soft liner, often supplied as a conforming insert, applied to the face of the bearing. The soft liner materials function as solid lubricants between the bearing and shaft during cold start, shut down, and transient contact conditions. Because the soft materials are easily abraded, the liners depend on a full hydrodynamic oil film to prevent wear during the major portion of engine operation. Hard contaminant particles can lodge in these soft liner materials. If securely embedded and large enough to bridge the oil film, these hard particles scratch and score surfaces of

the opposing journal. If not embedded, these particles tumble through the contact, scoring the journal and cutting away the liner material. Rough journal surfaces rubbing against bearings with insufficient liners result in smearing of the bearing; if not detected in time, the bearing will seize. As shown in Table C, test data indicate that the major wear of diesel engine plain bearings is caused by particles 10 microns and smaller.

ACCESSORY DRIVES - Many diesel engine accessories are gear driven. Gear contacts cycle between sliding to rolling as the teeth mesh and separate. Although engine gearing transmits relatively light loads, the contact area is small and the contact pressure is high. Lubricant contamination larger than one micron leads to abrasive wear in sliding contacts and surface fatigue in rolling contacts. Leakage wear paths can also form in oil pumps between the housing face plates and sides of the gear teeth.

THE SPECIAL PROBLEMS OF SOOT - Soot is a product of incomplete combustion. It has the consistency of lamp black(13). Soot is spawned by the high pressures of the diesel combustion process and is carried into the lube system with the blow-by gases. Upon formation, the size of an individual soot particle is 0.02-0.03 microns (14, 15). When entrained in the combustion gases, as well as suspended in the oil, individual particles link together into pearl-like chain structures. The resulting aggregates are up to 1 micron in size(15,16). The quantity and aggregate size of soot are a function of combustion efficiency. Rich fuel mixtures, typical of stop-go or mixed service operations, result in excessive soot generation(14,17).

Problems associated with soot are frequently described as the "pro-wear" characteristics of soot. These pro-wear properties include the following (2,15,17,18,19):

- a. The larger soot particles (near 1 micron in size) are abrasive, removing protective films formed by additives as well as inhibiting the formation of new films.
- b. Abrasive soot particles also directly wear metal surfaces.
- c. By virtue of the tremendous total surface area, soot may adsorb additives from the engine oil, leading to component wear.
- d. Soot acts as an oil thickener, increasing viscosity and even gelling the oil.
- e. At high concentrations, soot may clump into large masses which

settle out of the oil, fouling flow passages and clearances; this process is aggravated by water and fuel contamination.

f. Soot results in the formation of cylinder head sludge deposits.

7. REVIEW OF DIESEL ENGINE CONTAMINATION WEAR STUDIES

DIESEL ENGINE FIELD TESTING - An extensive field test of full flow lube oil filtration on diesel engines was conducted in 1985 by Pall Corporation. The engines used for this study were DDA 16V149 diesels, powering Wabco 150 ton diesel electric trucks used for hauling abrasive molybdenum ore. The field test site was an open pit mine near Tucson, Arizona. The trucks were operated round-the-clock, with a three part work cycle:

- 1) Descend into mine (5 minutes)
- 2) Dwell for loading (4 minutes)
- 3) Ascend and Dump (10 minutes)

Three grades of full flow filtration were evaluated:

- 1) Filter X: 6 micron ($\beta_{6 \geq 75}$) experimental medium
- 2) Filter P: 10 micron ($\beta_{10 \geq 75}$) production medium
- 3) Filter S: 60 micron ($\beta_{60 \sim 75}$) standard paper medium

The efficiency spectrum for each level of filtration is presented in Figure 10. Whereas all of these filters

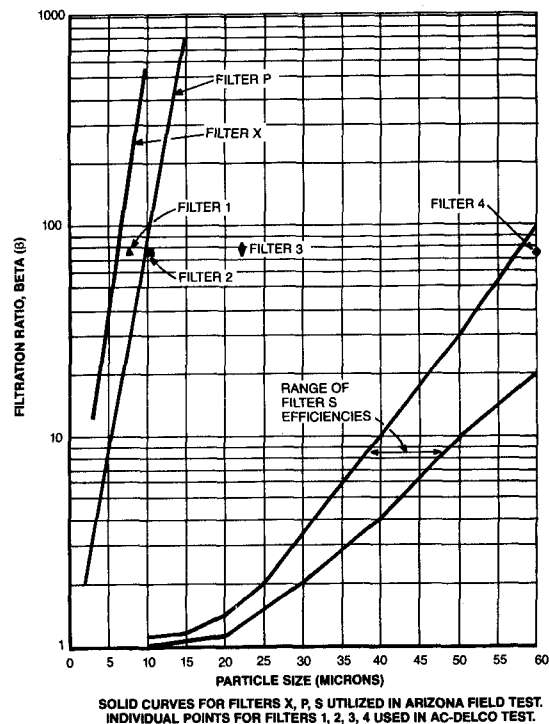


Figure 10. Comparison of diesel engine lube oil filters.

exhibit high efficiencies in retaining particles >60 microns, only the two finer filter are capable of controlling particles in the 1-10 micron range.

Each level of filtration was installed sequentially in each of four heavily used haul trucks. This arrangement averaged out variations in engine operating characteristics and histories. Each of the three different filter grades operated for 500 hours on each of the four trucks, accumulating a total of 6000 hours of testing. In selected cases, the two finer filters were allowed to operate for additional intervals until the differential pressure across the filter reached the change-out value.

Oil sampling was performed by adapting a metal sampling tube into the filter manifold of each truck. Each sampling event consisted of obtaining 125 milliliters of oil, with the engine running, from the pressurized sampling line via a ball valve. Analyses were then performed on more than 250 upstream and downstream oil samples and filter specimens. They included:

1. Optical particle counts over a range of 5 to 100 microns.
2. Spectrographic oil analysis for major wear metals and lubricant additives, using an inductive coupled emission spectrometer.
3. Filter differential pressure (at 1650 RPM).
4. Additional laboratory tests on selected samples for oil soot levels, viscosity, residual filter life, and filtration efficiency.

A number of important points were established in this study regarding the relationship between lube oil contamination and diesel engine wear:

1. The 10 micron filters P reduced the concentration of contaminant particles by a factor of 10-15 compared to the standard paper filters S (Figure 11).
2. Spectrographic oil analysis* revealed reductions in the four

*Footnote: It is important to note that although filters reduced particulate contamination ≥ 5 microns by more than an order of magnitude, wear metals as measured by spectrography were reduced by only ~20%. This is due to the severely limited capability of spectrographic oil analysis to detect particles 5 microns and larger (20). The consequence is that significant reductions in wear debris achieved by efficient filters are obscured in laboratory analyses using standard emission spectroscopic methods.

wear metals monitored for engines operating with filters P (Figure 12).

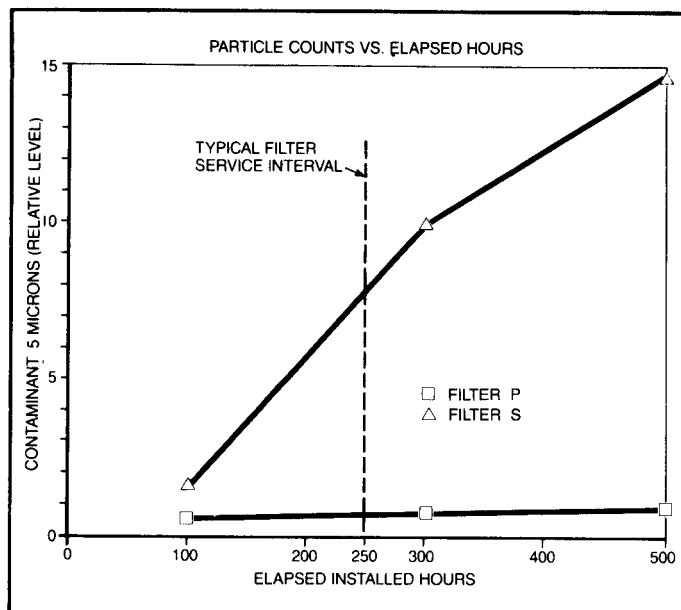


Figure 11. Particle counts vs. elapsed hours.

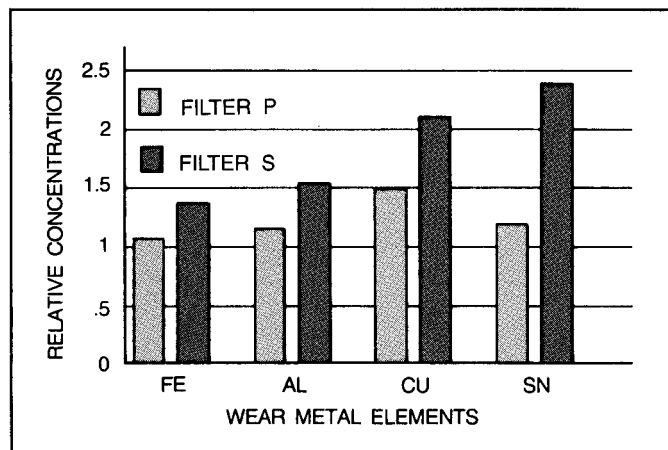


Figure 12. Wear metal concentrations measured by emission Spectrography.

3. The 10 micron filters P had clean pressure drops equivalent to those of standard paper filters S. In addition, the finer filters were capable of maintaining low levels of contamination under the severe operating conditions for more than twice the recommended service life of the standard paper filters.
4. Controlling engine oil contamination to low levels with filters P permitted lube oil service life to be more than doubled without adverse engine wear or lubricant degradation.

In summary, controlling particulate contamination in the >5 micron size

range with high efficiency filters retards the chain-reaction-of-wear; this results in significant reductions in component wear and lubricant breakdown. The beneficial consequences include greater component life, increased oil change intervals and extended service life of the high efficiency finer filters.

DIESEL COMPONENT WEAR TEST - An investigation into the relationship between lube oil filtration and rates of abrasive wear in diesel engines was performed by the AC Delco Division of General Motors(21). Wear of five critical component areas in a DDA 6V-53T engine were measured: upper and lower rod bearings, slipper bushings, compression and oil piston rings, piston pins, and the main bearings. Tests were run for eight hours with the engine operating at 2500 rpm with oil temperatures between 240-250° F. During this period, silica sand (AC Fine Test Dust) was added to the oil sump in 50 gram aliquots every hour, for a total of 400 grams of contaminant. The test was found to reproduce typical abrasive wear patterns. The same engine was used for all tests, and rebuilt after each run with new parts.

Four levels of filtration were investigated. The efficiency of these filters via J-806 and by the Multi-Pass Test method are listed in Table D.

TABLE D
EFFICIENCIES OF FILTERS
UTILIZED IN ENGINE WEAR CONTAMINATION STUDY

Filter	98% Spherical Bead Retention (microns)	J806 Wt. Eff. (%)	Multi-Pass Test Size Beta = 75 (microns)
1	7.5	96	7.5
2	8.5	94	10
3	12	92	22
4	45	82	60

These filters can be matched to the efficiencies of the filters used in the Arizona mine test, as shown in Figure 10: Filter 1 of the AC study is in the same range as Filter X of the mine study; Filter 2 = Filter P; Filter 4 = Filter S; and Filter 3 is intermediate to Filters P and S.

The results demonstrated that all engine parts experienced significantly less wear when protected with the two higher efficiency Filters 1 and 2. In addition, spectrochemical analysis found less wear metals (iron, lead, tin, copper, aluminum) in the oil with these two finer filters. It was concluded that control of particles in the "3-10 micron size range had the greatest

affect in reducing engine wear". By normalizing the component wear reported for each grade of filter, the results have been summarized as a Diesel Engine Component Life Curve, Figure 13.

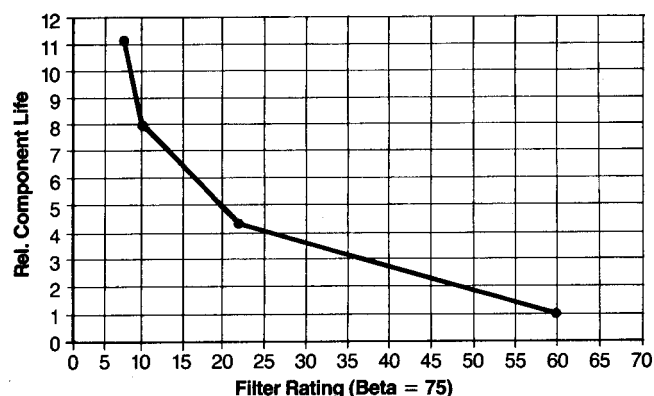


Figure 13. Diesel engine life and lube oil filtration.

DIESEL ENGINE WEAR AND FUEL ECONOMY - Fodor and Ling (affiliated with the Research Institute of Automotive Industry-Budapest and the Rensselaer Polytechnic Institute, respectively) have reported on a study of motored six cylinder diesel engines(22). In this investigation, standard oil filters were replaced with more efficient filtration. The rating for the more efficient filters is described as retaining 75% of the 6 micron particles. Although this rating system is not used in North America, this 6 micron rating equates to filters slightly coarser (less efficient) than the 10 micron Filter P evaluated in the Arizona mining test ($\beta_{10} \geq 75$). In one of the several experiments, two of these finer filters were used simultaneously, one in full-flow and the other in by-pass mode. This arrangement is believed to approach the oil cleanliness levels maintained by the 10 micron full-flow filter P.

In the study, it is was found that contamination levels could be reduced from 0.016% (by weight) with standard filtration to 0.0025% with the finer filtration. Iron wear debris generation, as measured by ferrography and neutron activation analysis, was similarly reduced from 1.7493 grams per test cycle (2 hours) to 0.1235 grams per cycle, a reduction in the wear rate by a factor of 14*.

*Footnote: It is interesting to note that in this study, as opposed to the Arizona mine study, reductions in wear metals were determined to be of the same order as reductions in contamination levels. This is a tribute to the sensitivity of the wear metal measurement performed by Fodor and Ling.

Perhaps the most significant result of the study was that the internal friction of the diesel engine was reduced by 2.9 percent when operating with clean oil. This friction reduction was equated to an increase in fuel economy of up to 5%. As a comparison, this significantly exceeds the 0.6-0.9 percent fuel economy gain experienced when converting from SAE 40 to multigrade lube oils.

8. SURVEY OF DIESEL ENGINE OIL CONTAMINATION LEVELS

Information on the level of engine oil contamination was gathered from a survey of diesels operating throughout North America. Oil samples from a total of 138 engines operating with standard paper filters S were analyzed. In addition, 117 oil samples were analyzed from engines operating with the 10 micron Filter P. In order for this study to be performed on a large variety of vehicles without any special adaptation, a simple sampling technique was employed: immediately after stopping a hot engine, a precleaned flexible tube was inserted into the oil level indicator "dipstick" port and fed into the bottom of the channel, then backed up 2 inches; oil was then drawn with a hand-held vacuum pump into a precleaned sample bottle. Particle counting was then performed.

Based on the relationship between dynamic oil films and sizes of wear generating particles, the important particle size range is 0-10 microns. The sampling procedure and analytical method used in the survey evolved natural bounds within this range. Because of the large amount of soot present in many oil samples, the analytical method required sieving out all particles <5 microns, so that the remainder of the contaminant could be accurately counted. The interval of 5-15 microns, which is a standard size interval in the particle counting procedure utilized and which also covers the 10 micron size domain indicated as critical for engine wear in the Cummins study (Section 5), was targeted as the particle size range for assaying levels of contamination in diesel lube systems.

Results of the survey are summarized in the cumulative distributions shown in Figure 14. The median engine operating with standard paper filters S was found to contain ~9,300 particles/ml. In contrast, the median engine operating with 10 micron filters P contained ~2,600 particles/ml. An important observation is the wide

variation in contamination levels,

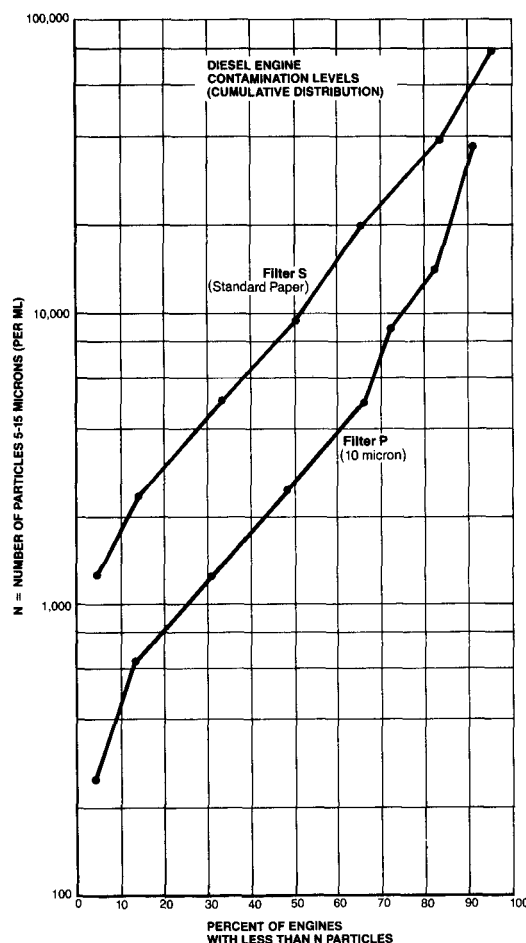


Figure 14. Diesel engine contamination levels (cumulative distributions).

extending over two orders of magnitude. It is likely that this dispersion is made up of several ingredients, including differences in duty service, operating environment, integrity of air induction system, history, and maintenance quality. Additional work is required to discover if the dominant reason for the most contaminated engines is a small subset of these factors.

A limitation of the sampling procedure is the likelihood of background contamination, scraped off the walls and bottom of the dipstick channel, entering the sample bottle. The resulting additional background counts would preclude the determination of the absolute number of particles representative of the engine lube systems. However, since the background interference may be assumed to be statistically averaged over the large number of samples examined for both the standard paper filter S and filter P, the difference in contamination levels between filters S and P is meaningful:

Contamination S - Contamination P $\approx$
6700 particles /ml (5-15 microns)

The disparity in the concentration of contaminant particles maintained by the two levels of filtration is significant, and, in part, reflects the decrease, due to the finer filter P, in wear debris generation. However, in order to relate rates of engine wear to particle concentrations, more accurate estimates of particulate levels are required. Several studies are currently in progress to provide this data. Results of one study are summarized in Table E. In this study of a DDA 8V92

TABLE E
COMPARISON OF DIPSTICK AND IN-LINE PARTICLE
COUNTS FROM A DDA 8V92 DIESEL ENGINE

Filter	Particle Counts/ml. 5-15 microns	
	Dipstick	In-line ¹
Standard Paper S	33,670	12,730
10 micron Filter P ²	3,280	630

Notes: 1. Oil sample obtained upstream of filter.

2. Sample taken 26 hours after retrofitting Filter S with Filter P.

diesel, the assembly into which the oil filter normally fits was adapted with a collar into which the oil filter was then installed. This adapter permitted obtaining pressurized in-line fluid samples with the engine operating in addition to dipstick samples. The data shows that the dipstick samples had approximately 3-5 times more particles than in-line samples taken upstream of the filter. The data also shows that, for this engine, the original contamination level maintained by paper Filter S was reduced by a factor of 20 when operated for 26 hours with the 10 micron Filter P.

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. There is a fundamental relationship between the size of contaminant particles and the thickness of dynamic oil films developed between moving surfaces of active components. Particles the size of, or larger than, the oil film thickness cause wear of components. By making simultaneous contact with both surfaces, these particles focus the load onto a small region of each surface, resulting in surface pitting,

plowing, and cutting.

3. The average oil film thickness associated with the majority of diesel engine components is in the 10 micron size domain. This is the size range of the most damaging contaminant particles. In addition, mechanical stress is accentuated during the high load/thinner oil film phases of the engine cycle. In order to minimize engine wear, emphasis must, therefore, be placed on controlling particles in the 10 micron size domain.

4. Oil contamination causes component wear which in turn generates more contamination. This is the chain-reaction-of-wear. If uncontrolled, this process results in an enormous number of oil suspended particles. The consequences of uncontrolled chain-reaction-of-wear are:

a) higher friction, leading to higher fuel consumption.

b) loss of material from sliding and rolling contacts, resulting in misalignment, vibration, and component replacement.

c) opening of piston dynamic sealing surfaces, leading to loss of compression, further fuel consumption, and contaminant ingress from the environment.

d) the accumulation of soot and combustion products in the lube oil and the formation of lubricant breakdown varnishes and sludges, leading to reduced oil service life.

5. The significance of proliferating particles in the 10 micron size domain is phenomenal. Each grain of contaminant (wear debris, mineral grain, metallic oxide) produces a small but finite amount of friction, abrasive wear, and catalytic oil breakdown. Because of the vast number of harmful particles, the total effect of this multitude is abbreviated oil life, substantially higher engine friction, and propagation of engine wear.

6. From a survey of over 250 diesel dipstick oil samples, estimates can be made of the contamination levels representative of operating engines. Depending on engine history, operation, maintenance, and filtration level, oil contaminant concentrations were found to vary by more than two

orders of magnitude. In the important 5-15 micron size range, a significant decrease of ~6700 particles/ml was observed in the typical (median) contamination level of engines operating with 10 micron filters P compared to the typical (median) contamination level of engines operating with standard paper filters S.

Results of a field test aimed at a more accurate estimate of the contamination level, through direct in-line sampling, show contamination levels (5-15 microns) of ~12,700 particles/ml and ~630 particles/ml for the test engine when operating with standard paper filter S and 10 micron filter P, respectively.

7. Oil cleanliness levels of the order of 100-1000 particles/ml are attainable in field service with 10 micron ($\beta_{10} \geq 75$) fine filters. Compared to operation at higher contamination levels, benefits these clean engines will achieve include:

- a) an 8 to 14 times reduction in engine component wear.*
- b) up to 2X increase in oil service life.
- c) up to 2X increase in filter service life.
- d) up to 5% improvement in fuel economy.

The ultimate benefits are greater diesel engine performance over extended life with lower operating costs.

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