

Investigation of Wear in Heavy Duty Diesel Engines: Part I - Use of Radioactive Tracer Technology

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ABSTRACT

This paper is first in a series of papers designed to investigate wear processes in modern heavy duty diesel engines. The objective of the series is to discuss the effects that engine drive cycle, lubricant formulations and in-service ageing of lubricants have on wear of critical engine components.

In this paper, the Radioactive Tracer Technology technique was used to study the steady state wear behavior of a number of contacting surfaces in a Caterpillar 1P engine, as a function of the drive cycle. A test protocol consisting of 7 modes or stages was used to simulate a variety of drive cycles. The results from this work provide useful insights into the wear behavior of these surfaces under a variety of speed and load conditions.

INTRODUCTION

Environment protection and resource conservation today are among the biggest drivers of change for the global transportation industry. Engine oil technologies are evolving in parallel with changes in engine hardware that are resulting from these global trends. A number of prominent sign posts, such as SAPS (Sulfated Ash, Phosphorus and Sulfur) constrained lubricants and the emerging fuel efficiency requirements for heavy duty diesel engines, clearly represent the fast-paced changes that are taking place in the lubricant and the additive industry.

In the face of these evolving requirements, the additive industry can no longer rely solely on traditional formulation approaches for protection of engine hardware against wear and other harmful effects. It is therefore important to re-examine some of the basic lubricant performance axes such as engine wear in the context of the new formulation constraints, with the objective to identify performance gaps, if any, and to develop appropriate formulation strategies to close these gaps.

To that end a program was designed to examine the steady-state wear behavior of a number of critical contacting surfaces in a heavy duty diesel engine as a function of the engine drive cycle. The Caterpillar 1P engine, a single cylinder version of the Caterpillar 3406 engine, was used for this work. Cylinder liner, top ring face, top ring side, lower end conrod bearings and fuel injector cam lobe were selected as the engine components to be studied. The Radioactive Tracer Technology (RATT) was used to track the progression of wear for the selected hardware components. Several combinations of engine speed and load were used to simulate engine duty cycles such as idling, line haul driving, high power output and high load driving.

This paper is the first in a series of intended publications to report on the results of this program. The main purpose of the paper is to discuss details of the methodology used in the study, and to share some preliminary observations on the steady-state wear behavior of the selected engine components. The paper also lays the groundwork for future publications where the effects of lubricant formulation variables as well as the effects of ageing will be discussed.

RADIOACTIVE TRACER TECHNOLOGY

The Radioactive Tracer Technology (RATT, sometimes also called Radio-Nuclide Technique (RNT), has been used to measure wear in engines for over 50 years^[1-8]. The technique is highly specialized and involves labeling engine components with radioactive isotopes. The isotopes are used as tracers to measure wear in near real-time with very high sensitivity. It has several distinct advantages over traditional wear measurement techniques.

Traditional techniques involve either loss-in-weight, surface profilometry or measuring changes to geometrical dimensions. In any of these cases an initial measurement is made, the parts are installed

an engine, operated over a series of conditions, often for hundreds of hours, then the engine is disassembled and the parts are re-measured to determine the amount of wear that was incurred. Measurements are often imprecise because the change measured is often very small compared with the quantity being measured. In addition, the measurement yields only the total amount of wear incurred over the entire test. This includes engine break-in, often several engine starts, transients and a variety of operating conditions. Wear rates determined are the average over this entire process. This makes it very difficult to analyze the underlying cause-and-effect relationships. In other words, such techniques do not offer any way to determine when and under what conditions during the operating cycle that wear was incurred.

RATT allows one to measure wear essentially in real time, from multiple engine component surfaces, while the engine is running. As the labeled parts wear, particles of radioactive material are transported from the labeled surfaces and mixed into the engine oil. By withdrawing a continuous sample of oil from the sump, passing it past a gamma particle spectrometer, the activity of radioactive isotopes in the oil can be easily measured. Using appropriate calibration and time-decay factors, the measured isotope activity can be correlated to the rate of wear of the labeled engine component. This ability to measure wear data in a short period of time without having to disassemble the engine makes RATT a powerful tool for investigating oil formulation effects on engine wear under different operating conditions.

EXPERIMENTAL

ENGINE PLATFORM

A Caterpillar 1Y3700 single cylinder diesel engine was chosen for this program. This is actually a Single Cylinder Oil Test Engine (SCOTE) based on Caterpillar's commercial 6 cylinder 3406 engine, and is used in the Cat 1P engine test procedure (ASTM D6681) to evaluate piston deposit performance of engine oils (Figure 1). This engine is an electronically controlled, direct injection, in-head camshaft, single-cylinder diesel engine with a four-valve arrangement. Further engine details are shown in Table 1.



Figure 1: Caterpillar 1P Test Cell

Table 1: Caterpillar 1P Engine Details

Bore	137.2 mm
Stroke	165.1 mm
Displacement	2.4 L
Compression Ration	16.2:1
Rated Power	65 kW @ 1800 rpm

The test bed is fitted with electronic control module (ECM) which controls engine fueling rate and timing, and limits maximum engine speed, maximum engine power, and other important operating conditions for the test. In order to accelerate wear for this study, the ECM was reprogrammed with a more severe fueling strategy than that used in the standard Caterpillar 1P test. The new fueling strategy moved the fuel injection timing from 13° BTDC to 6° BTDC and allowed for 240 g/min maximum fuel, or 30% higher fueling rate than that for the Caterpillar 1P calibration.

The test stand was instrumented to measure and control the operational parameters in Table 2. Data acquisition system was configured to record data at six-minute intervals during testing.

Table 2: Operational Parameters

Controlled	Measured
Speed	Power
Torque	Fuel Flow
Oil Gallery Pressure	Brake Specific Fuel Consumption
Fuel Pressure	Oil Filter Inlet Pressure
Inlet Air Pressure	Oil Filter Outlet Pressure
Exhaust Pressure	Coolant Out Pressure
Oil Gallery Temp	Crankcase Pressure
Fuel Temp	Coolant In Temp
Coolant Out Temp	Ambient Air Temp
Inlet Air Temp	Exhaust Temp
Oil Sample Temp	Ambient Air Humidity
Detector Temp	Coolant Flow
	Blow-by Rate
	Sample Loop Pressure

SELECTION OF ENGINE PARTS AND RADIOACTIVE TRACERS

A total of 5 engine surfaces were selected for this study: cylinder liner at top ring reversal (TRR), top piston ring face, top ring side, lower end rod bearing and fuel injector cam nose (Figure 2). Each selected surface was analyzed using SEM-EDX (Scanning Electron Microscope with Energy-Dispersive X-ray spectroscopy) to determine suitable tracer isotope as well as to ensure that the element chosen for activation was well distributed over the surface.



Figure 2: Engine Parts Selected for Wear Study

Figure 3 shows the SEM image of the top ring cross-section. The ring face contains an insert consisting of Cr, Fe, Ni and Mo (Table 3). Among these elements Cr was selected for this surface since it produces by far the most activity as Cr-51 (27.7 day half-life). The ring side surfaces are predominantly iron, which transforms into Fe-59 (44.5 day half-life) by bulk activation. The bulk activation was performed using the TRIGA Mark 1 research reactor at Texas A&M's Nuclear Science Center. Based on the prior experience with the technique and the anticipated wear rates for this surface, a thermal neutron flux exposure time of 80-hours at approximately 3×10^{12} neutrons/cm²/sec was chosen for the activation procedure.

Since the ring face also contains Fe, the ring side wear measurement actually contains contributions from both the face and the side. However, a decision was made to not correct the results for the contribution from the ring face for the fear of introducing additional sources of noise into the data. This decision will be revisited for future publications.

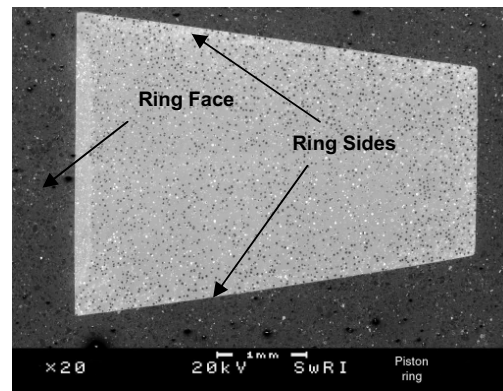


Figure 3: SEM Image of Top Piston Ring Cross-Section

Table 3: Composition of Top Ring and Conrod Bearing

Surface	Composition (wt %)
Ring Face	Cr (14.95%), Fe (46.43%), Ni (8.42%), Mo (29.75%)
Ring Sides	Fe (94.71%)
Lower Rod Bearing	Pb (93.52%), Sn (4.88%)

The conrod bearing consists of 3 layers with an outermost layer (~30 microns) containing lead-tin, a thin barrier layer containing mostly copper, and an inner layer consisting mostly of aluminum supported on steel backing (Figure 4). The outermost layer of the bearing is the wear surface; the tin component of this layer was converted to Sn-113 tracer (115 day half-life) using the same bulk activation procedure as for the top ring. A second isotope Sn-117 is also produced under bulk activation but has a relatively short half-life of 14 days.

The remaining two components to be studied were the fuel injector cam lobe and the liner at top ring reversal (TRR). These components were too large to be activated by bulk activation and would have produced competing isotopes by this method. In order to obtain unique isotopes and to restrict the activation to the cam lobe nose and TRR areas, surface layer activation (SLA) was chosen. The cam nose was labeled by Co-56 (77.2 day half-life) using a proton beam from a linear accelerator. A 5-mm wide strip across the width of the cam nose was activated. For the liner TRR area, Co-57 (272 day half-life) was generated using a deuteron beam. The area activated was a 15-mm wide band around the entire circumference with the upper edge located 10.8 mm from the top surface of the liner. ANS Technologies performed these activations using the accelerator at the University of Montreal.