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Forensic Engineering Investigation of the Catastrophic Breakdown of a Diesel Engine in an Emergency Generator Set

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Abstract

A large-displacement 16-cylinder diesel engine was coupled with a 1750 kW-rated generator set to provide emergency power to an international airport parking facility. It had been in service for seven years, and had accumulated only 242 operating hours from a regular monthly test procedure. On the day of the incident, less than three minutes after starting up, the engine began smoking, running roughly, and then failed catastrophically. A forensic engineering investigation was undertaken to determine the cause. Two cylinders in opposite banks had been damaged. The proverbial "smoking gun" was found — an obstruction comprising a rubber gasket within the main oil gallery leading to these cylinders. The investigation explored the probable method and means that this gasket was entrained into the gallery. The results of the analysis attempted to provide for an assessment of relative liability of the parties.

Keywords

Generator set, diesel engine failure, oil gallery obstructions, filter gasket, forensic engineering

Overview

An Airport Authority operates a 9,000-stall, eight-story parking garage at an international airport in Ontario, Canada. The mechanical room of the garage contains a 1,750ekW-rated emergency generator powered by an 1,879kW diesel engine. During the annual maintenance and load capability testing held on Nov. 3, 2010, smoke was reportedly observed emanating from the engine, and a catastrophic shutdown ensued. The author's forensic engineering firm was engaged to determine the cause of the engine failure.

Investigations and Observations

In this paper, the following actors were involved to various degrees:

- Company A, the local maintenance and monthly test firm;
- Company B, the local specialized electrical systems and load test contractor;
- Company C, the engine manufacturer;
- Company D, the aftermarket oil filter manufacturer; and
- Company E, a prior maintenance and monthly test firm.

The forensic engineering team attended the site three times to document the engine damage. The dismantlement of the diesel engine was witnessed at a local remanufacturing facility in early January 2011. The involved engine had been manufactured by Company C and was a simple mechanical engine without any electronic controls or engine control module (ECM), as shown in **Figure 1**. The lack of logged information obstructed the investigation of the engine breakdown. The generator set had been installed for emergency operation to support the power supply to the parking garage. The set had been commissioned for service approximately seven years prior, and the engine's hour meter showed around 254 hours of operation, 242 of which were known to be after installation.

Reported Circumstances

Under the supervision of the airport authority,

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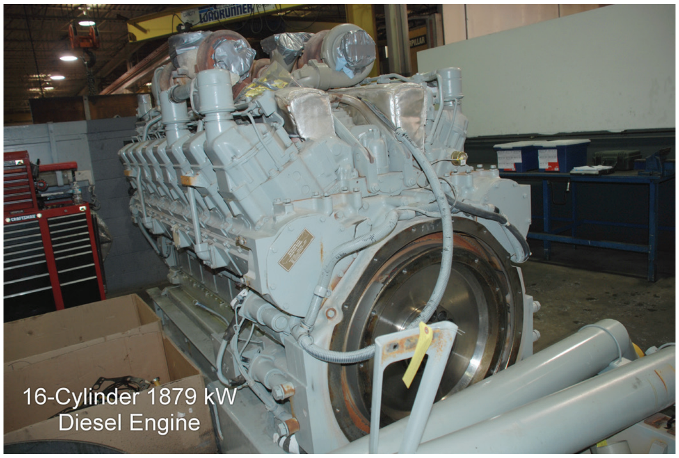


Figure 1
Diesel engine for parking garage generator set.

Company A started the engine every month. It was also serviced once yearly by Company B, which changed the oil filters and organized performance checks with a load bank.

The check sheets from the local maintenance company for Sept. 27 and Oct. 26, 2010 were reviewed and found to be uneventful. The engine oil levels were described as "good." The annual service procedures, including an oil change and replacement of oil filters, had been undertaken on the date of failure (**Figure 2**). Documents submitted for the maintenance history confirmed this narrative.

For example, the work orders by Company B for Sept. 7, 2007 and for June 10, 2008, indicated that four Company D filters had been changed, and 400 liters of 15W-40 engine oil had been added. The next oil change occurred on Oct. 20, 2009, at which time the filters were also changed. Paperwork for the annual inspection of November 2010 was incomplete because of the engine failure. It was assumed that the oil filters and oil were changed on that date as well. No performance anomalies were listed for the engine and generator on any of these records.

There had not been any power outages at the terminal requiring the operation of the generator prior to the 2010 service work. The specifications sheet noted that the average power output would be 70% of the standby power rating — and that typical operation would be 200 hours per year, with a maximum expected usage of 500 hours per year. The two-year warranty from Company C expired in 2004, according to correspondence.

The technician from Company B reported that engine began smoking heavily about three minutes after it was started while it was warming up to operating temperatures, prior to the application of the load bank to the generator.

Component Examination Findings

Company C, which had a large engine remanufacturing facility nearby, sent a crew who reported that the bolts on rods of cylinder #8 were loose, and its bearing was spun. The bearing shell had seized on to the crankshaft, and the shell had been spinning inside the big end of the connecting rod. The technicians opened the cylinder bank at this shop (**Figure 3**).

The spun bearing could have been the result of a lack of torque on the bolts, per the Company C's technician. Since Company B stated that it did not intervene at those cylinders, a suggestion was put forth that the bolts may not have been correctly torqued during the manufacturing process. One objective of the investigation was to determine whether this could have been the root cause.

Figure 2
Post-incident view of oil filter housing.

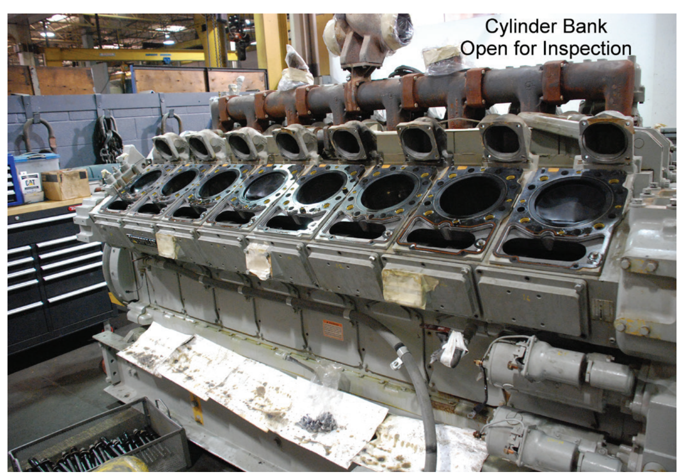


Figure 3
Cylinder bank open for inspection at the Company C shop.

Critical components located high up in the engine, such as the turbocharger shafts and bearings, indicated exposure to fine metal particles. The engine's sump contained metal fines, and the suction screen had metal particles embedded within it. The presence of fines within the sump (immediately after an oil change) suggested that fines were not being picked up by the oil filtration system.

The four new and four old oil filter canisters that were on the engine were identified as crucial to the investigation. The four new oil filter canister exteriors were examined visually at the site, and maintenance staff were requested to keep them with the engine for opening and inspection of the filter elements. However, they were misplaced somewhere between the garage and the remanufacturing facility, which prevented additional evaluation of the quantity and distribution of metal particles in the engine, under a few minutes of exposure to a new supply of oil and new filters.

In the lower engine, each of the bearing shells for the main and rod journals had notable contamination, again from metal particles, with some concentrated damage on big end and rod cap inserts for #7 and #8 cylinders (see **Figures 4** through **8**). Light wear was reported on the shanks of some cap bolts, showing movement and contact with the rod cap had occurred, such as bolt thread impressions (**Figure 9**). The crankpin journals for cylinders #7 and #8 were examined, and these showed (**Figure 10** through **13**) symptoms of frictional overheating and premature wear.

Figures 14 and **15** depict the crank throw shell sets, with the significant difference in appearance for cylinders #7 and #8 sets, while the heat discoloration damage can be seen in the shell on the fourth support block.

Figure 4
Shell damage on rod cap for cylinder #7.

Figure 5
Destroyed big end shell for cylinder #7.

Figure 6
Shell damage on rod cap of cylinder #7.

Figure 7
Shell damage on big end for cylinder #8.

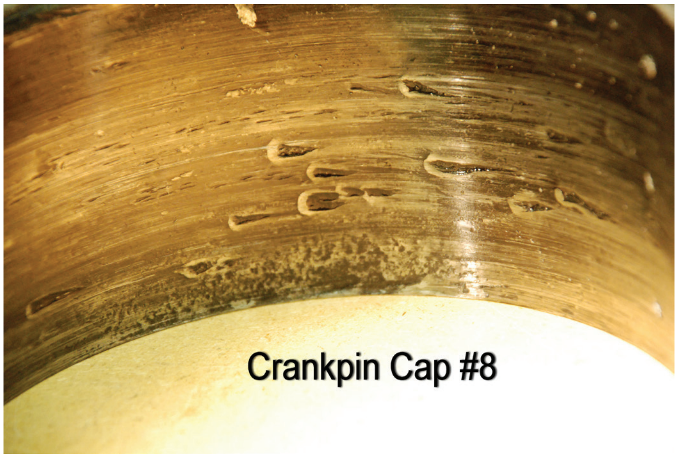


Figure 8
Shell contamination and damage on rod cap, cylinder #8.

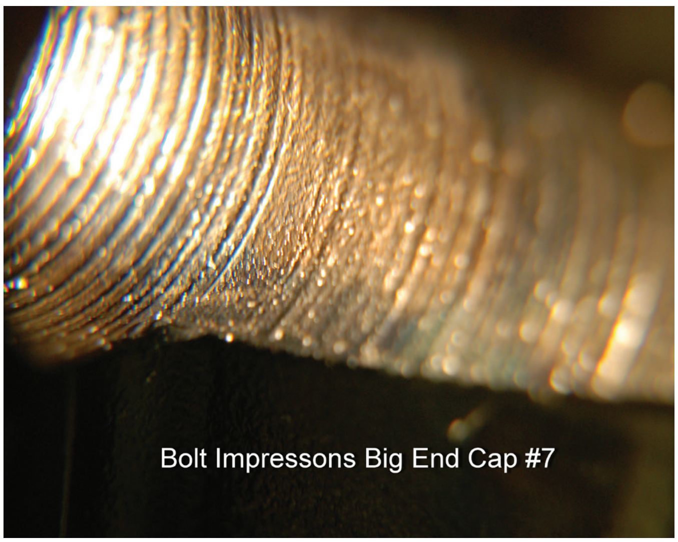


Figure 9
Bolt thread impressions on the rod cap, cylinder #7.

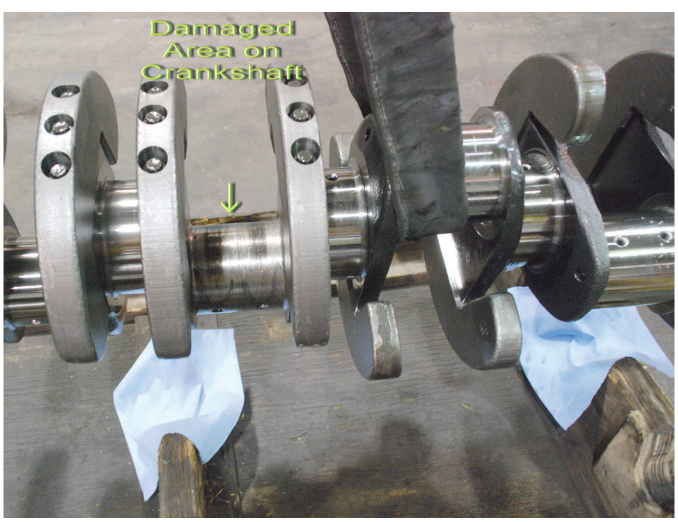


Figure 10
Damaged area on crankshaft rod journal for cylinders #7 and #8.

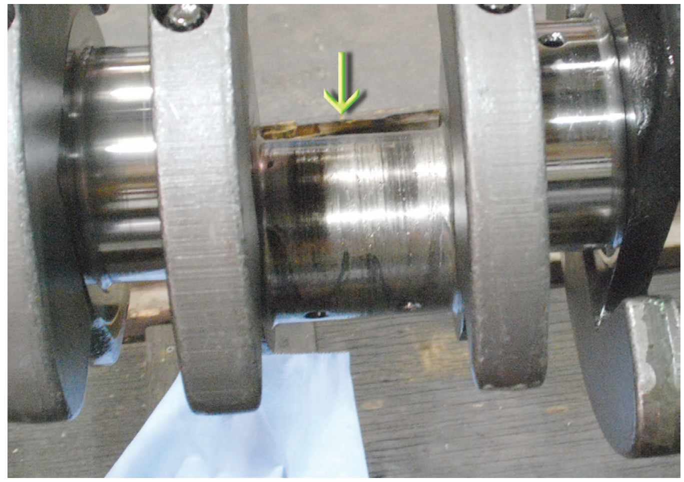


Figure 11
Damaged rod journal for cylinders #7 and #8.

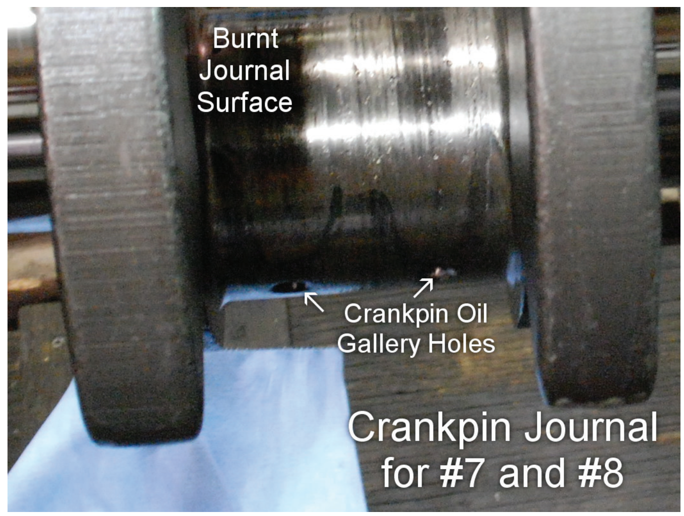


Figure 12
Zoom in on damaged rod journal, cylinders #7 and #8.

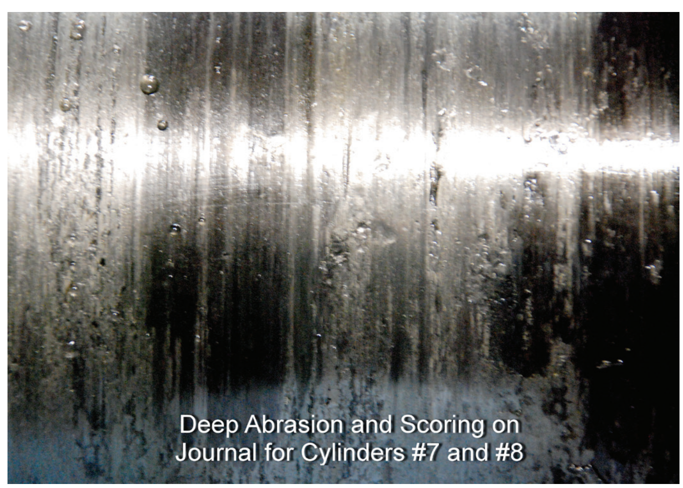


Figure 13
Deep abrasion and scoring at
the rod journal for cylinders #7 and #8.

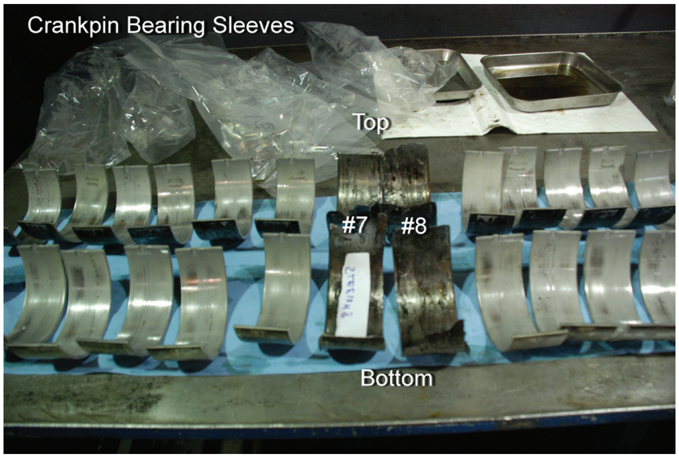


Figure 14
Crank throw shell sets — big end (top) and rod cap (bottom).

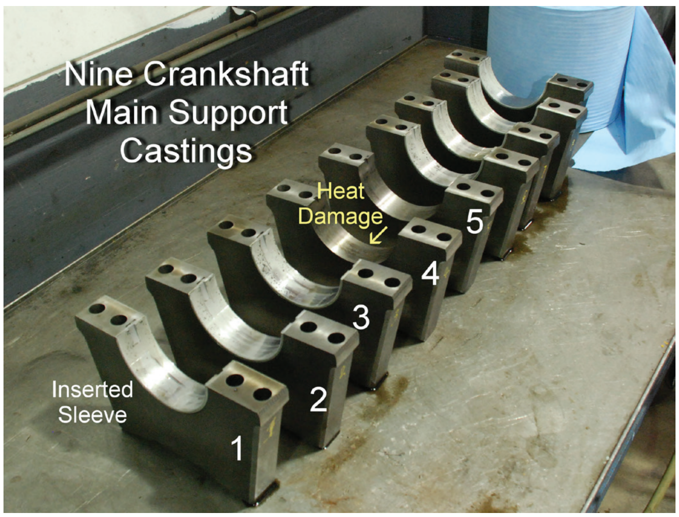


Figure 15
Crankshaft support castings with
inserted shells for the main journals.

The engine oil pump gears are driven by the front gear train, and the engine oil is pulled by the oil pump from the pan through a suction bell (with a screen) and elbow. The engine oil is pumped past the engine oil cooler (**Figure 16**) and the engine oil filter housing via the pipe to the main oil gallery in the cylinder block.

The engine oil bypass valve will open if the oil cooler becomes plugged or the engine oil is too thick. According to the engine service manual, if the oil filters become blocked during operation, this regulator opens the bypass to keep oil flowing to the engine. The pressure difference for this to occur is from 26 to 29 +/- 1 p.s.i. (180 to 200 +/- 7 kPa). The oil flow regulator and the bypass assembly were found to be in normal operating condition, ruling out oil starvation because of blocked filters or bypass malfunctions at the cooler or the filter housing. Given that most

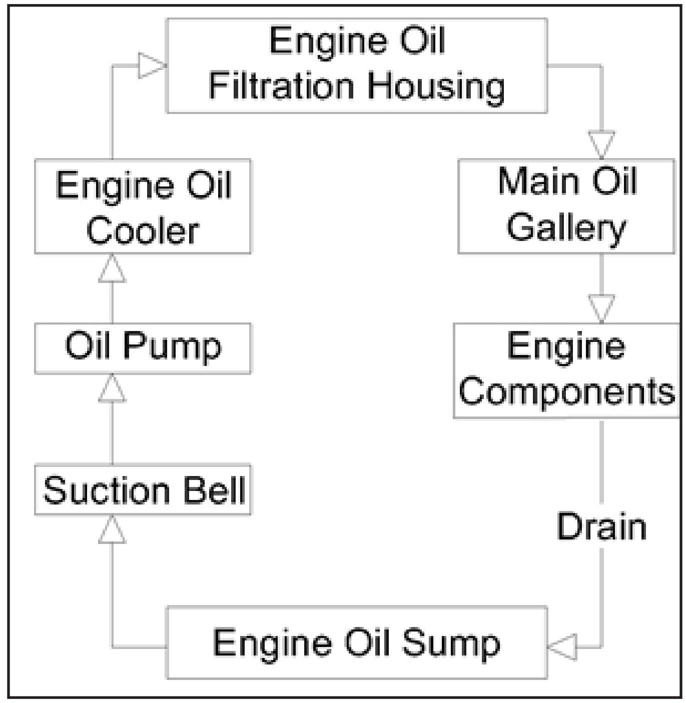


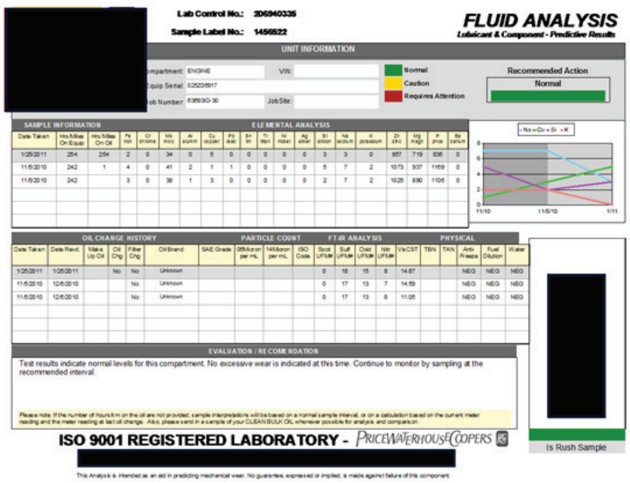
Figure 16
Approximate oil path configuration in the engine.

other bearings were found in good condition, the author concluded that they were being supplied with lubricant. This is consistent with the run to destruction philosophy, as the engine will run longer with dirty oil than with a limited supply.

After passing through the oil filters at the front of the engine, the filtered engine oil goes through an adapter into the cylinder block, circulating into the main oil gallery, with part of the flow going to the left camshaft oil gallery.

An oil analysis was completed after the incident on the new oil supplied on Nov. 10, 2011, and the findings compared to previous yearly oil test results. These were found to be in the normal range for wear elements such as copper and zinc (**Figures 17** and **18**). Given the normal range of results from the prior year, when extra elemental content would arise from premature wear, it followed that the degradation of the sleeves was a recent event, rather than one that occurred years earlier.

The symptoms of localized overheating and major oil supply failure to just two of the bearings on a common crank pin required that careful attention be paid to the side passages supplying oil to those areas. A boroscope with digital viewing screen was used to probe the side passages (**Figure 19**). The length for the probe to reach within to the other side of the main gallery in the block was 8.75 in.



[redacted]

Lab Control No.: 206940335
Sample Label No.: 1456522

FLUID ANALYSIS
Lubricant & Component - Predictive Results

UNIT INFORMATION

[redacted]mpartment: ENGINE VIN:
[redacted]quip Serial: 025Z06917
[redacted]ob Number: 63693ID-30 Job Site:

Normal
Caution
Requires Attention

Recommended Action
Normal

SAMPLE INFORMATION			ELEMENTAL ANALYSIS																	
Date Taken	Hrs/Miles On Equip	Hrs/Miles On Oil	Fe iron	Cr chrome	Mo moly	Al alumin	Cu copper	Pb lead	Sn tin	Ti titan	Ni nickel	Ag silver	Si silicon	Na sodium	K potassium	Zn zinc	Mg magn	P phos	Ba barium
1/25/2011	254	254	2	0	34	0	5	0	0	0	0	0	3	3	0	857	719	835	0
11/5/2010	242	1	4	0	41	2	1	1	0	0	0	0	5	7	2	1073	937	1169	0
11/5/2010	242		3	0	38	1	3	0	0	0	0	0	2	7	2	1025	890	1106	0

Na Cu Si K
8 6 4 2 0
1/1/10 11/5/10 1/11

OIL CHANGE HISTORY						PARTICLE COUNT				FT-IR ANALYSIS				PHYSICAL					
Date Taken	Date Recd.	Make Up Oil	Oil Chg	Filter Chg	Oil Brand	SAE Grade	06Micron per mL	14Micron per mL	ISO Code	Soot UFM#	Sulf UFM#	Oxid UFM#	Nitr UFM#	VisCST	TBN	TAN	Anti-Freeze	Fuel Dilution	Water
1/25/2011	1/25/2011		No	No	Unknown					0	18	15	8	14.87			NEG	NEG	NEG
11/5/2010	12/6/2010			No	Unknown					0	17	13	7	14.59			NEG	NEG	NEG
11/5/2010	12/6/2010			No	Unknown					0	17	13	8	11.05			NEG	NEG	NEG

[redacted]

Is Rush Sample

EVALUATION / RECOMMENDATION

Test results indicate normal levels for this compartment. No excessive wear is indicated at this time. Continue to monitor by sampling at the recommended interval.

Please note: If the number of hours/km on the oil are not provided, sample interpretations will be based on a normal sample interval, or on a calculation based on the current meter reading and the meter reading at last oil change. Also, please send in a sample of your CLEAN BULK OIL whenever possible for analysis and comparison.

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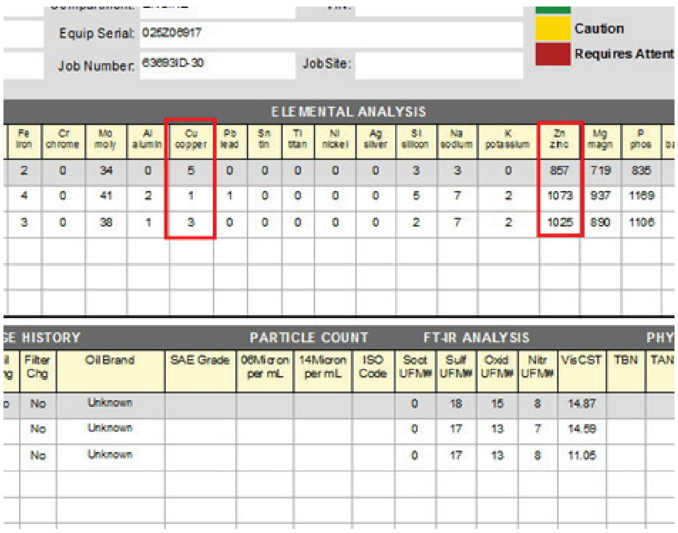
[redacted]

This Analysis is intended as an aid in predicting mechanical wear. No guarantee, expressed or implied, is made against failure of this component.

Figure 17
Oil analysis history for the engine.



Equip Serial: 025Z06917
Job Number: 63693ID-30 Job Site:

Caution
Requires Attent

ELEMENTAL ANALYSIS															
Fe iron	Cr chrome	Mo moly	Al alumin	Cu copper	Pb lead	Sn tin	Ti titan	Ni nickel	Ag silver	Si silicon	Na sodium	K potassium	Zn zinc	Mg magn	P phos
2	0	34	0	5	0	0	0	0	0	3	3	0	857	719	835
4	0	41	2	1	1	0	0	0	0	5	7	2	1073	937	1169
3	0	38	1	3	0	0	0	0	0	2	7	2	1025	890	1106

E HISTORY		PARTICLE COUNT				FT-IR ANALYSIS					PHY	
Filter Chg	Oil Brand	SAE Grade	06Micron per mL	14Micron per mL	ISO Code	Soot UFM#	Sulf UFM#	Oxid UFM#	Nitr UFM#	VisCST	TBN	TAN
No	Unknown					0	18	15	8	14.87		
No	Unknown					0	17	13	7	14.59		
No	Unknown					0	17	13	8	11.05		

Figure 18
Zoom in on oil element analysis.

Figure 19
Probe of side passage from main
oil gallery to cylinders #5 and #6 — all clear.

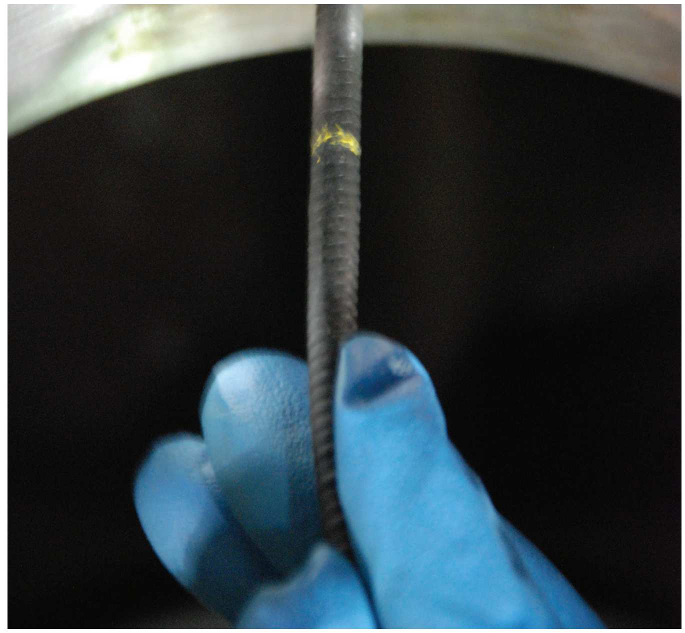


Figure 20
Recreation of the detection of obstruction
within the port for main #4 and cylinders #7 and #8.

(222 mm). However, during the inspection of the lateral port leading to cylinders #7 and #8, the probe met an obstruction at 7.5 in. (190 mm) depth, as shown in **Figure 20**.

The dark foreign object was visible in the boroscope device screen (**Figure 21**). Continued inspection along the length of the main gallery within the block found this dark object at 35 in. (890 mm) from the front end of the engine (**Figure 22** and **Figure 23**). The object was carefully removed by the mechanics with a pincer attachment on a telescopic rod. The object was 3-in. OD, 1½-in. ID, black rubber polymer gasket, with the letters NX 1 visible on one side (**Figure 24**).

Figure 21
Boroscope screen image with foreign object.

Figure 22
A longitudinal view toward the foreign object in the main oil gallery.

Figure 23
Removal of the object with a telescopic tool.

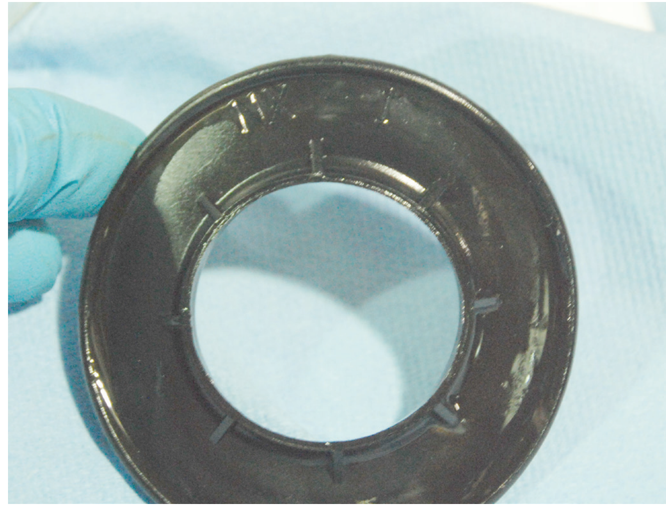


Figure 24
Foreign object extracted from the engine.

Figure 25
Comparison of Company D gaskets and the foreign object.

Continued disassembly of the engine did not reveal any alternate means of causing oil starvation to the crankshaft bearings of cylinders #7 and #8. The obstruction did not affect oil flow downstream from the main gallery to the other six cylinders, suggesting that only the port jointly serving these two was partially or fully blocked.

Analysis

When compared to the components of a Company D brand oil filter taken from the site, it was immediately apparent (**Figure 25**) that the foreign object was an inner end gasket from such a filter. The found object was still flexible, soft to the touch, and did not appear to have physically degraded by heat, when compared to the one just removed from the Company D filter. It wanted to retain its curved shape, matching the diameter of the main oil gallery, suggesting that some permanent set had been acquired. The width of the ring was wide enough to fully block the oil port. The lines seen in **Figure 24** were a portion of the letters identifying the gasket. The original equipment manufacturer's (Company C) canister was a different configuration with similar overall length (**Figure 26**). The Company D model had an outer and inner gasket, while the original equipment model had only the outer gasket ring, as seen in **Figure 27**.

The evidence showed that the rubber gasket escaped from the end of a canister and entered into the oil delivery system manifold and piping — and that it became lodged at the main oil gallery port for cylinders #7 and #8. This reduced and restricted oil flow to the journal, and initiated the overheating and wear issues.

The current set of filters were witnessed being put in place during the oil change operation, and each had gaskets in the expected place. It was inferred from this fact that the gasket had to have come from a prior annual oil change, rather from the current one.

Since the canisters were not OEM style, it was deduced that the replacement with Company D style canisters had to have happened after the first year of operation,

Figure 26
Company D and Company C OEM canisters were compared.

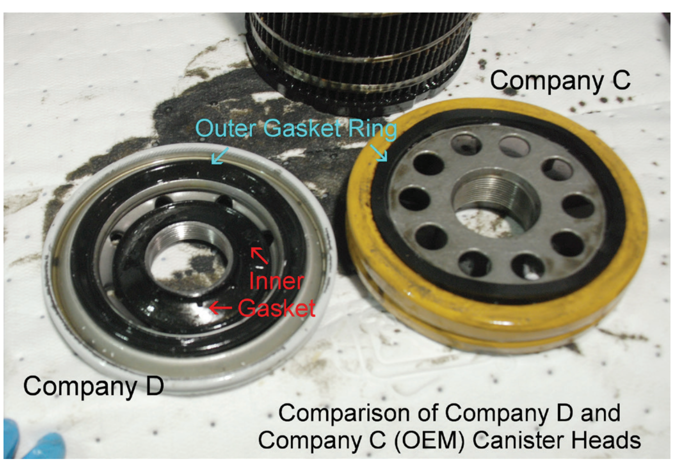


Figure 27
Comparison of different model canister heads.

but before the current date. This gave a range of five to six years; however, the scope of damage was restricted to one area and did not correspond to several hundred hours of running time without lubrication.

The theoretical gasket path based on engine schematics was reviewed to determine how the gasket had travelled almost three feet into the engine. **Figure 28** shows the probable path in red from the entry point in the engine oil filtration housing to the blockage at the port in the main oil gallery. The gasket would be pushed along the path by oil pressure in the system.

The gasket had to pass from the top of the Company D model canister, into the port in the oil filter housing, shown in **Figures 29** and **30**. Each of the four housing positions contains one port, but there were no means of determining which port the gasket had entered. In **Figure 29**, the cut-away end of the Company D model canister is shown. Note: This is put on from below, such that if a gasket “stayed behind” as seen in **Figure 30**, it might not be visible from above (**Figure 2**).

The potential path of the folded gasket was traced through the port (**Figure 31**) and up into the housing (**Figure 32**). From here, the gasket must cross into the supply pipe to the engine (**Figure 33**) and past the end of this pipe at the engine end (**Figure 34**). The gasket must pass by the adapter and then into the main oil gallery (**Figures 35** and **36**).

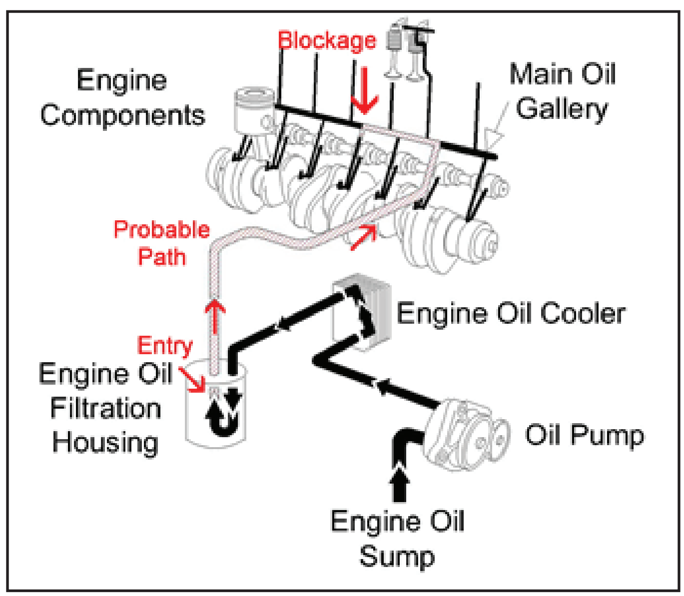


Figure 28
Probable path of the gasket from
the oil filtration housing to the blockage location.

Figure 29
Underside view of housing with port, with underside tope of a Company D filter.

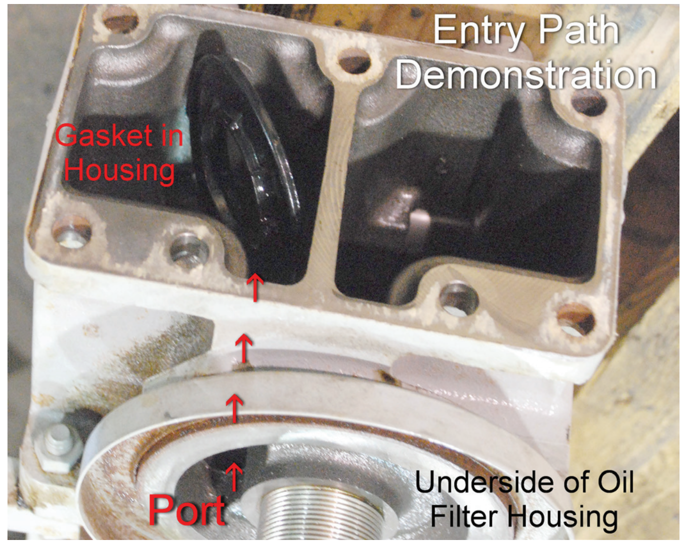


Figure 32
Entry path demonstration from port into housing.

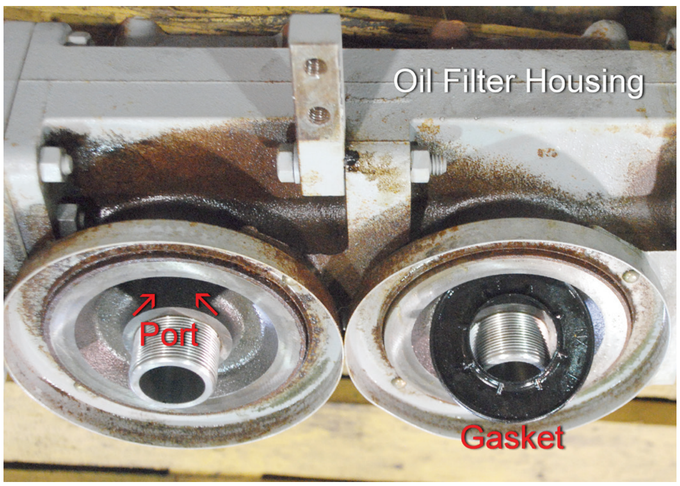


Figure 30
Underside of housing with port and gasket in loss position.

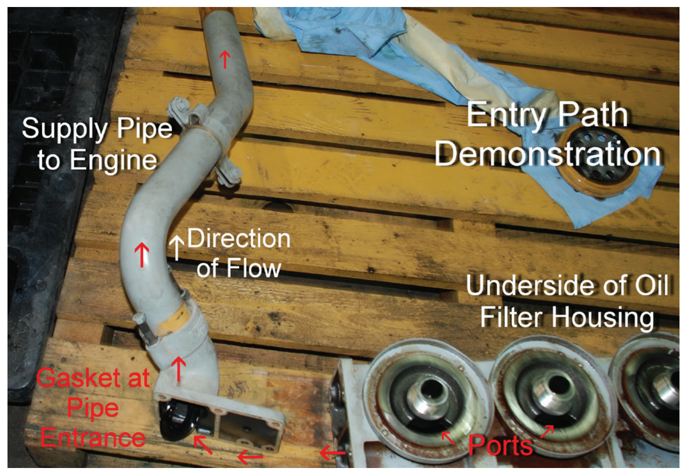


Figure 33
Entry path from housing into supply pipe.

Figure 31
Gasket folded into port demonstration.

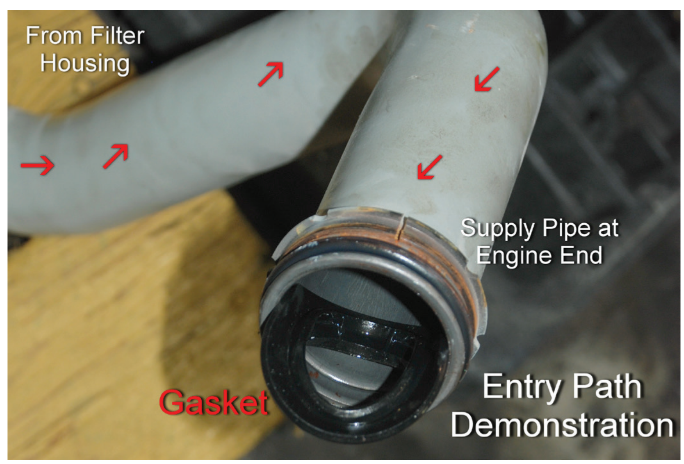


Figure 34
Continued entry path into end of supply pipe.

Gasket movement during the initial start-up on the day of the incident was considered but ruled out because the oil starvation and overheating evidence did not correspond to only three to five minutes without oil. This gasket was not degraded by heat, but it had become semi-permanently set to the curvature of the main oil gallery, which would have taken some time to induce. Had it been in place and exposed to localized heating, its properties would be expected to change.

The gasket was likely pushed along until a balance between friction with the main oil gallery wall and the flow kept it in place. The combination of the force from oil pressure and the tendency of the gasket to resist bending were enough to keep one side firmly against the port, partially or completely blocking flow to main #4 and the rod journal for #7 and #8 cylinders. The latter force kept the gasket in place — up until it was discovered during the overhaul.

Much thought was directed to the mechanism of detachment and entrapment of the gasket, the exemplar of which could be removed easily by hand from the end of a Company D filter canister. The chain of events leading to the movement of the gasket into the engine required that the gasket would have become loose when a canister was changed, sit near the bottom of the stem, and then free up from the threaded stem, before being rotated upward in place while the replacement filter was screwed in place. The gasket must come off the stem, which would otherwise hold it in place between the housing and the new filter canister. This is the key to permitting the gasket entry. Purposeful action (sabotage) was considered, but there were no obvious motives for such an act — and it was discounted as unlikely.

Company B performed independent tests to attempt to loosen a gasket on a canister under typical operating conditions, and could not duplicate or create a scenario in which the gasket would leave the end of the canister and pass into the engine. Its technicians were last in contact with the four oil filters on the engine but could not explain what had happened to these, or the four that had been on the engine before the incident. An argument of spoliation was put up against Company B by the plaintiff's counsel.

Company D also tested its aftermarket canister and compared it to Company C's OEM unit. Under low flow conditions, at between 50 to 70 p.s.i., the Company D version could not loosen the gasket on the current style.

The OEM canisters are much more expensive than the Company D version. On the other hand, there would have been absolutely no opportunity for a gasket from a Company C model to escape, since there was no inner ring gasket on that model at all.

Without an ECM to download because it was a mechanically driven diesel, there were no data showing temperature increases in the areas affected by oil starvation, until the catastrophic failure date. The presence of an ECM might have detected temperature problems at cylinders #7 and #8, inducing an auto-shutdown and preventing the engine damage.

Another firm, Company E, had provided service and oil changes at beginning of the engine's life, so there were questions about whether it was that company or Company B that would have been responsible. Whether or not Company E had used OEM canisters or Company D style canisters during that period was also a point of contention.

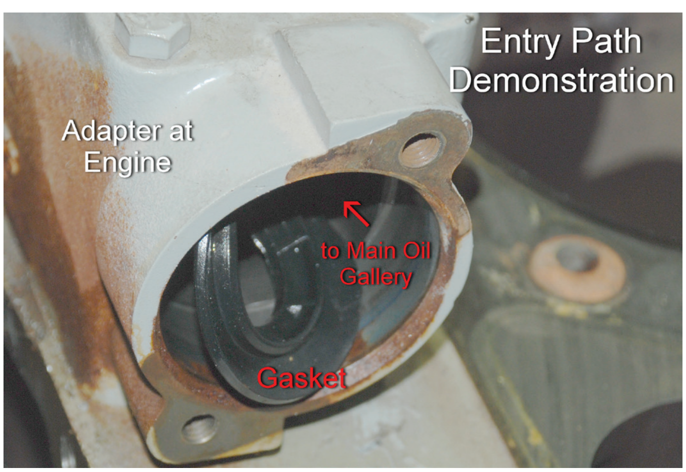


Figure 35
Entry path of gasket at the adapter on the engine.

Figure 36
Entry path at the side of the engine block into the main oil gallery.

The active blockage ruled out the possibility that the big end bolts had been loose at the time of the manufacturing of the engine by Company C, and this was discounted.

To have prevented the incident, a technician would have needed to notice that the gasket of the older canister was missing, and then undo the new canisters, in turn, to discover its location prior to it entering into the housing.

Discussion

The evidence was clear that a foreign object blocked the port in the main oil gallery to a certain pair of cylinders, leading to an absence of lubrication, which, in turn, engendered frictional heating to the level at which the unlubricated bearing material could deform and detach. The debris from this failure bypassed the filter assembly and engaged the engine's bearings and turbocharger components, resulting in significant damage.

The engine was operated monthly for several hours, which (for this type of diesel engine that typically lasts thousands of hours) was at the front end of its expected service life. The engine was not expected to have any wear or overheating issues. At its typical speed of 1,800 revolutions per minute (or 108,000 revolutions per hour), it would have had only about 26 million revolutions completed at the time of the incident. The engine was barely broken in, compared to similar models in the field.

The physical properties of the gasket were not assessed with FTIR or other methods, although this may have provided insight into heat exposure. The gasket was soft and undamaged when found in the engine, with only minor semi-permanent set, which suggests a medium range rather than a short period of exposure — or possibly at high temperature for a brief period.

The gasket can be present and be pushed along and through the manifold, yet not create havoc until it blocks a gallery porthole. It must come from the front of the engine through the adapter into the main oil gallery. **Figures 29** through **36** showed the probable path that it took before it was lodged in the oil supply port for the main journal #4 and the rod journal for cylinders #7 and #8. The gasket demonstrably fitted in each part of the path, when folded over upon itself.

Even though the proverbial "smoking gun" had been revealed, there was substantial uncertainty about how long it took for the blockage to develop once the gasket was left in the oil pipe. As a result of this uncertainty and that of the involvement and the timing of the interventions, the specific negligent party remained unidentified.

Conclusions

1. The diesel engine catastrophically failed when there was an oil starvation event for cylinders #7 and #8, caused directly by a foreign object that traveled into the engine until it became lodged about halfway down the main oil gallery, partially or fully blocking the oil porthole for these cylinders and main journal #4.

2. The method of entry of the rubber gasket into the engine was postulated, but was not conclusively identified, as through the oil filter housing assembly.

3. The gasket, given its exact similarity to a gasket from Company D's filter canister, must have originated from such a filter model.

4. Since the oil circuit is closed to the outside, an external human intervention was necessary to allow entry of the gasket into the oil circuit.

5. In the absence of ECM downloads for this mechanically controlled engine, the maintenance and oil analysis records were not enough to derive a valid conclusion about when the gasket had entered into the oil distribution system, or at which of six oil changes this had occurred.

6. As a result of this uncertainty in the involvement of the companies and the timing of the interventions, the specific negligent party remained unidentified.

Epilogue

Sometimes, even with the "smoking gun" in hand, one cannot develop a definitive opinion on causation from which the trier of fact may base its assessment of relative liability. The matter settled at mediation.